Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2025/063

Maritimes Region

Eastern Scotian Shelf Northern Shrimp (*Pandanus borealis*) Stock Assessment Framework: Model, Indicators, and Reference Point Development

R. R. McDonald, M. Cassista-Da Ros, and J. Cosham

Population Ecology Division
Fisheries and Oceans Canada
Bedford Institute of Oceanography
P.O. Box 1006, 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

September 2025

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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-78737-4 Cat. No. Fs70-5/2025-063E-PDF

Correct citation for this publication:

McDonald, R., Cassista-Da Ros, M., and Cosham, J. 2025. Eastern Scotian Shelf Northern Shrimp (*Pandalus borealis*) Stock Assessment Framework: Model, Indicators, and Reference Point Development. DFO Can. Sci. Advis. Sec. Res. Doc. 2025/063. viii + 209 p.

Aussi disponible en français :

McDonald, R., Cassista-Da Ros M., et Cosham, J. 2025. Cadre d’évaluation des stocks de crevette nordique (Pandalus borealis) de l’est du plateau néo-écossais : Élaboration du modèle, élaboration des indicateurs, et des points de référence. Doc. de rech. 2025/063. ix + 221 p.

ACRONYMS

ACF – Autocorrelation Function

AIM – An Index Method

AO – Area Occupied

AR – Autoregressive

AZMP – Atlantic Zonal Monitoring Program

CDD – Commercial Data Division

CL – Carapace Length

CPUE – Catch Per Unit Effort

CQ – Competitive Quota

CSAS – Canadian Science Advisory Secretariat

DFO – Fisheries and Oceans Canada

EAFM – Ecosystem Approach to Fisheries Management

ESS – Eastern Scotian Shelf

FRV – Fishery Research Vessel

FSP – Fish Stock Provisions

GoM – Gulf of Maine

GPS – Global Positioning System

GSL – Gulf of St. Lawrence

HCR – Harvest Control Rule

IFMP – Integrated Fishery Management Plan

IQ – Individual-vessel Quota

ITQ – Individual Transferrable Quota

LOA – Length Over All

LRP – Limit Reference Point

LW – Length-Weight

MARFIS – MARitimes Fisheries Information System

NAFO – Northwest Atlantic Fishing Organization

NL – Newfoundland and Labrador

NOAA – National Oceanic and Atmospheric Administration

PA – Precautionary Approach

PACF – Partial Autocorrelation Function

QA/QC – Quality-Assured and Quality-Controlled

QQ – Quantile-quantile

RPS – Recruits Per Spawner

RR – Removal Reference

RV – Research Vessel

SDD – Simplified Delay-Difference

SEAM – Spatially Explicit Assessment Model

SFA – Shrimp Fishing Area

SPDE – Stochastic Partial Differential Equations

SRR – Stock-Recruit Relationship

SS – Scotian Shelf

SSB – Spawning Stock Biomass

SSM – State-space Model

SST – Sea Surface Temperature

TAC – Total Allowable Catch

TLA – Traffic Light Approach

TLM – Tow Level Model

TMB – Template Model Builder

MSY – Maximum Sustainable Yield

USR – Upper Stock Reference

VMS – Vessel Monitoring System

VRN – Vessel Registration Number

WSS – Western Scotian Shelf

TABLE OF CONTENTS

ABSTRACT

The Eastern Scotian Shelf (ESS) Northern Shrimp fishery has been ongoing since the early–1980s, although its contemporary history began in 1991 with introduction of the Nordmøre grate that reduced bycatch and enabled fishery expansion. In support of the fishery, an ESS Northern Shrimp stock framework CSAS peer-review was held over two meetings:

1. model development was peer-reviewed at a first meeting held on October 29–31, 2024; and
2. new indicators for the traffic light approach (TLA) were examined in context of the new model, and options for a new limit reference point (LRP) based on modeled results, were peer-reviewed at a second meeting held on March 5–6, 2025.

This research document describes development of a stock assessment model for the ESS Northern Shrimp fishery in Shrimp Fishing Areas (SFA) 13, 14, and 15, as no analytical models have previously been implemented in these areas. Aspects of species and stock's biology, distribution, and stock structure are presented, along with a brief description of the history of stock assessment for the fishery, in order to contextualize new developments. Data sources include fishery-dependent data from logbooks, port samples and observer trips, and fishery-independent data from the Fisheries and Oceans Canada (DFO)-Industry survey, which deploys both a main trawl and a specialized belly bag. Three models —simplified delay-difference (SDD), tow level model (TLM), and Spatially Explicit Assessment Model (SEAM) — are described, fit to available data, and results compared to each other. While the SDD was deemed inappropriate for the ESS Northern Shrimp stock, both the TLM and SEAM indicated that exploitation rates have been relatively consistent over time, although ESS Northern Shrimp productivity has declined consistently since 2005, with 2023 demonstrating a marked decline and departure from past productivity expectations. There is evidence that the fishery has impacted stock dynamics, as both models indicated that biomass tends to decrease with exploitation rates above 6%. Both SDD and SEAM indicated that the least biased 1-year projection method was the mean growth approach. While both models are adequate for assessing the ESS Northern Shrimp stock, SEAM outperformed TLM, especially in terms of recruitment. As such, it is recommended that SEAM be used to provide science advice for the ESS Northern Shrimp stock using the median growth approach for 1-year stock projections. In the terms of reference points and indicators, results showed that LRPs based on maximum sustainable yield (MSY) simulations are not currently appropriate for the stock. An LRP based on an historical proxy for the theoretical long-term equilibrium biomass, in the absence of fishing (B_0), is proposed instead. In addition, most of the legacy TLA indicators demonstrated clear utility in the context of yearly science advice, with only a few inadequate indicators (i.e., Age 2, Snow Crab, Cod Recruitment, Turbot Abundance) being replaced by new and more useful indicators (i.e., Shrimp Bycatch, Area Occupied, and Atlantic Cod, Turbot, and American Plaice). In conclusion, the SEAM model, LRP, and stock indicators outlined in this framework research document received consensus support from peer-reviewers and meeting participants for use moving forward to assess the ESS Northern Shrimp stock.

INTRODUCTION

In support of the Eastern Scotian Shelf (ESS) Northern Shrimp (*Pandalus borealis*) fishery, a stock framework CSAS peer-review was held over two meetings:

1. model development was peer-reviewed at a first meeting held on October 29–31, 2024; and
2. new indicators for the traffic light approach (TLA) were examined in context of the new model, and options for a new limit reference point (LRP) based on modeled results, were peer-reviewed at a second meeting held on March 5–6, 2025.

Results presented herein will be used to establish a science framework to assess the status of the ESS Northern shrimp stock. Information on both peer-review meetings can be found on the Fisheries and Oceans Canada (DFO) Canadian Science Advisory Secretariat (CSAS) website.

BACKGROUND

The ESS Northern Shrimp fishery in shrimp fishing areas (SFAs) 13–15 was established in the late-1970s, after initial exploratory trawling and research trawl surveys confirmed commercial abundances of shrimp stocks in these areas (Mohn and Etter 1982). The SFA 13–15 are among 17 defined areas in the Atlantic region delimited by the Canadian 200-mile exclusive economic zone (Figure 1). Traditionally, commercial fishing has occurred in four areas of the ESS – Louisbourg Hole, Misaine Hole, Canso Hole, and an inshore area known as Bad Neighbour Shoal – all within Northwest Atlantic Fishing Organization (NAFO) divisions 4Vn and 4VsW (Figure 2). The Nova Scotia shrimp fishery expanded to its full potential once it was no longer limited by bycatch (or 'choke species') restrictions with introduction of the Nordmøre grate in 1991 (Figure 3). The Total Allowable Catch (TAC) was first reached in 1994, when individual SFA quotas were removed and replaced with an ESS region-wide TAC.

In the mid-1990s, more exploratory fishing occurred in inshore areas, leading to establishment of the Chedabucto Bay trap fishery in 1999 (Koeller et al. 1995). This development created an operationally-unique fishery, with the SFA 13–15 shrimp stock being commercially-harvested under two well-defined fishing practices. These two commercial fishing sectors, mobile and trap, now operate under a year-round quota, where a percentage of the annual TAC is allocated to each sector. In 1999, the TAC allocations were initially set at 90% and 10% for mobile and trap sectors, respectively. In 2005, the TAC allocations were revised to 92% and 8% for mobile and trap sectors, respectively, and have remained at these levels since this time. As described in the ESS Northern Shrimp Integrated Fisheries Management Plan (IFMP), the two sectors negotiate annually on transfers of uncaught trap quota from the trap fleet to the mobile fleets (DFO 2011). Table 1 shows annual catch in metric tonnes (mt) by commercial sectors and across SFAs since 1980, including the associated TAC allocation.

There are 56 shrimp fishing licences distributed across three separate fleets: 28 are individually owned licenses by the Scotia mobile fleet; 14 are owned by the Gulf mobile fleet; and 14 are owned by the Scotia trap fleet. Of these, Indigenous First Nations own 15 of the Scotia mobile fleet licences and one of the trap fleet licences. There have been no changes to the number of permanent licences in the fishery since 2005 (Hardie et al. 2018). Table 2 shows the number of active vessels across commercial sectors in the ESS Northern Shrimp fishery since 1993.

Since Northern Shrimp survival is strongly linked to temperature and predation pressures, both of which can be highly variable spatially and temporally, this stock was recognized to be a good fit to develop a spatio-temporal model to estimate stock biomass, while also accounting for variation in the aforementioned pressures. In addition, Northern Shrimp has substantial value as a forage species, so the fishery must not threaten conservation of other species for which Northern Shrimp is an important food source. The DFO Policy on New Fisheries for Forage Species ensures fisheries that target forage species are conducted in a manner that is compatible with conservation of the full ecosystem and that their sustainability is evaluated within an ecosystem context (DFO 2009a).

Current ESS Northern Shrimp fishery management measures in SFA 13–15 include:

- Fishing Season: Year-round quota (January 1st to December 31st);
- Nordmøre grate in all trawls of mobile sector vessels;
- Number of licenses: 56;
- Individual Transferable Quotas (ITQ) for mobile sector and Competitive Quota (CQ) for trap sector;
- Annual TAC, with mobile and trap sector allocations;
- Trap Limit: 100 per license; and
- Minimum trawl mesh size: 40 mm.

BIOLOGY AND ECOLOGY

SPECIES BIOLOGY

Northern Shrimp, *Pandalus borealis*, is a caridean ('true shrimp') species that has been of commercial importance for centuries (Gillett 2008). This crustacean has a life cycle similar to other decapod crustaceans characterized by several stages including egg, larva, juvenile, and adult, moulting its exoskeleton to grow and develop through each subsequent stage (Figure 4). Eastern Scotian Shelf Northern shrimp longevity can vary, but has been observed to extend beyond six years depending on locality and time (Shumway et al. 1985; Bergström 2000). Most Northern Shrimp exhibit protandrous sequential hermaphroditism, hatching as males and eventually transitioning into females; a unique biological feature linked to reproductive success. For this reason, faster growth coupled with lower mortality in males increases reproductive success of ESS Northern Shrimp (Henshaw 2018). Typically, mature females mate in late-summer/early-fall soon after moulting, while mature male shrimp fertilize the eggs as they are oviposited on the female's abdomen to form an external clutch (Shumway et al. 1985). Females carrying an egg clutch are referred to as 'ovigerous females', with this period lasting until spring. Around this time, eggs hatch into fully developed Stage I zoeae. The larvae then undergo a 2–3 month development period, with several pelagic zoea stages before settling to the bottom as post-larvae (Ouellet and Allard 2006).

Post-larval stages are benthic and exhibit nocturnal vertical migration (Shumway et al. 1985; Richards and Hunter 2021). Juveniles are commonly found in coastal waters before migrating offshore to join the mature stock. On the ESS, the majority of Northern Shrimp reach sexual maturity within their second year as males and enter a transitional stage to female at about Year 4 (20–23 mm carapace length) followed by a primiparous (first-time spawner) and a multiparous (repeat spawner) stage (Koeller 2006).

Much research has been conducted to further describe the timing and size at which Northern Shrimp initiate female transition (Charnov 1982; Charnov and Skùladóttir 2000; Koeller 2000,2006; Koeller et al. 2003). The ESS Northern Shrimp size-at-sex transition and maximum size are largely determined by growth rate rather than by density; although density may play a role in the timing of sex transition. Under cooler environmental conditions, Northern Shrimp grow more slowly, change sex later, and live longer, reaching a larger maximum size. Alternatively, faster growing shrimp under warmer environmental conditions initiate an earlier transitional stage and thus reach a smaller maximum size sooner (Hardie et al. 2018). Plasticity in this growth response, and the onset of the transitional stage, results in the growth rates being strongly influenced by variable environmental factors throughout all stages of the species life cycle (Koeller 2006).

Size-at-sex transition is an important life history parameter for stock assessment; particularly, when considering the relationship between body size and fecundity. While slow growing shrimp take longer to become female, they produce more eggs due to their larger size. Conversely, although fast growing shrimp become female and begin producing eggs sooner, they are less fecund. In addition, only a portion of very large year classes will change sex each year, which poses a challenge when attempting to use length-frequency tracking to forecast population status in future years.

DISTRIBUTION AND STOCK STRUCTURE

Northern Shrimp have a discontinuous circumboreal distribution, mostly north of the 45th parallel (Shumway et al. 1985). On the Atlantic coast of Canada, the ESS shrimp population is in proximity to the Gulf of St-Lawrence (GSL) shrimp population in the north and the Gulf of Maine (GoM) shrimp population in the south (Figure 5). The GoM population is at the southernmost limit distribution of Northern Shrimp (Apollonio et al. 1986) and by inference this population is at the extreme of its ecological and physiological limits (Koeller 1996).

Northern Shrimp, often described as ‘cold water’ shrimp, typically occur in commercial densities where colder deep water is a prevailing oceanographic feature. This includes areas of the ESS, outer GSL, Newfoundland and Labrador, and as far north as Greenland. Although temperatures over a wide area of the Scotian Shelf are suitable for Northern Shrimp, smaller areas of suitable habitat (described by depth, bottom type, and other features) on the ESS define limits of the commercially-viable population that has shrimp densities high enough to support commercial fishing.

Shrimp fishing areas 13–15 do not represent biological units, rather are based on historical fishing boundaries, with ecologically-relevant divisions occurring on a much broader scale. The marine environment in Atlantic Canada is divided into three bioregions: Newfoundland and Labrador (NL) Shelves, Scotian Shelf (SS), and Gulf of St-Lawrence (GSL), as represented in Figure 6 (Bernier et al. 2018). The characterization of these bioregions is mainly based on geographic differences in oceanic conditions and depth, as well as a recognition of the distinct features within each of these areas (Bernier et al. 2018). Science and management of Northern Shrimp stocks across these predominantly unique bioregions is done independent of each other, although ecologically the three bioregions exhibit some connectivity.

There is potential for larval exchange of Northern Shrimp between geographically-distinct areas at all life stages. However, Northern Shrimp migration patterns differ significantly between the three bioregional stocks, mostly due to differences in temporal and spatial availability of suitable substrate and temperature combinations. For example, temperatures of deep-water habitats are suitable year-round for shrimp in Newfoundland, so inshore migrations are not observed (DFO 2021a). In contrast, in the GoM and in the central and Western Scotian Shelf (WSS) deep water temperatures become too warm in the fall, so shrimp migrate inshore to spawn and then return to the deeper water, offshore area in the spring (ASFMC 2018).

Historically, ESS females and juveniles were found inshore and offshore, suggesting that spawning took place in both areas. Since 2013, however, a spatial shift in the occurrence of juveniles observed in belly bag samples collected from the DFO-Industry collaborative survey suggests that hatching may now be more limited to inshore areas (Figure 7). An increase in bottom temperatures observed on ESS since 2013, which has been near the upper limit for Northern Shrimp in the last few years, has resulted in decline of the high density components of the stock.

The ESS Northern Shrimp population has been experiencing variability in its suitable habitat distribution and in its settlement patterns in larval dispersal over time (Koeller 1996). This is a common observation throughout the North Atlantic ocean, as recent research has demonstrated further evidence of this trend in NL (Le Corre et al. 2019,2020,2021), GSL (Bourdages et al. 2020), and GoM (Richards et al. 2012,2016; Richards and Hunter 2021). Population connectivity through gene flow has also provided a better understanding of stock dynamics between and within the three bioregions (Jorde et al. 2015; Bourret et al. 2024). At a larger scale, the NL, SS, and GSL bioregions have shown genetic differentiation, which suggests limited gene flow between the three areas and highlights the importance of preserving each bioregion's Northern Shrimp stock through short-term and long-term sustainability measures.

On a finer scale, the ESS Northern Shrimp population is genetically-similar between SFAs 13–15, suggesting that the stock is well connected across the three SFAs (Bourret et al. 2024). Bourret et al. (2024) observed an interesting genetic substructure; patterns within SFA 13 that differentiate samples collected near the Laurentian Channel from those collected elsewhere in SFAs 13, 14, and 15. Results showed that winter bottom temperature and annual salinity may explain the genetic distinctiveness in SFA 13. Lastly, samples from SFA 16, located on the WSS and in the Bay of Fundy, revealed genetic differentiation from all other ESS SFAs, with gene flow into SFA 16 likely being from the GoM Northern Shrimp population rather than from ESS SFA 13–15.

Movement patterns in Northern Shrimp within the ESS provide further insight into stock structure. Koeller (1996) proposed a baseline hypothetical description of Northern Shrimp movement that suggests offshore shrimp larvae are transported in a southwesterly direction by the Nova Scotia Current and inshore by wind driven currents in the spring (Figures 8 and 9). Some offshore larvae are distributed further offshore to settle on the Scotian Shelf, and likely beyond, as the species can survive within a broad depth range. As shrimp grow, they gradually move to deeper waters, resulting in a cascading pattern of movement from inshore to offshore; for example, Chedabucto Bay towards Bad Neighbour Shoal, Bad Neighbour Shoal to the Big Hole, and from offshore holes to deeper water.

ENVIRONMENTAL AND ECOSYSTEM FACTORS

Northern Shrimp populations are strongly influenced by various environmental and ecological factors, as is true for many other crustaceans. Factors known to influence Northern Shrimp populations include ocean currents, temperature, depth, dissolved oxygen, salinity, habitat specifications, and prey-predator dynamics. Previous and more recent reports on the status of these factors in the Atlantic zone are available through DFO Canadian Science Advisory Secretariat (CSAS) publications (e.g., DFO 2021b). The most influential factors within the ESS region are discussed in further detail below.

Ocean Currents

The Atlantic Ocean offshore of Canada is heavily influenced by two strong ocean current systems (Figure 9). The Labrador Current transports colder Arctic water along the Newfoundland shelves onto the Scotian Shelf from the north, while the Scotian Shelf is also influenced by warmer waters transported by Gulf Stream water from the south (Casault et al. 2020). These two water masses create a transition zone along the Scotian Shelf, which can generate important shifts in temperature, especially when driven by changes in large-scale atmospheric pressure patterns (Petrie 2007). Residual and wind-driven surface currents on the ESS transport surface waters in a southwesterly direction, which is influenced by the Nova Scotia Current (Koeller 1996). This current originates from freshwater runoff in the GSL and mixes with Scotian Shelf offshore waters (Sutcliffe et al. 1976). This mixing is of biological importance to Northern Shrimp phenology, being an area of strong and constant upwelling.

The nearshore and offshore ocean currents benefit ESS Northern Shrimp by dispersing eggs and larvae, further serving as 'road maps' for the species' migration between areas. Under the influence of these strong currents, finer scale connectivity between the ESS shrimp population show little to no genetic divergence (Jorde et al. 2015), although recent findings by Bourret et al. (2024) provided evidence of some substructure within SFA 13. This insight explains distribution patterns within the ESS and enhances a general understanding of annual variability in stock productivity.

Temperature

From a localized perspective, trends in sea surface temperatures (SST) and bottom temperatures across the ESS are essential for understanding Northern Shrimp stock health and fishery sustainability. Northern Shrimp prefer colder water, and whilst they can be found in water between -1.6ºC and 12ºC, the species on the ESS is most commonly found in aggregations when water temperatures are between 0ºC and 6ºC. Extended periods of exposure to -1ºC water, or colder, have resulted in mass mortality events (Shumway et al. 1985) In contrast, extended periods of exposure to water temperatures greater than 6°C tend to reduce survival of shrimp recruits (pers. obs., Cassista-Da Ros, M., DFO Science). Developmentally, shrimp at all life stages (i.e., larvae, juveniles, and adults) are influenced by water temperature, as moulting frequency is increased at higher temperature (Shumway et al. 1985; Garcia 2007) resulting in early onset of maturity in warmer water and at smaller sizes (Hansen and Aschan 2000).

Depth

Northern Shrimp depth preferences vary with latitude, with higher densities occurring at greater depths and colder temperatures at higher latitudes than those observed in southern parts of the species' range. Northern Shrimp are most commonly found between 50 m and 500 m water depths, although they have been reported at water depths of 1,450 m. Further, the species does undergo diurnal vertical migration and move towards the sea surface at night, resulting in decreased catch rates with a bottom trawl at night.

On the ESS, the aforementioned depth profile for Northern Shrimp occurrence has been consistent throughout the time series, with commercial fishing activity concentrating in areas of greater densities (Figure 10). The ESS commercial trawl fishing activity from 2010 to 2020 has been greater on grounds where water depths are approximately 175 to 320 m, although a narrower depth range was deduced from vessel monitoring system (VMS) data from 2015 to 2020, with 80% of the fishing activity associated with depths ranging from approximately 130 to 255 m.

Habitat

Female Northern Shrimp tend to migrate to shallower waters to release their larvae, and hence, larvae and juveniles are found in different areas than the adults (Shumway et al. 1985). Inshore areas (i.e., Stratum 17 of the DFO-Industry collaborative trawl survey; see: Figure 11) are characterized by the presence of LaHave clay, which historically has been the preferred habitat for Northern Shrimp larval and juvenile stages on the ESS. LaHave clay provides for a soft mud or sand/silt bottom, with the occurrence of young shrimp being strongly correlated with the organic content of bottom sediments. In recent years, there has been a shift towards increased concentrations of larval and juvenile stages on small areas of mud substrate; as a result, local overfishing has become a potential concern in these areas.

If this shift persists, it is unlikely that the ESS could be re-seeded from the next upstream stock in the northern GSL, since there are limits to larval and gene flow (i.e., currents, decreased abundance, and migratory distances). Identifying variability within ESS SFA contributions to the stock would be valuable for the stock's sustainability. Furthermore, the highly-dynamic hydrogeographic regime, with horizontal tides and larval retention gyres larger than the area of suitable habitat, suggests that a high percentage of larvae settle onto unsuitable habitat or that currents carry larvae from the ESS to unsuitable habitats to the west. As a result, the ESS stock may experience high larval vulnerability that could lead to mortality, in which case harvest strategies that take this into account would be prudent, versus for other stocks where re-seeding from surrounding stocks is more likely (e.g. Newfoundland).

Predation

Most groundfish species on the ESS feed on crustaceans at some point in their lives, with shrimp identified as an important dietary component of Atlantic Cod, Silver Hake, redfish, various flatfish, and both Atlantic Halibut and Greenland Halibut (Shumway et al.1985). Since Northern Shrimp are a forage species, predation is an important aspect of stock health, as trends in predation should inform natural mortality. Variation in this trend has been captured from analyses of fish stomachs that have been collected by the DFO Summer Research Vessel (RV) Ecosystem trawl survey (referred to hereafter as the RV Ecosystem trawl survey) since 1995 (Figure 12). Some of these predators have size-selective diets; for example, smaller halibut tend to consume Northern Shrimp more readily than larger individuals. Therefore, diet habits can identify shifts in prey consumption as predators grow in size.

Data associated with the food habits program are largely dependent on collection from the RV Ecosystem trawl survey, where gear selectivity and catchability may not always be representative throughout a species' entire size distribution (i.e., Atlantic Halibut greater than 80 cm). Furthermore, the RV Ecosystem trawl survey receives a substantial amount of sampling requests, which has resulted in limited data availability in some years to help inform ESS Northern Shrimp indicators. As such, ESS Northern Shrimp prey-predator dynamics remain poorly understood, especially when changes in these dynamics and predator/prey abundances occur. Understanding prey-predator dynamics would benefit from more detailed analyses that better define diet composition and prey consumption of known and potential predators.

STOCK ASSESSMENT HISTORY

The ESS Northern Shrimp stock has a long history of stock assessment, with the earliest being presented by Mohn and Etter (1983). During the 1990s and early-2000s, as licences were still being issued, the ESS Northern Shrimp mobile sector was represented by a greater number of licensed vessels from the Gulf fleet and a lesser number of licensed vessels from the Scotia fleet (Table 2). Even though the total number of licences has remained the same since 2005, the number of active vessels has been decreasing across both fleet sectors. Only since 2019 has the Gulf mobile fleet seen a slight increase in active licence counts, while during the pandemic period (i.e., 2020–21) the Gulf mobile fleet was the only fleet where the increased number of active licences was maintained. In 2024, the Scotia fleet had the least number of active licences since the 1990s, while the Gulf fleet and trap fleet numbers decreased to a single active license, respectively, due to the stock's TAC in 2024, which was the lowest observed TAC since 1991 (Table 1).

Early stock assessments were focused on fishery performance, spatial extent, commercial catch rates, survey biomass estimates, and catch composition of survey data. The TAC quotas were allocated by SFA; however, the stock was annually underexploited, with catch totals rarely exceeding 10% of the total quota between 1982 and 1991 (Table 1). Bycatch limited the ESS Northern Shrimp fishery until the Nordmøre grate was introduced in 1991, which significantly reduced the retention of groundfish bycatch species and enabled the fishery to expand (Butler and Robert 1992).

In 1994, an individual SFA-based TAC was replaced by a single overall TAC for the stock (Roddick et al. 1994). Additionally, the Scotia mobile fleet began to operate under Individual-vessel Quotas (IQ) by which point all exploratory licences had been converted to permanent licences. Licence holders from the Gulf agreed to a resource sharing agreement, which limited access to six vessels and fishing 25% of the TAC. With increased commercial activity and landings, size frequency data collection from commercial catches was initiated through the groundfish port sampling program; however, logistics restricted ability to consistently collect samples throughout the year. The expansion of the fishery also prompted interest in developing an inshore trap fishery for ESS Northern Shrimp, which was being explored at that time. Stock assessments informed distribution of effort, catch, and seasonal trends on catch per unit effort (CPUE), although stock productivity was limited to only a few years of data.

In 1995, an industry-funded port sampling program was established that collected monthly samples from the commercial catch (Koeller 1996). Several metrics were devised from this data collection that provided new insight into stock dynamics. Most importantly, the monthly representation of stock composition from juveniles to multiparous females, including the identification of egg stages on ovigerous females, was now possible. A fishery independent trawl survey was also initiated through industry funds, further incorporating stock assessment considerations into its design and data collection. In 1996, the Scotia fleet moved from IQ to ITQ, while the Gulf fleet moved from a competitive fishery to IQ. The trap sector fishery in Chedabucto Bay was also operational, with several licenses actively fishing the area. In 1996, commercial trap catches were reported in a stock assessment for the first time (Koeller et al. 1996).

Annual developments of the fishery independent trawl survey on ESS Northern Shrimp were first incorporated in 1996 and continued annually thereafter. A catch-at-age and mean size metric were added to the stock assessment, having benefited from a few years of commercial samples collected from the ongoing port sampling program. In 1999, the ESS Northern Shrimp stock assessment incorporated further stock considerations, with the addition of environmental factors determined to have strong influence on ESS Northern Shrimp stock health. The Northwest Atlantic Fisheries Organization (NAFO) also adopted a TLA around this time, as a precautionary approach to assessment and management of data poor stocks. Koeller et al. (2000a) recognized early-on that assessment results would not be linked to management actions, so proposed a scoring system that outlined harvest control rule (HCR) responses to be used with application of the new TLA.

With ESS Northern Shrimp stock productivity still of concern, the early-2000s were spent developing a way to successfully sample recruits. Several iterations of sampling design were tested, resulting in the use of a small mesh ‘belly bag’ on the underside of the main trawl codend (Koeller et al. 2001). From 2002 to the present time, all stock assessments in support of the ESS Northern Shrimp fishery have included a recruitment indicator along with a suite of indicators across four characteristics (Abundance, Production, Fishing Effects, and Ecosystem) to holistically inform stock health. In 2009, reference points and HCRs were drafted to supplement TLA summary scores and meet conditions associated with development of a new IFMP for the stock (DFO 2011). The first framework assessment for the stock was conducted in 2015, which used the TLA to summarize 24 indicators across the four aforementioned characteristics to inform stock health. The framework also incorporated use of a precautionary approach, its reference points, and HCRs.

The process by which [DFO’s Precautionary Approach (PA)] framework is applied to a fish stock is through application of resource management measures and guided by science advice objectives for a stock (DFO 2009b). Science informs the determination of an LRP for the stock, although science does not direct determination of any other reference point (e.g., upper stock reference, or USR) or the reference period of which other reference points are based upon; resource management makes this determination based on its objectives for the stock. For example, the removal reference (RR) is based on a metric of fishing mortality (F) versus fishing mortality at maximum sustainable yield (F/F_{MSY}), which determines trends in exploitation. Fishing mortality should not exceed a level that would provide maximum sustainable yield ($F>F_{MSY}$), which is also mainly determined through resource management, although science does provide a proxy to inform this decision.

The 2015 framework highlighted attempts to apply a quantitative method to assess TLA scores, as indicated by Halliday et al. (2001). Discussion with many members of the ESS Northern Shrimp fishing industry supported a preference for TLA as a visual representation of indicators, which has facilitated an open and cooperative dialogue between DFO and industry since that time. In contrast, using a direct PA application resulting in a TAC would functionally exclude industry from a co-management process. Furthermore, use of TLA scores against a single indicator (biomass) used to develop the TAC was viewed as contrary to the holistic philosophy of the TLA. The framework tested development of quantitative HCRs for inclusion into the TLA. Difficulties were encountered when translating biological information into catch limits, as it oversimplified their input into stock health status determinations. Deterministic HCRs, which necessitate indicator weighting, were determined not to benefit the stock health assessment of the fishery until philosophical and practical issues could be mitigated.

Over the years, successes using the TLA and adaptive TAC adjustments, based on a holistic discussion of diverse stock, fishery, and ecosystem considerations, as guided by the TLA, have provided one of the best examples of a truly cooperative assessment and adaptive management framework for a fish stock. Further, national and regional initiatives to progressively move towards an Ecosystem Approach to Fisheries Management (EAFM) have been gaining momentum in the past few years. Complexity in analytical pursuits that support EAFM, however, often require the collection and accessibility of data-rich input not only from the fishery, but also from associated environmental variables.

More recently, some of these constraints have been overcome, as investigative methods have advanced to improve the abundance characteristic via an ESS Northern Shrimp survey biomass estimate. Understanding that significant temperature variations have been occurring worldwide, in the North Atlantic ocean and within the ESS region for the past decade, the impact of temperature on stock health is likely underestimated. Furthermore, there has been interest in using a modelling approach to forecast an ESS Northern Shrimp population biomass prediction a year ahead to improve the science advice provided to resource management. As such, a spatio-temporal delay-difference model, which implicitly incorporates the impact of environmental drivers through its use of spatial statistics, has been developed to resolve this issue and is recommended herein as the model to assess the ESS Northern Shrimp stock moving forward. Since reference points are method-specific, the selection and approval of a new assessment model required updating of the stock's LRP herein, as well as presenting additional guidance that may assist resource management in its determination of other reference points for the stock.

In addition to a new model and reference points, a new science assessment framework for the stock, as described herein, provides opportunity to reassess indicators used to date to assess the ESS Northern Shrimp stock, as part of the TLA. Combined with changes to the stock survey strata size calculations, a goal of the research presented herein is to document analyses that quantify correlations between stock indicators to assess their utility, propose new indicators that improve overall performance of the TLA, and to identify existing indicators that no longer contribute to the TLA.

DATA SOURCES

FISHERY DEPENDENT

Logbook Information

The ESS Northern Shrimp catch, effort, and self-reported location information has been available for SFAs 13–15 since 1993. The mobile sector became fully dockside monitored as early as 1994, while from inception the trap sector has had 20% dockside monitoring annually. Commercial logbooks capture information on date, location, depth fished, effort, and estimated catch. Mobile sector logbooks historically reported catch and effort data by day, grouping several fishing sets together. However, from an analytical perspective, recording commercial catch and effort by set provides a more accurate record of spatial distribution. Trap sector logbooks report catch and effort by trip, with a single entry summarizing all strings fished less than three nautical miles apart on a given trip. Any strings of traps laid farther apart are recorded as separate entries. A data table was added to the trap fleet logbook to report on bycatch; however, it has not been used consistently by harvesters and has a short list of pre-identified bycatch species that leads to uncertainty as to how well a broader scope of species are being recorded. As such, reporting accuracy of non-retained species while fishing remains uncertain.

The logbook data are entered into the DFO ESS Shrimp Science Database after they have been quality-assured and quality-controlled (QA/QC) for errors. Time is spent ensuring that the data are complete and that errors are kept to a minimum. This requires continual communication with vessel captains and the DFO Commercial Data Division (CDD), as CDD also enters logbook information into the Maritimes Fisheries Information System (MARFIS) database. It is important to note that there is a discrepancy in older logbook data, as MARFIS does not reflect all the corrections that have been made to logbooks throughout its time series. Due to archiving procedures for logbook documents, CDD is not able to edit entries that are older than eight years. In some cases, corrections have fixed some significant misinterpretations (e.g., duplicated records in MARFIS that have artificially inflated the CPUE for an entire trip). This limitation is significant when ESS Northern Shrimp commercial fishing information only uses data retrieved from MARFIS to inform commercial fishing activity. For the research presented herein, logbook data stored in the DFO ESS Shrimp Science Database has been used, as it is maintained by the DFO Northern Shrimp Unit.

Port Sampling of Commercial Catch

Annually, approximately 305 ESS Northern Shrimp are analyzed from every commercial mobile trawl and trap sample using a consistent protocol. Prior to 2006, samples of 500 ESS Northern Shrimp were analyzed. Each individual shrimp is checked for:

- sexual development stages;
- egg development stages;
- sternal spine condition;
- presence/absence of head roe; and
- presence and identification of disease.

Each individual shrimp is also weighed and measured for carapace length. These data are QA/QC and then uploaded to the DFO ESS Shrimp Science Database.

Trap samples are collected twice monthly from Chedabucto Bay trap vessels during periods of active commercial fishing. Sampling is a pseudo-random selection of shrimp from one vessel obtained by scooping a few pounds from three or four different traps along the same string. All collected samples are analyzed. The number of samples can range from 0 to 16 per season depending on the fishing activity. Sampling generally reflects the temporal distribution of effort, which occurs for a variable period depending on market conditions and catch rates, between September and March of the following year.

A similar 10 pound sample of shrimp is also collected from the last set of each mobile commercial trip provided by active vessels fishing in SFAs 13–15, collected and frozen on-site by volunteers at wharves located in Louisbourg, Canso, and Arichat, Nova Scotia. However, some Gulf fleet vessels land their catch in the DFO Gulf Region or DFO Quebec Region, which are unable to be sampled due to logistical constraints.

Annually, all trap samples and a maximum of 50 commercial trawl samples are analyzed. The 50 samples are selected in a manner that reflects the spatial and temporal distribution of the mobile fishery for each of the two fleets (e.g., if 10% of all shrimp is landed in March by Gulf vessels in SFA 13 then 10% of the 50 samples are selected from the Gulf fleet for the month and SFA). Once monitoring data has been entered into the MARFIS database, records are then used to estimate spatio-temporal distribution of catch by fleet.

The population length frequency is estimated from carapace lengths of the 305 shrimp measured in each of the main trawl survey samples. This value is then extrapolated to estimate the total number of shrimp of each length via a swept area. The total population estimate is subdivided into length frequencies of primiparous/transitional and multiparous ESS Northern Shrimp by multiplying the total population estimate of each length by the percentage of primiparous/transitional and multiparous shrimp in the samples, respectively. The male population length frequency is obtained by subtracting the primiparous/transitional and multiparous estimates for each length from the population totals.

At-sea Observations and Bycatch

Introduction of the Nordmøre grate in 1991 reduced bycatch and allowed the ESS Northern Shrimp fishery to expand to its present size. Bycatch data from 2013 to 2023 were derived from observer coverage of 16 commercial mobile sector trips (194 tows) on the ESS Northern Shrimp grounds (Table 3). Coverage from 2013 to 2023 for the mobile sector has been three or fewer trips per season across SFA 13–15. Between 0% and 2.6% of total reported mobile fishing hours were covered by observers annually. A spatial distribution of observer coverage from 2013 to 2023 for both sectors is shown in Figure 13.

Logbook data and observer data are reported by tow, allowing for a comparison of landed ESS Northern Shrimp to the observer estimated catch. The weight of shrimp landed, as reported in MARFIS, is used to determine the proportion of bycatch by weight, rather than shrimp estimated by the observer.

ESS Northern Shrimp has accounted for 96.1 to 99.9% of the total mobile catch by weight on observed trips since 2013 (average 99.0%). The three most common bycatch species, on average by weight, from 2013 to 2023 are Atlantic Herring (0.31%), Silver Hake (0.18%), and Alewife (0.1%) (Table 4). Weight values for bycatch are likely over-estimated due to the minimum 1-kg weight recorded by the observers (e.g., a single Sand Lance would be recorded as 1-kg despite weighing only a few grams). The annual frequency and timing of observer samples does not inform overall spatio-temporal patterns. However, bycatch information from mobile observed fishing trips suggests that the fleet's trawl configurations, including the use of the Nordmøre grate, continue to ensure low total bycatch.

Trap sector observer sampling was initiated in 2018 to provide bycatch information for the inshore region of SFA 15, also known as Chedabucto Bay (Table 5). The trap sector logbook includes a bycatch table, which allows reporting of bycatch species encountered while fishing; however, upon closer review there remain challenges associated with distinguishing when the table was not used and when bycatch was not encountered. In the interest of acquiring a bycatch baseline for the trap sector, observer samples were collected for the 2018–19 and 2019–20 seasons (Tables 5). Northern Shrimp accounted for 99.8–100% of the total trap catch by weight on observed samples (average 99.9%; Table 6). The most common bycatch species by weight during this time was snow crab; however, it was averaged at less than 1%. Since 2020, the trap fleet has seen little activity, so no more observer trips have been pursued. Once the data series extends to at least five years, reporting on trap bycatch will be more representative of trap-based fishing activity (see: Tables 5–8).

FISHERY INDEPENDENT

DFO-Industry Collaborative Trawl Survey

Although the RV Ecosystem trawl survey on the Scotian Shelf has been ongoing since 1970, Northern Shrimp catchability in groundfish gear without a codend liner has poorly represented trends in shrimp abundance. Despite this, groundfish survey records have been applied to questions of Northern Shrimp distribution, although only Northern Shrimp-specific surveys are considered for quantification of the stock. To date, Northern Shrimp surveys have included a biannual research survey carried out from 1982 to 1988 using Fisheries Research Vessel (FRV) *EE Prince* (Etter and Mohn 1989), an industry-led survey in 1993 using commercial vessels/trawls (Roddick 1994), and the ongoing contemporary DFO-Industry collaborative survey from 1995 to present using a commercial vessel and a standardized survey trawl. Additional details on these surveys can be found in Hardie et al. (2018).

The data series includes periods of low ESS Northern Shrimp abundance (1982–88), high abundance (1995–2015), and a more recent period of unstable abundance (2016–20). Although the entire range of data is included to provide a broad range of indicator values, comparative fishing experiments were not done to directly intercalibrate the surveys across the different abundance periods. Catch rates between the periods have only been adjusted to account for differences in the wingspread of the trawls used in 1982–88 (trawl specifications) versus the ongoing modern survey (actual trawl mensuration). Size selectivity of the trawls in the two times series is assumed to be identical given that the codend mesh used was 40 mm in all cases.

In 2020, due to COVID-19 pandemic restrictions, a comparable situation occurred when the survey vessel used in 2009–19 (i.e., FRV *Cody & Kathryn*) could not participate in the survey. Instead, FRV *Léry Charles* was chartered to fish the survey trawl gear in this year. Again, comparative fishing experiments were not completed. As these vessels fished the same gear and obtained similar net mensuration metrics to previous ESS Northern Shrimp surveys, size selectivity was assumed to be similar, although the survey occurred in July instead of June. The FRV *Nanny Bessie* took over as the new survey vessel in 2021 and surveys have since maintained a June survey schedule using consistent gear and fishing metrics.

The contemporary DFO-Industry collaborative survey has followed a mixed stratified random/fixed station design. There are four survey strata, the 'strata' nomenclature of which has been a source of confusion between *survey strata* and *SFAs.* The "inshore" Stratum 17 includes portions of SFA 13–15 (Louisbourg, Misaine, and Canso holes, respectively). Strata 13–15 includes portions of SFA 13–15 that are not captured in Stratum 17 (Figures 2 and 11). Another layer of complexity is associated with the "inshore line" represented in Figure 2, which delineates a management boundary for the Chedabucto Bay trap fishery. The area within the inshore line is exclusively fished by the trap sector and is not accounted for in Stratum 17. A decision not to survey the Chedabucto Bay area was informed by ESS Northern Shrimp stock dynamics, where the survey trawl would not be an efficient method for sampling in this area nor provide any additional stock information that is not already acquired across all other survey strata given they apply to the same stock.

Survey stations in Strata 13 and 15 are randomly stratified at depths greater than 100 fathoms. Until 2023, stations in Stratum 14 were fixed at depths of greater than 100 fathoms due to difficulty finding trawlable bottom. The fixed stations in Stratum 14 were assumed to be representative of Northern Shrimp abundance throughout the stratum. In 2023, recognizing advances in bottom-monitoring technology and that a portion of fishing activity was indicative of shallower, viable Northern Shrimp habitat, revision of the survey sampling design was conducted. A first step in implementation was to reduce the number of fixed stations by replacing them with randomly generated stations. A comparative study was then developed where an additional 15 randomized stations at greater than 100 fathoms were selected in Stratum 14. As outlined in Figure 14, the results indicated that both catch rates and length frequency of Northern Shrimp did not significantly differ between the fixed and random stations for Stratum 14. Through subsequent consultation with industry, it was agreed that the previously-fixed survey stations would be replaced by randomized stations.

With industry support to pursue randomly generated stations for the survey, a broader depth range under which the survey stations could be generated was specified. Vessel Monitoring System data (explained in more detail below) was used to best represent the commercial fishing depth range to inform expansion of the depth contour in Stratum 14, as it captures commercial activity at a higher resolution compared to commercial logs. The bounding contours for station selection in Stratum 14 were changed from greater than 100 fathoms to greater than 85 fathoms, in order to include shallower water depths where consistent fishing activity was being observed.

The survey now only has one remaining fixed station that is located in Stratum 15. This station could be converted to random, but some work should be done to determine why it was chosen to be fixed before implementing any such change. As for the stations in Stratum 17, they are all randomly-selected by the presence of a LaHave clay bottom sediment specification using the

Atlantic Geosciences surficial geology maps (which will be updated for consideration in the survey, as they become available).

The DFO-Industry collaborative survey does not extend beyond the boundaries of the stock distribution, focusing instead on main concentrations in the shrimp “holes”. Northern Shrimp distributions on the ESS are strongly correlated with organic mud habitats in the survey area (Koeller 2000), with their abundance herein considered to be representative of the abundance of the whole stock. To extend the survey beyond the stock range, while maintaining suitable coverage within the holes, would be prohibitively expensive for industry relative to any benefits that may be gained.

The annual survey consists of 15 survey stations in each of the 4 strata. Each station consists of a 30-minute tow at a target vessel speed of 2.5 knots. Because shrimp are known to be densely aggregated near the bottom during daytime, survey sampling is only conducted between dawn (0500 h) and dusk (2000 h), beginning on June 1st or as soon as possible thereafter as weather conditions permit (but not earlier). The survey typically requires 8–12 days of fishing, its duration primarily dependent on weather conditions. It is generally completed by mid-June at latest. Stations are not carried out in very poor weather (i.e., winds greater than 20 knots) for safety reasons and to ensure consistent trawl performance/catchability.

At the start of each day, the clock on the computer is synchronized with the temperature/depth recorders, vessel Global Positioning System (GPS), and a net mensuration system that is used to monitor trawl activity in real time (i.e., wingspread, headline height, door spread, and door pitch/roll). Time spent on bottom, bottom temperature, and depth are monitored using the net mensuration system and compared to other data sources for consistency and accuracy. The science staff and survey vessel skipper monitor trawl mensuration data during each tow and inspect the gear and catch when the trawl is brought aboard before determining if the set has been successful or not. If there are any concerns regarding representativeness of the catch, the issue(s) is resolved and the survey station repeated.

Changes to Survey Strata

Accurate estimates of the area covered by the ESS Northern Shrimp stock, as described above, are a critical element that feeds directly into the swept area abundance index. The estimates also affect the validity of any model of actual shrimp abundance. Recognizing this, there have been some refinements to the datasets used to characterize the shrimp holes and total area they occupy in the ESS.

There is some uncertainty around the methods used to calculate area estimates for the 100 fathom holes of each shrimp stratum. The earliest record of these calculations can be found in the 1983 ESS Northern Shrimp stock assessment (Etter and Mohn 1984), wherein the authors used a polar planimeter and a 100-fathom depth contour for each shrimp hole. The values published are similar to those used in recent assessments; however, the source of the depth contours has not been documented and attempts to reproduce the same area estimates have been unsuccessful. In 2018, new Geographic Information System shapefiles of the 100-fathom depth contour for each survey stratum and, more recently, for the 85-fathom depth contour in Stratum 14, were developed using bathymetric data from a Digital Elevation Model of the Scotian Shelf region (Greenlaw and McCurdy 2014).

The area of each stratum, using both the historical calculations and those obtained based on the updated shapefiles are shown in Table 9. These values illustrate that, while the areas of Strata 13 and 17 are similar, both Strata 14 and 15 are larger, with Stratum 14 being over 1,000 km^2 larger. Most, but not all of this difference is explained by the recent shift to a shallower 85 fathom cutoff in Stratum 14. While the updated area values produce swept area index trends that are similar to those produced using historical values, they estimate an overall higher biomass (31% larger on average; Figure 15). This number is close to the expected underestimation of the index (around 25%; as described in Hardie et al. [2018]). Assuming that current area estimates are more accurate compared to historical estimates, and considering the adjusted depth cutoff for Stratum 14, all subsequent analyses are performed using the more recent area estimates.

DFO Summer RV Ecosystem Trawl Survey

The RV Ecosystem trawl survey is operated by DFO Science on a biannual schedule in the Winter and Summer of each year. The surveys collect information on species distribution, abundance, and composition, as well as hydrographic data and other sampling across the Scotian Shelf. The Winter and Summer surveys cover NAFO divisions 4X5Z and 4VWX5Yb, respectively (DFO 2020a,b). The ESS Northern Shrimp stock assessment has relied on the Summer RV Ecosystem trawl survey since 2002 to provide data on sympatric species from tows that overlap with areas of shrimp occurrence (Summer RV Ecosystem trawl survey Strata 443–445 and 459; see: Figure 16. DFO [2002]). These include known predators such as Atlantic Cod and other finfish (all species with codes less than 1000 in the RV Ecosystem trawl survey database), as well as small Turbot (also known as Greenland Halibut) whose population is believed to fluctuate in tandem with ESS Northern Shrimp. Due to gear issues and logistics that may have reduced the RV Ecosystem trawl survey coverage over the years, data may not be collected in desired shrimp survey strata each year. This is further limited by the small area covered by the strata selected.

Snow Crab Survey

The Snow Crab survey occurs annually between the months of August and December, overlapping with areas of ESS Northern Shrimp abundance and providing a recruitment index for immature male Snow Crab less than 56 mm carapace length. Zisserson et al. (2021) described the survey specifications in further detail, with the locations of the 2023 survey shown in Figure 17. The Snow Crab index has demonstrated correlation with ESS Northern Shrimp abundance indices for over a decade. Due to timing of the Snow Crab survey, data are not typically available within the same year, so the index has been shifted forward by 1-year in the ESS Northern Shrimp TLA assessment.

Vessel Monitoring System (VMS) Monitoring

Use of VMS monitoring has been mandatory since 2011–12 for the mobile sector (both Scotian and Gulf fleets). This technology provides periodic satellite positioning of vessel activity. The information collected includes vessel identifiers (Vessel Registration Number, or VRN), position (latitude and longitude), date, time, direction of movement, and vessel speed while on water. The VMS positions, stored in a secure database, are invaluable to shrimp science in validating logbook spatial information, and by extension, estimates of effort across SFAs and in ensuring a representative allocation of port sampling.

The VMS data have also been used to infer areas of ESS Northern Shrimp presence/absence by highlighting areas repeatedly targeted by the commercial fleet, which can be used to verify the suitability of survey stratum selection criteria. The VMS data for 2013–23 were processed using the Mar.utils::VMS_clean_recs() function in R-language (available at: github.com/Maritimes/Mar.utils), which takes raw VMS data (i.e., a data frame having sequential coordinates and times) and removes records that are no more than a specified distance from the previous position. This removes periods where a vessel is inactive at port and/or has limited movement. The R-package also uses the timing between subsequent VMS datapoints to derive estimates of time spent within an area. The VMS and log data are then compared by vessel and by date to remove any times where logbooks do not indicate vessel activity and selected for vessel speeds between 2.2 and 2.5 knots. The remaining information is then plotted and aggregated by summed hours spent per 1-minute grid square to derive a spatial raster of fishing effort. The results provide an anonymized spatial representation of commercial activity (Figure 18).

MODEL DATA REQUIREMENTS

Main Trawl Data/Biomass Indices

Information on the total population biomass is obtained from the observed biomass within each individual survey tow between 2005 and 2023. While there are more years of data available for the main trawl, reliable belly bag data only exists from 2005 onward, which acts as the limiting factor. The total biomass in kilograms is directly measured for each tow and can be converted to density (kg/km^2) by dividing the totals by individual-towed distances and wingspread (spread of the main trawl net). Two of the three models (i.e., TLM, and SEAM) directly utilize the tow-specific observed biomass densities, so they require no further analysis (see: Figures 19 and 20 for their spatial distribution). The third model (i.e., SDD) requires an index of biomass, which is derived using the recalculated swept-area index described below based on the new strata sizes. The use of a spatio-temporal generalized linear mixed model, with depth and temperature as covariates to improve the index, was explored, but the resulting index was not significantly different from the swept-area index and offered no noticeable improvement to the analysis.

Historically, the swept-area method to calculate an index consisted of first standardizing the observed weights to a standard wingspread of 17.4 m and a standard towed distance of 1.25 nautical miles (or approximately 2.315 km) and then calculating a bootstrapped (non-parametric bootstrap with replacement) stratified estimate (Smith 1996) of the survey CPUE. The development of net mensuration systems allowed individual tow wingspread and distance values to be implemented into the swept-area calculations and provided real-time rather than theoretical metrics describing fishing efficiency. The strata-specific estimates are then multiplied by the number of towable units in the stratum (size of area divided by the size of a standard tow) and added together to obtain the total index of biomass for all SFA together.

Recruitment Data/Index

Length frequencies derived from both survey main trawl and commercial port samples indicate that very few shrimp smaller than 10 mm carapace length (CL) are captured. Recruitment, shrimp of 10 mm or less, are quantified with the use of a belly bag (a small mesh bag 1-metre wide, attached to the survey trawl footrope and net belly between the two middle rollers). This net is comprised of 3/4” (wing and belly) and 3/16” (codend) diamond mesh and is the only source of data characterizing recruit shrimp abundance in the ESS region. While this net has been in use since 2002, data quality prior to 2005 is uncertain, as this new sampling method and its analysis were being implemented; for this reason, analyses are restricted to 2005 onward.

Historically, when processing belly bag samples of shrimp recruits, only the first 50-shrimp CL were measured, and no weight-related measurements were taken. Any additional shrimp were counted. In 2023, while retaining the 50-shrimp cap, the sample protocol was revised to require individual lengths as well as total sample weights. It is assumed the length frequencies of the 50 sampled shrimp are representative of that particular tow’s catch and is applied to the remaining unmeasured recruits. A length-weight model (Froese, 2006), with a depth-specific intercept described in the Length-Weight Relationship section below, is utilized to predict the unmeasured shrimp weights, after which both predicted and measured weights within a tow are summed to obtain the observed recruit biomass.

Since the belly bag also captures shrimp larger than 10 mm CL, it is possible to assess whether that portion of the belly bag catch is comparable to the main trawl catch. Identifying a relationship between these two would strengthen confidence in utilizing belly bag samples as an index of recruitment. Before making comparisons, as the belly bag does not capture larger shrimp as well as the main trawl, the main trawl length frequencies are corrected to match up with the belly bag frequencies to compensate for the different selectivity (Figure 21). To do this, the carapace lengths of all shrimp in the detailed samples from both the main trawl and the greater than 10 mm CL shrimp in the belly bag are rounded to remove decimals, after which the proportion in numbers and weight of shrimp in each tow associated with each CL is calculated. Within each tow, the number of shrimp at each CL is adjusted as if it were the belly bag by multiplying the total number of shrimp in the detailed sample by the percentage at each CL seen in the belly bag. This value is then multiplied by the estimated weight of the average observed shrimp in the detailed sample of main trawl (calculated by dividing the number of shrimp in a given CL by the total weight associated with that CL) to obtain an estimated length frequency-corrected biomass of the main trawl.

The greater than 10 mm CL belly bag and main trawl weights, as well as the length frequencies, are directly compared using linear regressions on both the natural and log scales. If differences are identified, the main trawl biomass is corrected based on the belly bag length frequencies, and then the comparison is repeated using linear regressions. The index for recruitment is calculated using the swept-area method described for the main trawl biomass, with the difference being that the CPUE is standardized using the width of the belly bag and not that of the main trawl.

Landings

Landings used in the model are obtained from individual logbooks. To account for the timing of the survey, all logbook catches must be temporally aligned to ensure that all landings caught before a given year's survey are assigned to the previous year's biomass estimate to correctly quantify the fishery's impact. For the non-spatial models (SDD and TLM), this consists of assigning all logbooks between the start of a year's survey and the start of the previous year's survey to that "survey" year and then summing. As an example, if the survey starts on June 1st in 2010, all landings after June 1st, 2010, and before June 1st, 2011, are attributed to the survey year of 2010–11 and summed up to get the total landings in that survey year. The spatial model (SEAM) requires the additional step of using the logbook locations to attribute each logbook catch to the appropriate modelled location, while still accounting for the temporal alignment.

Modal Analysis

As there is no known discrete physiological indicator for shrimp age, cohorts and approximate ages are often identified using mixture model-based modal analyses (Hardie et al. 2018). This is done by estimating the mean CL of different Gaussian distributions with fixed standard deviations (fixed at 0.9) and then visually identifying cohorts based on those Gaussian mixtures. After identifying cohorts, ages are then attributed based on visual inspection and general knowledge of approximate size-at-age of shrimp.

Von Bertalanffy

Once ages are attributed to individual shrimp with measured lengths as part of the modal analysis, a Von Bertalanffy length-at-age curve is fitted to obtain a relationship that can be utilized for all shrimp. This curve follows the equation:

$$L_i = L_\infty[1 - exp\{-k(A_i - t_0)\}$$

where L_i is the CL of shrimp *i*, L_∞ is the asymptotic length parameter (often interpreted as the maximum length), *k* is a growth rate parameter and $t_0 > 0$ is the theoretical age at which fish have length zero (Dey, 2019). This model fitting is done using non-linear least squares assuming Gaussian deviations. The resulting relationship can then be utilized to age all shrimp.

Length-Weight Relationships

For the main trawl shrimp, year-specific and strata-specific length-weight relationships are obtained from shrimp that were individually weighed and measured. The length-weight (LW) model developed uses the following equation assuming a lognormal distribution:

$$\log(W_i) = \beta \cdot \log(d_s) + \alpha_s + b \cdot \log(L_i) + \epsilon_i$$

where W_i is the individual weight in grams of shrimp *i*, β is the coefficient associated with the effect of depth *d* in a given tow *s* (resulting in depth-specific intercepts), b is the allometric parameter associated with the CL L_i of individual shrimp *i*, and ϵ_i is a normally distributed error term. α_s is a spatial random effect at location of tow *s* modelled as a Gaussian Random Field with mean zero and covariance matrix $\Sigma(s, s') = Matern(||s - s'||)$ indicating that the covariance between locations s and s' follows an isotropic Matern covariance structure with smoothness parameter ν fixed at one. All these relationships are estimated using maximum likelihood in the Template Model Builder (TMB) package.

For belly bag shrimp, the same model is fitted separately by strata in 2023, since that is the only year with both weight and length measurements available for shrimp less than 10 mm on all shrimp in the belly bag.

Growths

Yearly growth rates are calculated using the results of the modal analysis, Von Bertalanffy relationships, and length-weight relationships, which are combined to obtain expected growth rates from one year to the next. This involves applying the tow-specific length frequencies of the sub-samples to the whole main trawl biomass and predicting numbers at length for all captured shrimp. The Von Bertalanffy relationship is then utilized to predict the age of all shrimp in a given tow. All shrimp are aged by one year and their new lengths for the following year are predicted using the same Von Bertalanffy curve. Since the model is based on biomass and not numbers-at-length, the new weight of each shrimp in every tow is predicted using the spatial length-weight relationships of the following years before calculating the proportional growth (next year's weight divided by this year's weight). Tow-specific expected growth rates are then calculated using tow-specific means; strata-specific growth rates are obtained by averaging across strata and overall yearly growth rates are obtained by averaging expected growth within one year.

MODEL DEVELOPMENT

DELAY-DIFFERENCE MODEL

The application of three modified delay-difference models (Deriso 1980; Schnute 1985; Smith and Hubley 2014) are evaluated to assess their ability to model the ESS shrimp population. All these models are based on the same underlying process equation:

$$B_t = e^{-m} g^I_{t-1}(B_{t-1} - C_{t-1}) + e^{-m} g^R_{t-1} R_{t-1}$$

where B_t is the biomass in year *t* where $t = 1,2,\ldots,T$, *m* is the instantaneous natural mortality, *C* are the commercial landings, g^I and g^R are the main trawl biomass and recruit biomass growth rates, and *R* is the recruit biomass.

MODELS

All three models are formulated in a state-space framework. State-space models (SSM) are hierarchical models defined by two stochastic processes:

1. an unobserved dynamic state process that describes the population dynamics between time-steps t and usually takes the notation $\boldsymbol{X_t}$, $t = 1,\ldots,T$, and
2. an observation process that links the observations to the underlying population dynamics of interest and usually takes the notation Y_t (Aeberhard et al., 2018). Model parameters are combined in a p-vector $\boldsymbol{\theta} \in \boldsymbol{\Theta} \subseteq \mathbb{R}^{\boldsymbol{p}}$ and known covariates are indicated by z_t.

As the frequentist approach to statistical analysis is selected, $\boldsymbol{\theta}$ is considered a vector of fixed effects while $\boldsymbol{X_t}$, is a vector of random effects predicted from estimates of $\boldsymbol{\theta}$. All these variables can be combined in the following joint likelihood $L(\cdot)$ and marginal log-likelihood $\mathcal{L}(\cdot)$:

$$L(\boldsymbol{\theta}, \boldsymbol{Y}_{1:T}, \boldsymbol{X}_{1:T}) = p(\boldsymbol{Y}_1|\boldsymbol{X}_1, \boldsymbol{\theta}) \prod_{t=2}^{T} p(\boldsymbol{Y}_t|\boldsymbol{X}_t, \boldsymbol{\theta}) p(\boldsymbol{X}_t|\boldsymbol{X}_{t-1}, \boldsymbol{\theta})$$

$$\mathcal{L}(\boldsymbol{\theta}, \boldsymbol{Y}_{1:T}) = log \int L(\boldsymbol{\theta}, \boldsymbol{Y}_{1:T}, \boldsymbol{X}_{1:T})\, d\boldsymbol{X}_{1:T}$$

These high-dimensional integrals cannot be directly optimized and must instead be approximated. For this purpose, the Laplace approximation, as implemented in the TMB package in R, is utilized (Kristensen et al. 2016). Furthermore, TMB's use of automatic differentiation has been shown to be highly efficient computationally without loss of accuracy (Kristensen et al. 2016; Auger-Méthé et al. 2017).

Simplified Delay-Difference (SDD)

This model, slightly modified from the original developed in Yin et al. (2019), is a frequentist version of the simplified delay-difference model presented in Smith and Hubley (2014), which has been extensively used in the assessment of scallops in the DFO Maritimes Region (Nasmith et al. 2016; DFO 2019a). It has three process equations, one each for the biomass dynamics, the recruitment dynamics, and the natural mortality:

$$B_t = (e^{-m} g_{t-1}^I (B_{t-1} - C_{t-1}) + e^{-m} g_{t-1}^R R_{t-1})\tau_t$$

$$R_t = R_{t-1}\phi_t$$

$$m_t = m_0 \eta_t$$

where τ_t, ϕ_t, and η_t are all lognormal variables with zero mean and separate variances $\sigma_\tau^2 . \sigma_\phi^2$, and σ_η^2 on the log scale. Recruitment is a simple random walk which, while these models have no biological basis, allows for some dependence in time, minimize the number of parameters to estimate, and is flexible enough to follow the recruitment data from the belly bag for the recruitment and contrast it with all other components for natural mortality. The initial state is estimated as a parameter R_0, where natural mortality is estimated using a stationary lognormal distribution with mean m_0.

The observation components are the following:

$$I_t = q_I B_t \epsilon_t$$

$$I_t^R = q_R R_t \upsilon_t$$

where I_t and I_t^R are the biomass and recruit biomass indices respectively, q_I and q_R are the biomass and recruit biomass catchability parameters, and both ϵ_t and υ_t are lognormal error terms with zero-mean and variances σ_ϵ^2 and σ_υ^2 on the log scale. There are no observations of natural mortality.

Formulated as an SSM, this means that $\boldsymbol{Y_t} = (I_t, I_t^R)^T$, $\boldsymbol{X}_t = (B_t, R_t, m_t)^T$, $\boldsymbol{z}_t = (g_t, g_t^R)^T$, and $\boldsymbol{\theta} = \left(q_I q_I^R, \sigma_\epsilon^2, \sigma_\upsilon^2, \sigma_\tau^2, \sigma_\phi^2, \sigma_\eta^2\right)^T$.

Tow Level Model (TLM)

The Tow level Model (TLM), originally developed in McDonald et al. (2022) is similar to the delay-difference model presented above. The observation components directly model each individual survey tow, eliminating the need for preliminary aggregation into indices for the modeled fitting process. Since the TLM uses the same process equations as the SDD model described above, they are not repeated here; however, the TLM does modify the observation equations in the following ways:

$$I_{i,t} = \frac{q_I B_t}{p_I} \epsilon_{i,t}$$

$$I_{i,t}^R = \frac{q_R R_t}{p_I^R} \upsilon_{i,t}$$

where the subscript *i* denotes an individual survey tow, and p_I and p_I^R are respectively the probability of encountering shrimp biomass in the main trawl and the probability of encountering recruits in the belly bag. These parameters are estimated separately following a hurdle model framework through separate binomial distributions:

$$Z_t^B \sim Bin(n_t, p_I)$$

$$Z_t^R \sim Bin(n_t, p_I^R)$$

where Z_t^B and Z_t^R are respectively the number of tows with no biomass in the main trawl and no recruits in the belly bag, and n_t is the total number of tows (both main trawl and belly bag) made in year *t*.

Formulated as an SSM, this means that $\boldsymbol{Y_t} = (\boldsymbol{I}_t, \boldsymbol{I}_t^R, Z_t^B, Z_t^R)^T$, $\boldsymbol{X}_t = (B_t, R_t, m_t)^T$, $\boldsymbol{z}_t = (n_t, g_t, g_t^R)^T$, and $\boldsymbol{\theta} = \left(q_I q_I^R, p_I, p_I^R, \sigma_\epsilon^2, \sigma_\upsilon^2, \sigma_\tau^2, \sigma_\phi^2, \sigma_\eta^2\right)^T$. Analyses of this model found that both q_I and q_R cannot be estimated and must therefore be informed (McDonald et al. 2022).

Spatially Explicit Assessment Model (SEAM)

The Spatially Explicit Assessment Model (SEAM) was originally developed in McDonald et al. (2021) with the aim of capturing spatial dynamics in the underlying population dynamics. The biomass and recruit process equations are therefore modified in the following way:

$$B_{s,t} = \left[exp(-m_t) g_{a,t-1}\left(B_{s,t-1} - C_{s,t-1}\right) + exp(-m_t) g_{a,t-1}^R R_{s,t-1}\right] exp(\omega_{s,t}^B)$$

$$R_{s,t} = R_{s,t-1} exp(\omega_{s,t}^R)$$

where the *s* subscript denotes the spatial location of a given knot, $g_{a,t}$ and $g_{a,t}^R$ are now different by strata *a* and $\omega_{s,t}^B$ and $\omega_{s,t}^R$ are the values of the biomass and recruit random fields at knot *s* and year *t* with mean zero and covariance matrices $\boldsymbol{\Sigma}_B$ and $\boldsymbol{\Sigma}_R$. As the calculations of these covariance matrices are computationally demanding, the random fields are approximated using A Stochastic Partial Differential Equations (SPDE) approach (Lindgren 2011), as implemented in the TMB package, and which requires parameters $\tau^B, \tau^R, \kappa^B, \kappa^R, \nu^B$, and ν^R, where ν^B and ν^R are fixed at one. Parameters τ^B and τ^Rrepresent the spatial variance, κ^B and κ^R are range parameters, and ν^B and ν^R are smoothness parameters. As there are no data for the natural mortality, the model is not capable of incorporating spatio-temporal natural mortality; thus, the equation is not modified from TLM. Furthermore, to reduce computational load, not all locations are modelled for random fields. The processes are modelled at a finite number of locations called "knots" that provide replicate observations within a given location and facilitate estimation (for more details see McDonald et al. 2021).

The observation processes are modified in the following ways:

$$I_{i,s,t} = \frac{q_s^I B_{s,t}}{p_I} \epsilon_{i,s,t}$$

$$I_{i,s,t}^R = \frac{q_R R_{s,t}}{p_I^R} \upsilon_{i,s,t}$$

where the notable differences are that the subscript s has been added to most variables and that the main trawl catchability is allowed to vary between locations. As this parameter could not be estimated in TLM, it is also therefore informed and treated as a random effect to facilitate model fitting.

Formulated as an SSM, this means that $\boldsymbol{Y}_{s,t} = \left(\boldsymbol{I}_{s,t}, \boldsymbol{I}_{s,t}^R, Z_t^B, Z_t^R\right)^T$, $\boldsymbol{X}_{s,t} = \left(B_{s,t}, R_{s,t}, m_{s,t}, q_s^i\right)^T$, $\boldsymbol{z}_t = (n_t, \boldsymbol{g}_t, \boldsymbol{g}_t^R)^T$, and $\boldsymbol{\theta} = \left(q_R, p_I, p_I^R, \sigma_\epsilon^2, \sigma_\upsilon^2, \sigma_\tau^2, \sigma_\phi^2, \sigma_\eta^2, \tau^B, \tau^R, \kappa^B, \kappa^R\right)^T$.

MODEL VALIDATION

Only the models that successfully converge out of SDD, TLM, and SEAM have been analyzed and compared below.

Sensitivity Analyses

Both the main trawl and belly bag catchabilities were found to be inestimable in previous analyses for TLM and SEAM (McDonald et al. 2021,2022). Therefore, these parameters need to be informed in some manner. For the main trawl catchabilities (q_I and q_s^I), they are fixed at one. This is common practice for shrimp assessments using similar gear, as there is little expectation that shrimp could escape the net due to their behavior (staying at the bottom during the day) and the height of the gear. For the recruit catchability, q_R, a prior distribution is added to help its estimation for all models. These prior distributions are beta distributions with parameters $\alpha = 10$ and $\beta = 2$ parameterized the following way:

$$q_R - B \sim \mathrm{B}(\alpha, \beta)$$

where B is a value that set the lower bound of the parameter distribution, as a beta distribution is bounded by 0 and 1. A sensitivity analysis was performed by varying B between 0.1 and 1 by steps of 0.1 and examining the impact this has on the modeled outputs, such as process errors and process predictions.

Residual Analyses

There are two types of residuals resulting from fitting the models: observation residuals and process errors. The observation residuals are the error terms from the observation equation that denote the deviation of the observation from the observation structure, including the underlying process (either biomass or recruitment). While these are modelled as independent in time series models such as SDD, they generally still contain temporal autocorrelation and need to be corrected into one-step ahead residuals (Thygesen et al. 2017) to assess if the model assumptions were respected. Conversely, the residuals from TLM and SEAM can be assessed directly on the log scale using scatterplots, as they are built as replicates of a given biomass instead of a 1:1 relation. The most reasonable scale for the SEAM residuals is knot-based, which is conditional on the knot-specific estimated biomass and calculated as $Residual = \epsilon_{i,s,t} = I_{i,s,t} - \frac{q_s^I B_{s,t}}{p_I}$.

Process errors cannot be used to assess model assumptions due to the presence of autocorrelation. However, they are useful to inform whether the model tends to generally underestimate or overestimate the process by identifying the presence of any consistent trends or patterns. The process errors for SDD and TLM can be assessed the same way; however, the process errors for SEAM are more complicated, as each year does not have one process error, but instead one random error field. To approximate a comparable process error to the SDD and TLM models, the median values of the random fields at the modelled location are analyzed in the same manner as the yearly process errors for SDD and TLM.

Retrospective analyses

A retrospective analysis consists of sequentially-removing one year of data and refitting models to the reduced dataset, iterating the process for several years. In this analysis, a retrospective analysis is conducted using terminal years from 2023 to 2013, with each retrospective model referred to by its terminal year (e.g., the model run using data from 2005 to 2015 is referred to as the 2015 retrospective model) and compared to the model run to 2023 (referred to as the full model). Retrospective analysis is performed for all three processes (biomass, recruitment, and natural mortality) for all models that converge. For all three processes the following was evaluated:

$$RPD_{t,retro} = \frac{P_{t,retro} - P_{t,full}}{P_{t,full}}$$

where $RPD_{t,retro}$ is the relative difference between the full model's process and a given retrospective model. Mohn's rho (Mohn 1999), which averages $RPD_{t,retro}$ over a given amount of years, was utilized to assess the overall retrospective model bias over all retrospective fits (overall Mohn's rho) and over the last five years (5-year Mohn's rho).

1-Year Projections and Decision Tables

A modelling approach enables estimates of total biomass to be projected for the upcoming year. This provides more targeted science advice for the ESS Northern Shrimp stock. To identify the best projection method, the impact of different assumptions on yearly growths against their respective retrospective model fits were compared. For example, the 2015 retrospective results can be used to project the total biomass into 2016 by using the realized commercial landings between June 2015 and June 2016. This 1-year projection can then be compared to the realized prediction of total biomass from the 2016 retrospective model fit, to assess how well it would have performed to predict that following year's result. This is repeated for all retrospective model fits, with conclusions inferred from these results.

For all projections, the terminal year's estimate of recruitment and the mean natural mortality were used. For the SDD and TLM models, the impact of different growth rate assumptions — specifically, using the previous year's growth rates, mean growth rates, or median growth rates — is evaluated. The same is completed for SEAM and projecting the total biomass forward. SEAM can also project spatially, so the same assumptions are made on a spatial scale by projecting each individual knot forward with the different growth assumptions and summing them to obtain a projected total biomass. The best approach is then used to calculate example decision tables for different years to illustrate how this information would have been presented. The results of these projections are meant to illustrate how using a decision table would have performed given the past TAC decision that was taken. For example the 1-year projection for 2022, given the model fit to 2021 as well as the TAC selected in that year, illustrates the percent difference between the projection that would have been presented in a decision table and the estimated biomass in 2022; this is an indicator of the general performance of these decision tables, as well as the model. The only difference between the 1-year projections and the decision tables is that 1-year projections account for known landings, while the decision tables operate as if the next calendar year's fishing is unknown; therefore, includes the impact of most of the fishing in that year (January to November). This would then include fishing before the survey, while also accounting for the landings after the survey in that survey year. The estimates and probabilities presented in the decision tables are based on simulating 5,000 iterations of projected biomass values in the following year, accounting for uncertainties in the biomass, natural mortality, and recruitment.

REFERENCE POINTS

As part of DFO's PA approach, reference points for the ESS Northern Shrimp stock are used for fishery decision-making following recently-defined guidelines for implementing the Fish Stock Provisions (FSP) pursuant to the *Fisheries Act* (DFO 2022). Key components of these approaches are the use of reference points and status zones (i.e., healthy, cautious, and critical) that are meant to guide harvest strategy and harvest decision rules. Development of these reference points must take into account uncertainty and risk (DFO 2009b). The role of DFO Science within the DFO PA approach framework is to develop and define the LRP, which represents the lowest biomass level believed to prevent serious harm to the stock from fishing (DFO 2023). Other reference points, which include the USR and the RR, are set by DFO Resource Management in consultation with stakeholders.

Current reference points for the ESS Northern Shrimp stock are applied to a spawning stock biomass (SSB) indicator and female exploitation rate based on the specific productivity period between 2000 and 2010. This decision was taken to avoid a scenario where moving-average based reference points would become less conservative during periods of biomass declines (Hardie et. al. 2018). The current LRP is set at 5,459 mt, which is 30% of the average SSB between 2000 and 2010 (implicitly assuming this SSB is a proxy for the biomass at maximum sustainable yield [MSY], as defined below). This is approximately equal to the average SSB in the low productivity period of the pre-1990s, which was set to avoid a decrease below which the stock would not be able to fulfill its ecosystem function (Hardie et. al. 2018). The current USR is set at 14,558 mt, which is 80% of the average SSB between 2000 and 2010. This is the default value that ensures a sufficient gap between the LRP and USR to account for uncertainty in stock status. Last, the current RR is set at 20% of the female exploitation when above the USR.

There are many ways to define reference points, but the predominant approaches have been to use proportions of either the theoretical long-term equilibrium biomass in the absence of fishing (B_0), also sometimes defined as the carrying capacity in surplus production model, or the biomass at MSY (B_{MSY}) (Barrett et. al. 2024). MSY, which has been viewed as the 'gold standard' in fisheries for decades, focuses on identifying the maximum long-term yield that a stock can produce given constant life history and selectivity parameters. MSY generally occurs at medium levels of fishing mortality, mostly based on observing larger per-capita growth rates at lower levels of biomass compared to B_0 (Barrett et. al. 2024). Generally, guidance around these metrics is to set the LRP at 20% of B_0 for high productivity stocks and typically 30%, 40%, or 50% of B_{MSY} depending on the jurisdiction.

Reference points can be estimated in many different ways depending on the underlying method used to assess a stock. Generally, a stock-recruit relationship (SRR) is used to directly calculate B_{MSY}. However, due to a need to incorporate uncertainty, simulation-based methods are the preferred approach when a stock assessment model is available. In using simulation-based methods, one can include all estimated parameters and their uncertainty to simulate the population forward in time, while accounting for all uncertainties and testing for different consistent exploitation rates. Such approaches can also identify B_0 directly from simulations without any fishing, as well as B_{MSY} and fishing mortality at MSY (F_{MSY}) from the exploitation rate associated with the largest average landings over a long time period. When simulations are either impossible or unsatisfactory, guidance suggests the use of historical proxies as estimates of B_0 and B_{MSY}. Alternative LRP candidates are often used as well, such as the lowest SSB observed (B_{loss}), lowest SSB with observed large recruitment ($B_{\lim}$), or minimum SSB that produced recruitment leading to stock recovery ($B_{recover}$) (Barrett et. al. 2024).

New candidate LRP that have been tested herein for the ESS Northern Shrimp stock are:

1. A proportion (0.2) of B_0;
2. A proportion (0.4) of B_{MSY}; and
3. The lowest SSB where large recruitment is observed (which coincides with the lowest SSB and is therefore both B_{lim} and B_{loss}).

Two different methods have been used to estimate B_0. The first method consists of selecting the highest SSB in the modeled outputs as a proxy for B_0 and the second method is to use simulations (as defined below) to estimate these parameters, as well as F_{MSY}.The B_{MSY} is only estimated through simulations.

SIMULATIONS

Simulations are performed using parameters obtained from the best model identified in the results on the scale of the total biomass, using a non-spatial general formulation of the delay-difference equation:

$$B_t = (e^{-m_t} g_{t-1}^I (B_{t-1} - C_{t-1}) + e^{-m_t} g_{t-1}^R R_{t-1}) \tau_t$$

The equation is used to project the biomass, B_t, into the future under different catch scenarios dictating C_t. However, this requires making assumptions as to how the recruitment R_t, growth rates g_t^I and g_t^R, natural mortality m_t, and the error term that aims to capture uncertainty τ_t are simulated over time. Furthermore, since these approaches are looking for SSB, but the delay-difference focuses on total biomass, the proportion of the biomass that is the SSB p_t also needs to be simulated.

For recruitment, two approaches for simulations were explored. To explore the realism of an SRR for shrimp, the relationship between SSB and recruits-per-spawner (RPS) were examined and fit with a Ricker model (Ricker 1954). As an alternative simplistic SRR, a hockey-stick approach was also developed (Barrowman and Myers 2000), wherein at levels of SSB larger than the lowest SSB, recruitment using a normal distribution with the mean set to the observed mean is simulated. The mean recruitment is set to decline linearly to zero at levels lower than the lowest observed SSB. While creating this linear decline still implies some relationship between stock and recruitment at lower levels, in reality there is no available data at lower SSB levels. The motivation behind the hockey-stick is that it is one of the most conservative approaches to a stock-recruit relationship given the absence of knowledge at lower SSB levels. To account for uncertainty, the recruit process error terms were simulated using an autoregressive model with a 4-year lag. While no autocorrelation in the process errors was observed using partial autocorrelation functions (PACF), this approach approximated the 4-year cycle that has been observed around recruitment in the available time series when examining recruitment, as simulated with this approach (Figure 22). Examinations of simulated long-term recruitment for both of these approaches seemed to indicate that they reproduced patterns of recruitment relatively similar to the historical observations in the survey (Figure 23).

Simulations of natural mortality were explored from the stationary distribution estimated by the selected model. However, due to large uncertainties estimated by the model for this distribution, closer examinations indicated routine simulations of natural mortalities either much higher (up to an instantaneous natural mortality of over 1) or much lower (as low as 0.1) than estimated for any points of the actual time series. Because of this, the natural mortality is simulated by randomly resampling the estimated natural mortalities from the actual time series.

The total biomass growth rate g_t^I is simulated with two different methods. The first method randomly resamples from the growth rates that were estimated in the observed time series (2005–24). The second method utilizes an autoregressive (AR) 2 model that was identified as the most reasonable time-series approach to model this parameter (Figure 24).

The recruit growth rate g_t^R is simulated using three different methods. The first method is to simply resample them from those estimated in the actual times series. The second method is to use an autoregressive AR(1) model to simulate them, as that model was the most reasonable one from preliminary analyses (Figure 25). For this method, while the correlation was mostly due to the trend seen in the recruit growth rate, the simulated growths were still broadly in line with what was observed, so the model was retained. For the third method, as a cross-correlation was identified between g_t^R and p_t (although again this was mostly related to strong relationships between trends instead of year-to-year changes; Figure 26), both of these parameters were simulated by jointly resampling them from those observed in the time series. For p_t, outside of the resampling, simulating it using an AR(1) model was also tested and deemed most appropriate given that it reproduced similar patterns as those directly observed, even if the correlation was mostly related to the trend (Figure 27).

PRODUCTIVITY PERIODS

While MSY approaches have seen successful in many parts of the world, they also come with limitations. Specifically, they assume that a relationship between recruitment and spawning stock exists and is well-understood (which is rarely the case), require a substantial amount of data and years of survey, exclusively base decision rules on biomass and fishing mortality without regard for other key information, and only consider the dynamics of a single species in an environmental and ecological stasis. In addition, the previous ESS Northern Shrimp reference points were all based on a specific productivity period and it is not clear that this productivity period remains a reliable measure of future productivity of the stock. For example, close examination of current stock indicators have shown two different temperature regimes in the last two decades: a low temperature regime coinciding with higher landings and higher estimates of biomass and SSB and a high temperature regime associated with a decline of the stock over the past decade (Figure 28).

To assess the impact of both assumptions, and of these different productivity regimes linked to temperature, four different climate/productivity scenarios with different combinations of the assumptions regarding model parameters, as described above, were tested: 1) a low productivity scenario (referred to as the Low scenario) where simulations are based on the parameters associated with the years of high temperatures (2011–24); 2) a high productivity scenario (referred to as the High scenario) where the parameters from the low temperatures (2005–10) are utilized; and 3) an overall scenario where the entire time series is utilized (referred to as the Baseline scenario). In addition, a second high productivity scenario (Scenario 4) is also tested, where all natural mortalities are utilized instead of only the ones between 2005 and 2010, in order to assess the impact of those mortalities on the results (referred to as the Mid scenario). For all simulation scenarios, 5,000 simulations were run and simulated forward 220 years (with the first 20 years being the actual time series), with only the last 50 years being retained where the biomass tends to stabilize, to analyze for the purpose of identifying B_0 and B_{MSY}. The different scenarios are tested with fishing mortalities between 0 and 0.05 in increments of 0.005. The different combinations of assumptions used to simulate within each productivity scenario are shown in Table 10.

ALTERNATE REMOVAL REFERENCE GUIDANCE

While the MSY simulations inherently provide guidance on RR points, another option for guidance around removal rates was explored. An Index Method (AIM) was used to assess the relationship between landings and the stock abundance (Rago and Legault 2014). This approach requires calculating the following two components:

$$relF_t = \frac{C_t}{\left(\frac{I_t + I_{t-1} + I_{t-2}}{3}\right)}$$

$$\Psi_t = \frac{I_t}{\left(\frac{\sum_{j\in\{4,5,6\}} I_{t-j}}{3}\right)}$$

where $relF_t$ is the relative fishing mortality in year *t* calculated as the landings C_t divided by the 3-year moving average of the last three year's index I_t and Ψ_t is the replacement ratio defined as the ratio of current stock size to the average size of the parental stocks that produced it. For purposes of the ESS Northern Shrimp stock, I_t is defined as the model-estimated SSB. Since it takes approximately 5-years for new shrimp to reach SSB, the I_t in the denominator of the second equation is further lagged. While it is common to use a 5 in the second equation's denominator, the short life expectancies of shrimp, and their tendency to take between 4 and 6 years to go from recruitment to SSB, a value of 3 was used herein instead. The AIM consists of fitting a linear regression between the log of these two variables where, if rates of loss are dominated by removals, a negative relationship between Ψ_t and $relF_t$ is expected. If that relationship holds, the $relF_t$ associated with $\Psi_t = 0$ indicates a level of relative fishing mortality that tends to result in a stable population.

ADDITIONAL DECISION TABLE IMPROVEMENT

A limitation of TLA that abetted need for a predictive stock assessment model is the ability to forecast stock status the following year. While decision tables were presented at the first framework meeting held on March 29–30, 2024, these were based strictly on total biomass, with further advancements needed to obtain decision tables based on SSB that can be used to inform management decisions. This requires an extra assumption around what percent of projected biomass would consist of SSB in the following year. Herein, a relationship between the proportion of the number of Age 4+ males over the total number of females (obtained from a combination of the mixture analysis and the length frequencies, as well as representing the amount of shrimp expected to transition before the next survey) and the following year's percentage of biomass that is SSB, are examined. An SSB decision table for 2024 is then recreated alongside the reproduced biomass decision table that would also have been presented in 2024, including a plot describing the performance of these methods as a retrospective on these decision tables.

TRAFFIC LIGHT APPROACH

The 'Traffic Light Approach', or TLA, was first coined by Caddy (1998) to describe a precautionary assessment framework for fisheries assessment in data-poor situations. Caddy (1998) proposed that the state of a fishery and ecosystem could be summarized using red (poor), yellow (neutral), and green (good) lights to characterize the status of a series of indicators. The TLA was viewed as a way to focus scientific attention on the biology of a resource and its interactions with the ecosystem and environment, in order to provide a broader and sounder basis compared to approaches based simply on an accounting of population change. The TLA also provides more opportunity for the integration of industry experience and knowledge, as well as allows results to be presented in a manner that promotes a broader understanding by all stakeholders in a much simpler and transparent way.

The holistic nature of the TLA is an attractive feature and has provided independent trends on several indicators associated with the ESS Northern Shrimp stock over the years. At present, a total of 24 ESS Northern Shrimp indicators have been used since the last stock framework assessment conducted by Hardie et al. (2018). The knowledge gained on stock dynamics by assessing many indicator trends provides an interactive context to stock health, as intended; however, DFO's PA policy still only integrates MSY based reference points. The basis of these reference points is limited by the same assumptions that:

1. a relationship between recruitment and spawning stock size exists and is understood;
2. requires lots of data;
3. bases decision rules only on biomass and fishing mortality; and
4. considers only a single species in an ecological and environmental stasis.

A TLA has been used to assess the status of the ESS Northern Shrimp stock for the provision of science advice since 1999 (Koeller et al. 2000a; Halliday et al. 2001; Mohn et al. 2001). This holistic, multiple-indicator approach considers the current value of each indicator relative to its time series and then categorizes individual indicators into four characteristics, yielding an overall stock summary. Since implementation of DFO's PA policy, the different zones (i.e., red, yellow, and green) for each indicator have been based on the 33rd and 66th quantiles of those indicators during the high productivity period between 2000 and 2010.

Herein, TLA indicators always represent summary data for the entire area (i.e., all SFA combined, according to the current practice of managing the fishery as one stock). Where appropriate, interpretation of the indicator time series themselves is supplemented by other data; however, supporting data may be quite independent from the data used to derive the main indicator. For example, if catch rates in the shrimp trap fishery supported an increasing shrimp aggregation demonstrated by the survey and CPUE data (anecdotal reports of large numbers of Age 1 shrimp found on Cape Breton beaches in 2002 supported survey data indicating a strong 2001 year class, etc.). Such additional information may be used in the interpretation of indicator trends, but it is not used in the summary of TLA 'scores'. The TLA is currently seen simply as a tool for displaying, summarizing, and synthesizing a large number of relevant yet disparate data sources into a consensus opinion on stock health. To date, however, TLA scoring has not been intended to translate directly into management action (e.g. in the form of stock management rules linked to summary TLA scores).

The current application of the TLA does not well-inform the degree of influence one indicator may have over others nor the strength of correlation between indicators. The index based on an overall trend for each summarizing characteristic is only the average of the overall indicators measured against the reference period of high productivity between 2000 and 2010. As such, the TLA only serves as a contextual tool for stock health, although the context is set-aside when applying the DFO PA policy using reference points that do not inform such context. With this in mind, the TLA indicators are refined herein to those that show explicit useful correlation with key stock parameters. The intent is that any new and retained indicators will add robustness to application of the DFO PA policy to the ESS Northern Shrimp stock, as well as improve the overall predictive capability of the TLA on stock health.

STOCK STATUS INDICATORS

In the following section, time series of stock status indicators are described, including their red, yellow, and green zones (Figure 29). Furthermore, while the zones are based on the productivity period between 2000 and 2010, the zones for all retained and proposed indicators are adjusted to be representative of the quantiles for all available years between 1995 and 2024. This means that future years will be compared to the period between 1995 and 2024 instead of a moving average, with an update to this comparative period planned for a future framework assessment for the stock. Comparing to this period has the advantage of the interpretation of each zone being clearer, where a green zone is now representative of the productivity period, red zone is representative of the recent large declines, and yellow zone is in between.

Comparisons between different indicators and key stock components (e.g., SSB, mortality, etc.) are done using cross-correlation functions (CCF), which identify correlations between time series. It is important to note that these identify correlation and not causation, meaning they identify how things relate to one another but not if there is a causal relationship, as there can always be something external that is causing a correlation without any associated cause. Last, it is also possible that, due to the large number of CCF utilized here, and the large numbers of examined components, that some relationships may likely be spurious while others may be missed. To try to minimize this risk, the analyses do not focus on p-values, rather focus on trying to relate any relationships directly to shrimp biology.

Abundance Characteristic

Proposed indicator updates to better assess the stock abundance characteristic include:

- Replace survey indices with modeled outputs (total biomass and its coefficient of variation);
- Explore a better standardization approach that could incorporate both the Gulf and Scotia mobile fleets and obtain a single standardized mobile CPUE;

- Add an indicator based on shrimp bycatch in the snow crab survey; and
- Explore a new spatial distribution indicator (i.e., area occupied) to further characterize stock dispersion, including areas not covered by the current survey.

DFO-Industry Collaborative Survey Biomass

The ESS Northern Shrimp survey biomass index has in the past provided a generally robust fishery independent metric of shrimp abundance trends in the ESS SFA (Figure 30). Coupled with commercial catch rate indices, with which it is generally strongly correlated, and the modal analysis of sample length-frequencies, the survey abundance index has in the past formed the basis of the most important data considered in the assessment of the stock. Many other indices, including SSB, Age 2 and Age 4 abundance, total exploitation, and female exploitation, were derived at least in part from this index. With application of the selected model for the ESS Northern Shrimp stock assessment moving forward, a model-based prediction of yearly total biomass within the survey domain is now available. The differences between the model-estimated biomass and the index-based biomass are examined, with a proposal to set the model-estimated biomass as one of the baselines to which other indicators are compared for correlations, with broad relationships therefore being examined herein. For this indicator, a high value is associated with the green zone.

Gulf Vessels CPUE

The Gulf fleet vessels are the largest vessels in the fleet at greater than 65 feet in length compared to compared to the Scotia fleet vessels that are less 65 feet in length. Catch data from this time series is particularly valuable because it includes periods of both low (preceding groundfish collapse) and high shrimp abundances on the ESS (Figure 3). The introduction of the Nordmøre grate in 1991 coincides approximately with the beginning of the increase during the period of high abundance of the stock, so the difference in this index between the two periods should be interpreted cautiously. The catch rate data, from which this index is derived, also tends to be temporally and sometimes spatially different from the Scotia fleet data, as the Gulf vessels typically fish most of their quota very early in the year; generally, returning in the late fall to complete harvesting their quota allocation or in the event of a transfer of trap quota to the mobile fleet.

The Gulf fleet is also more likely to fish in SFA 14 and 15 between March and June, followed by SFA 13 later in the season. Over the last few years, Gulf fleet fishing patterns have changed due to the influence of the pandemic, fishing only in the latter part of the season and focusing their effort in SFA 13 (although more recent trends have returned to pre-pandemic patterns). For this indicator, a high value is associated with the green zone. However, decreasing fishing effort due to recent TAC reductions have brought a new issue for the shrimp assessment, wherein, in 2024 the Gulf vessel CPUE could not be included in the official assessment due to the limited number of active licenses that is below the threshold for public reporting under Canadian privacy rules. As such an alternative approach is considered herein, with a proposed overall standardized CPUE being presented below.

Commercial Scotia Mobile Standardized CPUE

Although the overall, and by SFA, unstandardized CPUE time series are presented annually as supporting material for discussion, a standardized Scotia vessel CPUE time series indicator is also analyzed. The standardization uses commercial data from April to July (the month when the bulk of the TAC is generally caught) across all SFA, from vessels less than 65 feet in length that have fished for at least seven years in the time-series of 1995-present. A generalized linear model is used to standardize commercial CPUE using determinant variables, vessels, years, month, and SFA:

glm(formula = CPUE ~ BCODE + YEAR + MONTH + SFA, family = Gaussian)

The data fit best to a Gaussian distribution, which has the lowest Akaike information criterion value of those examined when this was developed. Predicted standardized CPUE values and confidence limits for a reference vessel, month, and area are then calculated for each year using the package predict.glm (R Development Core Team 2005). The standardization specifies parameters selecting for the high liner vessel for the current year, commercial fishing data in the month of the current year where the bulk of the TAC is generally caught, and in SFA 14 only. The standardized commercial CPUE index is interpreted alongside the Gulf fleet and ESS Northern Shrimp survey catch rates, as discussed above. In addition, divergences among catch rate time series are evaluated in the context of other indices of stock dispersion and predicted changes, based on length-frequency distributions from previous years.

For this indicator, a high value is associated with the green zone. Decreasing efforts due to reduced TAC in recent years have brought a new issue for the shrimp assessment, wherein in 2024 the commercial Scotia mobile standardized CPUE also could not be included in the official assessment due to the limited number of active licenses falling below the threshold for public reporting under privacy rules. An alternative approach is considered herein, with the proposed joint standardized CPUE being presented below.

Proposed Joint Standardized Commercial CPUE

Although both CPUE indices have been highly effective in the past, the year 2024 prevented their inclusion in the annual stock advice due to the limited number of active licenses falling below the threshold for public reporting under privacy rules. Since model outputs can still be shown, provided that the results cannot be traced to specific vessels or licenses, development of a new standardization model that incorporates and accounts for differences in year, strata, mobile fleet, and individual vessels, is explored further herein. As the histogram of commercial CPUE suggests potential issues with the use of Gaussian distribution, a lognormal model is utilized:

$$\log(CPUE_i) = \beta_y + \alpha_m + \eta_v + \upsilon_f + \nu_s + \epsilon_i$$

where $CPUE_i$ is the commercial CPUE from logbook i, β_y is the intercept in year y, α_m are Gaussian random effects by month m, η_v are Gaussian random effects for each vessel v, υ_f are Gaussian random effects for fleet f (either Gulf or NS), ν_s are Gaussian random effects for strata s, and ϵ_i are Gaussian error terms.

Using the β_y as a yearly indicator, which represents the average CPUE after accounting for all other modeled characteristics, the modeled output could not be directly tied to an individual vessel, but does still enable it to be incorporated and presented as information from the commercial CPUE without violating data privacy rules, as long as both fleets are active. If one fleet becomes dormant, however, and the other fleet has too few active licenses, the same problem is again encountered under privacy rules. While the approach to standardize catch rates can be seen as an attempt to extract more information on the stock status from catch-only sources, it is cautioned against interpreting this result on its own, especially if it does not reflect the changes observed by the survey, as catch-only methods are known to perform poorly overall (Ovando et al. 2021). This approach should therefore be interpreted in consideration of the fisheries-independent data, in order to develop a more complete picture of the stock. For this indicator, a high value is associated with the green zone.

Commercial Scotia Trap Catch Per Trap Haul

The trap sector active fishing season differs from that of the mobile sector. Historically, fishing would be initiated in July and continue until April or May of the following year (1996–97 to 2000–

01). Beginning in 2001–02, the fishing season began to decrease in length, and in the most recent years, fishing has occurred mostly in late-October or early-November to March. This index has been reported from an annual fishing season perspective, and thus, catch per trap haul is calculated within a fishing year (i.e. 2020), although the difference in active timing compared to the other fleets makes its interpretation more difficult. Its correlation to other key stock parameters is quantified and its usefulness is assessed. For this indicator, a high value is associated with the green zone.

DFO-Industry Collaborative Survey Coefficient of Variation

This measure of shrimp stock dispersion, along with the commercial fishing area index (described further below), are used to interpret changes in biomass indices; particularly, in cases where survey biomass is declining while commercial catch rates remain high. Under this scenario, an increase in this index would warrant consideration that the fishery may be maintaining high catch rates on remaining high-density aggregations of a declining resource, while the survey is revealing patchiness in the distribution of shrimp. This trend would be even more worrisome if the commercial fishing area index declined, indicating that the area within which high catch rates are being achieved is smaller, as the stock clusters in these areas. An introduction of model-based biomass predictions renders the interpretation of this indicator more difficult as it is currently defined, as the model itself accounts for spatial variability in its estimates. However, this indicator still provides a fairly good representation of how much observation uncertainty is present in the survey data compared to other years; thus, modification to it is not proposed. For this indicator, a high value is associated with the red zone.

Commercial Fishing Area

This indicator is calculated as the area of commercial catch rates greater than 250 kg/h, although trends in the area of several other ranges of catch rates are often also presented for discussion and to contextualize the interpretation of this index. The different catch rate thresholds in the context of the total biomass and the effort are re-examined herein to assess which provides the most useful information. For this indicator, a high value is associated with the green zone.

Bycatch of Shrimp Trend

The ESS Northern Shrimp survey yields substantial information about the distribution and abundance of the stock in June each year, although it does not capture intra-annual stock changes. However, other surveys occurring at different times of the year, but within the same area, could provide insight into trends from year-to-year, improving stock health monitoring capabilities with temporally aligned information across stock productivity stages. The snow crab survey, which takes place in the fall (roughly at the midpoint between shrimp surveys), routinely captures shrimp as bycatch in the same areas as the ESS Northern Shrimp survey conducted in June. Although the snow crab survey gear design likely makes this information unsuitable as a quantitative measure of ESS Northern Shrimp abundance, it may still offer a qualitative measure of increase or decrease in the shrimp population and/or reinforce the trends seen in the main ESS Northern Shrimp survey. As such, relationships between the average number of shrimp caught in the snow crab survey and model outputs are explored herein. To ensure a more clear comparison to the ESS Northern Shrimp survey domain, only snow crab stations located in the general area of the shrimp holes are used, instead of the entire snow crab survey domain (Figure 31). For this indicator, a high value is associated with the green zone.

Area Occupied

As discussed above, derivation of biomass and exploitation indices from survey coverage that is restricted to the ESS Northern Shrimp fishing grounds (rather than exceeding the stock boundaries, as survey design theory would recommend) is generally viewed as an extra measure of precaution in management of the fishery. However, this survey design cannot detect peripheral range retractions until they affect aggregations in central/optimal habitat in the shrimp holes, increasing the risk that a decline in the population is missed and only observed after meaningful management action can be taken. In contrast, the snow crab survey, which captures shrimp as bycatch, extends outside of the current ESS Northern Shrimp survey domain and may help inform on broad trends of space utilization by shrimp based on their presence or absence as bycatch in the survey. It is proposed herein to utilize the presence or absence of shrimp bycatch information from the extent of the snow crab survey to create an area occupied (AO) metric, which is similar to most effective area occupied metrics that utilize density (e.g., Thorson et al. 2016). However, this being bycatch data precludes a focus on density, as the catchability of the snow crab gear for shrimp remains unknown. This is done by creating a grid over the extent of the snow crab survey, with the AO being calculated in the following way:

$$AO_y = \frac{\sum_{i=0}^{n_y} I_i}{n_y}, \;\; where\; I_i = \begin{cases} 1\; if\; shrimp\; were\; found\; in\; that\; grid\; cell \\ 0\; otherwise \end{cases}$$

Where n_y is the number of 10 km x 10 km grid cells with an active snow crab survey set in year y. This approach accounts for changes in the extent and coverage of the snow crab survey by excluding grid cells without any snow crab sets, as their coverage varies slightly between years. This indicator should provide information on the range of the ESS Northern Shrimp stock outside of the key shrimp fishing holes. The usefulness of this is assessed herein by quantifying its relationship to key stock parameters. For this indicator, a high value is associated with the green zone.

Production Characteristic

On the ESS, stock production of Northern Shrimp is largely described by indicators related to recruitment. In this case, length frequency data collected primarily from the belly bag (juveniles) and main trawl shrimp catch from the annual DFO-Industry collaborative survey are utilized. Year-class strength is defined by the survival of the shrimp phases (i.e. larval to transitional males to primiparous/multiparous females); thus, annual tracking of these phases is important. Length frequency data from the commercial port sampling program also provides representative information of the fishery catch composition throughout the year. From these sources, growth patterns can be monitored to inform stock production. Proposed indicator updates to better assess this stock characteristic include:

- Replacement of the recruitment (belly bag) indicator with model-based outputs; and
- Analysis of other indicators to assess their utility.

Belly bag Abundance at Age 1

A need to develop an early index of recruitment of ESS Northern Shrimp was identified as a research priority in the late-1990s. Juvenile surveys using small-mesh beam trawls provided less effective results than the addition of a small-mesh ‘belly bag’ to the footgear of the survey trawl (Koeller et al. 2003). As a result, the latter method was chosen to provide data for an index of recruitment for this stock, which has been used since 2002. The belly bag is a 1-m wide, small mesh bag that is attached to the underside of the main trawl codend. A belly bag sample is obtained from each survey station, which is analyzed to obtain a swept area index estimate of shrimp of each CL class of less than 11-mm. The belly bag index of recruitment is the sum of this index for all SFA for all carapace lengths of 10-mm or less, which are interpreted as the CL in June that correspond to the preceding year's cohort. The model is able to estimate, based on the same data informing the belly bag index, a yearly recruitment. How related these two are to assess their comparative utility is examined herein. For this indicator, a high value is associated with the green zone.

Survey Abundance at Age 2

Survey Age 2 and Age 4 abundance indices for the TLA, as well as survey population estimates of all ages (e.g., Table 11), are estimated from the detailed analysis of survey samples using a mixture analysis. The number of shrimp of each length caught in each survey stratum is standardized and multiplied by the number of trawlable units in that stratum, as per the swept area method, in order to estimate the total number of shrimp in each stratum summed over the survey area. Survey population estimates by age group are then estimated by separating total population at length estimates from the swept area method into inferred age groups using modal analysis ("mixdist" in R; see: MacDonald and Du [2018] for more details). The data is usually assigned to seven age bins, which are interpreted as corresponding to Ages 1–7, although in some years the use of six bins for Ages 1–6 provides a more highly-significant fit to the length frequency. Although this is verified annually, and the most significant fit is presented, modes corresponding to older ages are binned together as Ages 5+ (Table 11), as the assignment of ages would be highly subjective for Ages 6 and older.

Although the length frequency modal analysis defines the Age 2 mode, it is uncertain how efficiently this size of shrimp is sampled by the main survey trawl. This may explain why concordance between indices of Age 1 and Age 2 abundance have been somewhat equivocal (i.e., changes in the Age 1 index are not always followed by concomitant changes in the Age 2 indicator the following year; Table 11). For this reason, relationships between the Age 2 indicator and other key components of the stock are explored herein, with its usefulness as an indicator assessed. For this indicator, a high value is associated with the green zone.

Survey Abundance at Age 4

The abundance of Age 4 shrimp is calculated as per abundance of Age 2 described above; that is, from survey population at length estimates from swept area and modal analysis. On the Scotian Shelf most Age 4 shrimp are in their final year as males, where they are believed to breed as males during the survey year and change sex the following year. Since females comprise most of the catch, the last-year males are a measure of recruitment to the fishery and of potential contribution to the following year's SSB. Correlations to other key stock parameters are quantified herein, with its usefulness assessed. For this indicator, a high value is associated with the green zone.

Survey Spawning Stock Biomass (Females)

A stock-recruitment relationship has not yet been described for ESS Northern Shrimp, although it has been done for some other pandalid stocks; albeit, with large uncertainties (Hannah et al. 1995; Boutillier and Bond 2000). The limited amount of 'good' shrimp habitat on the ESS, and the nature of currents as they pertain to shrimp settlement/colonization, suggests that a more precautionary approach is needed for this stock in terms of maintaining a high SSB relative to areas like Newfoundland (Koeller 2000). Because of evidence of recruitment cycles following high SSB, and because the fishery primarily targets females, the SSB index is used to define biomass reference points for this stock. The SSB, or total weight of females in the population, has historically been calculated with the swept area method from the weight of females in each set, determined by identifying females (including transitionals) and their lengths in the detailed sample, total catch weight, and a length-weight relationship.

Transitionals are included, as on the ESS, all transitionals are expected to complete sex change during the summer and extrude eggs during the late-summer/early-fall, which contributes to the SSB for that year. With introduction of model-based estimates of total biomass, a model-based SSB can be computed by estimating the proportion of the total biomass that consists of transitionals and females and then multiplying this by the model-based total biomass. It is proposed here that the previous method of estimating SSB be replaced with the new model-based SSB, and retain this new SSB index as the basis for DFO's PA policy, upon which the proposed LRP described above are further explored. For this indicator, a high value is associated with the green zone.

Average Size at Sex Transition (L_t)

Size indices, of which four are included in the TLA, provide important information about the Northern Shrimp stocks given that environmental (temperature) and demographic (density) factors influence shrimp growth and life history in ways that can have profound effects on a stock. Koeller et al. (2003) and Koeller (2006) demonstrated that shrimp size at transition is related to growth rate. It is hypothesized that an increase in growth rate, due to density-dependent effects or temperature increases (Koeller et al. 2000b), result in decreases in the size at transition, maximum size, longevity, and fecundity of shrimp, followed by a population decline. In contrast, during cooler periods, shrimp grow more slowly, undergo sex transition at a larger size and older age, and live longer.

Furthermore, delayed sex transition occurs during periods of high population density, which results in extra years of growth and, in turn, results in the production of larger females. Because of the relationship between female shrimp size and fecundity, a stock composed of larger females is potentially much more productive. The increased longevity of particularly-abundant year classes (e.g., 2013) can have important implications on qualitative projections (based on length frequency tracking) used to evaluate the potential exploitation rates that may result from different TAC. It is explored herein how average size at sex transition (L_t) relates to the stock parameters to better quantify how it can impact stock status. For this indicator, a high value is associated with the green zone.

Average Maximum Size (L_{max})

The ratio of size at sex transition to maximum size was hypothesized to be constant (invariant) at about 0.8–0.9 for all stocks of Northern Shrimp (Charnov and Skúladóttir 2000). This rule was shown to apply to the ESS Northern Shrimp stock (Koeller et al. 2003; Koeller 2006). Consequently, maximum size attained in the population is an indicator of growth; that is, change in maximum size likely indicates a change in growth rate. The relationship between L_t or average maximum size (L_{max})) to changes in growth rate is complicated by other factors, including concurrent changes in longevity and natural mortality (e.g., slower growing shrimp tend to live longer). Overall, when the biggest shrimp are particularly large in size, it is likely because they are slow growing and long-lived. These biological responses tend to be associated with periods of high abundance and slow growth due to cooler temperatures. A large maximum size is, therefore, indicative of favourable environmental and stock conditions. How this relates to stock parameters are explored further herein, to better quantify how it can impact stock status. For this indicator, a high value is associated with the green zone.

Fishing Effects Characteristic

Fishing effects that impact the ESS Northern Shrimp stock are described by various indicators, which are all based on commercial data (i.e., logbooks, port sampling, etc.).

Effort

Effort is tracked in the ESS Northern Shrimp fishery as the sum of fishing hours for the year, presented in thousands of hours. It is proposed that there be no change to this index given the usefulness in its relation to other commercial indicators as a contextual tool. For this indicator, a high value is associated with the red zone.

Commercial Counts

Harvesters determine the number of shrimp per pound (the “count”) in their catches soon after they are brought aboard a vessel, in order to determine the price that they will obtain from buyers, subsequently adjusting fishing practices accordingly (especially location). This information is of economic importance and is often conveyed to other harvesters or buyers before landing, so care is usually taken to obtain and record it. The methodology used is basic — number of shrimp in a fixed volume, often a tobacco can, that weighs about 1 pound — but generally agrees with more rigorous methods used by buyers. The index used here is the simple arithmetic average of all commercial counts reported in log books for the year. It is explored herein here how this relates to the stock parameters, in order to better quantify how it can impact stock status. For this indicator, a high value is associated with the red zone.

Exploitation Index

An overall index of exploitation rate is calculated as the total commercial catch weight divided by the estimate of ESS Northern Shrimp survey biomass. The resultant index value is presumably an overestimate of exploitation, as the survey coverage does not include the entirety of the stock area (as evidenced by fishing activity that occurs outside of the survey strata). It is expected that the new stock model-based estimate of total biomass will have a less conservative bias; however, as the survey still does not cover the entirety of the stock, and only focuses on “core” areas, some overestimation of exploitation is still expected. For this indicator, a high value is associated with the red zone.

Female Exploitation Index

As the ESS Northern Shrimp fishery is selective for larger females, female exploitation can be considered an important measure of fishing impacts on the reproductive potential of the stock; it is for this reason that it is used as the RR for the stock under the DFO PA policy (Smith et al. 2012). Female exploitation is calculated as the estimated weight of females in the catch divided by the weight of females in the population estimated from the survey; that is, SSB. Similar to the total exploitation, this indicator is recalculated based on the model-based estimates of SSB. For this indicator, a high value is associated with the red zone.

Mean Size of Females in Catch

A decrease in the mean size of females in catch indicator could indicate a decrease in the number of larger shrimp in the population due to fishing removals and an increased reliance on smaller shrimp; that is, possible growth overfishing and/or recruitment overfishing. It is explored herein how this relates to stock growth and size parameters, in order to better quantify how it can impact stock status. For this indicator, a high value is associated with the green zone.

Proportion of Females in Catch

The proportion of females in catch indicator is calculated using data obtained from the analysis of commercial samples (as described above); namely, the lengths and individual weights of female shrimp relative to the total catch weight. The index should be interpreted cautiously and in combination with other indicators, as it can also indicate good recruitment conditions and difficulty in avoiding younger shrimp. It is proposed that there be no change to this index given it is a key component in calculating female exploitation rate. For this indicator, a high value is associated with the green zone.

Ecosystem Characteristic

This characteristic contains information about the different environmental pressures impacting the ESS Northern Shrimp stock that are not inherent to the stock itself (i.e., external pressures) and thought to represent potential trends in natural mortality (note: there are no known direct estimation methods for natural mortality, although is generally thought to be high). The SEAM model provides indirect estimation of yearly natural mortality, which allows for further exploration of relationships between these different indicators and the stock parameters.

Predation

Shrimp are an important dietary component of several important commercial groundfish species that comprise most of the biomass on the ESS, including Atlantic Cod, Silver Hake, Greenland Halibut and various flatfish species (Koeller 2000). The predation index derives from the mean stratified catch per tow of the annual Summer RV Ecosystem trawl survey of all groundfish in strata coinciding with known areas of shrimp distribution (Strata 443–445, 459), as a proxy for predation pressure. Herein, ‘groundfish’ refers to all species with species codes less than 1000 in the Summer RV Ecosystem trawl survey database, which includes a broad range of species (Hardie et al. 2018). As a result, in recent shrimp assessments the term ‘finfish’ has been used rather than ‘groundfish’ to reflect this fact. The predation index does not reflect whether or not the species considered are confirmed to eat shrimp on the ESS and, if so, how much. Despite this, the unrefined index is still very likely a suitable index of predation. It is explored herein how this relates to the stock parameters, in order to better quantify how it can impact stock status. For this indicator, a high value is associated with the red zone.

Cod Recruitment

This cod recruitment index of natural mortality based on the abundance of Atlantic Cod recruits (less than 30 cm), as captured by the Summer RV Ecosystem Trawl survey in the strata overlapping the shrimp holes. It is explored herein how this relates to the stock parameters, in order to better quantify its impact. For this indicator, a high value is associated with the red zone.

Turbot Recruitment

The Turbot recruitment index is based on the abundance of Turbot that are less than 30 cm, as captured by the Summer RV Ecosystem Trawl survey, which are thought to be sympatric to shrimp (Hardie et al. 2018). This index focuses on recruitment as Turbot are also known shrimp predators, but generally at larger sizes. It is explored herein how this index relates to the stock parameters, in order to better quantify its impact. For this indicator, a high value is associated with the green zone, although the interpretation of this indicator can be very difficult.

Specific Predators Index

While the current predation indicator has been useful in the past, it includes many species whose impact on shrimp are unclear or have not been quantified before. A secondary predation indicator is therefore proposed, focused on a few key species thought to be important predators of Northern Shrimp: Shortfin Squid, American Plaice, Atlantic Cod, redfish species, Turbot, Silver Hake, and White Hake. These predators are selected based on the examination of stomach contents by the DFO Food Habits program from fish captured by the Summer RV Ecosystem Trawl survey in NAFO division 4Vn and DFO statistical unit areas, 4Vsb, 4Vsc,4Wd, and 4We, which encompass SFA 13–15. These predators have historically contained proportions of *Pandalid* shrimp (Figures 32 and 33).

The one exception is Shortfin Squid, whose stomach contents are not sampled by the DFO Food Habits program. However, a substantial amount of Shortfin Squid have been observed in shrimp nets in the years around 2020, and therefore, have been added to this list for further examination if there is anything useful in including them within this secondary predation index. The average numbers of all individual species have been calculated using the same method, as done for the overall predation index (aside from removing any size limitations given that Figures 32 and 33 did not appear to show substantial differences between smaller and larger animals of the same species), and their relationship to key stock parameters assessed. For those deemed useful for predicting one year ahead, a specific predator index has been created using the average number of those selected predators, in order to assess its relationship to key stock parameters. For this indicator, a high value is associated with the red zone.

Bottom Temperatures

For some Northern Shrimp stocks near the southern limits of their range, abundance is negatively correlated with water temperature (Appolonio et al. 1986). It is hypothesized that warmer water temperatures have a negative affect on shrimp populations because of decreased fecundity associated with increased growth rates, decreased size at transition, and decreased maximum size. Recent research also indicates that colder bottom temperatures increase egg incubation times, resulting in later hatching times that are closer to favourable spring growing conditions (i.e., warmer surface water and the spring phytoplankton bloom) (Koeller et al. 2009). On the ESS, a large population increase in shrimp that occurred from the mid-1980s to the mid-1990s is associated with colder surface and bottom water temperatures (Hardie et al. 2018). Shrimp survey bottom temperatures are monitored throughout each ESS Northern Shrimp survey set using a temperature recorder mounted to one of the trawl doors. Positioning of the temperature recorder is closest to the ocean bottom, while also protecting the recorder against damage or dislodgment while the tow is being fished. It is explored herein how bottom temperature relates to stock parameters, in order to better quantify how it can impact stock status. For this indicator, a high value is associated with the red zone.

Spring Sea Surface Temperatures

Up to 2023, SST were obtained from the DFO Maritimes Region [Atlantic Zone Monitoring Program (AZMP)](), which monitored satellite output from the U.S. National Oceanic and Atmospheric Administration (NOAA). Since 2023, SST is now monitored and maintained by the DFO Québec Region. The SST indicator for the TLA represents a combination of the two approaches for monitoring SST on the Scotian Shelf by DFO. Negative correlations between spring SST and lagged population estimates (four to five years in the Gulf of Maine) are common for southern Northern Shrimp stocks (Appolonio et al. 1986). This may be related to water column stability and a match-mismatch of resulting phytoplankton bloom conditions with hatching times, as hypothesized by Ouellet et al. (2006). Accordingly, the SST used are averages for a period encompassing average hatching times on the Scotian Shelf (mid-February to mid-March). The SST are calculated from satellite data as average temperatures within defined rectangles that encompass the shrimp holes (Figure 34). It is explored herein how this relates to the stock parameters, in order to better quantify how it can impact stock status. For this indicator, a high value is associated with the red zone.

Snow Crab Recruitment

The Snow Crab recruitment index, as described in Hardie et al. (2018), is now shifted forward by one year in the TLA (e.g., 2013 value used for 2014 TLA value) to account for the current-year value generally not being available in time for the annual ESS Northern Shrimp stock assessment or stock update. This is an index of immature male Snow Crab less than 56-mm carapace length, which would be 1–3 years pre-fishable biomass and about 6–8 years post-settlement. It is explored herein how this relates to the stock parameters, in order to better quantify its potential impact on stock status. For this indicator, a high value is associated with the green zone.

RESULTS

MODEL REQUIREMENTS

Relation between belly bag and main trawl

Scaling the weight of recruit shrimp caught in the belly bag and comparing it to the length-frequency corrected main trawl biomass shows an apparent link between the two, although it is not linear on the natural scale. Scaling it to match the wingspread of the main trawl gear shows that the main trawl consistently catches more than is explained by just the larger width (Figure 35). However, scaling it to both the wingspread and height of the main trawl net shows that the belly bag would be capturing more than the main trawl (Figure 36). The peaks observed in the distributions of both comparisons suggests a relationship between the comparable biomass estimates of both gear types, indicating a scaling relationship that lies between area (scaling to width) and volume (scaling to width and height) relationship.

Fitting a linear regression on the natural scale shows no relationship (Figure 37); however, a linear regression on the log scale shows a linear trend with a slope estimate of approximately 2.2 (Figure 38). On the natural scale, this indicates that the length frequency-corrected main trawl biomass is related to the belly bag biomass of shrimp greater than 10-mm by a power of 2.2. This suggests that the main trawl biomass and the belly bag catches are related, supporting the use of the belly bag less than 10-mm shrimp as an index of recruitment. However, this also suggests that the belly bag may be catching fewer shrimp than the main trawl. If this pattern also applies to smaller recruits, it is likely that the catchability of the belly bag is lower compared to the main trawl.

Recruitment

The LW models applied to the 2023 sample of shrimp from the belly bag successfully converged and their diagnostics were satisfactory (Figures 39 and 40). These estimates correspond to average differences of approximately 0.1 to 0.2 grams and are expected to have a marginal impact, while the slight overestimation in the lower tails may indicate a general overestimation of recruit weight. This allows for the prediction of weights of all non-sampled recruits (as only 50 shrimp are individually measured by tow) and total weight of recruits in each tow across all years (Figures 41 and 42). Stratum 17 consistently has the largest recruit biomass with virtually no zeroes, while Strata 13 and 14 tend to have lower recruit biomass and more zeroes. The index calculated using the swept area method is presented in Figure 43, with the largest peak observed in 2014.

Growths

The mixture models were all significant ($p<0.01$). For consistency, the models with the mixtures of seven lognormal distributions to match the observed length frequencies were selected (Figures 44 to 47). The Von Bertalanffy relationship fit to the ages attributed to each mode and those corresponding lengths converged successfully (Figure 48). The strata- and year-specific lognormal spatial LW relationships all successfully converged, with diagnostics being satisfactory (Figures 49 to 56). The resulting estimated growth rates for both the main trawl biomass and the recruit biomass (Figures 57 and 58) show different patterns by stratum. For the main trawl biomass, Stratum 17 is consistently higher than all other areas with the exception of Stratum 15 in 2009.

Prior to 2011, growth rates for all strata were relatively similar. After 2011, growth rates in all strata, except Stratum 17, decreased with increased divergence over time; however, Strata 14 and 15 remained more similar. Assuming higher growth rates indicate a higher proportion of smaller shrimp, and considering that Stratum 17 has historically had a larger proportion of smaller shrimp and recruits, this trend is expected. The spike in recruitment seen in 2014 in the recruit swept-area index is evident in the growth rates in 2015 for all strata (especially Stratum 15) due to a larger proportion of smaller shrimp recruiting into the fishery. This spike in growth lasts two years and peaks in 2016, indicating continued recruitment of small shrimp. The growth rate for all strata combined is close to the mean of all four strata-specific growth rates.

For the recruit biomass, there is a decreasing trend over time for all strata (ignoring the 2014–15 spike in Stratum 17), indicating that the recruits found in the belly bag have been increasing in size over time and potentially indicating a shift in the timing of spawning to earlier in the year. Due to the larger number of zeroes in all strata, except Stratum 17, the growth rate for all areas combined is largely driven by Stratum 17, indicating that most recruits are found there as was also found when calculating the observed recruit weights by tow (Figures 57 and 58).

MODEL RESULTS

Convergence

The SDD gave false convergence, while both TLM and SEAM converged successfully. To identify strategies to improve SDD convergence, iterative fittings were conducted by fixing various combinations of parameters at biologically-reasonable levels. It was able to converge successfully if the instantaneous natural mortality was fixed at a constant value of 0.35 and if the observation variance σ_{ϵ}^2 was fixed at various arbitrary numbers. Despite achieving convergence, and only estimating a total of four parameters ($\sigma_{\upsilon}^2, \sigma_{\tau}^2, \sigma_{\phi}^2$, and q_R), the Hessian matrix remained non-positive definite, and the recruit process variance σ_{ϕ}^2 was estimated arbitrarily close to zero. Fixing additional parameters would effectively dictate the model's outputs, providing no information outside of what the indices indicate. Consequently, the SDD model was excluded from further analysis and only the results from TLM and SEAM models are presented herein.

For equivalent parameters, the estimates obtained by SEAM and TLM are broadly similar (Tables 12 and 13), with the observation variances σ_{ϵ} and σ_{υ} being estimated at lower values for SEAM compared to TLM. The spatial parameters are all within biologically-reasonable values for SEAM (result in decorrelation ranges of approximately 57 km and 282 km for biomass and recruitment, respectively). In contrast, TLM appears to struggle with the biomass process variance σ_{τ}, which has a particularly large uncertainty around it and is estimated at a much lower value than expected.

Sensitivity Analysis

For SEAM, prior distributions bounded at 0.8, 0.9, and 1 led to convergence issues, resulting in false convergence rather than relative convergence. As a result, model outputs under these conditions may be unreliable. Otherwise, data appear to inform the estimation of q_R as it is estimated at higher values near the lower bound of 0.1 and closer to the center at the 0.2 bound (Figure 59). At higher values, the estimation is driven by the prior. All the fits that converged provided similar biomass estimates, while the false convergences provided spikier results (Figure 60). The recruit biomass trends are consistent between all prior distributions, although, magnitudes varied depending on the chosen prior (Figure 61). The fits that converged also provided similar natural mortality rates (Figure 62) and the process errors for both total and recruit biomass (Figures 63 and 64) were nearly identical when the model converged.

For TLM, results from the tested recruit catchability prior distributions suggest the data provide limited information or contrasts in the data to estimate q_R reliably, as the estimated values consistently settled approximately 0.12 above the lower bound of the beta distribution tested in this analysis (Figure 65). Furthermore, the choice of q_R prior distribution had a limited impact on the total biomass (Figure 66), impacted the magnitude of the total recruit biomass (Figure 67) and, to a much lesser extent, natural mortality (Figure 68), but had virtually no effect on the process errors of the recruitment and total biomass (Figures 69 and 70).

Since the sensitivity analyses, mostly from SEAM, indicated that neither a high nor low bound for q_R were likely, all subsequent results presented below use a prior that set the lower bound at 0.5. This resulted in estimated values around 0.6, which were deemed reasonable given the belly bag's small size makes it likely to miss shrimp and therefore would require a catchability below one.

MODEL VALIDATION

Residuals

Looking at SEAM residuals, the scatterplot of overall residuals against fitted values appears well centred around zero, with some slight heteroscedasticity likely caused by the small sample size of low fitted values (Figure 71). Examining the residuals by knot indicates that some knots exhibit more variability than others, most notably knot 3 in Stratum 13, knot 10 in Stratum 14, and knots 19 and 20 in Stratum 17 (Figures 72 and 73). This potentially indicates patchier shrimp distributions when compared to other knots. The overall quantile-quantile plot appears satisfactory with some issues in the tails (Figure 74). Examining the more appropriate scale by knot indicates the upper tail issues appear because the quantile-quantile line is slightly steeper for knots 3, 19, and 20, and that the lower tail issues are a bit more general but most of the issues are related to knot 19 (Figure 75). The TLM residual plot and quantile-quantile plot both appear satisfactory, with similar tail issues in the quantile-quantile plot (Figures 76 and 77).

Process Errors

The SEAM biomass random fields are consistent in most areas, with Stratum 17 showing the largest fluctuations in random field values (Figure 78). The recruit biomass random fields are more variable over time, but tend to not show strong spatial patterns in any given year, with relatively small differences from area to area (Figure 79). The median random field values of SEAM for the biomass are consistently centred close to zero, while the TLM process errors all appear to be zero, due to the difficulty in estimating the biomass process variance (Figure 80). Although the recruitment process errors and median random fields are similar for both models, within TLM they are consistently positive while in SEAM they are close to being centred at zero (Figure 81).

Retrospectives

The SEAM biomass retrospective analysis indicates consistent trends even with a minimal number of years, with all fits converging (Figure 82). The retrospective patterns are minimal for the biomass, with the overall Mohn’s rho at -0.040 and the 5-year Mohn’s rho at -0.022, indicating an improved performance in recent years. The recruitment retrospectives are not as good, with the overall Mohn’s rho of 0.045 and the 5-year Mohn’s rho of 0.103 (Figure 83). Last, the natural mortality retrospectives indicate that the model is not able to identify a trend in natural mortality without the 2023 data and estimates a consistent level of natural mortality otherwise (Figure 84). The median biomass random field values are different for every fit, but it is not clear that the natural mortality impacts it (Figure 85). The natural mortality overall Mohn’s rho is -0.131 and the 5-year Mohn’s rho is -0.119.

The TLM biomass retrospective analysis indicates that the trends are consistent, even with a minimal number of years retained (Figure 86). The overall Mohn’s rho is -0.100, indicating the model underestimated the total biomass of the fit with most data by about 10% and the 5-year Mohn’s rho is -0.068 indicating a better performance in recent years, but both indicate a poorer performance compared to SEAM. The recruitment retrospectives demonstrate similar trends, and the overall Mohn’s rho of -0.045 and the 5-year Mohn’s rho of 0.042 indicate a better performance than for the biomass and the recruitment retrospectives for SEAM (Figure 87). Last, the natural mortality retrospectives indicate that the model is not able to identify a trend in natural mortality without the 2022 and 2023 data and estimates a consistent level of natural mortality otherwise (Figure 88). The natural mortality overall Mohn’s rho is -0.038 and the 5-year Mohn’s rho is 0.021. The biomass process errors show the issues with false convergence and difficulties with estimating its variance, with fewer years with most values being functionally zero (Figure 89).

Biomass

The SEAM knot-specific biomass densities indicate that in most years the highest densities and largest portion of total biomass are located in Stratum 14, with occasional spikes in Stratum 17 (Figure 90). A consistent downward trend is evident across all knots and is reflected in the total biomass estimated by SEAM (Figure 91). The TLM also identifies this downward trend with values generally aligning in similar areas. The index, which should be on the same scale due to the catchability being fixed at one, appears more variable, generally at a lower magnitude and sees several additional spikes, but also shows the same overall downward trend. The lower magnitude of the index is likely caused by a small sample size in every year and stratum combination, which results in a poor performance and therefore bias from the use of the sample mean as an estimator for a highly skewed distribution.

The SEAM biomass analysis by stratum indicates that Strata 13, 15, and 17 have been generally consistent over time, with decreases occurring only recently. In contrast, marked decreases in biomass are evident in Strata 14, which accounts for the overall biomass decline. (Figure 92). Fitting TLM to individual strata provides similar results for Strata 13 and 15. In contrast, Stratum 17 exhibits higher biomass estimates with more uncertainty, while Stratum 14 has lower estimates (Figure 93). The largest differences between the SEAM strata-specific estimated biomass and index calculation occur in Stratum 14 (Figure 94), where the model consistently reports higher biomass estimates. This stratum is also the most heavily fished area. The SSB, calculated by multiplying the total biomass by the proportion of the weight composed of female and transitional shrimp, show similar patterns between the three approaches (both models and the swept-area index), although the modeled results have stronger dips and peaks than for the overall biomass (Figure 95).

Productivity (Recruitment, Natural Mortality, Exploitation)

The SEAM knot-specific recruit biomass densities indicate that Stratum 17 consistently has the highest concentration of recruits (Figure 96). Initially, recruitment also extended into Strata 14 and 15; however, in later years, recruitment was predominantly confined to Stratum 17, with the exception of 2014. SEAM, TLM, and the swept area index method all provide similar trends in total recruit biomass. TLM estimates the highest biomass levels, SEAM reports lower values and the index aligns more closely with SEAM in most years, except for 2014, when it peaks higher than both models (Figure 97). The SEAM and TLM natural mortalities are similar and both identify an evident increase in natural mortality starting in 2019–20 and peaking in 2023 (Figure 98). Exploitation rates are calculated on a calendar year basis to inform fisheries management, which compares annual landings to the biomass estimate within the same year.

The proportional exploitation rates estimated by SEAM are consistent in the first few years, but begin to fluctuate strongly starting in 2010, and peak at over 9.5% in the last year (Figure 99 to 101). The spatial distribution of exploitation rates suggest that higher rates are located in one knot within Strata 13 and 17. These areas do not experience extensive fishing activity in absolute terms but exhibit significant exploitation rates relative to their low estimated biomass densities. Several knots, primarily in Strata 13 and 17, show unreasonably high exploitation rates (almost exactly 1), which is likely due to extensive fishing just outside of Stratum 17 and a historical tendency for fishing in Stratum 13 to occur towards the fall. Otherwise, the exploitation generally focuses on the knots right at the boundary of Stratum 14 and 15. Plotting the temporal exploitation rates against the resulting change in biomass indicates that no increase in biomass was seen with exploitation rates above approximately 7% (Figure 102). The TLM plots show similar results (Figures 103 to 105).

1-Year Projections

The SEAM 1-year projection indicates that all the spatial projections tend to be positively biased and that the least biased method is the median growth and projecting on the scale of the total biomass instead of individual knots (Figure 106). However, all of them failed to fully capture the decrease seen in 2023, as that year is the outlier for all projection methods. While the magnitude of the decrease was not well captured, all projection methods still predicted a decrease in 2023 (Figure 107). The TLM 1-year projections suggest that using the median growth rate also has the least bias, although the differences between the three approaches are small (Figure 108). However, it clearly shows that the model was strongly biased for the last two years, with the largest difference being the 2023 year, indicating that the drop in biomass from 2022 and 2023 was much stronger than the model had anticipated (although it would still have predicted a decrease, just not the magnitude of the decrease; Figure 109). This contrasts with SEAM, where only the year 2023 was problematic instead of both 2022 and 2023.

Decision Table Example

The SEAM decision table example (Table 14) predicts a decline in total biomass regardless of the catch scenario, with the lowest probability of 77.1% with no fishing and increasing to 87.6% with a catch of 1,000 metric tonnes. The predicted change in biomass goes from -1,635 metric tonnes (-10.3%) with no fishing to -2,635 metric tonnes (-16.5%) with a catch of 1,000 metric tonnes, along with corresponding exploitation rates of 0.0% to 7.5%. The projected biomass from the decision tables, which accounts for both the known landings and the projected TAC instead of just the known landings, would have performed almost equally well as the 1-year projections, with a slightly more conservative approach, but overall capturing the subsequent biomass given the known TAC fairly well (Figure 110).

The TLM decision table example (Table 15) presents similar outcomes, with a probability of decline going from 86.2% with no fishing to 94.1% with a catch of 1,000 metric tonnes. The predicted change in biomass goes from -1,712 metric tonnes (-14.2%) to -2,712 metric tonnes (-22.6%) with a catch of 1,000 metric tonnes, along with corresponding exploitation rates of 0.0% to 10.1%. Last, comparing the projected biomass from the decision tables against the 1-year projections on their own shows that decision tables would have been conservative, most often underestimating the future biomass (Figure 111). To illustrate model performance in less favourable years, the decision table that would have been produced in 2018 for the 2019 fishing year using both SEAM and TLM are presented, highlighting TLM's overconservative predictions (Tables 16 and 17).

REFERENCE POINTS

Consensus was reached (as described in the conclusion) that SEAM was the best model presented as part of this work. Therefore, it is the one utilized for all reference point and removal reference analyzes, and all subsequent references to "the model" refer to SEAM.

Stock Recruit Relationship

Plotting SSB against the recruit-per-spawner in the following year (Figure 112) roughly follows the shape of the expected theoretical Ricker SR model (p-value = 0.041, r^2=0.224). However, the relationship is entirely driven by the last year of data. Removing the last year of data produces a near flat line, as opposed to a relationship, indicating that there is very little evidence of an actual stock-recruit relationship for the stock (p-value = 0.526, r^2=0.026). Plotting SSB against the resulting recruits, and then applying a theoretical Ricker curve, also provides no evidence of a stock-recruit relationship (Figure 113). This suggests that the model would also find the current, historically low stock level to be very close to B_{MSY}, as the peak of the curve aligns with the 2024 datapoint. This illustrates that there is no evidence of recruitment levels at lower levels of SSB. The hockey-stick recruitment fit is shown by the solid line in Figure 114, denoting the mean level used for simulations at that SSB.

Simulation Results

In terms of simulations without fishing to identify B_0, all combinations of assumptions under three climate/productivity scenarios (Baseline, Low, and Mid) eventually stabilized (see examples of each scenario in Figures 115 to 118). However, all High productivity scenario simulations without any fishing did not stabilize, even after 200 simulated years, and appeared to increase linearly towards infinity (Figure 116). The simulation results suggest that this combination of productivity parameters (those estimated for the years 2005 to 2011) is not fully realistic, creating surplus production that linearly increases with the biomass and SSB (with no density-dependence at high biomass levels). This is reflected in the estimated B_0 values from this scenario, which are substantially higher than the observed maximum SSB in the available time series (Figure 119).

This would be higher if the simulations were run using a longer time period. Furthermore, the substantial differences between the different B_0 estimated by the High productivity scenario indicate that these results are likely driven by the assumptions used for the simulation; especially, given the low number of years of the observed time series for this productivity period. By contrast, simulations run under the other three productivity scenarios produced results with less variability, especially the Baseline scenario, indicating greater resilience to the assumptions. All scenarios and settings still have a substantial number of simulations going almost to zero, due to the large uncertainties around most stock components (Figures 115 to 118).

In terms of identifying B_{MSY}, all exploitation rates identified as maximizing average long-term landings are between 1.0% and 3.5%, with the Low scenario generally having lower exploitation rates (Figure 120). For the other productivity scenarios, most identified exploitation rates are either at 2.0% or 3.5%. However, when looking at the actual landings in metric tonnes, identified as the long term average yearly landings, there are clear differences between each productivity scenario: the Baseline scenario hovers around 500 mt; Low productivity scenario hovers closer to 250 mt; Mid productivity scenario hovers close to 700 mt; and High productivity scenario centers around 1,500 mt, albeit with much larger differences between the different simulation assumptions (Figure 121). With the exception of the High productivity scenario, all of these average landings are lower than the historical average landings since 1991 at 804 mt (Table 1). The standard deviations around yearly landings are all relatively similar for the Baseline, Mid, and High productivity scenarios, which hover around 280–300 mt, while the Low productivity scenario tends to have lower standard deviations (Figure 122). The stable SSB identified at these MSY exploitation rates are shown in Figure 123.

The different LRPs, either from simulation-based B_0 and B_{MSY} or based on historical proxies (as described above), are shown alongside observed SSB (Figure 124). All MSY LRP, except for the High productivity scenario, are substantially below anything that has been observed in the ESS Northern Shrimp stock to date, even looking at indices prior to introduction of the Nordmøre grate. The B_0 based estimate from the High productivity scenario is substantially larger than all other LRP, which is expected given its unrealistic results. The two historical proxies, as well as the B_{MSY} LRP from the High productivity scenario, place the LRP either exactly at the lowest observed SSB (i.e., 10,805 mt) or approximately 27% below this value (i.e., 7,834 mt).

Removal Reference

The AIM analysis identified a positive relationship between $relF_t$ and Ψ_t, which is the opposite of the expected relationship if fishing mortality is the primary driver of change in stock abundance (Figure 125). This is partly due to the low number of years that are utilized in this analysis (only 11 data points are examined herein, given the 5 year lag and moving average approach), which likely reflects management of the shrimp stock that has reacted to changes in the stock, rather than the stock responding to management decisions. In this instance, the positive relationship indicates that, as the stock status worsened, the management approach was responsive and followed negative changes by decreasing the relative fishing mortality on average. However, this approach is inappropriate to provide guidance for an RR point given the absence of a negative relationship. Unfortunately, even simpler methods around simple visual observations of exploitation rates, and the resulting biomass changes in the following year, do not provide more guidance, whether by total biomass (Figure 126) or by SSB (Figure 127). While a negative relationship for the biomass (and not the SSB) appeared to exist when the observation was done at the October 29–30, 2024, framework meeting, which did not account for 2024 data, this apparent relationship has disappeared with the inclusion of the 2024 data.

Decision Tables

A linear relationship is identified between the proportion of Age 4+ males over the total females from the mixture analysis and yearly change in percentage of biomass that is SSB (Figure 128). Using a linear model, the SSB decision tables present similar outcomes as the biomass decision tables (Tables 18 and 19). They also demonstrate a similar performance to the biomass decision tables, historically (Figure 129).

STOCK STATUS INDICATORS

Abundance Characteristic

The swept-area survey biomass index correlates strongly to the model-based total biomass, although it appears to vary more strongly from year-to-year than the model does (Figure 130). This indicates no issues with using the model-based total biomass instead of the index.

Diagnostics of the proposed mobile fleet joint standardized CPUE indicate minor issues with the lower tail of the distribution, but an overall reasonable fit to modeled assumptions (Figure 131). Compared to previous methods, the joint modelled CPUE is noticeably lower in magnitude than either of the two older CPUEs (Figure 132). This is mainly related to the modelling structure, which removes the average effect of each fleet, average effect of each stratum, average effect of each individual vessel (which may positively bias the CPUE when a couple vessels perform substantially better), and average impact of month (and therefore season). All three models show similar trends in CPUE, as well as the model-based total biomass (Figure 133), supporting a broad agreement between approaches. While this does indicate usefulness of the new CPUE indicator, it would represent a different type of information (likely getting closer to the underlying population) than the previous CPUE that were closer to the average observed CPUE in that year (and therefore are more representative of the fishery itself).

Comparing different potential CPUE cutoffs for the commercial fishing area indicator alongside yearly effort, it becomes evident that almost every examined threshold for CPUE mirrors trends with effort (Figure 134). This questions their utility, as the belief that changes in commercial area reflects changes in the population would imply differences between effort and this indicator. However, the cutoff of 450 kg/h does not appear to mirror effort as well as the others, indicating a greater independence from effort than the other cutoffs. This suggests that the cutoff of 450 kg/h is more informative about the distribution of population densities, based on commercial data than other cutoffs, which appear to only contain information related to effort.

The average number of shrimp caught by the snow crab survey follows similar patterns to SSB (Figure 135). The highest correlation is when the new shrimp bycatch number indicator leads SSB by one year, meaning that number (which is captured in the fall) is more related to the following year's June survey than the one in the same calendar year. This trend may therefore contain useful information on shrimp population at a time of year when fishery-independent data have previously been lacking.

The area occupied indicator presents moderate inter-annual variability, but an overall decline since the peak of 2009 (excluding a spike in 2014; Figure 136). Both of these years coincide with spikes in recruitment, as captured by the model, and tracks a similar pattern to the model-based biomass (Figure 30). The SSB seems to lead this by one year, similar to the shrimp bycatch indicator. When looking at the spatial distribution of presence or absence for shrimp bycatch in the snow crab survey, this decrease is primarily driven by a disappearance of shrimp from two areas: along the Nova Scotia shoreline starting in 2011 and in a region north of Sable Island (Figure 137).

Productivity Characteristic

Trends in model-based recruit biomass and the belly bag index are virtually identical and highly-correlated (Figure 138), indicating that the model-based recruit biomass should provide similar information as the belly bag index.

The Age 2 indicator is not correlated with any other stock component in any biologically-meaningful way, whether that is recruitment-based (which would have been expected) or SSB (Figure 139). This suggests that the Age 2 indicator is not capturing recruitment moving into the fishery, suggesting a potential selectivity issue, and therefore does not appear to provide useful information in the context of strategic yearly advice.

The Age 4 indicator also is not strongly correlated with other stock components (Figure 140). However, this is less likely due to selectivity issues and more likely due to Age 4, including a relatively large category of shrimp from still-juvenile male shrimp to early transitional shrimp. Exploring improvements to the mixture analysis to more clearly identify age classes is worth further exploration.

The model-based SSB is very similar to the previous swept-area SSB (Figure 141), providing similar information and indicates that basing decisions on the model-based SSB should be as reliable as previous approaches.

Size at sexual transition has correlations to both the detrended model-based biomass and SSB (Figure 142), indicating that an increase in size at sexual transition is associated with an increase in biomass and SSB in the following year. Another interesting correlation is with recruitment, wherein a 4-year cycle pops out, with higher recruitment leading to higher size at sexual transition in the following year. This is then correlated to a decrease in size at transition the following year. This could be interpreted as evidence of density-dependence for small shrimp and could be partially responsible for the 4-year cycle in recruitment that has historically been observed in the ESS Northern Shrimp stock. Further evidence of this can be seen in the correlations with the main trawl growth rates, which is a proxy of length frequencies, where the growth rates lead size at sexual transition in both positive (4 and 5 year lags) and negative (1 and 2 year lags) directions.

Correlations for maximum size are with the detrended biomass and SSB (Figure 143), where an increase in biomass (and potentially SSB, although the correlation is not significant) is associated with an increase in the maximum size in the following year. This is then associated with a decrease in the maximum size 2 and 3 years down the line. This supports the possibility of a density-dependent relationship and could also partially explain the 4-year cycle of the stock.

Fishing Effects Characteristic

Commercial counts are correlated with SSB, indicating that they tend to track similar patterns (Figure 144), although these are mostly caused by the downward trend in both. Commercial counts also are negatively correlated with recruitment in the same year, indicating count tends to be lower when recruitment is high (Figure 144). This is unexpected, as a lower count means larger shrimp on average and, although commercial fishing does not capture recruit-sized shrimp, it is still unexpected that a relationship would be identified. Given the low number of years for these analyses, and the large amount of ACF being examined, it is possible that this relationship is spurious, but it could potentially indicate that targeting for larger shrimp is easier in years with large recruitment; for example, through behavioral change. More research is required to identify any causal link. What is more likely is that an increase in recruitment leads to higher counts two years later, when the recruits become large enough to appear in commercial nets. Given the survey gear is similar to commercial gear, this might support the possible occurrence of a selectivity issue for Age 2 shrimp.

The newly-calculated exploitation rates (overall and female) follow similar trends as the previous methods, albeit consistently lower due to the higher scale of the model-based estimates (Figure 145). The first few years are slightly different between the model-based and index-based indicators, although overall the trends are almost identical. However, the model-based exploitation rates are all substantially lower than index-based, due to the increased magnitude of the model-based estimates. This is related to the use of a more appropriate lognormal distribution, as was discussed in the framework meeting held on October 29–30, 2024.

The unexpected correlation with female mean size suggests that an increase in SSB is associated with a decrease in female mean size the following two years (Figure 146). This may be an indication of density dependence due to competition within larger larval contributions from a larger SSB, resulting in earlier transition. There is also an indication that an increase in mean female size results in lower recruit growth rate (meaning a larger proportion of very small shrimp) the following year, potentially indicating later spawning from larger females.

Ecosystem Characteristic

The predator index does not appear to have any clear and/or biologically-meaningful correlations, although this may be partially due to data availability (this analysis only uses 13 years of information, since cross-correlations cannot be used with breaks in time series) (Figure 147). When assessing the individual predator indices, the main correlation is that total recruitment leads Atlantic Cod recruits positively by one year, potentially indicating that Atlantic Cod recruitment is responsive to shrimp recruitment and not the other way around (Figure 148). There are a few relationships with Turbot recruitment (Figure 149), although none have obvious biological meaning.

Looking at candidate predator species (Figures 150 and 151), extreme fluctuations in Redfish numbers suggest interference by external factors (i.e., behavioral changes, catchability issues, etc.), making these values unreliable. This does not mean that Redfish do not predate on shrimp; rather, the Redfish index as captured by the Summer RV Ecosystem trawl survey is not a good representation of their possible predatory pressure. Shortfin Squid has notably large spikes in 2019–20; however, since the rest of the time series is mostly flat (and the ACF methods cannot account for missing years) it is not useable for purposes herein. White Hake are scarce compared to the other species and any changes in their numbers would be completely overshadowed when included in a general indicator. In contrast, the Silver Hake indicator appears promising, although it unfortunately does not relate to the stock parameters (Figure 152). This leaves American Plaice, Atlantic Cod, and Turbot. Taking the average number of all three predator species to create an indicator, a positive correlation shows up with SSB, although this new indicator leads to a decrease in SSB when you remove the trend in SSB (Figure 153). Overall, this suggests that shrimp and these predators might be seeing similar decreases, with a high specific predator indicator being associated with a decrease in SSB in the following year. This relationship supports use of this indicator to inform the stock the following year.

The relationships between biomass, SSB, natural mortality, and recruitment to survey bottom temperatures are interesting. Without detrending them, high biomass and SSB appear to lead to lower temperatures at a couple lags (Figure 154), but this is mostly the overall trend with the higher temperature regimes associated with the lower biomass over the past decade. Similarly, high natural mortality is associated with high temperatures the following year, mostly due to the period of time with a higher temperature regime. Recruitment appears uncorrelated. In detrending these components, an annual increase in temperature aligns with increases in both biomass and SSB (Figure 155). This points towards a potential dual impact of temperature, whereby a yearly increase can lead to better conditions and increases in biomass, but longer-term high temperatures lead to worsened biological conditions for ESS Northern Shrimp. A one year forward negative relationship between recruitment and bottom temperature is unexpected, as there is no obvious biological explanations for this, indicating a potentially spurious relation.

The SST is not correlated with biomass, SSB, and recruitment (Figure 156), although there appears to be a slight positive correlation in the same year with natural mortality. This disappears with detrending (Figure 157); however, it may be more indicative of the higher temperature regime being associated with years of higher mortality than a direct one-to-one relationship.

Snow Crab recruitment, which only uses 16 years of data due to gaps in the time series, appears to mainly be correlated to natural mortality, wherein higher natural mortality in shrimp appears to lead lower Snow Crab recruitment the following year (Figure 158). This would track with expectations of sympatric species, which respond similarly to environmental pressures that are reflected in natural mortality. However, given that it provides no new information compared to all other indicators, consensus was to remove this index from the TLA moving forward.

The final list of stock indicators for the ESS Northern Shrimp TLA moving forward are shown in Table 20, with all new indicators shown in Figure 159, along with updated characteristic-specific indicators. All new mean indicators are shown in Figure 160.

SOURCES OF UNCERTAINTY

The calculations of expected age-at-length use cohort and modal analyses lack a discrete means of aging shrimp and/or accounting for aging errors. As such, having a methodology to provide more concrete age data would improve quality of the Von Bertalanffy fit and subsequent growth calculations.

There is uncertainty associated with the shapefile for Stratum 17, illustrated by the unreasonably large local exploitation rates estimated by the models. This large exploitation rate combined with VMS activity for the area indicates that a proportion of fishing occurs just north of the shapefile boundary. When this shapefile is used to generate survey stations, this area is excluded from the annual survey and the resulting data feeding into the model may not fully reflect the activity in this region. Although the research team is in the process of acquiring an updated shapefile for Stratum 17 it could not be completed in time for the framework.

The possible appearance of primary females, which are known to occur in more southern populations, is a source of uncertainty associated with climate change. (Bergstrom 1997). While these have not been observed on the ESS, increasing temperatures related to climate change are likely to impact shrimp maturation and the calculations of SSB, if primary females start appearing. There is also an assumption that juveniles and mature females move between areas, which the models currently cannot track. Implementing a movement component for these age-classes would likely improve the model's ability to track recruitment for the spatial model; however, this has not been developed for the SEAM and would require substantial research to do so.

The ESS Northern Shrimp survey has a highly-constrained spatiotemporal coverage, happening in June within defined strata. While shrimp consistently aggregate in those areas at that time of year, their spatial distribution is known to change substantially by season, which is not tracked herein. Furthermore, given the constrained extent of the survey, comparisons to external data become harder (e.g., predation index) in that correlations could be identified (or missed) not because there is not one, rather because the scales where both components are observed do not match up well enough for these relationships to be clear.

For reference points, MSY simulations are based on a very short time series (i.e., 20 years), which represents a one-way trip down. The rule of thumb for these simulations is to have a time series with at least two declines and two recoveries, in order to obtain representative reference points. The simulations presented herein are likely negatively biased, given they only have one decline and no recoveries.

The difficulty to age shrimp and use of the mixture analysis to age cohorts introduces uncertainty in the estimates of growth for the population, especially compared to other species that can be directly aged. Furthermore, the relationships between growth, productivity, and aging to changes in temperature and food resources would benefit from further research to better disentangle them.

The extensive spatial footprint of the snow crab survey overlaps well with the ESS SFA, and even though shrimp catch is only incidental and comes with catchability uncertainties, it offers an alternative source on stock distribution. Furthermore, as the survey occurs late in the year (which is advantageous for a time of year the ESS shrimp survey data are lacking), data are not available in time for the annual ESS shrimp stock assessment or stock update. This means that, as in previous years, the data presented from the snow crab survey are delayed by one year, reflecting data from the previous fall/winter rather than the current period.

Since the snow crab and Summer RV Ecosystem trawl survey are not led by the DFO Science Northern Shrimp unit, there have been times in the past where gaps in the respective time series have been introduced due to external factors (e.g., vessel delays), which introduces uncertainty in the ESS Northern Shrimp stock assessment. Last, correlations examined herein utilize short time series of approximately 20-years, and even less for time series with gaps, from which conclusive making statements may be difficult.

FUTURE RESEARCH

Much work went into obtaining guidance regarding an RR for the ESS Northern Shrimp stock; however, the methods explored herein were not successful due to the short time series and large environmentally-driven variations in the shrimp stock. However, this does not mean that no guidance can ever be provided on an adequate RR, rather other methods need to be explored first. This is a high priority for future research.

A key conclusion from the first ESS Northern Shrimp framework meeting held on October 29–30, 2024, was that the ESS Northern Shrimp survey, as currently designed, is too constrained to properly capture what is happening to the shrimp stock away from core areas. This has multiple implications, the foremost being that biomass was likely underestimated at the peak of the fishery, but that it is probably not underestimated anymore. This implies that the decline might have been greater than indicated. Exploring options for improving and expanding survey coverage in the future should also be seen as a high priority for this stock.

The SEAM stock assessment model, as currently designed, cannot incorporate all available survey data given the absence of trusted recruitment information prior to 2005. A research priority prior to the next ESS Northern Shrimp framework should be to explore improvements and modifications to make all available data useable, in a unified framework and in a statistically reasonable way. Another underutilized source of data in regard to shrimp health, as markers of health such as disease prevalence are tracked within the survey detailed sampling. Examination of this data and expanding analyses to obtain indicators of shrimp health would be a net benefit to the TLA for the stock. Additional improvements to many of the TLA indicators would also help improve the overall stock assessment. For example, work has already been done on utilizing a larger area to obtain predation indices from the RV Ecosystem trawl Survey, with full implementation of this broader approach likely improving these indicators. Furthermore, age-specific predator impacts could be examined and utilized to improve the methods.

Most of the work presented herein has focused extensively on an ability to improve the 1-year out forecasting and improving science advice provided to DFO Resource Management. However, developing a better understanding of long-term stock outlook would likely be beneficial, which could include the impact of mid- and long-term effects of changes in ocean drivers, such as warming temperatures, ocean acidification, oxygenation levels, and salinity, as examples. These drivers could also help improve understanding of stock dynamics, especially as they pertain to recruitment and fertility.

Failure of the Age 2 indicator to relate to the Age 1 indicator (recruits), or later indicators, in any way has two potential explanations:

1. either the mixture analysis does not successfully separate cohorts; or
2. they are not well captured by the survey gear and therefore selectivity issues are preventing proper quantification of these smaller shrimp.

Identifying which of these two explanations is correct would be difficult, and a two-pronged approach to this problem is likely a better option; that is, researching mixture analysis methods as well as shrimp ageing and growth modelling methods. Once there is more confidence in the shrimp age classification at smaller sizes, proper selectivity analyses can be completed.

CONCLUSION

The TLM and SEAM models yielded results with similar scales and trends, while a lack of proper convergence makes the SDD model unusable for the ESS Northern Shrimp stock assessment. The TLM presented a consistent downward trend, while SEAM captured two plateaus in different years, but with an overall downward trend since 2005. SEAM estimated all parameters reliably, while TLM struggled with the biomass process variance, likely due to too few years of data. Both models present evidence that the fishery can impact the stock health, with the total biomass usually declining when the exploitation rate exceeds 6%.

The retrospective patterns for total biomass are smaller for SEAM than for TLM, but the two produce comparable population trends over time. Neither model captured a trend in natural mortality without the 2022 and 2023 data and, while both models correctly predicted the decrease observed in 2023, both underestimated the magnitude of the drop. The TLM also underestimated the decrease observed in 2022.

Following several lines of reasoning (increase in natural mortality, consistent process errors and random fields, etc.), evidence from both models suggests a dramatic drop in productivity since 2005. Both models were broadly successful in their predictions until 2022 for TLM and 2023 for SEAM, where the drop in population was predicted but not its magnitude. Otherwise, the projections from both models using median growth rates and mean natural mortality were consistent and unbiased. This suggests that while the decrease has been consistent, 2023 was a departure from the norm in terms of productivity and natural mortality.

The analyses presented herein concluded that both TLM and SEAM provide reasonable modelling approaches for use in the ESS Northern Shrimp stock assessment. Both models identified a relationship between total biomass and fishing mortality, which further supports their potential in providing reliable data that could be used to support fisheries management decisions. Despite this, use of SEAM is recommended to be used for stock assessment moving forward due to

1. a spatially aggregated fishing mortality that SEAM can directly model,
2. superior performance in terms of biomass retrospective analyses,

3. provision of more granular and more accurate information on stock dynamics through its spatial component, and
4. the capacity to account for future concerns, such as introducing a movement component.

The SSB decision tables appear to perform just as well as the biomass, so it is therefore proposed that both tables be provided as part of the annual science advice for the ESS Northern Shrimp stock. In contrast, there is no strong stock-recruit relationship for the ESS Northern Shrimp stock, at least not within the current years of data. The limited information available is predominantly influenced by a single year, which happens to be the final year in the time series.

For reference points, the MSY-based simulations are problematic for multiple reasons. The High productivity scenario, which is the closest approach to the previous reference points based on a similar (albeit shorter in the model approach) productivity period, appears biologically unrealistic, as its simulations do not reach a stable level without the presence of fishing. This yields positively-biased estimates of B_0 and B_{MSY}. This is further compounded by the large differences in values depending on the underlying assumptions, indicating that these assumptions, and not the data, are driving these differences (especially given the very low number of years utilized for this scenario). The other scenarios give more reasonable outputs in that they stabilize without the presence of fishing; however, they stabilize at levels substantially lower than the maximum observed shrimp SSB in the time series, placing B_0 at around two-thirds of the maximum observed SSB. Additionally, these other scenarios all come to the conclusion that B_{MSY} is near the current SSB. This is almost entirely due to the impact of the 2024 recruits-per-spawner, which basically informs the entirety of the Ricker curve and is the cutoff to decrease recruits-per-spawner below it in the hockey-stick approach. All of these simulations therefore place the LRP at levels below anything that has ever been observed for this stock, even including information earlier than the time series obtained from the model. Furthermore, the scenarios all place F_{MSY} at extremely low levels compared to historical landings, both in terms of percentages and in terms of average landings (with the variability resulting in some years having “sustainable” landings of 150 mt). Last, large uncertainties in all stock components and the relationships cause a substantial amount of simulations, even under the best conditions, to collapse to zero even without fishing, which would preclude their selection under normal guidance.

While some signs of an expected negative relationship under visual analysis for biomass was shown at the October 29–30, 2024, framework meeting, it did not use data from 2024, with this relationship disappearing herein following incorporation of the 2024 data. In addition, SSB never had a negative relationship, even when ignoring the 2024 data. In contrast, the relationship between exploitation rates and stock changes shown in the analyses presented herein has given results opposite to what would be expected if fishing was a driver of stock dynamics, which most of these types of analyses assume. This suggests that the stock does not respond to management measures, rather that management measures are responding to changes in the stock. This is not necessarily a negative outcome, as it suggests that management has been responsive and has made efforts to address stock declines appropriately. However, it also indicates that the main drivers of change to the ESS Northern Shrimp stock are environmental rather than fishery-driven. This does not mean that fishing does not impact the stock, rather that its impact becomes confounded with larger natural mortality caused by changes in the environment, making it much harder to differentiate. This is supported by comparing the model-based estimates of exploitation rates, which range between 2% and 10% in general, while the proportional natural mortalities estimated by the same model range between 25% and 45%.

Given that MSY implicitly assumes fishing activity to be the primary driver of stock change, this conclusion further discredits the use of MSY-based LRPs to guide management of the ESS Northern Shrimp stock, rather it further supports an LRP based on B_0 (such as from a historical proxy), which is likely more appropriate for this stock than one that assumes fishing is a main driver of population change, such as B_{MSY}. The previous LRP functionally treated the average stock size during the productivity period that was chosen as an estimate of B_{MSY}. However, when it is observed that the effort and CPUE rates only started to trend together around 2001–02 (Figure 134), it does not seem unrealistic to assume that the peak SSB, which occurred in 2010 but was relatively similar to the levels seen in 2005–06, is a fair representation of carrying capacity given its proximity to the onset of full efficiency fishing.

The MSY reference points presented herein are considered to be inappropriate for the ESS Northern Shrimp stock due to the stock-recruit relationships being entirely driven by the 2024 recruitment event (resulting in the simulations putting the stock at B_{MSY} at present, which is also at historically low levels of SSB), biologically unrealistic results when utilizing the High productivity period, and extreme risk of placing the LRP at levels substantially below anything that has been observed for this stock. This leaves the historical proxies presented earlier. Setting the LRP at the lowest level of SSB associated with recruitment would place it at the 2023 SSB of 10,805 mt. Although this is the most conservative approach examined herein, there is evidence that critical harm to the stock's reproductive capabilities had not happened yet at this level given that it is associated with the largest recruits-per-spawner on record.

The LRP based on the historical proxy of B_0, as the maximum SSB observed, is therefore recommended, with the consensus of setting the LRP at 0.2 of this maximum SSB in each year. In other words, due to the estimated SSB shifting slightly in its overall magnitude whenever a year is added, the LRP will slightly shift from year to year. In this specific example, this would set the LRP at 7,834 mt for 2024. While this appears to be higher than the previous LRP used to manage the stock, when accounting for the difference in magnitude between the modeled outputs and index on which the previous LRP was based, this recommended new LRP places stock status in a very similar place as before from a stock health perspective (Figure 161). This seems appropriate given that there is no evidence of critical harm being done to the stock at levels that have been observed; particularly, given that the MSY LRPs are demonstrably too risky, based on few data points, and inappropriate assumptions.

In terms of TLA indicators, there is a strong relationship between the legacy index-based stock descriptors and new methods proposed herein (e.g., survey CPUE and total biomass, index-based SSB and model-based SSB, belly bag and model-based recruit biomass, old versus model-based exploitation rates, etc.), indicating that the modeled outputs should perform at least as well as the indices have in the past, and with no sign of any new issues or concerns. It is recommended that these be replaced by those with the modeled outputs moving forward.

The majority of the legacy indicators also demonstrated clear utility as supplementary contextual indicators, owing to their distinct relationships with the components of the stock. There were a few exceptions, namely the Age 2 indicator, Age 4 indicator, and legacy predation index. For the Age 2 indicator, the primary issue likely stems from challenges in accurately identifying cohorts through the mixture analysis. As a result, removal of this indicator from the TLA is recommended. Although the Age 4 indicator's utility was not immediately obvious, retaining it provides important context and allows possibility for improving it if a better approach to the mixture analysis is identified. Last, even though the legacy predation index was not clearly related to stock parameters, it is believed that there is value in having some context as to finfish abundance, so it is recommended that it be retained as well.

The newly-proposed and updated indicators all appear strongly related to pertinent stock components and will therefore be useful for providing stock advice within the TLA. For the commercial CPUEs, while they clearly have been useful, the current issues around public reporting under Canadian privacy rules prompt need to create a new model incorporating both mobile fleets into a single metric. This proposed indicator appears to have strong relationships to stock components and provides similar information to the previous two separate mobile CPUE indicators. Assuming that it takes a few years for the stock to recover, leading to continued issues with presenting CPUEs, it is recommended that this new indicator be adopted as a CPUE index (i.e., when the Gulf CPUE and Standardized CPUE indices cannot be presented publicly due to privacy considerations).

The two indicators from shrimp bycatch on the Snow Crab survey both broadly track and provide information from a different season, which would strengthen the TLA. The Atlantic Cod and Turbot indices have been useful in the past, but replacing them with the new Atlantic Cod, Turbot, and American Plaice indices is recommended, which further includes information about American Plaice that is a potentially important predator of ESS Northern Shrimp. The Snow Crab recruitment indicator did not provide any additional, meaningful information that is not already reflected by other indicators, so there was agreement on its removal from the TLA moving forward.

The new and updated mean characteristic indicators are very difficult to compare to those previously used in the TLA. Due to changes in both the reference period, number of indicators, and their composition, these new mean characteristic indicators generally appear smoother than the previous ones. This apparent smoothness is almost entirely a function of the new reference period, given that in the past some indicator quantiles would be exactly zero (when below values seen in the high productivity period) or exactly one (when above). Given that the mean characteristic indicators are now based on the entire time series, this results in a greater smoothness and makes comparisons between the two very difficult. This also highlights the confusing interpretation of the overall mean indicator. Due to the very low fishing and improvements of temperature in 2024, the overall mean indicator would end in the yellow zone even though the abundance is at its lowest level yet and productivity remains in the red. Given that this overall mean indicator is not actually representative of stock status, and given its inclusion of fishing effects and ecosystem indicators, there was agreement on its removal from the TLA moving forward.

In conclusion, the SEAM model, LRP, and stock indicators outlined in this framework research document, as presented at the October 29–31, 2024, and March 5–6, 2025, CSAS peer-review meetings, received consensus support from peer-reviewers and meeting participants for use moving forward to assess the for ESS Northern Shrimp stock.

REFERENCES CITED

Aeberhard, W.H., Mills Flemming, J. and Nielsen, A. 2018. Review of State-Space Models for Fisheries Science. Ann. Rev. Stat. App. 5:215-235.

Appolonio, S., Stevenson, D.K. and Dunton E.E. Jr. 1986. Effects of Temperature on the Biology of Northern Shrimp, *Pandalus borealis*, in the Gulf of Maine. NOAA Tech. Rep. NMFS 42. 22 p.

Atlantic States Marine Fisheries Commission (ASFMC). 2018. Northern Shrimp Benchmark Stock Assessment and Peer Review Report. 356 p.

Auger-Méthé, M., Albertser, C.M., Jonsen, I.D., Derocher, D.E., Lidgard, D.C., Studholme, K.R., Bowen, W.D., Crossin, G.T., Mills Flemming, J. 2017. Spatiotemporal modelling of marine movement data using Template Model Builder (TMB). Mar. Ecol. Prog. Ser. 565:237-249.

Barrett, T.J., Marentette, J.R., Forrest, R.E., Anderson, S.C., Holt, C.A., Ings, D.W. and Thiess, M.E. 2024. Technical Considerations for Stock Status and Limit Reference Points under the Fish Stock Provisions. Can. Sci. Advis. Sec. Res. Doc. 2024/029. v + 57 p.

Barrowman, N., and Myers, R. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. Can. J. Fish. Aqu. Sci. 57:665-676.

Bergström, B. I. 2000. The biology of Pandalus. Adv. Mar. Biol. 38:55-245.

Bernier, R.Y., Jamieson, R.E. and Moore, A.M. (eds.). 2018. State of the Atlantic Ocean Synthesis Report. Can. Tech. Rep. Fish. Aquat. Sci. 3167: iii + 149 p.

Bourdages, H., Marquis, M.C., Ouellette-Plante, J., Chabot, D., Galbraith, P. and Isabel, L. 2020. Assessment of northern shrimp stocks in the Estuary and Gulf of St. Lawrence in 2019: commercial fishery and research survey data. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/012. xiii + 155 p.

Bourret, A., Leung, C., Puncher, G. N., Le Corre, N., Deslauriers, D., Skanes, K., Bourdages, H., Cassista-Da Ros, M., Walkusz, W., Jeffery, N. W., Stanley, R. R.E. and Parent, G. J. 2024. Diving into broad-scale and high-resolution population genomics to decipher drivers of structure and climatic vulnerability in a marine invertebrate. Mol. Ecol. 33(15):e17448.

Boutillier, J.A. and Bond, J.A. 2000. Using a Fixed Escapement Strategy to Control Recruitment Overfishing in the Shrimp Trap Fishery in British Columbia. J. Northw. Atl. Fish. Sci. 27:261- 271.

Butler, M.A.E. and Robert, G. 1992. Update of the Scotian Shelf Shrimp Fishery - 1991. DFO CAFSAC Res. Doc. 1992/033.

Caddy, J.F. 1998. A short review of precautionary reference points and some proposals for their use in data-poor situations. FAO Fish. Tech. Pap. No. 379.

Charnov, E.L. 1982. The Theory of Sex Allocation. (MPB-18), Volume 18. Princeton University Press, 1982.

Charnov, E. and Skùladòttir, U. 2000. Dimensionless Invariants for the Optimal Size (Age) of Sex Change. Evol. Ecol. Res. 2:1067-1071.

Casault, B., Johnson, C., Devred, E., Head, E., Cogswell, A., and Spry, J. 2020. Optical, Chemical, and Biological Oceanographic Conditions on the Scotian Shelf and in the eastern Gulf of Maine during 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/071. v + 64 p.

Deriso, R.B. 1980. Harvesting Strategies and Parameter Estimation for an Age-Structured Model. Can. J. Fish. Aqu. Sci. 37: 268-282.

Dey, R., Cadigan, N, and Zheng, N. 2019. Estimation of the Von Bertalanffy growth model when ages are measured with error. Appl. Statist. 68 (4): 1131-1147.

DFO. 2002. A new Traffic Light Assessment for northern shrimp (*Pandalus borealis*) on the eastern Scotian Shelf. DFO Can. Sci. Advis. Sec. Sci. Resp. 2002/006.

DFO. 2009a. Policy on New Fisheries for Forage Species. Fisheries Management, National Capital Region, Ottawa, ON.

DFO. 2009b. A Fishery Decision-Making Framework Incorporating the Precautionary Approach. Fisheries Management, National Capital Region, Ottawa, ON.

DFO. 2011. Scotian Shelf Shrimp (Pandalus borealis) Integrated Fishery Management Plan. Fisheries Management, Maritimes Region, Dartmouth, NS.

DFO. 2019a. Stock Status Update of Georges Bank 'A' Scallops (Placopecten magellanicus) for the 2019 Fishing Season. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/036.

DFO. 2019b. Canada's Oceans Now: Atlantic Ecosystems 2018. Fisheries and Oceans Canada DFO/2018-2011. 47 p.

DFO. 2020a. 2020 Maritimes Winter Research Vessel Survey Trends on Georges Bank. DFO Can. Sci. Advis. Sec. Sci. Resp. 2020/048.

DFO. 2020b. Maritimes Research Vessel Survey Trends on the Scotian Shelf and Bay of Fundy. DFO Can. Sci. Advis. Sec. Sci. Resp. 2020/019.

DFO. 2021a. An Assessment of Northern Shrimp (*Pandalus borealis*) in Shrimp Fishing Areas 4-6 in 2019. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/010.

DFO. 2021b. Oceanographic Conditions in the Atlantic Zone in 2020. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/026.

DFO. 2022. Guidelines for Implementing the Fish Stock Provisions in the Fisheries Act. Fisheries Management, National Capital Region, Ottawa, ON.

DFO. 2023. Science advice on guidance for limit reference points under the Fish Stock Provisions. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2023/009.

DFO. 2024a. Maritimes Research Vessel Survey Trends on the Scotian Shelf and Bay of Fundy for 2023. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2024/010.

DFO. 2024b. Assessment of Scotian Shelf Snow Crab from 2023. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2024/062.

Etter, M.L. and Mohn, R.K. 1984. Scotia-Fundy Shrimp Stock Status – 1983. CAFSAC Res. Doc. 84/11.

Etter, M.L. and Mohn, R.K. 1989. Scotia-Fundy Shrimp Stock Status – 1989. CAFSAC Res. Doc. 89/4.

Froese, R. 2006. Cube law, condition factor and weight-length relationships: History, meta-analysis and recommendations. J. Appl. Icht. 22: 241–23.

Garcia, E.G. 2007. The Northern Shrimp (*Pandalus borealis*) Offshore Fishery in the Northeast Atlantic. Adv. Mar. Biol. 52:147-266.

Gillett, R. 2008. Global study of shrimp fisheries. FAO Fisheries Technical Paper. No. 475. Rome, FAO. 331 p.

Greenlaw, M.E. and McCurdy, Q. (2014). A Digital Elevation Model of the Scotian Shelf.

Halliday, R.G., Fanning, L.P. and Mohn, R.K. 2001. Use of the Traffic Light Method in Fishery Management Planning. DFO Can. Sci. Advis. Sec. Res. Doc. 2001/108.

Hannah, R.W., Jones, S.A., Long, M.R. 1995. Fecundity of the ocean shrimp (*Pandalus jordani*). Can. J. Fish. Aqu. Sci. 52(10):2098-2107.

Hansen, H.O. and Aschan, M. 2000. Growth, Size- and Age-at-Maturity of Shrimp, *Pandalus borealis*, at Svalbard Related to Environmental Parameters. J. Northw. Atl. Fish. Sci. 27:83- 91.

Hardie, D., Covey, M. and Cook, A. 2018. 2015 Eastern Scotian Shelf Shrimp (*Pandalus borealis*) Framework. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/005. Vi+ 117 p.

Henshaw, J.M. 2018. Protandrous Hermaphroditism. In: Vonk J., Shackelford T. (eds) Encyclopedia of Animal Cognition and Behavior. Springer, Cham.

Jorde, P.E., Søvik, G., Westgaard, J.I., Albretsen, J., André, C., Hvingel, C., Johansen, T., Sandvik, A.D., Kingsley, M. and Jørstad, K.E. 2015. Genetically distinct populations of northern shrimp, *Pandalus borealis*, in the North Atlantic: Adaptation to different temperatures as an isolation factor. Mol. Ecol. 24(8):1742-1757.

Koeller, P., King, M., Newell, M.B., Newell, A. and Roddick, D. 1995. An inshore shrimp trap fishery for eastern Nova Scotia? Can. Tech. Rep. Fish. Aquat. Sci. 2064: 41 p.

Koeller, P. 1996. The Scotian Shelf Shrimp (*Pandalus borealis*) Fishery 1995. DFO Can. Sci. Advis. Sec. Res. Doc. 1996/008.

Koeller, P, Covey, M. and King, M. 1996. Scotian Shelf Shrimp (*Pandalus borealis*) Fishery in 1996. DFO Can. Sci. Advis. Sec. Res. Doc. 1996/128.

Koeller, P. 2000. Relative Importance of Environmental and Ecological Factors to the Management of the Northern Shrimp Fishery (*Pandalus borealis*) on the Scotian Shelf. J. Northw. Atl. Fish. Sci. 27:37-50.

Koeller, P., Savard, L. Parsons, D. and Fu, C. 2000a. A Precautionary Approach to Assessment and Management of Shrimp Stocks in the Northwest Atlantic. J. Northw. Atl. Fish. Sci. 27:235-247.

Koeller, P., Mohn, R. and Etter, M. 2000b. Density Dependant Sex Change in Pink Shrimp, *Pandalus borealis*, on the Scotian Shelf. J. Northw. Atl. Fish. Sci. 27:107-11.

Koeller, P., Covey, M. and King, M. 2001. Northern shrimp (*Pandalus borealis*) on the eastern Scotian Shelf – review of the 2000 fishery and outlook for 2001. Can. Sci. Advis. Sec. Res. Doc. 2001/003.

Koeller, P., Covey, M., and King, M. 2003. Is Size at Transition a Measure of Growth or Abundance in Pandalid Shrimp? Fish. Res. 65:217-230.

Koeller, P. 2006. Inferring Shrimp (*Pandalus borealis*) Growth Characteristics from Life History Stage Structure Analysis. J. Shell. Res. 25:595-560.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., Skùladòttir, U., Wieland, K., Savard, L. and Aschan, M. 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Sci. 324:791-793.

Kristensen, K., Nielsen, A., Berg, C.W., Skaug, H. and Bell, B.M. 2016. TMB: Automatic Differentiation and Laplace Approximation. J. Stat. Soft. 70(5):1-21.

Le Corre, N., Pepin, P., Han, G., Ma, Z. and Snelgrove, P.V.R. 2019. Assessing connectivity patterns among management units of the Newfoundland and Labrador shrimp population. Fish. Oceanogr. 28:183–202.

Le Corre, N., Pepin, P., Burmeister, A., Walkusz, W., Skanes, K., Wang, Z., Brickman, D. and Snelgrove, P.V.R. 2020. Larval Connectivity of Northern Shrimp (*Pandalus borealis*) in the Northwest Atlantic. Can. J. of Fish. and Sci. 77(8):1332-1347.

Le Corre N, Pepin P, Han G, Ma Z. 2021. Potential impact of climate change on northern shrimp habitats and connectivity on the Newfoundland and Labrador continental shelves. Fish Oceanogr. 30:331–347.

MacDonald, P. and Du, J. 2018. *mixdist*: Finite Mixture Distribution Models. R packages version 0.5-5.

McDonald, R.R., Keith, D.M., Sameoto, J.A., Hutchings, J.A. and Mills Flemming, J. 2021. Explicit incorporation of spatial variability in a biomass dynamics assessment model. ICES J. Mar. Sci. 78(9):3265-3280.

McDonald, R.R., Keith, D.M., Sameoto, J.A., Hutchings, J.A., and Mills Flemming, J. 2022. Incorporating intra-annual variability in fisheries abundance data to better capture population dynamics. Fish. Res. 246: 106152.

Mohn, R.J. 1999. The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. ICES J. Mar. Sci. 56 (4): 473-488.

Mohn, R.J., and Etter, M.L. 1982. Review of the Scotian Shelf Shrimp Fishery. Can. Atl. Fish. Sci. Advis. Comm. Res. Doc. 82/16.

Mohn, R.J. and Etter, M.L. 1983. Scotia-Fundy Shrimp Stock Status - 1982. Can. Atl. Fish. Sci. Advis. Comm. Res. Doc. 83/36.

Mohn, R., Black, J. and Koeller, P. 2001. Traffic Light Indicators. BIO Review 2000. 88 p.

Nasmith, L., Sameoto, J.A., and Glass, A. 2016. Scallop Production Areas in the Bay of Fundy: Stock Status for 2015 and Forecast for 2016. Can. Sci. Advis. Sec. Res. Doc. 2016/021.

Ouellet, P. and Allard, J.P. 2006. Vertical distribution and behaviour of shrimp *Pandalus borealis* larval stages in thermally stratified water columns: Laboratory experiment and field observations. Fish. Oceanogr. 15:373–89.

Ovando, D., Free, C., Jensen, O. and Hilborn, R. 2021. A history and evaluation of catch-only stock assessment models. Fish and Fisheries. 23(3):616-630.

Petrie, B. 2007. Does the north Atlantic oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmos. Ocean 45(3):141-151.

Rago, P. and Legault, C. 2014. Application of Some Index Methods to Georges Bank Yellowtail Flounder. Trans. Res. Assess. Comm.

Richards, R.A., Fogarty, M.J., Mountain, D.G. and Taylor, M.H. 2012 Climate change and northern shrimp recruitment variability in the Gulf of Maine. Mar. Ecol. Prog. Ser. 464:167- 178.

Richards, R.A., O'Reilly, J.E. and Hyde, K.J.W. 2016. Use of satellite data to identify critical periods for early life survival of northern shrimp in the Gulf of Maine. Fish. Oceanogr. 25:306-319.

Richards, R.A., Hunter M. 2021. Northern shrimp *Pandalus borealis* population collapse linked to climate-driven shifts in predator distribution. PLoS ONE 16(7):e0253914.

Ricker, W. 1954. Stock and Recruitment. J. Fish. Res. Boa. Can. 11:559-623.

Roddick, D., Bradford, B. and Scott, W. 1994. Status of the Scotian Shelf Shrimp (*Pandalus borealis*) Fishery 1993. DFO Can. Atl. Fish. Sci. Advis. Comm. Res. Doc. 94/52.

Schnute, J. 1985. A General Theory for Analysis of Catch and Effort Data. Can. J. Fish. Aqu. Sci. 42: 414-429.

Smith, S.J. 1996. Analysis of data from bottom trawl surveys. NAFO Sci. Coun. Stud. 28:25-53.

Smith, S.J., and Hubley, B. 2014. Impact of survey design changes on stock assessment advice: sea scallops. ICES J. Mar. Sci. 71(2):320-327.

Smith, S.J., Bourdages, H., Choi, J., Dawe, E., Dunham, J.S., Gendron, L., Hardie, D., Moriyasu, M., Orr, D., Roddick, D., Rutherford, D., Sainte-Marie, B., Savard, L., Shelton, P., Stansbury, D., Tremblay, M.J. and Zhang, Z. 2012. Technical Guidelines for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Section 7 – Invertebrate Species. Can. Sci. Advis. Sec. Res. Doc. 2012/117.

Shumway, S.E., Perkins, H.C. Schick, D.F. and Stickney, A.P. 1985. Synopsis of Biological Data on the Pink Shrimp, *Pandalus borealis* Krøyer, 1838. NOAA Tech. Rept. NMFS 30.

Sutcliffe, W.H. Jr., Loucks, R.H. and Drinkwater, K.F. 1976. Coastal circulation and physical oceanography of the Scotian Shelf and the Gulf of Maine. J. Fish. Res. Board Can. 33:98-115.

Thorson, J.T., Rindorf, A., Gao, J., Hanselman, D.H. and Winker, H. 2016. Density-dependent changes in effective area occupied for sea-bottom-associated marine fishes. Proc. Biol. Sci. 283(1840):20161853.

Thygesen, U.H., Albertsen, C.M., Berg, C.W., Kristensen, K., and Nielsen, A. 2017. Validation of ecological state space models using the Laplace approximation. Environ. Ecol. Stat. 24: 317-339.

Zisserson, B.M., Cameron, B.J., Glass, A.C. and Choi, J.S. 2021. Assessment of Scotian Shelf Snow Crab in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/048. ix + 148 p.

TABLES

Table 1. Time series (1980–2024) of Eastern Scotian Shelf Northern Shrimp fishery by annual total allowable catch (TAC) quotas (mt) and total catch (mt) for Shrimp Fishing Areas (SFA) 13–15. Dashes (—) indicate no data; < = less than.

Year	Trawl TAC	Trap TAC	Trawl Catch SFA 13	Trawl Catch SFA 14	Trawl Catch SFA 15	Total	Trap Catch	Total Catch
1980	5,021	—	491	133	360	984	—	984
1981	—	—	418	26	10	454	—	454
1982	4,200	—	316	52	201	569	—	569
1983	5,800	—	483	15	512	1,010	—	1,010
1984	5,700	—	600	10	318	928	—	928
1985	5,560	—	118	—	15	133	—	133
1986	3,800	—	126	—	—	126	—	126
1987	2,140	—	148	4	—	152	—	152
1988	2,580	—	75	6	1	82	—	82
1989	2,580	—	91	2	—	93	—	93
1990	2,580	—	90	14	—	104	—	104
1991[a]	2,580	—	81	586	140	804	—	804
1992	2,580	—	63	1,181	606	1,850	—	1,850
1993[b]	2,650	—	431	1,279	317	2,027	—	2,027
1994[c]	3,100	—	8	2,656	410	3,074	—	3,074
1995	3,170	—	168	2,265	715	3,148	—	3,148
1996	3,170	—	55	2,299	817	3,171	158	3,329
1997	3,600	—	570	2,422	583	3,575	208	3,783
1998	3,800	—	562	2,014	1,223	3,799	107	3,906
1999	4,800	200	723	1,525	2,456	4,704	134	4,838
2000	5,300	200	486	1,822	2,927	5,235	200	5,435
2001	4,700	300	692	1,298	2,515	4,505	263	4,768
2002	2,700	300	267	1,573	860	2,700	245	2,945
2003	2,700	300	612	1,623	373	2,608	154	2,762
2004	3,300	200	2041	755	376	3,172	96	3,268
2005	4,608	392	1190	1,392	1,054	3,636	9	3,645
2006	4,608	392	846	1,997	1,111	3,954	32	3,986
2007	4,820	200	267	2,633	1,678	4,578	4	4,582
2008	4,912	100	349	2,703	1,265	4,317	4	4,321
2009	3,475	25	315	1,949	1,078	3,342	5	3,347
2010	4,900	100	280	1,847	2,453	4,580	2	4,582
2011	4,432	168	254	2,340	1,653	4,247	111	4,358
2012	3,954	246	197	2,269	1,227	3,693	199	3,892
2013	3,496	304	158	2,514	708	3,380	224	3,604
2014	4,140	360	773	2,263	1,043	4,079	250	4,329
2015	4,140	360	341	2,067	1,701	4,109	314	4,423
2016	2,990	260	177	2,097	719	2,993	108	3,101
2017	2,392	208	278	1947	150	2,375	65	2,440

Year	Trawl TAC	Trap TAC	Trawl Catch SFA 13	Trawl Catch SFA 14	Trawl Catch SFA 15	Total	Trap Catch	Total Catch
2018	2,392	208	320	1927	148	2,395	116	2,511
2019	2,392	208	846	1397	149	2,392	130	2,522
2020	2,392	208	1,443	714	264	2,421	58	2,479
2021	2,392	208	1,321	782	326	2,429	<1	2,429
2022	2,116	184	1,118	737	344	2,199	<1	2,200
2023	1,590	138	112	1,405	123	1,640	<1	1,641
2024	460	40	18	359	22	399	1	400

[a] Nordmøre separator grate introduced.
[b] Total TAC not caught because TAC for SFA 14 and 15 were exceeded.
[c] Individual SFA TAC combined.

Table 2. Number of active vessels and total licenses (in brackets) for the Eastern Scotian Shelf Northern Shrimp fishery.

Year	Trap Sector [a]	Scotia Trawl Sector [b]	Gulf Trawl Sector [c]
1993	0	23	6
1994	0	22	6
1995	4	23(23)	6(23)
1996	12(17)	21(23)	6(23)
1997	10(17)	18(23)	6(23)
1998	19(26)	17(28)[d]	10(23)[e]
1999	15(22)	19(28)[d]	10(23)[e]
2000	13(21)	18(32)[f]	10(23)[e]
2001	12(28)	21(28)[d]	10(23)[e]
2002	13(14)[g]	16(23)	6(23)
2003	9(14)	15(23)	5(23)
2004	6(14)	18(23)	6(23)
2005	7(14)	20(28)[h]	7(24)[i]
2006	11(14)	18(28)	7(24)
2007	5(14)	19(28)	7(24)
2008	1(14)	18(28)	7(24)
2009	1(14)	17(28)	6(14)[j]
2010	4(14)	17(28)	7(14)
2011	9(14)	23(28)	5(14)
2012	11(14)	16(28)	5(14)
2013	11(14)	13(28)	6(14)
2014	10(14)	10(28)	5(14)
2015	11(14)	10(28)	5(14)
2016	9(14)	11(28)	5(14)
2017	8(14)	9(28)	4(14)
2018	8(14)	9(28)	5(14)
2019	7(14)	8(28)	7(14)
2020	8(14)	8(28)	7(14)
2021	1(14)	7(28)	7(14)
2022	2(14)	5(28)	8(14)

Year	Trap Sector [a]	Scotia Trawl Sector [b]	Gulf Trawl Sector [c]
2023	3(14)	5(28)	6(14)
2024	1(14)	3(28)	1(14)

[a] All but one active trap licence are vessels less than 45'. Trap licences receive 8% of the total allowable catch (TAC).
[b] Vessels receive approximately 70% of the TAC according to the Eastern Scotian Shelf (ESS) Northern Shrimp integrated fishery management plan. Inactive NAFO 4X licences (15) not included in total.
[c] All licences 65-100' length over all (LOA). Eligibility to fish in ESS for about 23% of the TAC.
[d] Temporary allocation divided among 5 vessels.
[e] Temporary allocation divided among 4 vessels.
[f] Temporary allocation divided among 9 licences.
[g] Nine (9) licences were made permanent for 2002. The reduction in the total number of trap licences is due to the cancellation of some non-active exploratory licences.
[h] Five (5) temporary licences made permanent.
[i] One (1) temporary licence made permanent.
[j] The previously reported number of licenses included (10) that were invalid for a number of reasons.

Table 3. Annual mobile sector port sampling by survey stratum allocation. Total number of samples collected annually and the number of Northern Shrimp these represent. The target size for port samples decreased from 500 to 305 shrimp in 2005. Dashes (—) indicate no data.

Year	Stratum 13	Stratum 14	Stratum 15	Stratum 17	Total Number of Sample	Total Number of Northern Shrimp Analyzed
1995	—	14	18	—	32	7,959
1996	—	11	11	—	22	8,544
1997	1	17	5	1	24	10,553
1998	4	16	3	5	28	12,495
1999	7	12	1	31	51	20,409
2000	—	17	13	21	51	23,084
2001	5	12	13	20	50	23,092
2002	6	28	6	10	50	20,334
2003	16	37	1	5	59	22,851
2004	34	13	5	5	57	26,898
2005	15	24	9	12	60	28,919
2006	3	24	5	5	37	11,656
2007	1	32	13	5	51	15,867
2008	2	30	5	3	40	12,361
2009	—	19	6	25	50	15,359
2010	—	20	11	23	54	16,400
2011	—	26	6	17	49	14,817
2012	—	30	8	12	50	14,832
2013	—	37	9	4	50	15,103
2014	—	22	7	21	50	15,215
2015	1	24	1	24	50	15,249
2016	1	35	—	14	50	15,248
2017	3	43	—	4	50	15,240
2018	6	41	—	3	50	15,250
2019	13	29	—	8	50	15,249
2020	26	19	—	4	49	14,710
2021	19	20	—	13	52	15,858
2022	21	18	—	12	51	15,553
2023	1	41	—	5	47	14,333
TOTAL	**179**	**716**	**156**	**313**	**1,364**	**473,438**

Table 4. Annual trap sector port sampling by survey stratum allocation. Total number of samples collected annually and the number of Northern Shrimp these represent. The target size for port samples decreased from 500 to 305 shrimp in 2005. Dashes (—) indicate no data.

Year	Stratum 13	Stratum 14	Stratum 15	Stratum 17	Total Number of Sample	Total Number of Northern Shrimp Analyzed
1995	—	—	1	5	6	2,448
1996	—	—	—	10	10	4,614
1997	—	—	—	6	6	2,627
1998	—	—	—	4	4	1,468
1999	—	—	—	7	7	3,312
2000	—	—	—	18	18	8,056
2001	—	—	—	12	12	5,657
2002	—	—	—	13	13	6,212
2003	—	—	—	11	11	5,210
2004	—	—	—	6	6	2,639
2005	—	—	—	1	1	323
2007	—	—	—	2	2	905
2011	—	—	—	4	4	1,216
2012	—	—	—	11	11	3,386
2013	—	—	—	7	7	2,189
2014	—	—	—	7	7	2,128
2015	—	—	—	11	11	3,364
2016	—	—	—	6	6	1,845
2017	—	—	—	2	2	601
2018	—	—	—	6	6	1,803
2019	—	—	—	9	9	2,730
2020	—	—	—	5	5	1,525
2021	—	—	—	—	—	—
2022	—	—	—	—	—	—
2023	—	—	—	1	1	305
TOTAL	—	—	1	165	**165**	**64,563**

Table 5. Summary of at-sea observer sampling frequency, catch, and spatial distribution from 2010 to 2024 for the mobile sector by Shrimp Fishing Area (SFA). Dashes (—) indicate no data. MARFIS = MARitimes Fisheries Information System.

Year	Trips Observed	Sets Observed	Fishing Hours Observed	Shrimp Catch (MARFIS, mt)	Shrimp Catch (Observer, mt)	SFA Covered
2013	1	13	67	45.661	47.865	14
2014	2	21	83	39.013	37.981	14, 17
2015	2	27	131	45.630	42.459	14, 17
2016	1	14	39	30.748	30.792	14
2017	2	23	109	37.240	38.703	14,17
2018	2	32	167	72.384	69.848	14,17
2019	3	31	158	64.711	63.263	13,14,17
2020	1	13	76	35.100	32.244	13,14
2021	0	0	0	—	—	—
2022	0	0	0	—	—	—
2023	2	20	101	47.353	44.961	14
2024	0	0	0	—	—	—
Total	**16**	**194**	**931**	**417.840**	**408.116**	**—**

Table 6. Species bycatch as a percentage (%) by year reported on all observed trips on the Eastern Scotian Shelf from 2010 to 2024 relative to the shrimp catch and number of tows (number of tows in brackets under years in table header). Dashes (—) indicate no catch; < = less than.

SPECIES	Total Catch (%)	Total Weight (kg)	2013 (13)	2014 (21)	2015 (27)	2016 (14)	2017 (23)	2018 (32)	2019 (32)	2020 (13)	2021-22 (0)	2023 (20)	2024 (0)
SHRIMP	**98.99%**	**41,7843**	**99.29%**	**97.21%**	**99.46%**	**96.07%**	**98.45%**	**99.76%**	**99.36%**	**99.86%**	—	**99.76%**	—
Herring, Atlantic	0.31%	1,298	0.02%	2.43%	0.27%	—	0.27%	0.08%	0.03%	—	—	0.02%	—
Hake, Silver	0.18%	739	0.07%	0.01%	0.04%	1.95%	0.01%	<0.01%	0.05%	—	—	0.04%	—
Alewife	0.10%	402	—	0.26%	<0.01%	0.92%	—	—	<0.01%	—	—	—	—
Plaice, American	0.08%	319	0.09%	0.01%	0.04%	—	0.52%	0.03%	0.05%	—	—	—	—
Turbot	0.07%	314	0.02%	0.01%	0.04%	0.61%	0.08%	0.01%	0.08%	—	—	—	—
Flounder, Witch	0.07%	289	0.26%	0.02%	0.05%	—	—	0.03%	0.13%	0.05%	—	0.02%	—
Redfish, NS	0.07%	281	0.08%	0.01%	0.02%	0.42%	0.16%	0.01%	0.03%	—	—	0.01%	—
Shrimp, Glass	0.02%	70	—	—	—	—	—	—	0.11%	—	—	—	—
Rockling, NS	0.01%	62	0.04%	—	—	—	—	0.03%	0.04%	—	—	—	—
Eelpouts, NS	0.01%	58	—	0.01%	0.02%	—	0.11%	—	—	—	—	—	—
Flounder, Winter	0.01%	57	—	—	—	—	0.15%	—	—	—	—	—	—
Capelin	0.01%	53	—	0.01%	<0.01%	—	0.01%	0.01%	0.01%	0.08%	—	—	—
Eels, NS	0.01%	47	0.10%	—	—	—	—	—	—	—	—	—	—
Halibut, Atlantic	0.01%	40	—	—	—	—	—	—	—	—	—	0.08%	—
Shanny, NS	0.01%	39	—	—	—	—	—	0.03%	0.03%	—	—	—	—
Squid, NS	0.01%	37	—	—	—	—	0.10%	—	—	—	—	—	—
Sand Lance, NS	0.01%	34	—	0.01%	—	—	0.04%	—	—	—	—	0.04%	—
Alligatorfish, NS	0.01%	28	—	—	—	—	0.07%	—	<0.01%	—	—	—	—
Skate, Thorny	<0.01%	18	0.01%	<0.01%	0.01%	—	<0.01%	—	0.01%	—	—	—	—
Squid, Shortfin	<0.01%	13	—	—	—	—	—	0.00%	0.01%	0.01%	—	—	—
Barracudina, White	<0.01%	13	—	—	<0.01%	—	—	—	0.02%	—	—	—	—
Crab, Snow	<0.01%	11	<0.01%	—	0.02%	0.01%	—	—	—	—	—	—	—
Cod, Atlantic	<0.01%	10	—	—	—	0.02%	<0.01%	—	—	—	—	<0.01%	—
Herring, Blueback	<0.01%	9	—	—	—	—	—	—	—	—	—	0.02%	—
Hake, Red	<0.01%	7	—	—	<0.01%	—	0.02%	—	—	—	—	—	—
Rockling, Fourbeard	<0.01%	6	—	—	0.01%	—	—	—	—	—	—	—	—
Blenny, Snake	<0.01%	5	—	—	—	—	—	—	0.01%	—	—	—	—
Lancetfish, Longnose	<0.01%	5	—	—	—	—	0.01%	—	—	—	—	—	—

SPECIES	Total Catch (%)	Total Weight (kg)	2013 (13)	2014 (21)	2015 (27)	2016 (14)	2017 (23)	2018 (32)	2019 (32)	2020 (13)	2021-22 (0)	2023 (20)	2024 (0)
Shad, American	<0.01%	3	—	—	—	—	—	—	<0.01%	—	—	—	—
Poacher, Atlantic	<0.01%	2	—	—	—	—	—	—	—	—	—	<0.01%	—
Wolffish, NS	<0.01%	2	—	—	—	<0.01%	—	<0.01%	—	—	—	—	—
Pollock	<0.01%	2	—	<0.01%	—	—	—	—	—	—	—	—	—
Wrymouth	<0.01%	2	—	—	—	—	—	—	<0.01%	—	—	—	—
Basket Star, NS	<0.01%	2	—	—	<0.01%	—	—	—	—	—	—	—	—
Haddock	<0.01%	1	—	<0.01%	—	—	—	—	—	—	—	—	—
Lanternfish, NS	<0.01%	1	—	—	—	—	—	—	<0.01%	—	—	—	—
Sculpin, Mailed	<0.01%	1	—	—	—	—	—	—	<0.01%	—	—	—	—
Rockling, Threebeard	<0.01%	1	—	—	—	—	—	—	<0.01%	—	—	—	—
Flounder, NS	<0.01%	1	—	—	—	—	—	—	—	—	—	<0.01%	—
GRAND TOTAL	**100%**	**42,9816**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**—**	**100%**	**—**
% BYCATCH	**1.01%**	**4,282**	**0.71%**	**2.79%**	**0.54%**	**3.93%**	**1.55%**	**0.24%**	**0.64%**	**0.14%**	**—**	**0.24%**	**—**

Table 7. At-sea observer sampling frequency, catch, and spatial distribution from 2013 to 2024 for the trap sector. Note there have been no observed trips since 2020 due to fleet inactivity. MARFIS = MARitimes Fisheries Information System.

Season	Trips Observed	Sets Observed	Fishing Hours Observed	Shrimp Catch (MARFIS, kg)	Shrimp Catch (Observer, kg)	Areas Covered
2018-19	4	40	216	932	925	17
2019-20	5	50	192	1,026	1,074	17
Total	**9**	**90**	**408**	**1,958**	**1,999**	**17**

Table 8. Species bycatch by year reported on all observed trap trips on the Eastern Scotian Shelf from 2013 to 2024 relative to the shrimp catch and number of tows (number of tows in brackets under years in table header). Dashes (—) indicate no catch.

Species	Total Catch (%)	Total Weight (kg)	2018-19 (40)	[1]2019-20 (50)
Shrimp	99.92%	1999	99.83%	100.00%
Crab, Snow	0.08%	2	0.17%	—
GRAND TOTAL	**100%**	**2001**	**100.00%**	**100.00%**
% BYCATCH	**0.08%**		**0.17%**	**0.00%**

[1] Most recent data shown. There have been no observed trap trips since 2020 due to fleet inactivity.

Table 9. Size of each stratum estimated using the old calculations and on shapefiles currently utilized for the Eastern Scotian Shelf Northern Shrimp survey station selection.

Stratum	Old Calculations (km^2)	Calculations from Shapefiles (km^2)
13	1619.6	1568.8
14	1516.7	2549.6
15	948.0	1282.9
17	1415.0	1434.9

Table 10. Different assumptions for each productivity parameter associated with each individual setting explored for the Maximum Sustainable Yield simulations.

Setting	Stock-Recruit Relationship	Natural Mortality	Main Trawl Growth Rates	Recruit Growth Rates	Percent of Biomass that is Spawning Stock Biomass
1	Ricker	Resample	Autoregressive model	Autoregressive model	Autoregressive model
2	Hockey Stick	Resample	Autoregressive model	Autoregressive model	Autoregressive model
3	Ricker	Resample	Resample	Joint Resampling	Joint Resampling
4	Hockey Stick	Resample	Resample	Joint Resampling	Joint Resampling
5	Ricker	Resample	Resample	Resample	Mean
6	Hockey Stick	Resample	Resample	Resample	Mean

Table 11. Survey population numbers-at-age of Eastern Scotian Shelf Northern Shrimp (millions of individuals) from modal analysis. Mean and median values are based on 1999–2024 data. The table is representative of numbers across all Shrimp Fishing Areas.

Age	2022	2023	2024	Mean	Median
1 [a]	52	77	436	276	244
2	106	62	56	170	114

Age	2022	2023	2024	Mean	Median
3	309	230	422	573	383
4	687	426	839	959	822
5+	1,341	889	1,230	2,851	2,956
Total	2,495	1,683	2,983	4,742	4,458
Age 4+ Males [b]	994	572	1060	2136	1982
Primiparous [c]	388	251	379	709	664
Multiparous	646	491	673	949	973
Total Females	1,034	742	1,052	1,621	1,561

[a] Belly bag. Time series began in 2002.
[b] Total population less Ages 2 and 3 males, transitionals (i.e., males that will potentially change to females the following year) and females.
[c] Includes transitionals.

Table 12. The Spatially Explicit Assessment Model parameter estimates and standard errors, along with estimates transformed to natural scale. SE = standard error.

Parameter	Estimate (SE)	Estimate on Natural Scale
$\log(\sigma_\epsilon)$	-0.07 (0.02)	0.93
$\log(\sigma_\upsilon)$	0.26 (0.03)	1.30
$\log(\kappa_B)$	-2.94 (0.24)	0.05
$\log(\tau_B)$	2.69 (0.20)	14.73
$\log(\kappa_R)$	-4.76 (0.15)	0.01
$\log(\tau_R)$	4.02 (0.19)	55.70
$\log(B_0)$	9.09 (0.17)	8866.19
$\log(R_0)$	3.41 (0.93)	30.27
$\log(m_0)$	-1.01 (0.14)	0.36
logit(p_I)	6.40 (0.71)	0.998
logit(p_I^R)	1.43 (0.07)	0.81
$\log(q_R)$	-0.55 (0.14)	0.58
$\log(\sigma_\eta)$	-0.82 (0.32)	0.44

Table 13. Tow Level Model parameter estimates and standard errors, along with estimates transformed to natural scale. SE = standard error.

Parameter	Estimate (SE)	Estimate on Natural Scale
$\log(\sigma_\epsilon)$	0.12 (0.02)	1.13
$\log(\sigma_\upsilon)$	0.50 (0.02)	1.65
$\log(\sigma_\tau)$	-9.53 (239.22)	$7.26X10^{-5}$
$\log(\sigma_\phi)$	-0.37 (0.18)	0.69
$\log(\sigma_\eta)$	-0.74 (0.25)	0.48
$\log(q_R)$	-0.51 (0.16)	0.60

Parameter	Estimate (SE)	Estimate on Natural Scale
logit(p_I)	6.35 (0.71)	0.998
logit(p_I^R)	1.43 (0.07)	0.81
$\log(B_0)$	11.13 (0.12)	68,186.37
$\log(R_0)$	6.23 (0.75)	507.76
$\log(m_0)$	-1.04 (0.12)	0.35

Table 14. Decision table using the 2023 output from the Spatially Explicit Assessment Model to predict the total biomass of shrimp in the Eastern Scotian Shelf in 2024 using the mean growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass Change (mt)	Probability of Decline (%)
0	0.0	14,314	-10.3	-1,635	77.1
100	0.7	14,214	-10.9	-1,735	78.2
200	1.4	14,114	-11.5	-1,835	79.5
300	2.1	14,014	-12.1	-1,935	80.6
400	2.9	13,914	-12.8	-2,035	81.6
500	3.6	13,814	-13.4	-2,135	82.7
600	4.4	13,714	-14.0	-2,235	83.7
700	5.1	13,614	-14.6	-2,335	85.0
800	5.9	13,514	-15.3	-2,435	85.9
900	6.7	13,414	-15.9	-2,535	86.2
1,000	7.5	13,314	-16.5	-2,635	87.6

Table 15. Decision table using the 2023 output from Tow Level Model to predict the total biomass of shrimp in the Eastern Scotian Shelf in 2024 using the last year's growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass Change (mt)	Probability of Decline (%)
0	0.0	10,316	-14.2	-1,712	86.2
100	1.0	10,216	-15.1	-1,812	87.3
200	2.0	10,116	-15.9	-1,912	88.1
300	2.9	10,016	-16.7	-2,012	89.1
400	3.9	9,916	-17.6	-2,112	89.9
500	5.0	9,816	-18.4	-2,212	90.8
600	6.0	9,716	-19.2	-2,312	91.7
700	7.0	9,616	-20.1	-2,412	92.4
800	8.0	9,516	-20.9	-2,512	93.0
900	9.1	9,416	-21.7	-2,612	93.6
1,000	10.1	9,316	-22.6	-2,712	94.1

Table 16. Decision table using the 2018 output from the Spatially Explicit Assessment Model to predict the total biomass of shrimp in the Eastern Scotian Shelf in 2019 using the mean growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass change (mt)	Probability of Decline (%)
0	0.0	41,385	3.5	1,390	41.1
300	0.7	41,085	2.7	1,090	43.2
600	1.5	40,785	2.0	7,900	45.6
900	2.2	40,485	1.2	490	48.1
1,200	3.0	40,185	0.5	190	50.3
1,500	3.8	39,885	-0.3	-110	53.0
1,800	4.5	39,585	-1.0	-410	55.1
2,100	5.3	39,285	-1.8	-710	57.4
2,400	6.2	38,985	-2.5	-1,010	59.9
2,700	7.0	38,685	-3.3	-1,310	62.2
3,000	7.8	38,385	-4.0	-1,610	64.9

Table 17. Decision table using the 2018 output from Tow Level Model to predict the total biomass of shrimp in the Eastern Scotian Shelf in 2019 using the last year's growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass Change (mt)	Probability of Decline (%)
0	0.0	32,680	-1.8	-614	59.8
300	0.9	32,380	-2.7	-914	64.2
600	1.9	32,080	-3.6	-1,214	68.5
900	2.8	31,780	-4.5	-1,514	71.7
1,200	3.8	31,480	-5.5	-1,814	75.0
1,500	4.8	31,180	-6.4	-2,114	78.3
1,800	5.8	30,880	-7.3	-2,414	81.6
2,100	6.7	30,580	-8.2	-2,714	84.6
2,400	7.9	30,280	-9.1	-3,014	87.2
2,700	9.0	29,980	-10.0	-3,314	88.8
3,000	10.1	29,680	-10.9	-3,614	90.6

Table 18. Decision table for the total biomass using the 2024 output from the Spatially Explicit Assessment Model to predict the total biomass of shrimp in the Eastern Scotian Shelf in 2025 using the mean growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass Change (mt)	Probability of Decline (%)
0	0.0	23,890	9.5	2068	28.3
100	0.4	23,790	9.0	1968	29.3
200	0.8	23,690	8.6	1868	30.3

Catch (mt)	Exploitation (%)	Biomass (mt)	Biomass Change (%)	Biomass Change (mt)	Probability of Decline (%)
300	1.3	23,590	8.1	1768	31.3
400	1.7	23,490	7.6	1668	32.1
500	2.1	23,390	7.2	1568	33.3
600	2.6	23,290	6.7	1468	34.3
700	3.0	23,190	6.3	1368	35.5
800	3.5	23,090	5.8	1268	36.7
900	3.9	22,990	5.4	1168	37.6
1000	4.4	22,980	4.9	1068	38.6

Table 19. Decision table for Spawning Stock Biomass (SSB) using the 2024 output from the Spatially Explicit Assessment Model, a prediction of the percent of biomass that is SSB and the mean proportion of females in the commercial catch to predict the SSB of shrimp in the Eastern Scotian Shelf in 2025 using the mean growth method and accounting for variability in total biomass, total recruit biomass, and natural mortality.

Total Catch (mt)	Female Exploitation (%)	SSB (mt)	SSB Change (%)	SSB Change (mt)	Probability of Decline (%)
0	0.0	13,185	6.2	768	35.3
100	0.5	13,130	5.7	713	36.4
200	1.0	13,075	5.3	658	37.3
300	1.6	13,019	4.9	602	38.3
400	2.1	12,964	4.4	547	39.3
500	2.6	12,909	4.0	492	40.4
600	3.2	12,854	3.5	437	41.4
700	3.7	12,799	3.1	382	42.6
800	4.3	12,744	2.6	326	43.6
900	4.8	12,688	2.2	271	44.5
1000	5.4	12,633	1.7	216	45.8

Table 20. Previous Traffic Light Approach (TLA) indicators used to assess the stock alongside a proposed list of new indicators to be used in stock assessment going forward. Dash (—) indicates no indicator; CPUE = Catch Per Unit Effort; CV = Coefficient of Variation; SSB = Spawning Stock Biomass; and Std = Standardized.

Abundance Characteristic Old Indicators	Abundance Characteristic New Indicators	Productivity Characteristic New Indicators	Productivity Characteristic New Indicators	Fishing Effects Characteristic New Indicators	Fishing Effects Characteristic New Indicators	Ecosystem Characteristics New Indicators	Ecosystem Characteristic New Indicators
Survey CPUE	Total Biomass (Model)	SSB	Model SSB	Commercial Count	Commercial Count	Survey Bottom Temperature	Survey Bottom Temperature
Gulf CPUE	Gulf CPUE	Belly bag	Model Recruitment	Exploitation	Exploitation (Model)	Sea Surface Temperature	Sea Surface Temperature
Std CPUE	Std CPUE	Age 2	Age 4	Female Exploitation	Female Exploitation (Model)	Cod Recruitment	Snow Crab Recruitment
Trap CPUE	Trap CPUE	Age 4	Mean Length at Sexual Transition	Effort	Effort	Snow Crab Recruitment	Predation
Survey CV	Survey CV	Mean Length at Sexual Transition	Max Length	Female Proportion in Catch	Female Proportion in Catch	Turbot Recruitment	Specific Predators
Commercial Area	Commercial Area (new cutoff)	Max Length	—	Female Mean Length	Female Mean Length	—	—
—	Shrimp Bycatch	Predation	—	—	—	—	—
—	Area Occupied	—	—	—	—	—	—

FIGURES

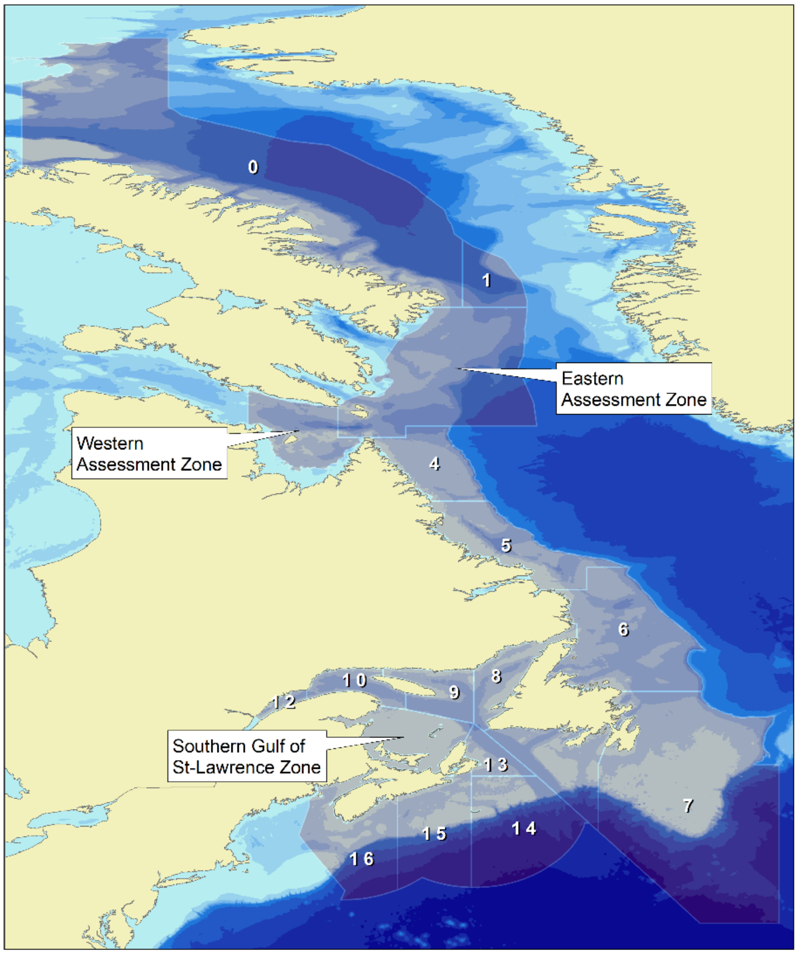


Figure 1. The 17 Shrimp Fishing Areas (SFA) in Atlantic Canada within the 200-mile exclusive economic zone. The Eastern Scotian Shelf Northern Shrimp fishery is comprised of SFA 13–15.

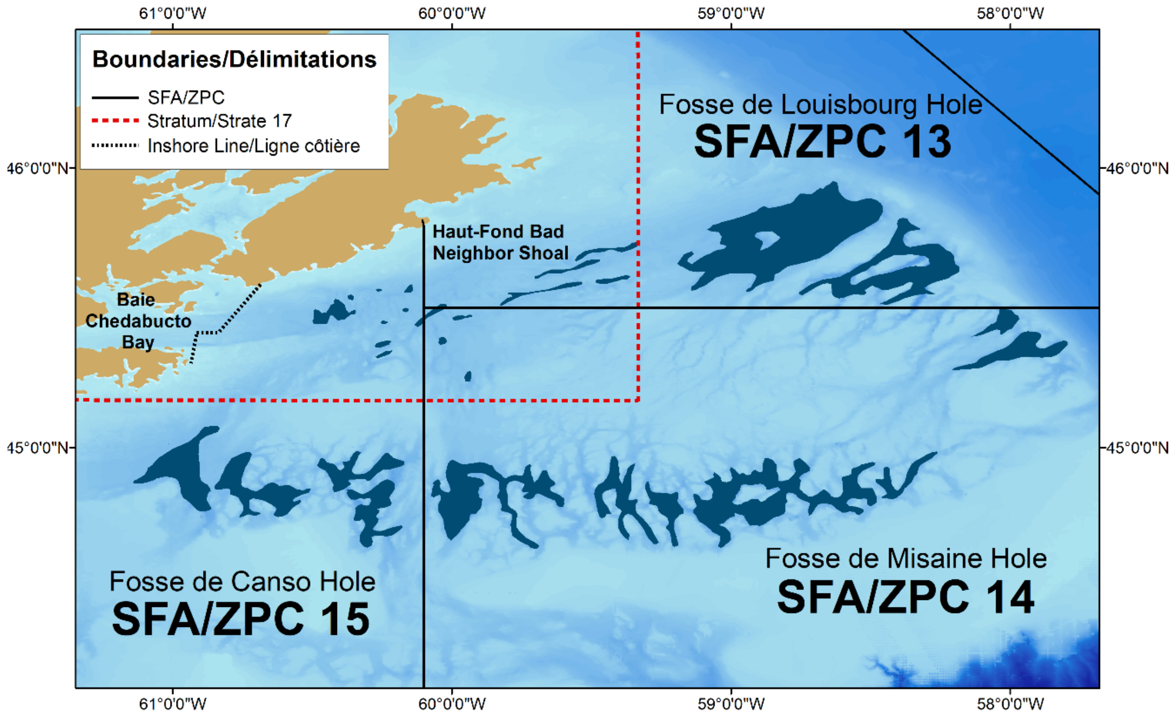


Figure 2. Boundaries of the Eastern Scotian Shelf Northern Shrimp fishery. The Shrimp Fishing Areas (SFA) fall within Northwest Atlantic Fishing Organization divisions 4Vn and 4VsW. The fishery is characterized by four areas: Louisbourg Hole (SFA 13), Misaine Hole (SFA 14), Canso Hole (SFA 15), and an inshore area within SFA 13–15 known as Bad Neighbour shoal (stratum 17).

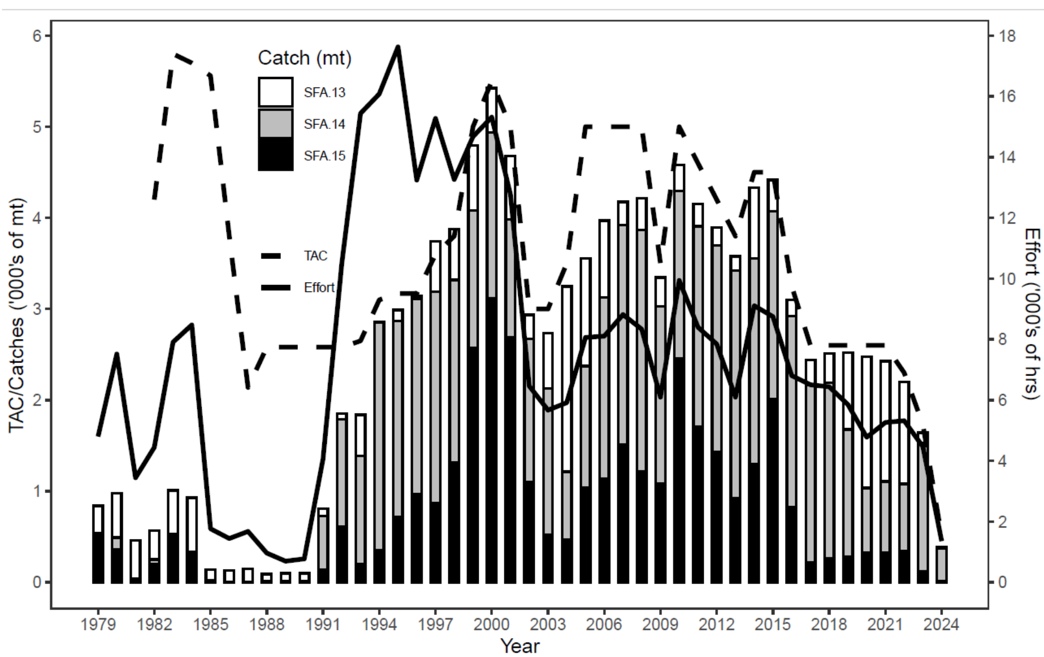


Figure 3. History of Eastern Scotian Shelf Northern Shrimp fishery catches for Shrimp Fishing Areas 13–15 by Total Allowable Catch (thousands of mt) and Effort (thousands of hours) from 1979–2024. TAC = total allowable catch.

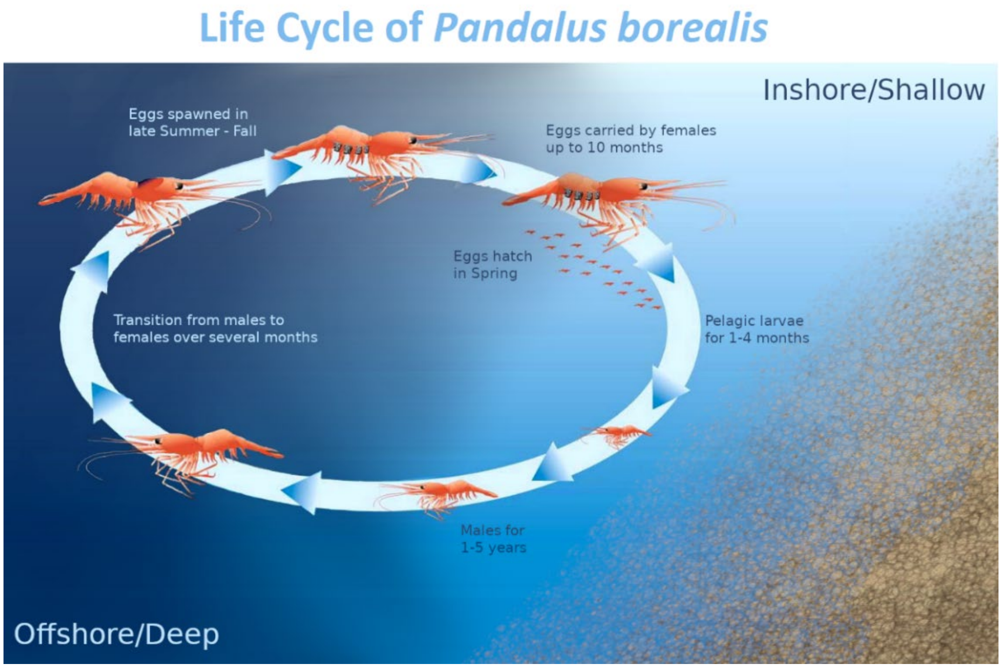


Figure 4. Life cycle of Northern Shrimp (Pandalus borealis), as expected on the Eastern Scotian Shelf region.

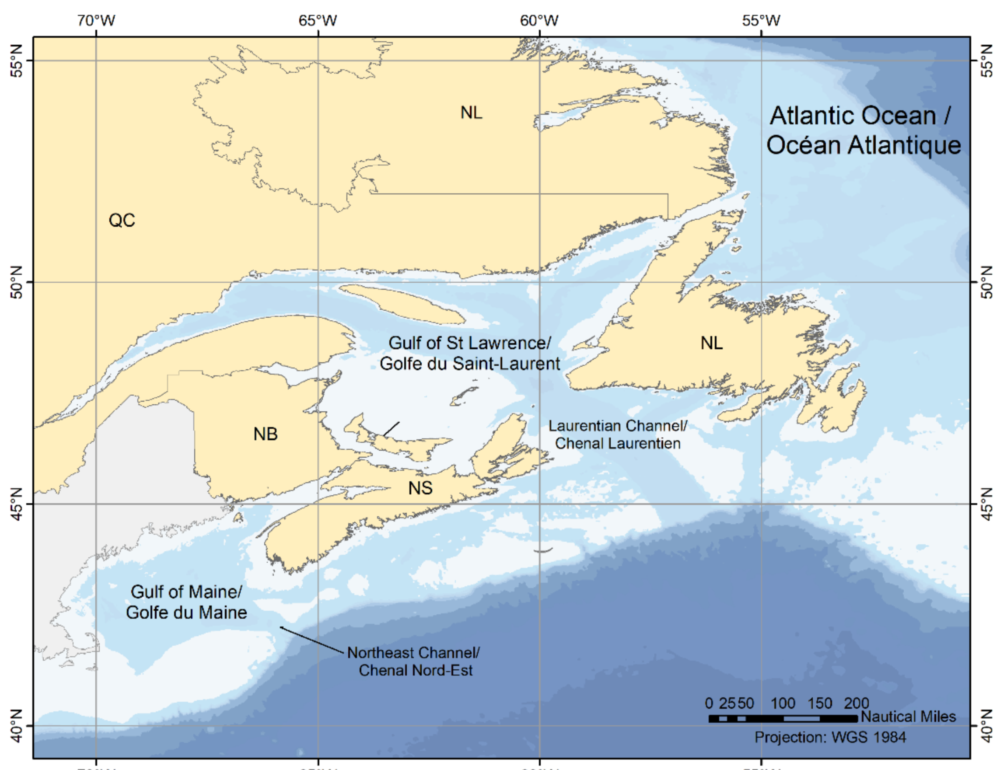


Figure 5. Geographical representation of the Scotian Shelf, including adjacent areas of influence in the North Atlantic region.

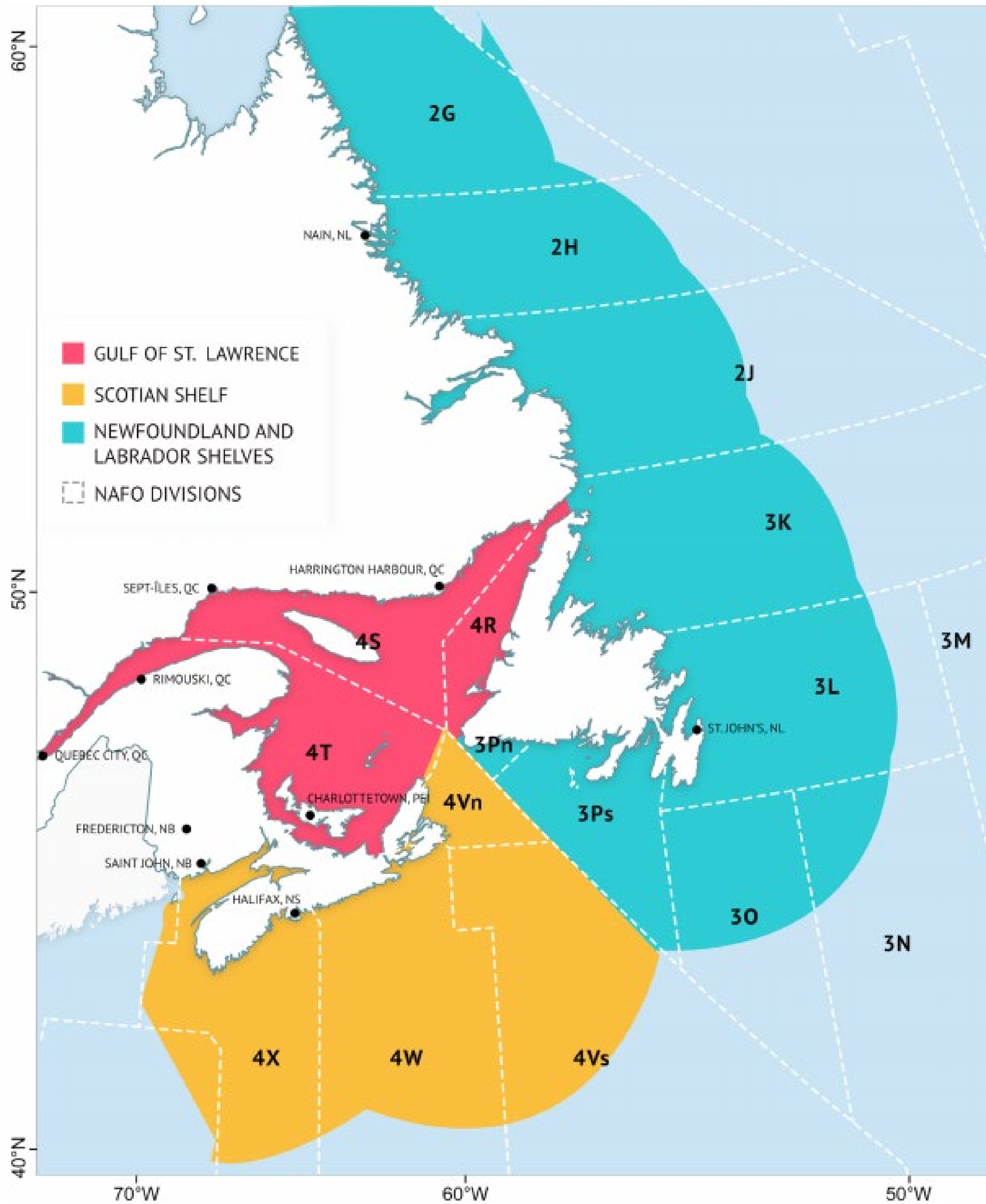


Figure 6. Three bioregions of Atlantic Canada. The bioregions are defined by ocean condition and depth (DFO 2019b). The regions are also delineated by the Northwest Atlantic Fisheries Organization divisions.

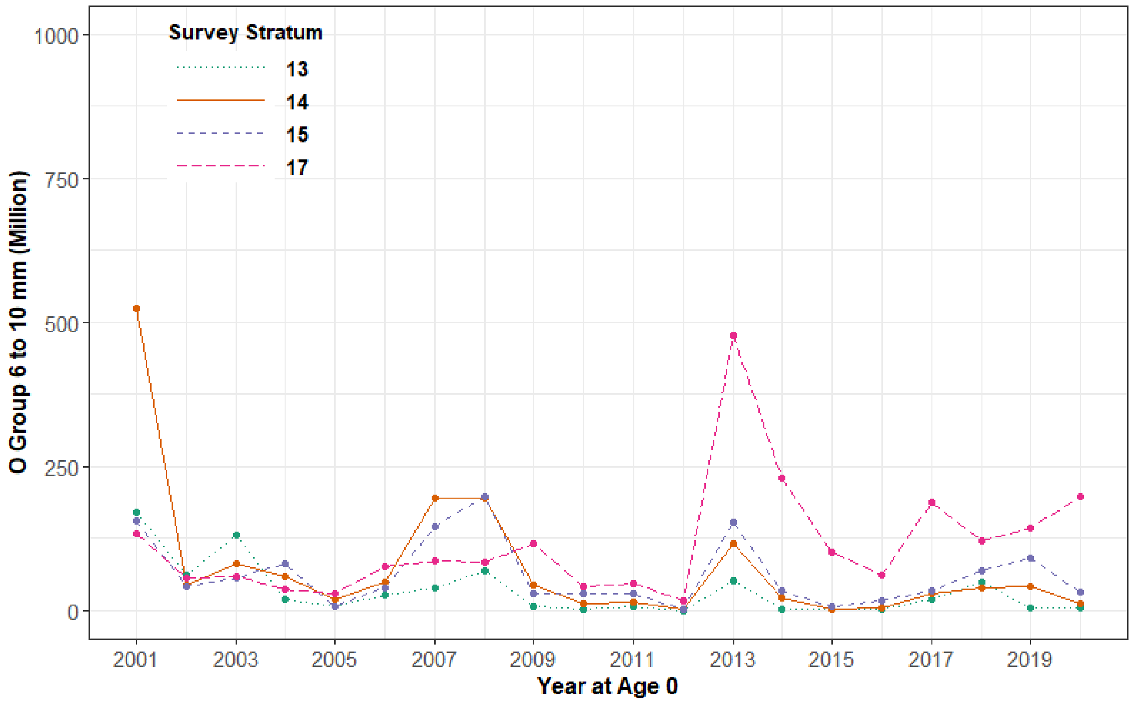


Figure 7. Annual Eastern Scotian Shelf Northern Shrimp (6 mm to 10 millimetres (mm)) recruitment for Year at Age 0 collected from belly bag set samples on the DFO-Industry collaborative survey, 2001–20. Sum of results of 15 sets per stratum per year.

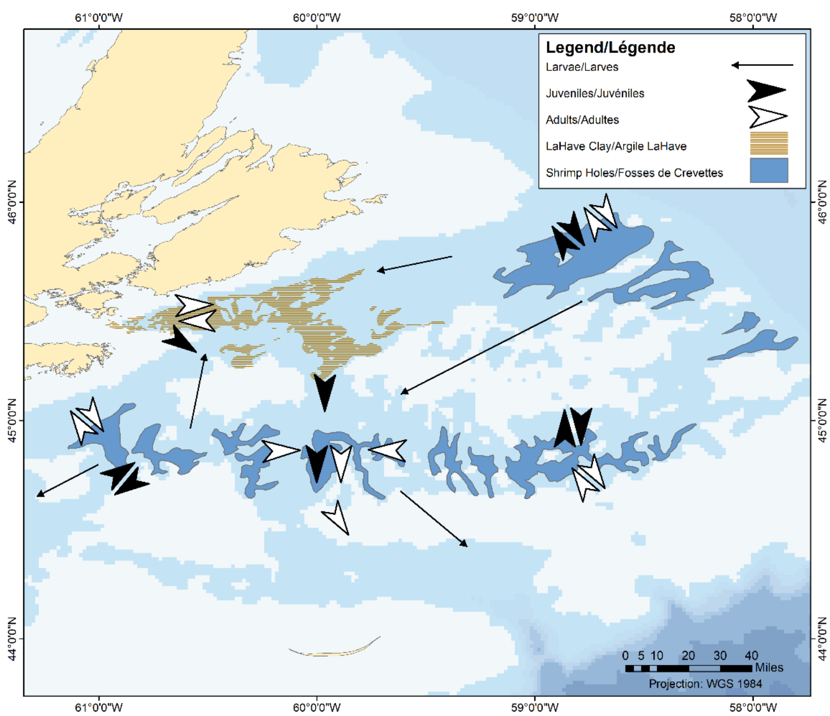


Figure 8. Hypothetical Northern Shrimp movements at different life cycle stages across the Eastern Scotian Shelf. Inshore movements are also characterized by the presence of LaHave clay habitat. Map modified from Koeller (1996).

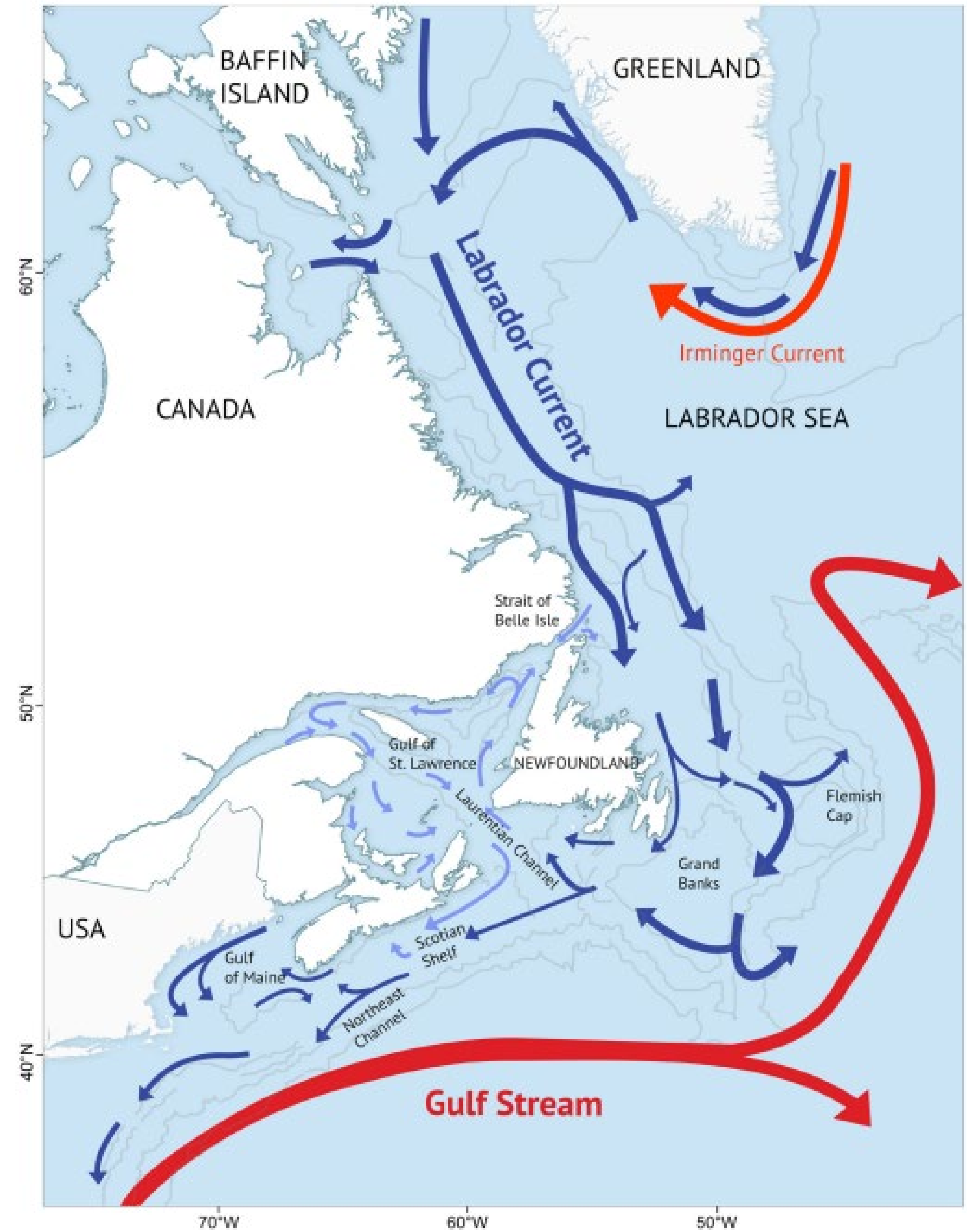


Figure 9. Dominant ocean currents in the offshore of Atlantic Canada. The Labrador Current transports colder Arctic water from the north and along the Scotian Shelf, while the Gulf Stream transports warmer water towards the east and northward past the Grand Banks (DFO 2019b).

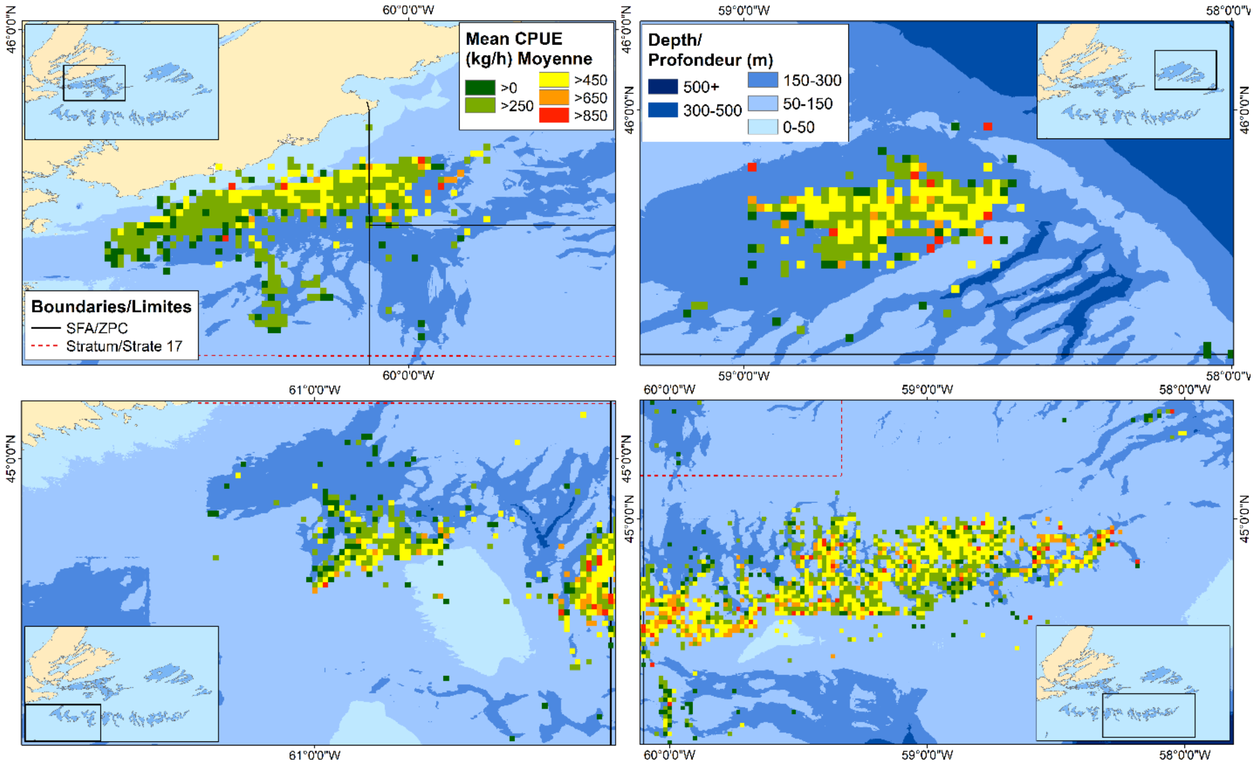


Figure 10. Spatial distribution of Eastern Scotian Shelf Northern Shrimp commercial fleet mean catch per unit effort (CPUE) in kilograms per hour (kg/hr) from 2010 to 2020. Depth (m) is indicated. SFA = Shrimp Fishing Area.

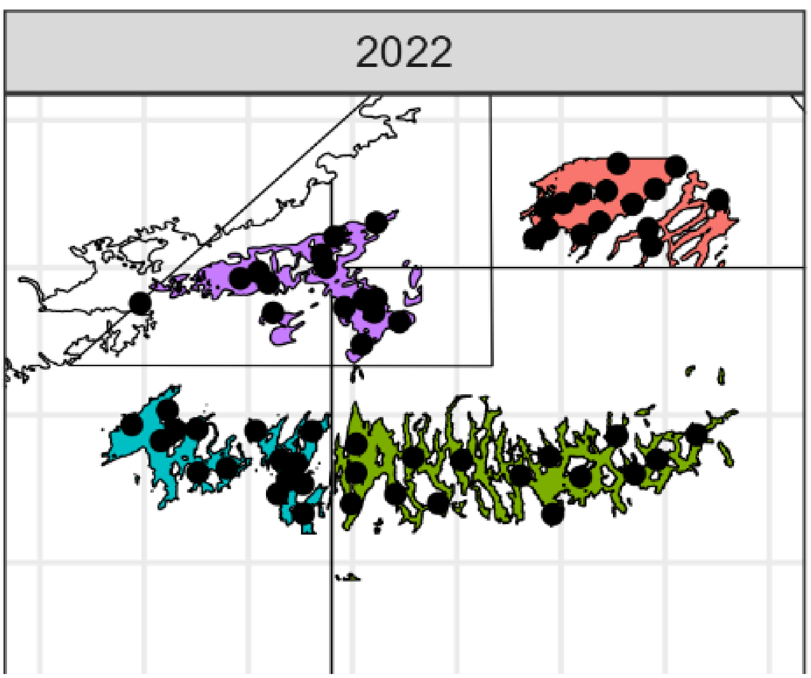


Figure 11. Example of survey locations (black points) in 2022 associated with each survey strata: Stratum 13 at the top right in red, Stratum 14 at the bottom right in green, Stratum 15 in the bottom left in teal, and stratum 17 in the top right in purple.

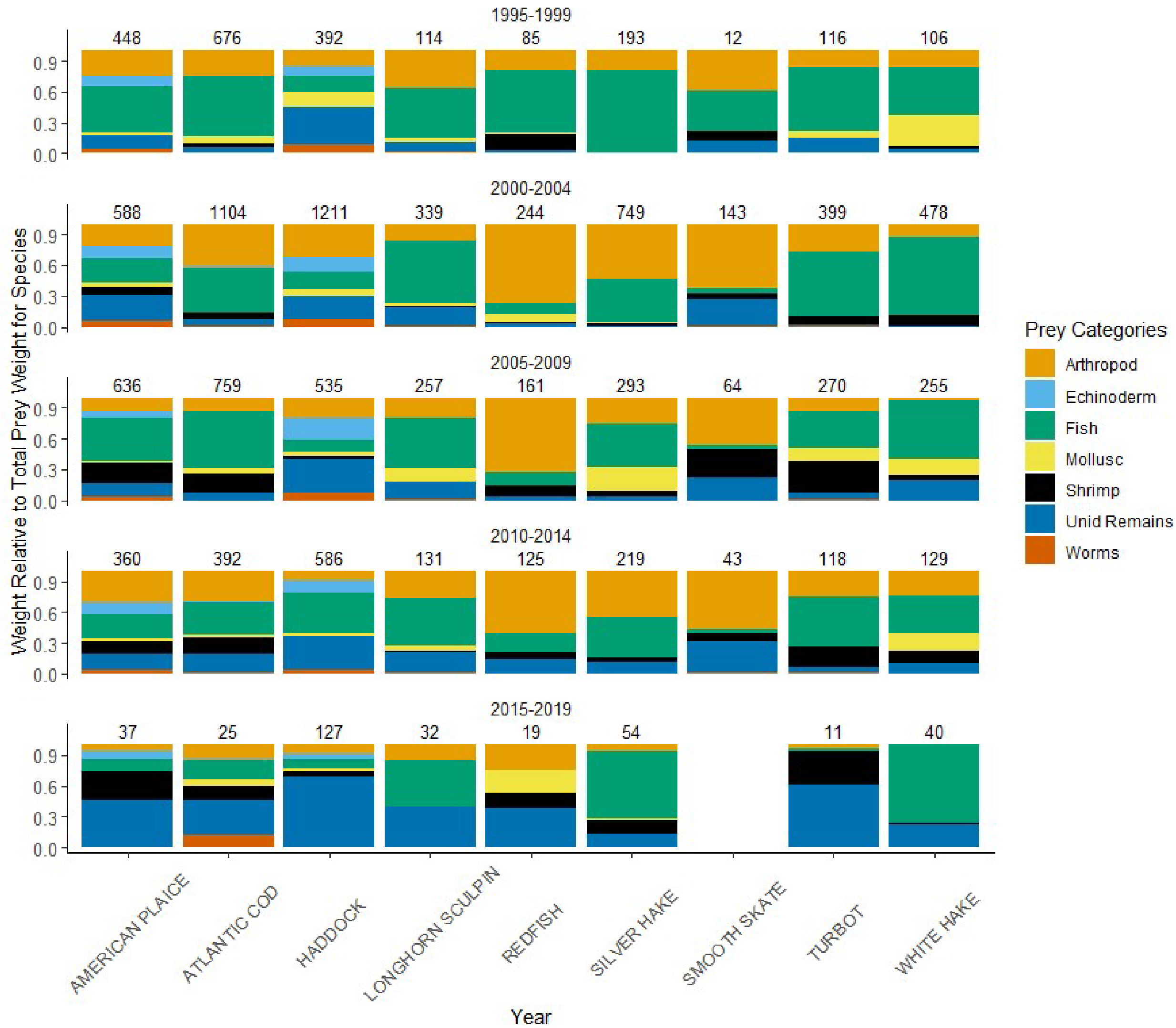


Figure 12. Relative weight of shrimp compared to other prey found in finfish across fish predators sampled from the DFO Summer Research Vessel Ecosystem trawl survey from 1995 to 2019. Number of stomachs sampled in each analysis is indicated above each column.

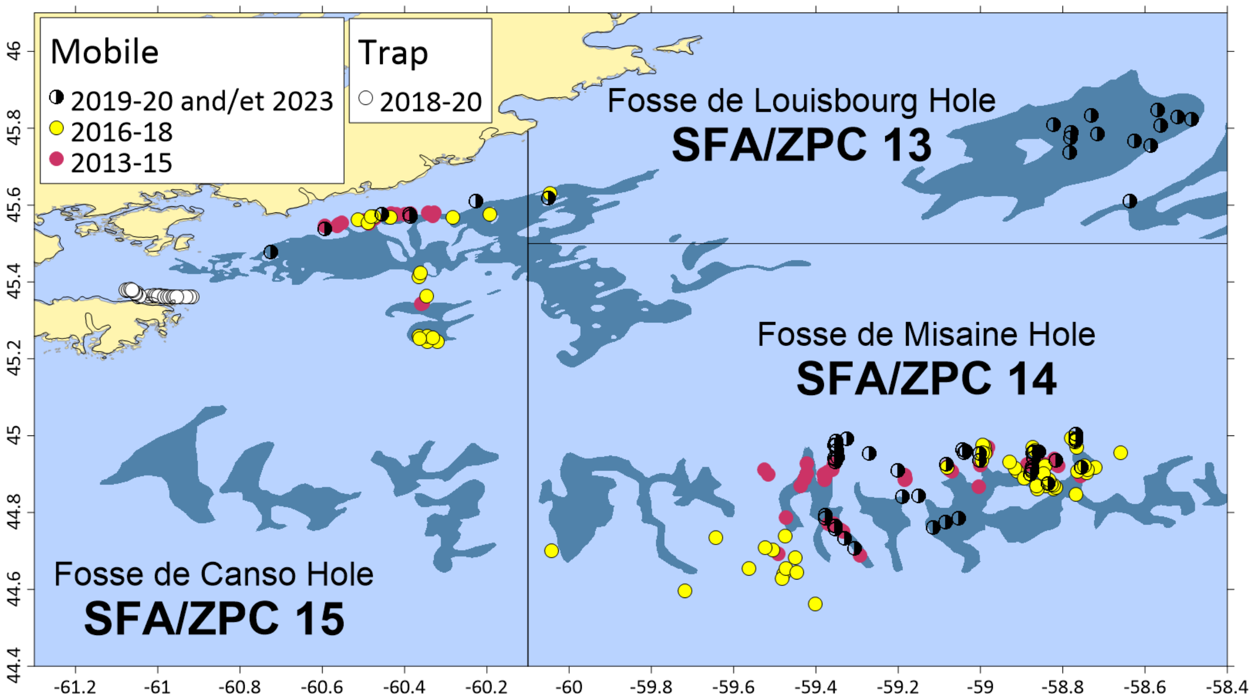


Figure 13. At-sea Observer sampling distribution from 2013 to 2023 for the Eastern Scotian Shelf Northern Shrimp mobile and trap sector. SFA = Shrimp Fishing Area.

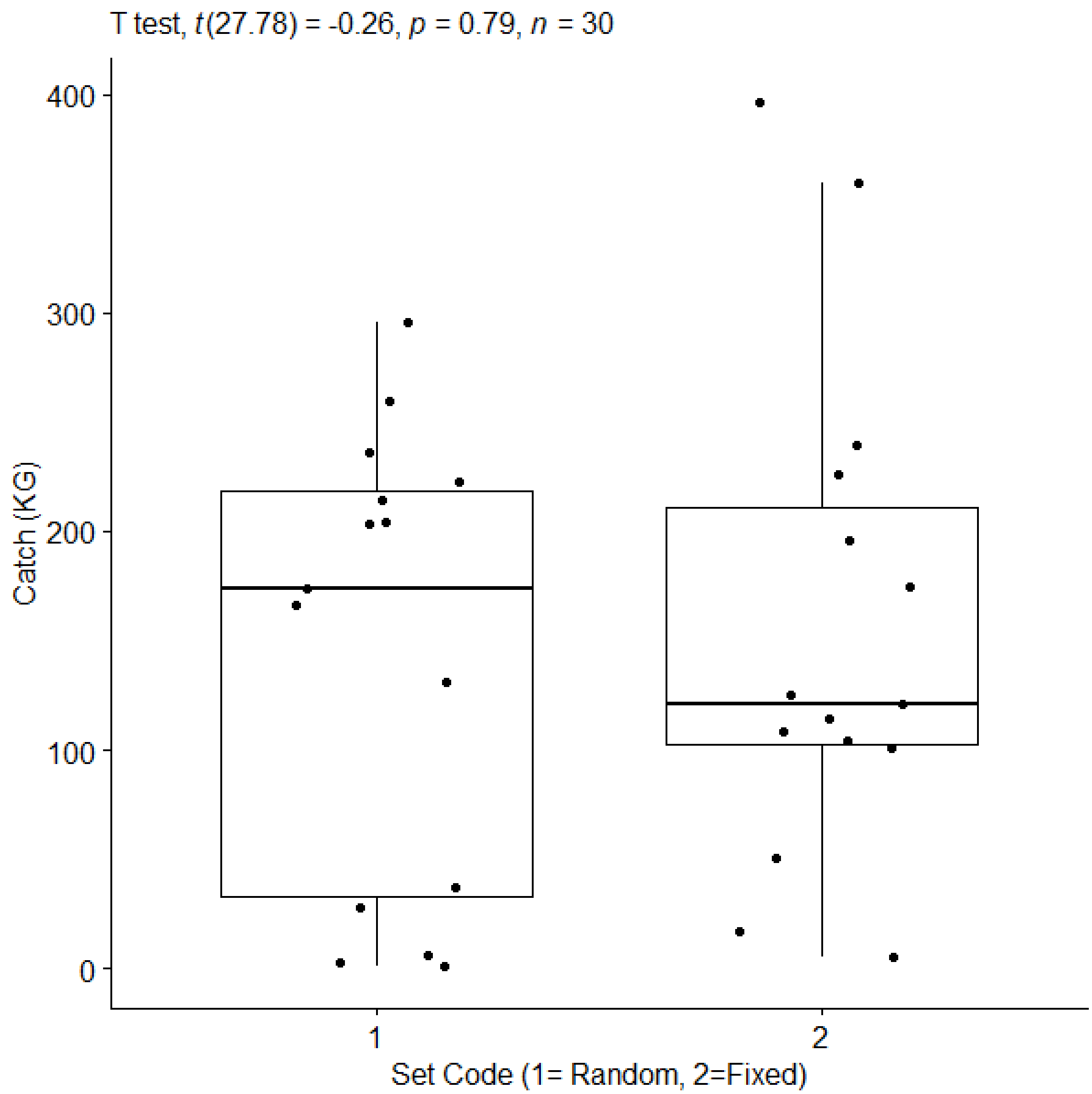


Figure 14. Boxplots and results of t-test comparing fixed and randomized stations in Stratum 14 in 2023.

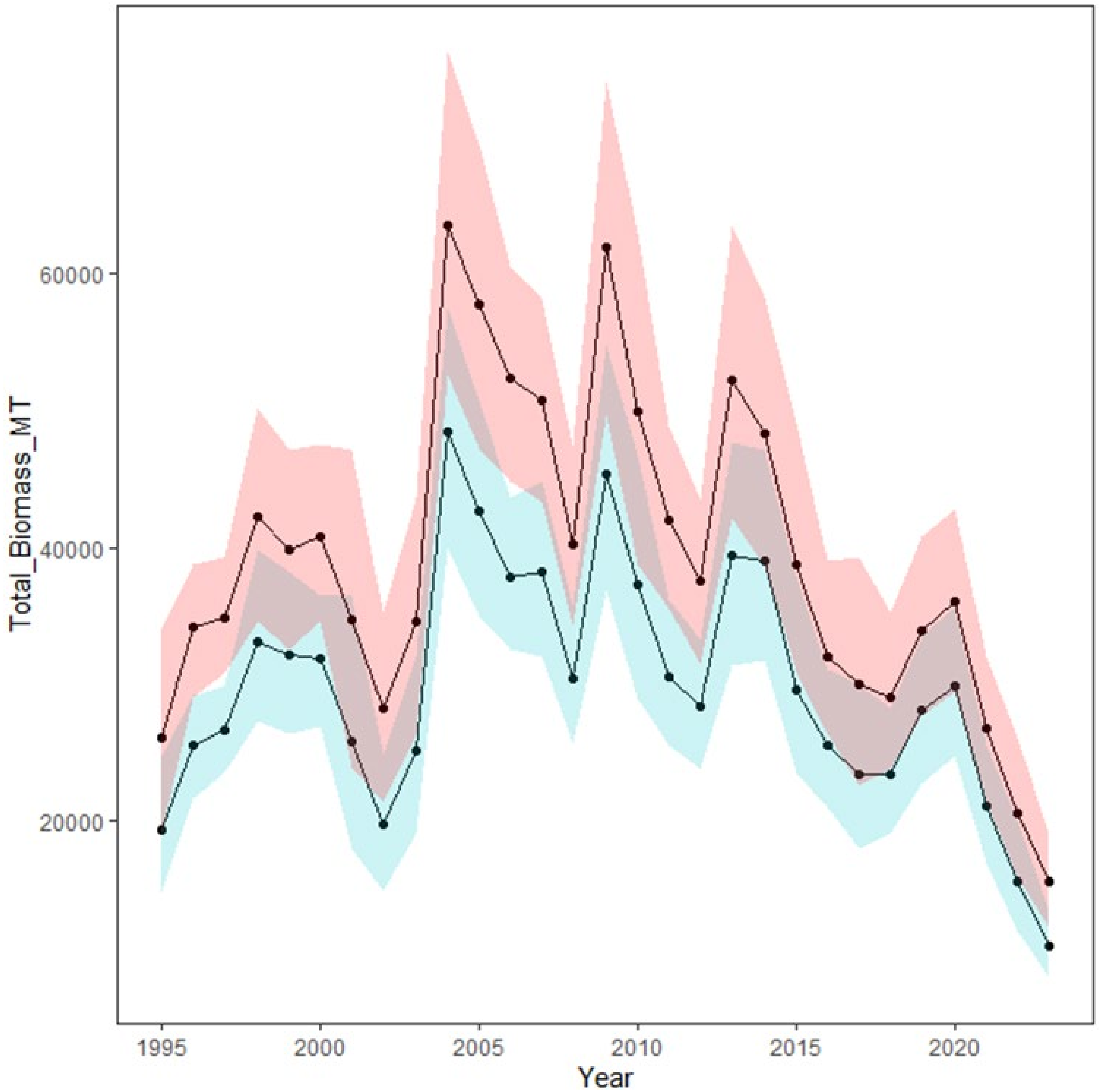


Figure 15. Total Northern Shrimp swept area biomass estimate, in metric tonnes, calculated from the DFO-Industry collaborative surveys from 1995 to 2023 using the old areas (turquoise) and the updated shapefile areas (red).

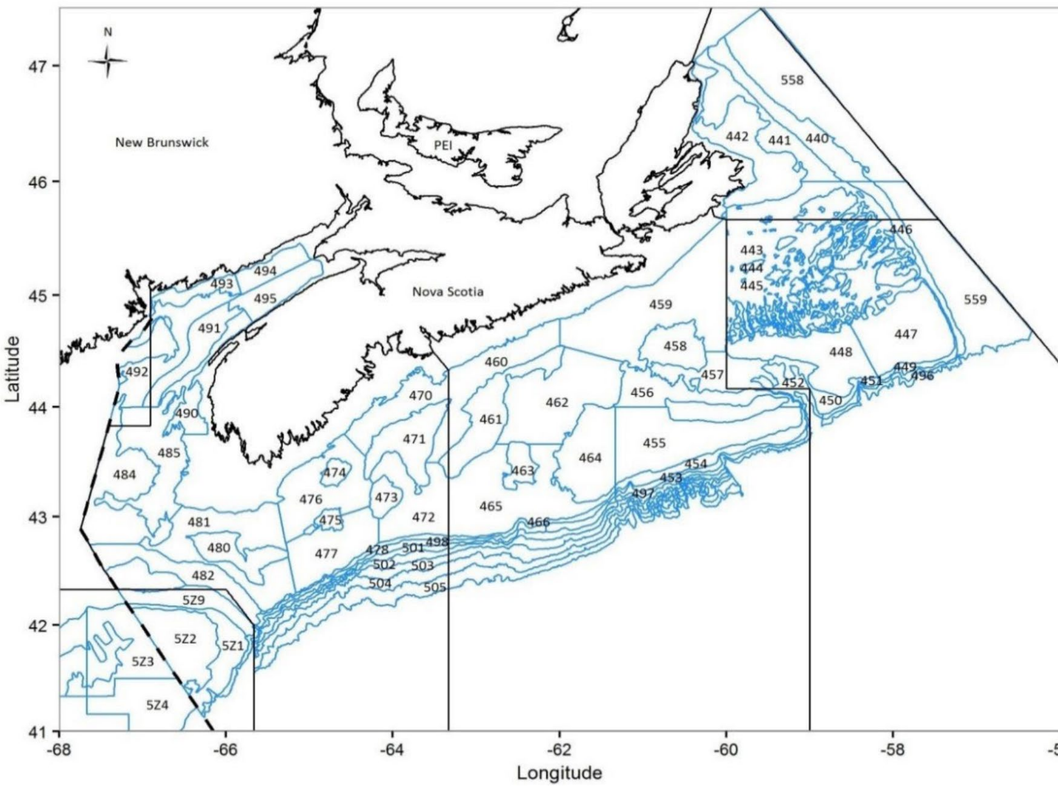


Figure 16. The DFO Summer Ecosystem Research Vessel trawl survey strata replicated from DFO (2024a).

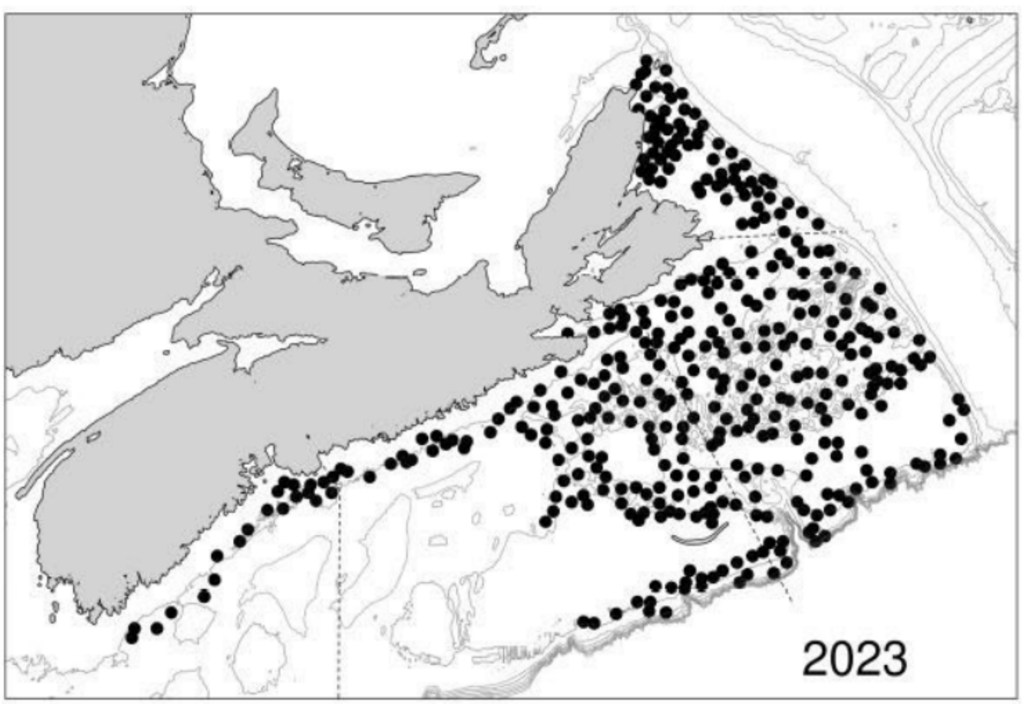


Figure 17. Snow Crab survey station locations from 2023 replicated from DFO (2024b).

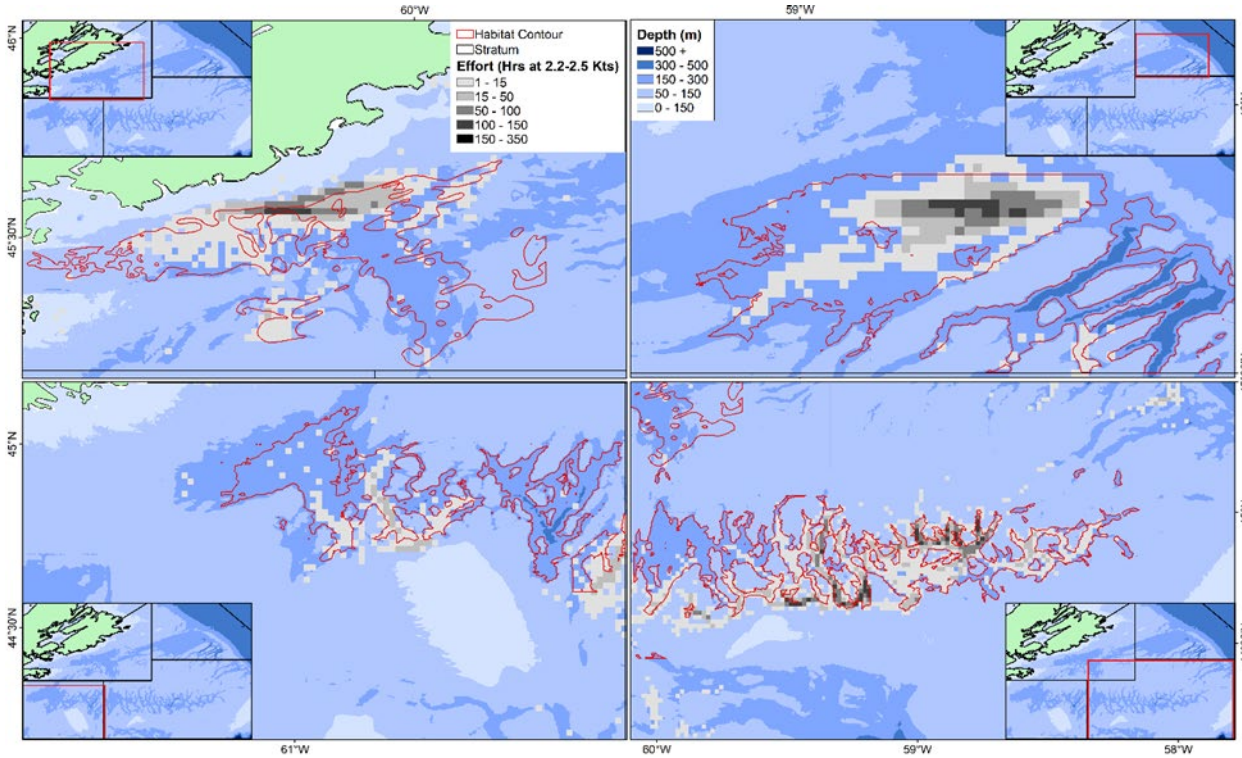


Figure 18. Vessel monitoring system spatial distribution of Eastern Scotian Shelf Northern Shrimp fishery vessel activity between 2.2 and 2.5 knots (kt) across Shrimp Fishing Areas depth profile (m) from 2013 to 2023. Depth and sediment contours used in generating the randomized survey stations are indicated in red.

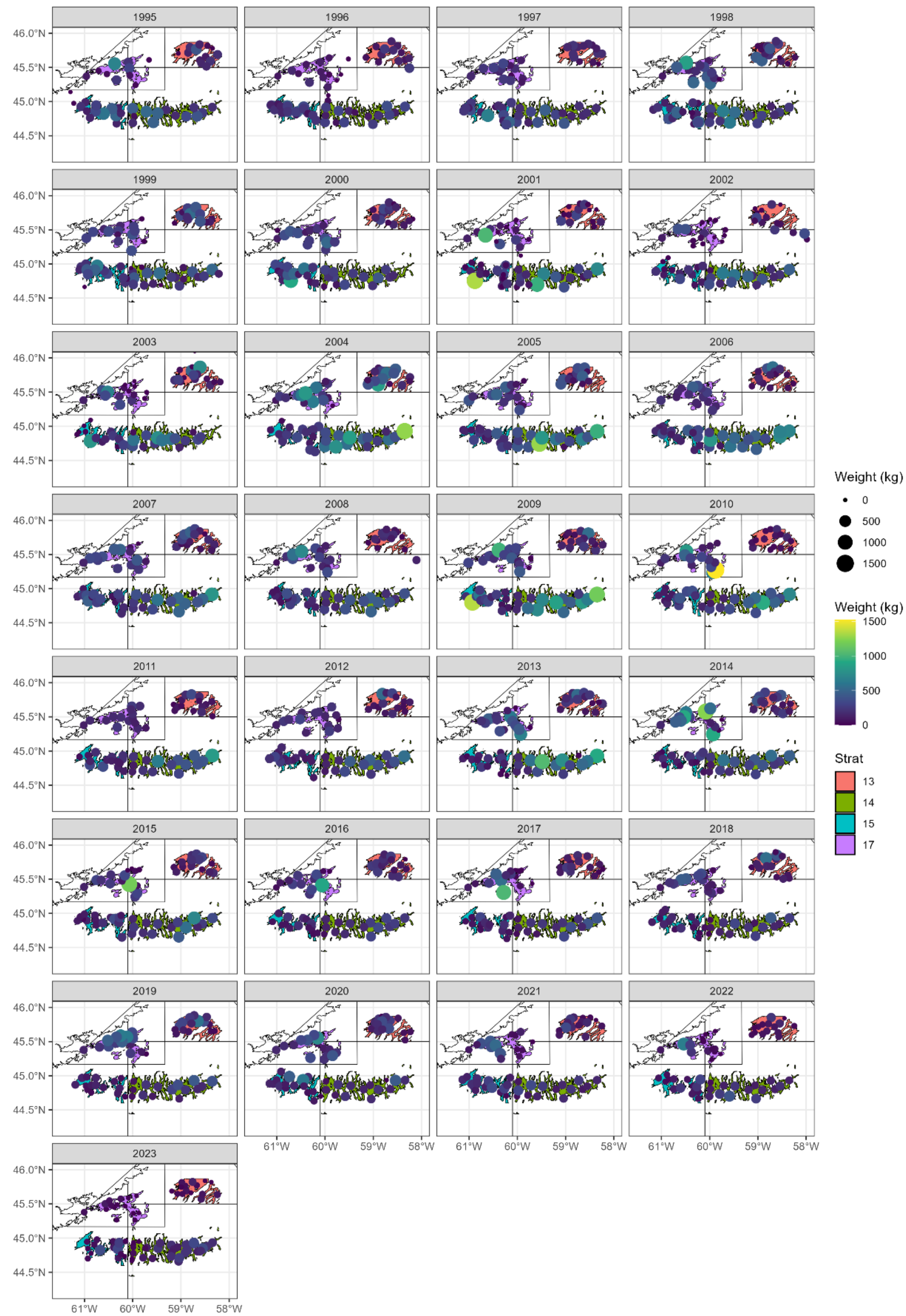


Figure 19. Total main trawl weight in kilograms (kg) within each tow from 2005 to 2023. Black lines denote land in the north-west, strata within each area, Shrimp Fishing Area divisions, and the inshore separation line.

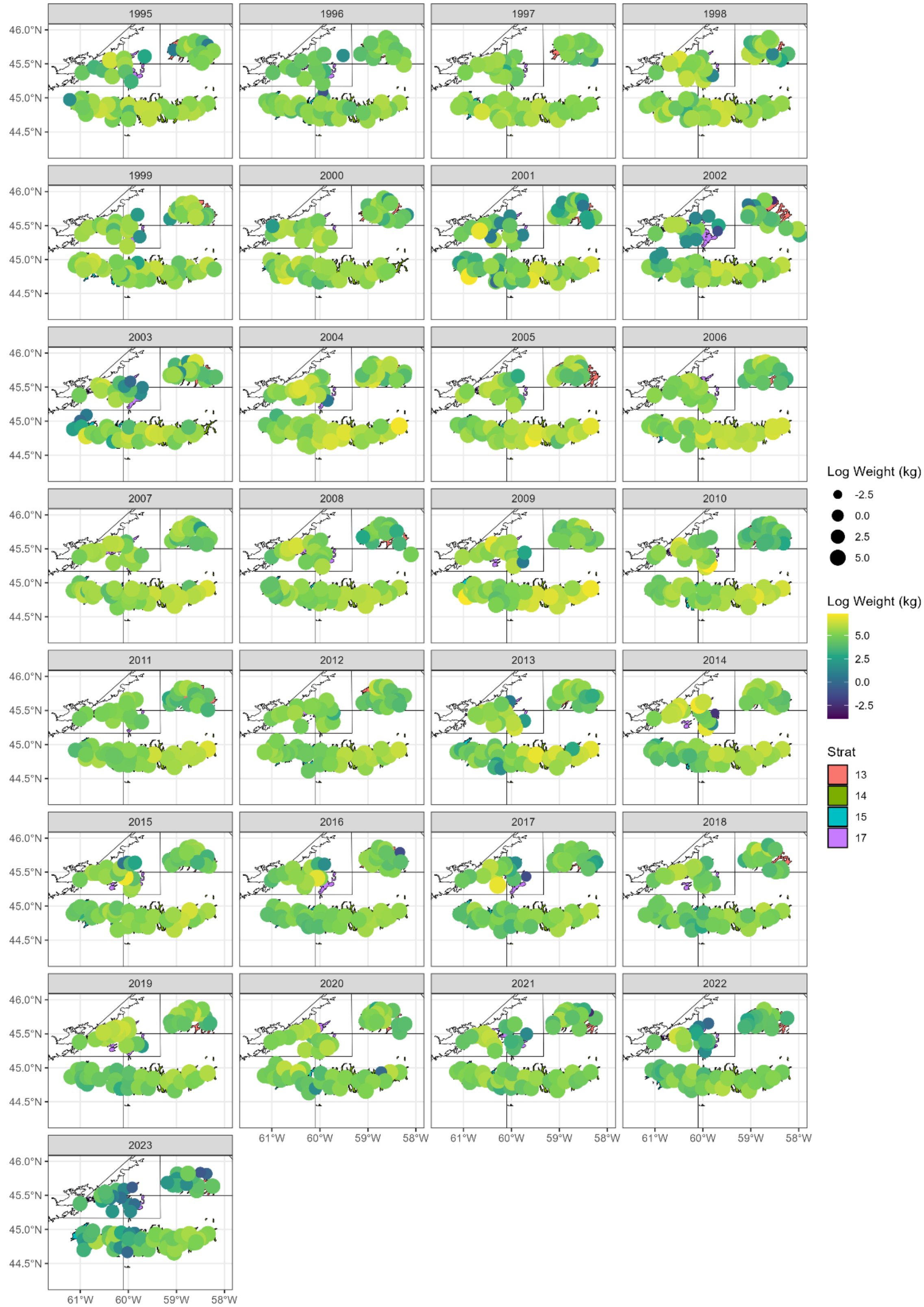


Figure 20. Log total main trawl weight in kilograms (kg) within each tow from 2005 to 2023. Black lines denote land in the north-west, strata within each area, Shrimp Fishing Area divisions, and the inshore separation line.

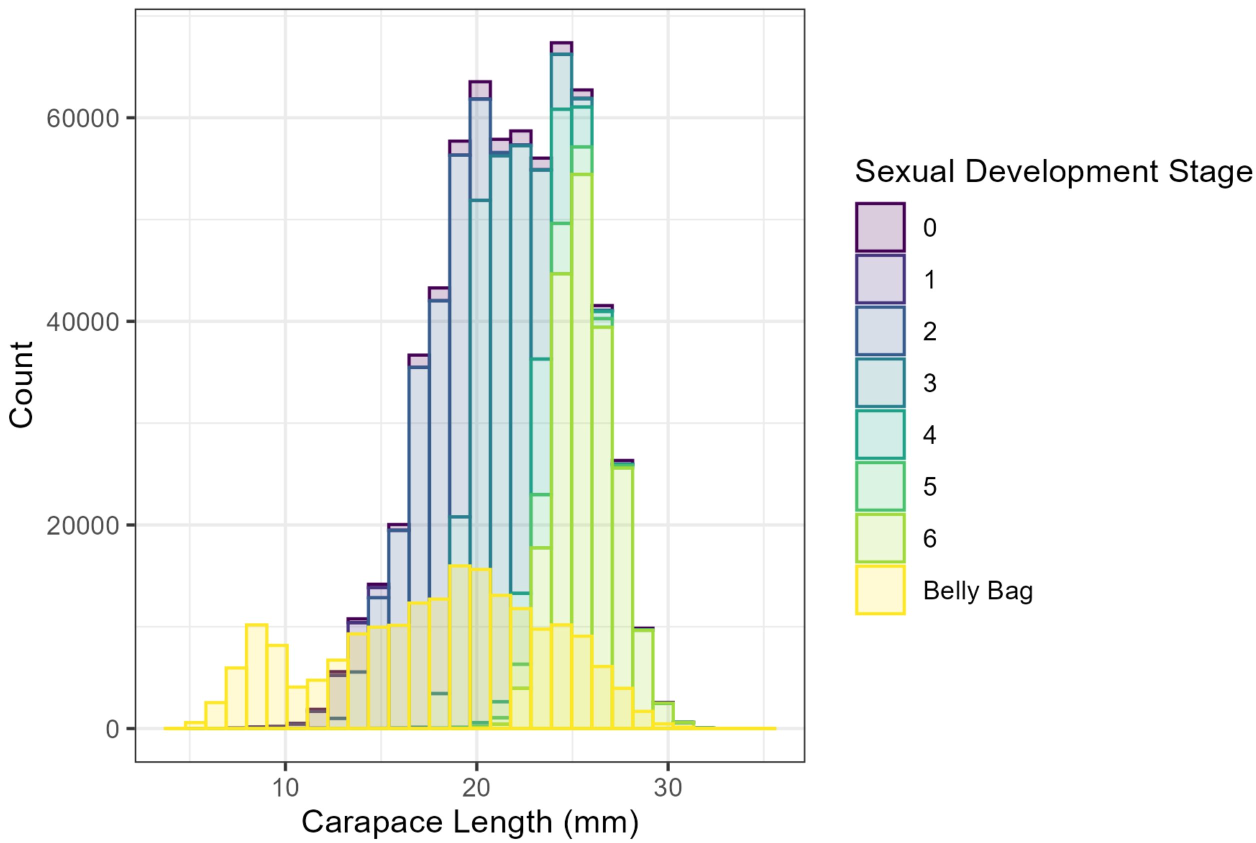


Figure 21. Histogram of carapace lengths, in millimetres (mm), of shrimps caught in the belly bag (yellow) overlaid on top of the histogram of carapace lengths of the shrimps in the detailed sample of the main trawl separated by sexual development stages (0 = not determined, 1 = juvenile, 2 = immature male, 3 = mature male, 4 = transitional, 5 = immature female, 6 = aggregate of all types of mature females).

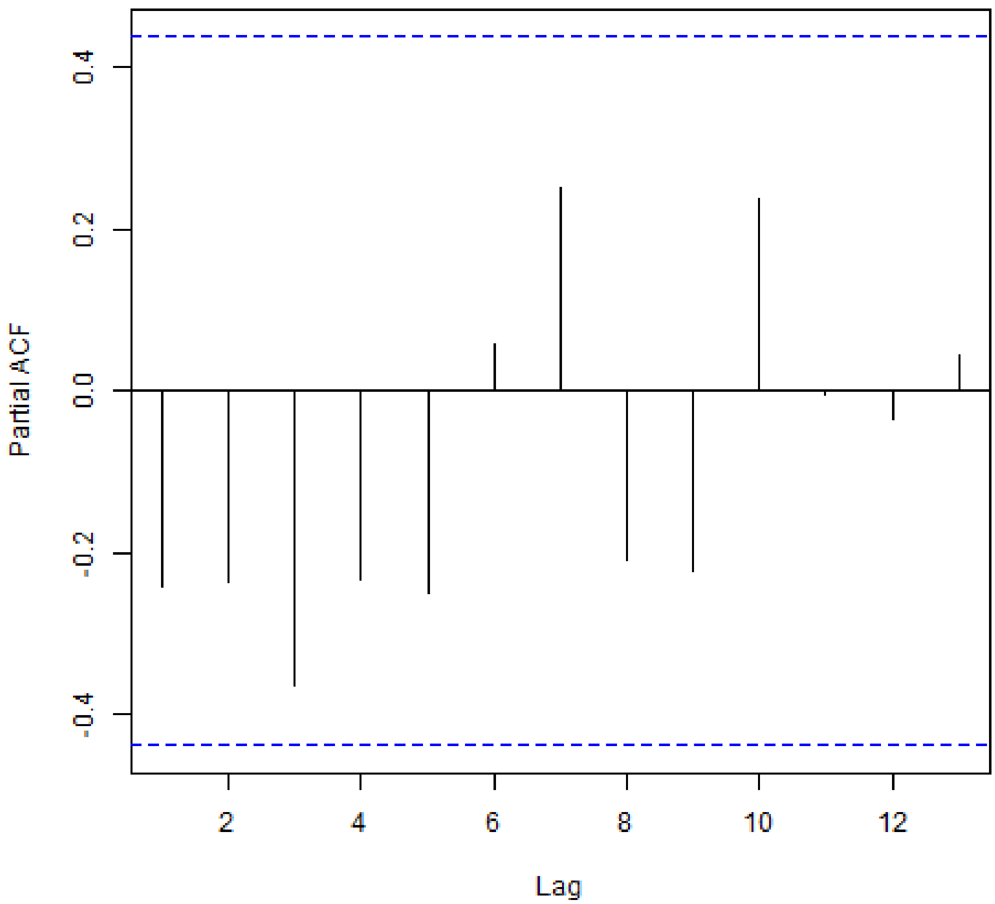


Figure 22. Partial autocorrelation function (ACF) for the recruitment process errors.

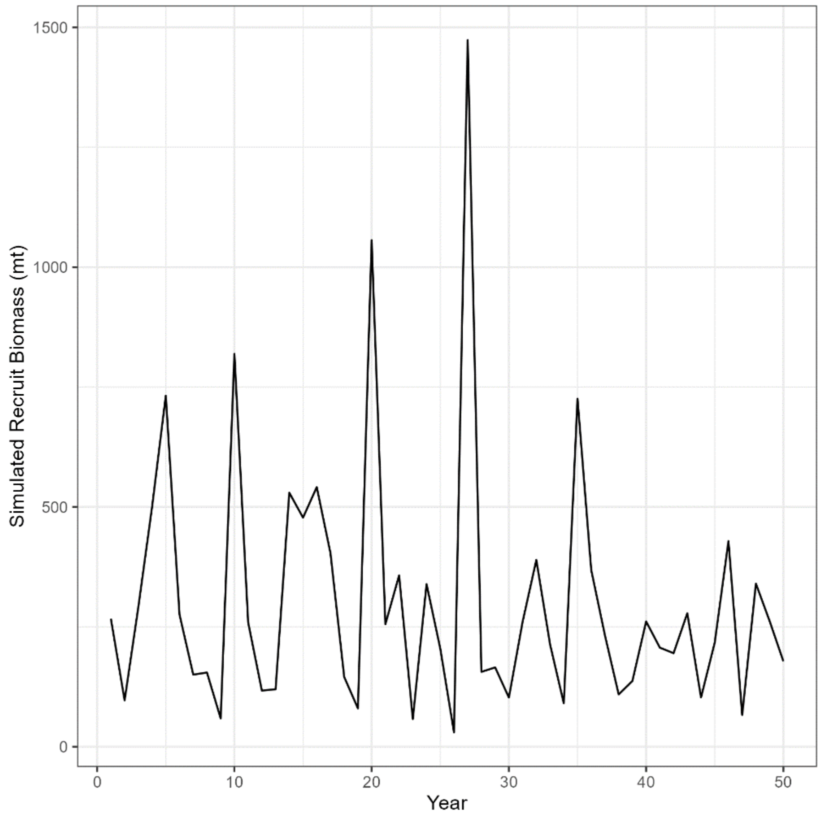


Figure 23. Example of the first 50-years of simulated biomass in metric tonnes (mt) from one iteration using the hockey stick method. The first 20 years shown here are the actual model estimates for reference.

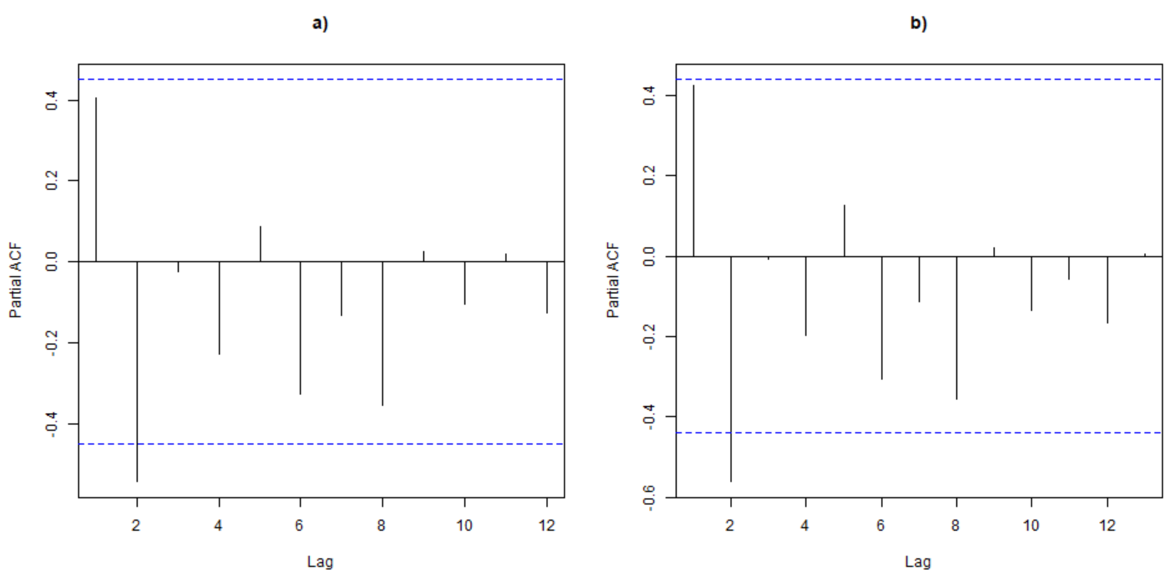


Figure 24. Partial autocorrelation function (ACF) for the main trawl growth rates (a) and the detrended main trawl growth rates (b).

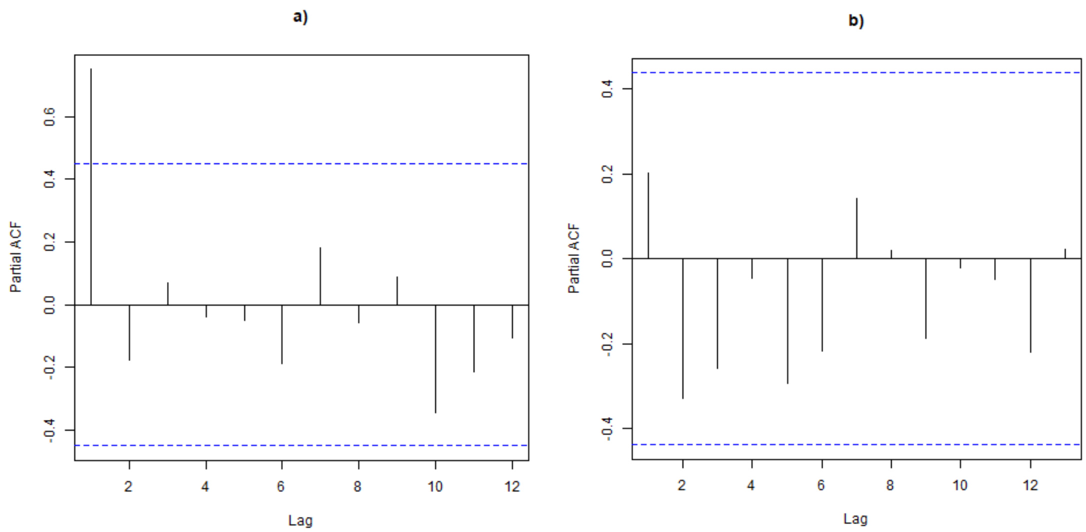


Figure 25. Partial autocorrelation function (ACF) for the recruit growth rates (a) and the detrended main trawl growth rates (b).

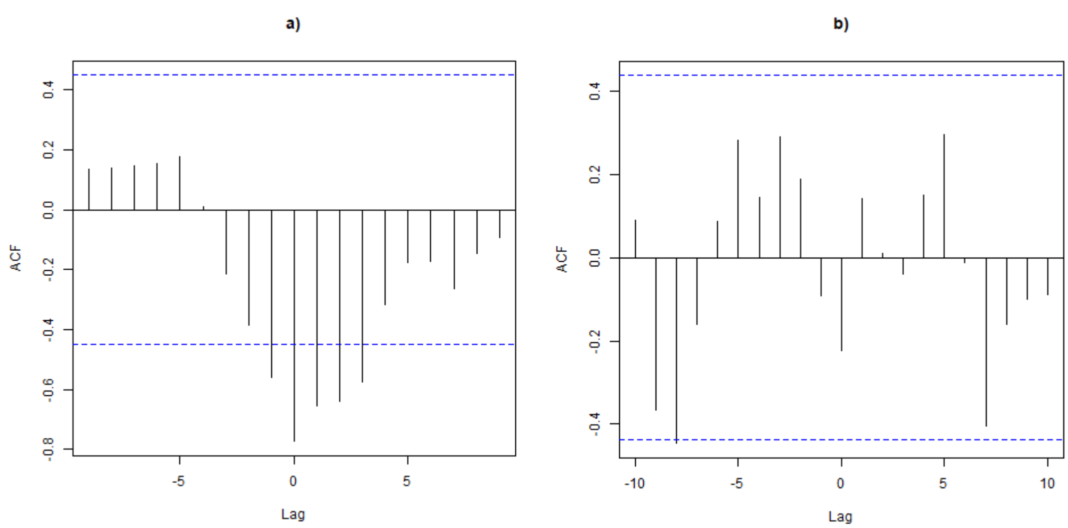


Figure 26. Cross autocorrelation function (ACF) between recruit growth rate and percent of biomass that is Spawning Stock Biomass (a) and after detrending both (b).

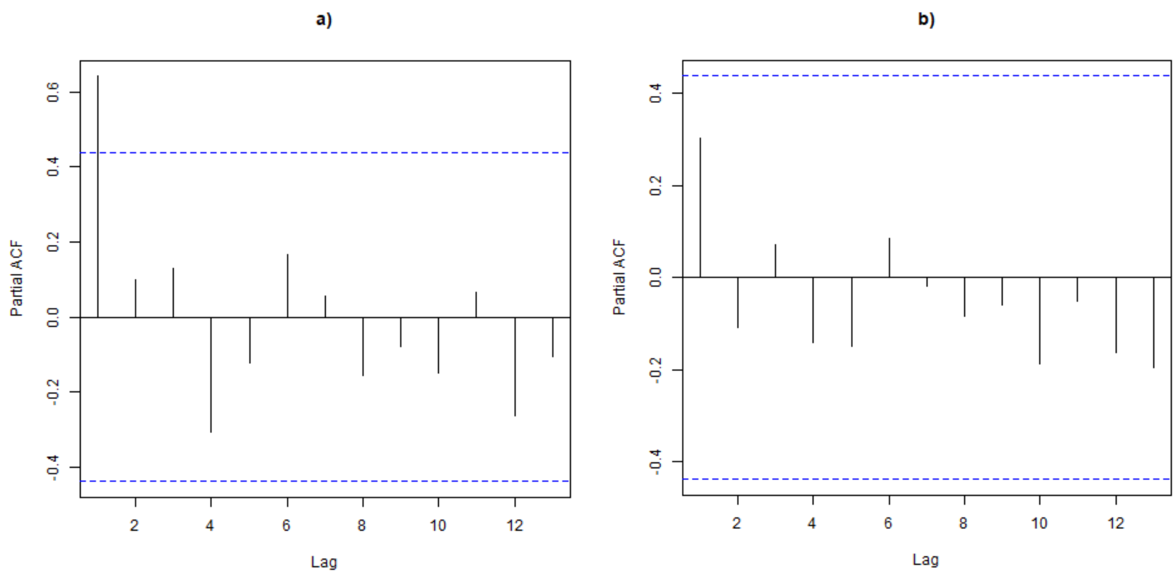


Figure 27. Partial autocorrelations function (ACF) for the percent of total biomass that is Spawning Stock Biomass with trend (a) and detrended (b).

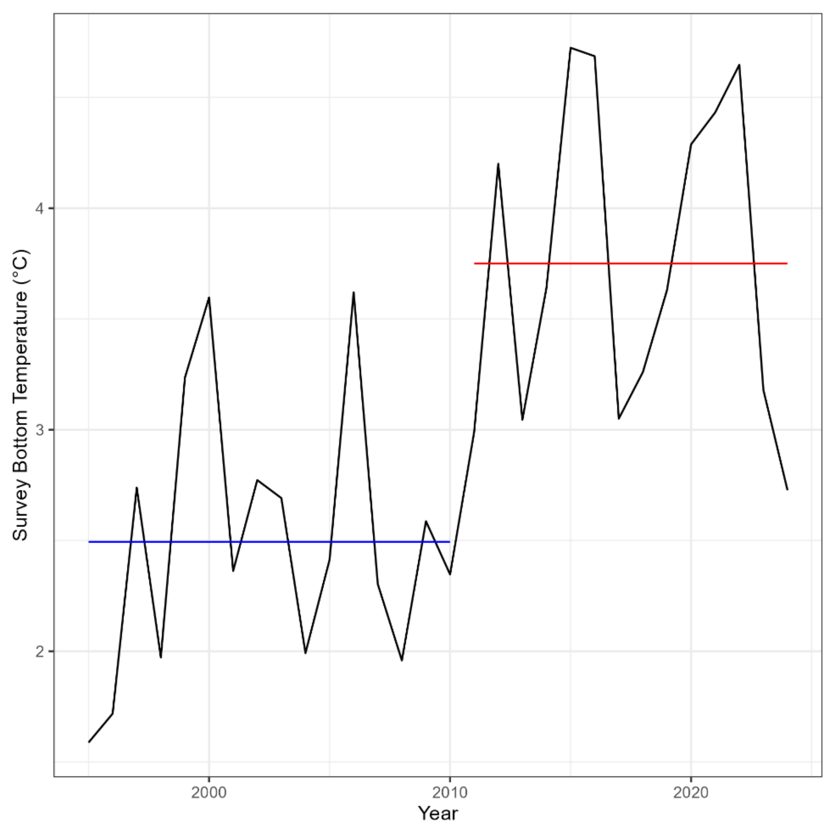


Figure 28. Average bottom temperatures, in degrees Celsuis (°C), recorded on the yearly shrimp survey in June (blue line is mean temperature between 1995 and 2010, red line is mean after 2010).

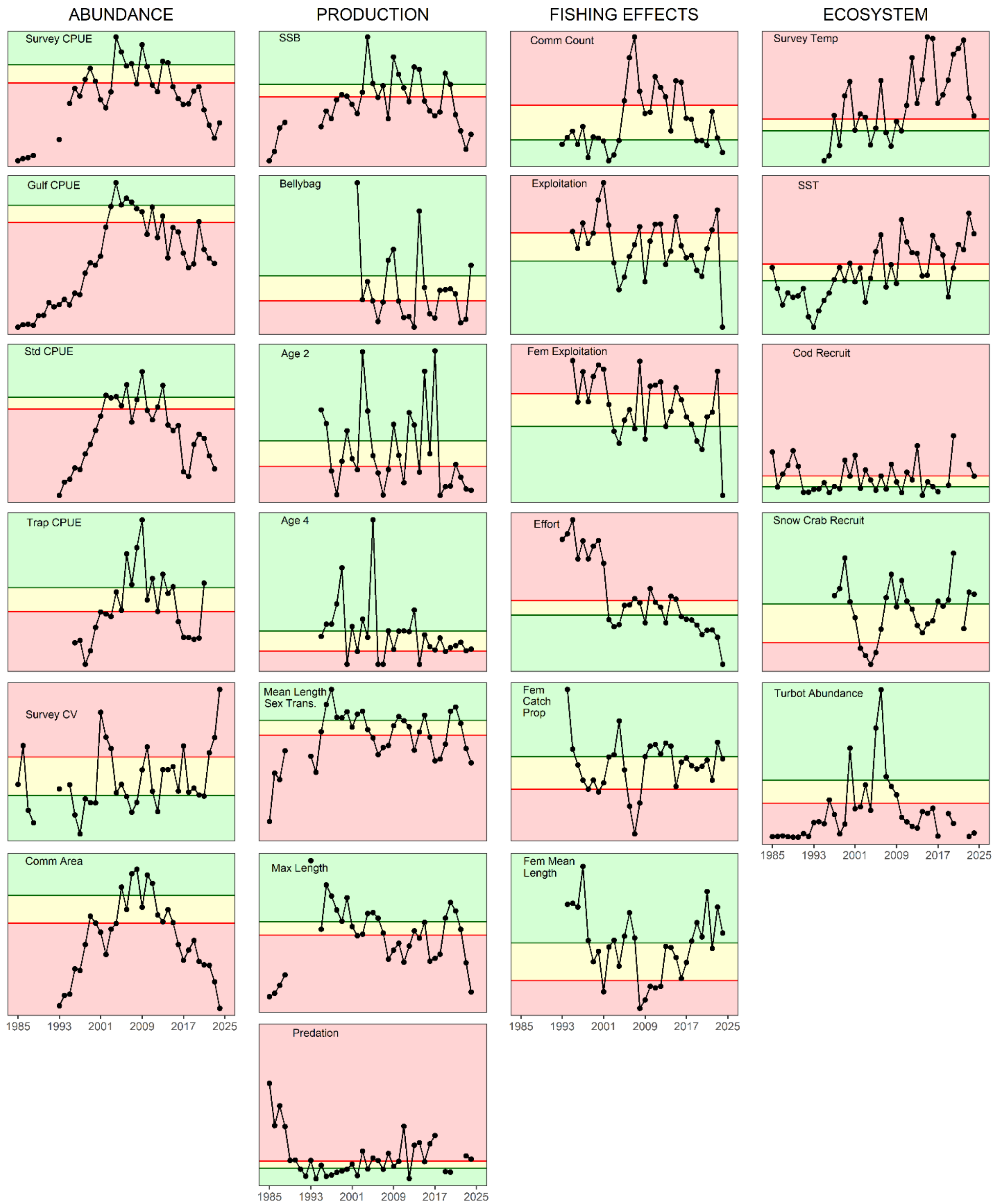


Figure 29. Time series of individual Eastern Scotian Shelf Northern Shrimp indicators prior to this new framework. Due to the limited number of active licenses and privacy rules associated with the Privacy Act, the three commercial catch per unit effort (CPUE) indicators (i.e., Gulf CPUE, Std CPUE, Trap CPUE) are not updated in 2024. SST = Sea Surface Temperature; Std CPUE = Maritimes mobile fleet standardized catch per unit effort index; Comm count = commercial counts of shrimp per pound.

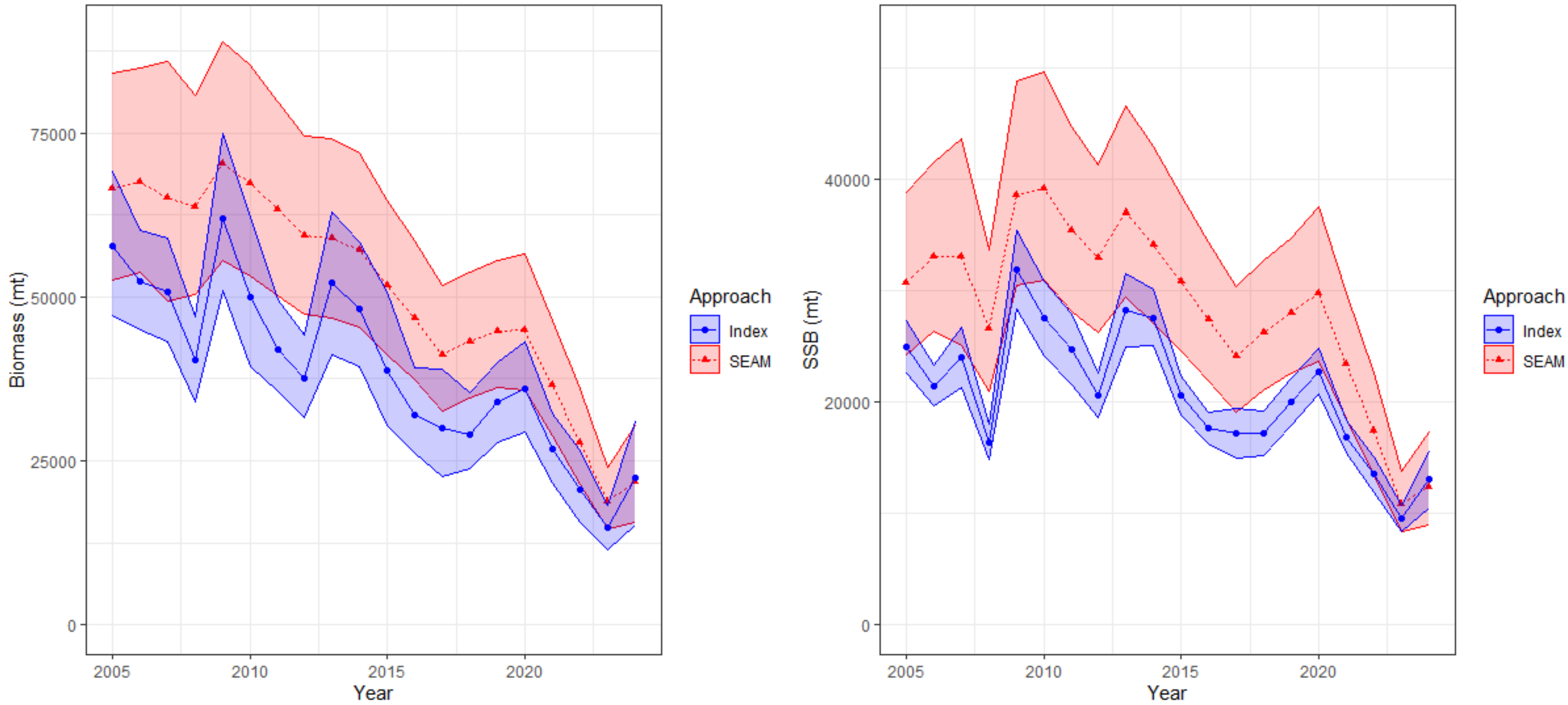


Figure 30. Total biomass in metric tonnes (mt) from 2005 to 2024 estimated using the swept-area index (blue circles, solid line) and by the Spatially Explicit Assessment Model (SEAM) (red triangles, dashed line) (left panel). Spawning stock biomass (SSB) in mt from 2005 to 2024 estimated using the swept-area index (blue circles, solid line) and by SEAM (red triangles, dashed line) (right panel).

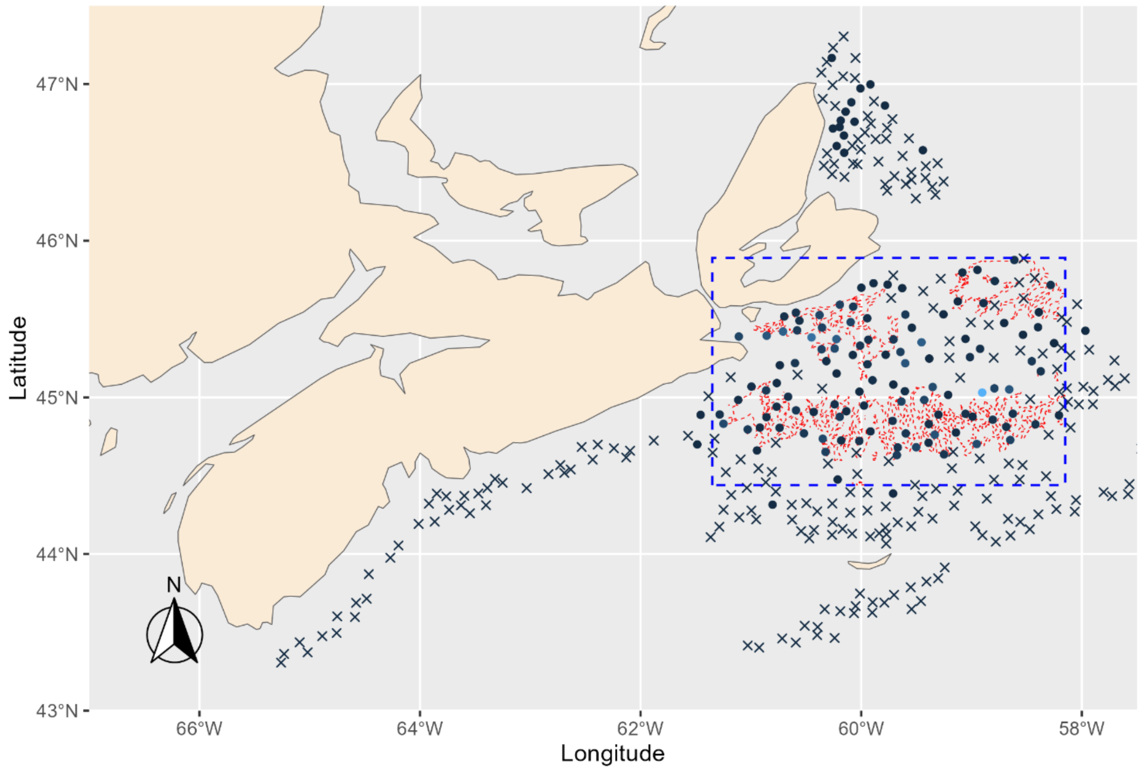


Figure 31. Snow Crab survey sets for 2024. Crosses denotes no shrimp caught while colored dots indicate presence of shrimp. The shrimp survey strata are denoted by the red polygon outlines, and the blue dashed box indicates all the survey tows utilized for the shrimp bycatch indicator. Figure credit: Amy Glass, DFO Snow Crab Unit.

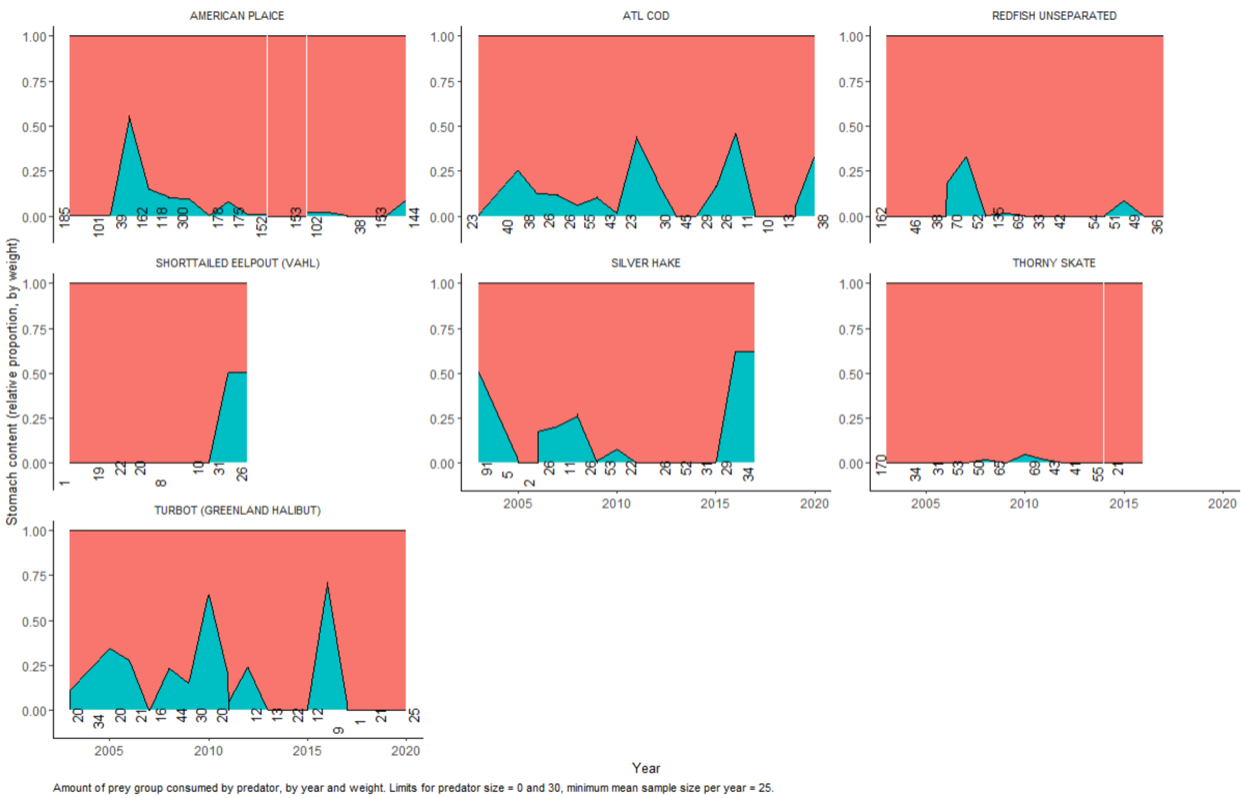


Figure 32. Relative proportion of pandalid species by weight (in blue) within stomach contents of various predators less than 30 centimetres long with at least 25 stomachs sampled per year on average. Number on x-axis indicates sample size in that year.

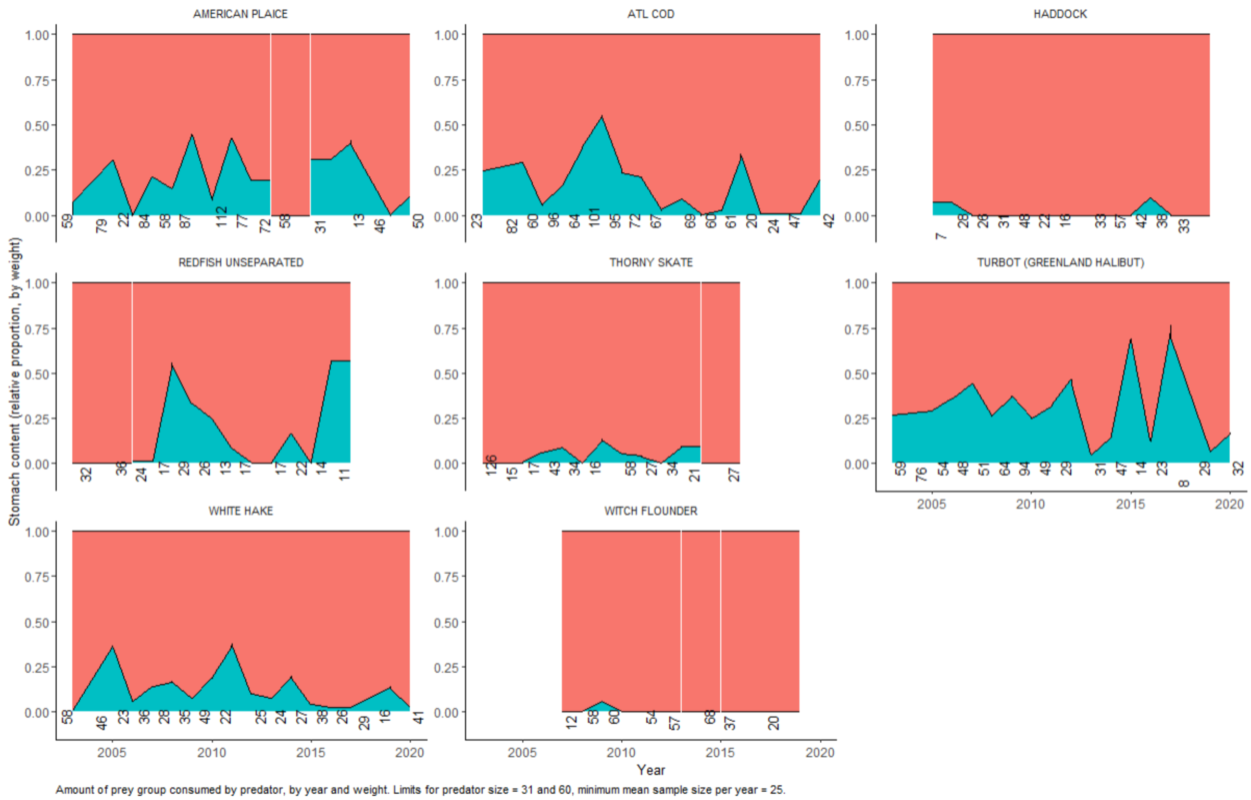


Figure 33. Relative proportion of pandalid species by weight (in blue) within stomach contents of various predators between 30 and 60 centimetres long with at least 25 stomachs sampled per year on average. Number on x-axis indicates sample size in that year.

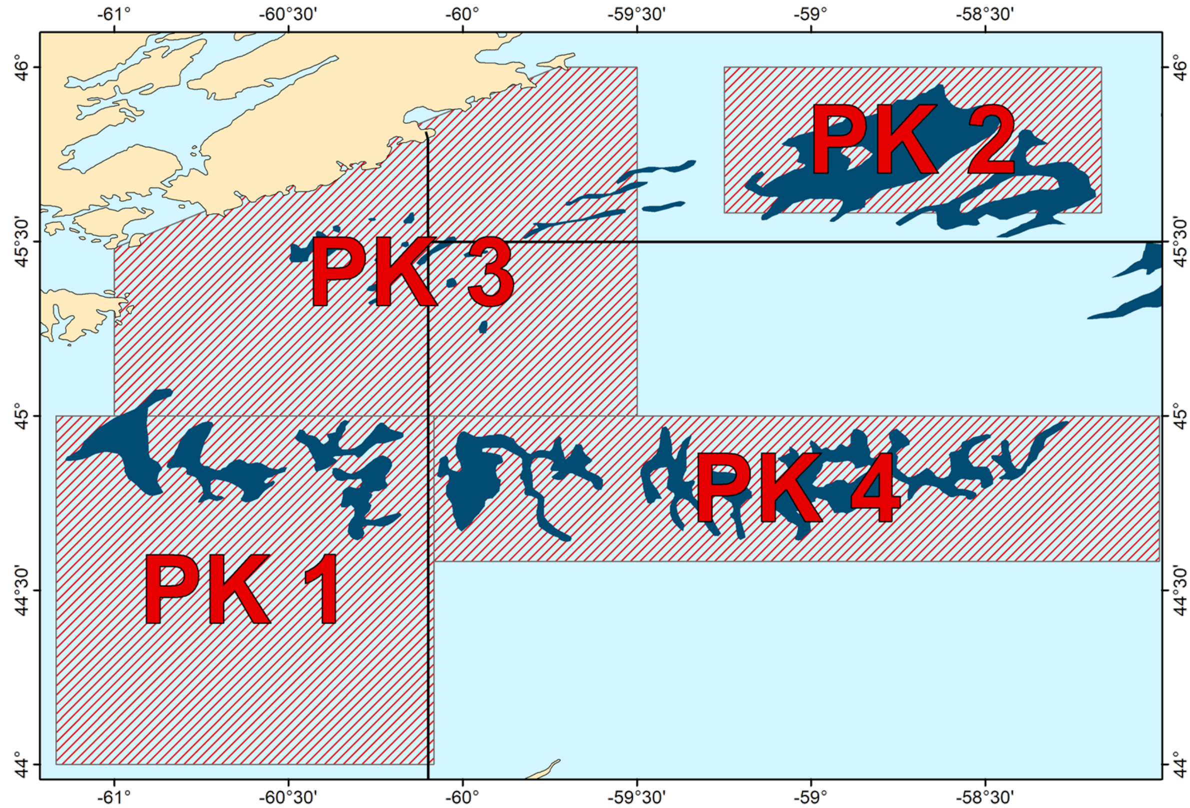


Figure 34. Coverage of satellite data utilized for the calculations of the sea surface temperatures.

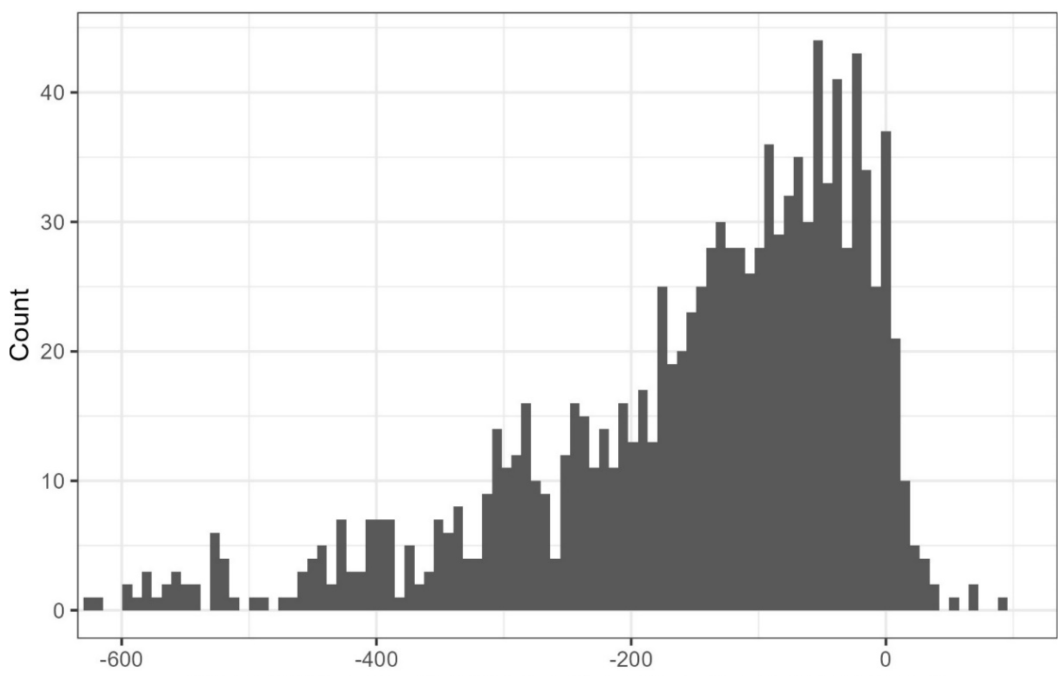


Figure 35. Histogram of the weight difference in kilograms (kg) between the greater than 10 millimetre shrimp caught in the belly bag scaled up to match the width (area) of the main trawl net and the main trawl biomass corrected for the belly bag length frequency.

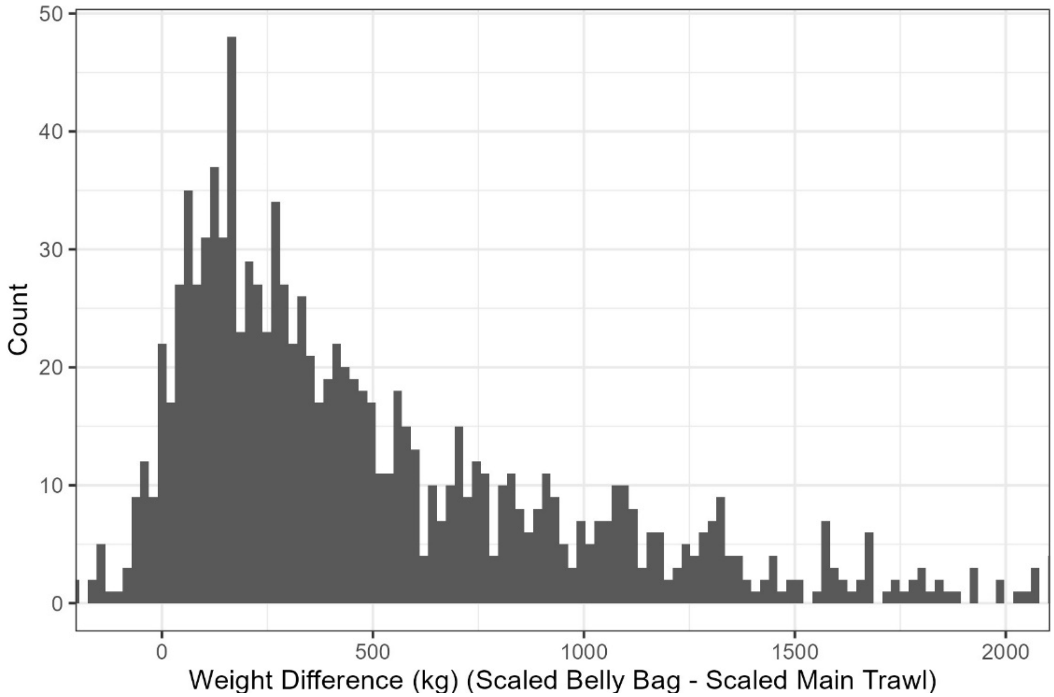


Figure 36. Histogram of the weight difference in kilograms (kg) between the greater than 10 millimetre shrimp caught in the belly bag scaled up to match the width and height (volume) of the main trawl net and the main trawl biomass corrected for the belly bag length frequency.

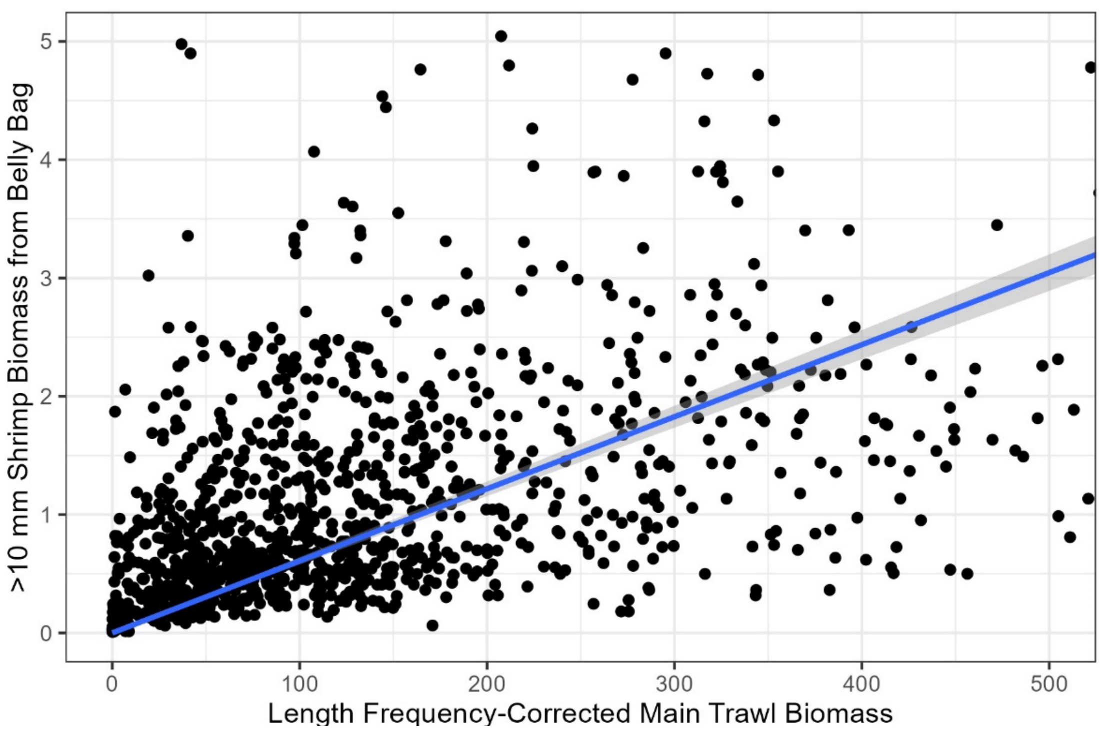


Figure 37. Scatterplot of length frequency-corrected main trawl biomass against greater than 10 millimetre (mm) shrimp biomass from belly bag, with linear regression line in blue.

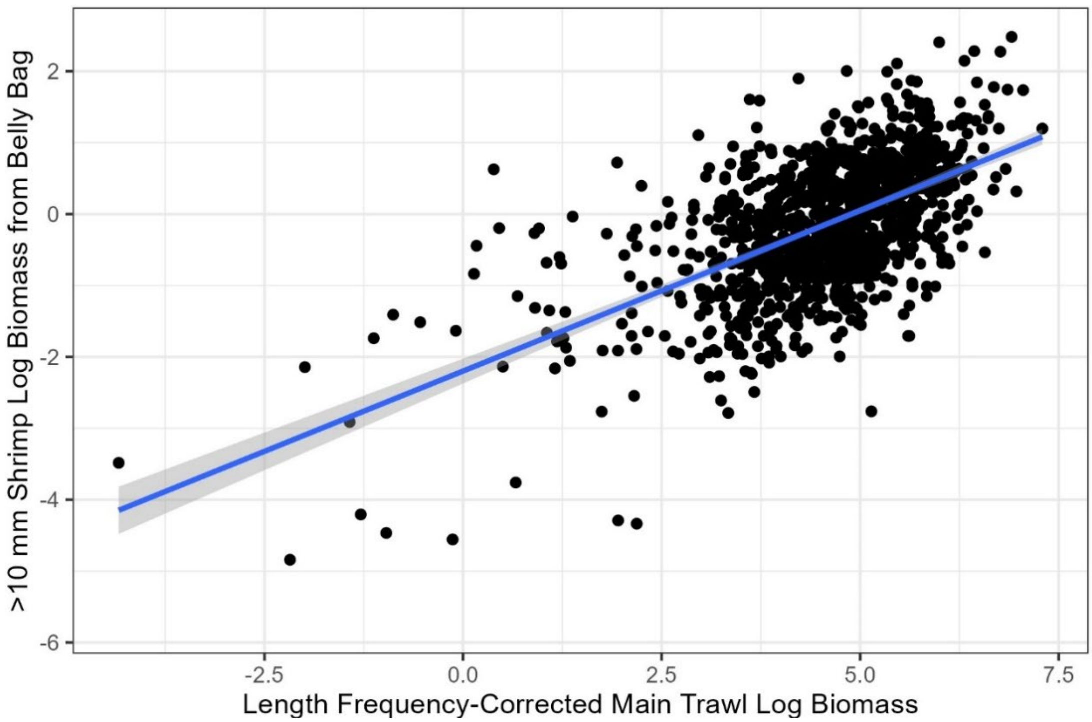


Figure 38. Scatterplot of length frequency-corrected main trawl log biomass against greater than 10 millimetre (mm) shrimp log biomass from belly bag, with linear regression line in blue.

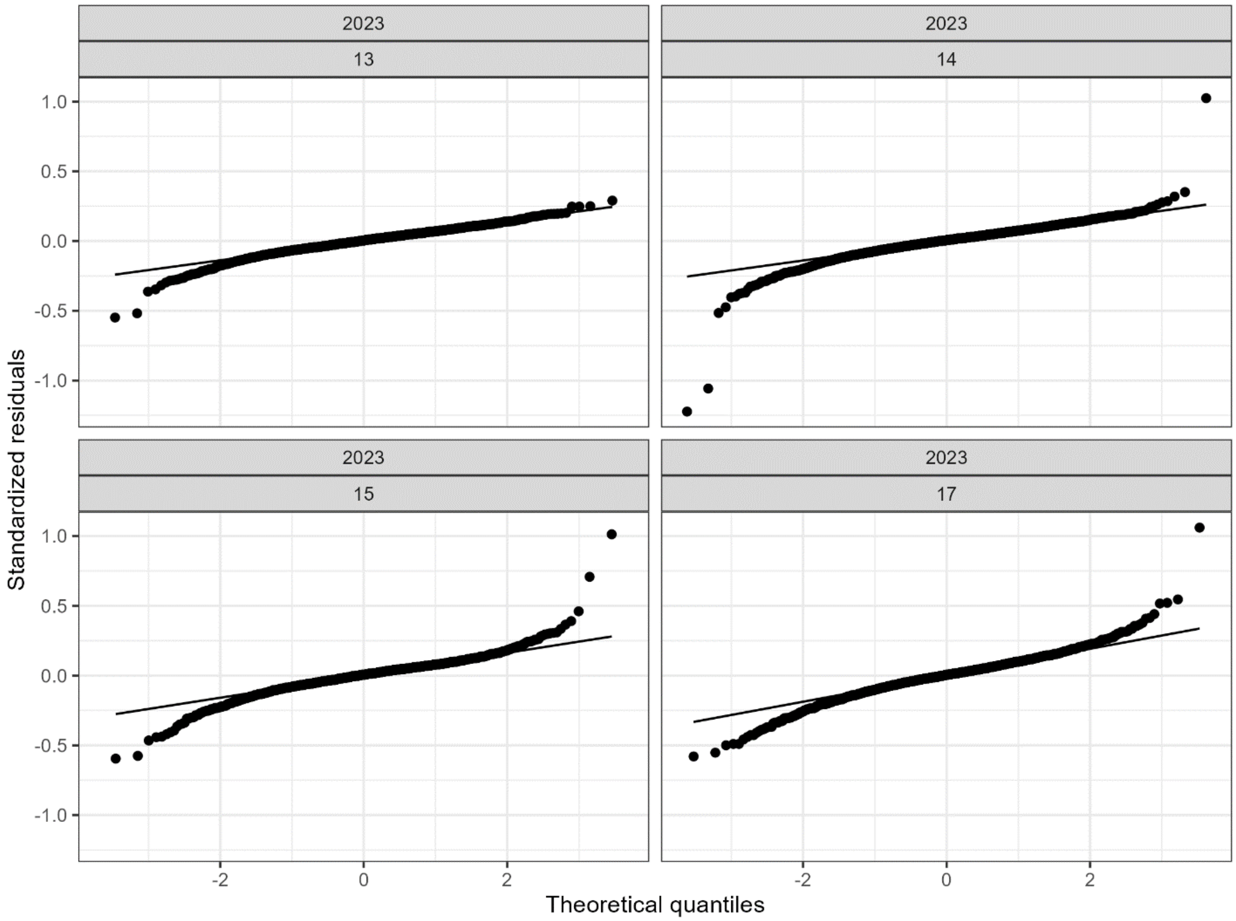


Figure 39. Quantile-quantile plots for the standardized residuals of the strata-specific length-weight models applied to all shrimps from the belly bag.

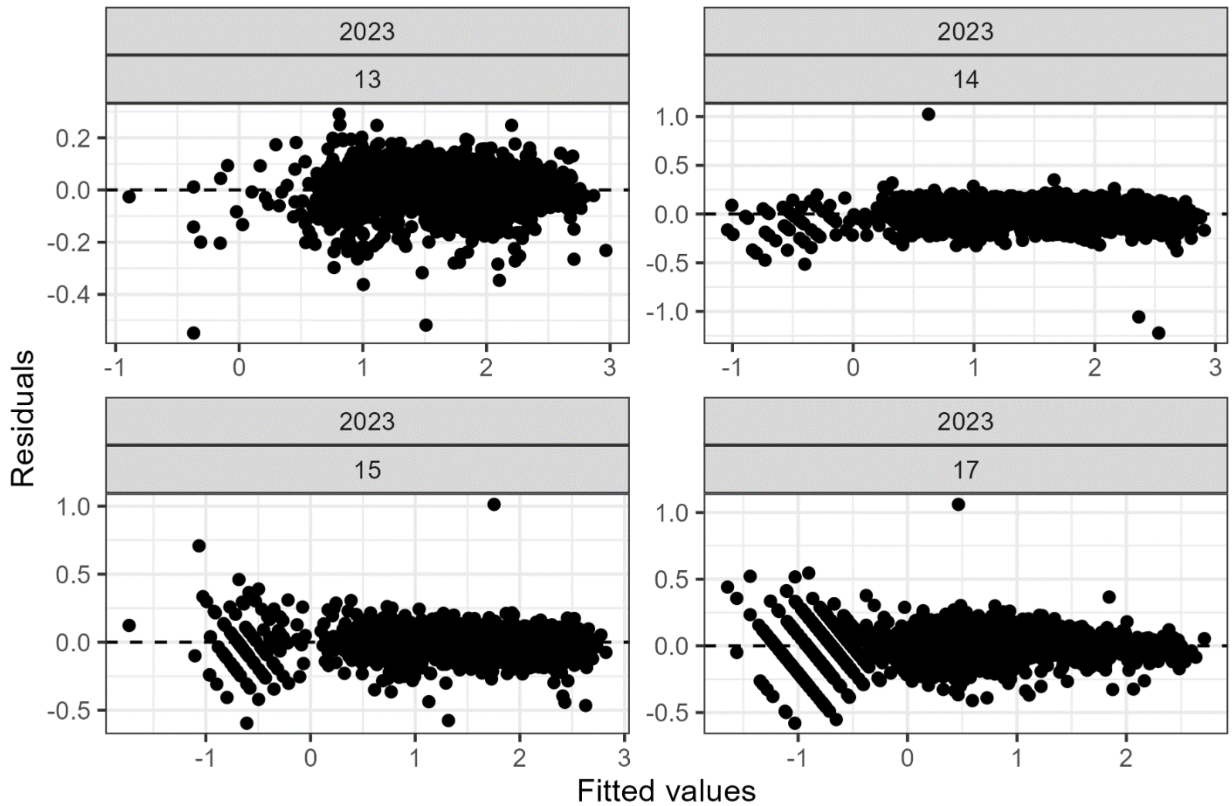


Figure 40. Scatterplots of residuals against fitted values from the strata-specific length-weight models applied to all shrimps from the belly bag. The stripes at lower values are caused by the precision of the equipment used to measure them, wherein the data appear rounded for both the weight and the carapace lengths at those very small sizes.

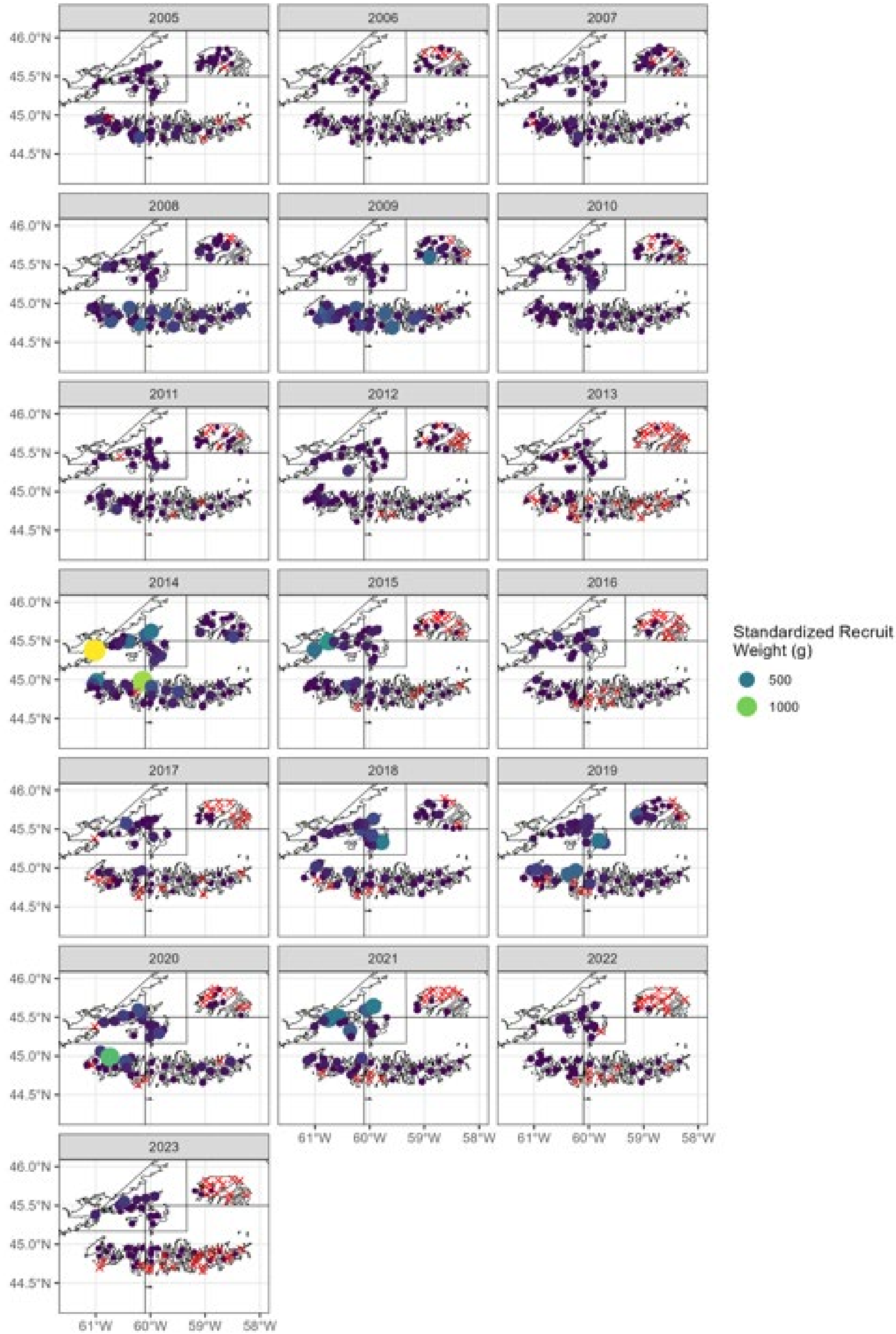


Figure 41. Standardized total recruit weight in grams (g) within each tow from 2005 to 2023, with zeroes denoted by a red x. Black lines denote land in the north-west, strata within each area, Shrimp Fishing Area divisions, and the inshore separation line.

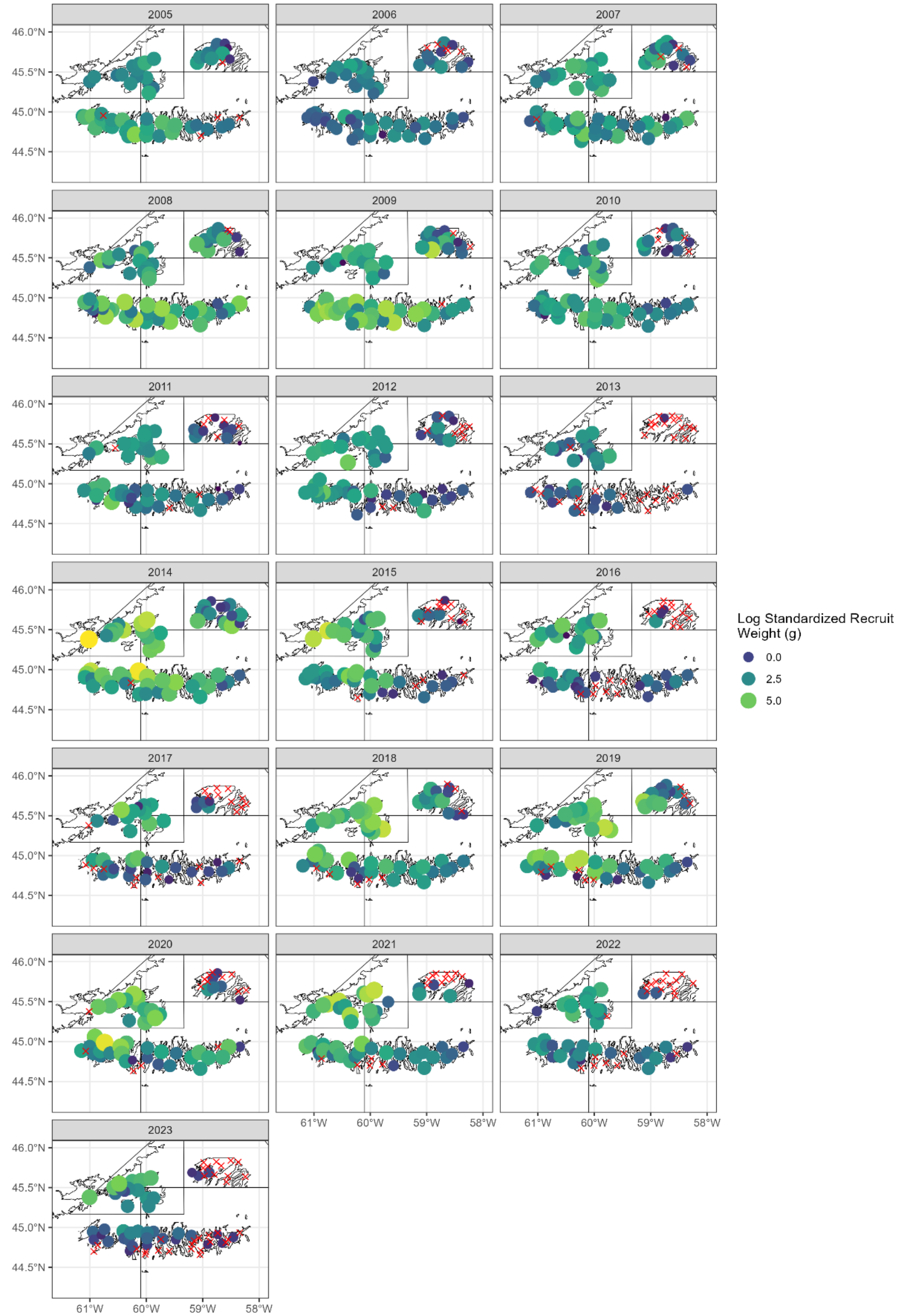


Figure 42. Log standardized total recruit weight in grams (g) within each tow from 2005 to 2023, with zeroes denoted by a red x. Black lines denote land in the north-west, strata within each area, Shrimp Fishing Area divisions, and the inshore separation line.

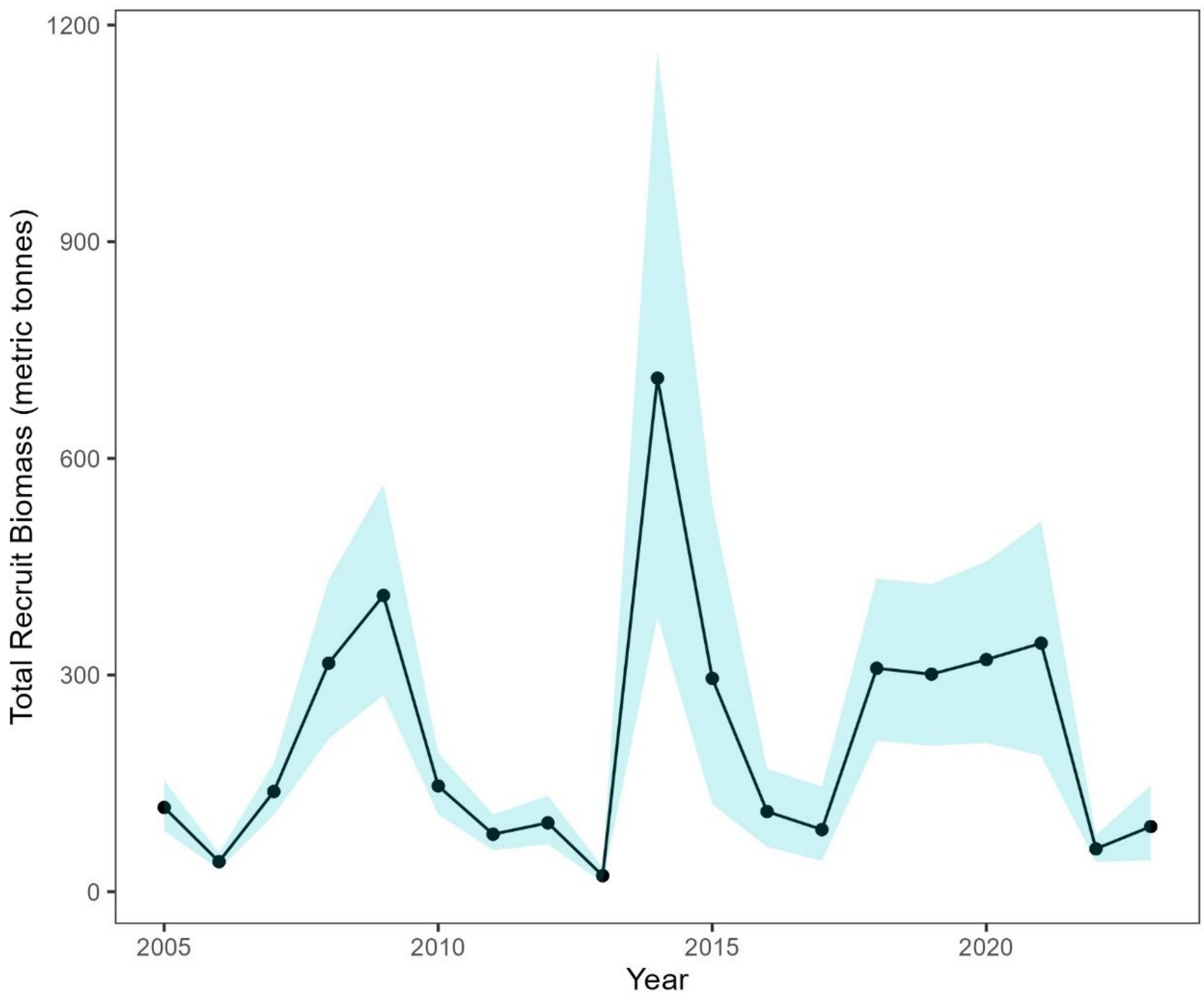


Figure 43. Recruit biomass index in metric tonnes as calculated by the swept area method between 2005 and 2023.

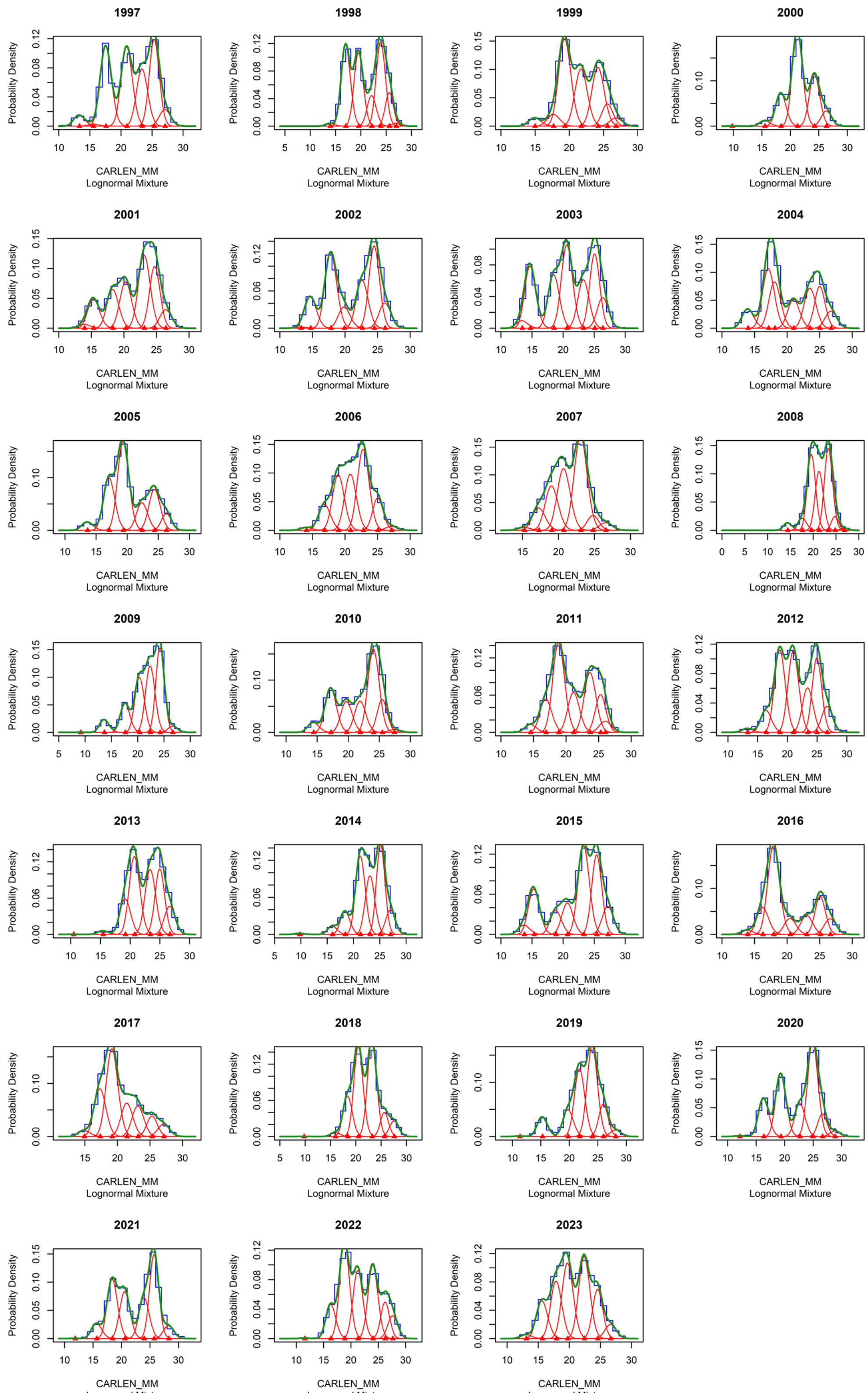


Figure 44. Length frequency and log-Gaussian mixture distributions identified by modal analysis between 1997 and 2023 in Stratum 13. Individual log-Gaussian distribution modes identified by red triangles on x-axis.

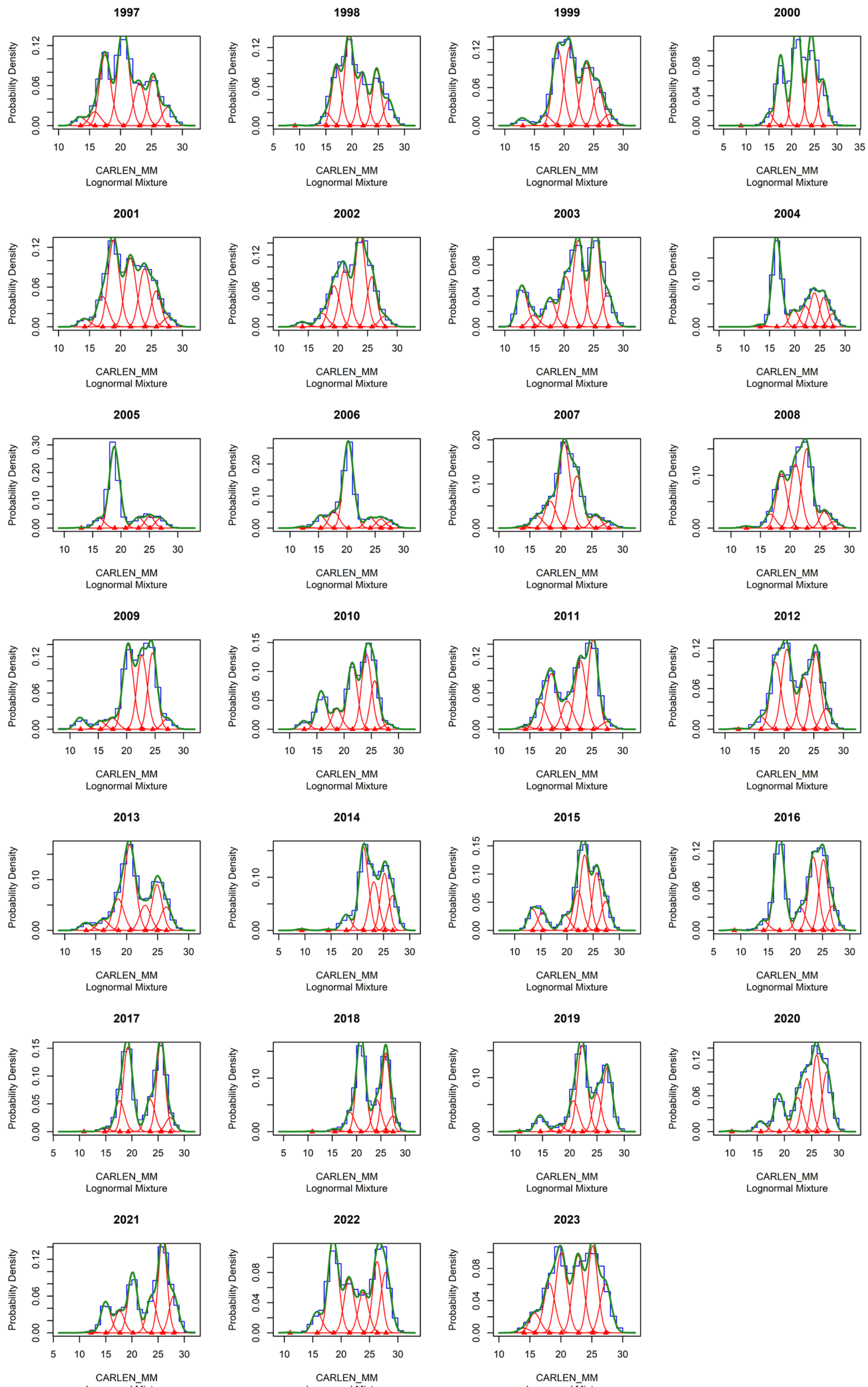


Figure 45. Length frequency and log-Gaussian mixture distributions identified by modal analysis between 1997 and 2023 in Stratum 14. Individual log-Gaussian distribution modes identified by red triangles on x-axis.

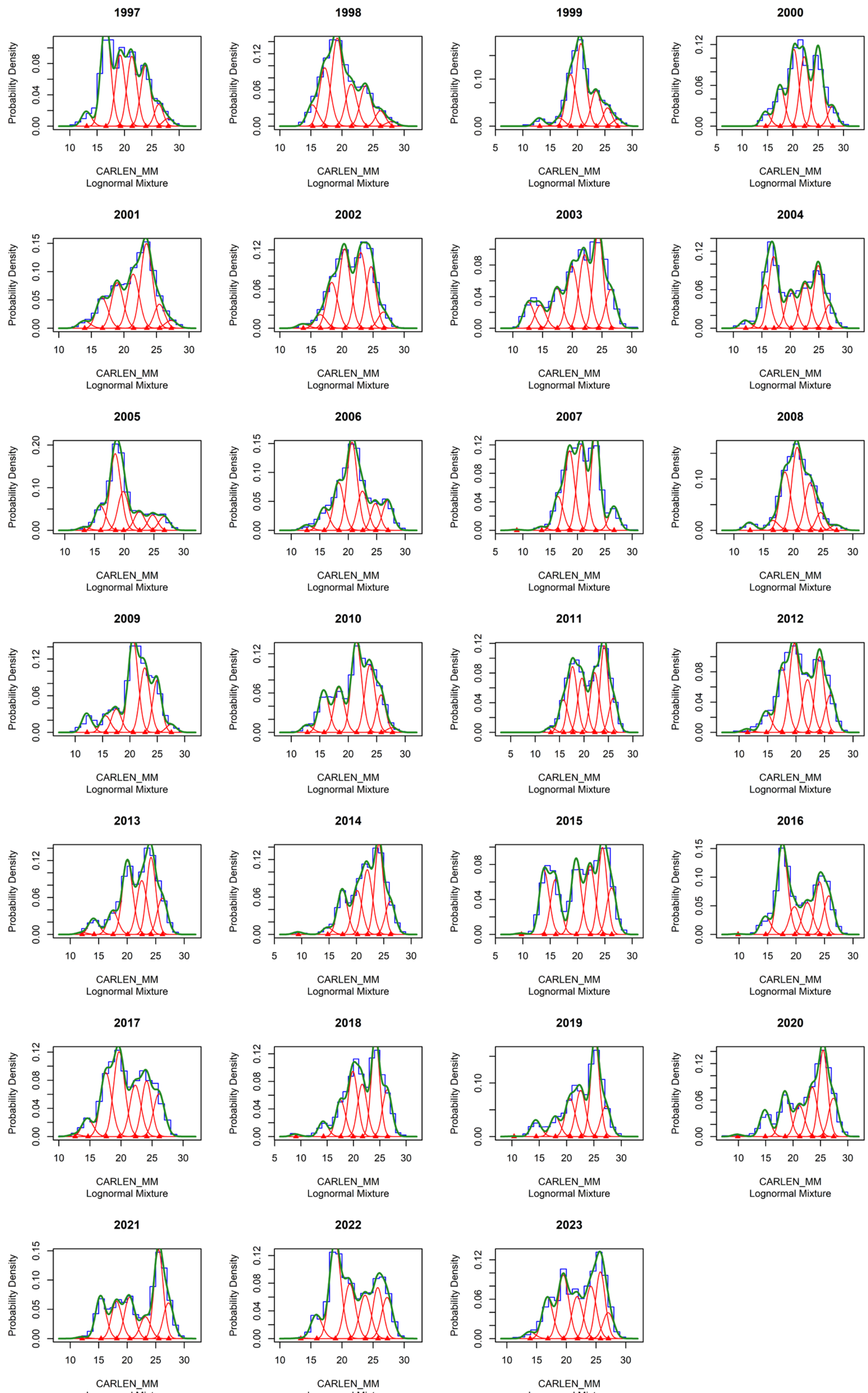


Figure 46. Length frequency and log-Gaussian mixture distributions identified by modal analysis between 1997 and 2023 in Stratum 15. Individual log-Gaussian distribution modes identified by red triangles on x-axis.

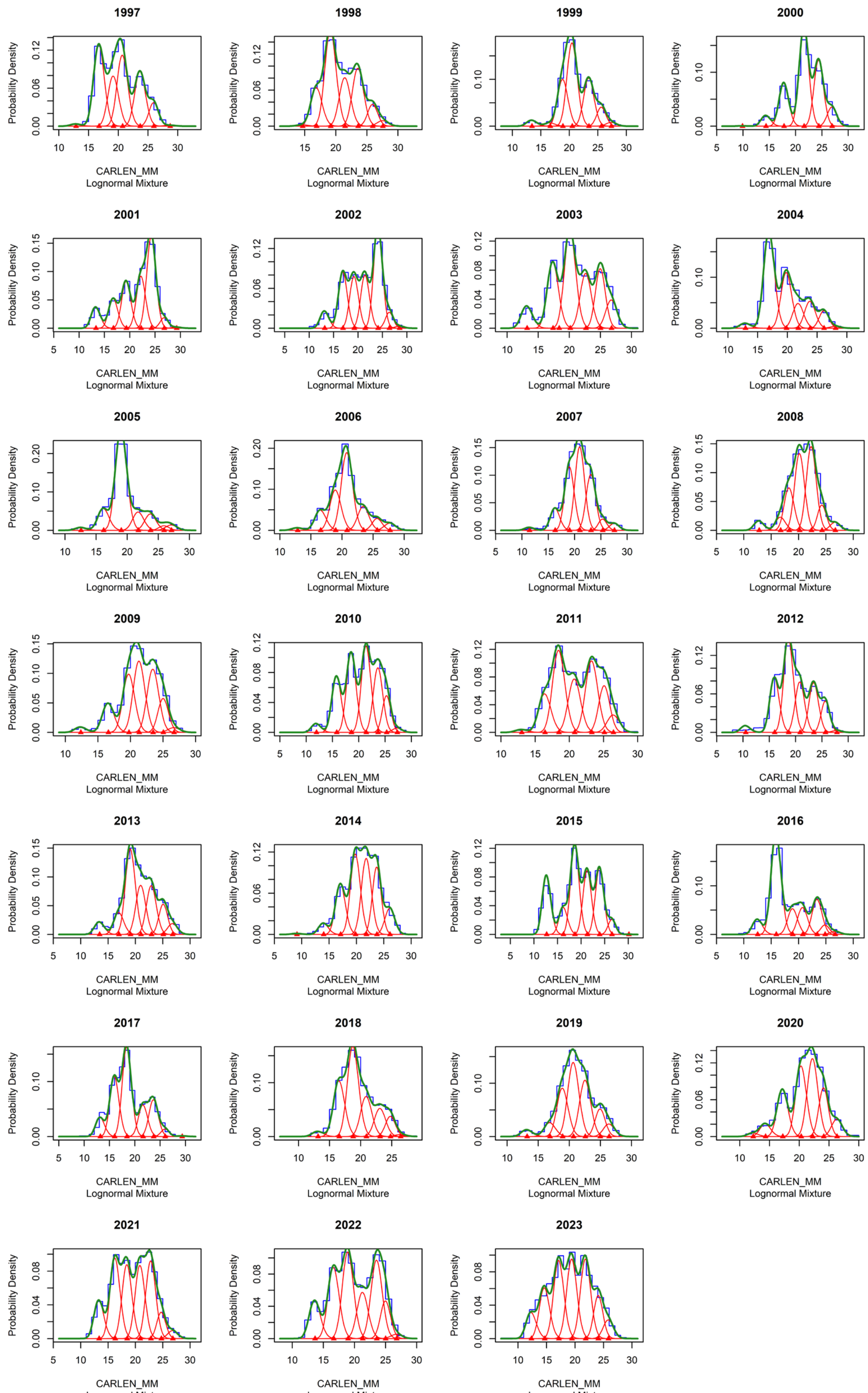


Figure 47. Length frequency and log-Gaussian mixture distributions identified by modal analysis between 1997 and 2023 in Stratum 17. Individual log-Gaussian distribution modes identified by red triangles on x-axis.

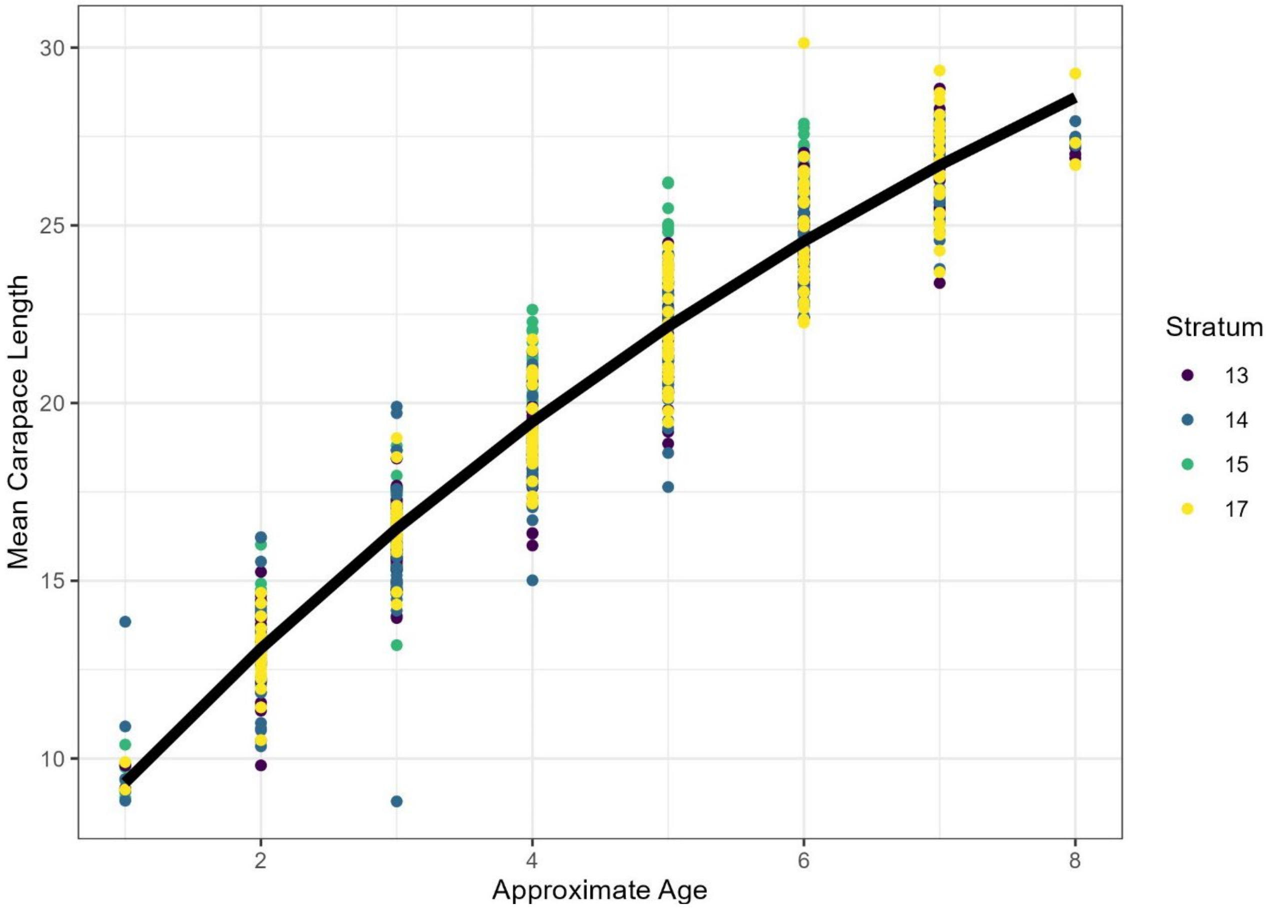


Figure 48. Mean carapace length at approximate ages assigned to estimated modes from modal analysis, with fitted Von Bertalanffy age-length relationship shown by the black line.

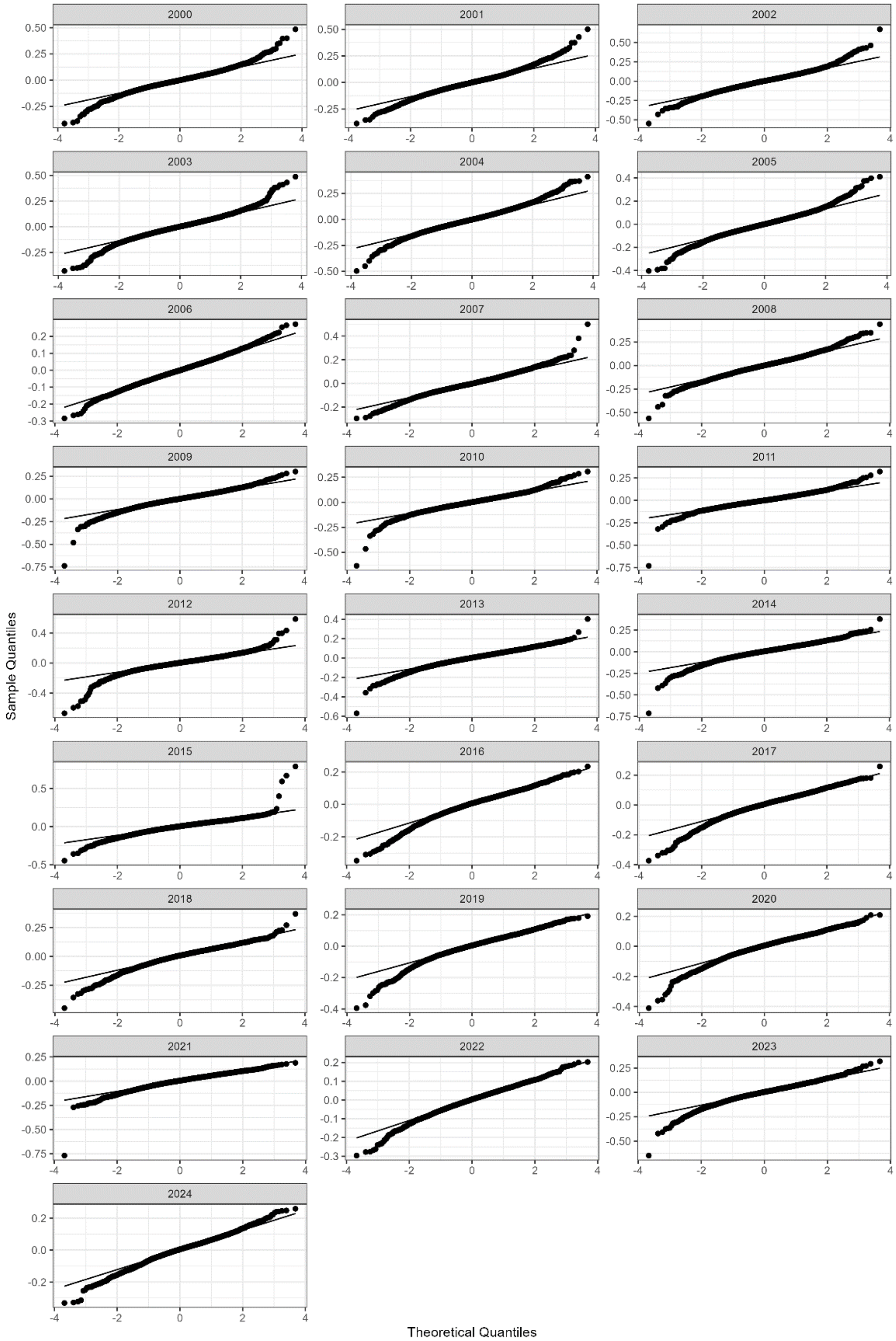


Figure 49. Quantile-quantile (plots for strata- and year-specific lognormal spatial length-weight relationships for Stratum 13 between 2000 and 2023.

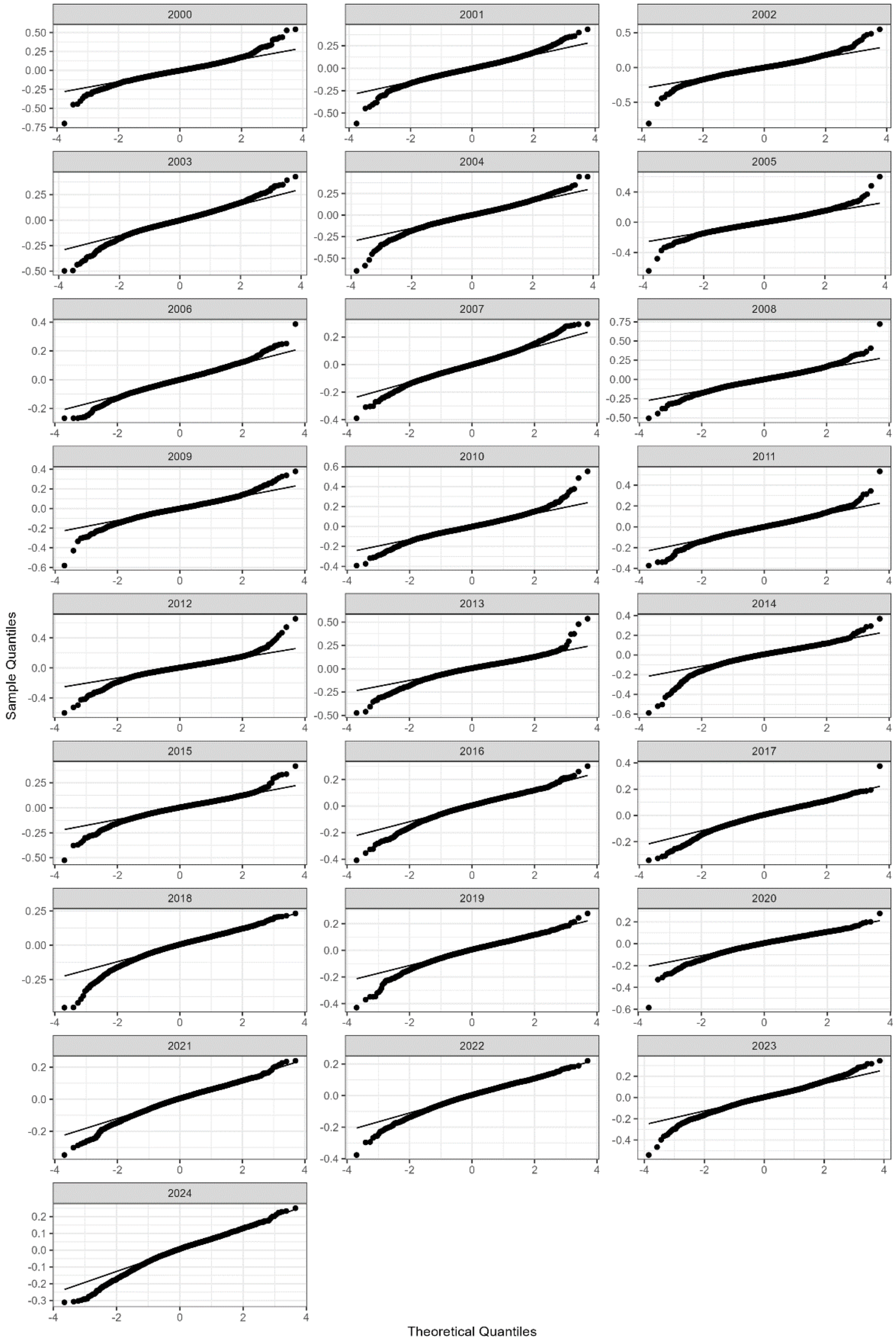


Figure 50. Quantile-quantile plots for strata- and year-specific lognormal spatial length-weight relationships for Stratum 14 between 2000 and 2023.

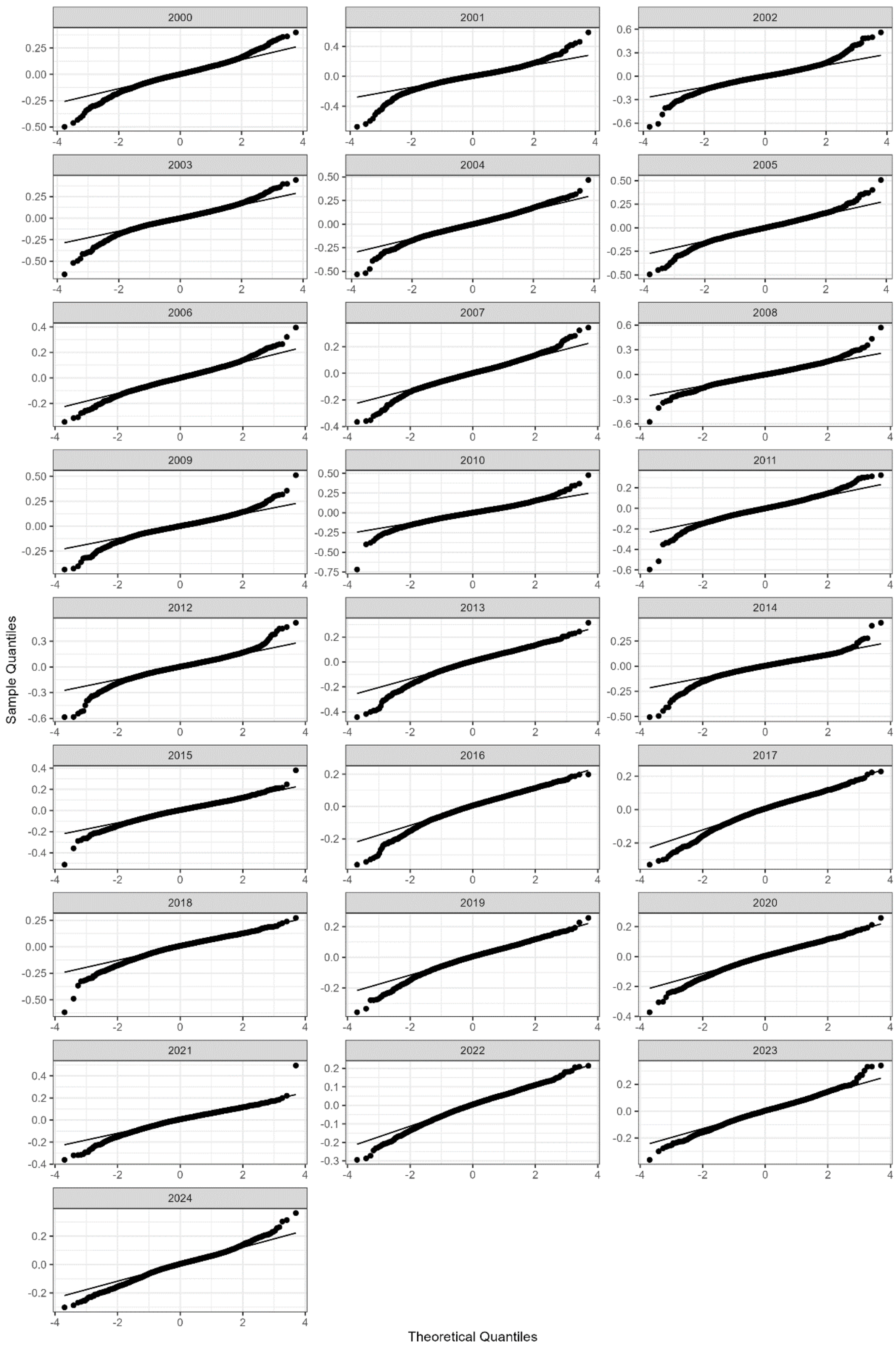


Figure 51. Quantile-quantile plots for strata- and year-specific lognormal spatial length-weight relationships for Stratum 15 between 2000 and 2023.

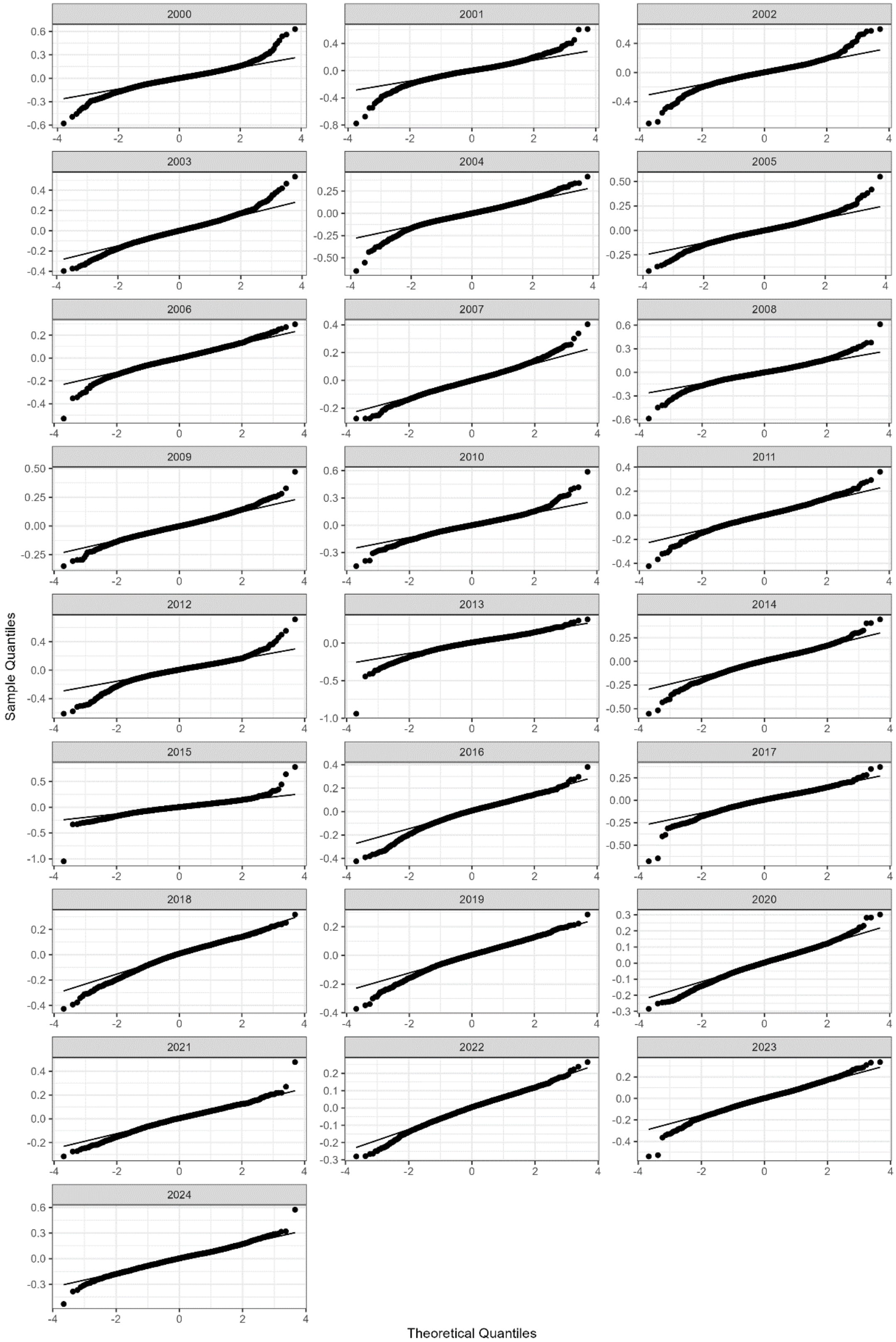


Figure 52. Quantile-quantile plots for strata- and year-specific lognormal spatial length-weight relationships for Stratum 17 between 2000 and 2023.

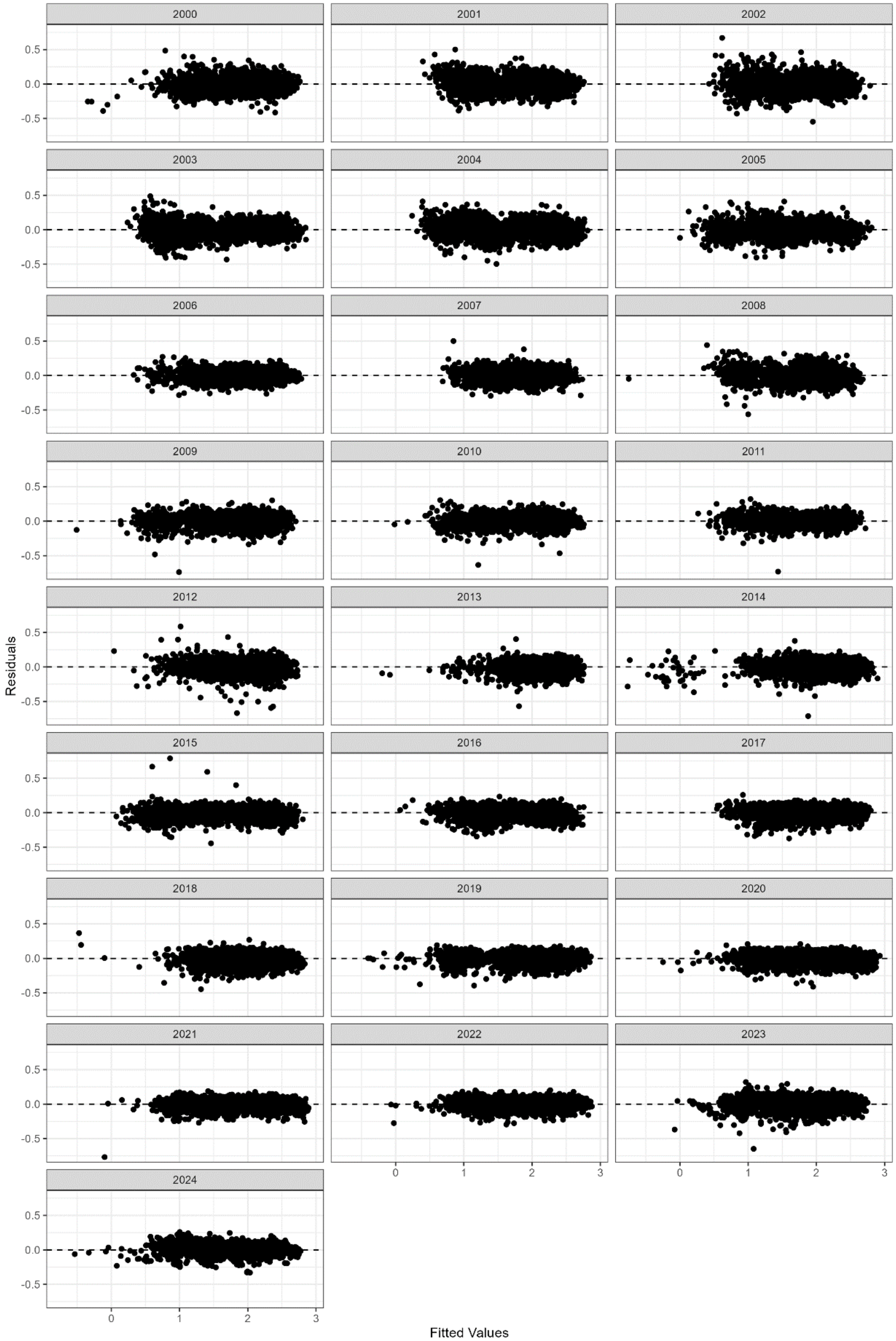


Figure 53. Scatterplot of residuals against fitted values for strata- and year-specific lognormal spatial length-weight relationships for Stratum 13 between 2000 and 2023.

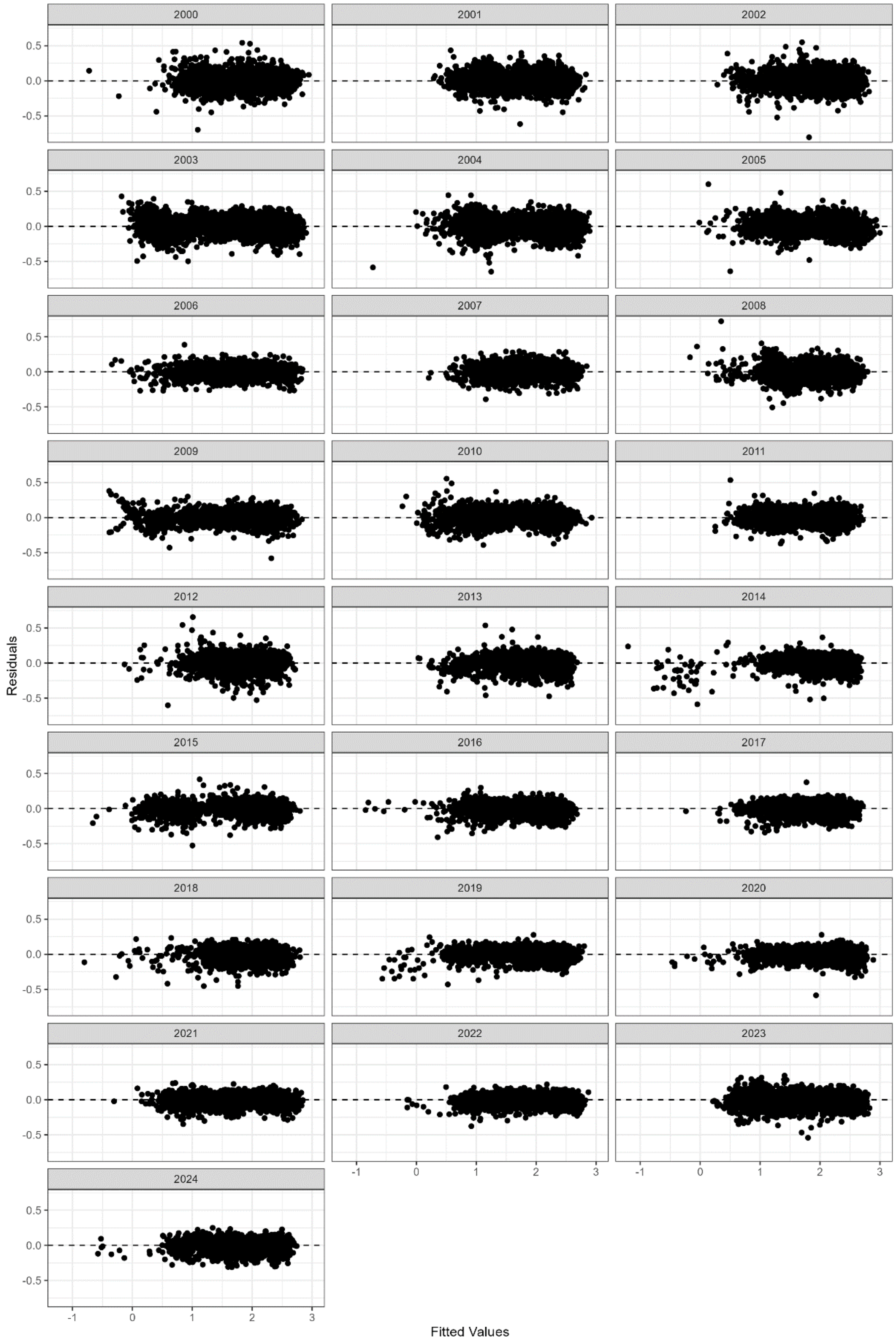


Figure 54. Scatterplot of residuals against fitted values for strata- and year-specific lognormal spatial length-weight relationships for Stratum 14 between 2000 and 2023.

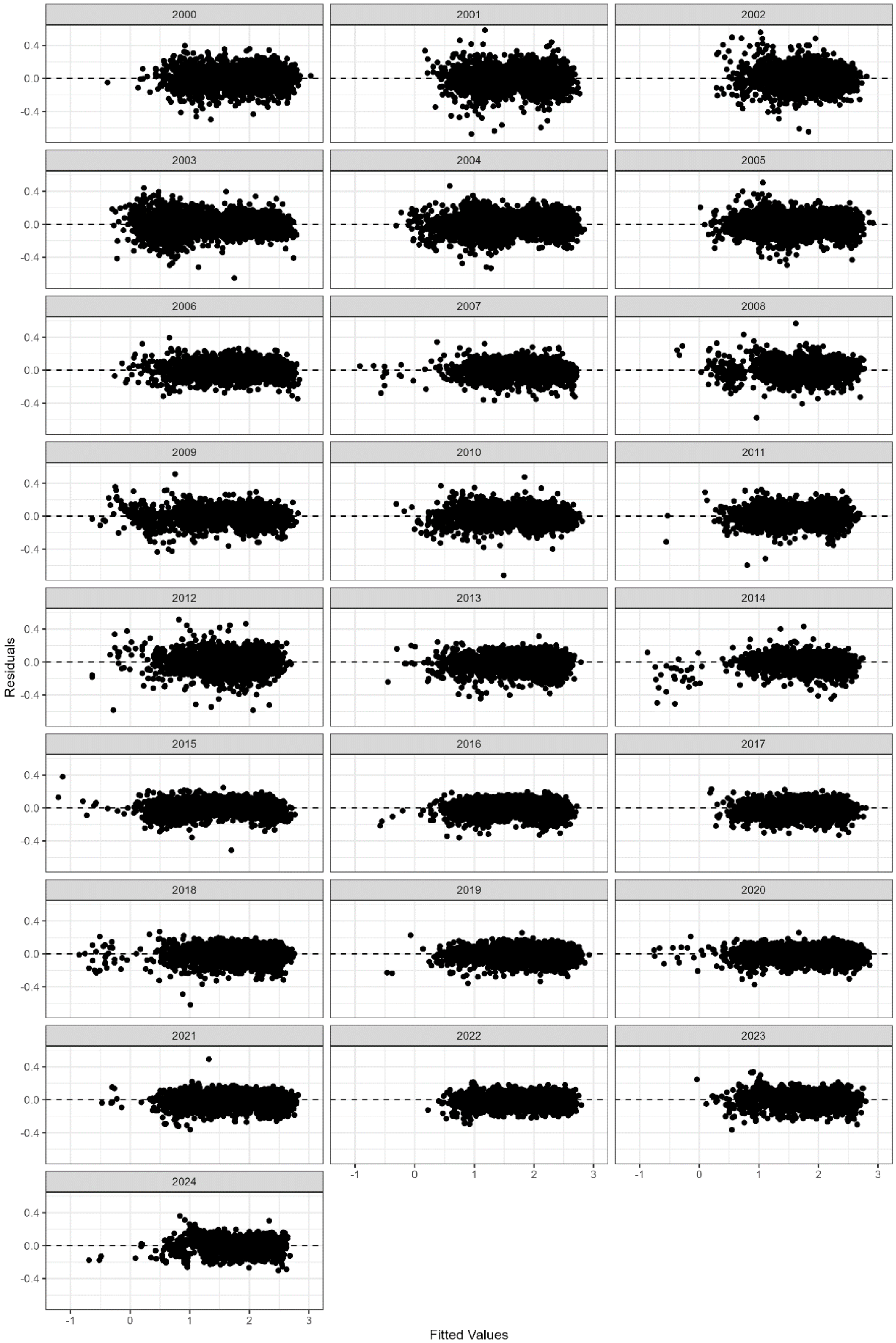


Figure 55. Scatterplot of residuals against fitted values for strata- and year-specific lognormal spatial length-weight relationships for Stratum 15 between 2000 and 2023.

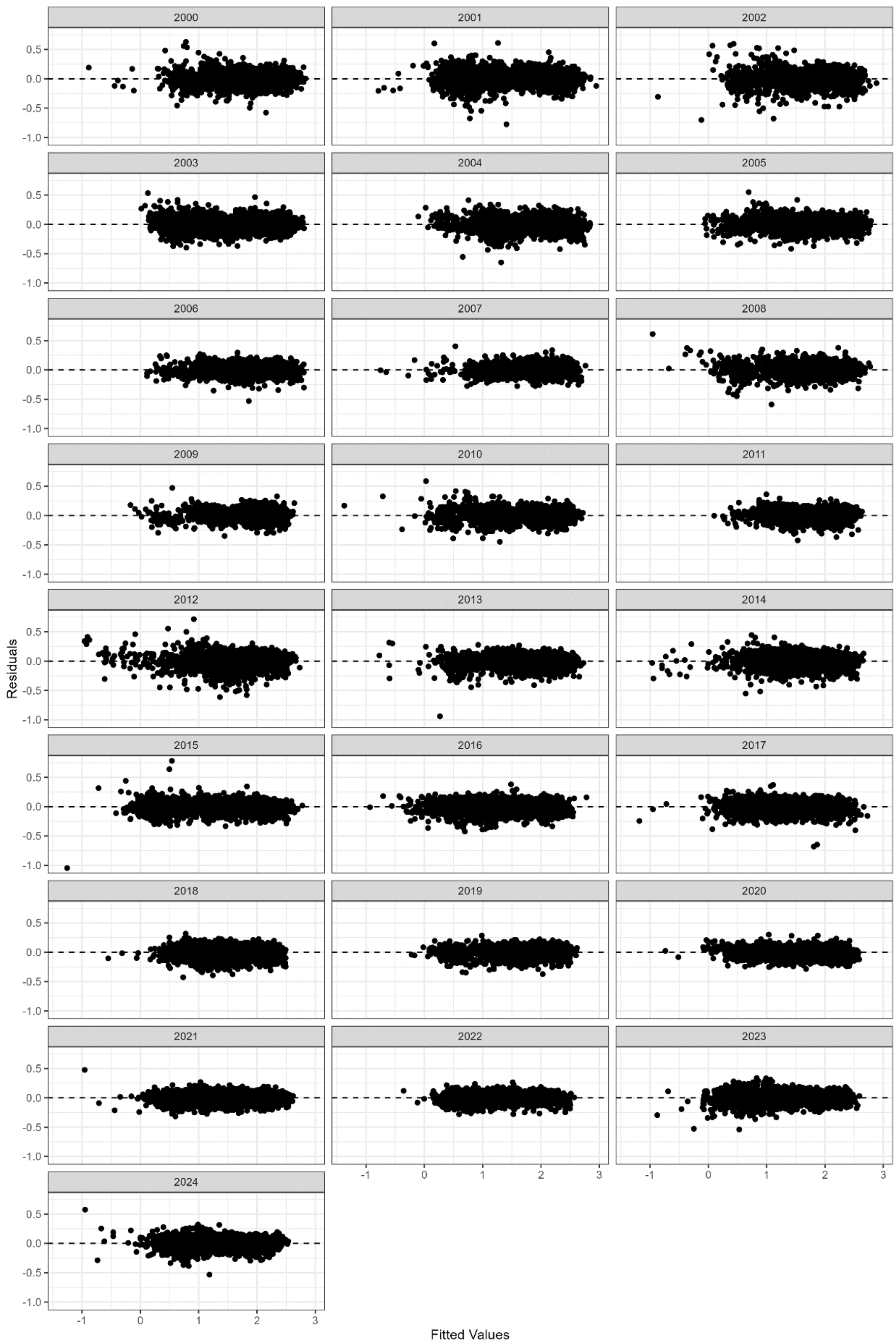


Figure 56. Scatterplot of residuals against fitted values for strata- and year-specific lognormal spatial length-weight relationships for Stratum 17 between 2000 and 2023.

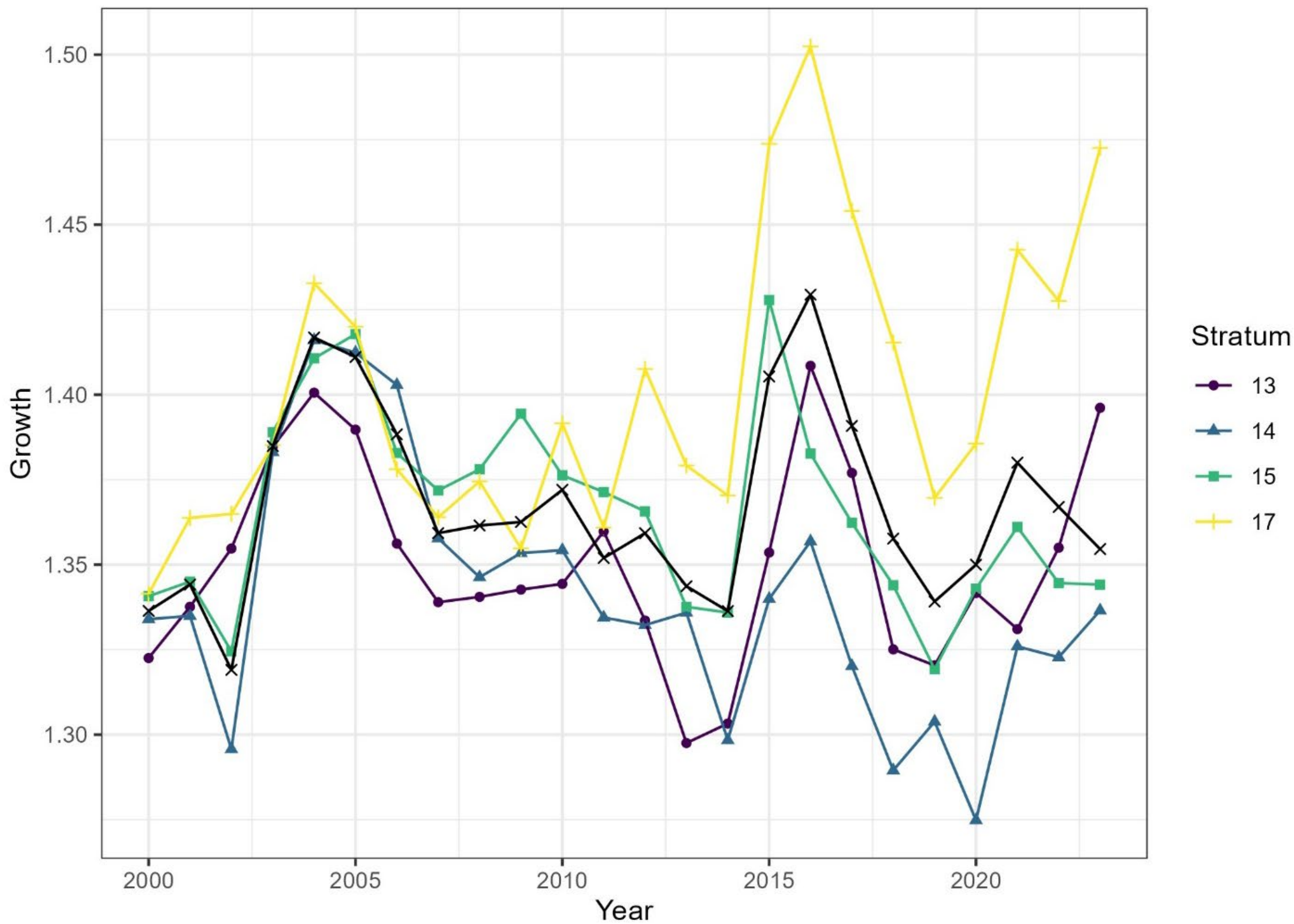


Figure 57. Estimated yearly growth rates in each stratum (as depicted in figure legend) and for all areas together (black exes and line) for main trawl biomass between 2000 and 2023.

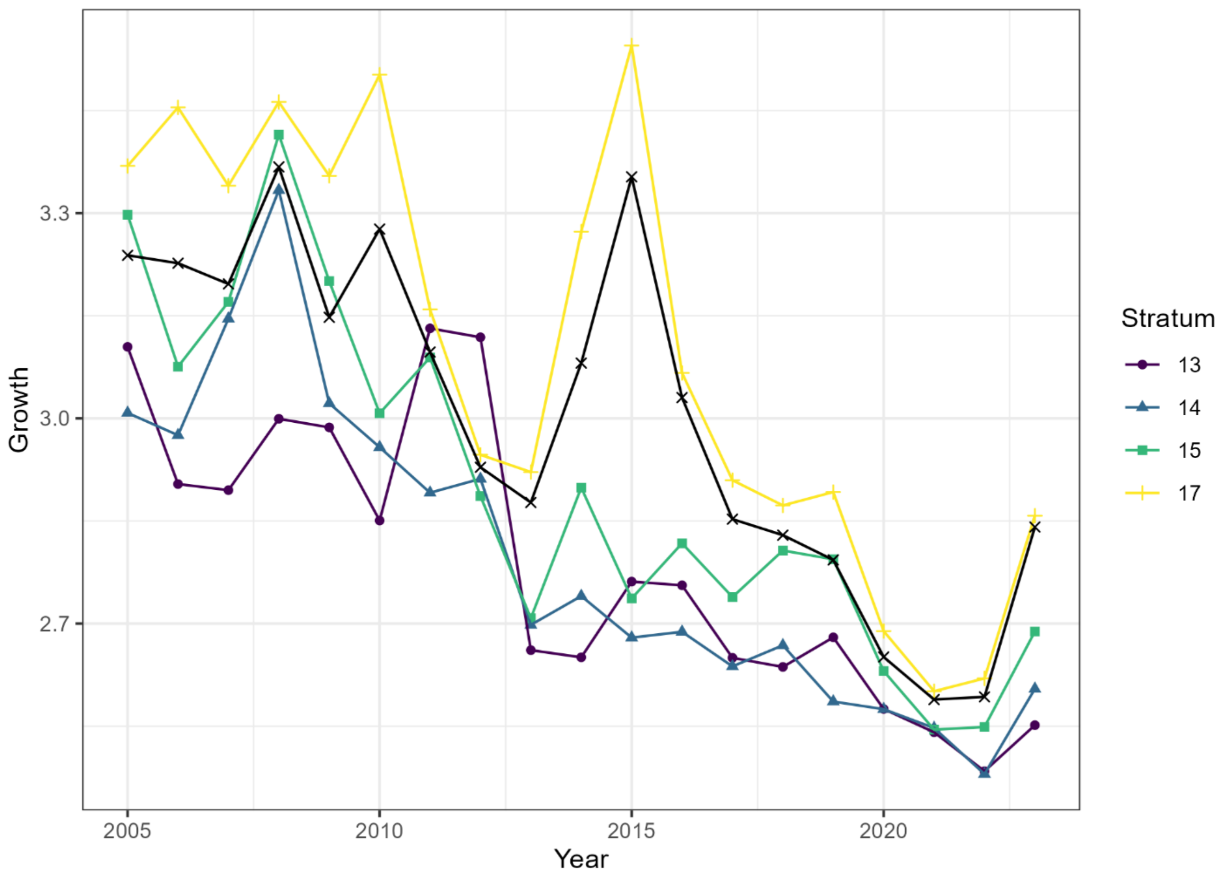


Figure 58. Estimated yearly growth rates in each stratum (as depicted in figure legend) and for all areas together (black exes and line) for recruit biomass between 2005 and 2023.

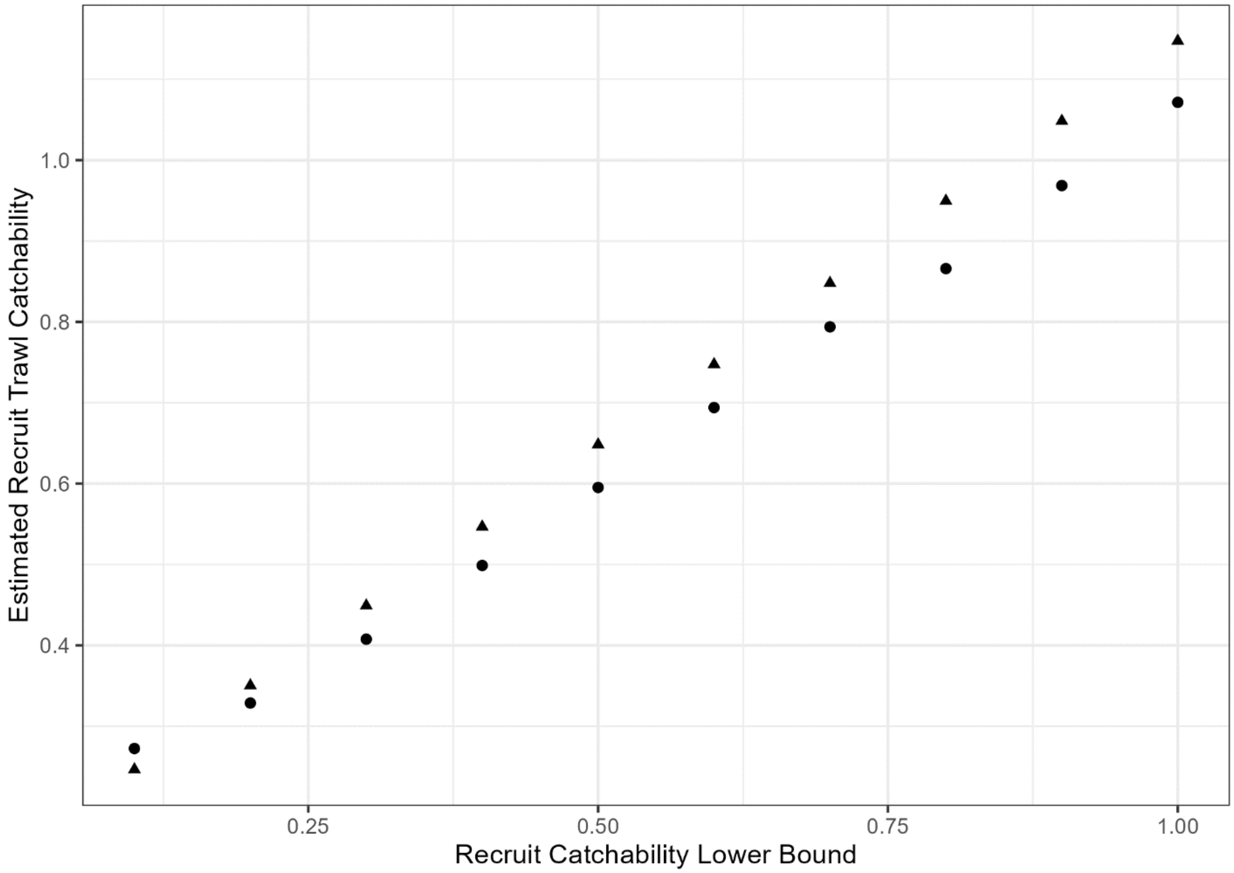


Figure 59. Estimated recruit catchability by the prior distribution from the Spatially Explicit Assessment Model (beta with shape parameters and shifted by pre-chosen values from 0.1 to 1 which become the distribution's lower bound). The triangles indicate the median of the prior distribution.

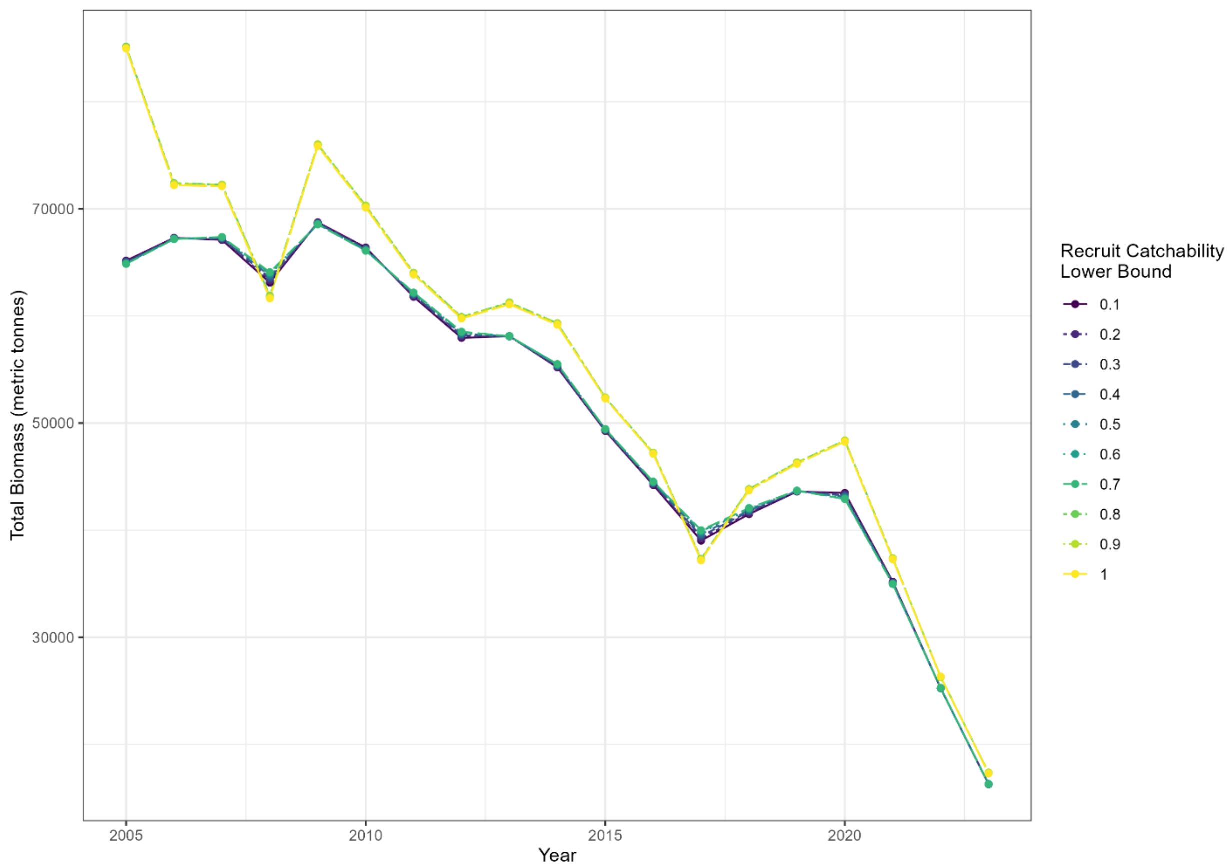


Figure 60. Estimated total biomass from the Spatially Explicit Assessment Model in metric tonnes between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

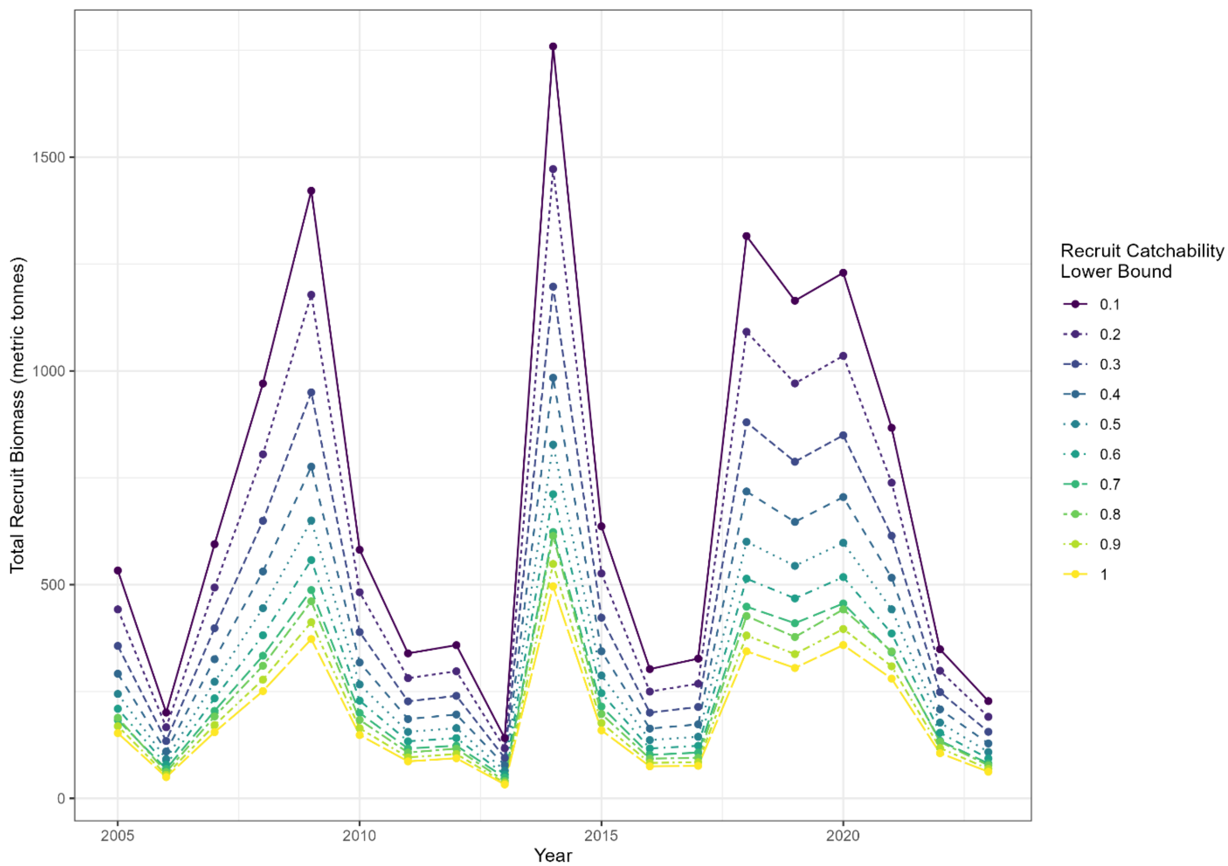


Figure 61. Estimated recruit biomass from the Spatially Explicit Assessment Model in metric tonnes between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

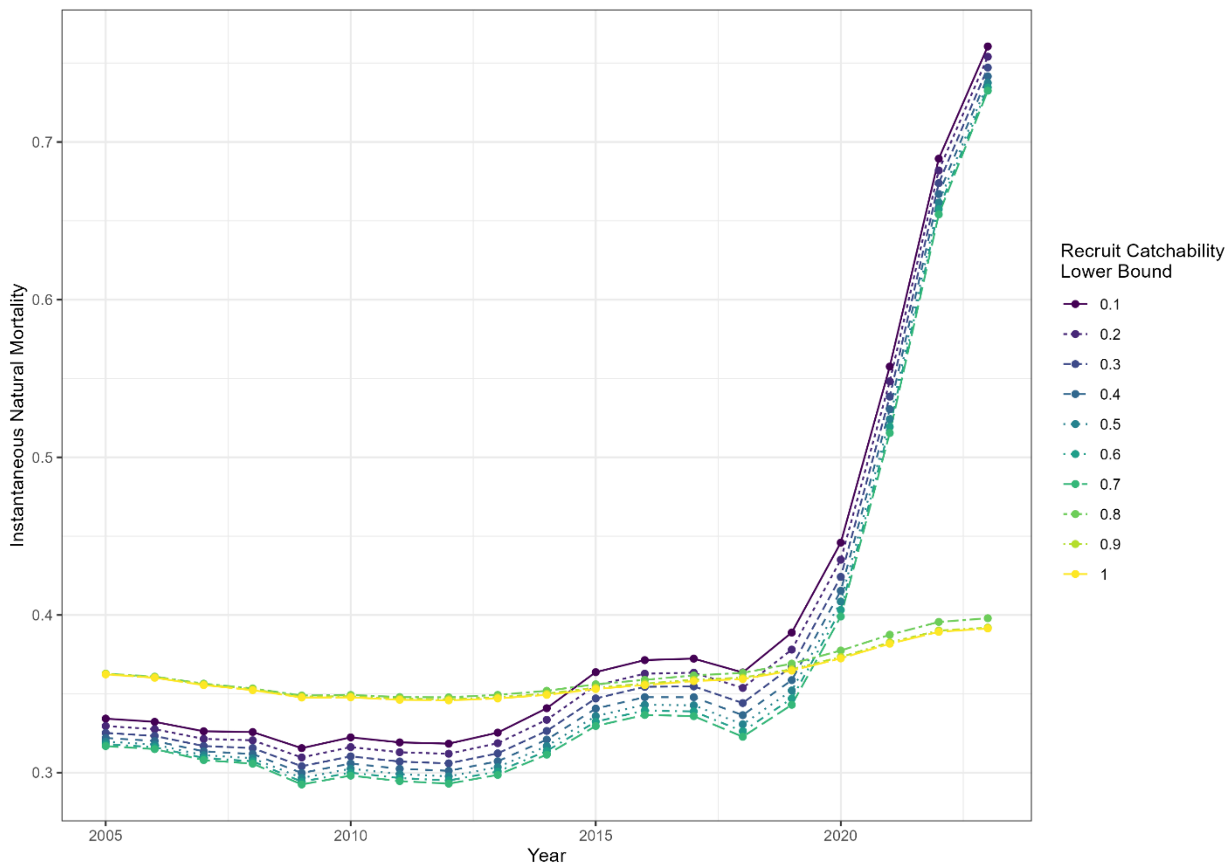


Figure 62. Estimated instantaneous natural mortality from the Spatially Explicit Assessment Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

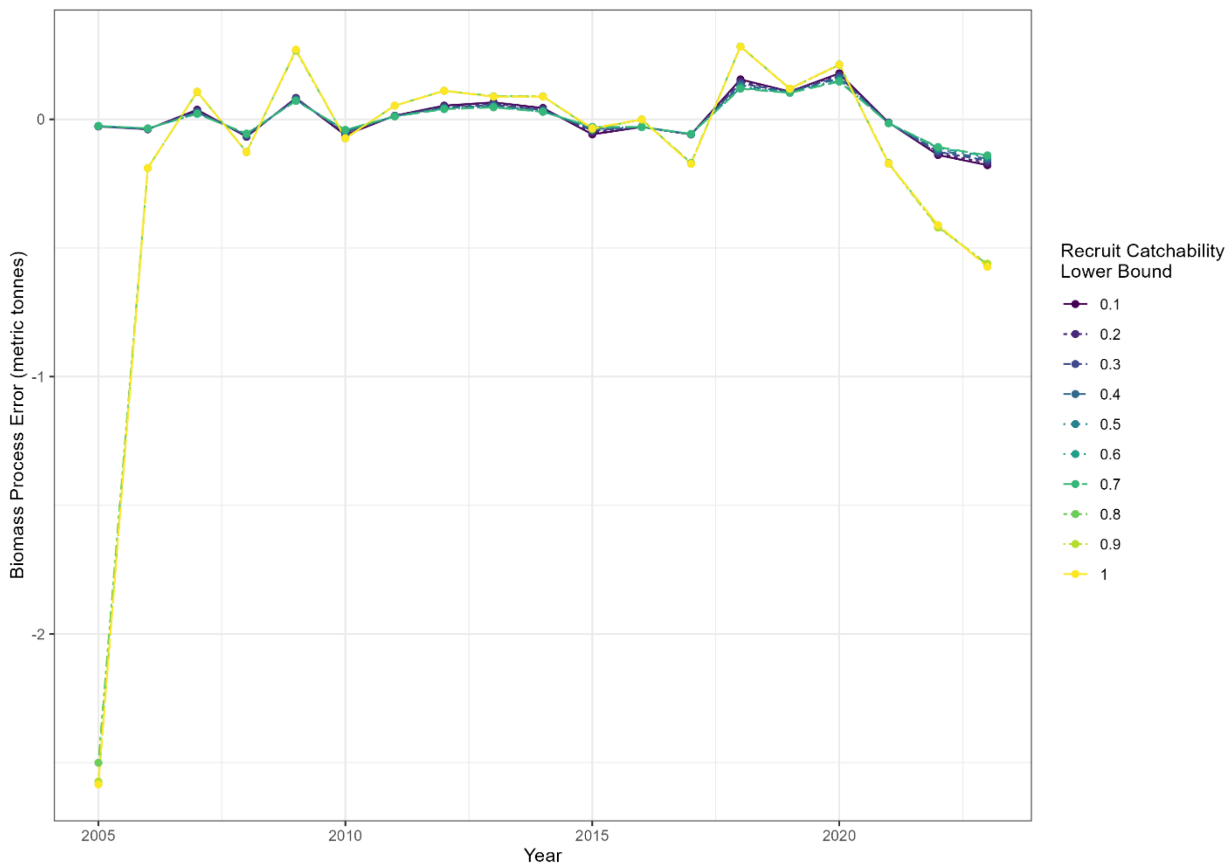


Figure 63. Biomass density median random field value from the Spatially Explicit Assessment Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

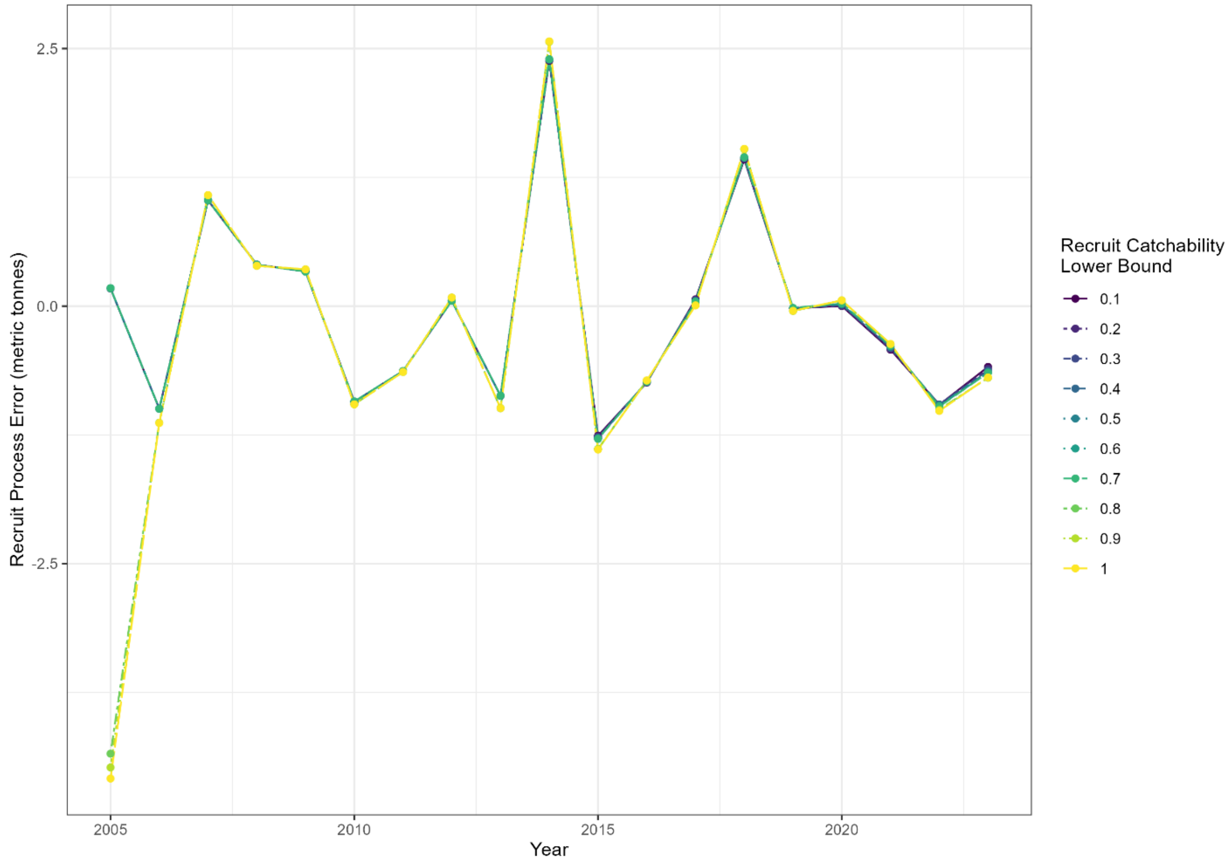


Figure 64. Recruit biomass density median random field value from the Spatially Explicit Assessment Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

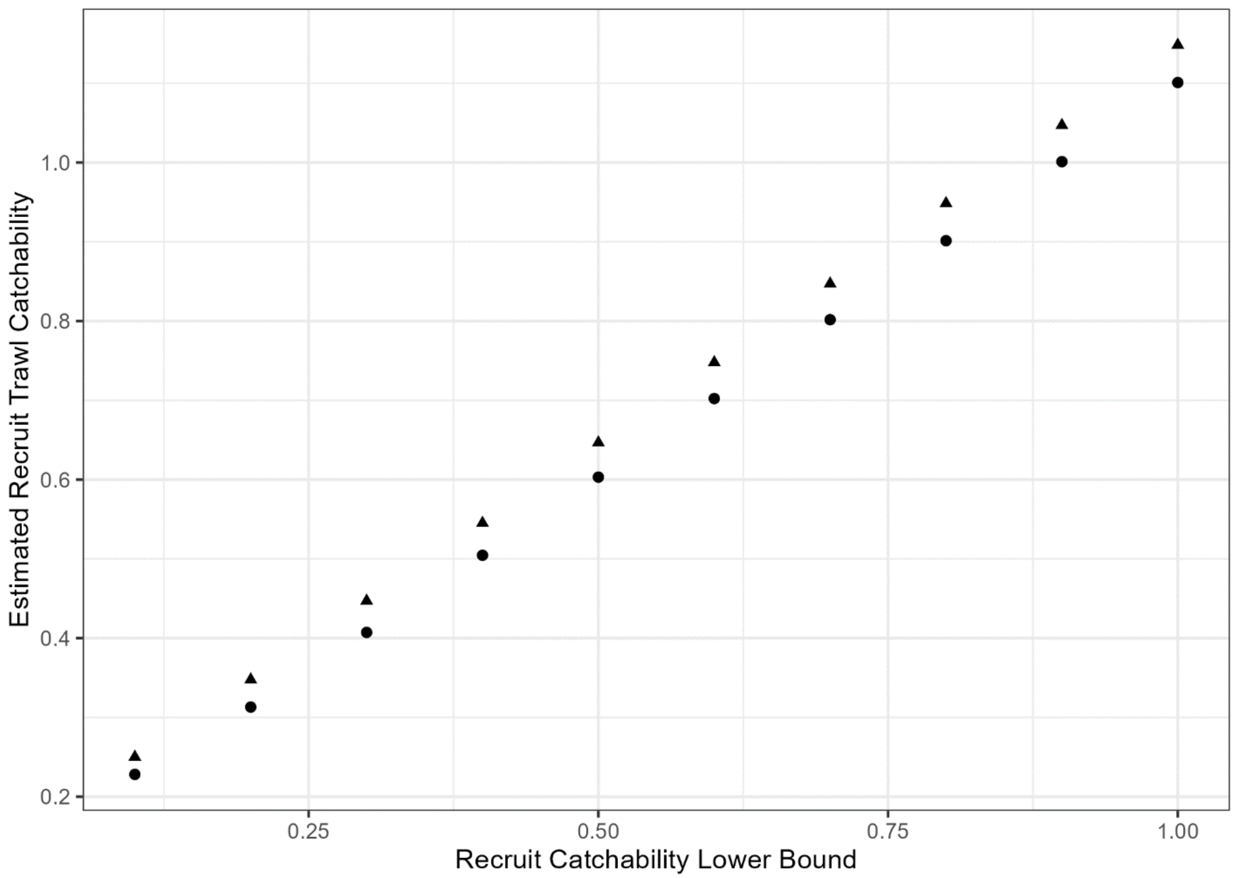


Figure 65. Estimated recruit catchability (q_R) by the prior distribution from the Tow Level Model (beta with shape parameters $\alpha = 2$ and $\beta = 10$ shifted by pre-chosen values from 0.1 to 1 which become the distribution's lower bound). The triangles indicate the median of the prior distribution.

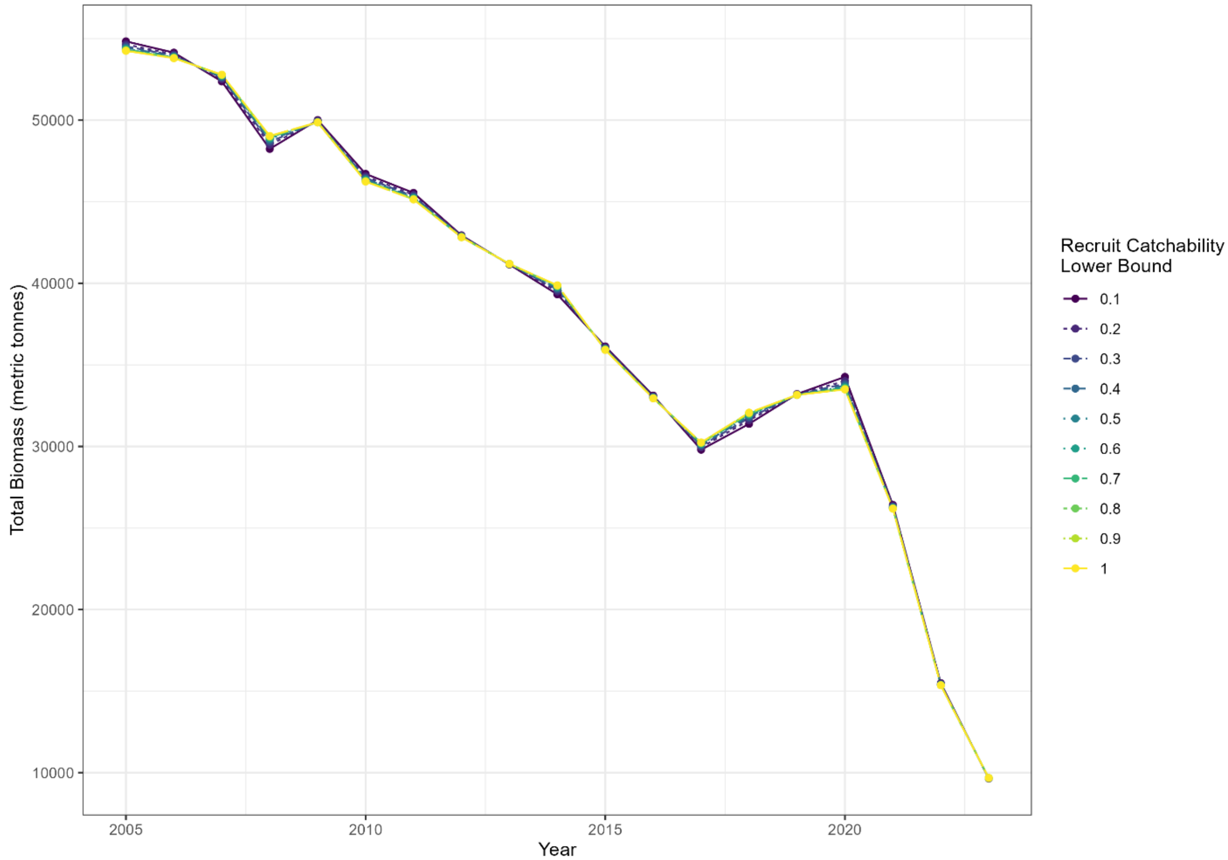


Figure 66. Estimated total biomass from the Tow Level Model in metric tonnes between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

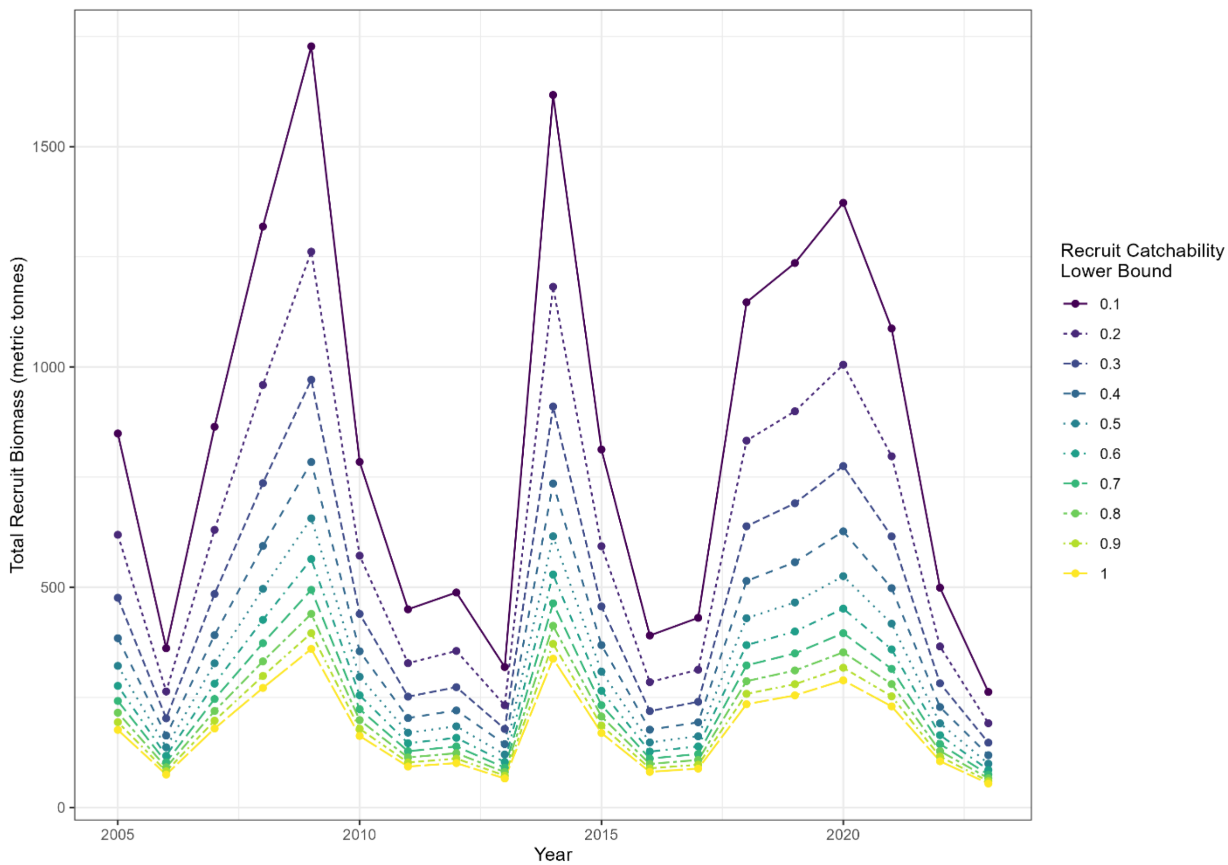


Figure 67. Estimated recruit total biomass from the Tow Level Model in metric tonnes between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

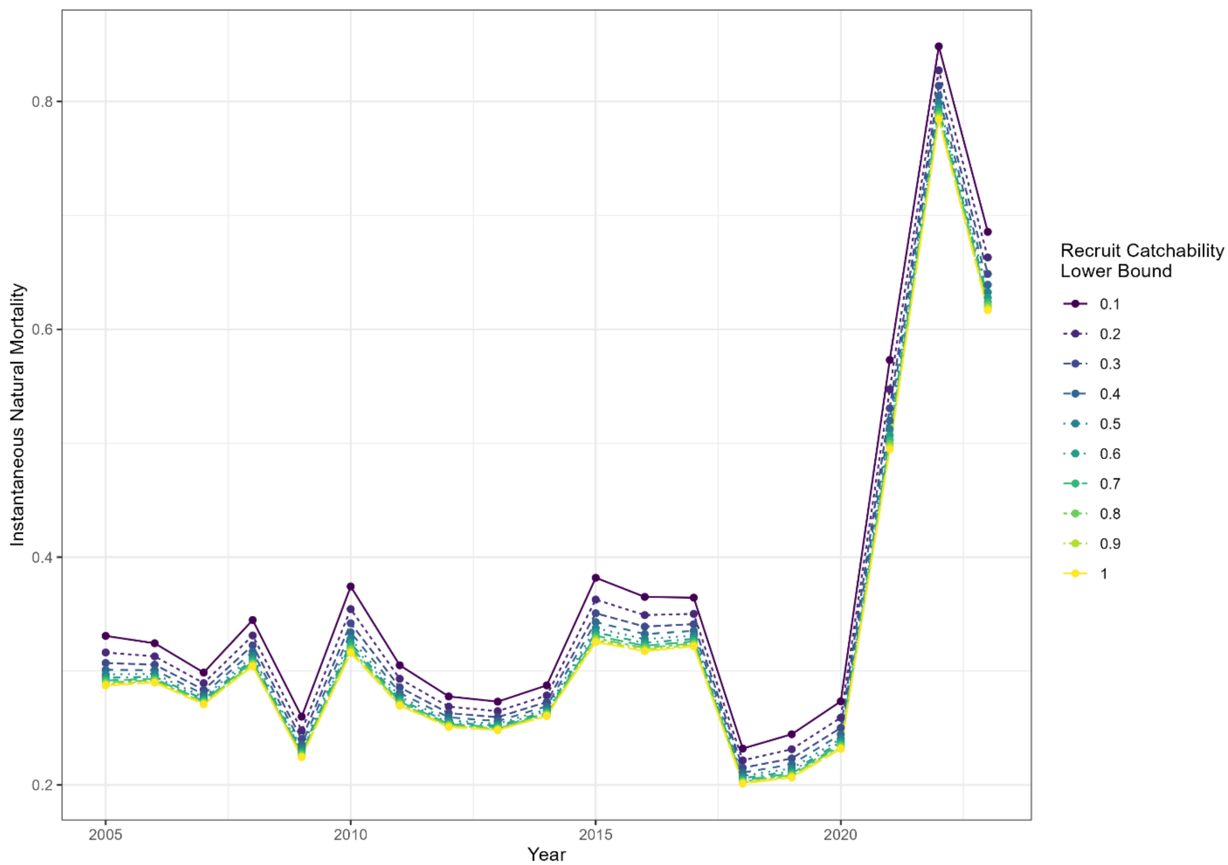


Figure 68. Estimated instantaneous natural mortality from the Tow Level Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

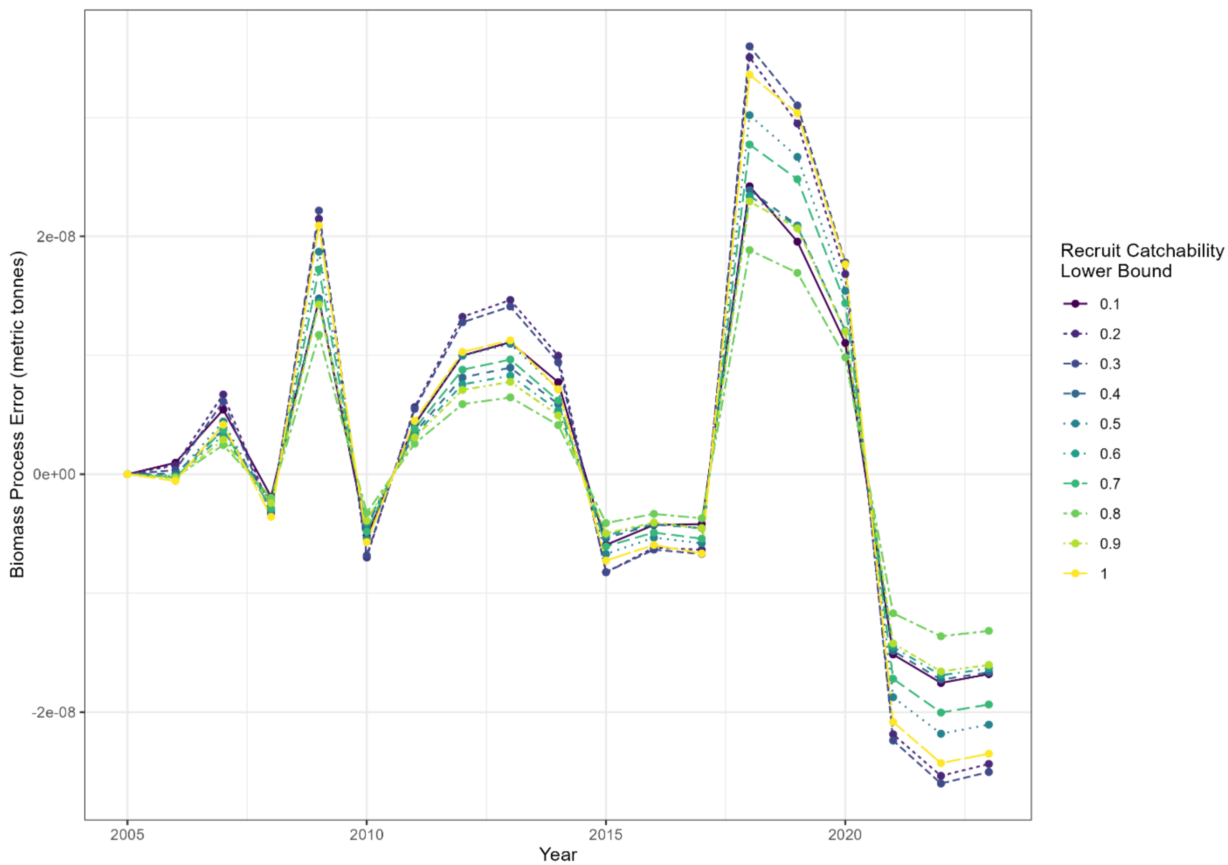


Figure 69. Total biomass process error from the Tow Level Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

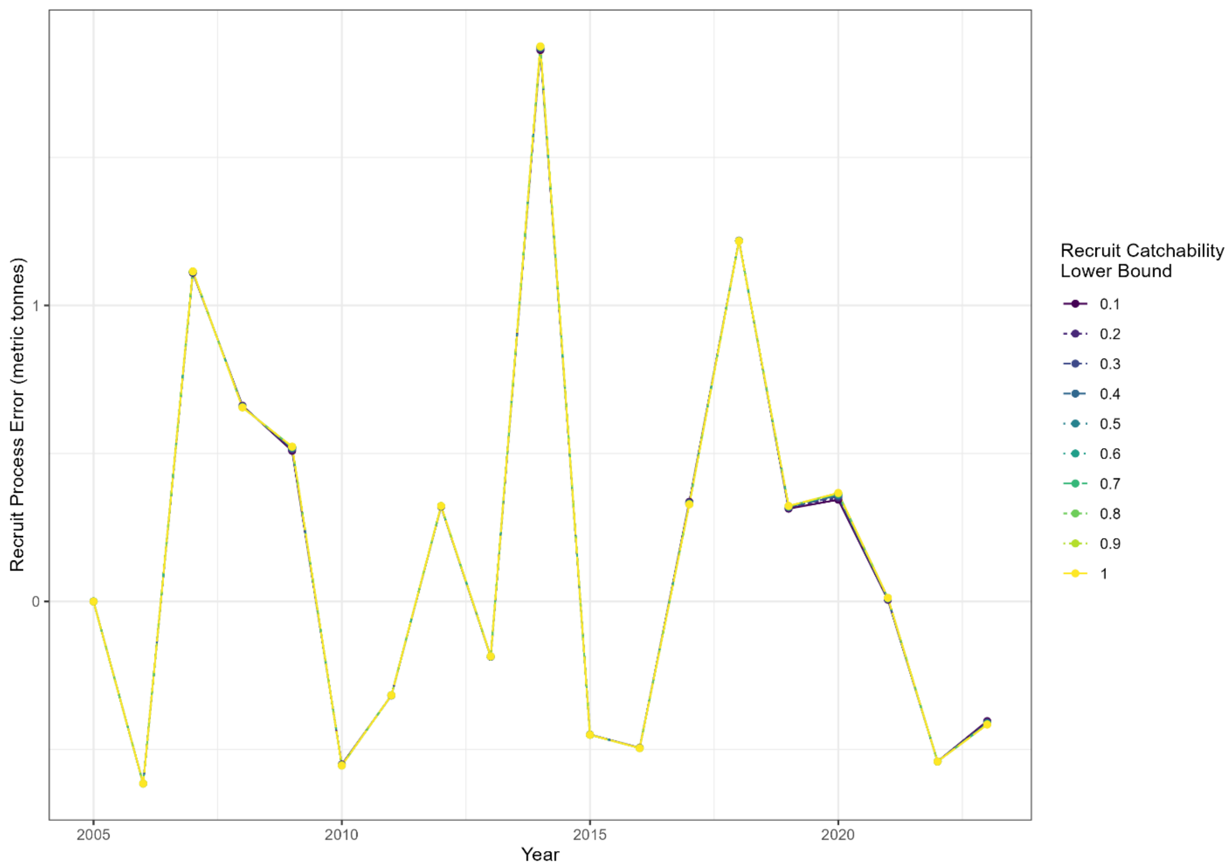


Figure 70. Recruit biomass process error from the Tow Level Model between 2005 and 2023 based on the prior distribution of recruit catchability (q_R).

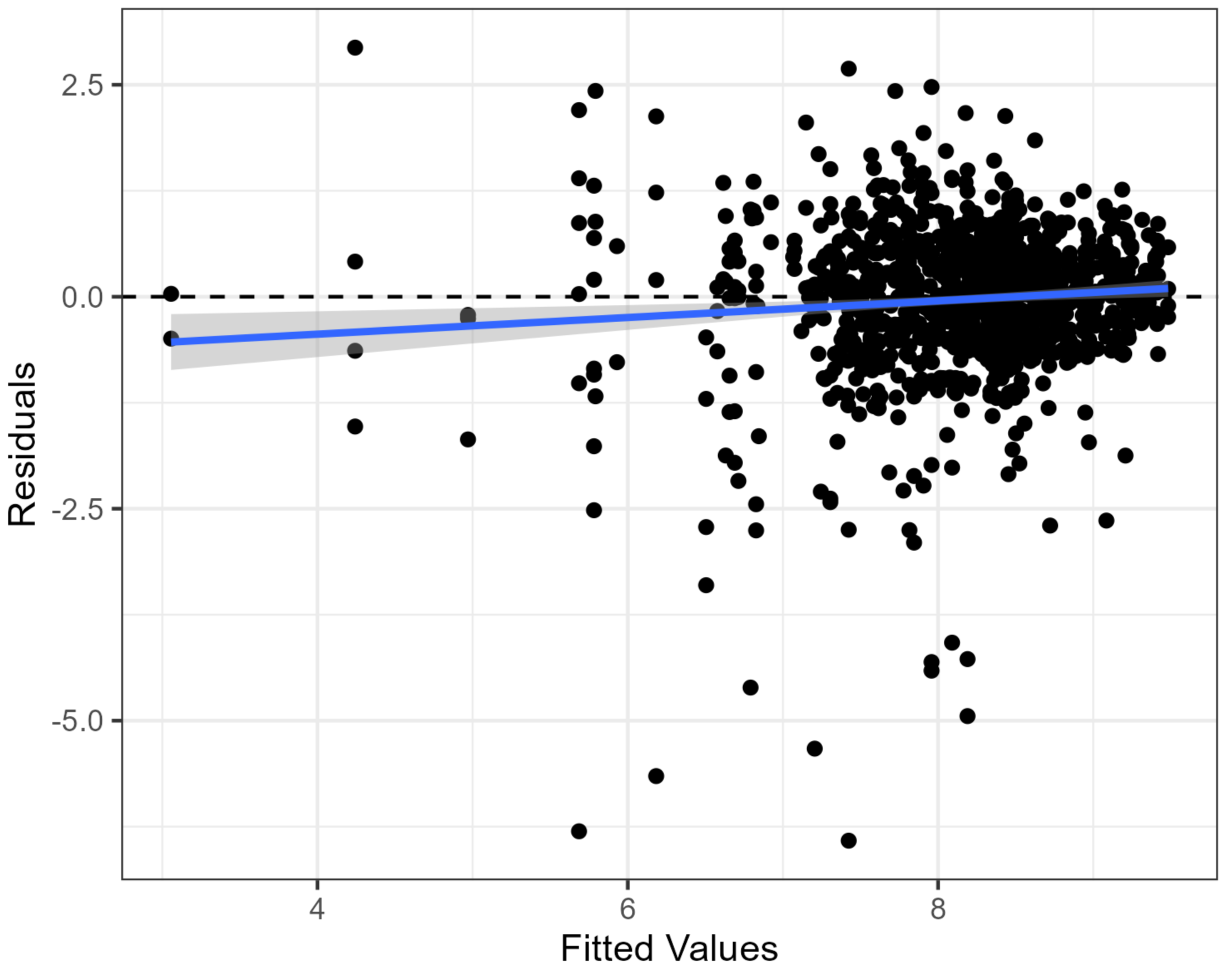


Figure 71. Scatterplot of residuals against fitted values for the Spatially Explicit Assessment Model main trawl biomass observations on the log scale. Blue line is a simple linear regression.

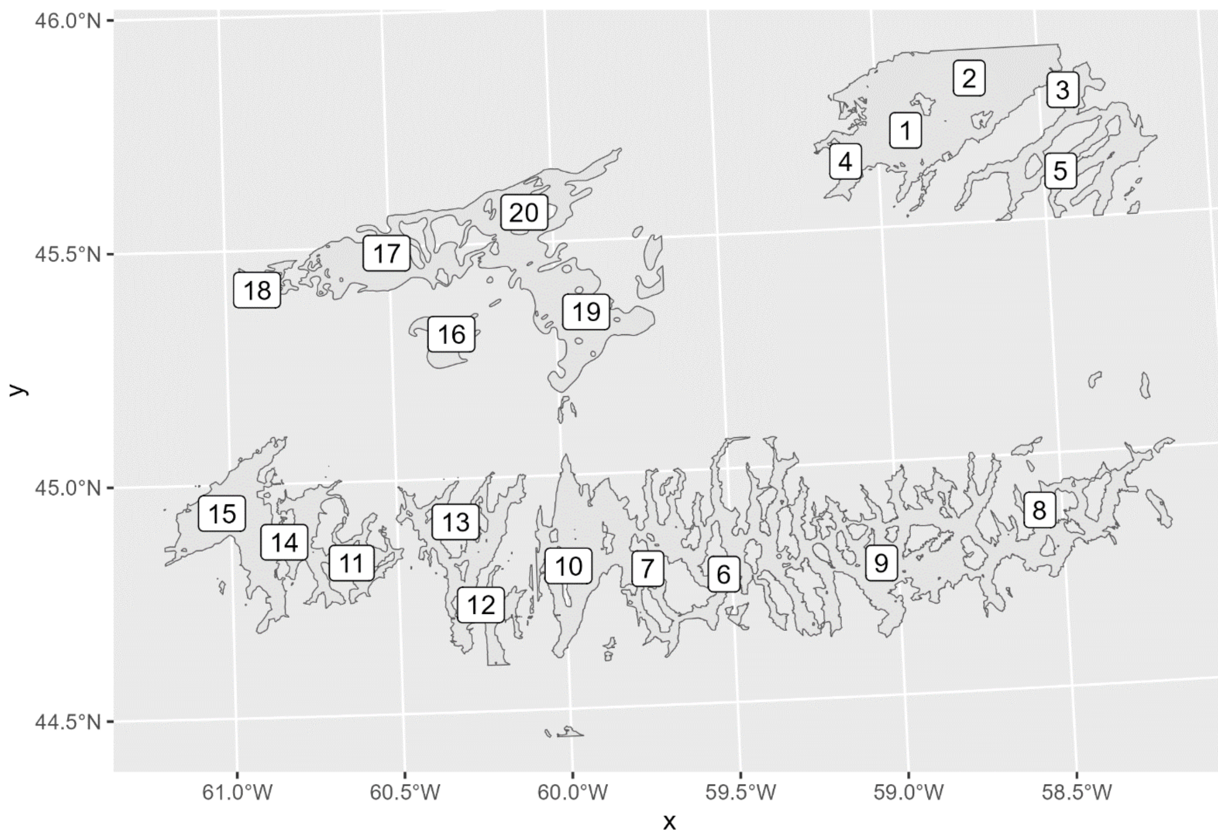


Figure 72. Location of knots and their associated number.

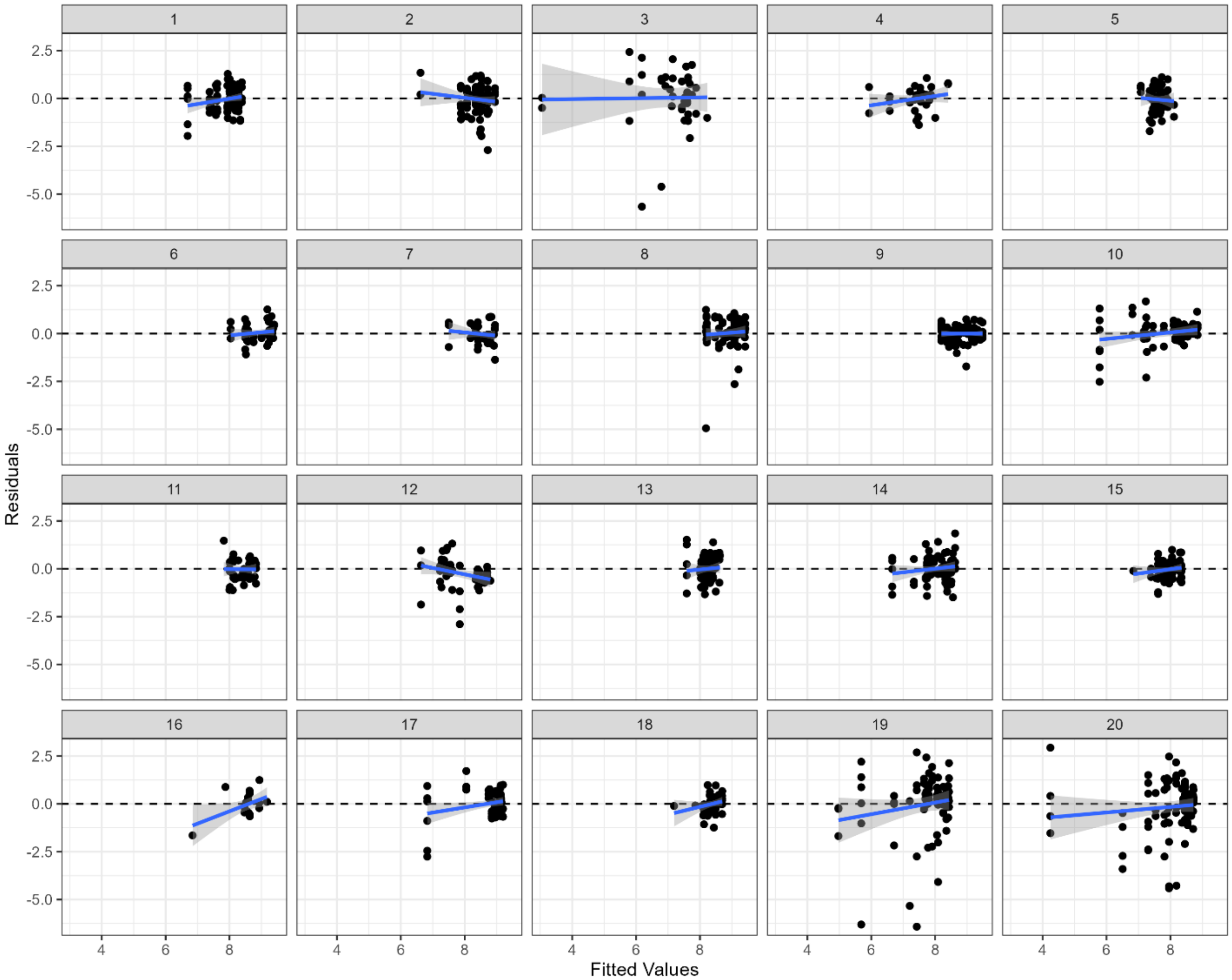


Figure 73. Scatterplot of residuals against fitted values by knot for the Spatially Explicit Assessment Model main trawl biomass observations on the log scale. Blue lines are simple linear regressions.

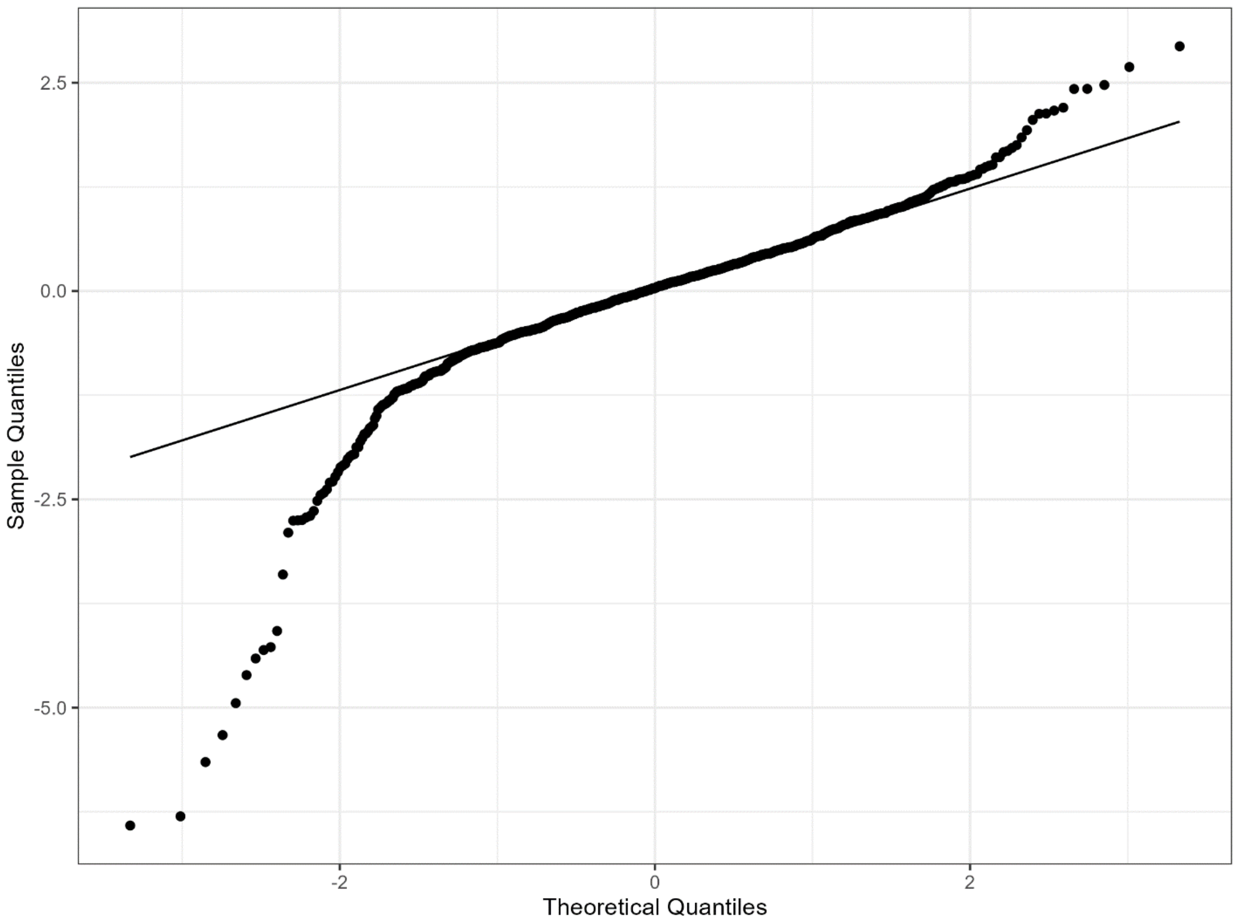


Figure 74. Quantile-quantile plot of residuals for the Spatially Explicit Assessment Model main trawl biomass observations on the log scale.

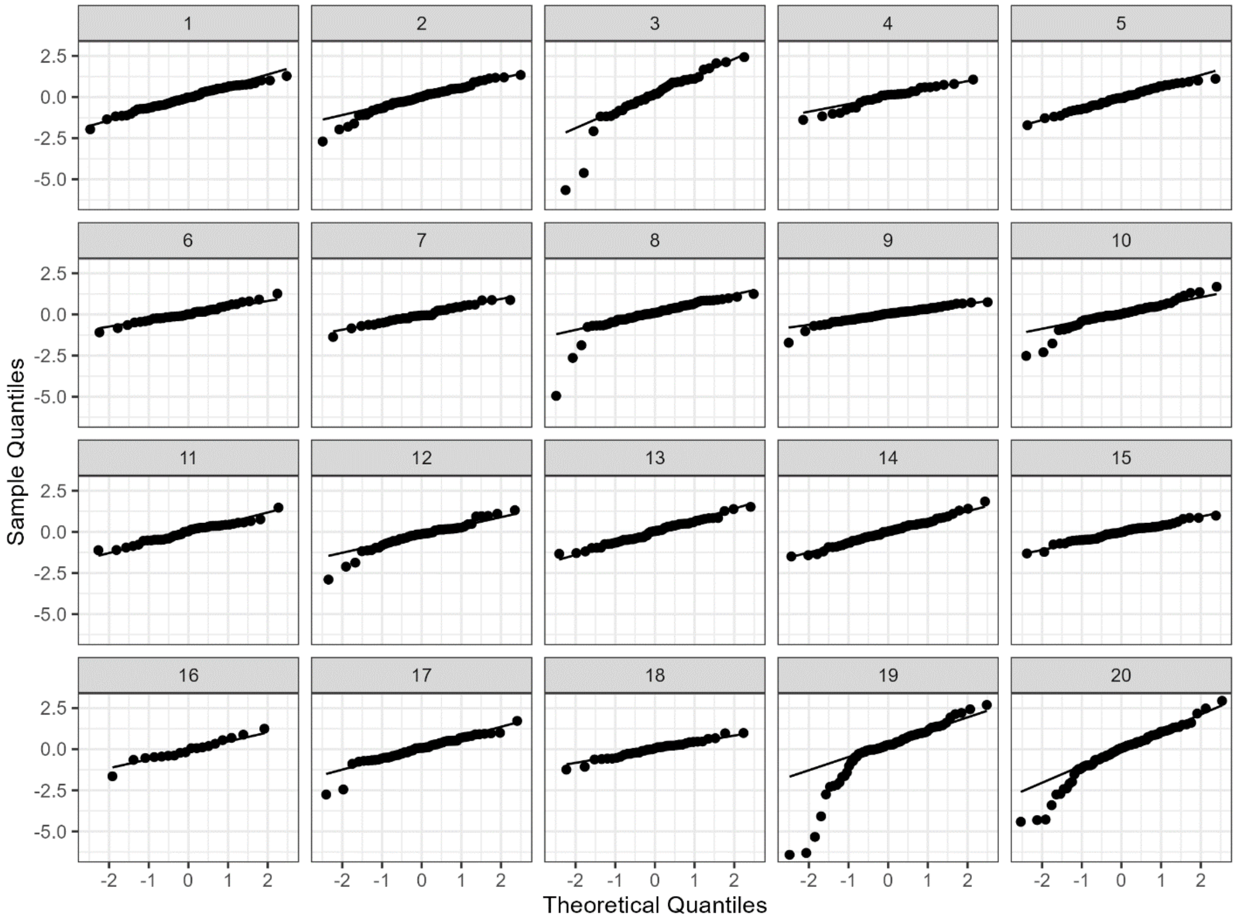


Figure 75. Quantile-quantile plot of residuals by knot for the Spatially Explicit Assessment Model main trawl biomass observations on the log scale.

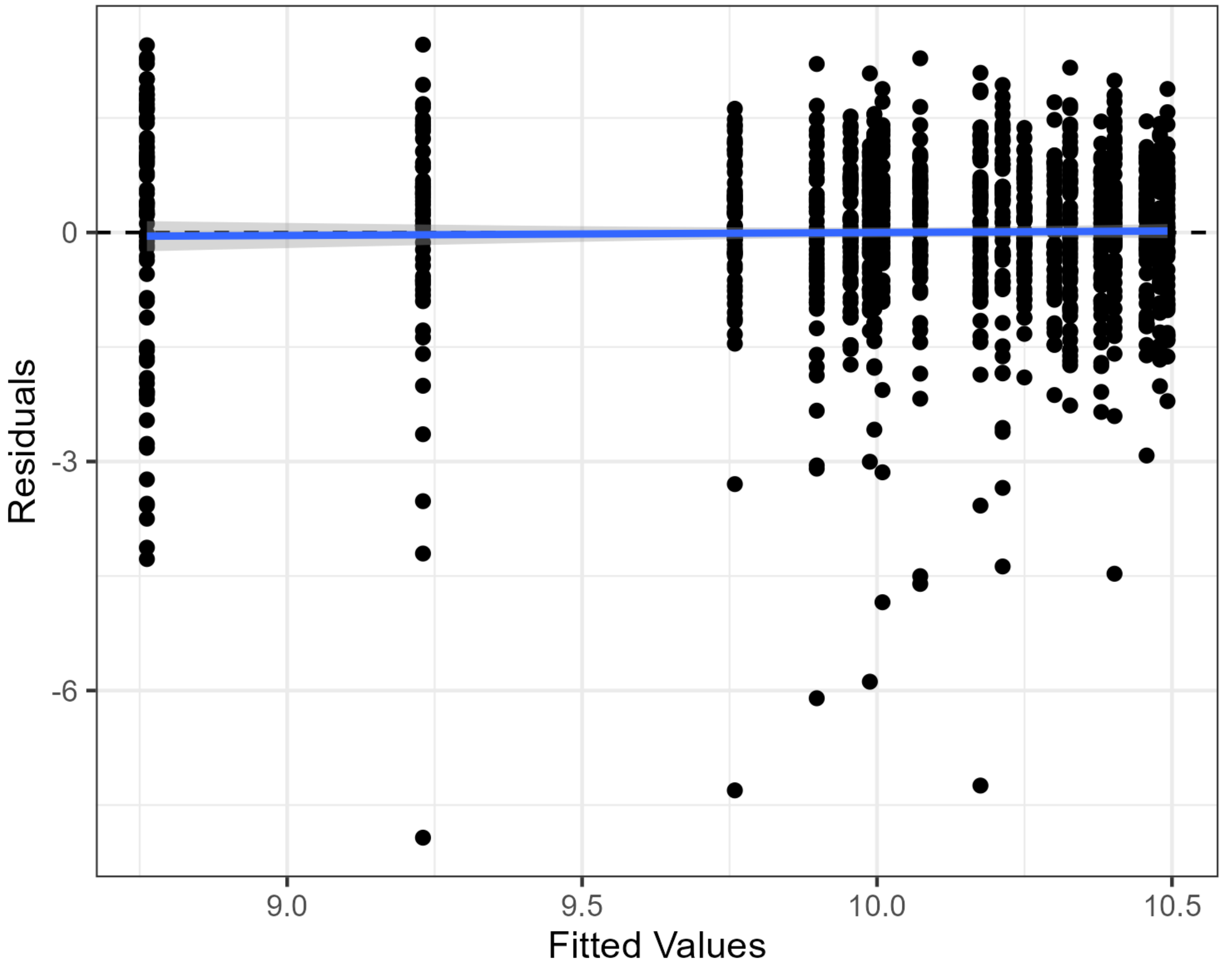


Figure 76. Scatterplot of residuals against fitted values for the Tow Level Model main trawl biomass observations on the log scale. Blue line is a simple linear regression.

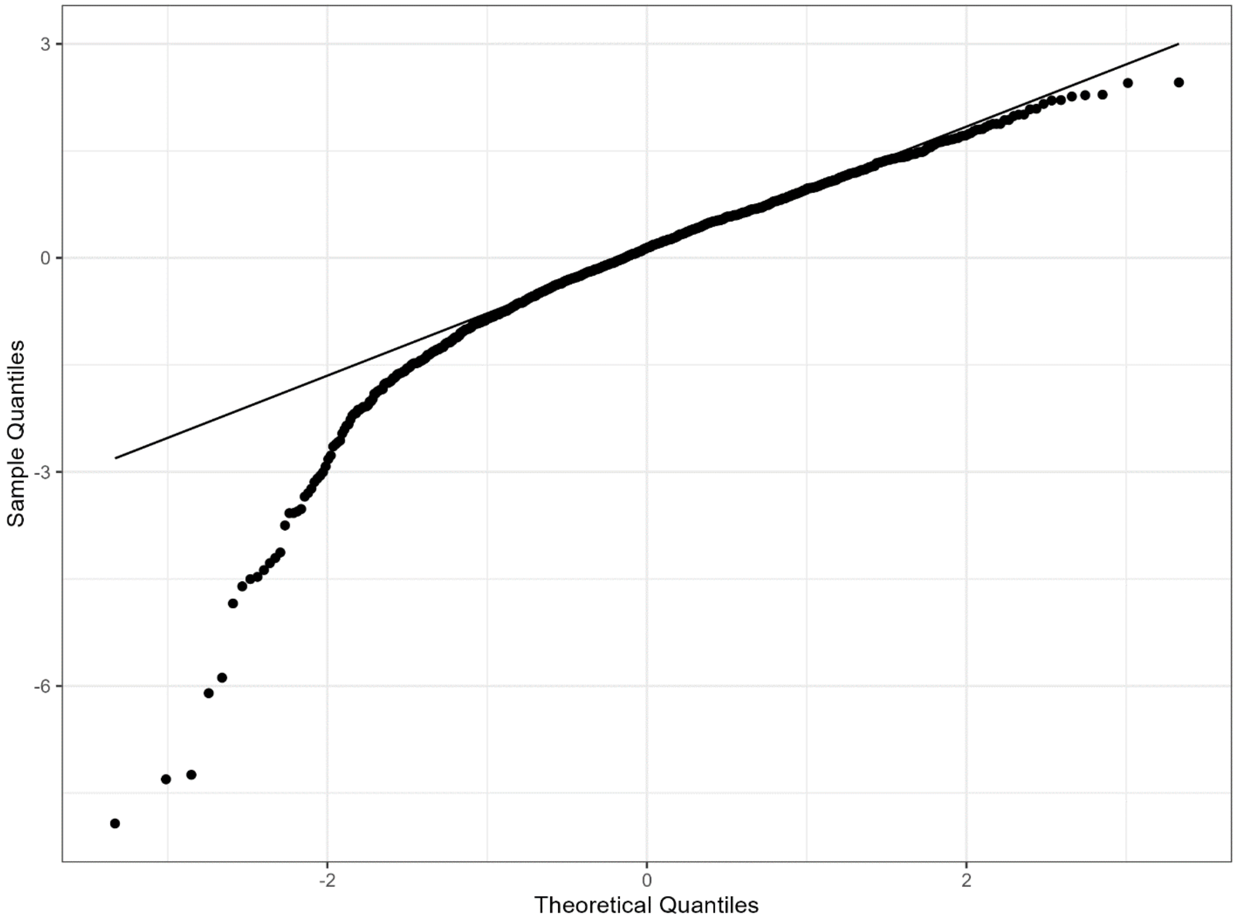


Figure 77. Quantile-quantile plot of residuals for the Tow Level Model main trawl biomass observations on the log scale.

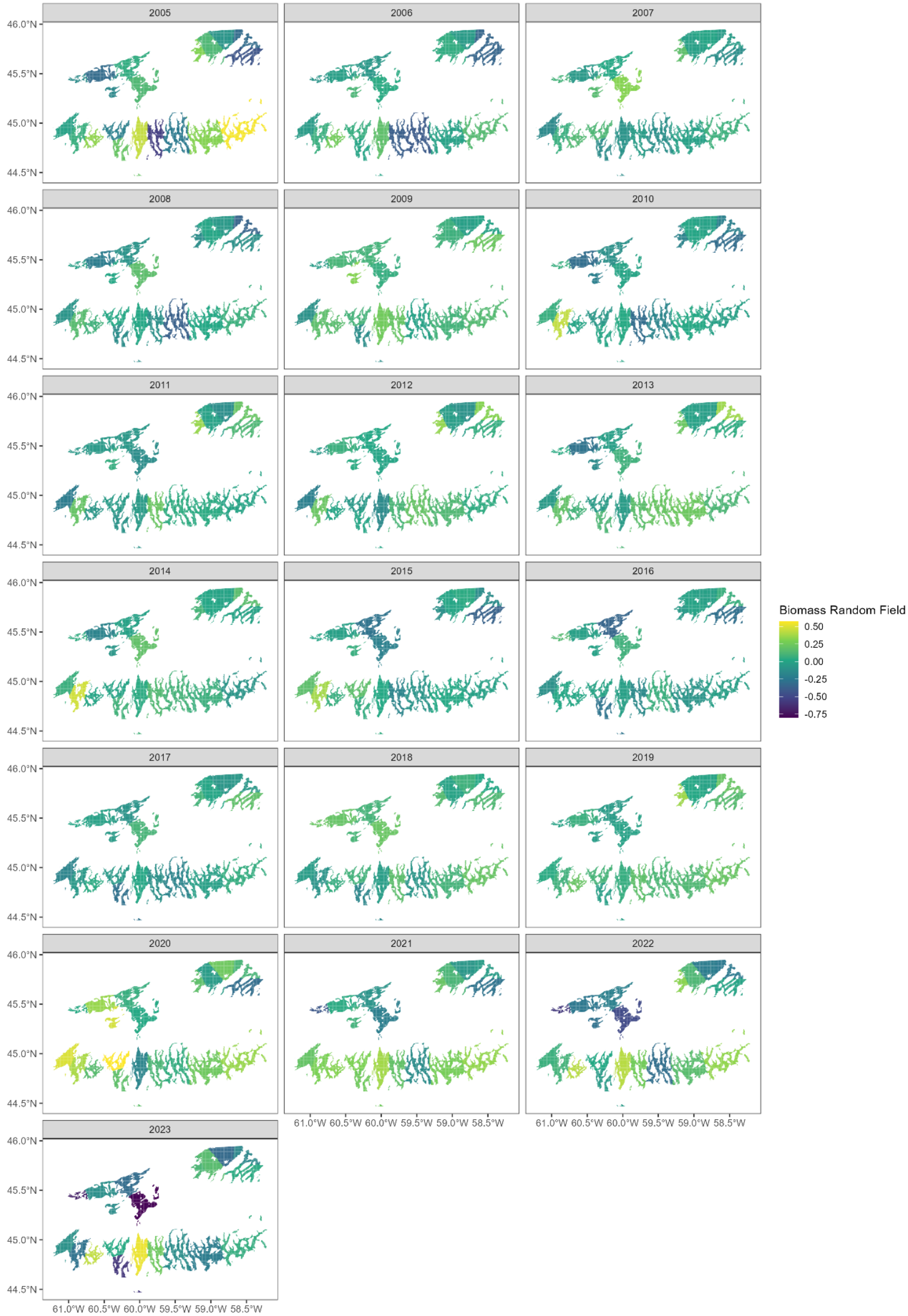


Figure 78. Spatially Explicit Assessment Model biomass random field values at each knot from 2005 to 2023.

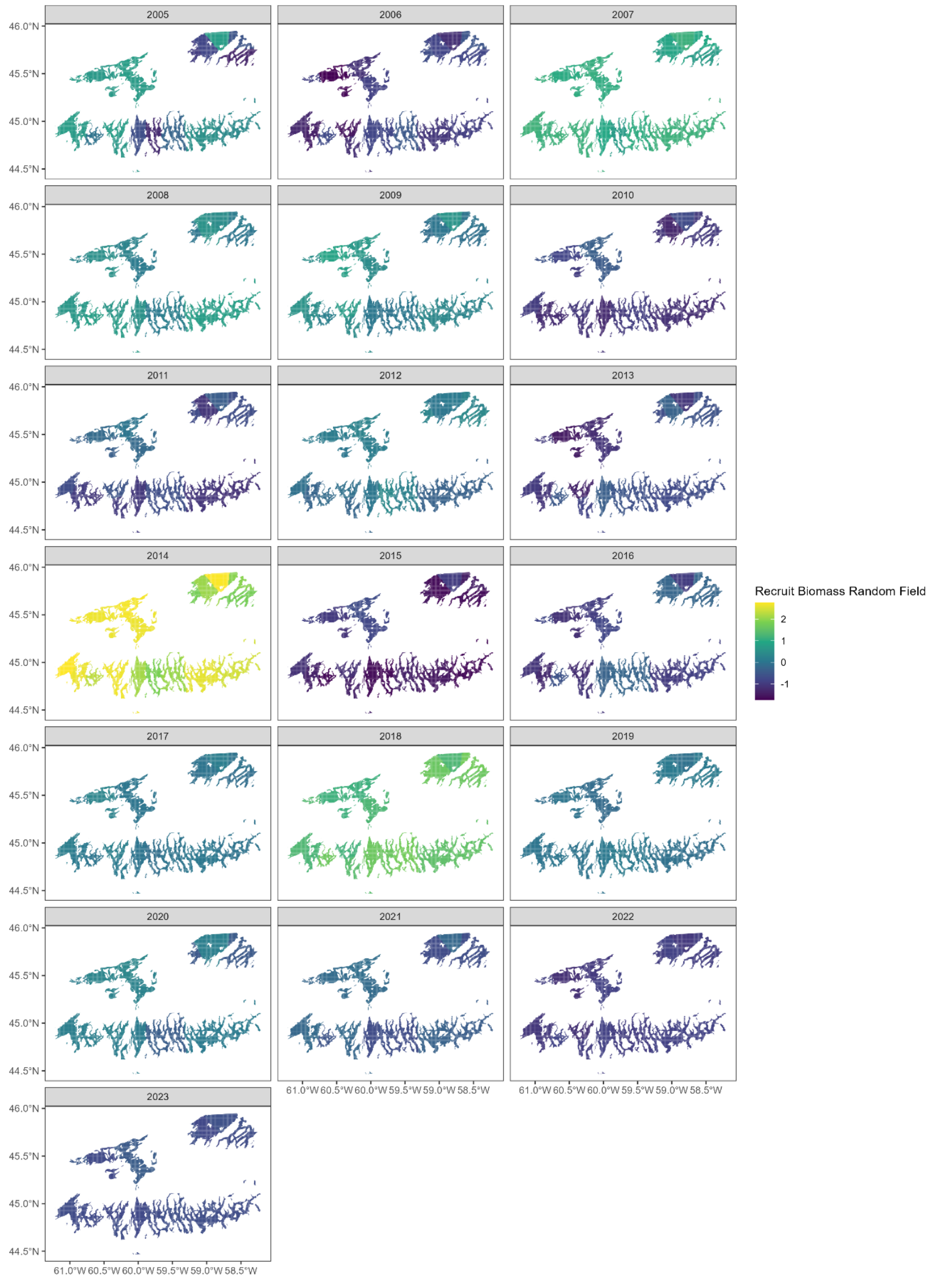


Figure 79. Spatially Explicit Assessment Model recruit biomass random field values at each knot from 2005 to 2023.

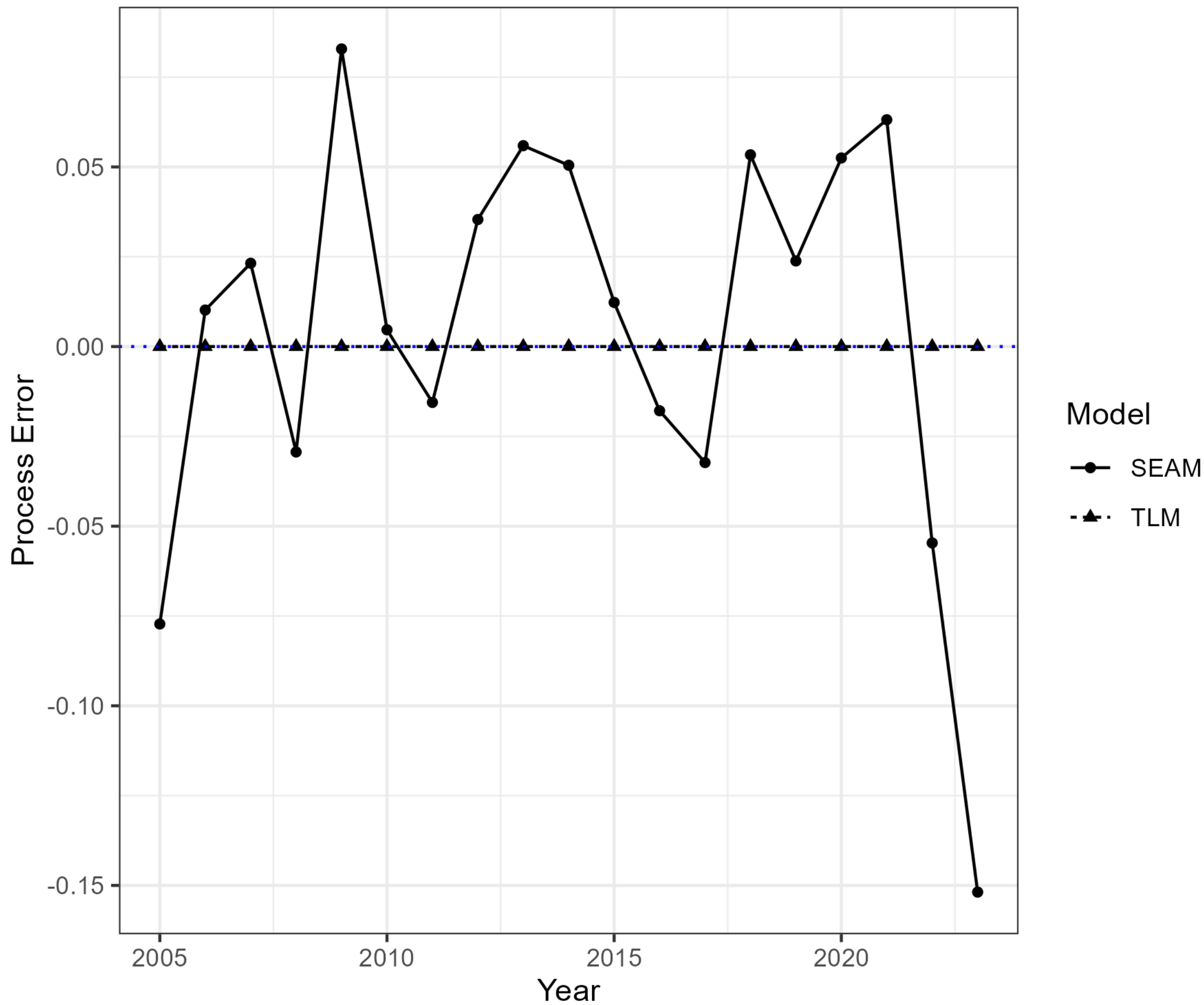


Figure 80. Biomass process errors from the Tow Level Model (TLM) and median random field values Spatially Explicit Assessment Model (SEAM), with zero line indicated by dotted blue line.

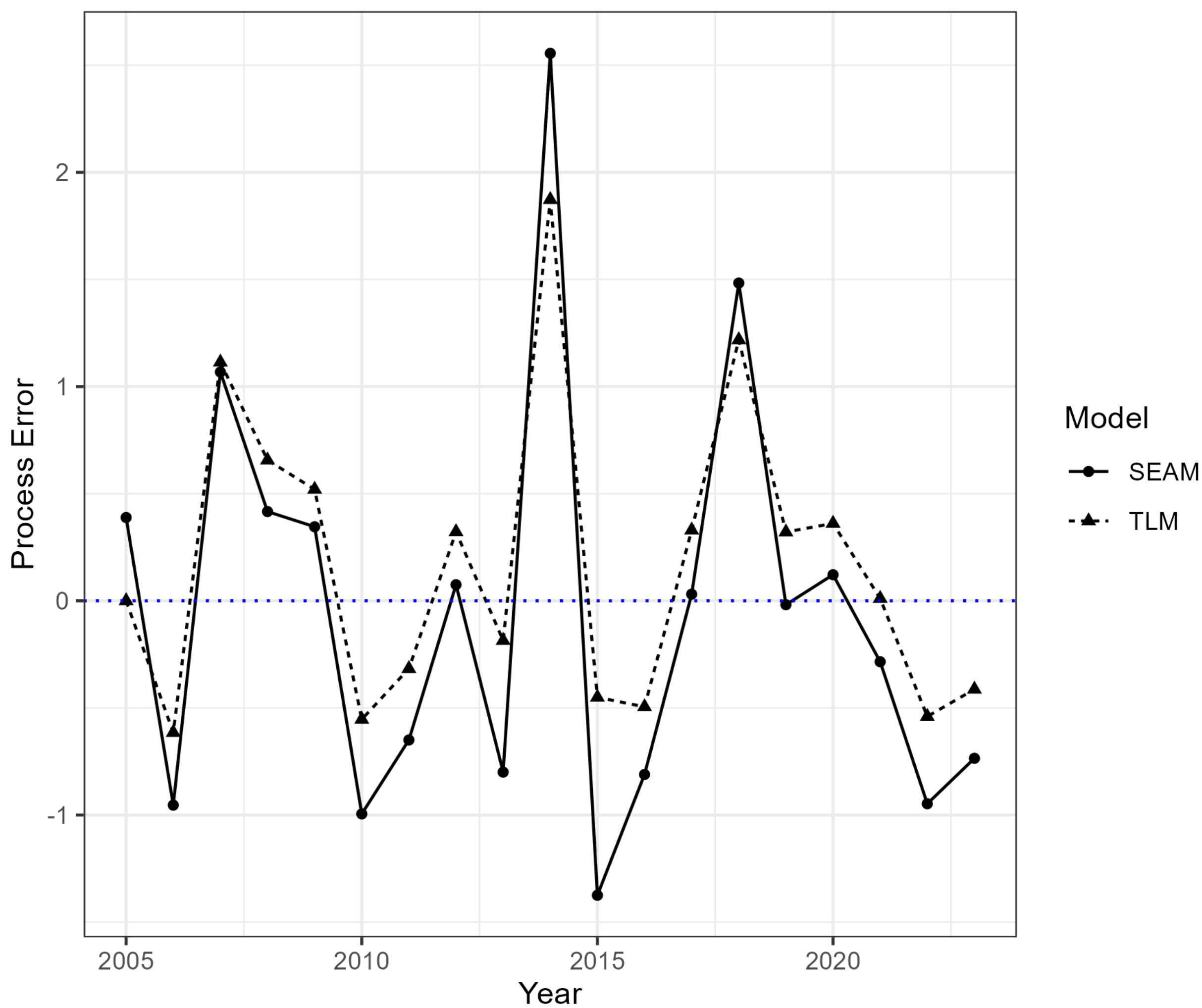


Figure 81. Recruit biomass process errors from the Tow Level Model (TLM) and median random field values from the Spatially Explicit Assessment Model (SEAM), with zero line indicated by dotted blue line.

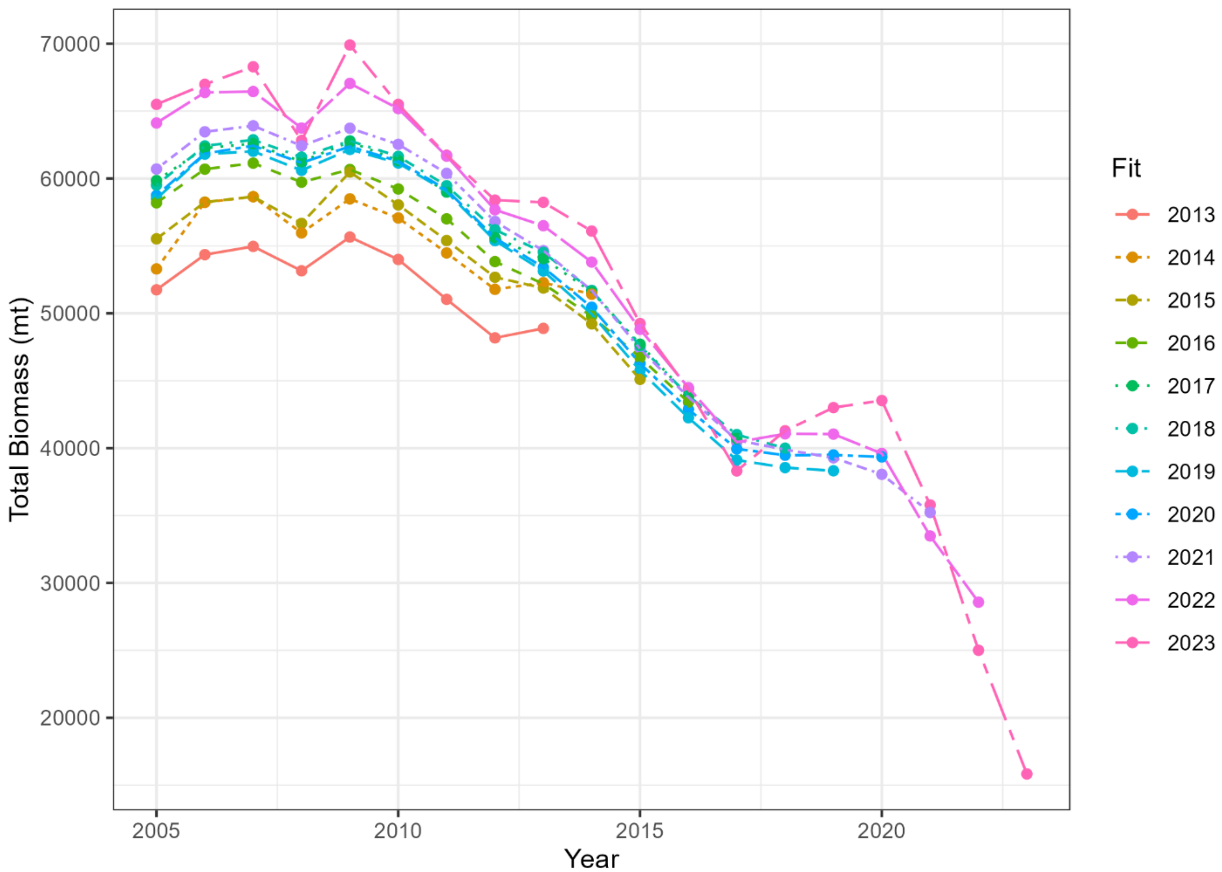


Figure 82. Estimated total biomass in metric tonnes (mt) of each retrospective fits of the Spatially Explicit Assessment Model to data from 2005 to the retrospective fit's year.

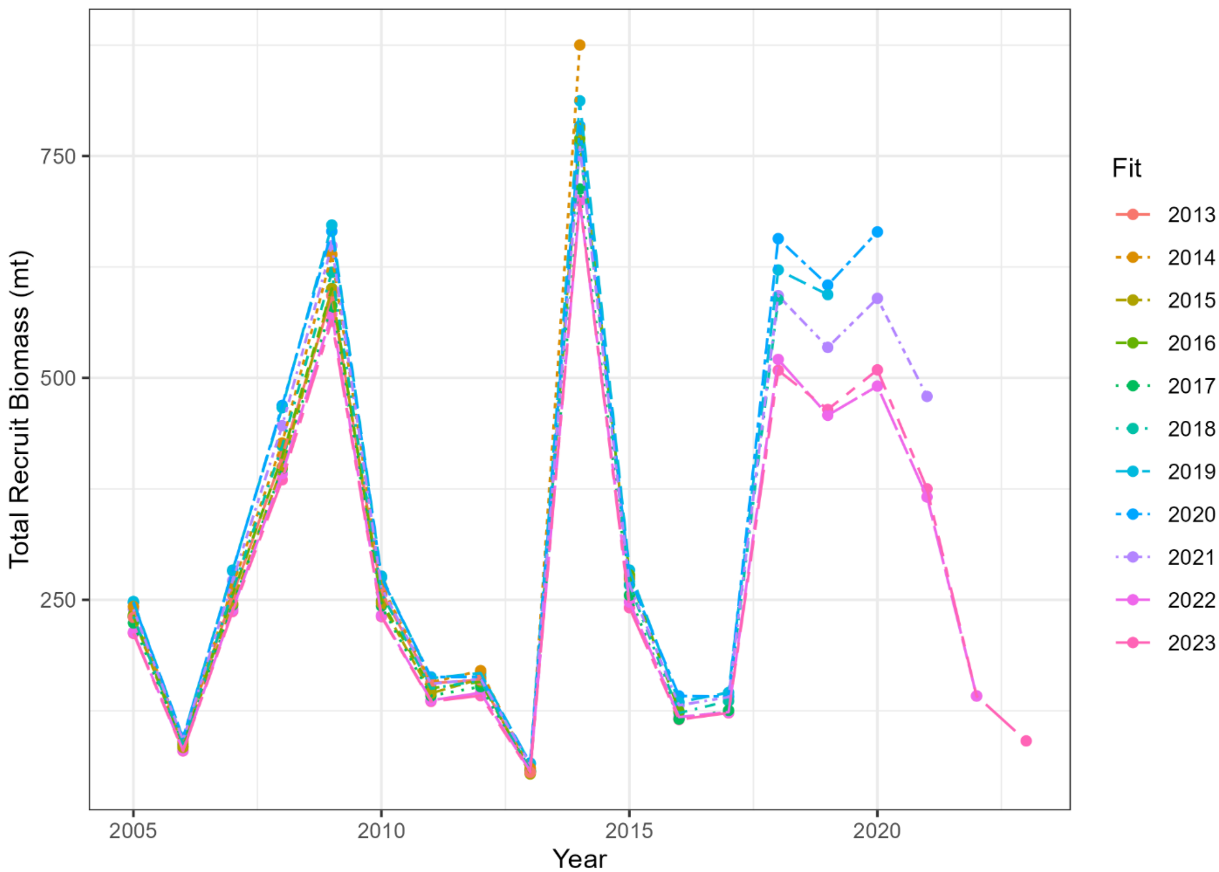


Figure 83. Estimated recruit biomass in metric tonnes (mt) of each retrospective fits of the Spatially Explicit Assessment Model to data from 2005 to the retrospective fit's year.

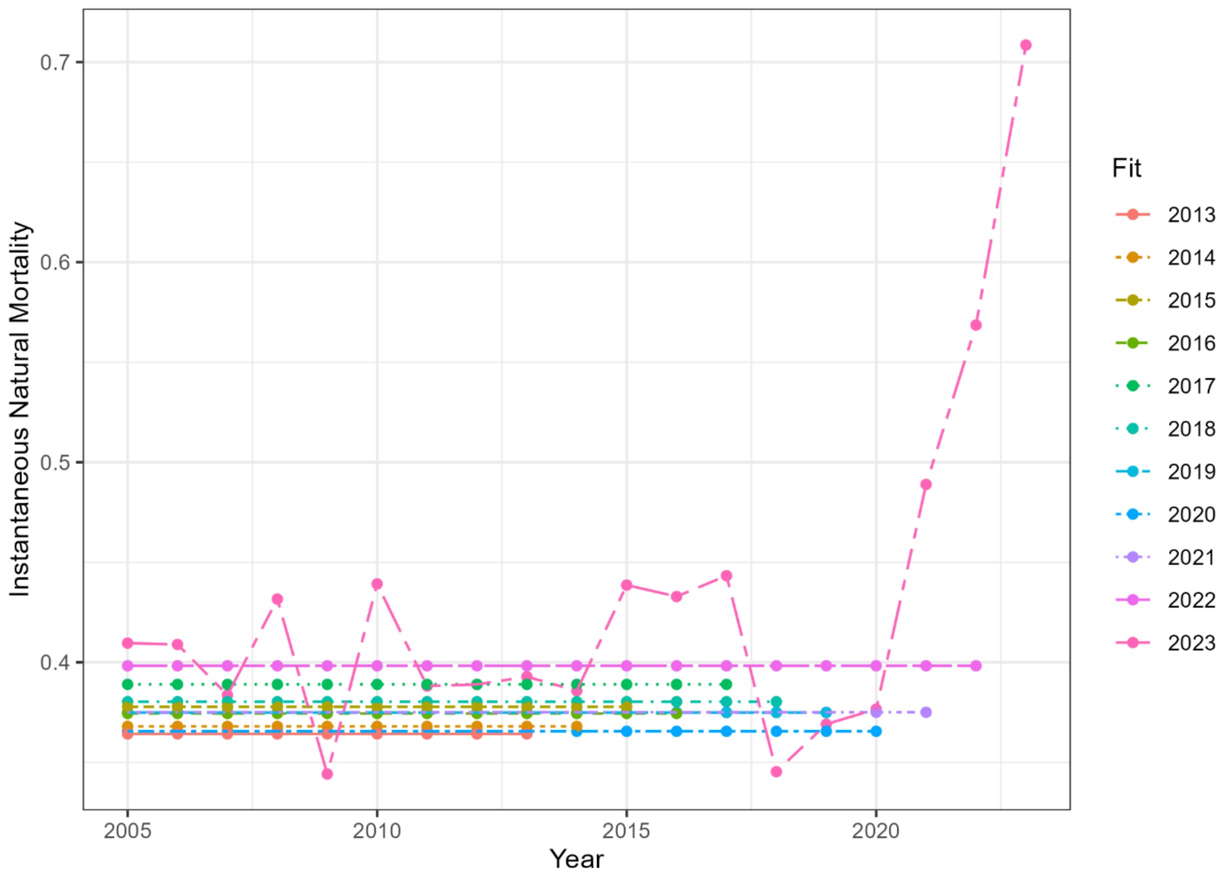


Figure 84. Estimated instantaneous natural mortality of each retrospective fits of the Spatially Explicit Assessment Model to data from 2005 to the retrospective fit's year.

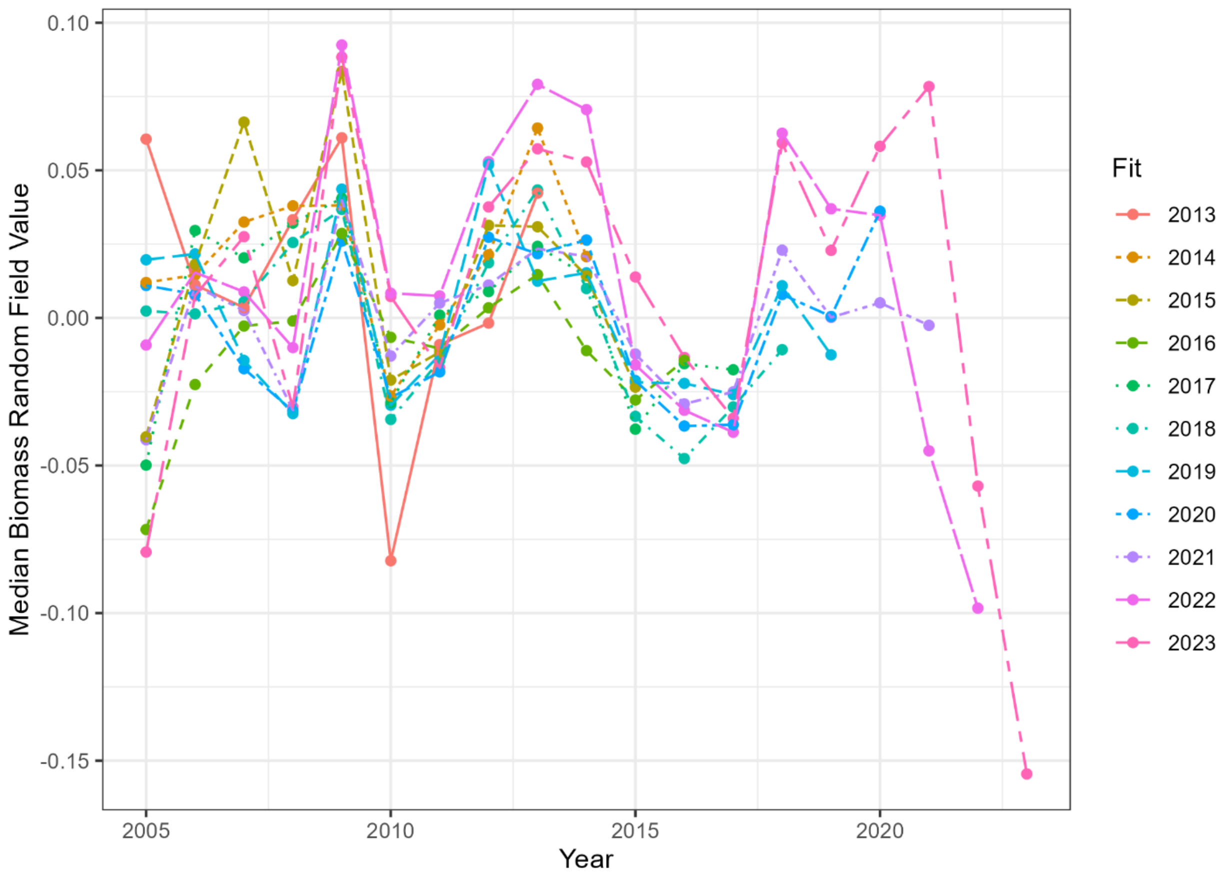


Figure 85. Median biomass random field value of each retrospective fits of Tow Level Model to data from 2005 to the retrospective fit's year.

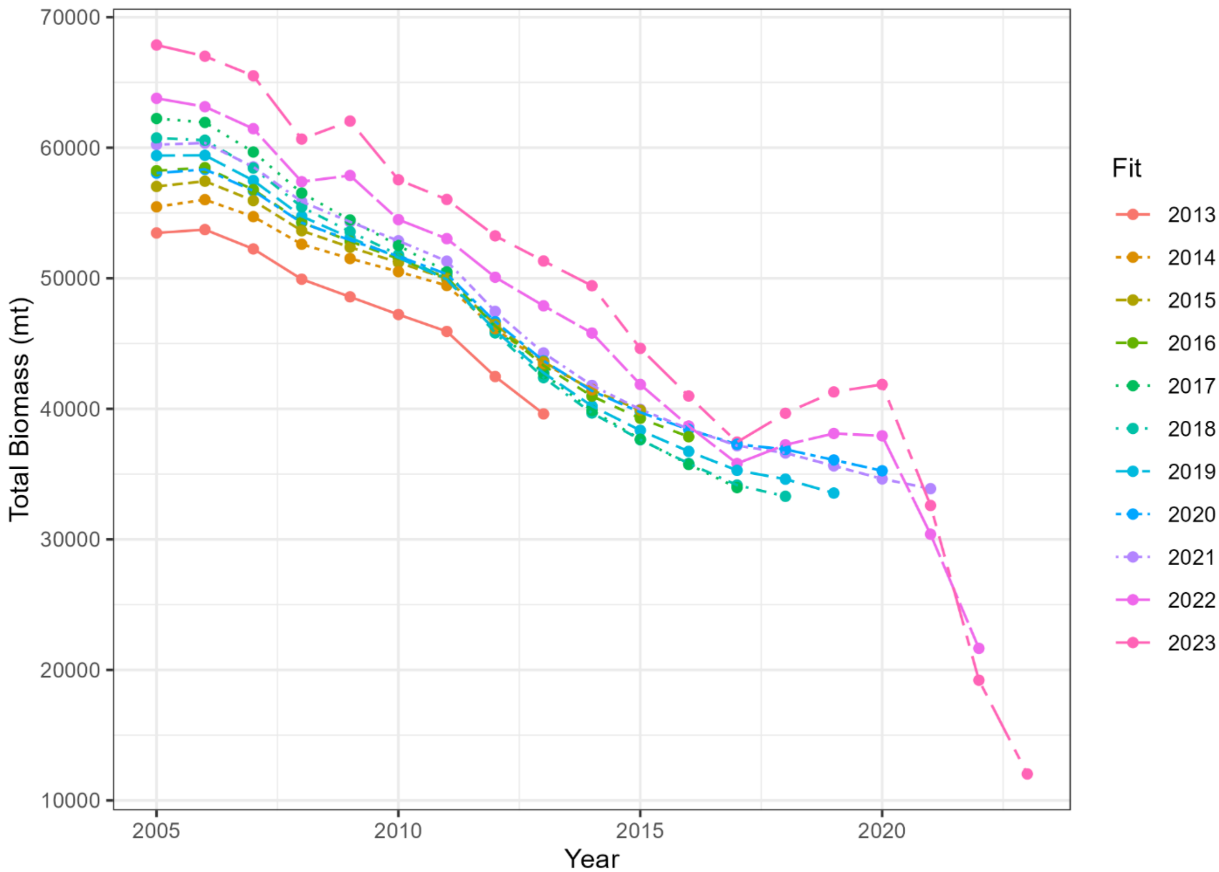


Figure 86. Estimated total biomass in metric tonnes (mt) of each retrospective fits of Tow Level Model to data from 2005 to the retrospective fit's year.

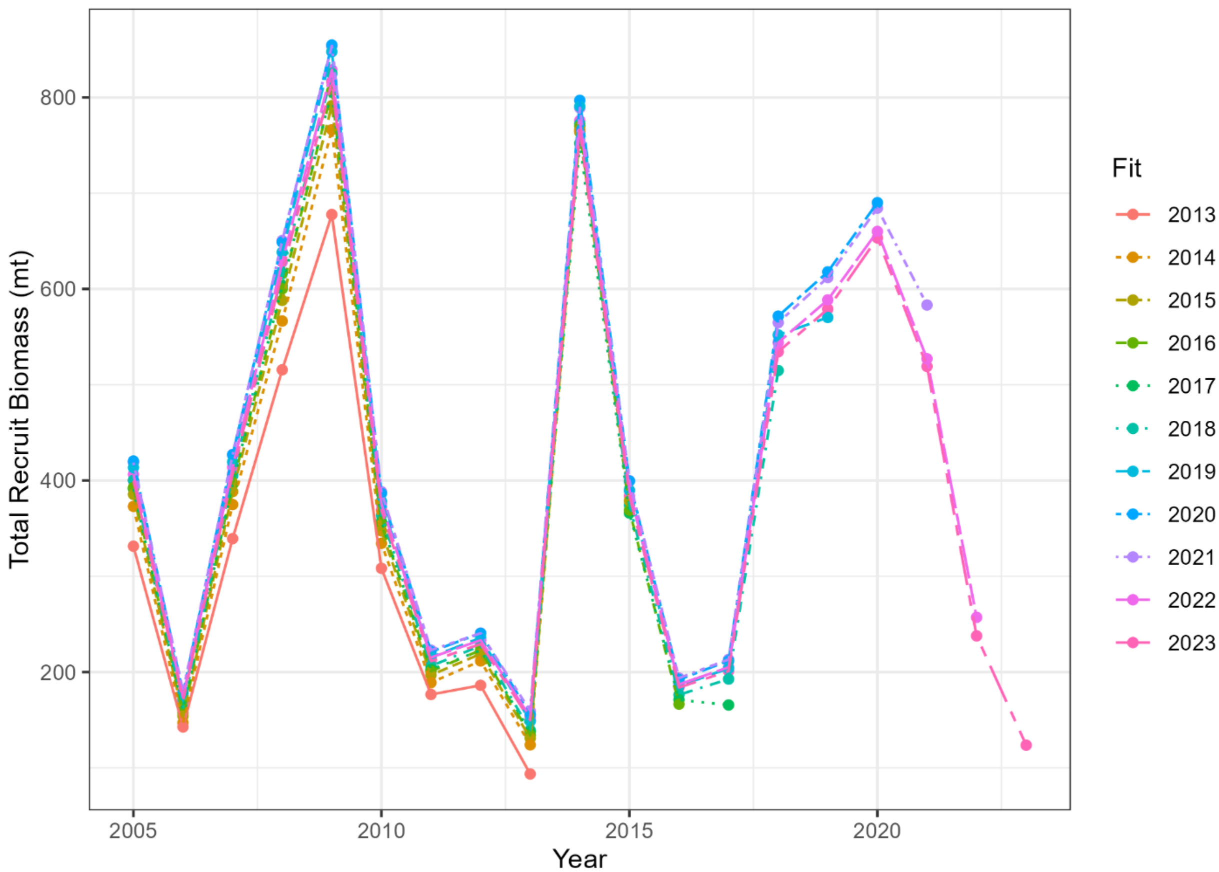


Figure 87. Estimated recruit biomass in metric tonnes (mt) of each retrospective fits of Tow Level Model to data from 2005 to the retrospective fit's year.

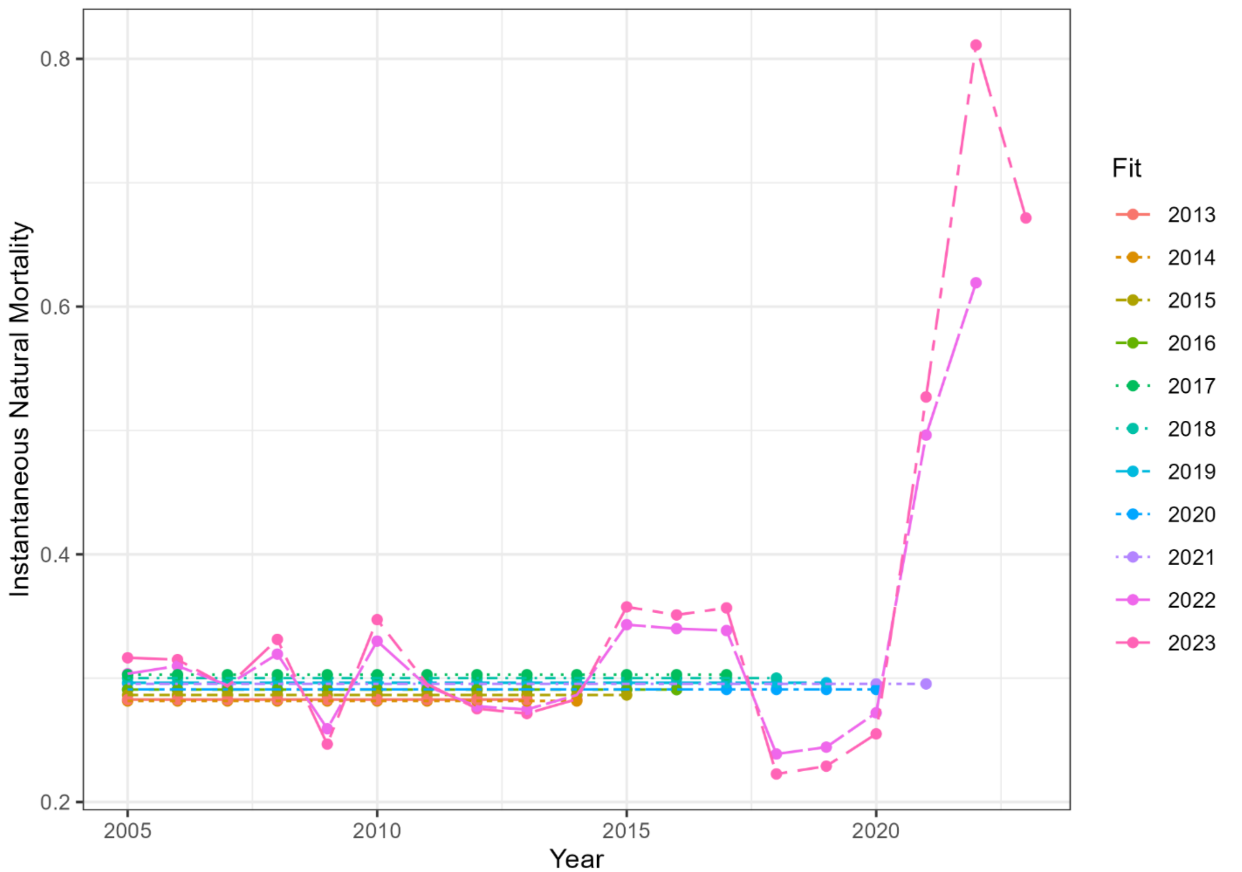


Figure 88. Estimated instantaneous natural mortality of each retrospective fits of Tow Level Model to data from 2005 to the retrospective fit's year.

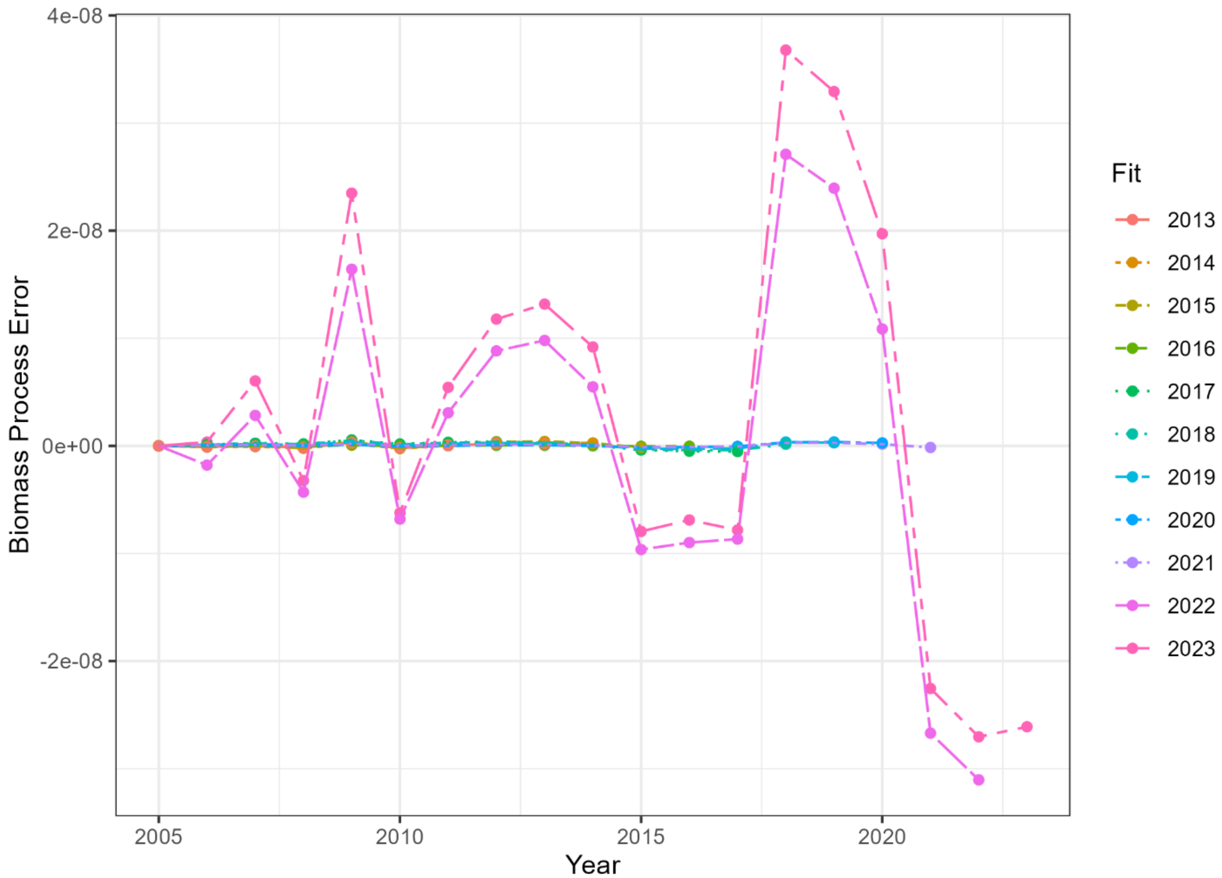


Figure 89. Biomass process errors of each retrospective fits of Tow Level Model to data from 2005 to the retrospective fit's year.

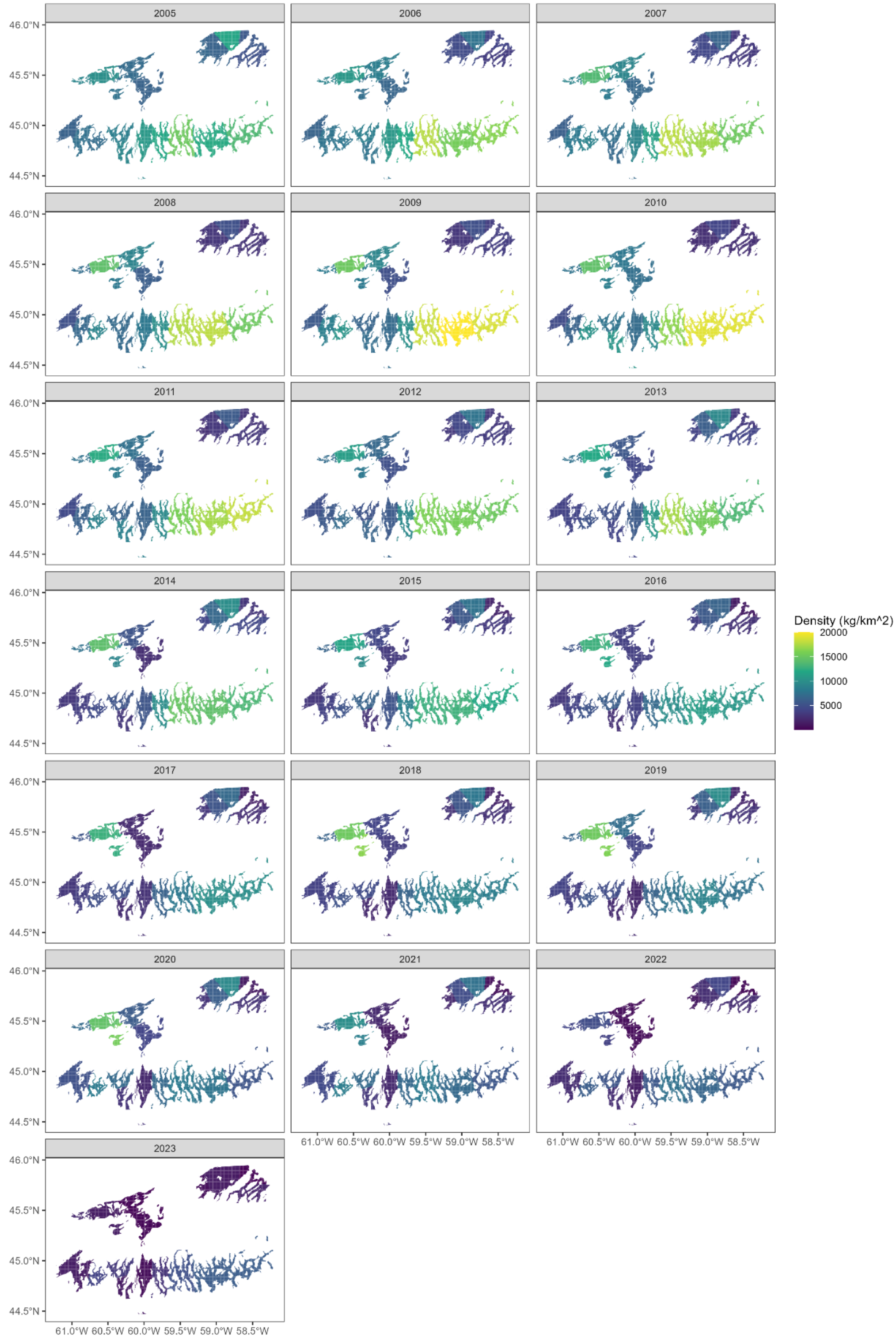


Figure 90. Biomass densities in kilograms per square kilometre (kg/km^2) in each knot between 2005 and 2023 from the Spatially Explicit Assessment Model.

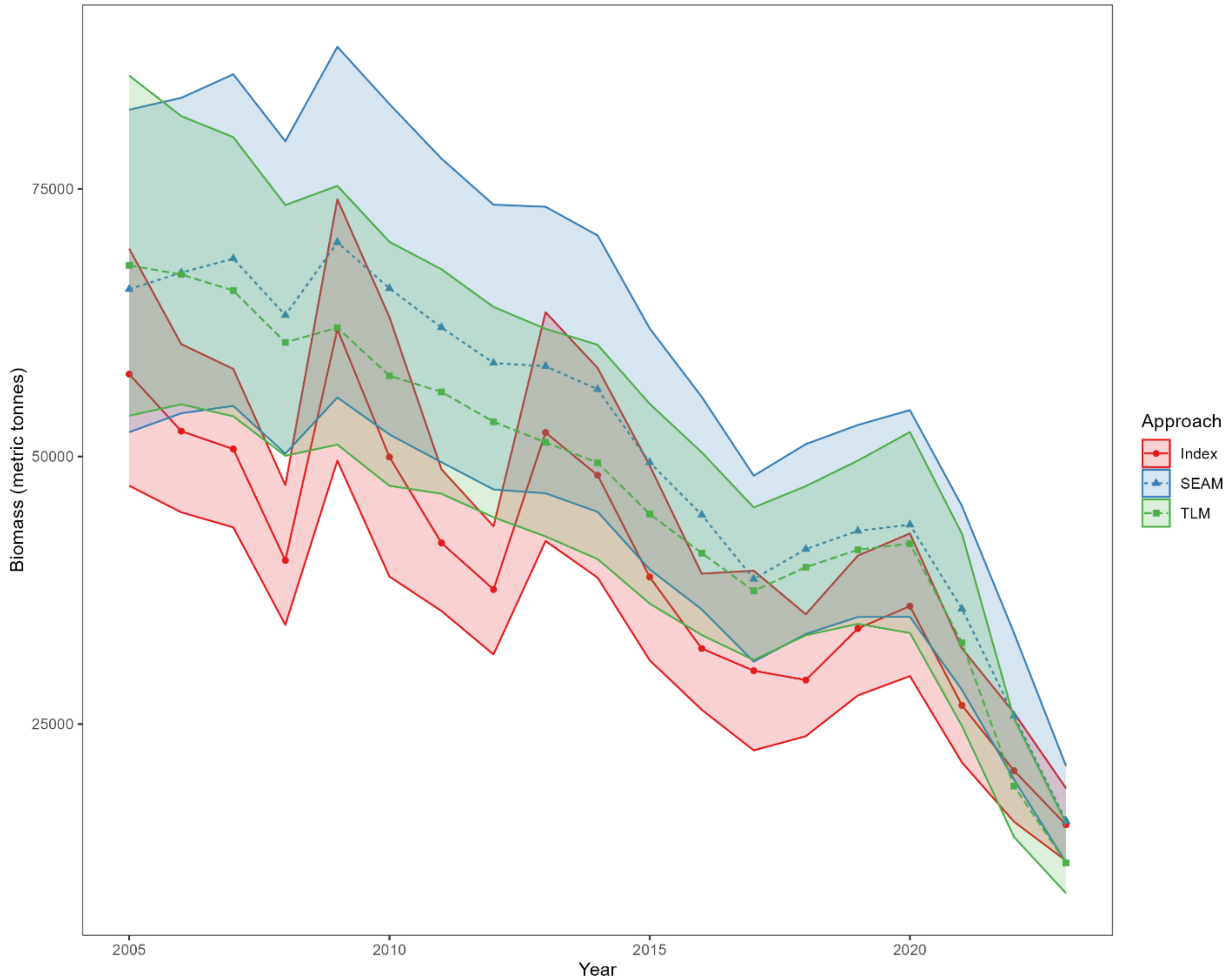


Figure 91. Total biomass in metric tonnes between 2005 and 2023 estimated by the index (red circles, solid line), by the Spatially Explicit Assessment Model (SEAM) [blue triangles, dashed line] and by the Tow Level Model (TLM) [green squares, long dashed line].

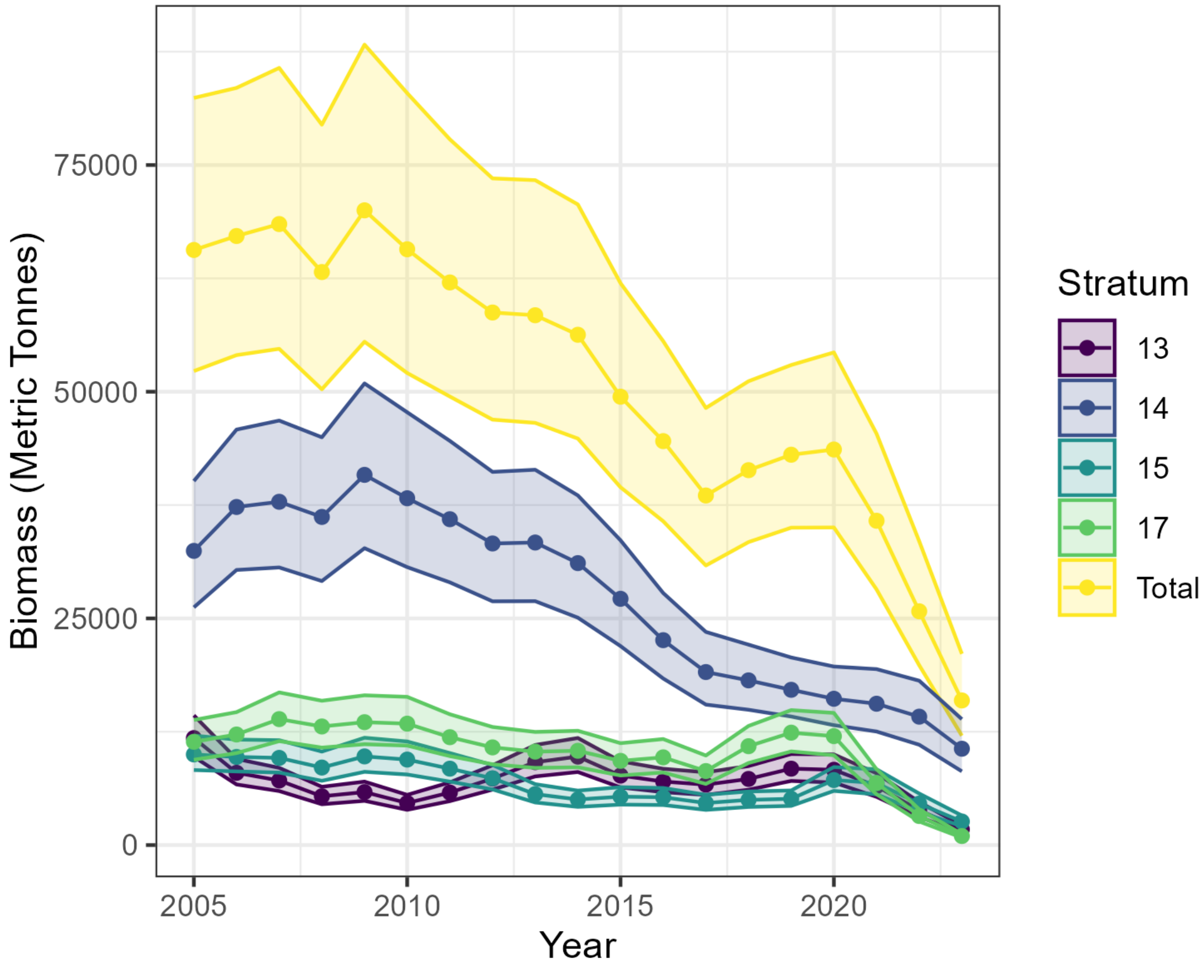


Figure 92. Total biomass and strata-specific biomass estimated by the Spatially Explicit Assessment Model between 2005 and 2023.

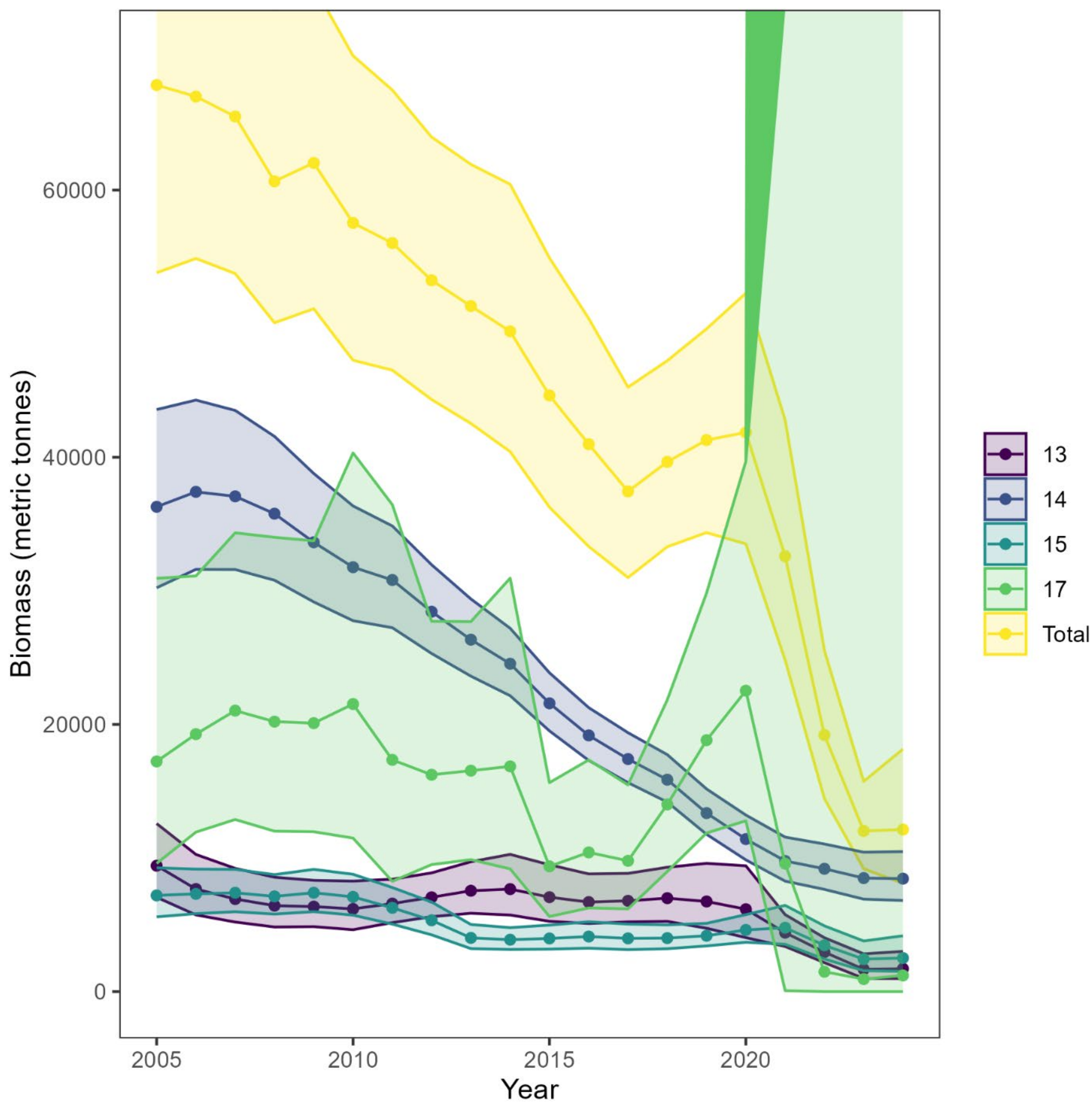


Figure 93. Total biomass and strata-specific biomass estimated by Tow Level Model between 2005 and 2023. The extreme uncertainty for the biomass in Stratum 17 are caused by a false convergence and the natural mortality breaking due to low amounts of data and years, and the estimates of biomass for Stratum 17 are likely not reliable.

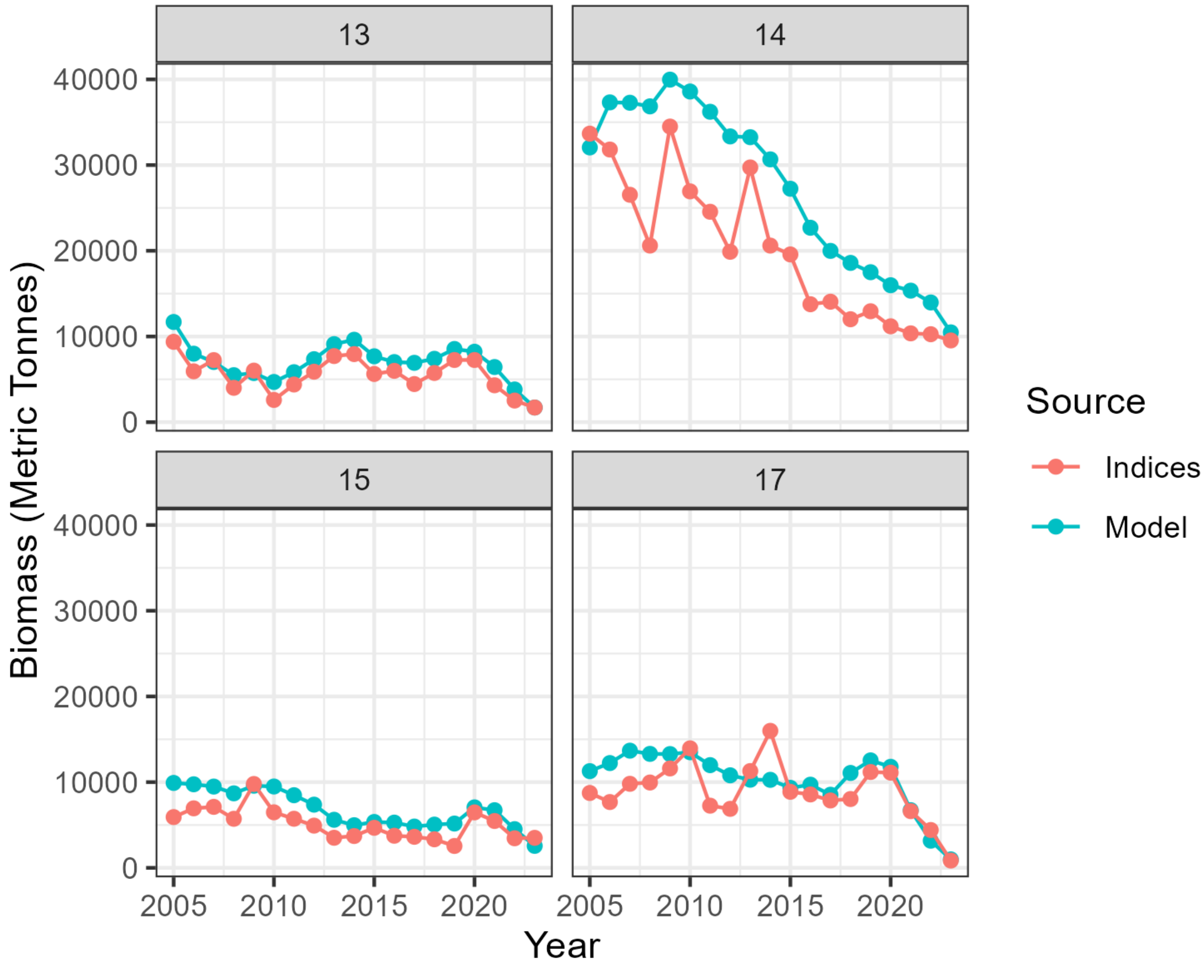


Figure 94. Strata-specific biomass between 2005 and 2023 estimated by the Spatially Explicit Assessment Model [blue] and using the swept-area index method [red].

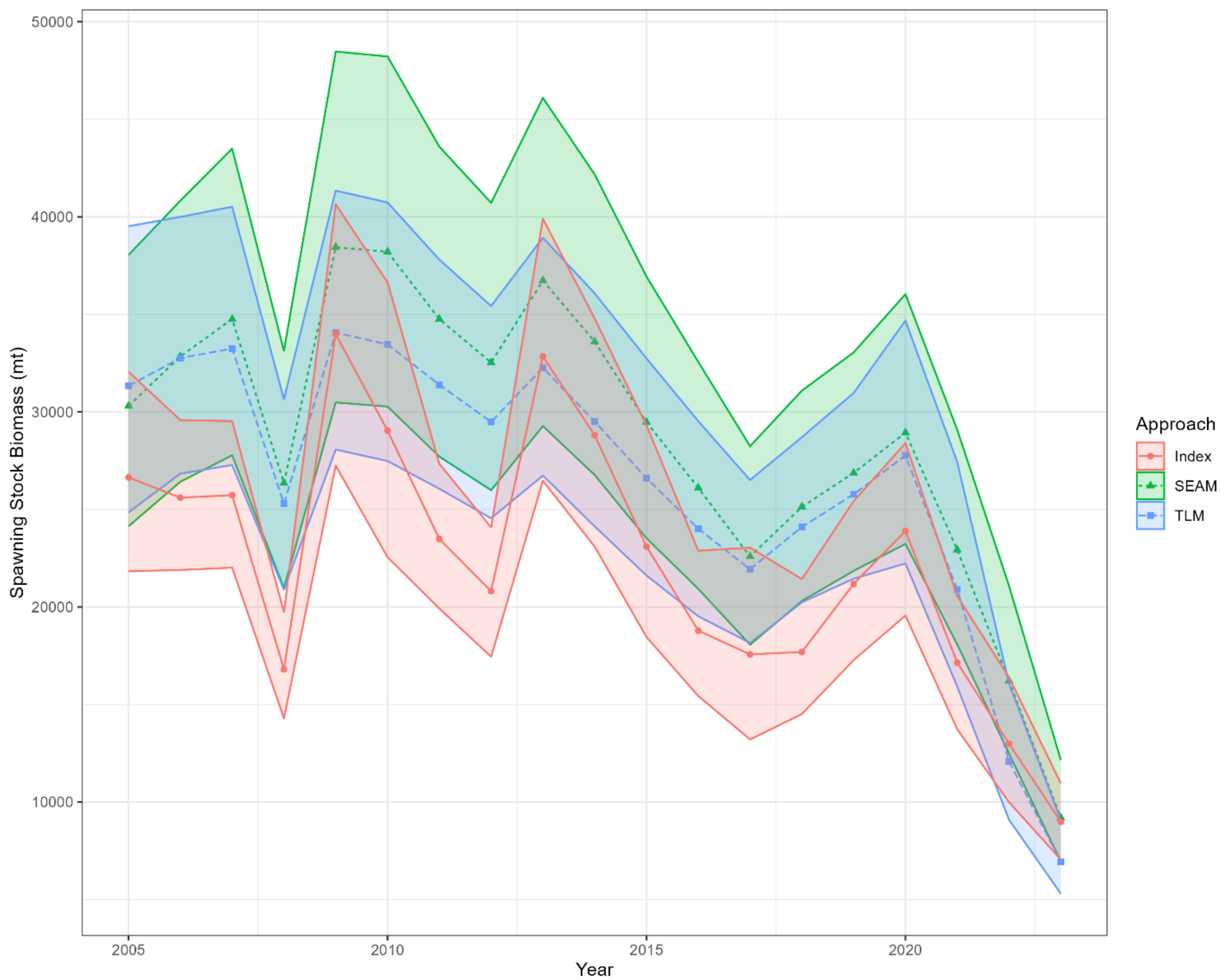


Figure 95. Spawning stock biomass in metric tonnes (mt) (biomass of transitional and female shrimps) between 2005 and 2023 calculated using the swept-area method (index, red circles), from the Spatially Explicit Assessment Model (SEAM) [green triangles] and by the Tow Level Model (TLM) [blue squares].

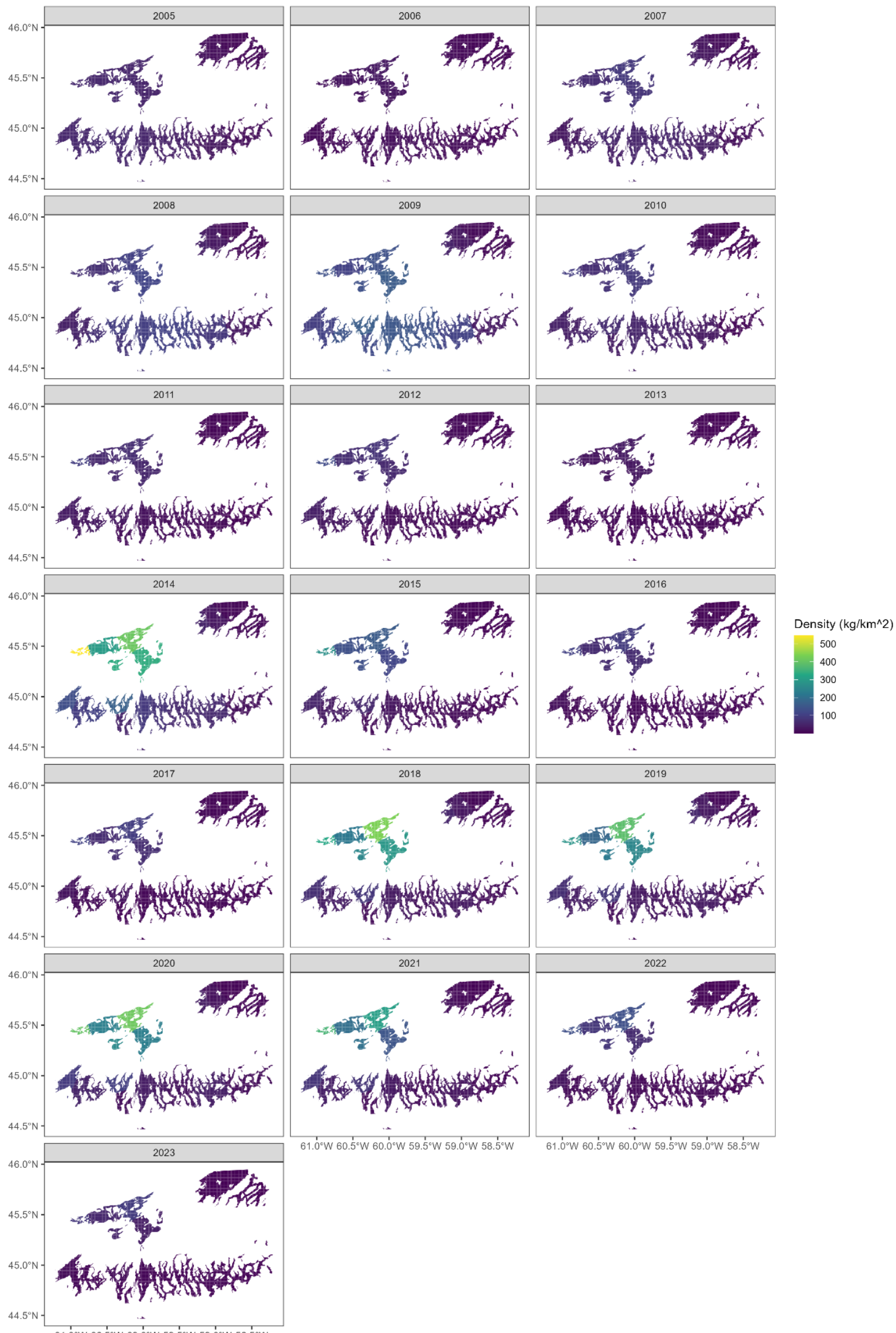


Figure 96. Recruit biomass density in kilograms per square kilometre (kg/km^2) at each knot between 2005 and 2023 estimated by the Spatially Explicit Assessment Model.

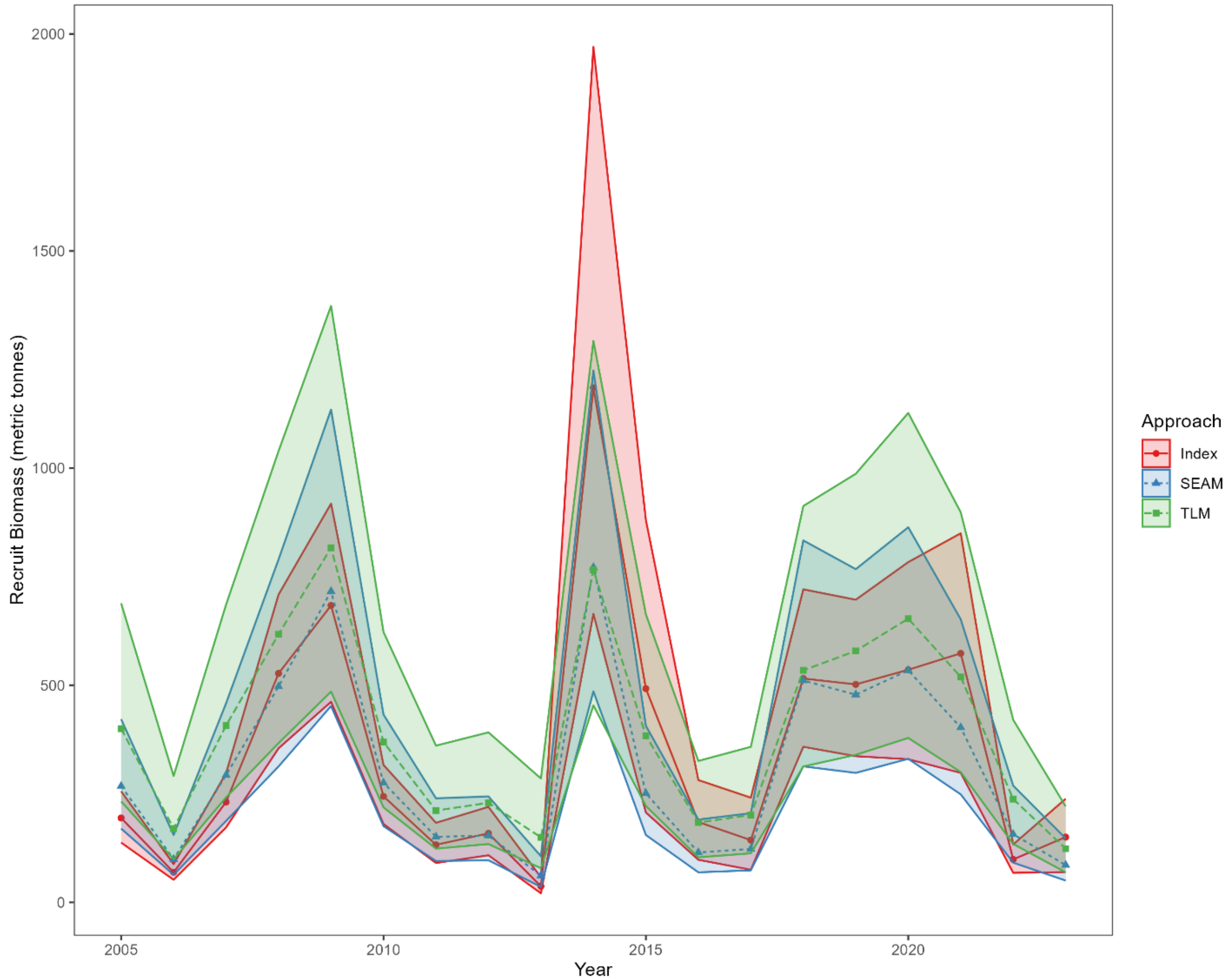


Figure 97. Total recruit biomass in metric tonnes between 2005 and 2023 estimated by the swept area index method corrected for the recruit catchability (red circles), by the Spatially Explicit Assessment Model (SEAM) [blue triangles] and by the Tow Level Model (TLM) [green squares].

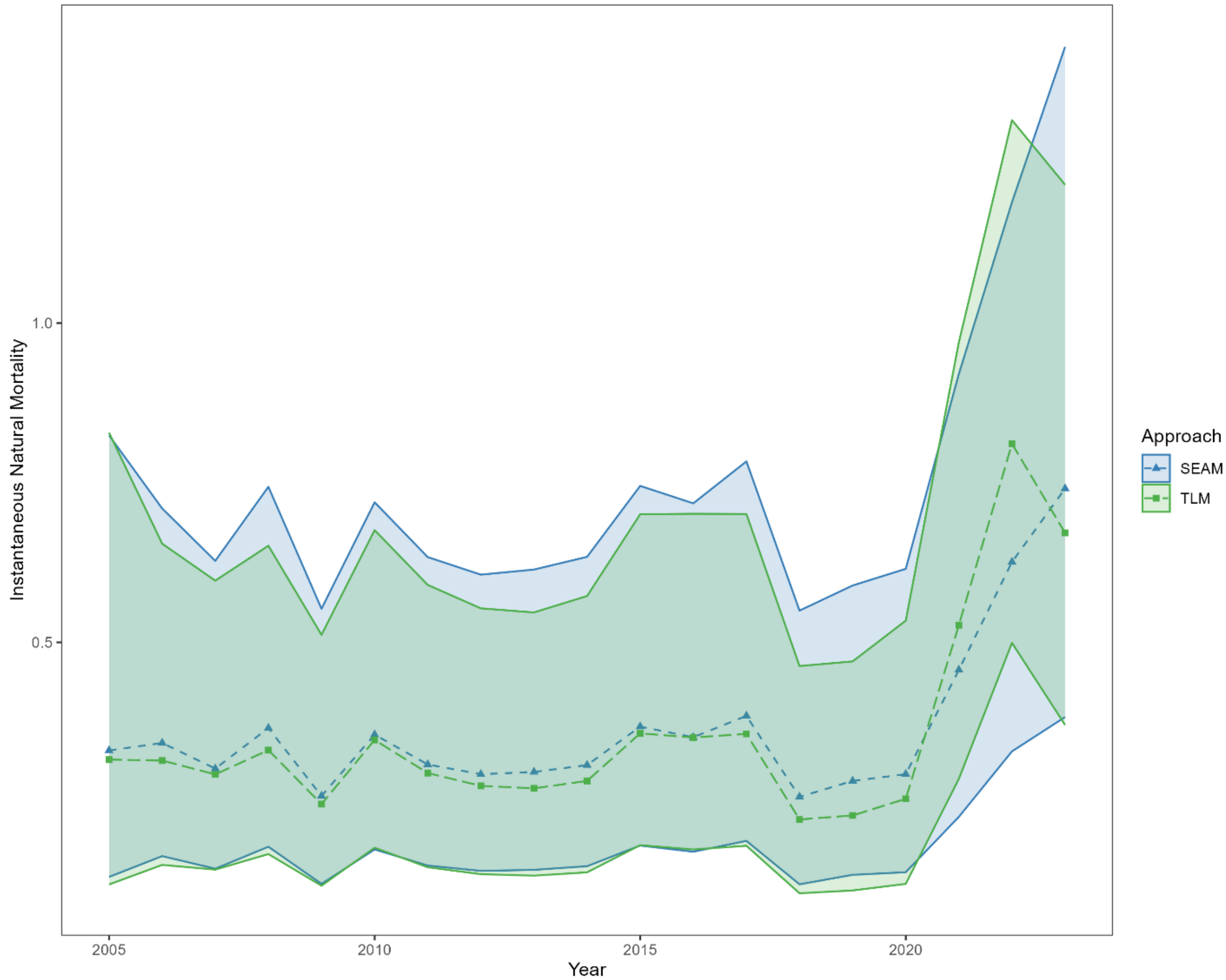


Figure 98. Instantaneous natural mortality estimated by the Spatially Explicit Assessment Model (SEAM) [blue triangles] and by the Tow Level Model (TLM) [green triangles].

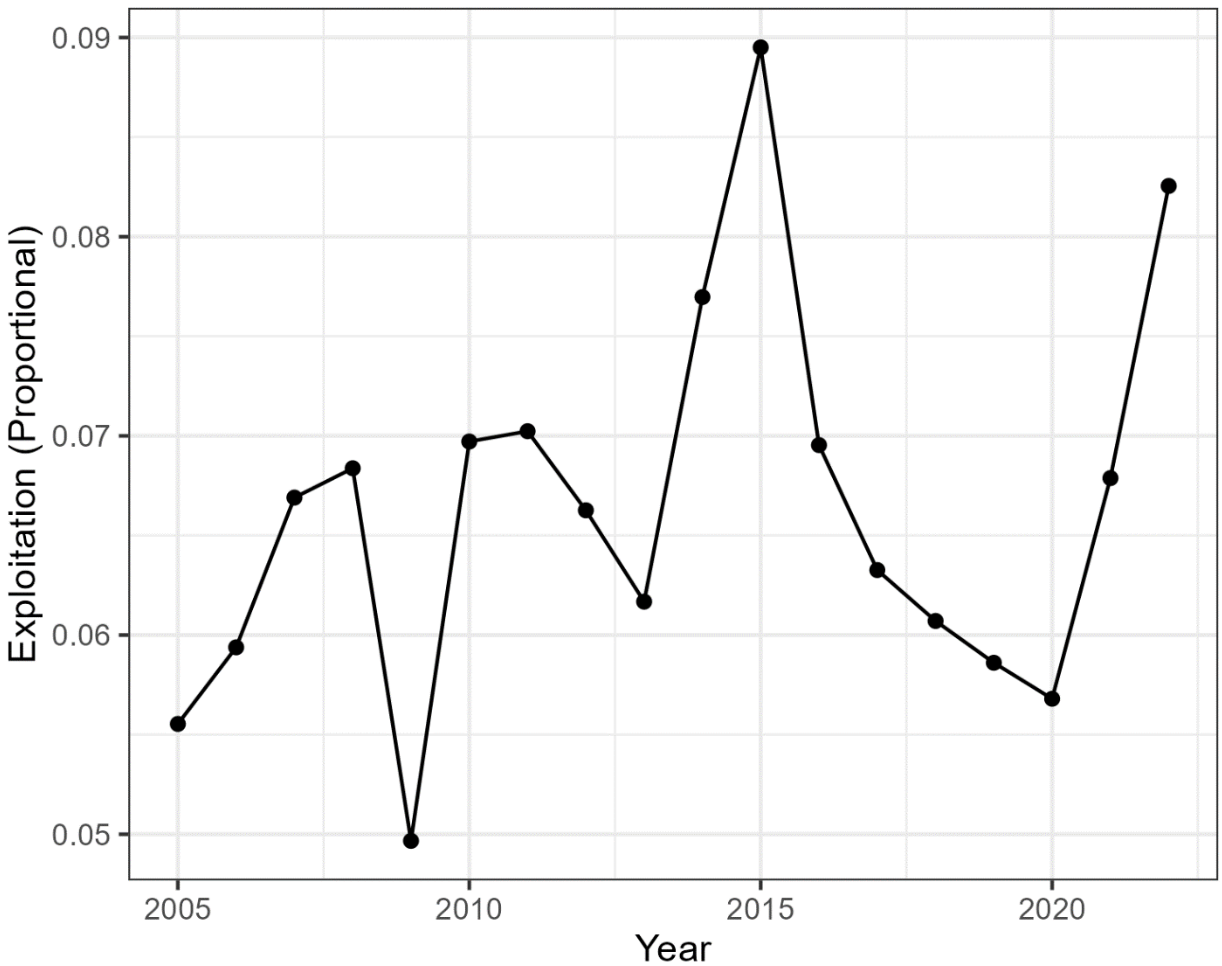


Figure 99. Proportional exploitation rate estimated by the Spatially Explicit Assessment Model.

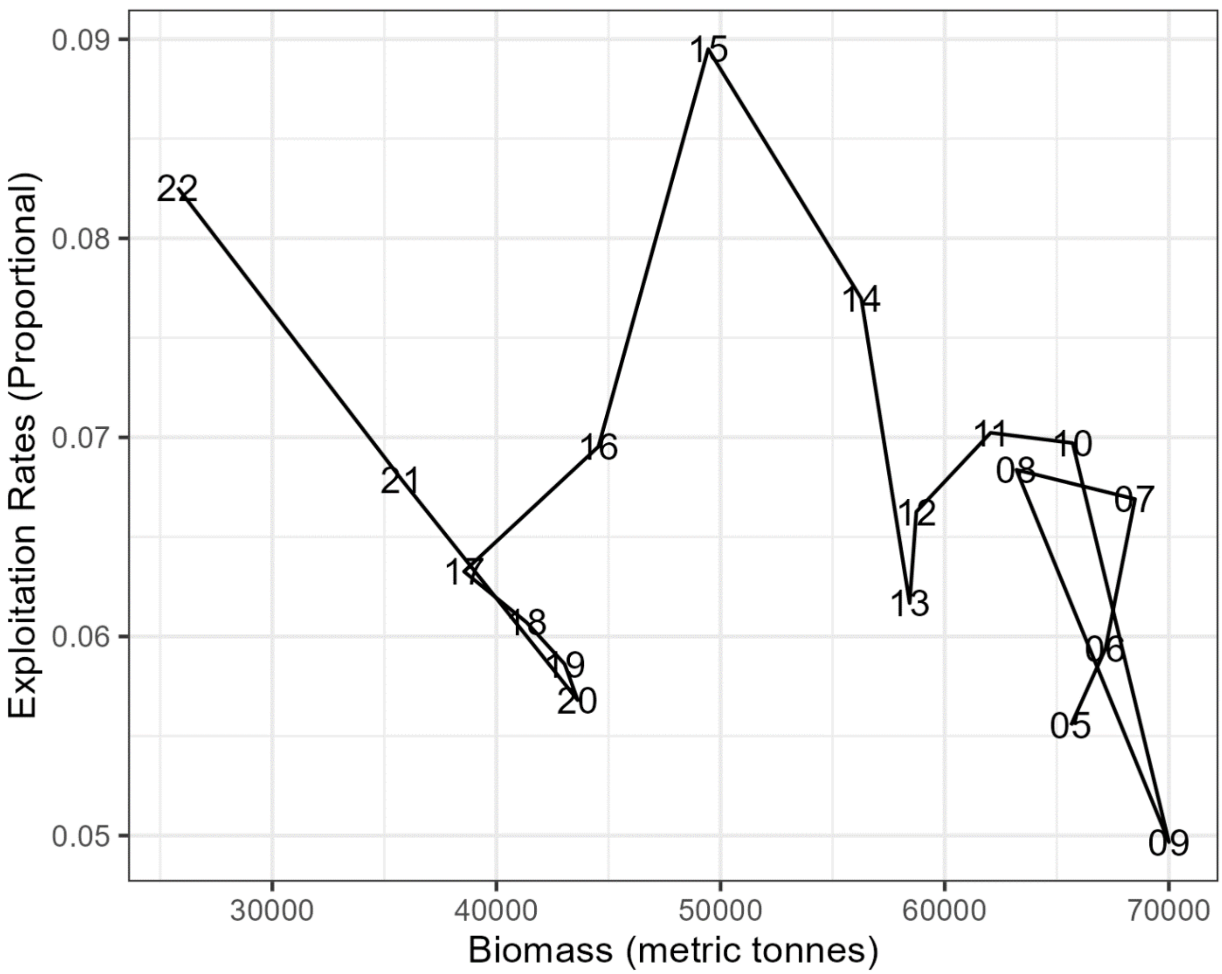


Figure 100. The Spatially Explicit Assessment Model phase plot showing proportional exploitation rates against biomass with numbers indicating the year.

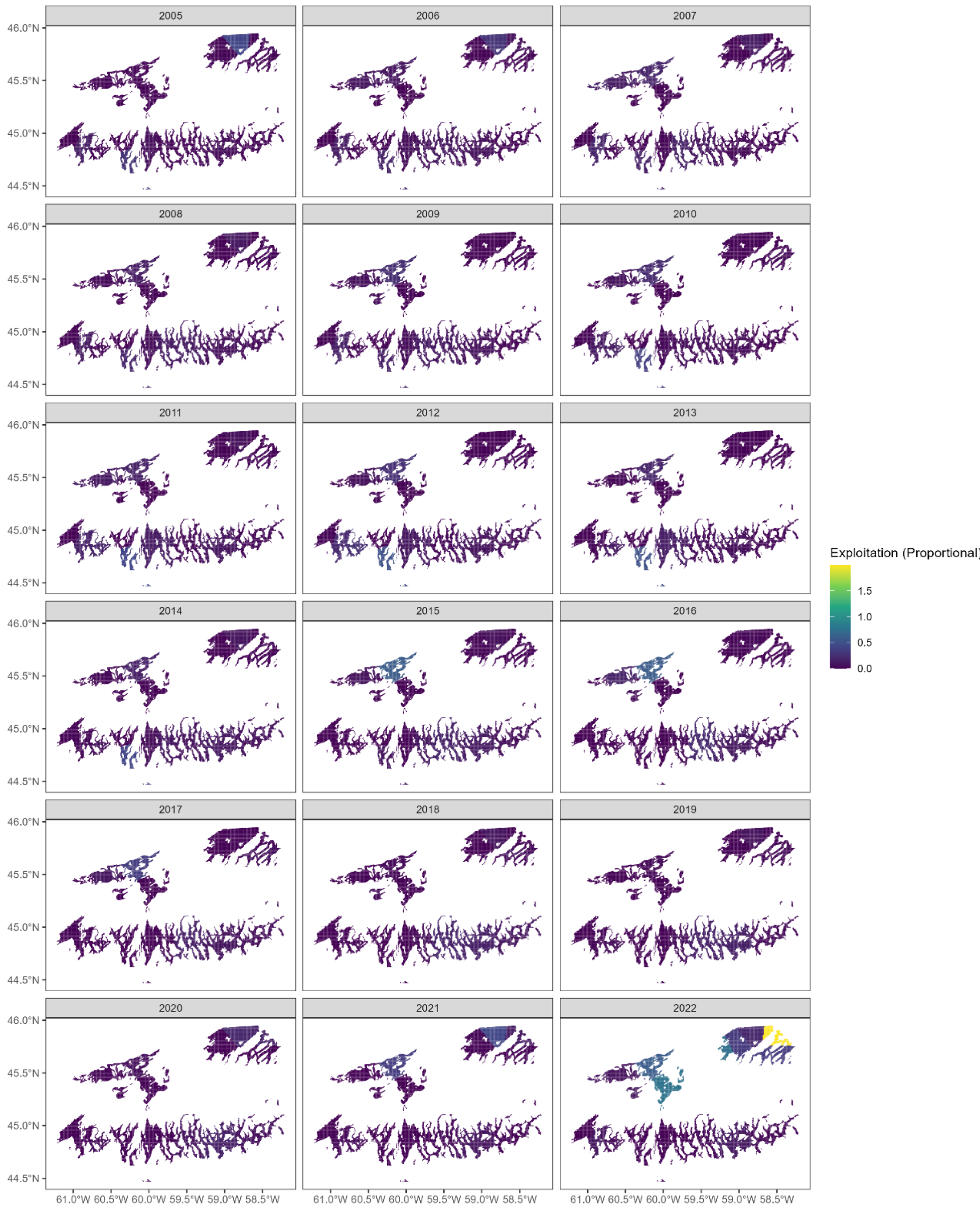


Figure 101. Proportional exploitation rates at each knot between 2005 and 2022 estimated by the Spatially Explicit Assessment Model.

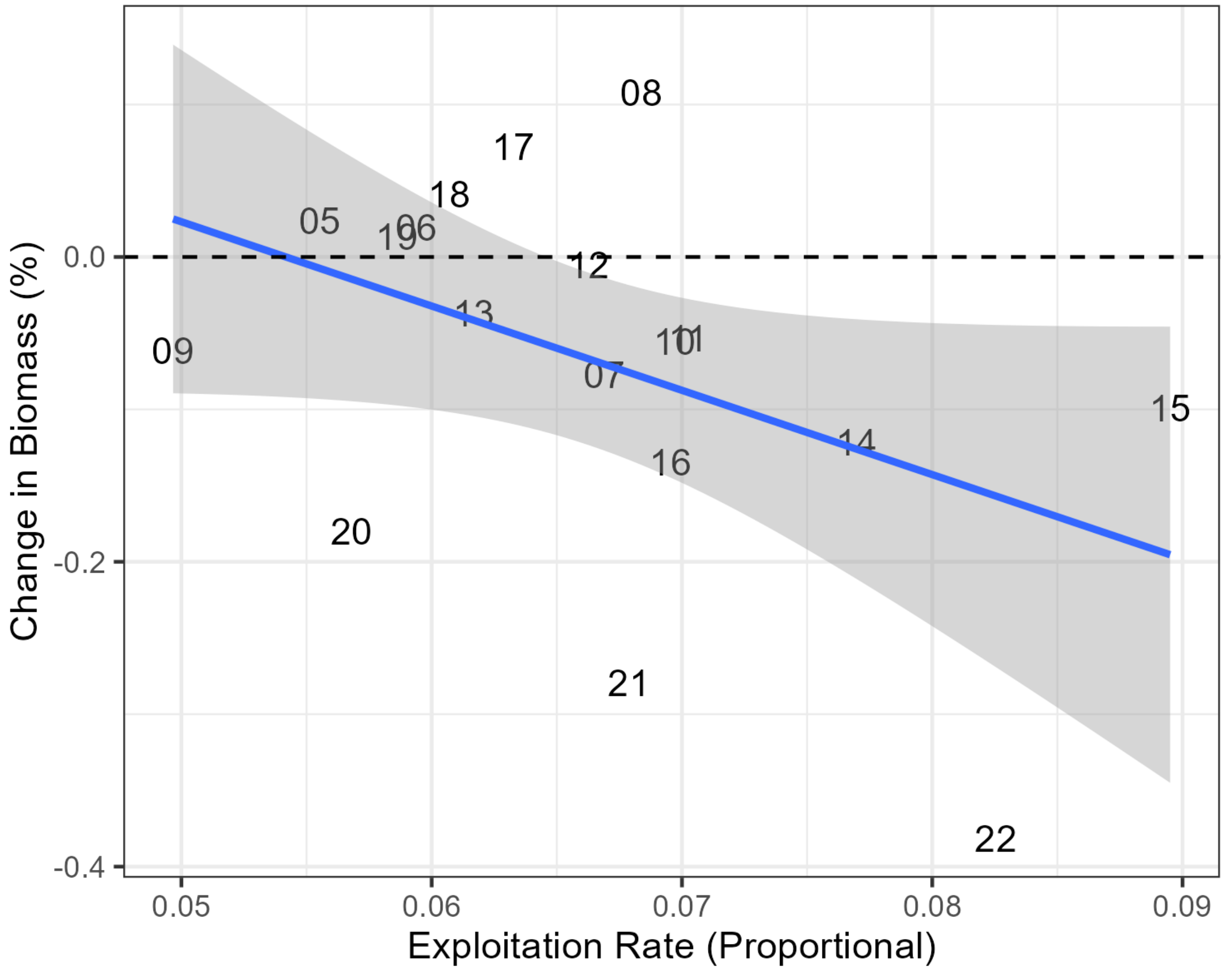


Figure 102. Proportional exploitation rate against the change in biomass in percentage in the following year by the Spatially Explicit Assessment Model with the numbers indicating year of fishing. Blue line is a simple regression line.

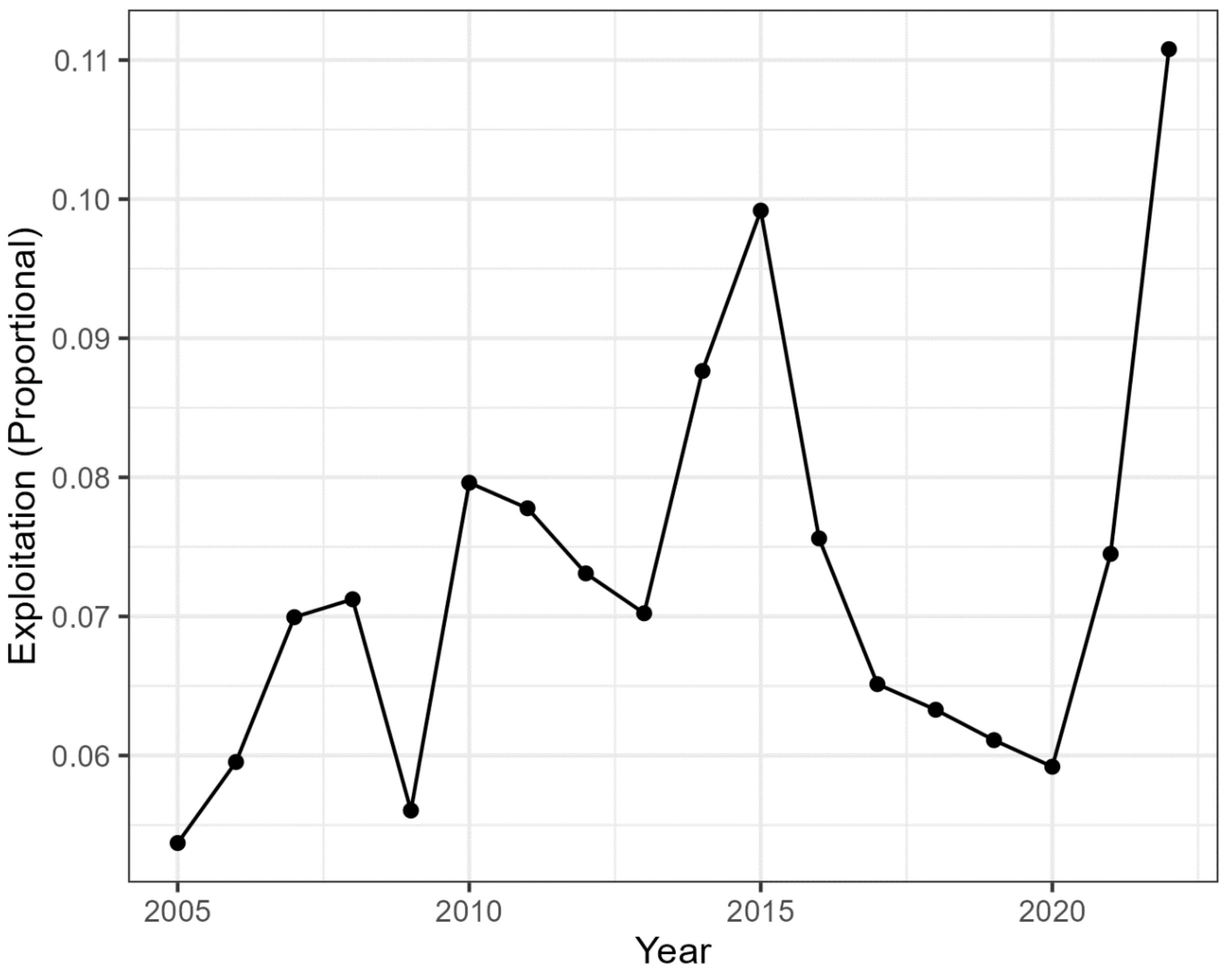


Figure 103. Proportional exploitation rate estimated by Tow Level Model.

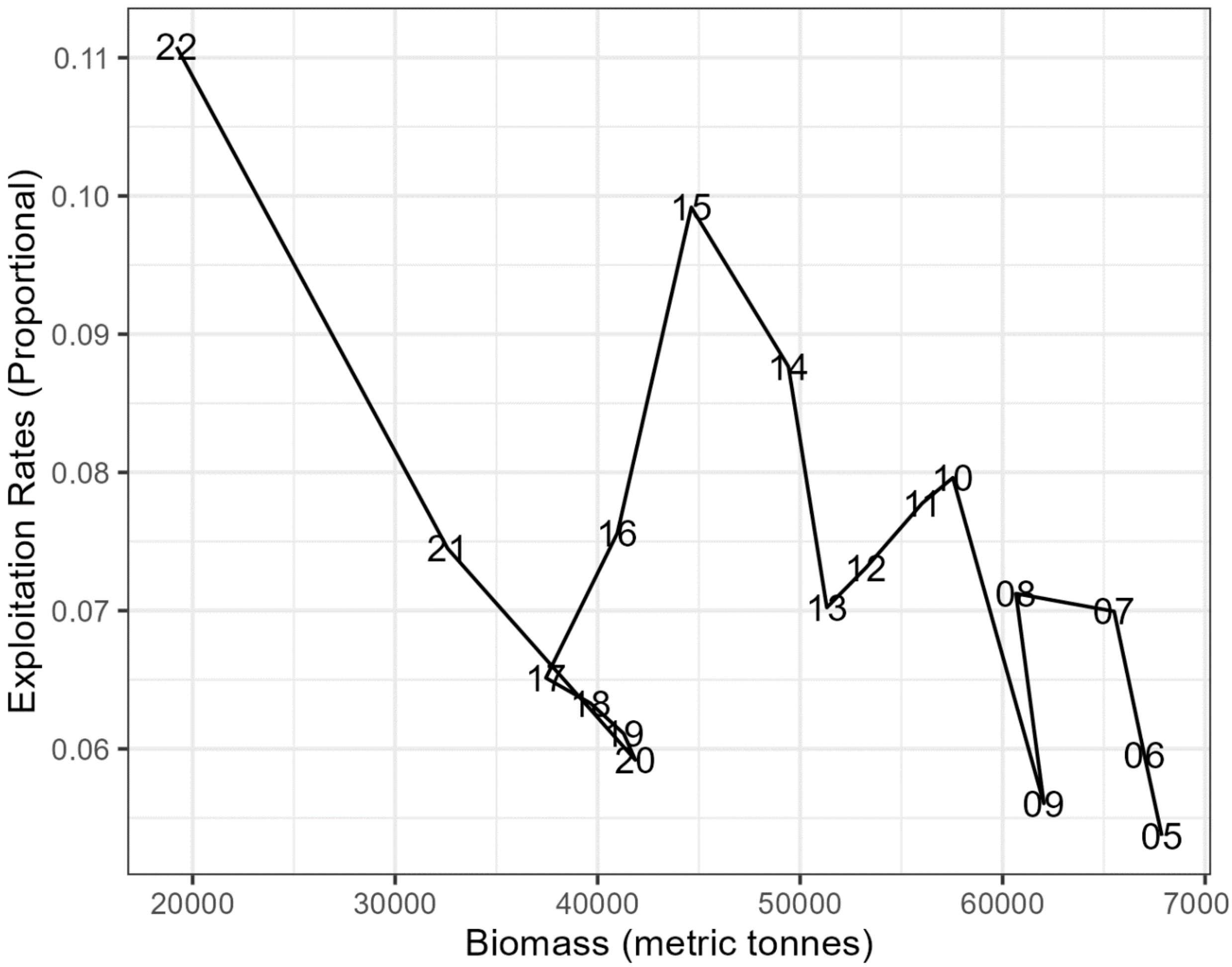


Figure 104. The Tow Level Model phase plot of exploitation rates against biomass with numbers indicating the year.

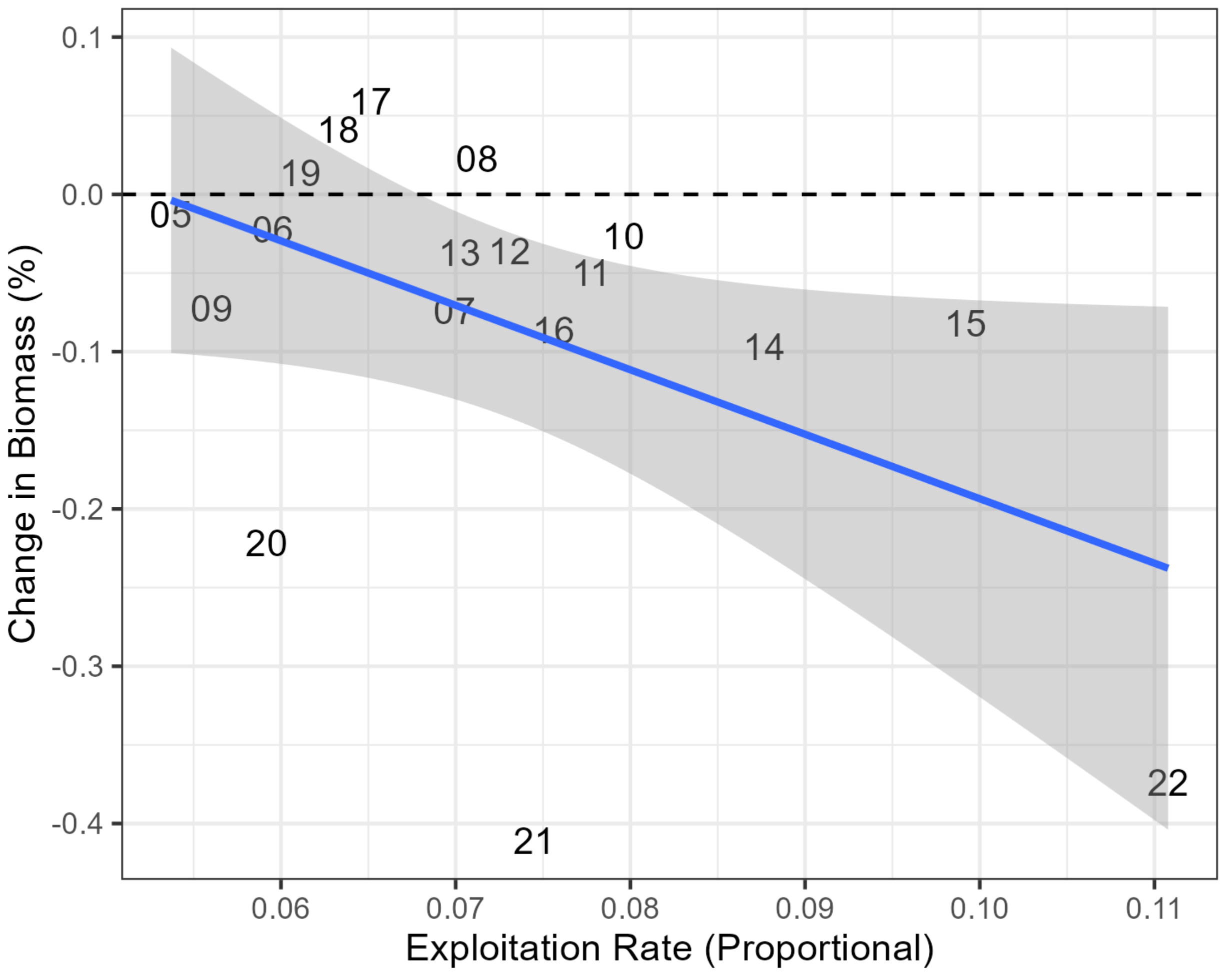


Figure 105. Proportional exploitation rate against the change in biomass in percentage in the following year by the Tow Level Model with the numbers indicating year of fishing. Blue line is a simple regression line.

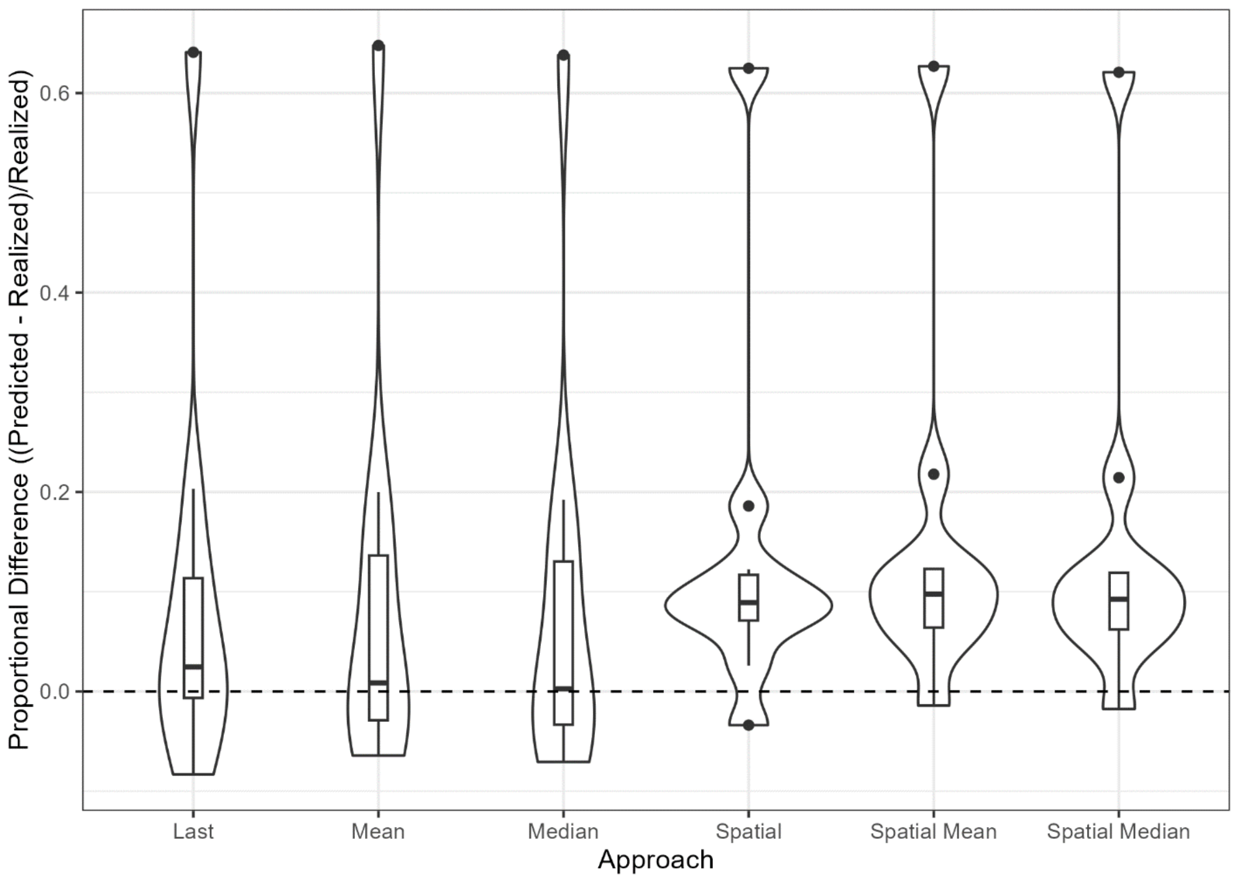


Figure 106. Violin plots showing proportional difference between 1-year projection and estimate once next year's data is added to the model fit for the Spatially Explicit Assessment Model.

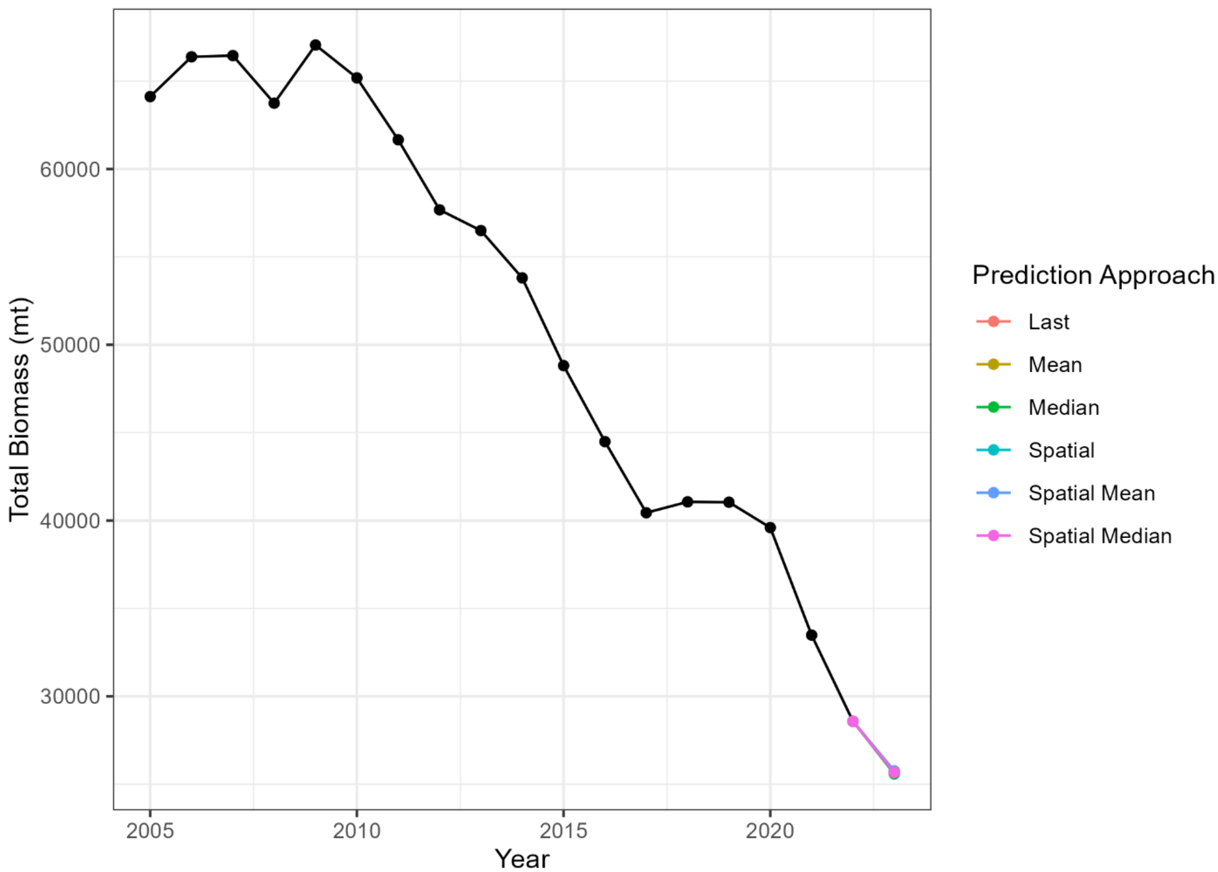


Figure 107. Total biomass estimates in metric tonnes (mt) between 2005 and 2022 along with different 2023 one-year projections from the Spatially Explicit Assessment Model.

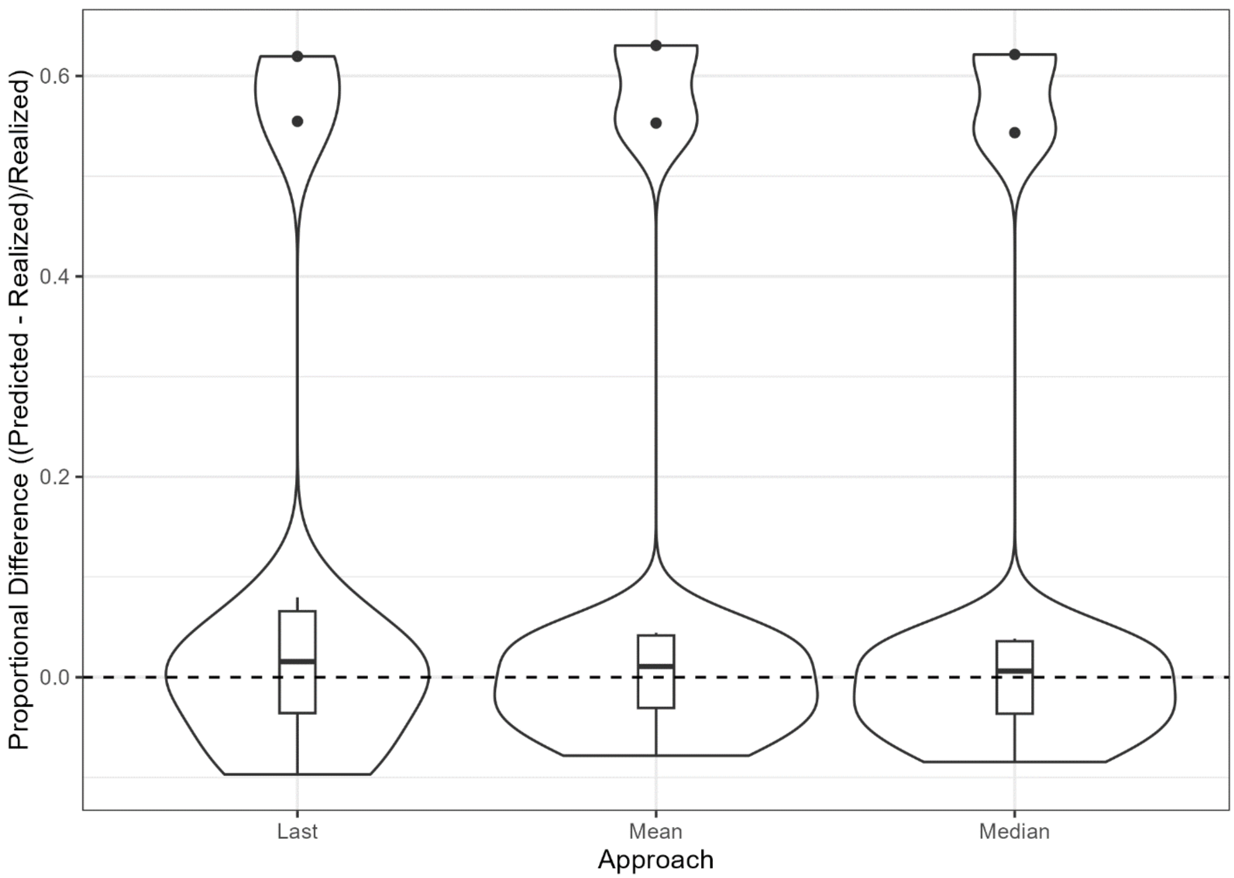


Figure 108. Violin plots showing proportional difference between 1-year projection and estimate once next year's data is added to the model fit for Tow Level Model.

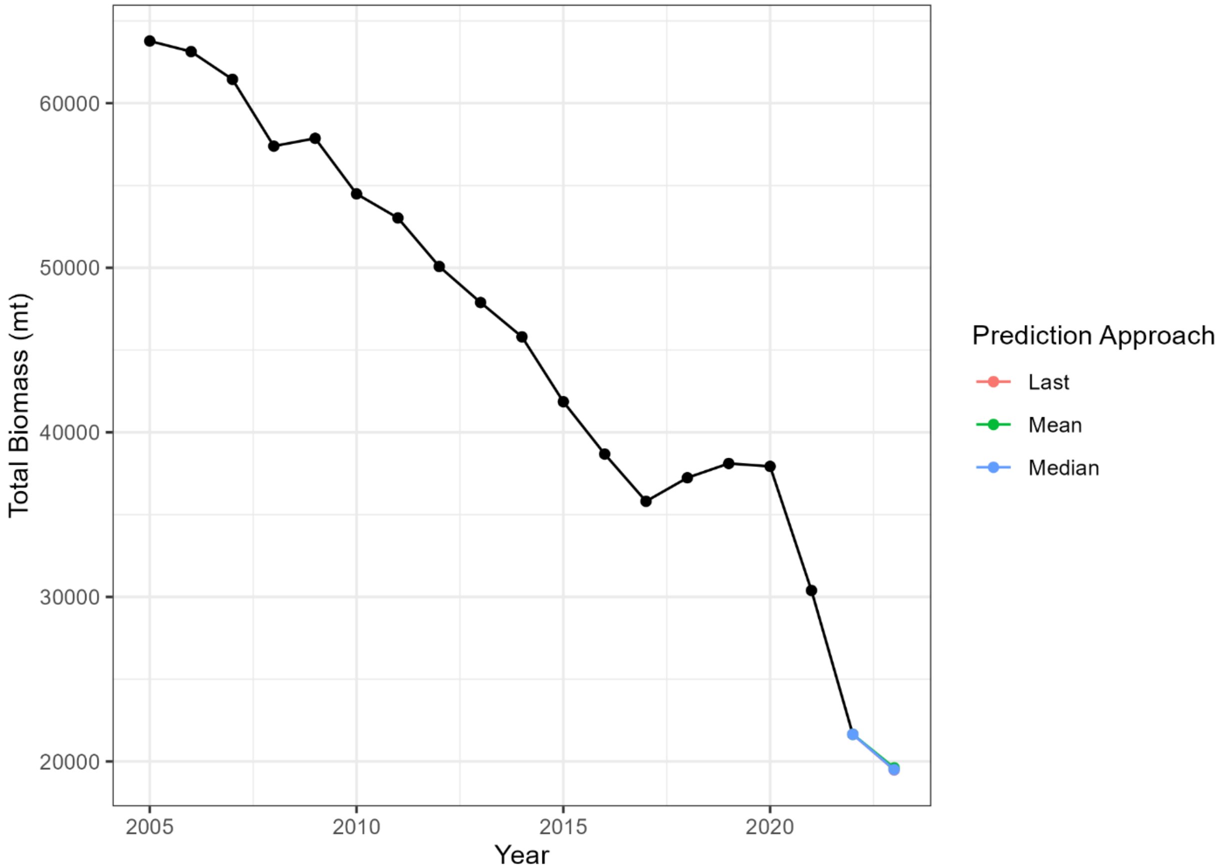


Figure 109. Total biomass estimates in metric tonnes (mt) between 2005 and 2022 along with different 2023 1-year projections from Tow Level Model.

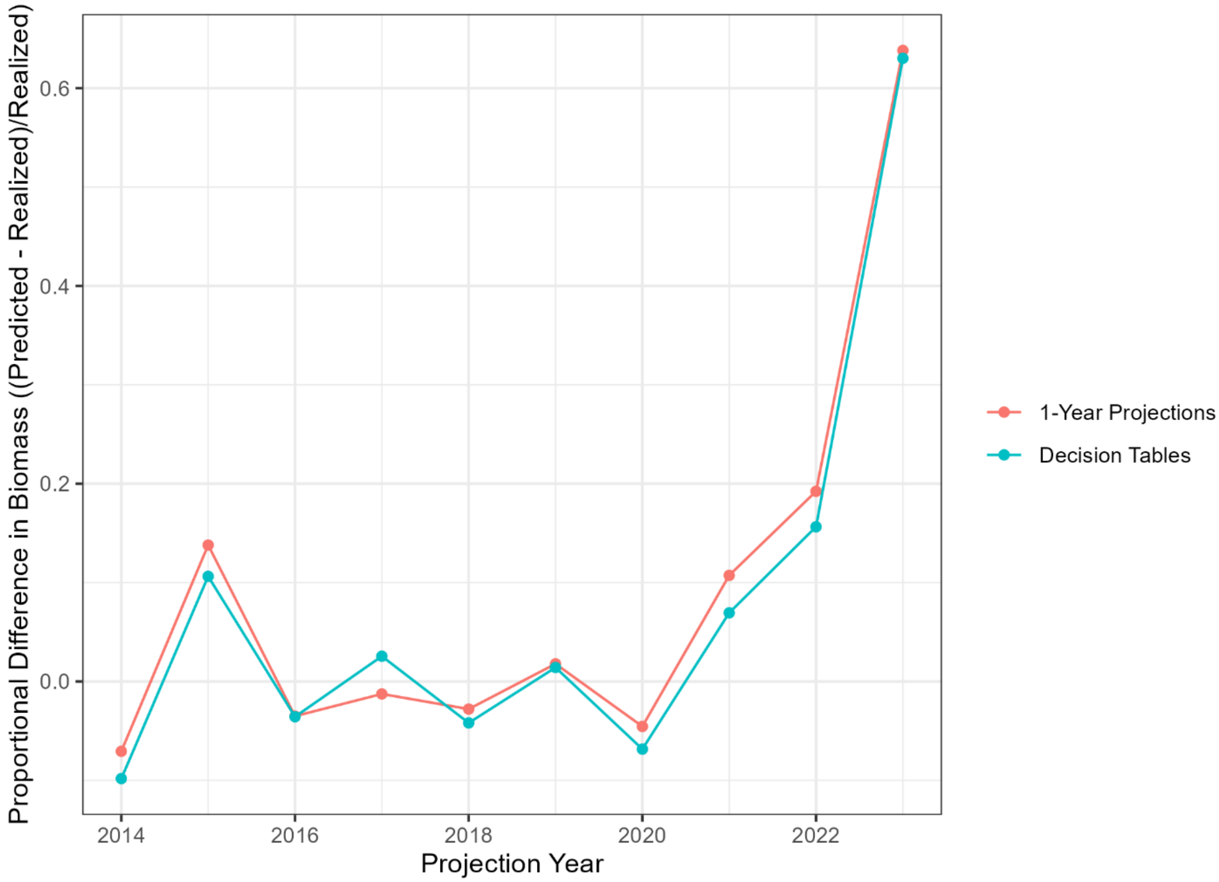


Figure 110. Proportional difference for the Spatially Explicit Assessment Model in the biomass projected by the 1-year projections (red), which only account for known landings, and the decision tables (teal), which account for both known and projected landings, and the biomass estimated once data becomes available.

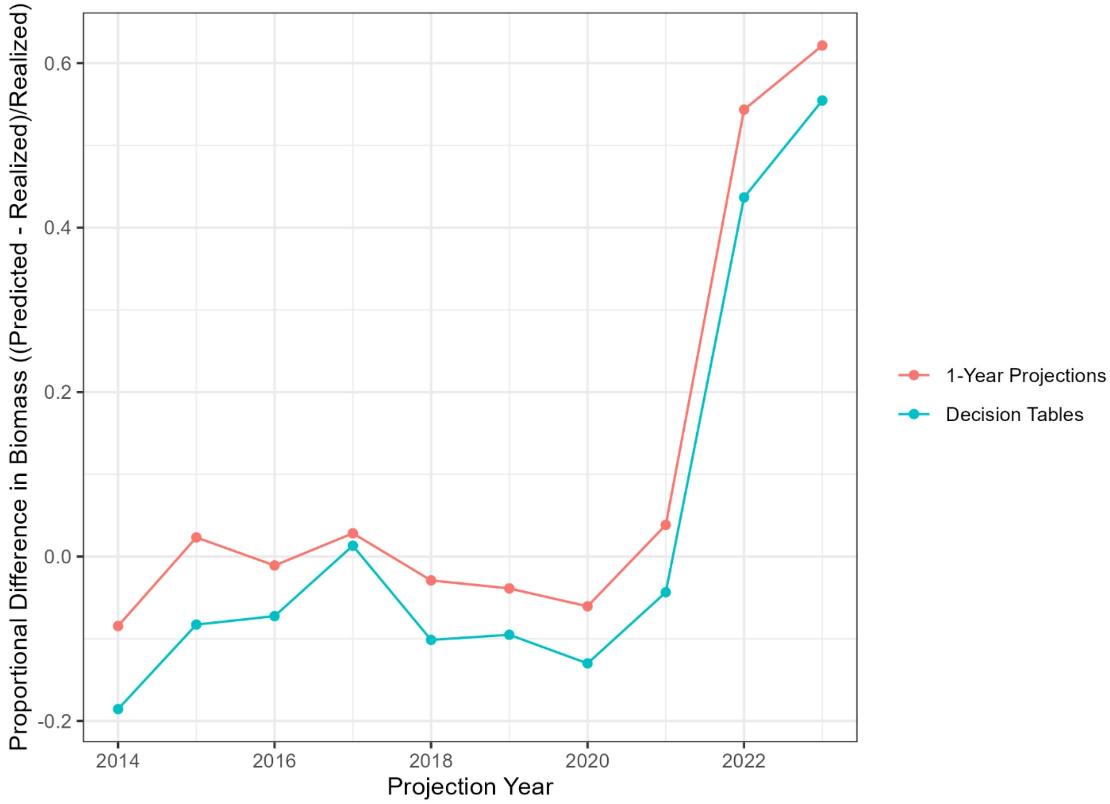


Figure 111. Proportional difference for the Tow Level Model in the biomass projected by the 1-year projections (red), which only account for known landings, and the decision tables (teal), which account for both known and projected landings, and the biomass estimated once data becomes available.

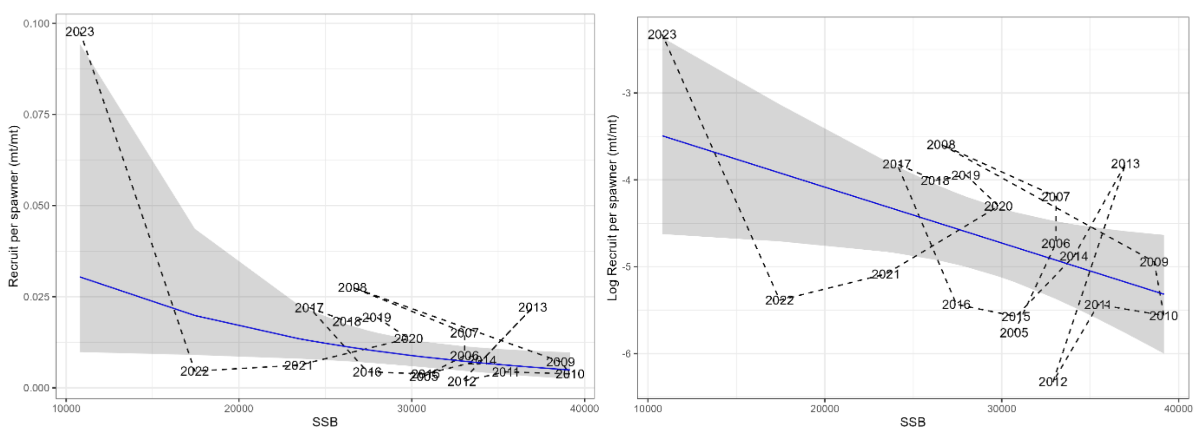


Figure 112. Recruit-per-spawner (left panel) and log recruit-per-spawner (right panel) against spawning stock biomass in metric tonnes (mt) with the fitted Ricker curve in blue. The 95% confidence interval is shown in grey.

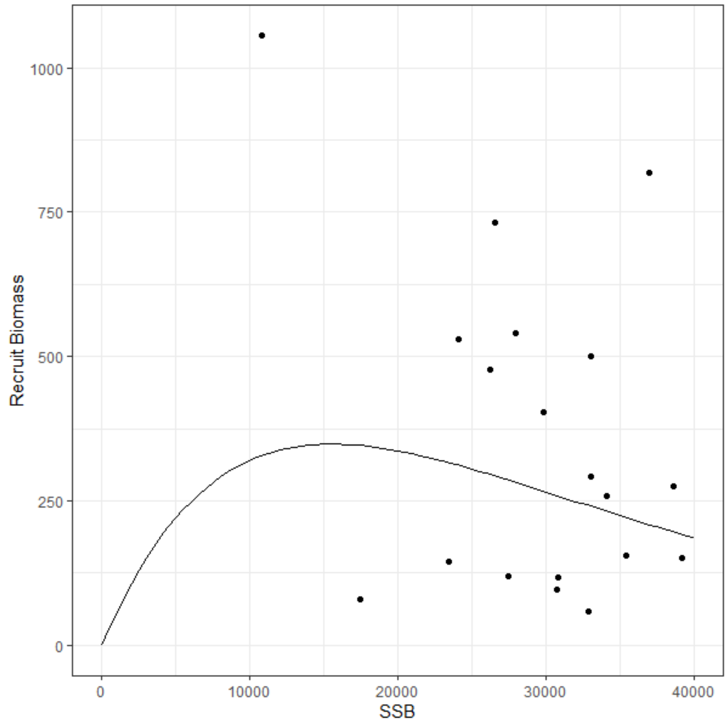


Figure 113. Theoretical Ricker Stock-Recruit curve plotted with spawning stock biomass (SSB) against next year's total recruit biomass.

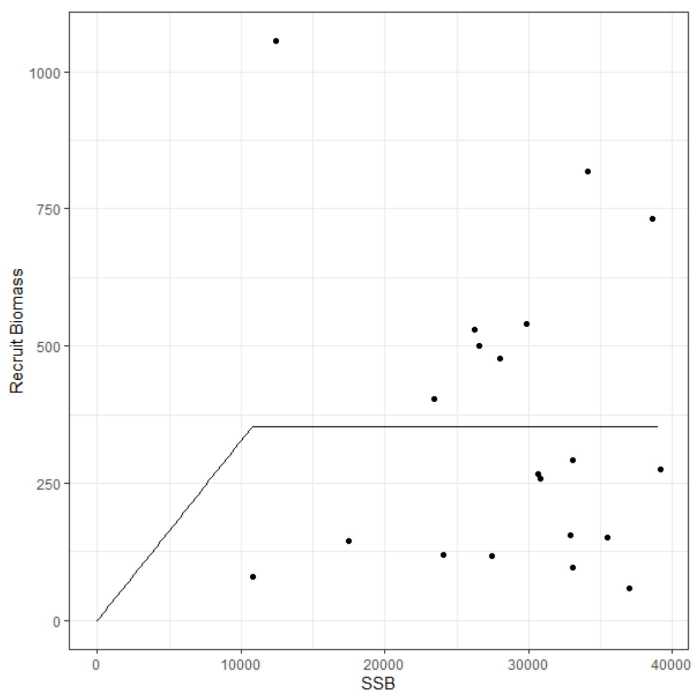


Figure 114. Hockey-stick approach plotted with spawning stock biomass (SSB) against next year's total recruit biomass.

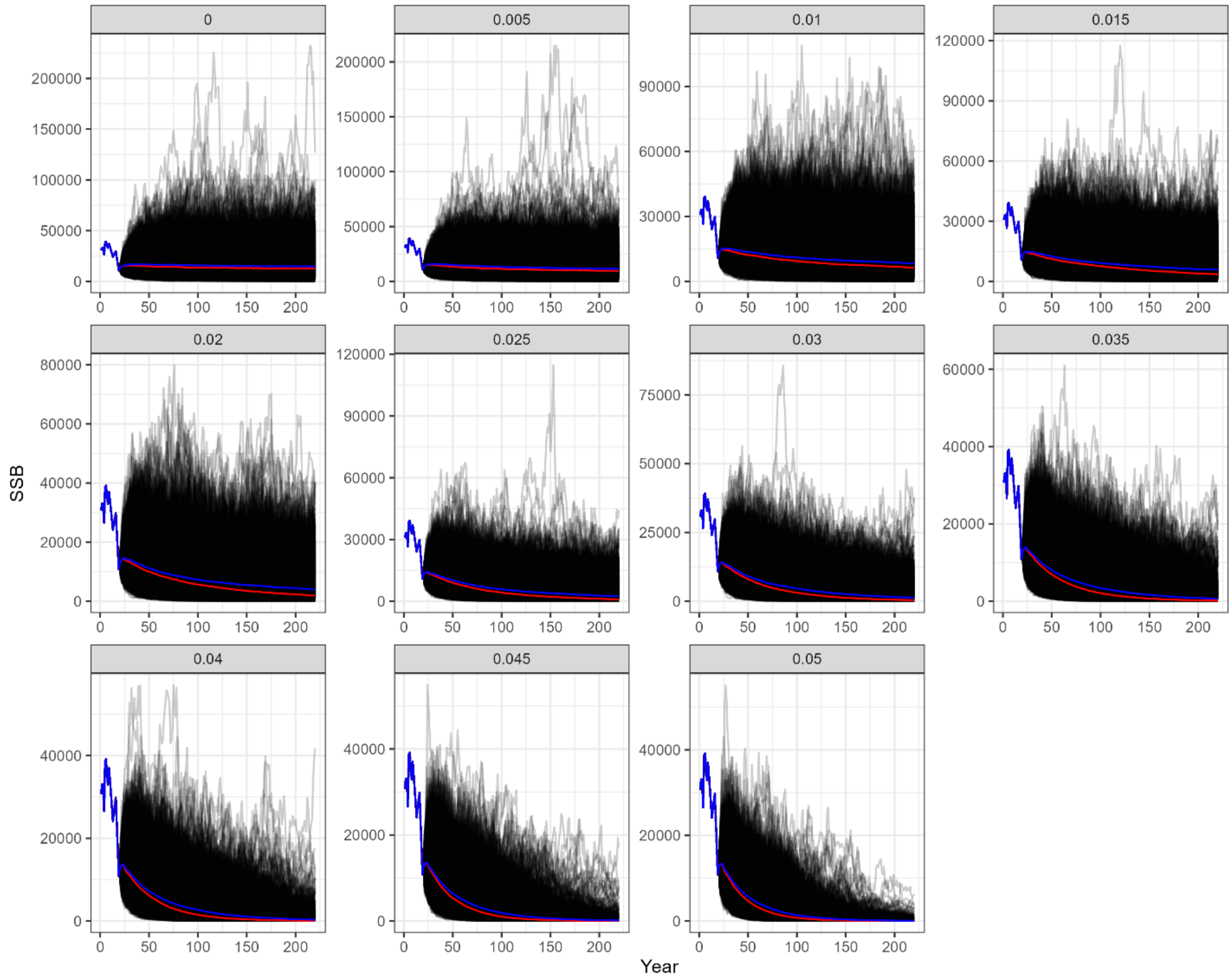


Figure 115. All simulated time series of spawning stock biomass (SSB) for Setting 1 with the Low productivity scenario. The first 20 years shown here are the actual observed time series (2005–24), with individual simulations in grey. The blue line denotes the mean simulated SSB, while the red line denotes the median, and each panel represents a different exploitation rate.

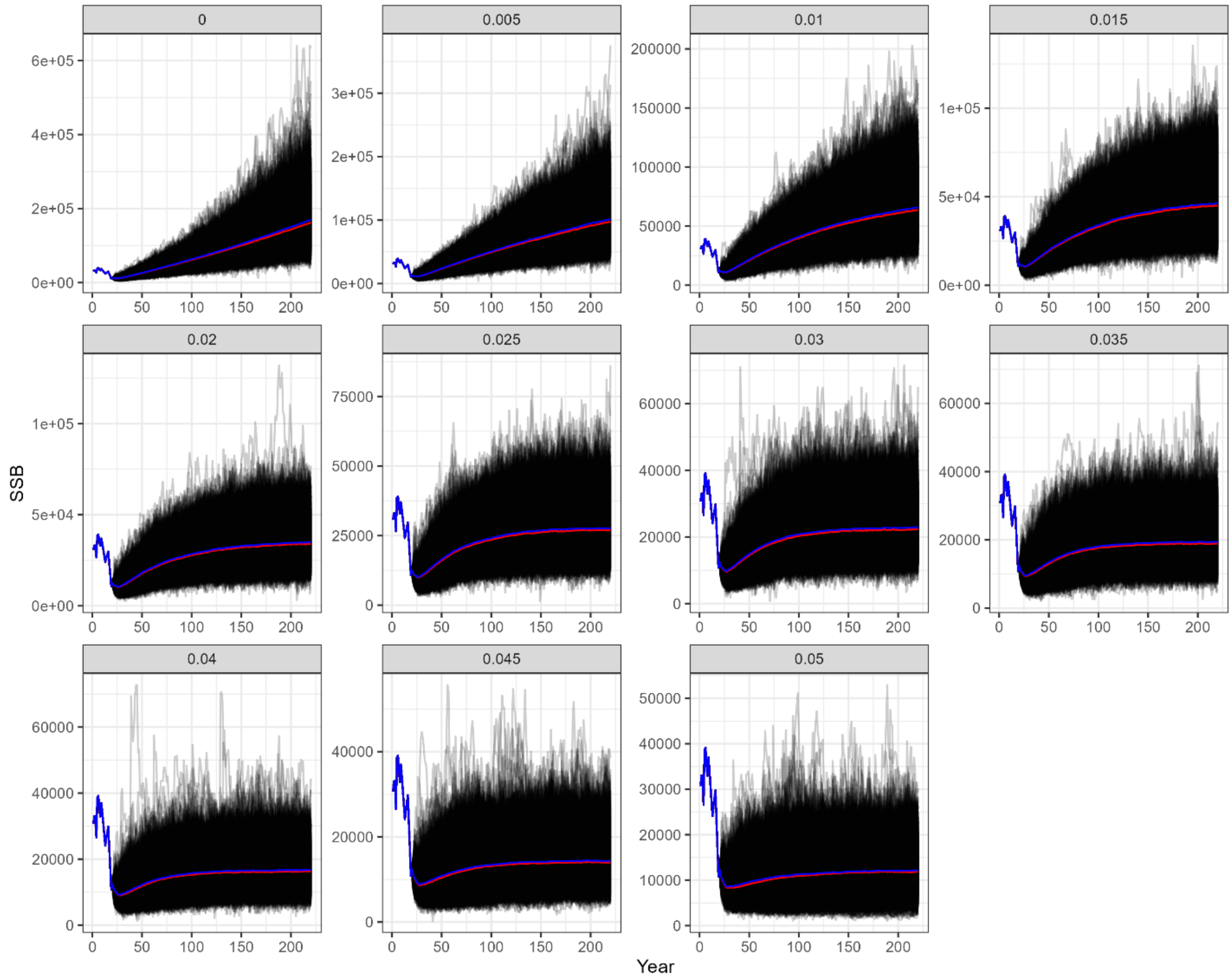


Figure 116. All simulated time series of spawning stock biomass (SSB) for Setting 1 with the High productivity scenario. The first 20 years shown here are the actual observed time series (2005–24), with individual simulations in grey. The blue line denotes the mean simulated SSB, while the red line denotes the median, and each panel represents a different exploitation rate.

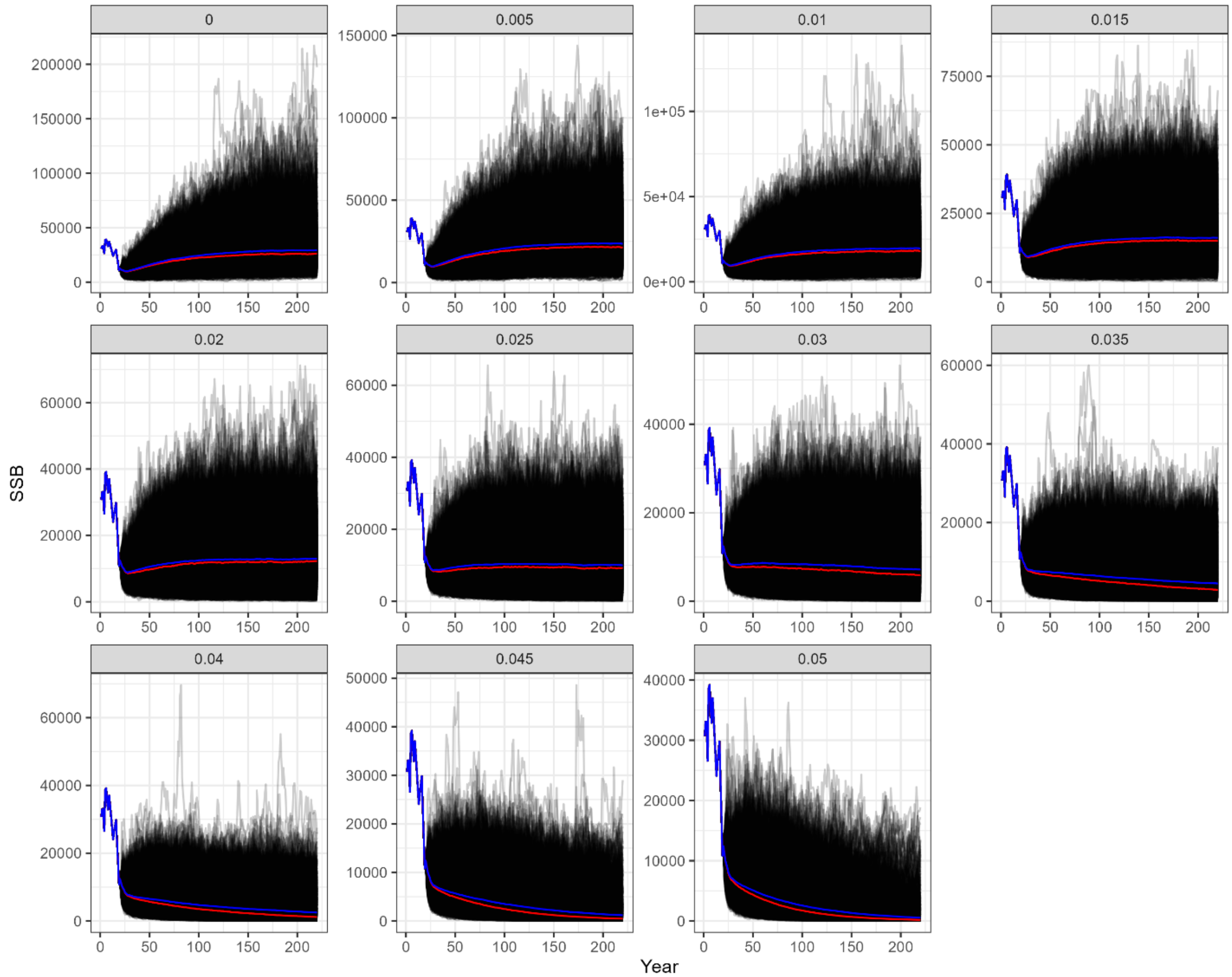


Figure 117. All simulated time series of spawning stock biomass (SSB) for Setting 1 with the High productivity with all natural mortalities (Mid) scenario. The first 20 years shown here are the actual observed time series (2005–24), with individual simulations in grey. The blue line denotes the mean simulated SSB, while the red line denotes the median, and each panel represents a different exploitation rate.

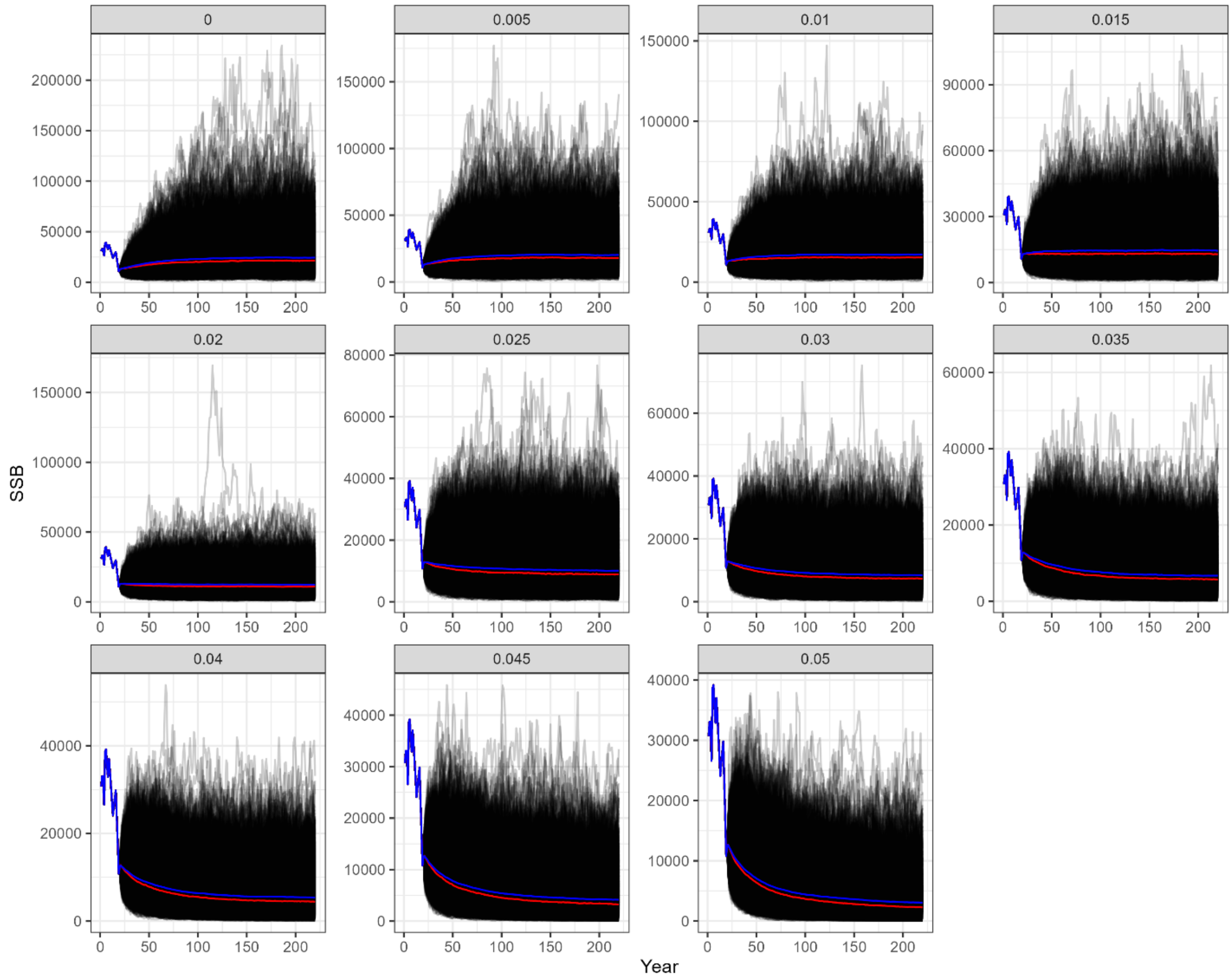


Figure 118. All simulated time series of spawning stock biomass (SSB) for Setting 1 with the Baseline scenario. The first 20 years shown here are the actual observed time series (2005–24), with individual simulations in grey. The blue line denotes the mean simulated SSB, while the red line denotes the median, and each panel represents a different exploitation rate.

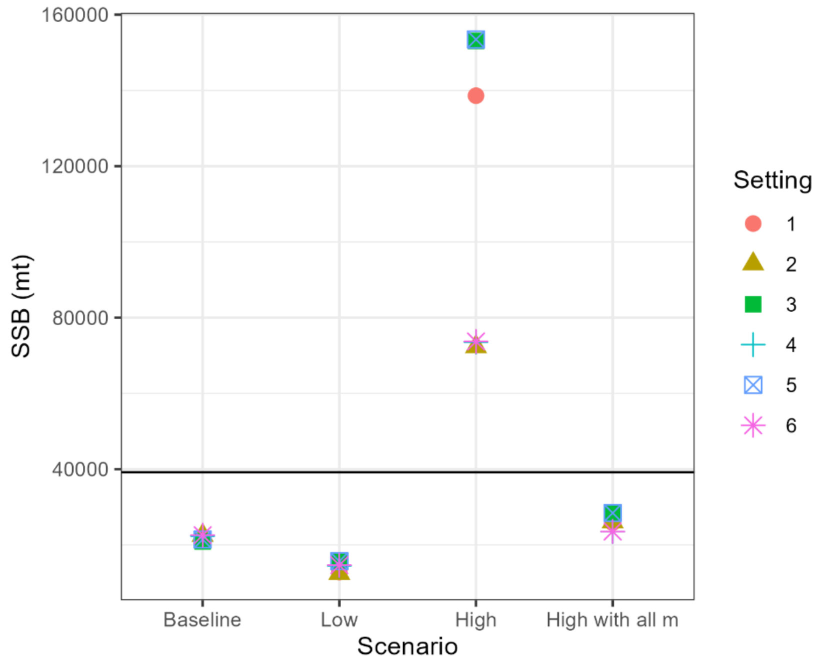


Figure 119. Median spawning stock biomass (SSB) in metric tonnes (mt) in the last 50 years of the Maximum Sustainable Yield simulations without fishing by productivity scenario and setting. The horizontal black line denotes the maximum observed SSB from 2005 to 2024.

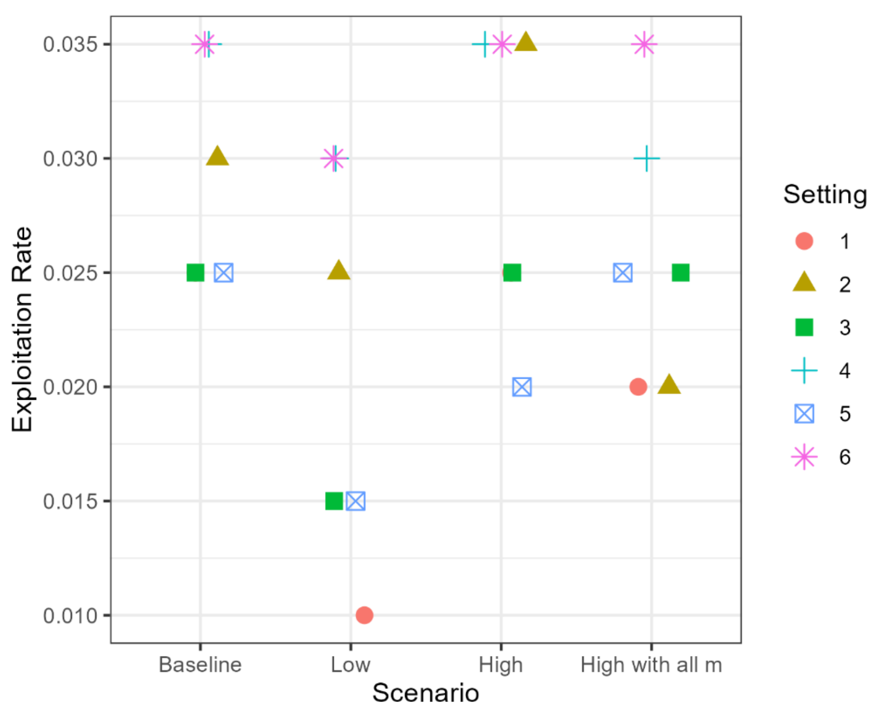


Figure 120. Exploitation rate associated with long-term highest average landings in maximum sustainable yield simulations by productivity scenario and setting.

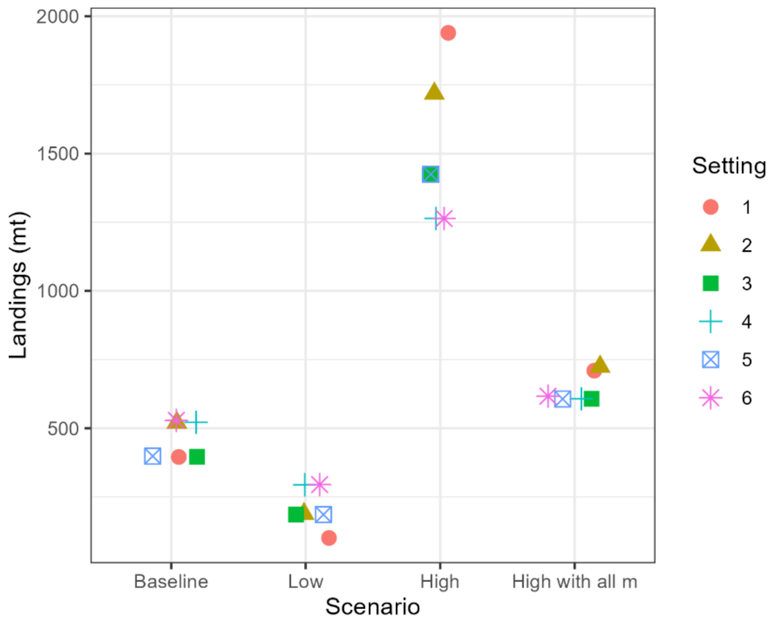


Figure 121. Mean landings, in metric tonnes (mt), associated with the identified optimal exploitation rates in the maximum sustainable yield simulations by productivity scenario and setting.

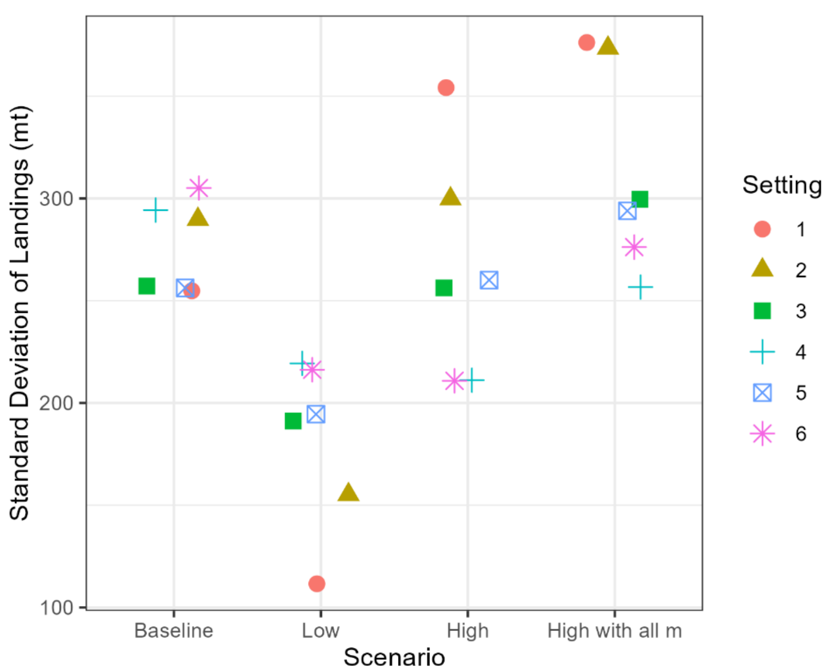


Figure 122. Standard deviations of landings in metric tonnes (mt) associated with optimal exploitation rates in the maximum sustainable yield simulations by productivity scenario and setting.

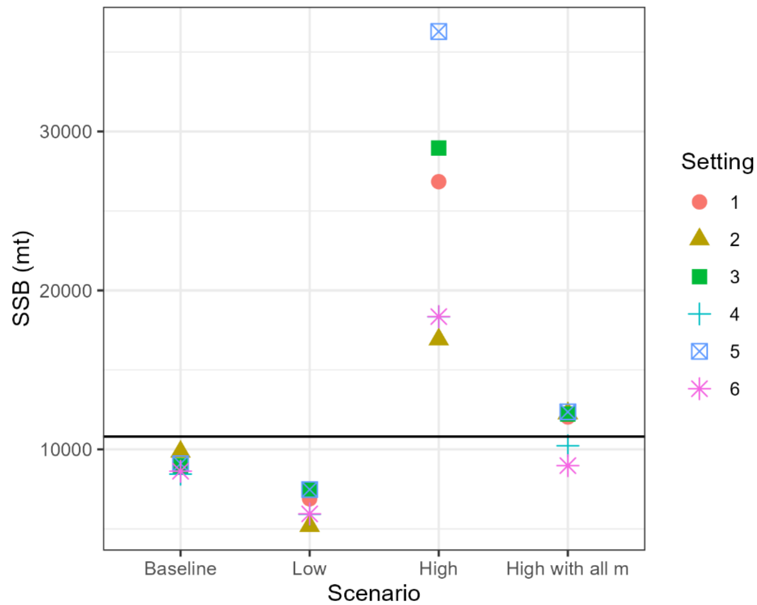


Figure 123. Median Spawning Stock Biomass (SSB) in metric tonnes (mt) in the last 50 years of the maximum sustainable yield (MSY) simulations at the MSY exploitation rates by productivity scenario and setting. The horizontal black line denotes the minimum observed SSB between 2005 and 2024.

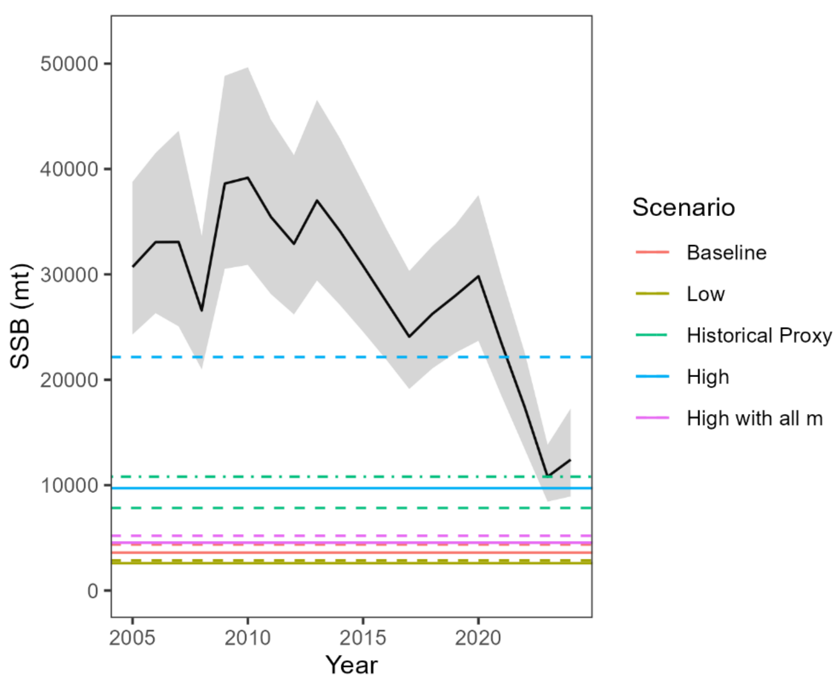


Figure 124. Comparison of different limit reference points (LRP) scenarios with observed time series of Spawning Stock Biomass (SSB), in metric tonnes (mt), with the solid lines representing 40% of different biomass at Maximum Sustainable Yield (B_{MSY})estimates, dashed lines representing 20% of the theoretical long-term equilibrium biomass in the absence of fishing (B_0) estimates, and the dot-dashed line representing the minimum observed SSB. The LRPs from the different scenarios are the average LRP from all six different settings for visual clarity.

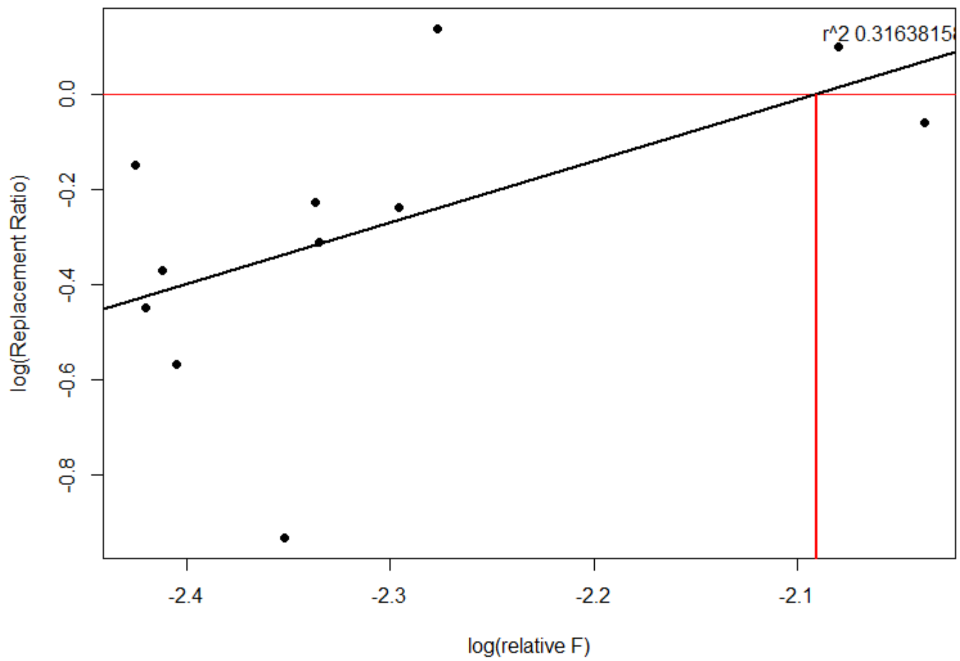


Figure 125. Log relative fishing mortality ($relF_t$) plotted against the log replacement ratio (Ψ_t), with the black line denoting the fit of a linear regression between the two variables, the horizontal red line denoting a Ψ_t of 0, and the vertical red line indicating the value at which the linear regression line crosses 0 (thank you to Adam Cook for providing the code for this figure and analysis).

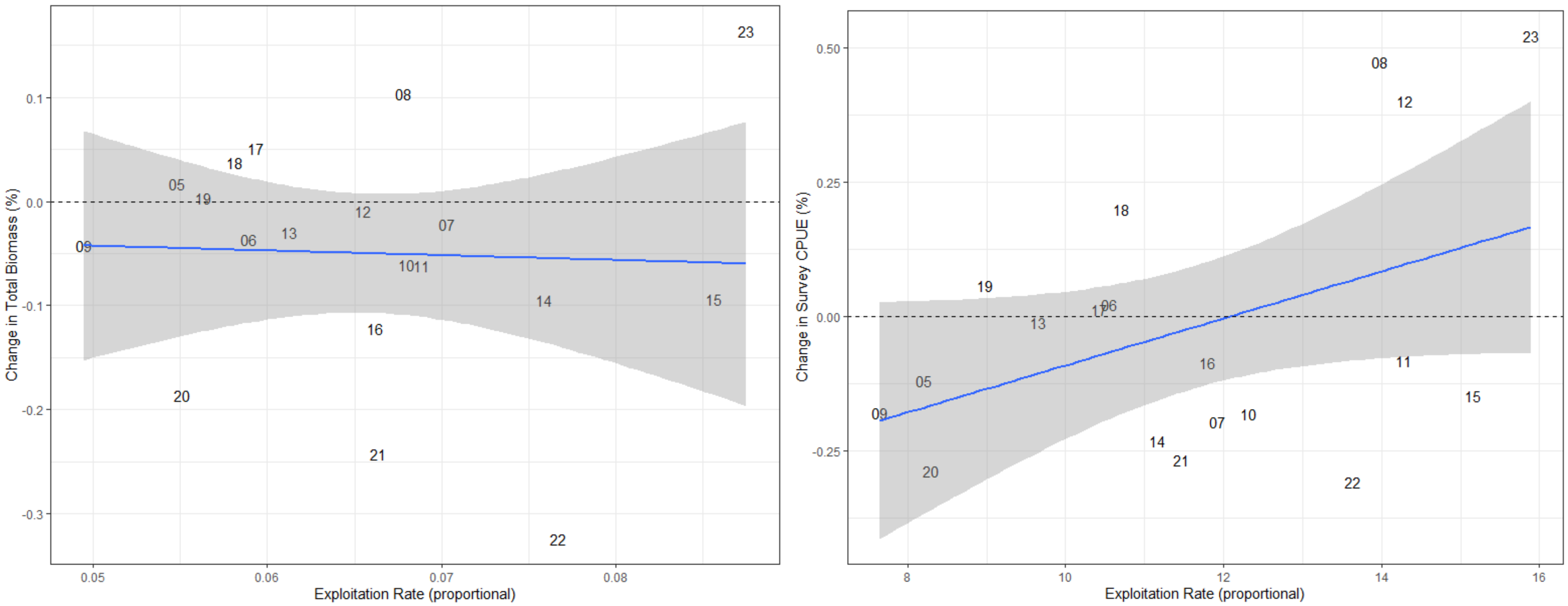
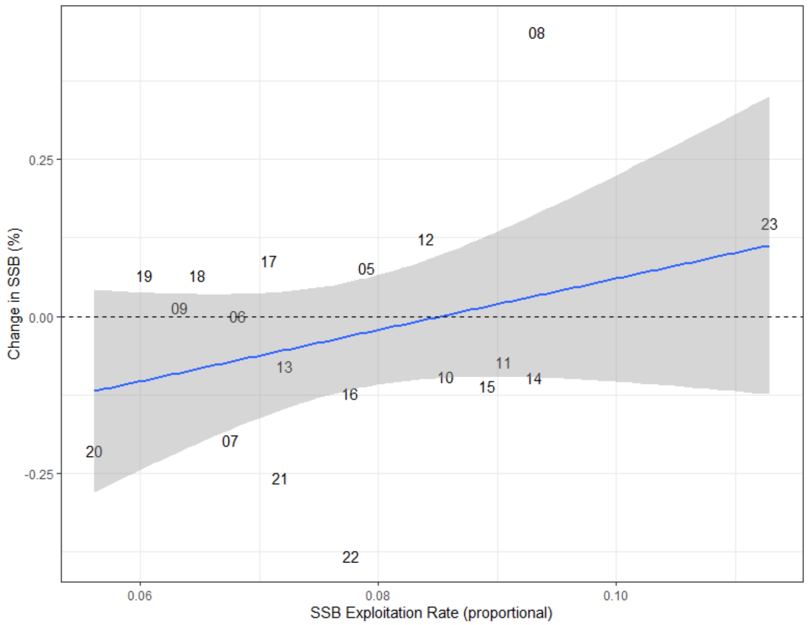


Figure 126. Observed exploitation rates plotted against the resulting change in model-based biomass (%) in the following year(left panel) and observed exploitation rates against resulting change in survey catch per unit effort (CPUE) (%) in the following year (right panel).



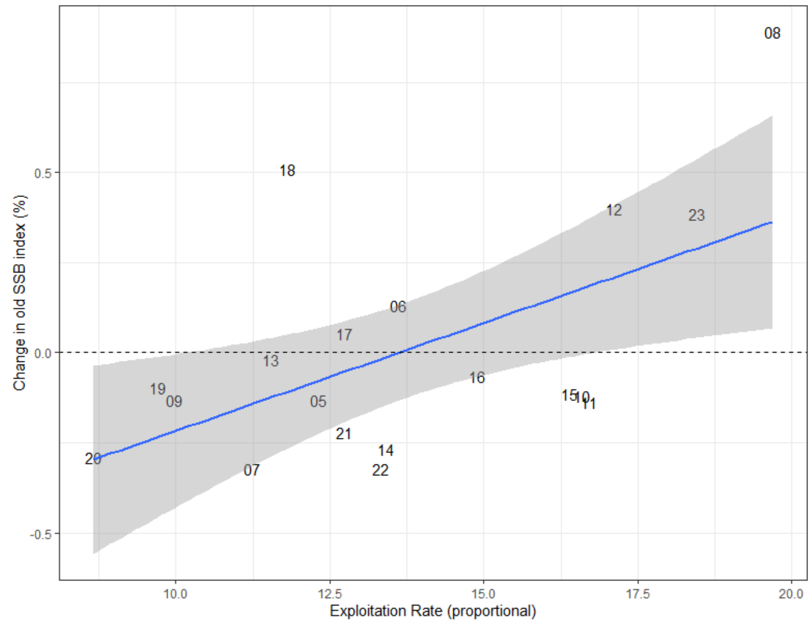


Figure 127. Observed exploitation rates plotted against the resulting change in model-based spawning stock biomass (SSB) (%) in the following year (left panel) and observed exploitation rates plotted against resulting change in index-based SSB (%) (right panel).

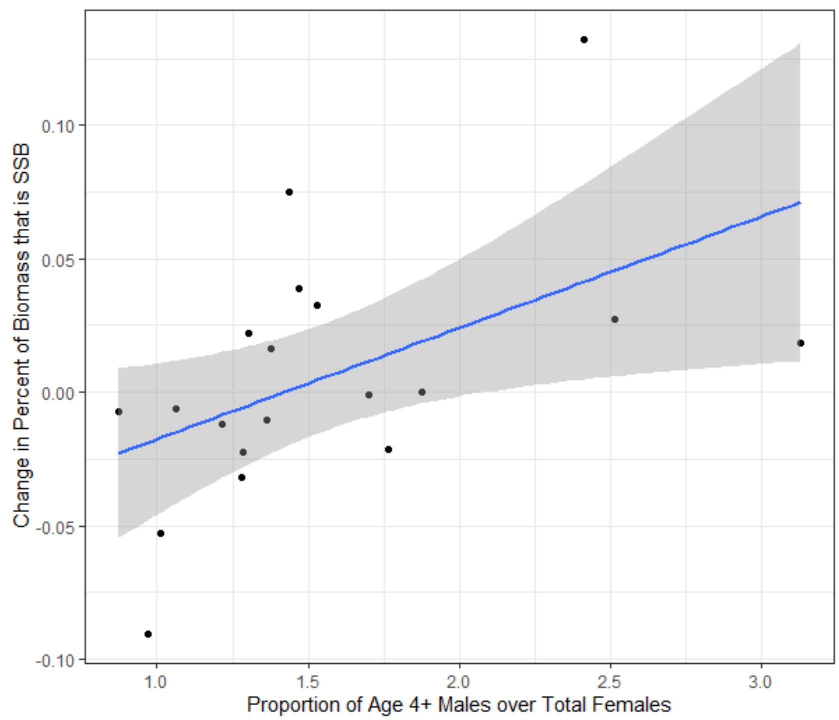


Figure 128. Proportion of numbers of Age 4+ Males over number of Total Females against change in the percent of biomass that is spawning stock biomass (SSB) in the following year, with blue line representing a linear fit between the two variables and the grey ribbon the 95% confidence interval.

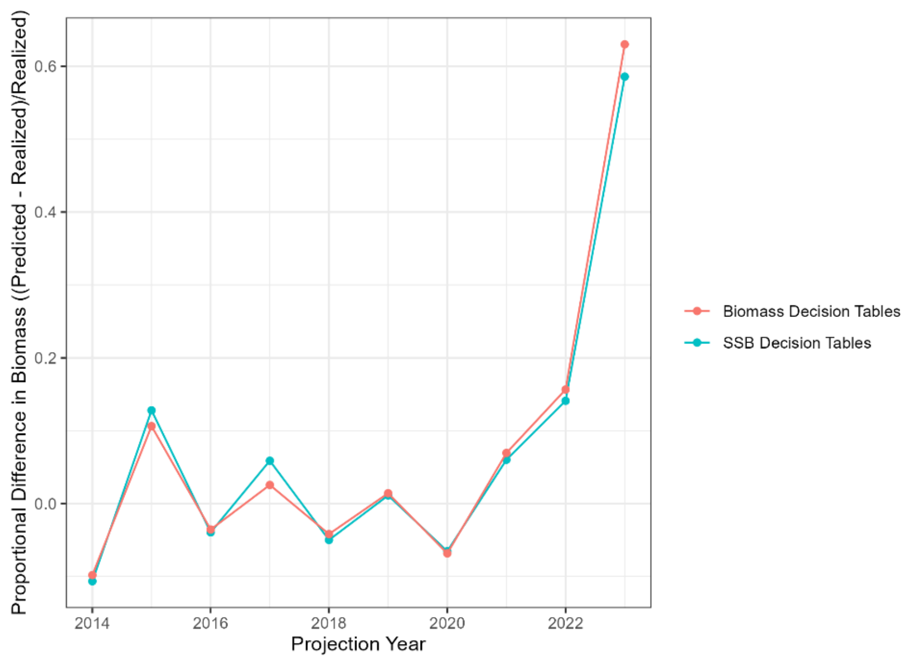


Figure 129. Proportional difference for the biomass decision tables (red) and the biomass estimated once data become available, as well as the proportional difference for the spawning stock biomass (SSB) decision tables (teal) and the SSB estimated once data become available.

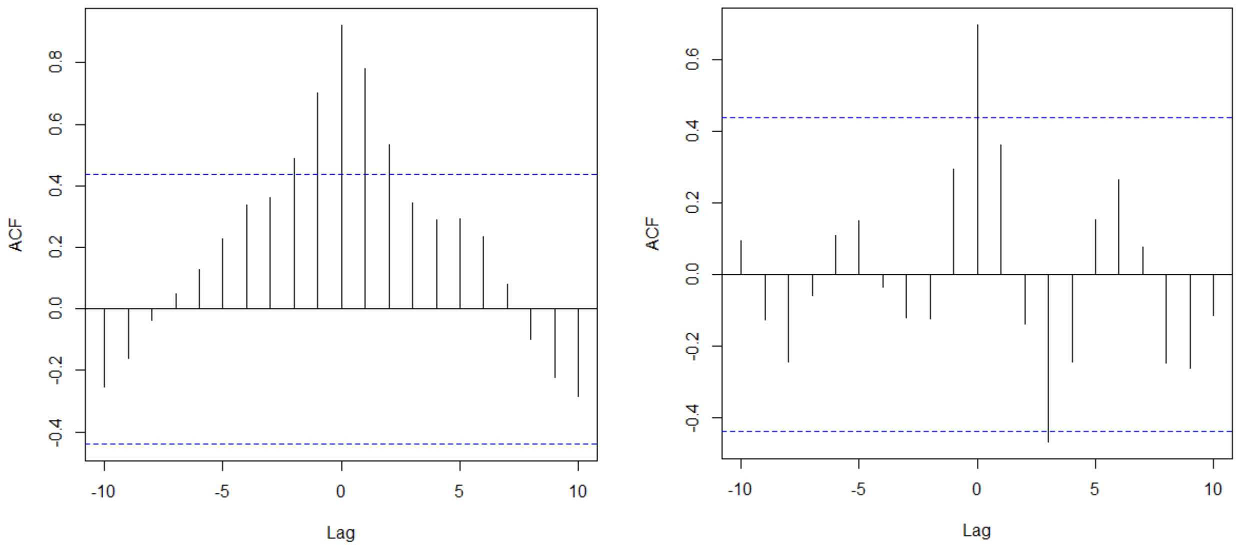


Figure 130. Cross autocorrelation function (ACF) between model-based biomass estimates and the survey catch per unit effort (CPUE) both without removing the trend (left panel) and detrending both (right panel).

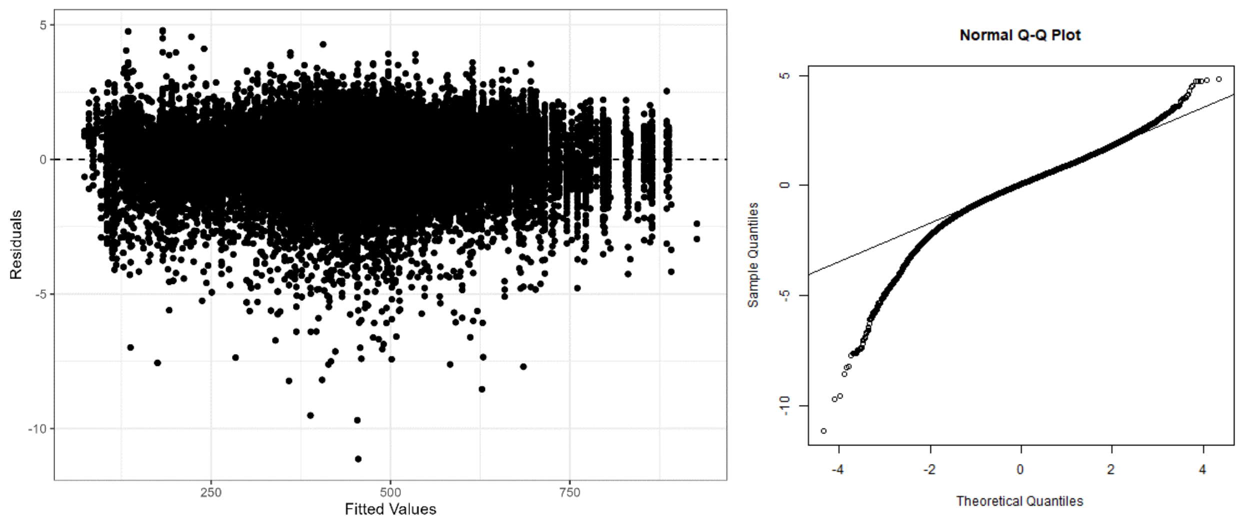


Figure 131. Diagnostic plots for the proposed joint catch per unit effort (CPUE) indicator model with the residual versus fitted value plot (left panel) and quantile-quantile plot (right panel).

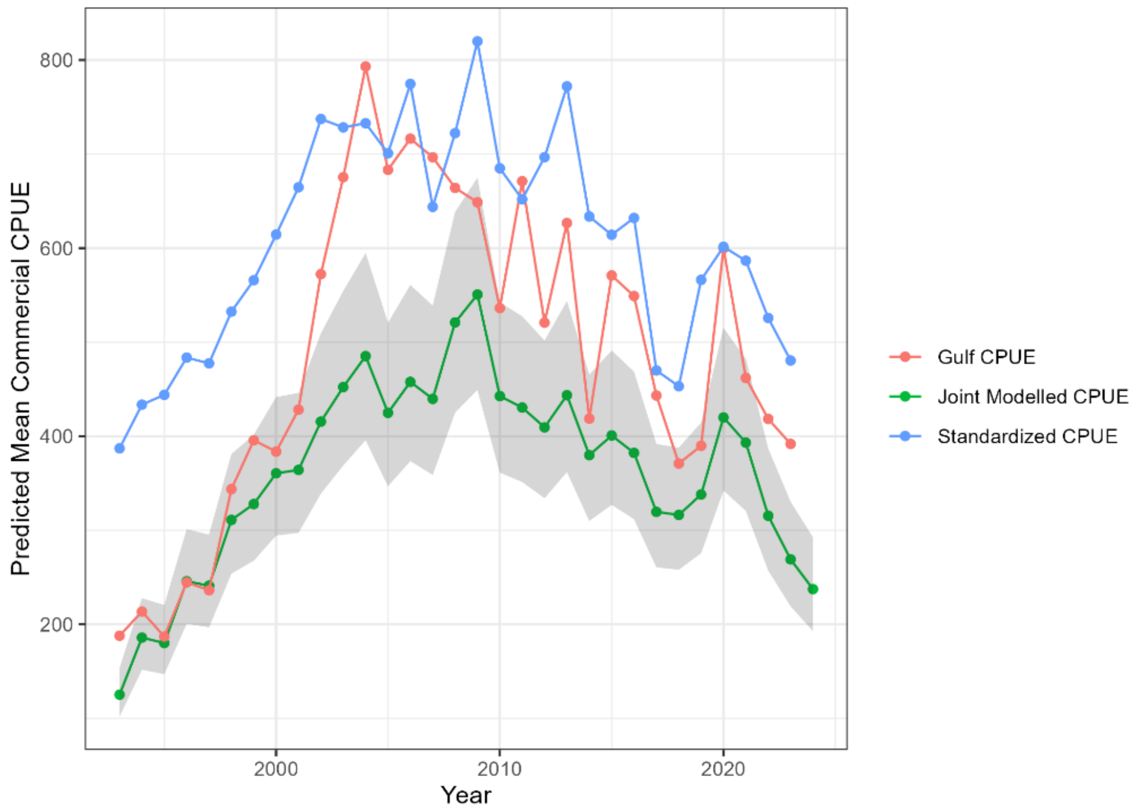


Figure 132. Joint modelled catch per unit effort (CPUE) (green line with grey ribbon is 95% confidence interval) from 1993 to 2024 compared to the Gulf CPUE and the standardized CPUE from 1993 to 2023.

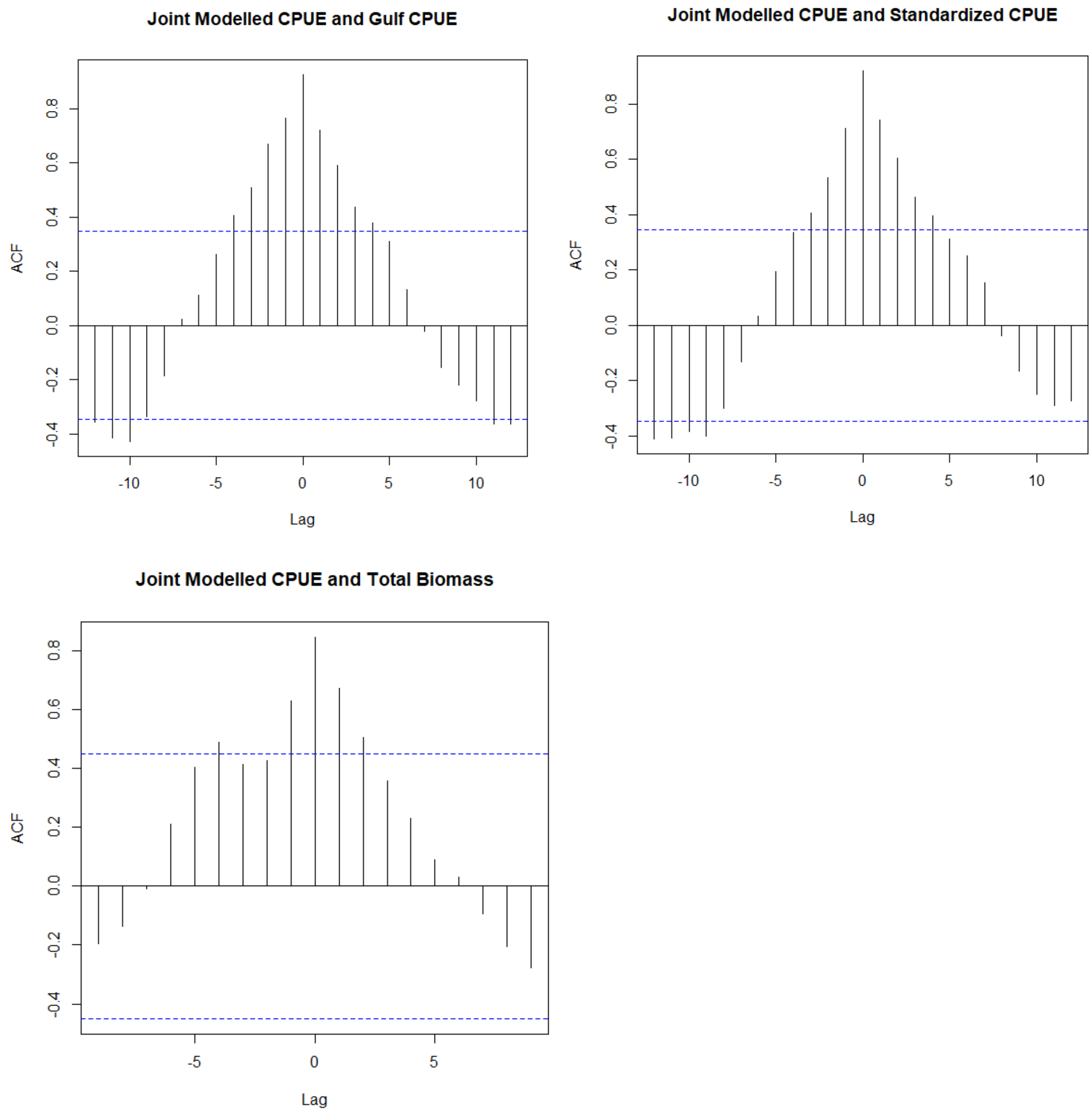


Figure 133. Cross autocorrelation function (ACF) between the joint modelled catch per unit effort (CPUE) and the Gulf CPUE (upper left panel), standardized CPUE (upper right panel), and the model-based total biomass (lower left panel).

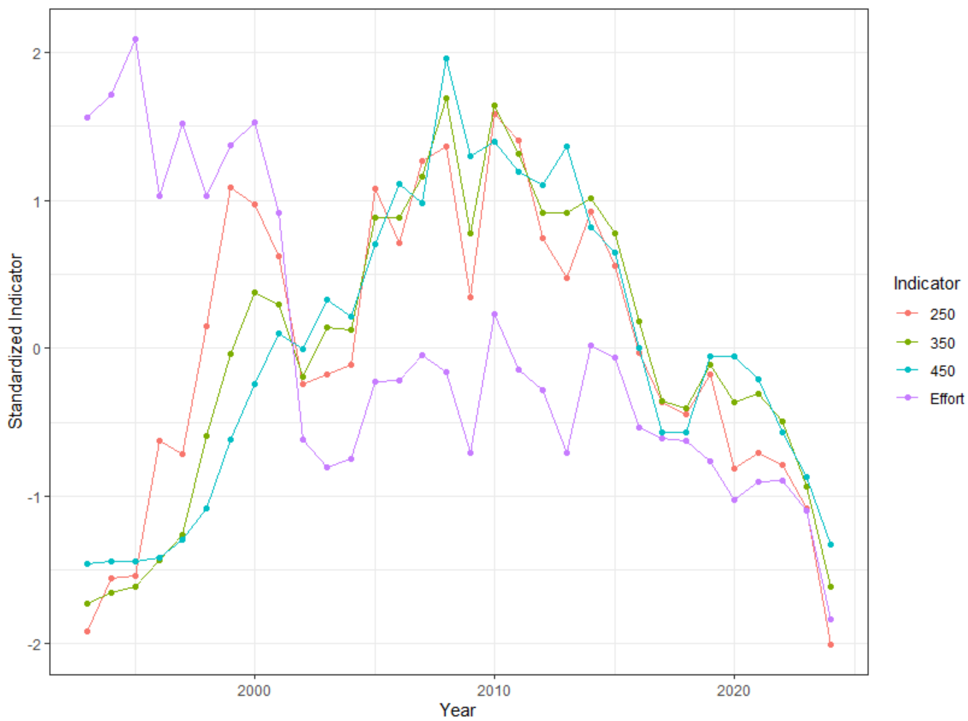


Figure 134. Standardized commercial area indicators based on different catch per unit effort cutoffs (250, 350, and 450 kilograms per hour (kg/hr)) alongside standardized effort (thousands of hours).

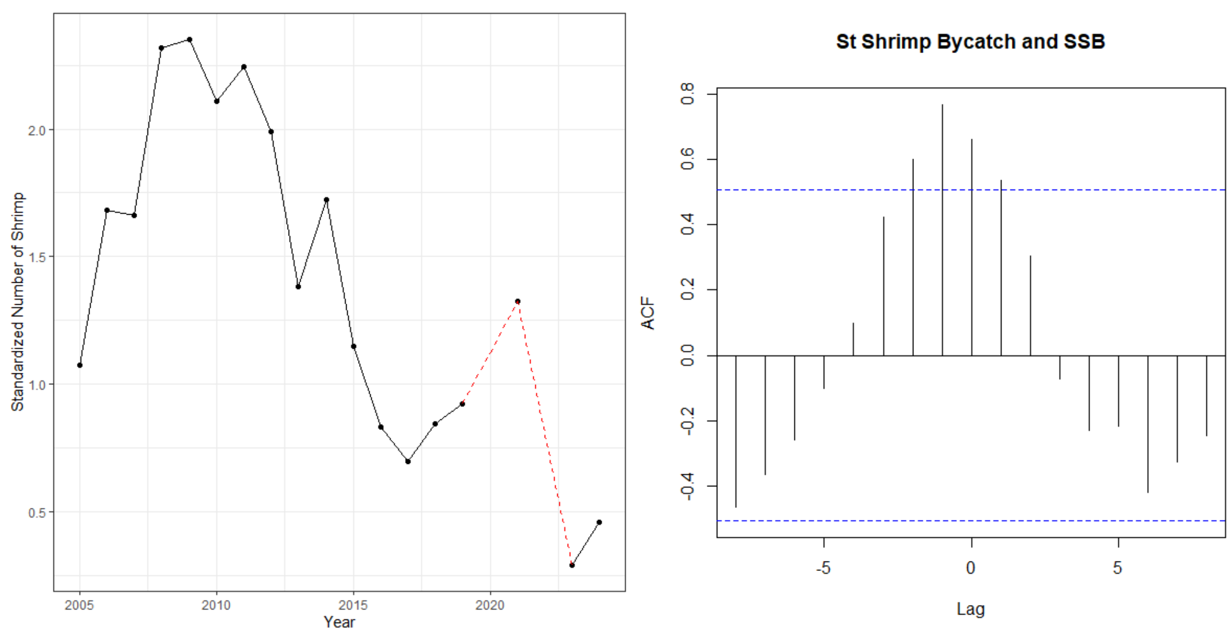


Figure 135. Standardized average number of shrimp caught as bycatch in the snow crab survey by year (left panel, dashed red lines indicate years where no snow crab survey happened or the coverage of the survey was insufficient). The cross-correlation function between the shrimp bycatch indicator (St Shrimp) and the spawning stock biomass (SSB) (right panel).

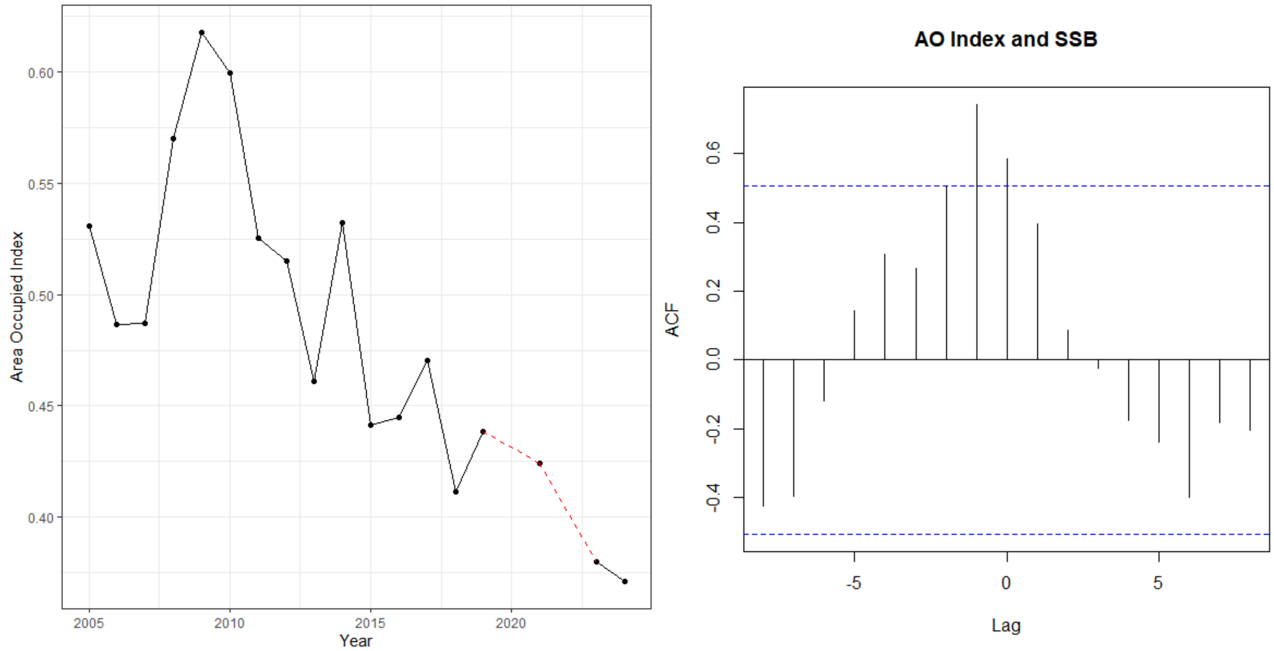


Figure 136. Area occupied (AO) Index obtained from the snow crab survey (left panel, dashed red lines indicate years where no snow crab survey happened or the coverage of the survey was insufficient). The cross autocorrelation function (ACF) between the AO index and the model-based spawning stock biomass (SSB) (right panel).

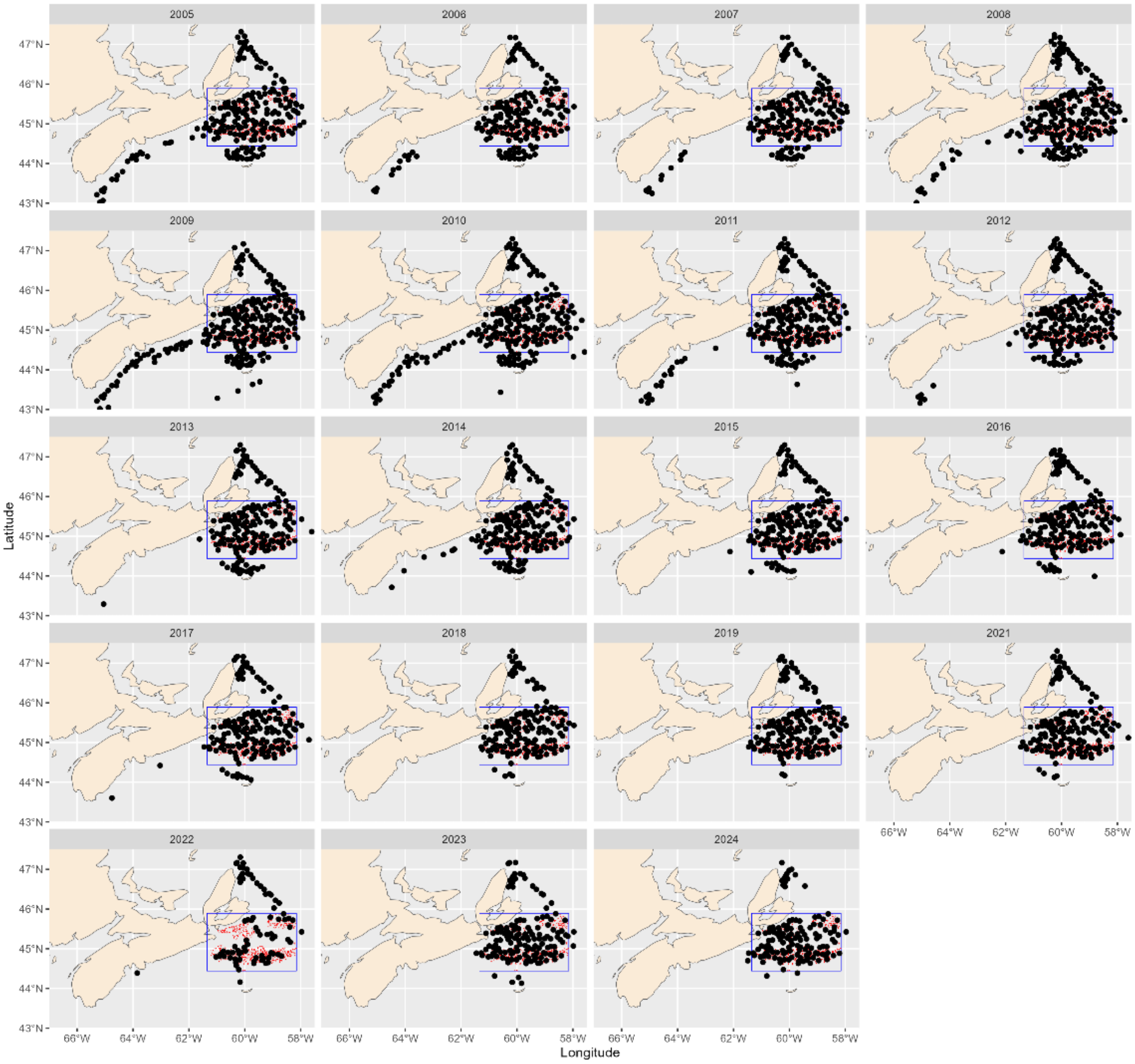


Figure 137. Presence of shrimp in the snow crab bycatch data across space from 2005 to 2024. No survey happened in 2020and the distribution in 2022 is due to the survey not being finished due to vessel issues, so are therefore not included in the new indicators. Credit for this figure goes to the snow crab unit and Amy Glass specifically.

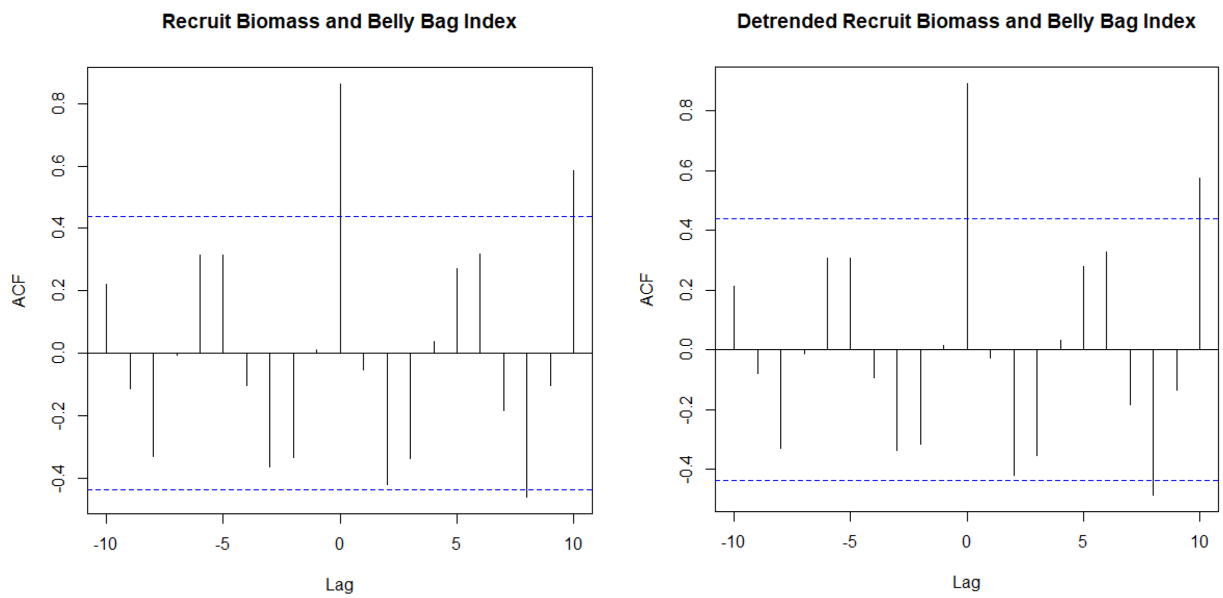


Figure 138. Cross autocorrelation function (ACF) between the model-based recruit biomass and the belly bag index, both without removing the trend (left panel) and detrending both variables (right panel).

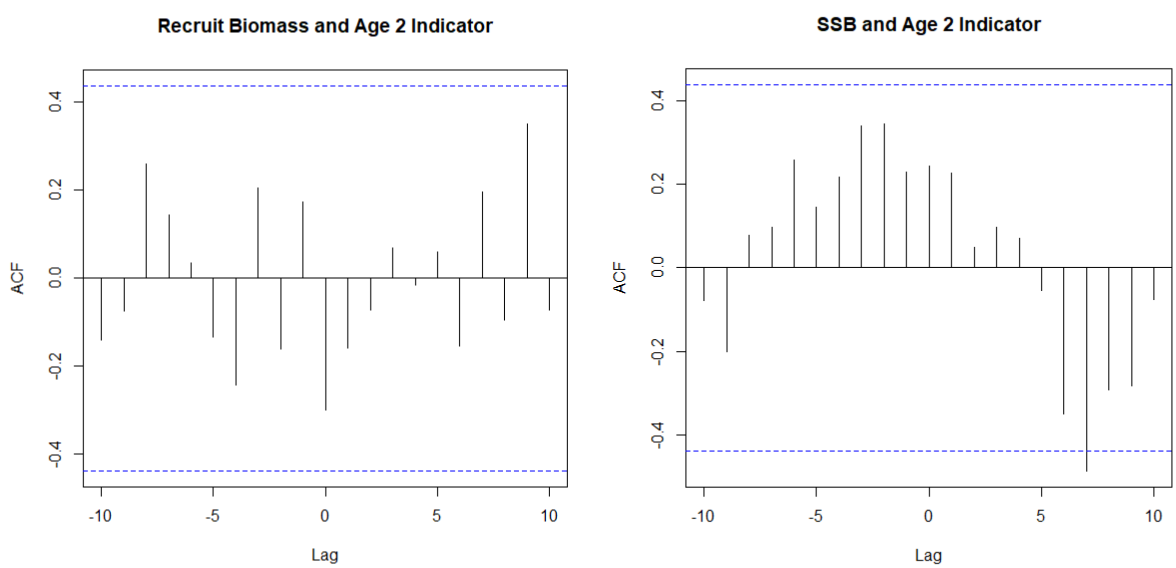


Figure 139. Cross autocorrelation function (ACF) between the recruit biomass and the Age 2 indicator (left panel) and the spawning stock biomass (SSB) against the Age 2 indicator (right panel).

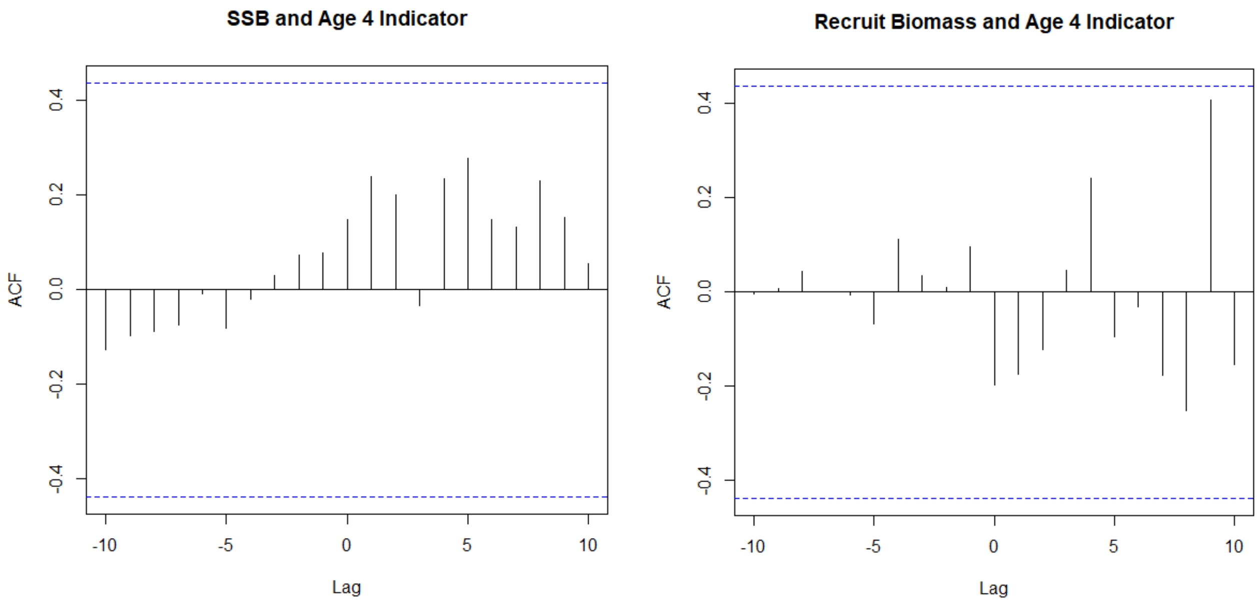


Figure 140. Cross autocorrelation function (ACF) between spawning Stock biomass (SSB) (left panel), recruit biomass (right panel) against the Age 4 indicator.

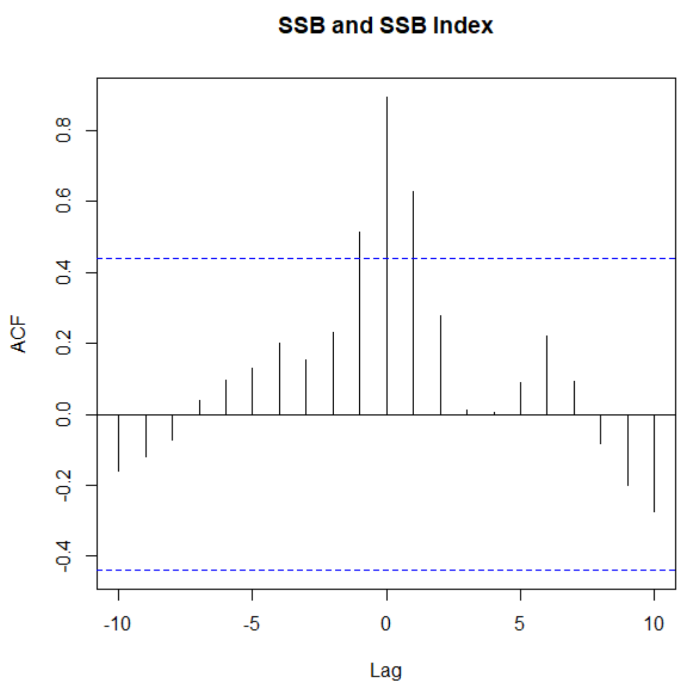


Figure 141. Cross autocorrelation function (ACF) between the model-based spawning stock biomass (SSB) and the legacy SSB indicator.

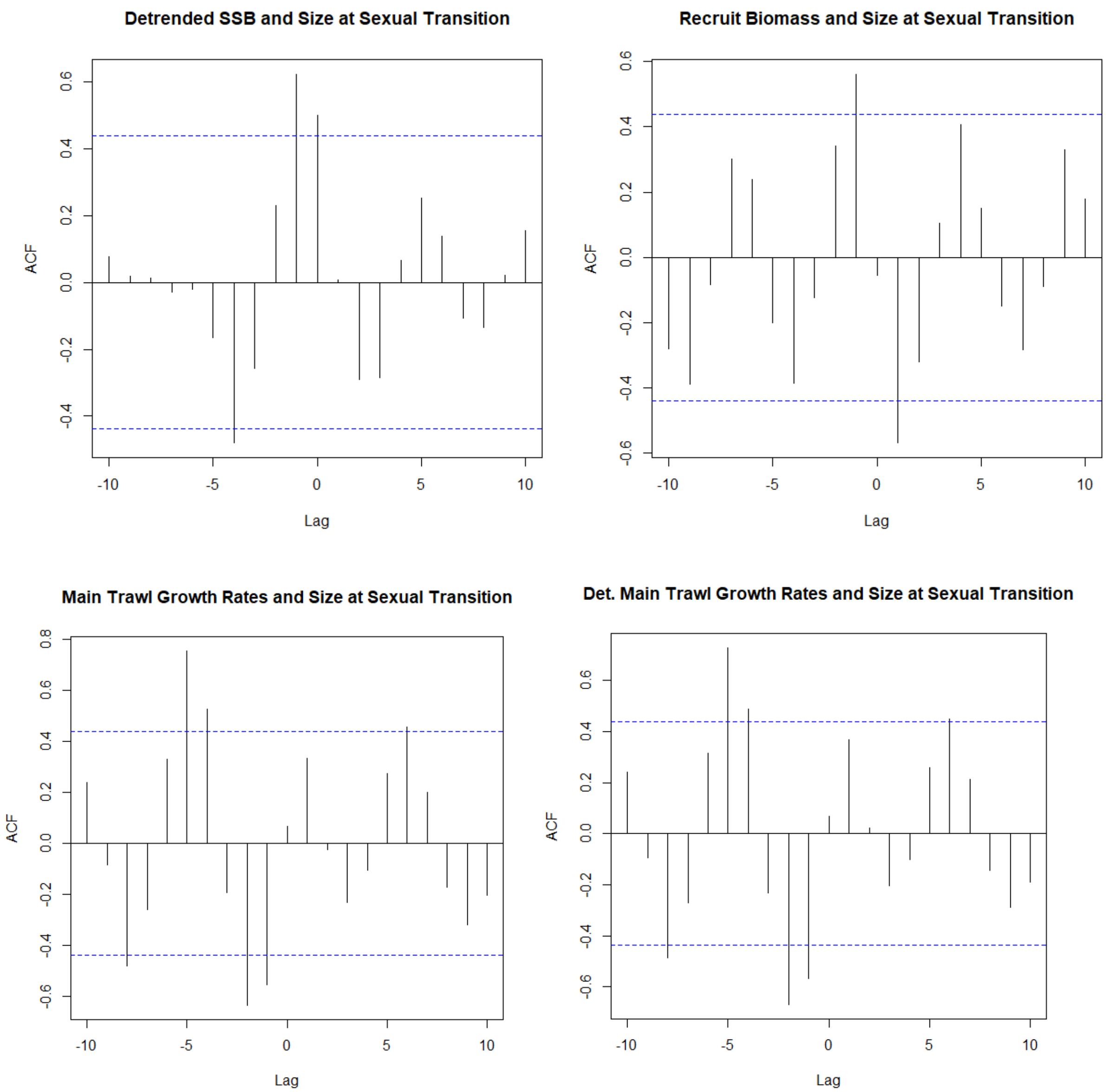


Figure 142. Cross autocorrelation function (ACF) between spawning stock biomass (SSB) and size at sexual transition when both are detrended (top left panel), between the recruit biomass and the size at sexual transition (top right panel), and between the main trawl growth rates and the size at sexual transition both without (bottom left panel) and with detrending (bottom right panel).

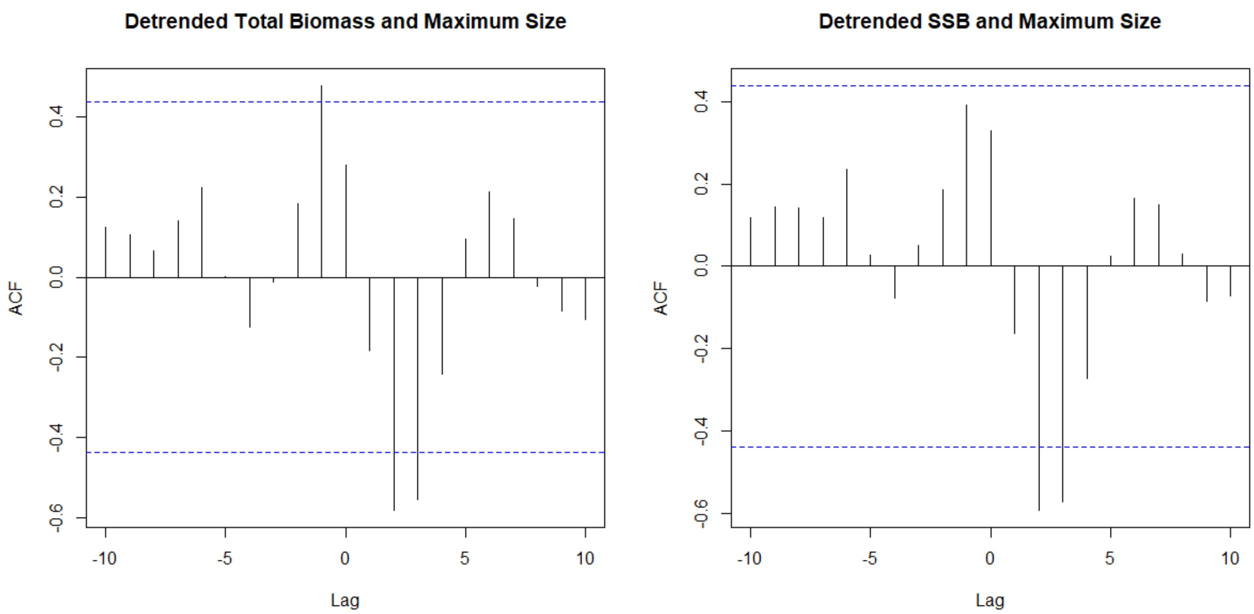


Figure 143. Cross autocorrelation function (ACF) between the detrended total biomass (left panel) and spawning stock biomass (SSB) (right panel) against maximum size.

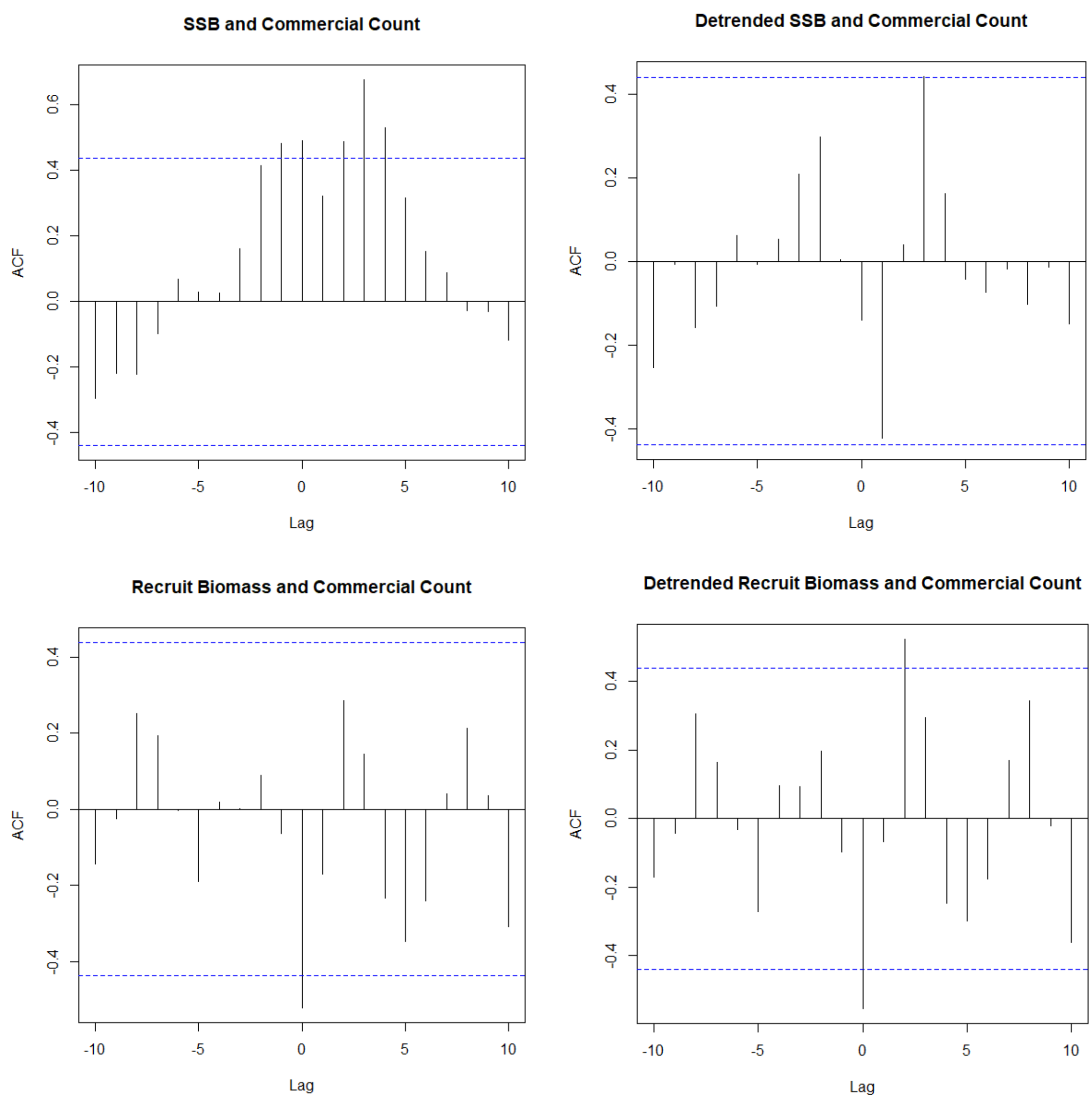


Figure 144. Cross autocorrelation function (ACF) between spawning stock biomass (SSB) (with trend, top left panel; detrended, top right panel) and commercial count and between the recruit biomass (with trend, bottom left panel; detrended, bottom right panel) and commercial count.

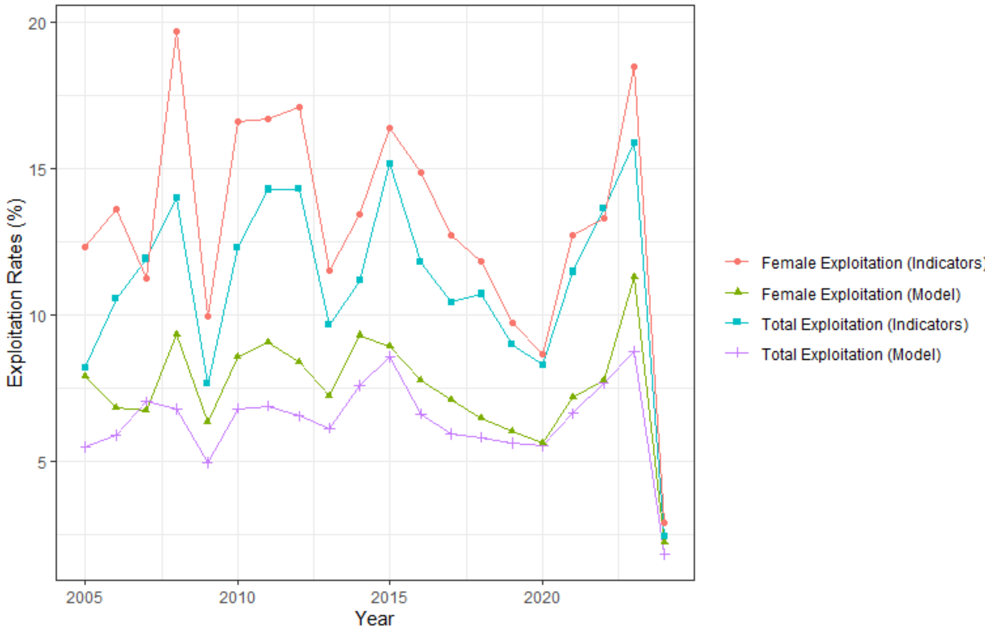


Figure 145. Exploitation rates in percent (both total and female) based on the model-based and index-based total biomass and spawning stock biomass.

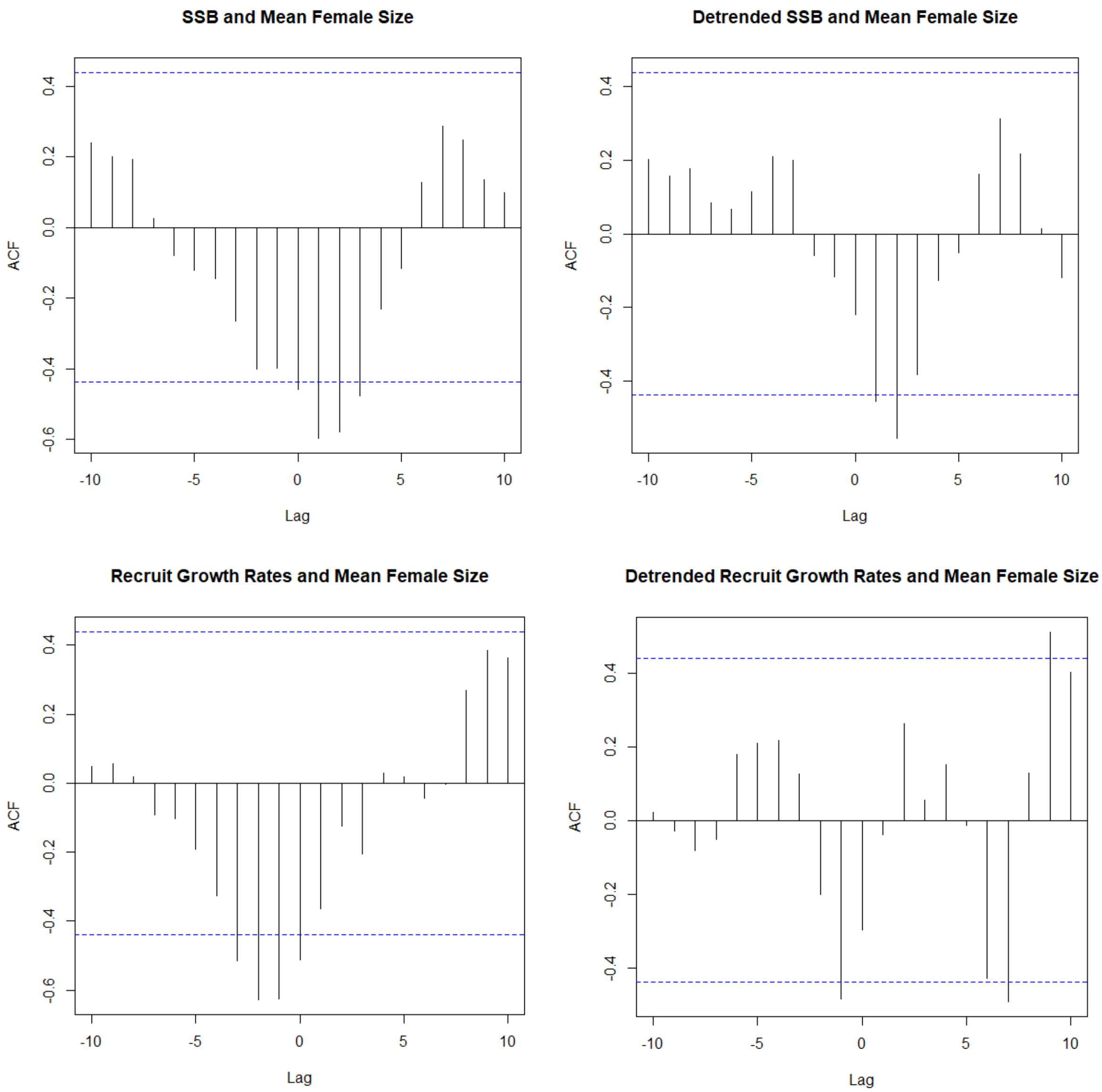


Figure 146. Auto correlation function (ACF) of spawning stock biomass (SSB) (with trend, top left panel; detrended, top right panel) and recruit growth rates (with trend, bottom left panel; detrended, bottom right panel) with mean female size.

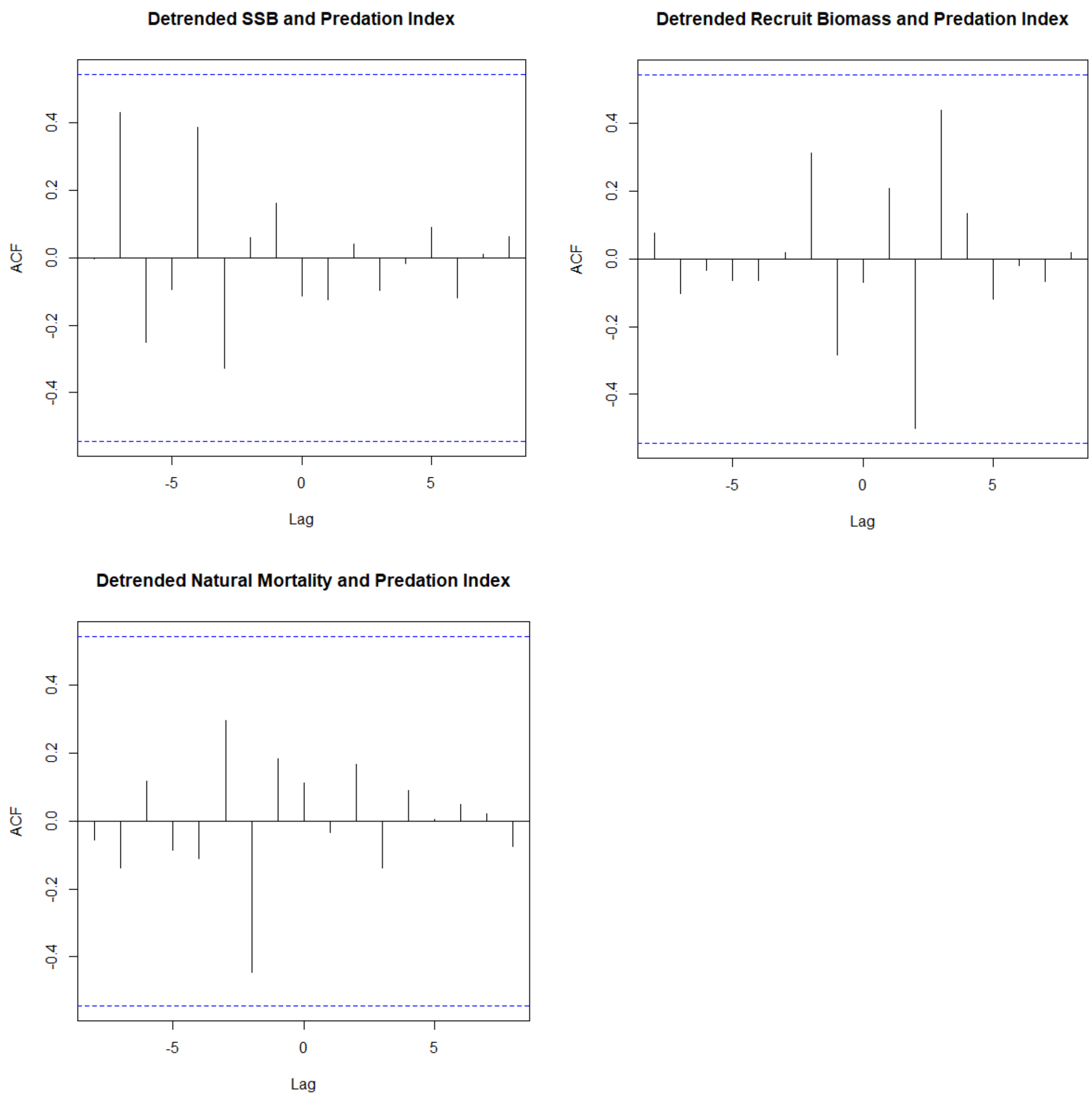


Figure 147. Cross autocorrelation function (ACF) of detrended spawning stock biomass (SSB) (top left panel), recruit biomass (top right panel), and natural mortality (bottom left panel) with predation index.

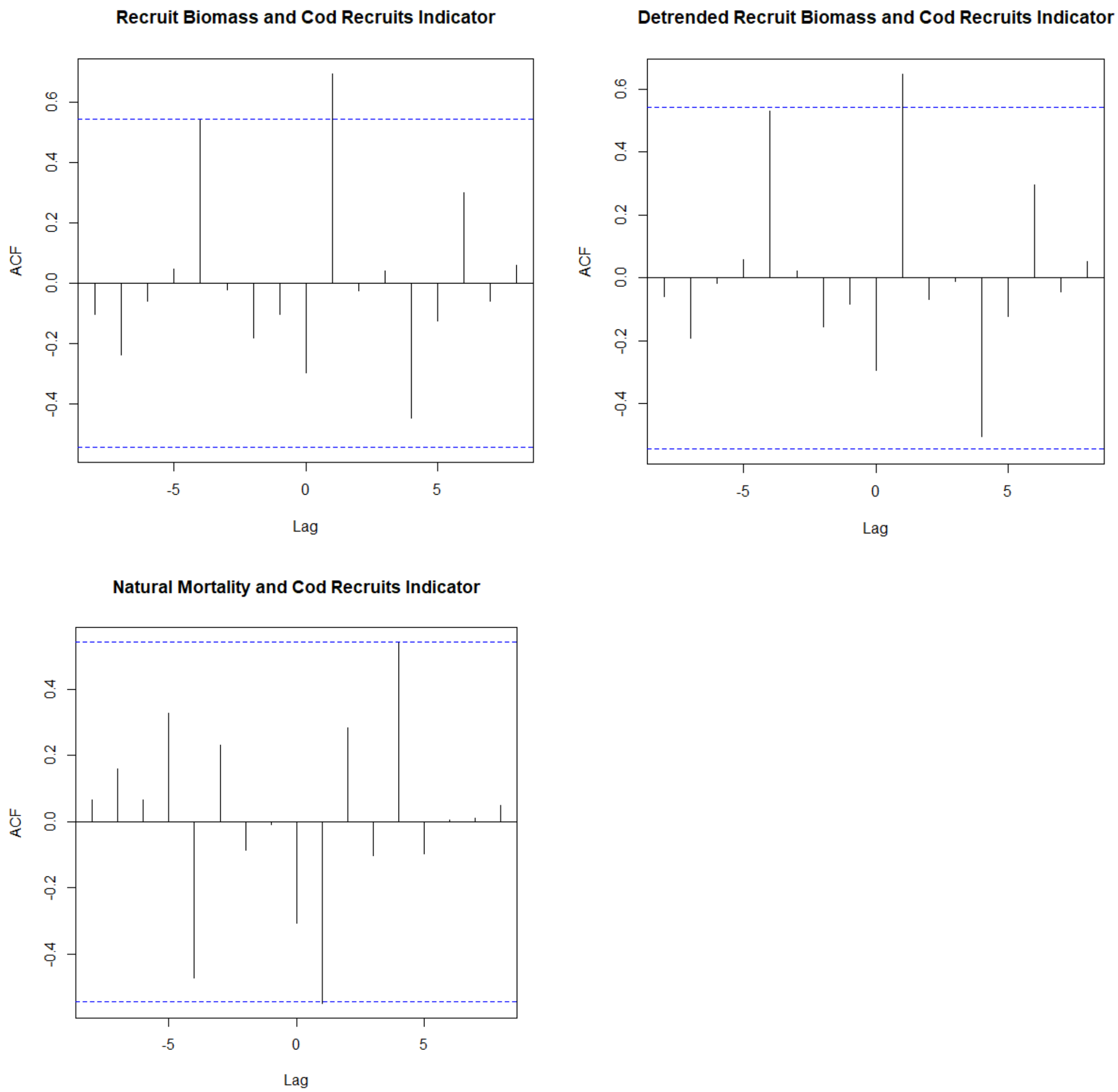


Figure 148. Cross autocorrelation function (ACF) of recruit biomass (with trend, top left panel; detrended, top right panel) and natural mortality with cod recruit indicator (lower left panel).

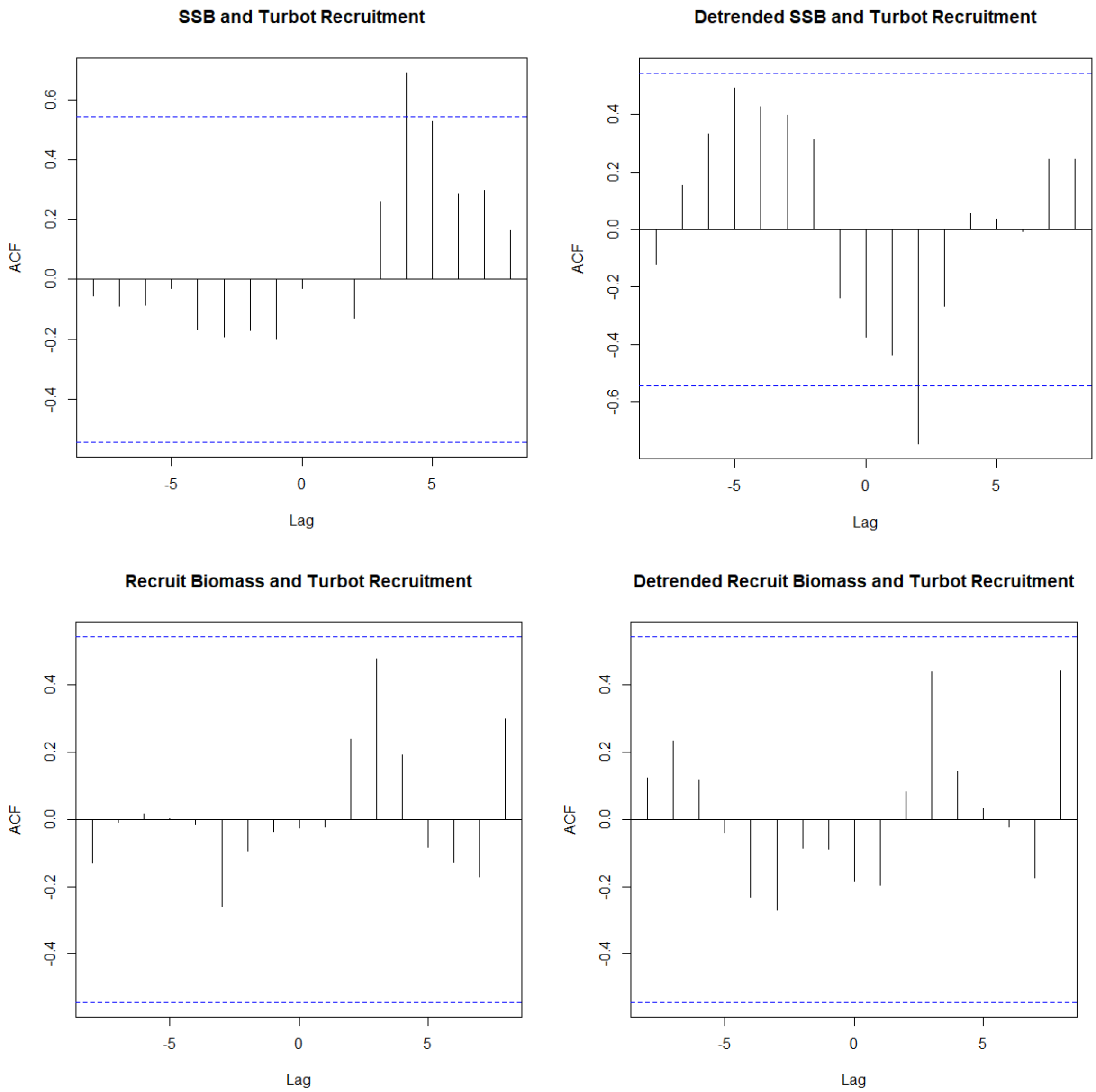


Figure 149. Cross autocorrelation function (ACF) of spawning stock biomass (SSB) (with trend, top left panel; detrended, top right panel) and recruit biomass (with trend, bottom left panel; detrended, bottom right panel).

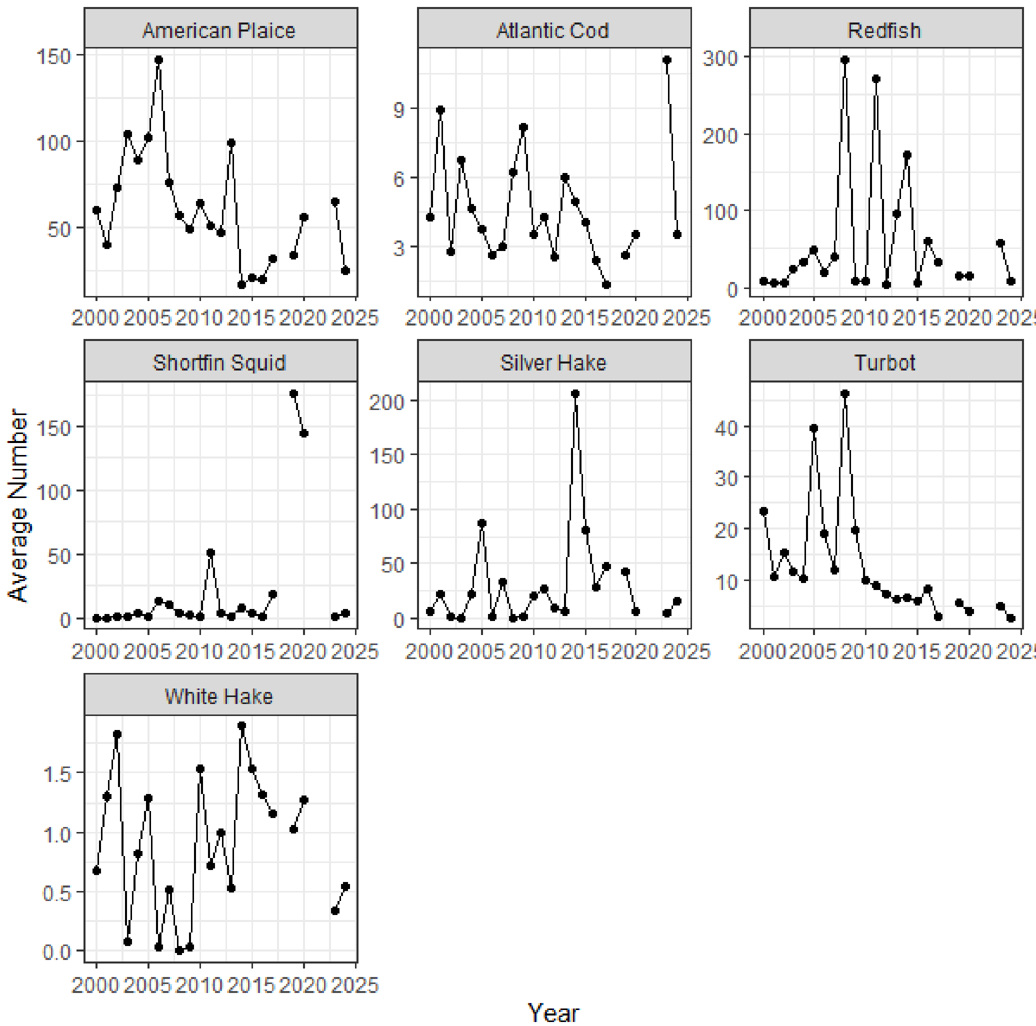


Figure 150. Average number of potential predators captured in the DFO Summer Research Vessel Ecosystem Trawl survey in the strata around the shrimp fishing holes. Gaps in years are caused by the survey not going in the shrimp areas.

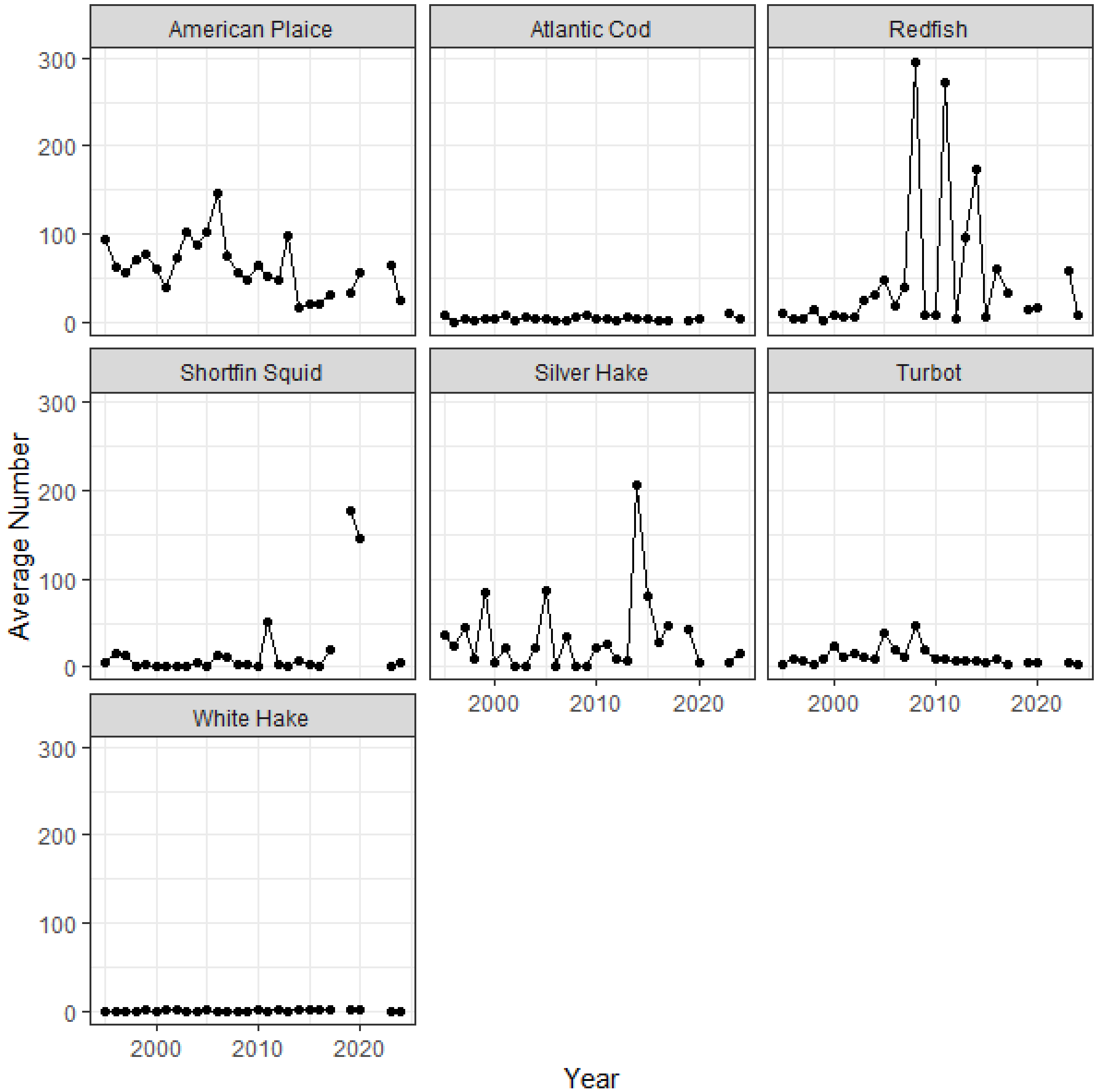


Figure 151. Average number of potential predators captured in the DFO Summer Research Vessel Ecosystem Trawl survey in the strata around the shrimp fishing holes on the same scale. Gaps in years are caused by the survey not going in the shrimp areas.

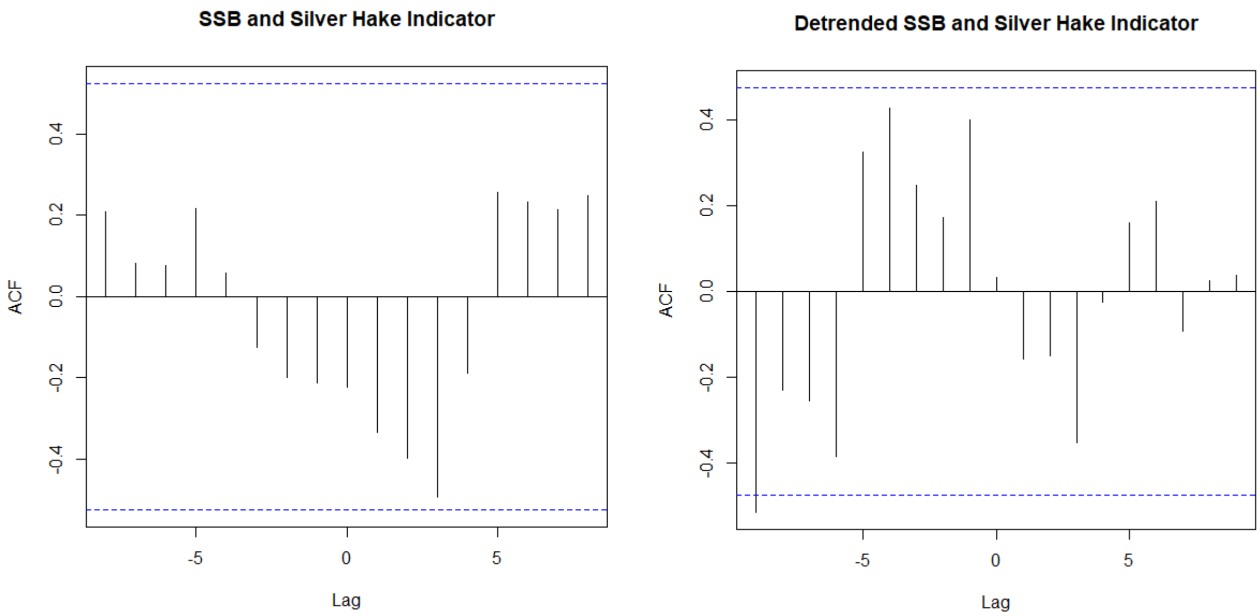


Figure 152. Cross autocorrelation function (ACF) between spawning stock biomass (SSB) (with trend, left panel; detrended, right panel) and the Silver hake indicator.

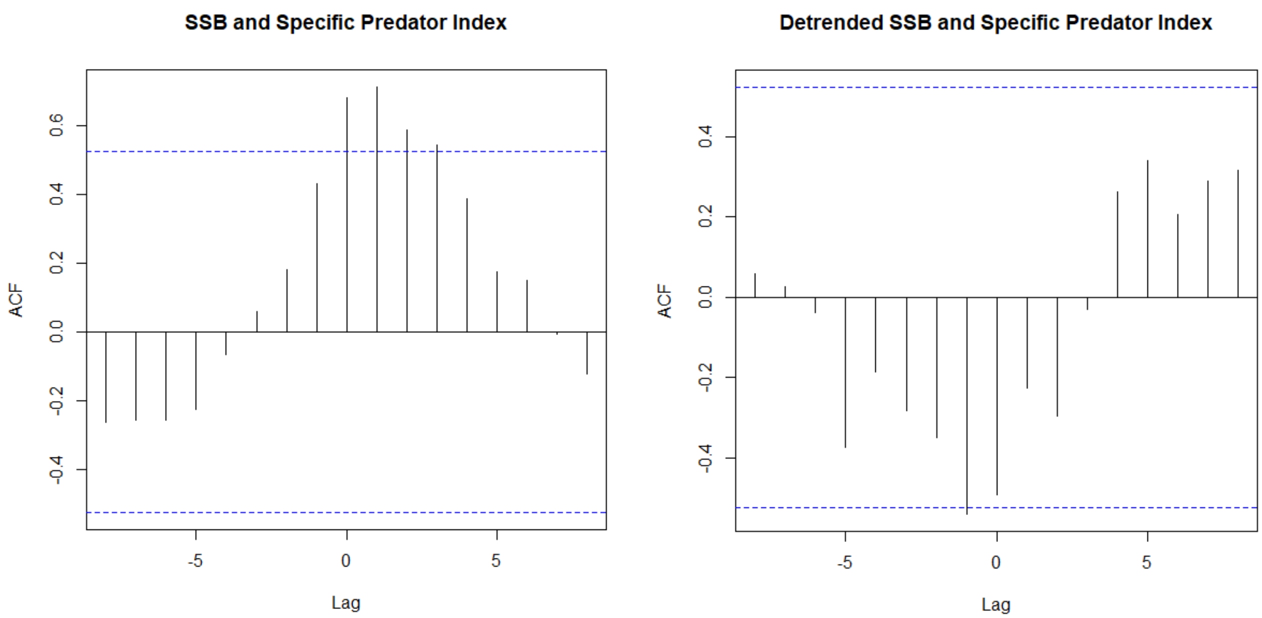


Figure 153. Cross autocorrelation function (ACF) between spawning stock biomass (SSB) (with trend, left panel; detrended, right panel) and the new specific predator index.

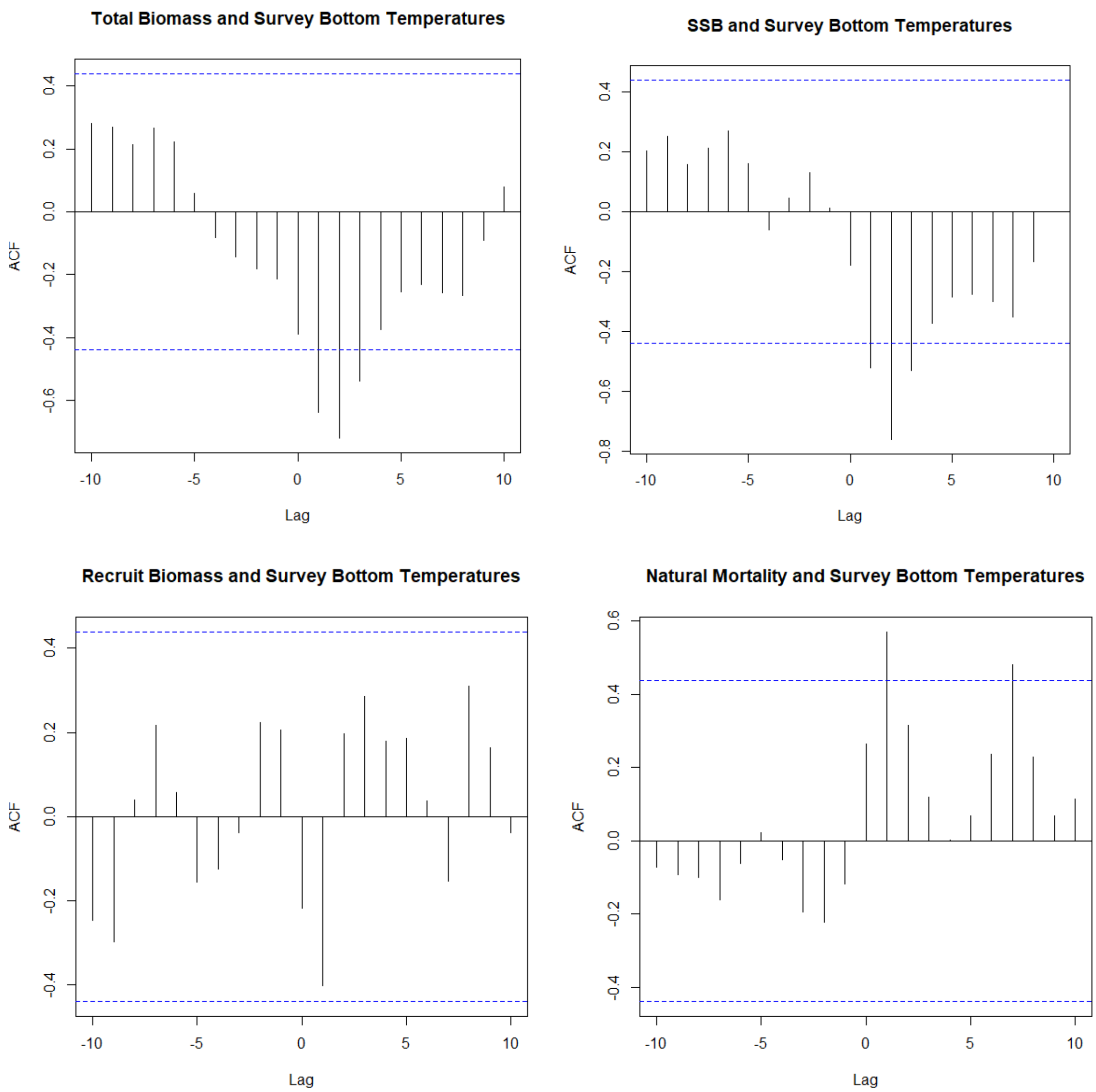


Figure 154. Cross autocorrelation function (ACF) of biomass (top left panel), spawning stock biomass (SSB) (top right panel), recruit biomass (bottom left panel), and natural mortality (bottom right panel) with the survey bottom temperatures.

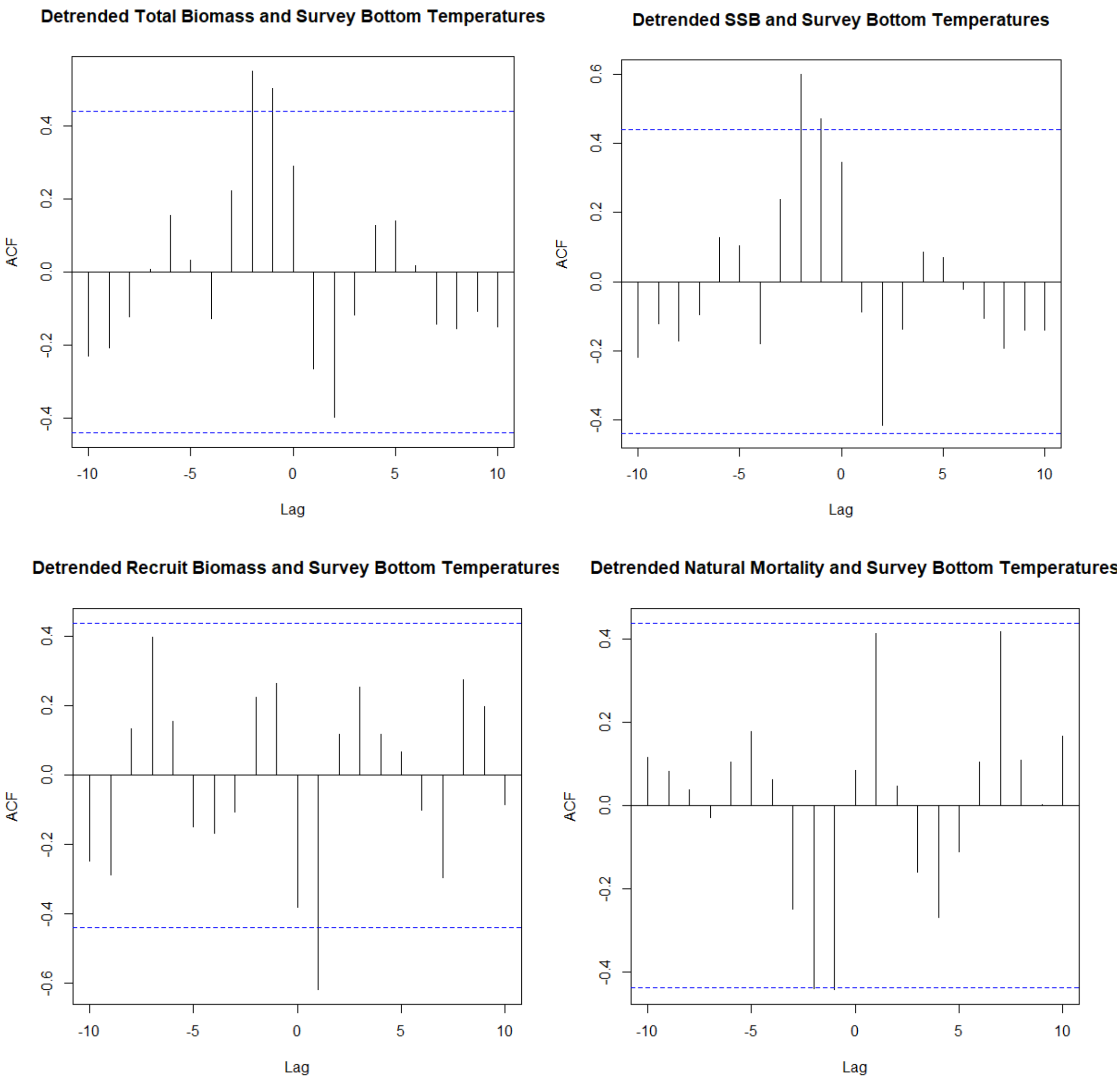


Figure 155. Cross autocorrelation function (ACF) of detrended biomass (top left panel), spawning stock biomass (SSB) (top right panel), recruit biomass (bottom left panel), and natural mortality (bottom right panel) with the detrended survey bottom temperatures.

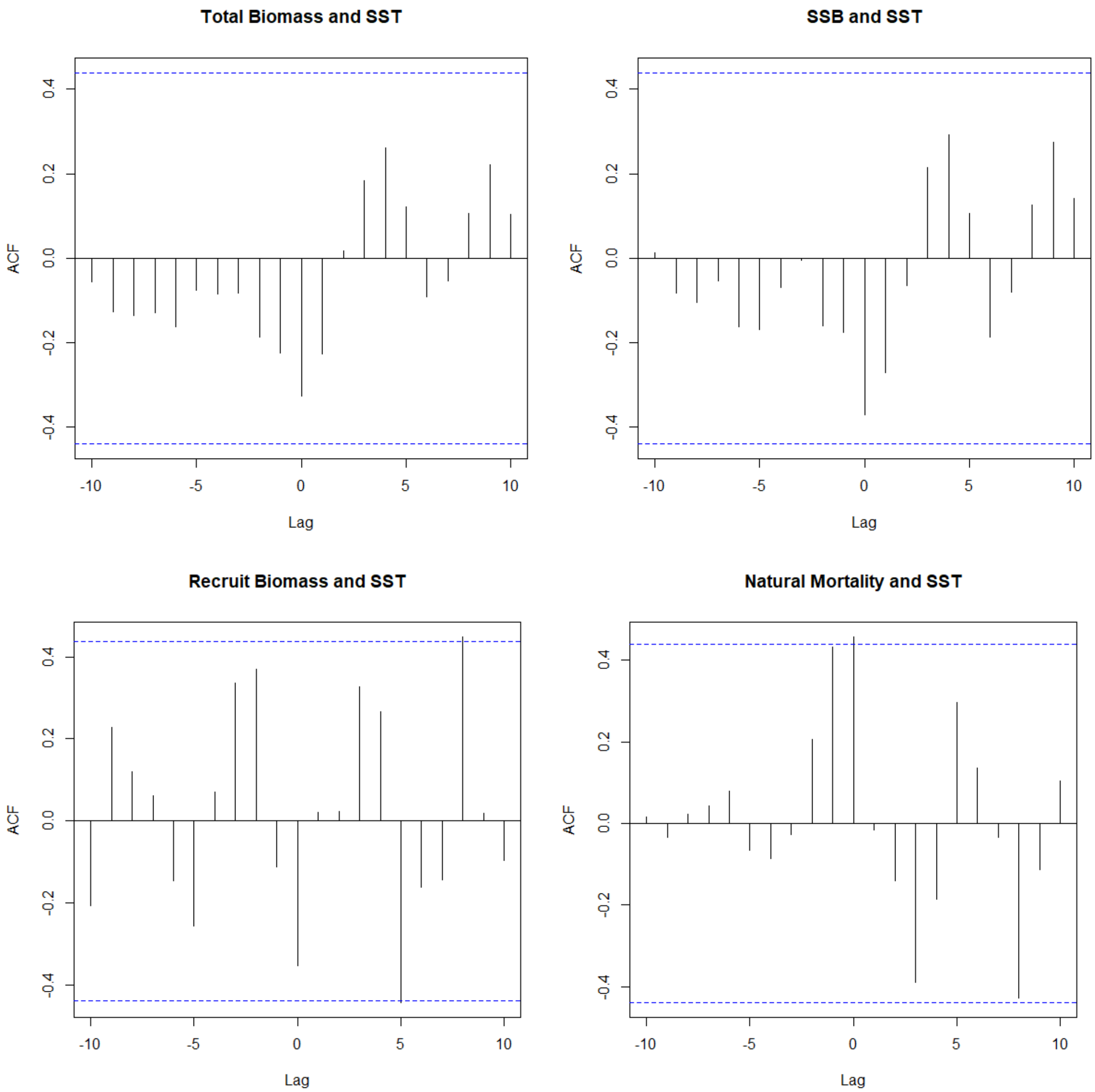


Figure 156. Cross autocorrelation function (ACF) of biomass (top left panel), spawning stock biomass (SSB) (top right panel), recruit biomass (bottom left panel), and natural mortality (bottom right panel) with the sea surface temperatures.

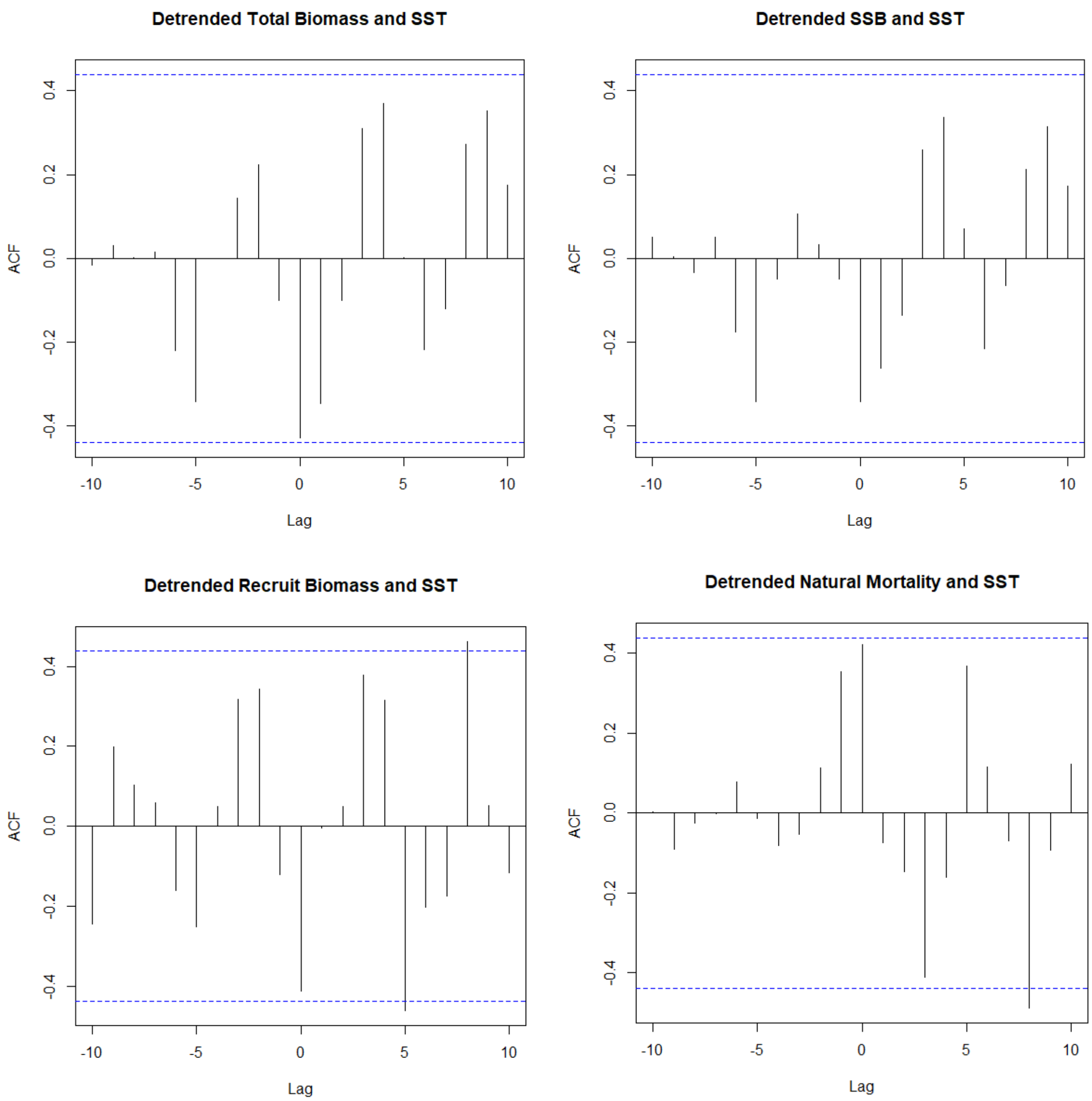


Figure 157. Cross autocorrelation function (ACF) of detrended biomass (top left panel), spawning stock biomass (SSB) (top right panel), recruit biomass (bottom left panel), and natural mortality (bottom right panel) with the detrended sea surface temperatures.

Figure 158. Cross autocorrelation Function (ACF) between natural mortality and the snow crab recruitment index.

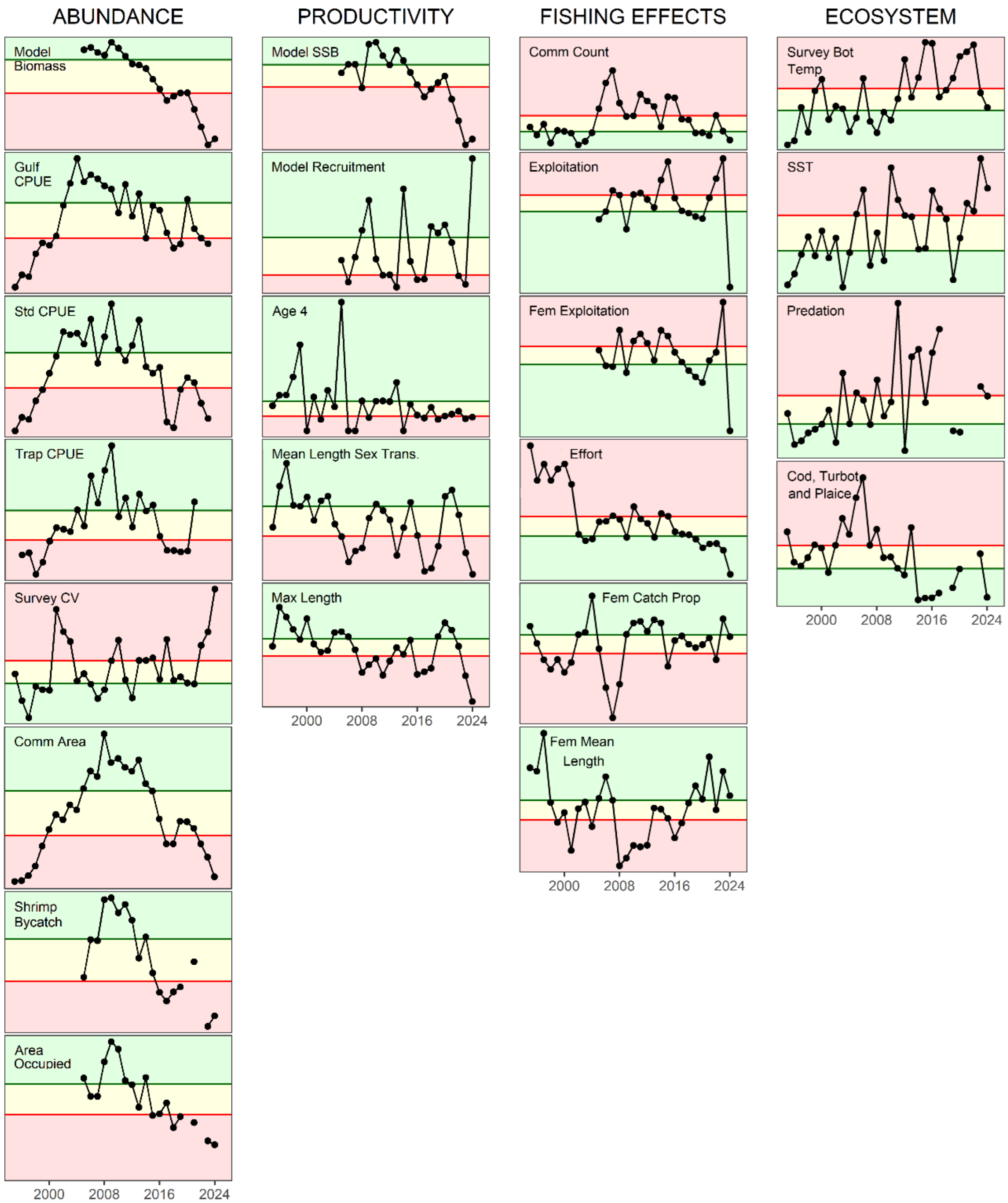


Figure 159. Updated time series of individual Eastern Scotian Shelf Northern Shrimp indicators. Due to the limited number of active licenses and guidelines associated with public reporting pursuant to the Privacy Act, the three commercial catch per unit effort (CPUE) indicators (Gulf CPUE, Std CPUE, and Trap CPUE) are not updated in 2024. SST = Sea Surface Temperature; Std CPUE = Maritimes mobile fleet standardized catch per unit effort index; Comm count = commercial counts of shrimp per pound.

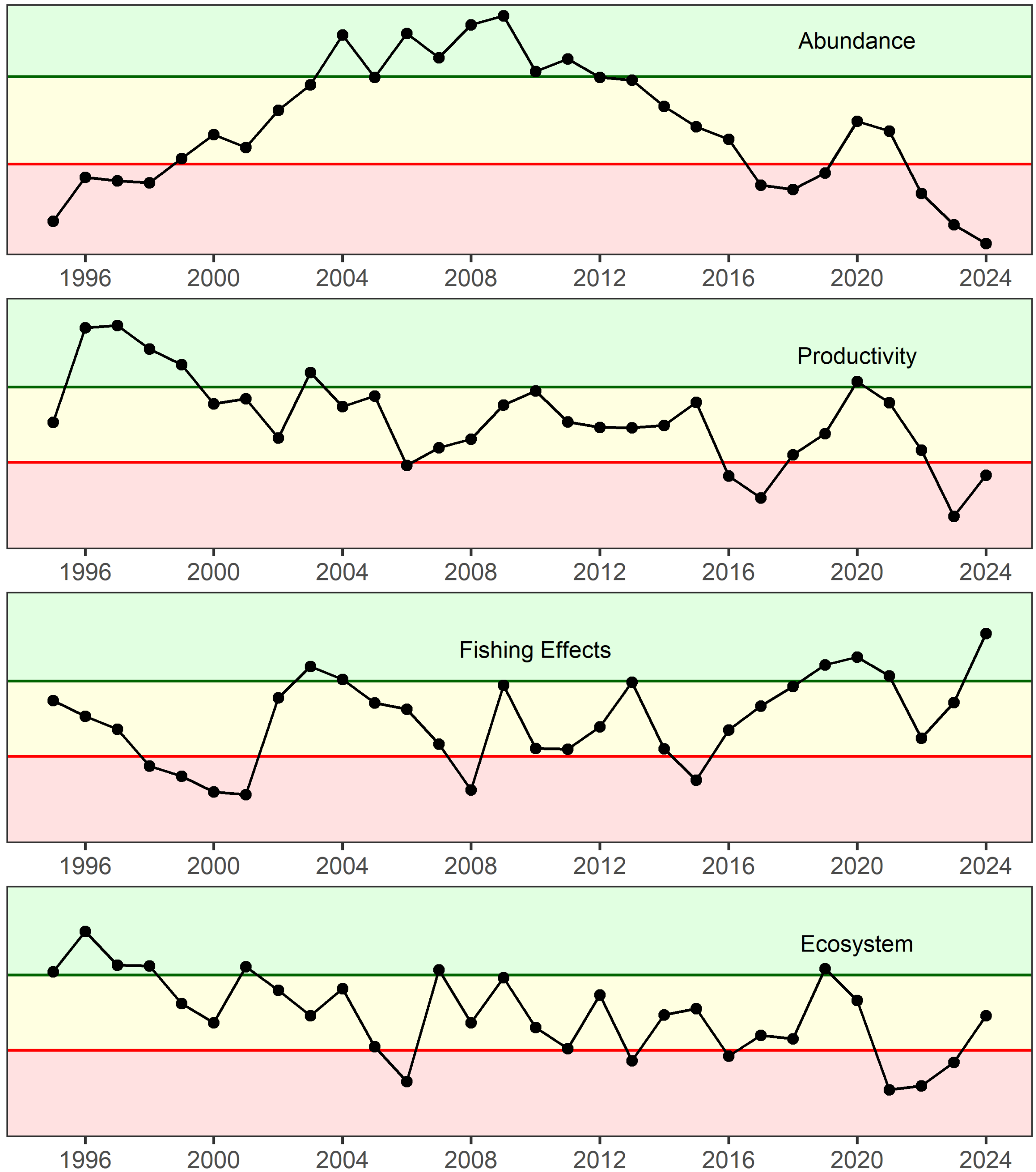


Figure 160. Updated characteristic-specific mean indicators along with overall mean indicator for Eastern Scotian Shelf Northern Shrimp Traffic Light Approach.

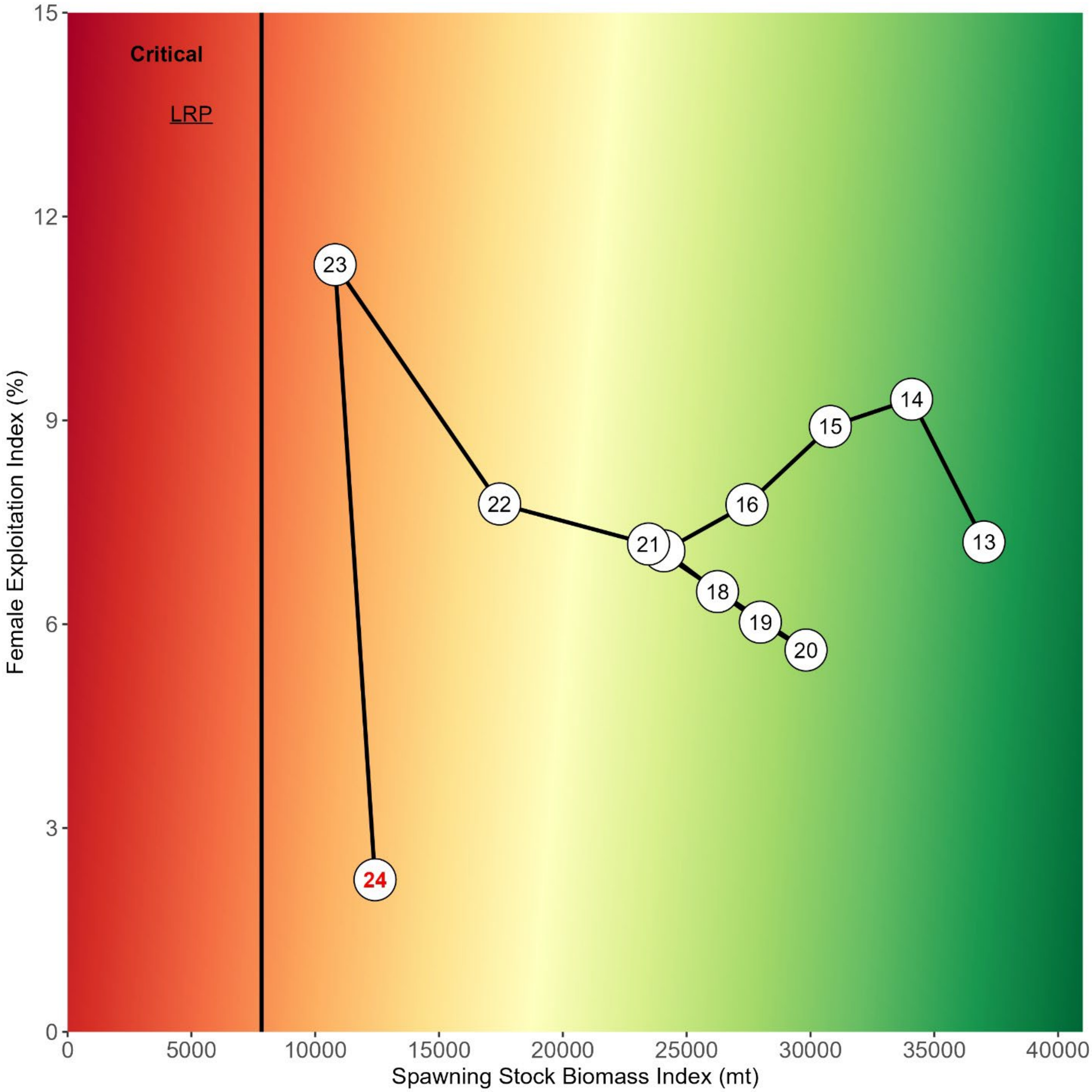


Figure 161. Preliminary DFO Precautionary Approach plot with proposed limit reference point.