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Impact of an expanding Redfish (*Sebastes* spp.) fishery on southern Gulf of St. Lawrence White Hake (*Urophycis tenuis*)

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Foreword

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

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ABSTRACT

The southern Gulf of St. Lawrence (sGSL) White Hake Designatable Unit (DU) has been assessed as Endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). This DU consists primarily of White Hake occurring in the Northwest Atlantic Fishery Organization (NAFO) Division 4T. The Recovery Potential Assessment for this stock found that extremely high natural mortality was preventing the recovery of this stock, while fishing mortality with a bycatch limit of 30 t has a negligible effect on the population trajectory. However, if fishing effort is increased as proposed with the expansion of the Redfish fishery, the impacts of bycatch fisheries on this population may no longer be considered negligible.

This report aimed to examine existing information from surveys and fisheries to evaluate whether increased catch levels of Redfish would result in increased bycatch of White Hake. Significant overlap in the spatial distribution of White Hake and Redfish was noted in along the deep waters of the Laurentian Channel. This is partly the result of diet interdependencies among these species and the shift of White Hake to deeper waters to avoid predation. Bycatch of White Hake associated with Redfish was lower at depths greater than 380 m, whereas bycatch was much greater in the months of June, July, and December. Bycatch did not differ significantly based on gear type, however bycatch was overall greater in the southern region of the Laurentian Channel. Overall, the mean value of bycatch was 10.5% in the Redfish fishery. Even in the absence of fishery removals, the sGSL White Hake stock is expected to decline due to extremely high natural mortality. The sGSL White Hake population was projected forward 25 years assuming that productivity would remain at recent levels. SSB was estimated to decline by 38.7% with no catch and 39.3% with annual bycatch of 20 t, the recent level. With annual bycatch of 150 t to 350 t, SSB was estimated to decline by 43% to 48%. With bycatch of 500 t to 1,500 t, SSB declined by 53% to 70%. At present, the White Hake stock is sustained by unusually high recruitment rates which depend largely on a single cohort each year (age 4). The extinction risk for this stock (below 2,000 t) is 22 to 26% with no bycatch up to 150 t, and increases to 30% and 49% at bycatch levels of 350 t to 1,500 t respectively. If recruitment rates were to decline even slightly to the levels seen in the 2000s, the extinction risk for this stock would increase. At the present 30 t bycatch limit for White Hake, White Hake will become a choke species for the future Redfish fishery.

INTRODUCTION

Two concurrent activities are occurring within Fisheries and Oceans Canada that are interlinked and have potentially divergent outcomes. The first, the Species at Risk Programs, needs to provide a listing recommendation for southern Gulf of St. Lawrence (sGSL) White Hake under the Species at Risk Act. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the sGSL White Hake Designatable Unit (DU) as Endangered (COSEWIC 2013). In the development of management scenarios as part of the listing process, ongoing bycatch could be permitted under a SARA listing scenario as natural mortality is so elevated that current bycatch levels of 30 t have negligible effects on the stock trajectory (DFO 2016). At the same time, the imminent arrival of Redfish cohorts from 2011 to 2013 at sizes greater than the minimum regulatory size is generating strong interest from a number of stakeholders, for example, provincial and federal governments, industry (fishing, processing, and marketing), First Nations, and environmental groups. Resource Management is considering expanding the Redfish fishery to exploit this new biomass. The commercial Redfish fishery reopening in Unit 1 may have significant impacts on bycatch of sGSL White Hake and may mean that fishing mortality is no longer considered negligible.

In this instance, we have a productive stock, Redfish, and a weak stock, White Hake that may both be caught in an expanding fishery. The spatial distribution, vertical position within the water column, and seasonality of both White Hake and Redfish will determine whether policies developed to rebuild the weak stock will be in contrast to efforts to maximize yield in the productive Redfish stock. This is referred to as the “weak stock problem” and is one of the most challenging aspects facing fisheries management (Caddy 1999, Hall et al. 2000). At present the regulations for sGSL White Hake are a 30 t annual bycatch limit and a maximum bycatch of less than 5% per trip in the Redfish and in other fisheries in order to minimize preventable decline in this stock. It is possible that White Hake will be the choke stock constraining harvest of the Redfish stock.

The purpose of this report is to examine existing information to evaluate the potential impacts of increased bycatch of sGSL White Hake in fisheries for Redfish. In order to answer this question, we identified the spatial overlap of Redfish and White Hake in the sGSL, provided information on the distribution of White Hake along the deep waters of the Laurentian slope where they now occur, and examined the areas and depths where White Hake was less prone to bycatch. We also provided up-to date mortality estimates for sGSL White Hake as bycatch in directed fisheries and total mortality and we used the White Hake model and average estimates of bycatch to provide estimates of potential change in fisheries mortality at various Redfish catch levels.

We were unable to respond to the request to provide advice on the seasonal distribution of White Hake and Redfish as information was only available from the bottom trawl research surveys conducted in August and September. We were, however, able to use the existing data on the index and experimental Redfish fishery to examine bycatch of White Hake seasonally from June to December. We were also unable to examine vertical distribution of the two species within the water column.

SPECIES INFORMATION

sGSL White Hake

White Hake (*Urophycis tenuis* Mitchill) was historically a commercially important groundfish in the sGSL, ranking third or fourth in terms of annual landings. However, the directed fishery for

White Hake was closed in 1995 due to low White Hake abundance, and has remained under moratorium. Roy et al. (2012) reported that White Hake in the sGSL were genetically distinct from White Hake in other areas of Atlantic Canada. The sGSL DU was assessed as Endangered by COSEWIC, whereas the Atlantic and Northern Gulf of St. Lawrence DU (Atlantic DU hereafter) is Threatened (COSEWIC 2013). The most recent assessment of the sGSL stock was the recovery potential assessment (RPA) in January 2015 (DFO 2016, Swain et al. 2016) with the most recent indicator update occurring in 2020 (DFO 2020a). The stock continues to be in the Critical Zone of the Precautionary Approach using the abundance recovery target as defined in the RPA (40% of the spawning stock biomass (SSB)) as the limit reference point.

A combination of genetic, spawning behavior, and meristic information were used to identify the two DUs of White Hake in Canada. The sGSL DU occurs in the southern Gulf of St. Lawrence predominately Northwest Atlantic Fishery Organization (NAFO) Division 4T (Fig. 1), it has distinct genetic composition and spawns in the summer in shallow, inshore waters. White Hake in the Atlantic DU spawn in deep, offshore water in early spring (Roy et al. 2012, COSEWIC 2013). The northern portion of NAFO SubDivision 4Vn (Fig. 1) also showed the sGSL genotype. For the purposes of this report it was assumed that the status the sGSL DU could be assessed based on analysis of the NAFO Division 4T management unit, which is dominated by the sGSL DU and comprises the bulk of the area occupied by this DU. This was also the same assumption made for the RPA. NAFO Division 4T includes the St. Lawrence Estuary, however the genetic identity of White Hake occurring in this area (NAFO unit areas 4Topq) is unknown as there were no genetic samples collected. The contribution of this area to landings of 4T White Hake is minor (1985-2010 average, 1.1%). The Laurentian Channel represents an area of overlap between the two DUs. Over 90% of White Hake collected in the sGSL (NAFO Division 4T, Fig. 1) at depths less than 200 m are of the Gulf type, with this proportion declining as depth increased, from about 80% in the 200 – 250 m range to 34% at depths greater than 350 m (Swain et al. 2012).

sGSL White Hake overwinter in the Laurentian Channel in NAFO Division 4T and SubDivision 4Vn (the Cabot Strait), occurring at depths greater than 200 m (Chouinard and Hurlbut 2011). In summer, White Hake either remain in relatively deep water (> 100 m) or move into shallow water (mostly < 50 m) along the Gulf coasts of New Brunswick, Prince Edward Island, mainland Nova Scotia, and southwestern Cape Breton Island. The inshore migration generally begins in April-May and proceeds rapidly until June, when most of the traditional summer habitats have been occupied. The return migration to the overwintering grounds in the Laurentian Channel historically occurred in November and December (Darbyson and Benoît 2003), but now appears to occur in July. The proportion of White Hake occurring in inshore areas has declined over time, with White Hake virtually absent from these areas in recent years (Swain et al. 2016). This shift in the distribution of adult White Hake is strongly related to risk of predation by Grey Seal, an important predator of White Hake (Hammill et al. 2014; Swain et al. 2015). As seal abundance increased, White Hake distribution shifted into deep waters where risk of predation by Grey Seal remained low. Fishing mortality has declined to very low levels, nonetheless from 2008 to 2013 the majority of White Hake bycatch in sGSL has been taken by the Redfish fishery (Swain et al. 2016). The main threat to White Hake is high natural mortality which is considered to be caused by predation by Grey Seal.

Unit 1 Redfish

Two Redfish species are present in Unit 1 namely: Deepwater Redfish (*Sebastes mentella*) and Acadian Redfish (*S. fasciatus*). Redfish was intensely exploited in the GSL from 1954-56, 1965-1976, and 1987-1992. A moratorium was declared in Unit 1 in 1995, but an index fishery started in 1998. In 2010, COSEWIC designated the Deepwater Redfish (*S. mentella*) as Endangered and Acadian Redfish (*S. fasciatus*) as threatened (DFO 2011). The most recent assessment of Unit 1 Redfish was in January 2020 (Senay et al. 2019; DFO 2020b; Senay et al. 2021). Based on the empirical reference points Deepwater Redfish in Unit 1 are in the Healthy Zone of the Precautionary Approach, while Acadian Redfish are in the Cautious Zone (DFO 2020b).

Redfish inhabit cold waters at depths of 100 to 700 m. Deepwater Redfish are typically found in deeper waters than Acadian Redfish. In the sGSL, Redfish is almost exclusively found in the Laurentian Channel. The two species of Redfish can be distinguished based on anal fin ray count, genetics, and extrinsic gasbladder muscle passage patterns (Senay et al. 2019). For the purpose of this report, we will be grouping the species and referring to them as Redfish.

Redfish recruitment success is highly variable, with large year classes being produced at irregular intervals (5-12 years). In 2011, 2012, and 2013, three strong cohorts recruited to the stock. Genetic analyses showed that these cohorts are dominated by Deepwater Redfish with the Gulf of St. Lawrence ecotype (Benestan et al 2020). The Deepwater Redfish biomass has continued to increase in research surveys. The 1980 cohort was the last large cohort in Unit 1 (Brassard et al. 2017). If the anticipated growth of these cohorts continues, 51% of the individuals of the 2011 cohort should be larger than 25 cm by 2020.

Given the expected opening of Redfish commercial fishery in the near future, a Management Strategy Evaluation was conducted in 2018 (DFO 2018). Five Management Procedures were selected, all using the same harvest control rule, but differed in the year in which the harvest control rule was first implemented, limits on the magnitude of interannual changes in total allowable catch and with respect to the presence or absence of a: maximum in total allowable catch caps, adjustment of harvest control rule catch limits by a factor of 0.8 and the use of fixed total allowable catches in early years. The four Management Procedures that met the goal of maintaining Redfish spp. in the healthy zone included total allowable catches (TACs) of a minimum of 14,500 t in 2020 reaching upwards of 60,000 t by 2028 for both Units 1 and 2.

Species interaction

Stomach content analysis of White Hake and Redfish collected between August 2015 to August 2017 has provided a glimpse into the trophic relationship between these species and why they are commonly caught together. White Hake (22 to 65 cm length) stomach fullness indices revealed that fishes contributed the most to their diet and that, when all prey types were combined, Redfish was their most important prey. The shrimp group and zooplankton ranked second and third, respectively. Due to frequently regurgitated stomachs, Redfish stomach content analysis is limited. The stomach contents obtained revealed that Redfish diet is size dependent. Redfish smaller than 25 cm (7 to 24 cm) preyed mainly on zooplankton and those larger than 25 cm (25 to 48 cm) fed mostly on shrimp and to a lesser extent fish. Less than 5% of the analyzed Redfish stomachs contained fishes and no White Hake was observed in any of the stomachs (Ouellette-Plante et al. 2020).

DATA SOURCES

The information available to respond to this request are the multispecies bottom trawl research vessel surveys, the sGSL mobile Sentinel survey, and landings data.

Multispecies Bottom Trawl Research Vessel Surveys Southern Gulf of St. Lawrence

The sGSL multispecies bottom trawl research vessel (RV) survey has been conducted annually in September since 1971 (for details see Hurlbut and Clay 1990; Chadwick et al. 2007). This survey uses a stratified-random design, with stratification based on depth and geographic area

(Fig. 2). Fishing was by the E.E. Prince using a Yankee 36 trawl from 1971 to 1985, by the Lady Hammond using a Western IIA trawl from 1985 to 1991, by the CCGS Alfred Needler using a Western IIA trawl from 1992 to 2005 (except 2003), and by the CCGS Teleost using a Western IIA trawl since 2004. When gear and/or vessels were changed, comparative fishing experiments were conducted and conversion factors have been applied where necessary (Benoît and Swain 2003; Benoît 2006) to maintain the consistency of the time series. In 2003, the regular survey vessel, the CCGS Alfred Needler, was disabled by a fire and the survey was conducted by the CCGS Wilfred Templeman, however due to missed strata this year was excluded from analyses.

The trawlable biomass of White Hake has declined dramatically over the time series (Fig. 3). White Hake biomass began to decline in the late 1980s and early 1990s to reach a stable low level from 1995 to present day. Meanwhile, the trend in abundance was not as severe (Fig. 3). Following Swain et al. (2012), White Hake 45 cm and longer and 4 years and older are considered to be mature. The adult (≥ 45 cm) abundance and biomass indices both showed a sharp decline from 1985 to 1995, and have remained at very low levels since (Fig. 4). The estimated decline in the abundance of the adult length class from 1985 to 2014 (about 3 generations) was over 90%. For juveniles (< 45 cm) there was no observable trend in biomass or abundance between 1971 and 2019 (Fig. 4).

In the 1970s, White Hake occurred predominately in shallow inshore areas (≤ 50 m depth) in September (Fig. 5). The 1980s showed increasing abundance of White Hake in deeper waters offshore (> 100 m) along the slopes of the Laurentian Channel and in the Cape Breton Trough, while still remaining abundant in the inshore areas. Since then, adult distribution progressively shifted into deeper waters. By the 2000s, the proportion of White Hake inshore was almost non-existent with White Hake occurring almost exclusively in the offshore areas of the Laurentian Channel and Cape Breton Trough (Fig. 5).

The trawlable biomass and abundance of Redfish spp. was high in the 1970s and 1980s but declined to low levels in 1993 where it remained until 2011 when biomass began to increase to a peak in 2017 (Fig. 6). Redfish in the sGSL is mainly found in deeper offshore waters of the Laurentian Channel and at lower densities in the northern portion of the Cape Breton Trough (Fig. 7). During the 1990s and 2000s when Redfish were at lower biomass they were still located throughout their historical range (Fig. 7).

Northern Gulf Of St. Lawrence

The northern Gulf of St. Lawrence (nGSL) multispecies bottom trawl research vessel (RV) survey has been conducted annually in August since 1984 (for details see Bourdages et al. 2020). This survey uses a stratified-random design, with stratification based on depth and geographic area (Fig. 2). Over the years, different vessels and fishing gears have been used. From 1984 to 1990, research surveys were conducted aboard the vessel CCGS Lady Hammond using a Western IIA bottom trawl. From 1990 to 2005, the vessel CCGS Alfred Needler and a URI 81 '/ 114' bottom trawl were used. Finally, from 2004 to 2020, the vessel CCGS Teleost and a Campelen 1800 bottom trawl were used. All of these data were compared to establish conversion factors that were applied to the time series (Bourdages et al. 2007). For this report, only the data from nGSL strata that overlapped with sGSL strata were used (Fig. 2) and was only used to characterize the overlap of White Hake and Redfish (see methods described below).

Mobile Sentinel (Ms) Survey

Since 2003, the mobile gear component of the sGSL Sentinel survey program (MS) has consisted of a bottom trawl survey conducted annually in August by three to four commercial fishing vessels using the same standardized bottom trawl and standardized fishing protocols (for details see Savoie 2012). Data collection has been conducted by at-sea observers. This survey follows the same stratified-random survey design used for the sGSL RV survey. There have been several vessel changes since 2003. Calibration of relative fishing efficiency between vessels is attempted annually using a negative binomial model with terms for year, stratum and vessel. However, because of the restricted spatial distribution of White Hake, stratum and vessel effects may be confounded in calibrations for this species. Thus, we report indices with no adjustment for possible vessel effects.

The MS index fluctuated without trend between 2003 and 2019 (Fig. 8). White Hake were at a low but relatively stable level during this period according to the sGSL RV survey (Fig. 8). The age-aggregated abundance and biomass indices from the MS are consistent with the sGSL RV results.

THE FISHERIES

White Hake

Landings of White Hake in the 4T management area fluctuated between about 4,000 and 7,000 t between 1961 and 1978, and then rose sharply to a peak of 14,000 t in 1981 (Fig. 9; Table 1). A precautionary TAC of 12,000 t was established in 1982 and reduced in subsequent years. Landings declined beginning in 1982 and averaged 5,000 t in the 1985-1992 period. The fishery for White Hake in NAFO Division 4T was closed in January 1995, and has remained under moratorium with a 30 t quota for bycatch in commercial fisheries, recreational fisheries, scientific surveys, and Aboriginal fisheries.

Most landings were made from July to September prior to the moratorium and in June and July in recent years (Fig. 10). Trawls and longlines were the dominant gears in the 1990s to mid-2000s, when seines and gillnets were the dominant gears catching White Hake (Fig. 10). From 2008 to 2018 the majority of White Hake bycatch in sGSL has been taken by the Redfish fishery, though White Hake were also captured in the directed Greenland Halibut, Witch Flounder and Atlantic Halibut fisheries (Fig. 10). In 2019 and 2020, the Greenland Halibut fishery started to land more White Hake than the Redfish fishery (Fig. 10).

In the 4T management zone, the maximum allowable bycatch of White Hake is 5% of target species catch weight by fishing trip for Redfish and for other species. In addition to bycatch limits, a small fish protocol is enforced. The groundfish fishery is closed if small fish (i.e., fish < 45 cm in length) exceed 15% of the catch in numbers. To further minimize the bycatch of White Hake, restrictive fishing seasons for both the fixed and mobile gear sectors directed at other species have been implemented. The purpose of this management measure was to permit the spring hake migration into inshore areas to be completed before opening the area to groundfish fishing activity.

Redfish

Redfish in the GSL was marked by three intense exploitation episodes from 1954-56, 1965-1976, and 1987-1992 (Fig. 11; Table 1). Landings of Redfish in the 4T management area fluctuated between about 2,000 and 15,000 t from 1960 and 1994 until a moratorium was declared in 1995 (Fig. 11; Table 1). A global TAC for Unit 1 Redfish was first established in 1976 and ranged from 16,000 to 60,000 t until the moratorium (Fig. 11; Table 1). From 1995 to 1997, Redfish landings were restricted to bycatch only. An index fishery began in 1998 with a TAC of 1,000 tons that increased to 2,000 t in 1999 and has remained at this level since. This index fishery takes place between June 15 and October 31. From 1998 to 2006, the majority of fishing effort was conducted using bottom trawls, and since 2007, there has been a sharp increase in the proportion of catches by Scottish seines (Senay et al. 2019). In 2017, an experimental fishery with a TAC ranging from 2,500 to 3,950 t was initiated to collect biological data on Redfish and testing gear techniques to reduce bycatch. Redfish landings in 4T in the index and experimental fisheries varied between about 75 and 525 t since 1998 (Fig. 11; Table 1).

METHODS

OVERLAP BETWEEN REDFISH AND WHITE HAKE

Spatial and vertical distribution of White Hake and Redfish from fishery-independent data source

The recent spatial distribution of White Hake and Redfish in NAFO Division 4T was evaluated using the 2015-2019 data collected during the sGSL and nGSL multispecies bottom trawl RV surveys. The analyses are presented here for the 24 strata (415 to 439) from the sGSL RV survey (640 sets), while only strata 401 to 408 (103 sets) were considered for the nGSL RV survey as they are the only ones that overlap with NAFO Division 4T (Appendix 1). The individual catch of each species, expressed in kg per tow, were standardized for tow distance as per the surveys protocols (Benoît and Swain 2003, Benoît 2006 and Bourdages et al. 2020). The depth preference and abundance of both species were also estimated based on their total catch per depth interval for 2015 to 2019.

Evaluation of White Hake bycatch in both fishery-dependent and fishery-independent data sources

The experimental and index fisheries targeting Redfish and conducted by the industry, were used as a fishery-dependent data source with 100% at-sea observer coverage. The data was extracted to only keep sets that were conducted in NAFO Division 4T between 2015 and 2018. A total of 108 fishing trips were conducted using either bottom-trawl (n = 51), pelagic-trawl (n = 20) or seine (n = 37), White Hake was captured on 76 of these fishing trips. The information collected from both sGSL and nGSL RV surveys were also used as fishery-independent data source. To comply with gear type specifications, the recorded fishing depth was used for the depth distribution analyses. For both data sources, the bycatch of White Hake was estimated in each set as the amount (kg) of White Hake over Redfish (1).

$$White\ Hake\ catch\ (kg) \times 100 / Redfish\ catch\ (kg) \qquad (1)$$

For the fishery-dependent dataset, in the event a set had no Redfish but White Hake the bycatch was set at 100%. Finally, for the fishery-independent dataset, in order to simulate a directed fishery on Redfish, only the sets that caught Redfish were kept in the analyses (n = 103 for the nGSL and n = 186 for the sGSL). The values of bycatch of White Hake, especially in the sGSL dataset, had strong outliers (> 150,000%) in rare instances where only a few Redfish were caught in a catch dominated by White Hake. Therefore, the observed maximum bycatch from the fishery-dependent data source (202.2%) and the nGSL RV survey (244.4%) were used to develop a cut-off limit (rounded up to 250%) at which the range of bycatch of White Hake from the sGSL dataset would be limited. For each data source, boxplots were developed to evaluate the overall distribution of bycatch of White Hake in any set where Redfish were caught. Moreover, to estimate the bycatch of White Hake across the season, monthly boxplots were developed from the fishery-dependent data.

An inverse distance weighting algorithm was used to explore the spatial distribution of where White Hake are most likely to be caught when Redfish are the target species. This model used log-transformed catch ratio of White Hake over Redfish to scale the values and help visualize the output.

Finally, both data sources were combined to calculate standardized catch ratios (r) of bycatch and evaluate the vertical distribution of bycatch of White Hake. For each set (s), the standardization was used to constrain the values between 0 and 1 (2) and the resulting results were plotted on a log-scale y-axis.

$$\frac{ratio_s - \min(r)}{max(r) - \min(r)} \tag{2}$$

In order to test how the bycatch was being influenced by the gear type, gear depth, and region where the gear was set, the dataset was explored following methods presented in Zuur *et al.* (2010), and model selection was done following Zuur *et al.* (2013). For that purpose, only the depths where White Hake and Redfish overlap were used and the original dataset was truncated to depths of 180-380 m. At depths shallower than 180 m Redfish were not captured, and at depths greater than 380 m White Hake were not captured. The Laurentian Chanel was divided into three regions (North, Middle and South) for the purpose of this analysis, the limit of the regions are shown in Figure A1. Bycatch of White Hake in the Redfish fishery was modelled as a function of factor Gear, factor Region, and the continuous variable Depth. Model fits were tested for statistical overdispersion and sources of overdispersion considered were missing covariates, missing interaction terms, outliers, non-linear patterns, and variation larger than the Poisson distribution allows. We ultimately used the negative binomial distribution because the Poisson fits were overdispersed. Model assumptions were verified by plotting the residuals against the fitted values, and the Pearson's residuals against each of the covariates. Independence was assessed by plotting the Pearson's residuals against the model variable and factors. Autocorrelation was estimated to be weak at less than 2% and an autocorrelation term did not improve the generalized least square model. Hence, no auto-correlation term was added to the model. We also found that the White Hake bycatch variable was zero inflated (33%), therefore we also tested the models using the zero inflated negative binomial model with the intercept as the logistic model (Zuur *et al.* 2012). We compared the negative binomial model with the zero inflated negative binomial model using a Vuong test to examine if the zero inflated model was an improvement over the standard model. Models were also compared using AIC.

WHITE HAKE POPULATION MODEL

This analysis used a Statistical Catch-at-Age (SCA) model, similar to the model used in the 2015 RPA of White Hake in the sGSL (Swain et al. 2016). The model was implemented using AD Model Builder (Fournier et al. 2011). SCA is a forward projecting model starting from abundance at age in the first year and at the first age in all years. In these cases, abundance was included as a parameter to be estimated by the model. SCA assumes that there is observation error in the proportion-at-age in the fishery and survey catches. It fits to the age-aggregated biomass indices and to the proportion-at-age in the fishery and survey catches; this accounts for the lack of independence between catches at different ages in the same year.

The model extended from 1978 (the first year with reliable fishery catch-at-age data) to 2019 and from age 2 to ages 10 and older (10+). Data inputs were: total annual fishery catch (t), age-aggregated trawlable biomass in the sGSL RV (ages 2-7) and MS (ages 2-7) surveys, and proportion-at-age in the fishery, sGSL RV and MS catches. Indices from the Sentinel longline program were not used for model fitting because these indices are thought to be hyperdepleted due to the movement of White Hake out of nearshore areas.

Our model was a state-space model, incorporating both observation and process error. Process error was incorporated in two components of White Hake productivity, natural mortality and recruitment.

Fu and Quinn (2000) and Jiao et al. (2012) have demonstrated that it is possible to estimate time-varying natural mortality (*M*) using length- or age-structured population models. In our model, independent time series of the instantaneous rate of *M* were estimated for three age groups: ages 2-3, 4-5 and 6+. These time series were estimated as random walks:

$$M\mathrm{j},1 = M\mathrm{init}j \tag{3}$$

$$M_{j,y} = M_{j,y-1} e^{M\mathrm{dev}_{j,y}} \text{ if y} > 1 \tag{4}$$

where $M\mathrm{init}_j$ is *M* in year 1 (1978). $M\mathrm{init}_j$ and $M\mathrm{dev}_{j,y}$ are parameters estimated by the model. The *M*dev's were assumed to be normally distributed with a mean of 0 and a standard deviation set at 0.05. Priors were supplied for $M\mathrm{init}_j$. These priors were normally distributed with means of 0.55, 0.3 and 0.2 for White Hake aged 2-3, 4-5 and 6+ years, respectively. These values were selected based on empirical relationships between *M* and length and growth characteristics of marine fishes (Gislason et al. 2010). Standard deviations for the *M* priors were set at 0.05, 0.03 and 0.03 for White Hake aged 2-3, 4-5 and 6+ years. Simulation tests of VPA models for SGSL White Hake indicate that they result in reliable conclusions about changes in *M* for ages 4+ (Swain and Benoît 2015). Both VPA and SCA models for sGSL White Hake yield similar conclusions about changes in *M* (Swain et al. 2016).

Annual recruitment of age-2 fish was modelled as an average value, $\log_e$ (AvgR) and annual log recruitment deviations. The annual deviate was assumed to be normally distributed with a mean of 0 and a standard deviation of 0.5. A similar approach was used to estimate abundance at age in the first model year.

Parameters were estimated by minimizing an objective function with the following components: 1) components for the discrepancy between observed and predicted values of the age-aggregated biomass indices for the sGSL RV and MS surveys, 2) components for the discrepancy between observed and predicted proportion-at-age in the fishery, sGSL RV and MS catches, 3) a normal prior for the log *M* deviations; 4) a normal prior for the initial values of *M*, and 5) a normal prior for the log recruitment deviations. The proportion-at-age were assumed to follow a multivariate logistic distribution. This avoids the need to specify effective sample sizes, which can have a large impact on model results. Approximate 95% confidence intervals were obtained for estimated variables based on 501,000 Markov chain Monte Carlo (MCMC) samples, with every 100th sample saved. The first 1000 samples were omitted to exclude the initial period when the sample acceptance rate was being optimized.

Both fishery and survey selectivities were modelled as logistic functions, and thus survey catchability was constrained to be flat-topped. Fishery selectivity was allowed to change in 1995 when the moratorium on directed fishing for White Hake was established.

Like in the 2015 model, survey catchability (*q*) was estimated separately for the 1978-1984 period (when the Yankee 36 was used in the sGSL RV survey) and the 1985-2019 period (when the Western IIA was used in the sGSL RV survey). Comparative fishing in 1985 suggested that catchability of White Hake was greater to a Western IIA trawl fished by the Lady Hammond than to a Yankee 36 trawl fished by the Lady Hammond (Nielsen 1994). Although the estimated difference in *q* was substantial it was not significantly different, reflecting small sample size in the experiment (*n* = 12 for White Hake). When estimated in the population model the difference in *q* was in the same direction and stronger than in the comparative fishing experiment.

PROJECTIONS

Population projections were used to evaluate potential impacts of the fishery for Redfish on the status of White Hake in the sGSL. Projections were conducted at several levels of White Hake catch: 0, 20, 150, 250, 350, 500, 750 and 1,500 t. Because of the uncertainty in the eventual bycatch rates in an expanding Redfish fishery, projections of the White Hake population were based on White Hake bycatch levels and not linked to particular levels of Redfish catch. The reported bycatch of White Hake in fisheries other than the Redfish fishery averaged 10 t annually over the past decade. This value is considered negligible compared to the potential bycatch in the fishery for Redfish. For comparison, additional projections were conducted assuming no catch of White Hake by fisheries or annual catches of 20 t, the average for all fisheries over the last five years.

Projections were conducted during the MCMC sampling in the population modelling. Consequently, uncertainty in the model estimates are taken into account in the projections. The population was projected forward 25 years in time (to 2044). Current productivity conditions were assumed to persist over the projection period. For each age group, *M* was assumed to be the average of the last 5 years (2015-2019). No changes in the growth rate of White Hake are evident over the 1990 to 2013 period (Fig. 18; 2015-2019 could not be examined due to lack of ageing). Thus, for each projection year and iteration, the weight-at-age vector was randomly selected from those observed over the last 20 years (2000-2019). Recruitment productivity has been high in this population for the past 20 years or more (Fig. 26). Projections assumed that this component of productivity would remain high over the next 25 years and recruitment rates were randomly selected from those observed since 2000. Fishery selectivity-at-age was assumed to remain the same as the estimate for 1995 to 2019 (Fig. 20).

A linear model regressing median estimates of SSB against year was used to estimate the linear change in SSB over the projection:

$$\log_e(S_t) = \beta Y_t + \varepsilon_t \tag{5}$$

$$\Delta S = 100 * (\exp(\beta) - 1) \tag{6}$$

where S_t is the median estimate of SSB in year *t*, Y_t indexes year, β is the regression slope and ΔS is the percent change in SSB over the projection period.

Probabilities that projected SSB would decline below 4,000, 2,000, and 1,000 t were also estimated based n MCMC sampling. For a population that had an SSB near 60,000 t in the early 1980s, an SSB near 2,000 t represents a very high risk of local extinction.

RESULTS

SPATIAL DISTRIBUTION AND BYCATCH

From 2015 to 2019, White Hake were caught in a total of 213 sets, with 127 sets from the sGSL RV survey and 86 sets from the nGSL RV survey. Redfish were caught in 198 sets during the sGSL RV survey and 103 sets on the nGSL RV survey. When the two surveys are combined, both White Hake and Redfish were encountered at the same time in a total of 170 sets, therefore 79.8% of the time Redfish were caught White Hake were also part of the catch.

The spatial distribution of both species from the fishery-independent data sources revealed that they share the slopes along of the Laurentian Channel, the deepest part of the southern Gulf of St. Lawrence (Fig. 12). White Hake were distributed throughout the Laurentian Channel at relatively even densities. The only area where Redfish were mostly not captured alongside White Hake was within the Cape Breton Trough (Fig. 12).

When the two RV surveys are combined, the depth profile at which White Hake were caught follows a unimodal distribution centered around 250 m deep (Fig. 13). The interaction of both species was observed at depth intervals ranging from 140 to 410 m. Shallower than 250 m, White Hake catch proportion averaged 4.3% of the combined catch of both species, while deeper than 250 m, the co-occurrence drops to 0.9%. Interestingly, the Redfish depth profile follows a bimodal distribution, with one mode centered at 250 m and the other at 330 m deep which may be a reflection of the two Redfish species.

Evaluation of the bycatch of White Hake from both fishery-dependent and fishery-independent data is evaluated on an individual set-basis and was on average 10.5%, with a median ranging from 0 to 1.6% (Table 2; Fig. 14). The high averages were driven by some sets where the bycatch was over 100% White Hake. The average bycatch would also have been greater in the sGSL RV survey if we had not constrained sets to the maximum bycatch observed in the other data sources (cut-off of 250%). Although for each data sources the bycatch distribution is skewed toward the median (Fig. 14), the observed maximum and mean values of the fishery-dependent data source that specifically targeted Redfish revealed that in some instances the interaction with White Hake could be extremely high (> 130%; Table 2; Fig. 14). The targeted Redfish fishery had very high bycatch of White Hake in June (mean of 42.6% and median of 11.4%), July (mean of 35.2% and median of 6.6%), and in December (mean of 47.6% and median of 7.1%) (Table 2; Fig. 15). The other months had lower bycatch with medians of 1.7%, a maximum of 6.2% and a mean of 3.3% (Table 2; Fig. 15).

As observed in the spatial distribution of both species, the area where White Hake are most likely to be caught if Redfish are the targeted species cover the entire Laurentian channel portion of the sGSL (Fig. 16). The area north of Gaspé, north of the Orphan Bank and north-east of the Magdalen Island have the highest probability of bycatch (high overlap between both species) whereas the Cape Breton Trough has the lowest values (very low abundance of redfish). Moreover, the depth distribution of the standardized catch ratios of bycatch confirmed that at depths below 280 m, the bycatch values of the combined datasets were almost entirely under 10% with only few instances of values between 10 and 250% (Fig. 17). Deeper than 380 m, all catches had bycatch less that 10% and below 440 m the bycatch was at 0%. However, shallower than 280 m the range of bycatch are much higher with only few cases of bycatch values less than 10%.

The bycatch values (%) by gear and region are presented in Fig. B1. Of the total number of sets (n = 349), bottom trawl were the most abundant source of information (83.7%), while Scottish seines and mid-water trawl represents 10.6% and 5.7%, respectively. All three regions were well covered, with 108 samples in the North, 101 in the Middle and 140 in the South. The best models were selected based on lowest AIC value and most parsimonious with models with delta-AIC < 2 (Burnham and Anderson 2002; Arnold 2010). The models that best fit the data had Region and Depth as significant covariates (Table B1). The zero inflated model showed the intercept to not be significant and the model performed slightly worse than the same model when zero inflation was not included (delta-AIC = 2). The zero inflated model also did not substantially improve the dispersion statistics. Results of the Vuong test showed that the standard negative binomial model is superior to the zero inflated model ($p < 0.001$). The variable covariate Gear was not significant in the any model ($p > 0.86$). Poisson models were overdispersed, while negative-binomial models had dispersion parameters closer to 1.5. The θ parameter of the negative binomial distribution and zero inflated negative binomial models was estimated to be 0.26. Diagnostic plots from the best fit negative binomial model showed no evidence of patterns in the residuals based on fits of the residuals to each of the covariates.

WHITE HAKE MODEL

Fisheries catch-at-age

The fishery catch-at-age, as well as mean length- and weight-at-age in the landings, were updated from 2014 to 2019 (Table 3). The last year with ageing of White Hake in the sGSL was 2014. The catch-at-age in 2015 to 2019 was obtained by applying an age-length key based on the 2013 and 2014 data to the length frequency distributions for each of these years. This approach assumes that growth of White Hake has not changed over the 2013-2019 period. Based on the aged sGSL RV survey data (1971-2013), this assumption is supported for the 1990-2013 period (Fig. 18).

A broad range of ages was caught by the fishery in the 1970s and 1980s, extending from age 2 to 10+ years (Fig. 19). The main ages caught were ages 5-7 years. The age range in the catch contracted after the 1980s, with very few fish older than 8 years caught in the 1990s or older than 7 years in the 2000s and 2010s. Ages 5 and 6 years dominated the fishery catch starting in the 1990s.

Abundance indicators

Age-based abundance indices and the mean weight-at-age in sGSL RV survey are shown in Table 4. Based on RV survey catches, the age composition of the sGSL White Hake population has contracted substantially over time (Table 4; Fig. 20). In the 1978-1989 period, White Hake were caught up to ages 10 years and older (maximum age 15), though catches were very low at ages 9 and older. No White Hake over 8 years of age has been observed in the survey since 1998. The most abundance juvenile and adult ages were 3 and 4 respectively. The oldest ages caught were 8 in 1990-1995, 7 in 1996-2001, and 6 in the periods 2002-2007 to 2014-2019. Catches at age 6 were also very rare in these latter periods. Since the 2002-2007 period, the spawning population has been restricted to essentially ages 4 and 5 years, with age 4 comprising about 75% of the spawners.

Stratified mean catch rates at age and mean weight- and length-at-age in the MS survey are given in Tables 5. The average length and weight of the fish caught decreased substantially in 2012 and 2013 due to a sharp decline in the abundance of fished aged 3 years and older. As of 2011, the MS survey has not caught White Hake older than age 6 (Table 5).

Model results

Fully-recruited catchability was estimated to be 0.40 to the sGSL RV survey in 1978-1984 (Yankee 36 trawl), 0.70 to the sGSL RV survey in 1985-2019 (Western IIA trawl) and 0.52 to the MS survey (Fig. 21). Age-6 White Hake were estimated to be almost fully selected to the fishery in 1978-1994 (before the moratorium) but less than 70% selected in 1995-2019 (since the moratorium, Fig. 21).

Model fit to both the sGSL RV and MS biomass indices was good, though there was little contrast in the MS index which was confined to a period of low biomass (Fig. 22). Fit to the proportion-at-age in the sGSL RV and MS surveys and the fishery catches were adequate (Fig. 23). There were no indications of year effects but there was some relatively weak blocking along age.

Estimated juvenile abundance (ages 2-3 years) fluctuated without trend over the 42 year time series (1978-2019, Fig. 24). Juvenile abundance was estimated to be 123 million at the start of the time series in 1978 and 169 million at the end of the time series in 2019. Average juvenile abundance was 102 million in the 1980s, 83 million in the 1990s, 107 million in the 2000s and

110 million in the 2010s. In contrast, adult abundance was at a high level from the late 1970s to and the late 1980s, peaking at 56 million fish in 1980 and 51 million in 1986. It then declined steadily to 15 million in 1995, and remained at a low level for the remainder of the time series. Average adult abundance since 2005 is estimated to be 11.6 million, about an 80% decline from the peak levels in the 1980s.

Estimated spawning stock biomass (SSB) was at a high level from 1979 to 1987, averaging 56,425 t and peaking at 63,400 t in 1981 (Fig. 25). Estimated SSB then declined sharply in the late 1980s and the 1990s, falling to 8,860 t by 2000, an 85% decline. SSB has remained at a very low level since then. Estimated SSB at the start of 2019 was 7,396 t, about 13% of the average level in 1979 to 1987. The estimates reported here using data up to 2019 closely match those obtained by the 2015 RPA model using data from 1978 to 2013.

Despite the severe decline in SSB, recruitment of age-2 fish has fluctuated without trend since 1978 (Fig. 26, upper panel). Some of the strongest recruitment has been produced by the weakest SSB. The estimated recruitment in 2019 is the strongest on record, though the uncertainty in this estimate is very high. Continued strong recruitment at very low SSB indicates that recruitment rate (i.e., recruits per unit of SSB) has increased. The estimated recruitment rate has increased substantially since the early 1990s (Fig. 26, lower panel). The average estimated recruitment rate for the 1978-1992 cohorts was 1,400 age-2 fish per kt of SSB. The average rate for the 2008-2017 cohorts was 13,900 age-2 fish per kt of SSB. The estimate for the most recent cohort (2017) is the highest on record (23,800 age-2 fish per kt of SSB), though again uncertainty in the estimate is very high.

The instantaneous rate of fishing mortality *F* has been at a negligible level for the past 10-15 years (Fig. 27). Average *F* for juveniles (ages 2-3 years) was negligible (< 0.001) in all years and is not shown in the figure. Average *F* for ages 4-5 combined was also low for the entire time series. Average F for this age group varied between 0.04 and 0.09 in all years prior to the moratorium except 1992 when *F* peaked at 0.13. Since the moratorium, *F* of this age group has been estimated to be less than 1% annually in all years except 1999 (1.6%) and less than 0.5% since 2002. However, the youngest age with non-negligible selectivity to the fishery is age 5 (Fig. 21, 50% selectivity prior to 1995 and 13% since then). Considering age 5 alone, *F* averaged 0.13 in 1978 to 1988 and then increased to 0.4 in 1992 before declining to 0.005 in 1995 when the moratorium on directed fishing was put in place. During the moratorium (1995-2019) *F* at age 5 averaged 0.02. The temporal trend in average *F* for ages 6 years and older is similar to that exhibited by *F* of age-5 White Hake. *F* for ages 6+ varied between 0.2 and 0.3 in the 1970s and 1980s and then increased to a peak of 0.7 in 1992. *F* then declined to 0.03 in 1995 when the moratorium on directed fishing was imposed. *F* of 6+ hake has remained low since then (0.02 - 0.12), except for a period in the late 1990s and early 2000s when *F* peaked at 0.37.

While *F* of White Hake has been negligible since the mid-2000s, the population is now so low that very small landings can cause significant fishing mortality. For example, in 1978 to 1986 annual landings averaged about 8000 t, SSB averaged 54,660 t, and 6+ *F* averaged 0.25. However in 1998 to 2001, when SSB averaged 8,670 t, average annual landings of only 236 t resulted in the same average 6+ *F*.

In most years, the dominant source of mortality for sGSL White Hake has been natural mortality (Fig. 27). For juveniles (ages 2-3 years), estimated *M* increased from 0.58 in 1978 to 1.13 in 2013 (44% to 68% annual mortality). For older ages, increases in *M* were even more extreme, from 0.38 in 1978 to an average value of 1.97 since 2000 for ages 4-5 (from 32 to 86% annually), and from 0.32 to 1.67 (from 27 to 81% annually) for ages 6 years and older. For ages 2-3, *M* has been gradually increasing since the late 1980s and may be continuing to increase.

For the older ages, *M* steadily increased from the start of the time series in 1978 to about 2000 and has since been roughly stable at a very high level.

In summary, the biomass and abundance of adult White Hake in the sGSL population was at a relatively high level in the late 1970s and early 1980s, peaking at about 63,000 t and 56 million individuals. The population then collapsed, declining to 8,860 t (an 85% decline) and 13 million individuals (a 77% decline) by 2000. In the 20 years since then, the population has shown no sign of recovery despite negligible fishing mortality. Failed recovery is due to unusually high natural mortality of adult fish (ages 4+). Adult *M* has increased to unprecedented levels (81-86% annually) in recent years. In contrast to adults, juveniles have fluctuated without trend over the time series. This reflects strong recruitment over the past twenty years even though SSB had declined to very low levels. Given the extremely high *M* currently experienced by adult White Hake, this population remains viable only because of the coincident increase in recruitment rates to extremely high levels. The high adult *M* has been attributed to increased predation by Grey Seal (Hammill et al. 2014, Swain and Benoît 2015, Swain et al. 2015). The increase in recruitment success may be due to a relaxation of density-dependent constraints on productivity. White Hake are known to be cannibalistic (Davis et al. 2004; Benoît and Swain 2008), and cannibalism is one factor that may promote strong compensation in their stock-recruit relationship. However, the increase in recruitment rate at the low SSB seen since the mid-1990s seems to be too great to be attributed solely to compensation. Increases in the survival of small fish appear to be widespread throughout this ecosystem since the mid-1990s (Benoît and Swain 2008, Swain et al. 2013, Swain and Benoît 2015), and this ecosystem change may contribute to the increased recruitment rate of White Hake in recent years.

POPULATION PROJECTIONS

Uncertainty around the SSB projections was high, presumably reflecting the high variability in recruitment rate incorporated in the projections. The projections also exhibited a dampening 4-year cycle in SSB. This reflects effects of the 2017 cohort, the most recent cohort observed and the strongest on record. However, this cohort has been observed only once and its actual strength remains highly uncertain.

Projected SSB declined at all catch levels, including no catch (Table 6; Fig. 28). Based on the median estimates of SSB, a 38.7% decline in SSB was projected to occur over the 25-year period with no fishery catch. The estimated decline was virtually the same (39.3%) with an annual bycatch of 20 t, and only slightly greater (43.0%) with bycatch of 150 t. Estimated declines were substantial (57.2% and 69.9%) with bycatch of 750 and 1,500 t, respectively (Table 6).

Probabilities that projected SSB would decline below 4,000, 2,000 and 1,000 t was estimated at each catch level based on the MCMC sampling (Table 6; Fig. 29). With no fishery catch, the probabilities that SSB would be below 1,000, 2,000 and 4,000 t were 8%, 22% and 46%, respectively. Probabilities were nearly identical with annual bycatch of 20 t (the recent average), and similar with 150 t of bycatch. These probabilities were substantially greater with bycatch of 750 or 1,500 annually. The probability that SSB would be less than 4000 t at the end of the 25-year projection was estimated to be 46.2% with no bycatch, increasing to 53.1% with 350 t of bycatch and 67.3% with 1,500 t of bycatch. The probabilities of a decline below 2,000 t of SSB were 21.8%, 30.2% and 49.4% at these levels of bycatch. The probabilities of a decline in SSB to below 1,000 t at these three bycatch levels was estimated to be 7.9%, 13.8% and 32.4 %, respectively.

The results above are all for SSB at the beginning of the year. However, depletion during the year before recruitment is extreme (Fig. 30). For example, at the end of the projection with bycatch at 750 t, adult abundance is 5.2 million at the start of the year and 0.7 million at the end of the year, 14% of the starting abundance. With bycatch of 1,500 t, the decline over the final projection year is from 3.7 million to 0.4 million. At these levels of bycatch, the adult stock would appear to be on the verge of disappearance each year until replenished by recruitment.

The White Hake population in the sGSL currently appears to be unviable at recruitment rate levels that are less than extraordinary. Our projections incorporated the recruitment rates observed over the past 20 years (2000-2019). These rates were all very high, particularly those observed in the last five years (which were all the highest rates on record). To examine how much our results depend on the assumption that these exceptional recent rates will persist, we also conducted projections with recruitment rates sampled from those observed from 2000 to 2010. These are all very high rates, but less extreme than those estimated for 2015 to 2019. These rates are also more reliably estimated than the most recent rates whose estimates are based on cohorts that have been observed as little as once.

At these less extreme recruitment rates, projected SSB declined to very low levels at all catch levels (Fig. 31). Based on the median estimates of SSB, an 82.3% decline in SSB was projected to occur over the 25-year period with no fishery catch, a substantial increase from the 38.7% decline using the most recent high recruitment. The estimated decline was virtually the same (82.7%) with an annual bycatch of 20 t, and only slightly greater (84.9%) with bycatch of 150 t. Estimated declines were extreme (91.5% and 95.7%) with bycatch of 750 and 1,500 t, respectively.

As expected, probabilities of decline were estimated to be much greater when recruitment rates were drawn from those observed in 2000 to 2010 (Fig. 32). With no fishery catch, the probabilities that SSB would be below 1,000, 2,000 and 4,000 t were 42%, 66% and 85%, respectively. Probabilities were nearly identical with annual bycatch of 20 t (the recent average), and similar with 150 t of bycatch. These probabilities were substantially greater with bycatch of 750 or 1,500 t annually (corresponding to catches of 5,000 or 10,000 t in the fishery for Redfish).The probability that SSB would be below 4,000 t at the end of the 25-year projection was 91% with bycatch of 750 t and 93% with bycatch of 1,500 t. The probabilities of declines below 2,000 t or 1,000 t were 79% and 64%, respectively, with bycatch at 750 t, and 87% and 75% with bycatch at 1,500 t. If the very high recruitment rates estimated to have occurred within the past five years do not persist, SSB would be expected to decline within 25 years to near 1,000 t with no fishing and to near 0 with bycatch of 750 t or more.

The fishing mortality rates estimated during the projections with bycatch levels of 150 t or less annually are very low (Fig. 33). With annual bycatch of 750 t fishing mortality increases to a high level (*F* near 1 or 63% annually) near the end of the projection. With annual catches of 1,500 t, *F* would increase to 3 or more (greater than 95% annually). Levels near 1 or more would clearly not be sustainable for the White Hake population at any recruitment rate that would be plausible. An *F* of 3 or more seems unlikely. A level this high would require extremely high fishing effort and/or catchability to the fishery. This would be expected to be especially unlikely for a bycatch species. On the other hand, large White Hake have tended to be caught in survey catches containing large quantities of Redfish in recent years (Fig. 12). White Hake preying on Redfish may concentrate in the vicinity of Redfish aggregations. This would result in high catchability to the Redfish fishery and high vulnerability to effort in this fishery.

DISCUSSION

The sGSL DU of White Hake was assessed as Endangered by COSEWIC in 2013 (COSEWIC 2013). Continued decline of the population was expected even if fishing mortality were reduced to 0 (Swain et al. 2016). The failed recovery of this population even with fishing mortality reduced to negligible levels is due to extremely high natural mortality, which has reached levels near 90% annually. This high natural mortality has been attributed to predation by Grey Seal (Hammill et al. 2014, Swain and Benoît 2015, Swain et al. 2015).

The status of this population remains very precarious. The spawning stock, consisting of ages 4 to 10 years and older in the past, now consists mostly of 4 year olds. This would be expected to result in a serious decline in productivity and represents a high risk to this population, with only a single reproductive cohort. Natural mortality remains extremely high and this population currently persists only because recruitment rates have also increased to extreme levels. The causes of these unusually high recruitment rates are not known and it is not known whether they will persist. These rates increased further to unprecedented levels in recent years. Projections indicate that if these rates declined to the levels observed from 2000 to 2010 the population would begin to rapidly decline. Nevertheless, the 2000 to 2010 recruitment rates were still considered to be exceptionally high, though not as extreme as some of the rates estimated more recently from 2015 to 2019. Assuming that productivity of this population remains at the levels estimated for recent years, projections indicate a gradual decline even with no fishing mortality. An approximately 40% decline in SSB is projected over 25 years. In the absence of fishing mortality, the probabilities that SSB would be below 4,000 t, 2,000 t, or 1,000 t was estimated to be 46%, 22%, and 8% respectively after 25 years. Results were similar at bycatch of 20 t, the average level in recent years.

White Hake and Redfish have largely overlapping distributions, as White Hake have shifted their distribution almost exclusively to the deep waters of the Laurentian Channel which is the same distribution as Redfish. This is also further compounded by the diet interdependencies and overlap between these species. The primary item in the diet of White Hake is Redfish followed by shrimp and zooplankton, while the primary diet items of Redfish are shrimp in larger specimens and zooplankton in smaller specimens. Both White Hake and Redfish are evenly distributed along the slope of the Laurentian channel, with no specific areas within the channel where both species were not caught together. However, the Cape Breton Trough was one of the few areas where White Hake was captured at greater densities than Redfish. Given the spatial overlap between both species, it was expected that bycatch of White Hake in the Redfish fishery could be substantial. This overlap was found to be greater at depth shallower than 380 m, and in water deeper than 440 m, White Hake were not captured. Moreover, deeper than 350 m, the proportion of White Hake is 34% sGSL DU and 66% Atlantic DU.

Based on our analyses, the average bycatch rate of White Hake associated with catches of Redfish was 10.5% utilizing three independent data sources. The Redfish experimental and index fisheries also revealed that this level of bycatch could be much higher depending on the month that fishing occurred. Bycatch was very high in June, July, and December. In June bycatch of White Hake averaged 42,6% (up to 135%) meaning that in some instances more White Hake was captured in the fishery targeted for Redfish. While there have been no landings in the index and experimental fisheries in the month of September, the sGSL RV survey was conducted in September with bycatches as high as 250%.

This analysis is based on small scale fishery and multi-species surveys, however we had to assume that the average estimated bycatch rate of 10.5% would also apply to the expansion of the Redfish fishery. In reality, the bycatch rate may not be 10.5% for various reasons including the fishing technology, timing, and location that could reduce bycatch of White Hake. As Redfish continue to grow they may become too large for White Hake to consume which may have implications on the potential overlap of the species. Nonetheless, we used the average bycatch for our projections to be consistent with the precautionary approach. The 10.5% bycatch is also above the limit bycatch level for the Redfish fishery (up to 5%). As White Hake continue to decline the bycatch will also likely decline, but so will their ability to sustain bycatch. Because of the uncertainty in the eventual bycatch rates in an expanding Redfish fishery, projections of the White Hake population were based on White Hake bycatch levels and not linked to particular levels of Redfish catch. As the Redfish fishery develops it will be necessary to closely monitor White Hake bycatch in this fishery to ensure that it does not exceed acceptable levels.

Projections for White Hake were calculated at various bycatch levels from 0, 20 t, up to 1,500 t, which would correspond to Redfish catches of 200 t to 14,000 t (assuming the average bycatch rate of 10.5%). These values of Redfish catch may be much lower than what may occur in the future as the Redfish fishery increases. The estimated 25-year decline in the SSB of White Hake with bycatch at 150 t differed little from the decline with bycatch of 0 or 20 t. However, bycatch of more than 150 t resulted in increases in the projected decline of White Hake SSB. The estimated decline increased from 39% with bycatch of 20 t to 57% or 70% with bycatch of 750 or 1,500 t, respectively. If current productivity conditions were to persist, there is a probability that that White Hake would decline to local extinction (SSB below 2,000 t) at the end of the projection with a probability of 23% with no bycatch and 33% and 49% with bycatch of 500 and 1,500 t, respectively. If recruitment rates declined to the 2000 to 2010 levels, extinction risk would be even higher. Extinction risk is also high for White Hake given that the stock is currently sustained by unusually high recruitment rates which depend on a single cohort each year (age 4).

For the Redfish Management Strategy Evaluation, the four Management Procedures that met the goal of maintaining Redfish in the Healthy Zone of the Precautionary Approach Framework started at 14,500 t TAC in 2020 reaching upwards of 60,000 t by 2028 for both Units 1 and 2 (DFO 2018). It is unknown how fishing effort would occur spatially and temporally and thus how much of the effort could overlap with the sGSL White Hake DU. At present the Redfish experimental and index fisheries have targeted the Laurentian Channel. Using the average bycatch value of 10.5% calculated from the available data, a starting Redfish TAC of 14,500 t could land 1,500 t of White Hake. Our model projections did not extend beyond this value of White Hake catch; however our analyses indicate that even at lower levels of Redfish catch, White Hake have a high probability of substantially increasing the extinction risk. If the Redfish fishery is ramped up as proposed in the four Management Procedures defined, the extinction risk for White Hake will continue to be greater. No data are available to test this assumption because catches at levels this high have not occurred since 1994 or earlier. White Hake catches ≥ 1,500 t would require very high fishing mortality (> 95%). It is questionable whether this is plausible.

At present, the maximum allowable bycatch of White Hake is 30 t in the 4T management zone. Bycatch of White Hake is limited to less than 5% of target species catch weight by fishing trip for Redfish. Based on our analyses, a 30 t bycatch limit could be captured by the Redfish fishery alone at TAC of 280 to 300 t. This number does not consider that several other groundfish fisheries also catch White Hake as bycatch. Our estimate is greater than what has been observed in recent years when approximately 200 t of Redfish has been captured. Actual bycatch of White Hake in the last 5 years of the experimental and index Redfish fisheries have averaged 4% of total landings. In the last 5 years, an average of 20 t of White Hake has been captured as bycatch, of this 20 t approximately 50% has been from the experimental and index Redfish fisheries. As such, of the 30 t bycatch limit of White Hake only 20 t is available to be caught in an expanding Redfish fishery. This would require setting the Redfish TAC substantially lower than the 14,500 t starting TAC proposed in the Redfish management strategy evaluation for Unit 1 and 2 Redfish. It is important to note that it is unknown where the fishing effort will be distributed and Redfish appear to be distributed throughout the deep waters of the northern Gulf of St. Lawrence (NAFO Division 4RS). Prior to the moratorium on Redfish, the fishery largely took place in NAFO Division 4RS, however both the experimental and index fisheries have targeted the Laurentian Channel along the boundary of NAFO Division 4T and 4S. In considering the development of a future Redfish fishery, the bycatch rate may be lower for various reasons that could reduce bycatch of White Hake, including improvement in the fishing technology, fishing season (timing), location of the fishing grounds and species interaction.

With their overlapping distributions White Hake are likely to be a choke species for the Redfish fishery at 30 t bycatch. sGSL White Hake has also been identified as a major fish stock and as a stock that has declined below its limit reference point (i.e., is in the Critical Zone of the Precautionary Approach Framework), Bill C-68, which received assent in June 2019, requires that a rebuilding plan be developed that is in line with the Precautionary Approach Framework which states that management actions must promote stock growth and removals by all human sources must be kept to the lowest possible level (DFO 2006). Based on projections, White Hake catches of ≤ 150 t would result in very little increase in population decline. However, catches > 150 t would increase the rate of decline and lead to local extinction if persistent. From our analyses, the bycatch of White Hake at depths greater than 280 m was lower than at depths shallower than 280 m. Deeper than 280 m declined to an average of less that 10%, however there were still a few bottom trawls where bycatch was still quite high with values between 10 and 250% of White Hake. Deeper than 380 m, all catches had bycatch less that 10% and below 440 m the bycatch was at 0%. At depths greater than 350 m, only 34% of the White Hake captured represented the sGSL DU (Swain et al. 2012). It is unknown if the distribution of the two White Hake DUs have changed since sGSL White Hake have shifted their distribution almost exclusively to deep waters.

The distribution of White Hake and Redfish in the Laurentian Channel was fairly ubiquitous. With the data available, we were unable to detect any specific areas in Laurentian Channel where bycatch of White Hake was lower compared with other areas. However, bycatch was overall higher in the southern extent of the Laurentian Channel. This is likely due to the area in and around the Cape Breton Trough because this was one of the few areas where White Hake was captured at greater densities than Redfish. With its water column being strongly stratified in summer (Chassé 2001), this narrow and moderately deep channel (140 m at its eastern part) isolates cold, oxygen and nutrients rich water layers at the bottom, promoting ideal growth conditions for gadidae species such as White Hake, which could be considered as a refuge for that species. Seasonally, bycatch of White Hake was lowest in October and November, but very high in December. There was no data available for winter months (January to March), however the Laurentian Channel represents overwintering habitat for more than just White Hake; Atlantic Cod, and Atlantic Herring have also been shown to overwinter in this area (Hodder and Parsons1971; Winters and Hodder, 1975; Swain et al. 1998; Campana et al. 2011; Harvey et al. 2012). The sGSL stock of Atlantic Cod overwinters in dense aggregations in relatively warm water along the southern slope of the Laurentian Channel in the sGSL and the neighbouring Cabot Strait area. It is now believed to have moved further to the northeast. White Hake, Atlantic Cod, and Atlantic Herring aggregate during overwintering and as mid- to deep waters of the Laurentian Channel continue to warm at rapid rates in winter (Galbraith et al. 2020), these aggregations could becomes more concentrated of fish at certain depth, thus increasing potential interaction with fishing gear. Increased bycatch of multiple species at low abundance is unlikely to increase the rebuilding potential of these species in the long term.

In conclusion, our analyses indicate that White Hake catches of 150 t or less will accelerate declines in White Hake only slightly at the current high recruitment rates; however catches of more than 150 t will substantially increase the extinction risk of the sGSL DU of White Hake. However, because the extinction risk of the White Hake population remains very high, the precautionary approach should prevail.

CONSIDERATIONS FOR AN EXPANDING REDFISH FISHERY

- To decrease the potential for bycatch of White Hake, the Redfish fishery should avoid June, July, and December in 4T.
- The area in and around the Cape Breton Trough is has bycatch of White Hake that exceeds catches of Redfish and Redfish are rare in this area.
- Bycatch of White Hake is lesser at depths greater than 380 m. Furthermore at this depth there is a lower proportion of the sGSL White Hake DU.
- Laurentian Channel represents overwintering habitat for multiple species already at low abundances. Caution should be taken when considering opening a fishery on overwintering grounds.
- Catches of White Hake greater than 150 t will substantially increase the likelihood of extinction of White Hake.

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TABLES

*Table 1. Nominal landings (tonnes) of White Hake and Redfish from NAFO Division 4T, with yearly total allowable catch (TAC). *For Redfish, the TAC represents the global TAC for 3Pn4RSTVn.*

	White Hake		Redfish			White Hake		Redfish	
Year	**Total**	**TAC**	**Total**	**TAC***	**Year**	**Total**	**TAC**	**Total**	**TAC***
1960	2008	-	2028	-	1990	5175	5500	3929	57000
1961	5323	-	1982	-	1991	4501	5500	6503	57000
1962	7244	-	1532	-	1992	3931	5500	8198	57000
1963	6550	-	3212	-	1993	1501	3600	4132	60000
1964	6206	-	2890	-	1994	1042	2000	5173	30689
1965	4706	-	5195	-	1995	71	Moratorium	13	Moratorium
1966	7024	-	8025	-	1996	157	Moratorium	41	Moratorium
1967	6550	-	8468	-	1997	195	Moratorium	20	Moratorium
1968	4261	-	7092	-	1998	241	Moratorium	200	1000
1969	4208	-	10840	-	1999	399	Moratorium	456	2000
1970	5668	-	9252	-	2000	177	Moratorium	258	2000
1971	5707	-	7912	-	2001	121	Moratorium	370	2000
1972	5757	-	7457	-	2002	70	Moratorium	465	2000
1973	5702	-	14496	-	2003	37	Moratorium	288	2000
1974	3616	-	6909	-	2004	64	Moratorium	413	2000
1975	4125	-	6064	-	2005	45	Moratorium	325	2000
1976	3758	-	1626	30000	2006	27	Moratorium	512	2000
1977	3984	-	2314	18000	2007	21	Moratorium	78	2000
1978	4825	-	4155	18000	2008	31	Moratorium	348	2000
1979	8110	-	3642	16000	2009	33	Moratorium	524	2000
1980	12423	-	1898	16000	2010	16	Moratorium	330	2000
1981	14039	-	2691	20000	2011	20	Moratorium	475	2000
1982	9776	12000	3222	31000	2012	14	Moratorium	378	2000
1983	7305	12000	2547	33000	2013	20	Moratorium	280	2000
1984	7050	12000	9988	33000	2014	16	Moratorium	286	2000
1985	6014	12000	3594	50600	2015	26	Moratorium	366	2000
1986	4948	12000	3954	55600	2016	30	Moratorium	231	2000
1987	6372	9400	5992	50000	2017	16	Moratorium	121	2000
1988	3887	5500	7578	56000	2018	12	Moratorium	191	4500
1989	5354	5500	10016	57000	2019	14	Moratorium	214	5950

Table 2. Descriptive statistics of bycatch of White Hake from the fishery-dependent observer dataset, and the fishery-independent RV surveys datasets (sGSL and nGSL).

Statistic	Bycatch (%)									
	Observer (by month)								sGSL	nGSL
	6	7	8	9	10	11	12	All		
n	14	8	38	na	32	3	13	108	186	103
Min	0.00	2.48	0.11	na	0.00	1.48	0.00	0.00	0.00	0.00
25th	0.00	5.40	1.13	na	0.00	2.17	1.47	0.00	0.00	0.16
Median	11.40	6.60	2.20	na	0.00	2.86	7.11	1.62	0.00	1.05
75th	86.76	26.55	3.31	na	0.00	3.63	100.00	6.15	2.31	2.60
Maximum	135.43	39.87	6.19	na	0.00	4.41	100.00	13.33	5.76	6.15
Mean	42.59	35.22	2.78	na	4.23	2.92	47.56	16.17	5.85	9.58

Table 3a. Commercial fishery catch-at-age (by 1000) for White Hake in NAFO Division 4T from 1982 to 2019. na means no catch and 0.00 indicates a non-zero number less than 0.005.

Age	0-2	3	4	5	6	7	8	9	10	11	12	13+	Total
1978	na	79	354	579	545	345	172	61	26	4	8	2	2175
1979	na	90	470	833	972	672	315	101	47	8	11	4	3523
1980	na	91	452	1028	1661	1196	540	137	75	7	6	5	5198
1981	na	66	427	1075	1976	1391	604	154	94	4	1	8	5800
1982	na	7.6	184.38	658.33	1156.11	1169.35	628.58	184.42	81.92	22.76	14.75	14.75	4122.94
1983	13.01	59.52	179.1	693.71	902.98	720.87	546.78	117.18	36.81	8.73	5.94	2.59	3300.23
1984	1.47	57.21	327.71	807.03	813.95	558.3	286.09	147.01	71.25	22.91	17.03	6.94	3118.37
1985	2.99	66.29	224.99	631.63	610.42	404.26	233.38	112.82	52.94	17.5	19.02	12.18	2391.41
1986	na	1.37	206.63	511.34	489.74	332.24	236.08	78.91	46.67	22	13.94	8.49	1947.4
1987	na	29.74	513.68	1377.85	936.06	417.46	153.5	64.19	17.97	3.51	2.35	3.56	3519.87
1988	0.22	0.4	35.61	462.4	648.91	513.32	109.48	15.78	5.91	2.03	0.86	0.84	1795.97
1989	5.01	8.93	116.81	585.01	830.99	685.56	213.8	76.72	11.25	12.99	5.45	5.45	2562.95
1990	na	14.84	454.01	1197.71	1047.61	437.92	91.43	18.98	6.47	2.87	0.97	0.53	3273.32
1991	na	27.22	400.29	1027.54	891.51	503.22	79.11	17.17	5.59	1.87	1.05	4.78	2959.37
1992	0.17	112.32	1010.98	1017.5	553.6	271.75	61.46	25.95	10.05	3.47	0.5	0.84	3068.74
1993	na	55.18	286.88	415.77	217.46	91.41	26.55	11.77	1.27	1.84	0.44	0.08	1108.65
1994	na	25.18	133.74	184.15	201.21	86.04	27.7	4.9	0.69	na	na	0.17	663.76
1995	na	0.01	0.63	2.15	9.85	11.2	3.99	0.29	na	na	na	na	28.12
1996	0.73	2.26	16.6	26.41	23.74	13.14	6.41	1.72	0.46	0.06	0.17	na	92.44
1997	0.19	1.11	13.71	39.73	33.97	13.88	5.43	1.1	0.39	0.07	na	na	109.77
1998	0.27	1.45	19.94	57.07	45.03	11.16	3.86	0.84	0.34	0.11	0.01	0.02	140.36
1999	0.51	3.72	42.57	114.54	74.88	15.82	2.12	0.73	0.07	0.02	na	na	255,50
2000	0.61	1.77	18.63	38.45	35.36	15.43	2.93	1.13	0.13	0.17	0.02	na	115.26
2001	0.12	2.89	20.97	28.47	20.29	7.48	2.12	0.31	0.17	0	na	na	82.82
2002	0.41	1.49	7.72	18.61	14.02	2.75	0.43	0.16	na	na	na	na	46
2003	0.54	2.58	11.19	12.27	5.44	0.63	0.14	na	na	na	na	na	33.33
2004	0.42	0.66	9.61	23.48	9.44	1.42	0.16	na	0.02	0.11	na	na	45.73
2005	2.14	2.23	10.82	14.1	8.32	1.7	0.22	0.02	na	na	na	na	41.68
2006	0.71	0.59	4.38	9.01	4.85	0.74	0.19	0.04	na	na	na	na	21.22
2007	0.53	0.99	3.55	5.48	3.48	0.46	0.36	0.02	0.04	0.01	na	na	15.43
2008	0.74	8.93	15.56	9.22	2.34	0.28	na	na	na	na	na	na	37.81
2009	0.25	0.86	2.81	10.28	6.69	1.38	0.1	na	na	na	na	na	22.62
2010	0.55	1.20	4.96	5.48	2.02	0.18	0.03	na	na	na	na	na	14.97
2011	0.13	0.39	2.31	6.22	3.33	0.85	0.22	na	na	na	na	na	13.58
2012	0.15	0.31	2.77	4.65	1.96	0.52	0.07	0	0.03	na	na	na	10.6
2013	0.16	0.12	1.1	7.15	4.55	0.41	0.1	0.04	0.03	na	na	na	13.8
2014	0.00	0.07	1.37	3.91	4.08	0.71	0.06	0.06	0.03	na	na	na	10.30
2015	0.00	0.00	1.65	7.54	5.19	1.33	0.20	0.08	0.08	na	na	na	16.08
2016	0.00	0.16	2.46	9.44	6.33	1.08	0.17	0.07	0.04	na	na	na	19.75
2017	0.00	0.16	1.32	4.62	3.84	0.54	0.08	0.05	0.01	na	na	na	10.62
2018	0.00	0.04	0.51	2.60	3.25	0.68	0.13	0.06	0.0	na	na	na	7.27
2019	0.00	0.10	0.61	2.42	3.55	0.94	0.23	0.10	0.0	na	na	na	7.96

Table 3b. Commercial fishery weight-at-age (kg) for White Hake in NAFO Division 4T from 1982 to 2019.

Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13+	wtAvg[1]
1982	na	na	na	1.11	1.35	1.61	2.19	2.48	2.97	3.34	3.99	3.9	3.83	5.22	2.37
1983	na	0.39	0.63	0.91	1.41	1.79	2.06	2.55	2.51	3.54	4.36	5.98	6.26	10.39	2.23
1984	na	na	0.55	0.9	1.16	1.65	2.12	2.64	3.18	3.56	5.26	4.74	6.65	9.25	2.27
1985	na	na	0.95	1.37	1.5	1.95	2.27	2.73	3.57	3.89	4.79	6.37	6.6	8.18	2.52
1986	na	na	na	2.81	0.98	1.54	2.37	2.94	3.88	4.67	5.72	6.84	6.96	9.39	2.57
1987	na	na	na	0.62	0.8	1.29	2.04	2.89	3.77	4.35	5.61	8.42	9.7	10.72	1.81
1988	na	na	0.28	0.36	0.96	1.3	1.95	2.79	3.68	5.13	6.03	8.85	10.69	9.56	2.16
1989	na	0.11	0.21	0.41	0.89	1.25	1.79	2.51	3.51	4.19	5.98	6.25	9.46	10.41	2.1
1990	na	na	na	0.59	0.85	1.18	1.7	2.52	3.53	4.95	5.84	7.11	9.26	8.29	1.58
1991	na	na	na	0.53	0.8	1.13	1.59	2.34	2.89	4.3	6.9	5.95	7.19	10.04	1.52
1992	na	na	0.17	0.53	0.77	1.1	1.71	2.38	3.12	4.32	5.58	5.59	6.06	9.09	1.28
1993	na	na	na	0.58	0.92	1.21	1.74	2.12	3.1	2.99	3.38	4.36	4.23	10.19	1.35
1994	na	na	na	0.62	0.83	1.22	1.82	2.47	3	3.44	4.02	na	na	9.38	1.56
1995	na	na	na	0.79	0.92	1.37	1.99	2.75	3.62	5.42	na	na	na	na	2.49
1996	na	na	0.18	0.53	0.94	1.4	1.93	2.5	2.6	2.92	3.31	2.27	3.5	na	1.7
1997	na	0.11	0.22	0.51	0.87	1.41	2.02	2.58	2.95	3.72	3.29	5.95	na	na	1.78
1998	na	0.17	0.43	0.57	0.84	1.44	2.1	2.55	2.89	4.01	3.45	2.84	6.35	6.83	1.71
1999	na	0.16	0.25	0.58	0.86	1.38	2.07	2.75	3.32	3.36	4.79	6.97	na	na	1.59
2000	na	0.11	0.24	0.51	0.75	1.21	1.85	2.38	2.94	3.04	2.34	4.32	5.31	na	1.54
2001	0.08	0.14	0.27	0.58	0.76	1.24	1.99	2.64	3.23	3.42	3.94	7.37	na	na	1.47
2002	na	0.16	0.33	0.56	0.81	1.39	2	2.55	3.48	4.43	na	na	na	na	1.54
2003	na	0.13	0.23	0.55	0.79	1.2	1.8	2.42	2.98	na	na	na	na	na	1.12
2004	na	0.1	0.22	0.47	0.89	1.33	1.95	2.72	3.68	na	6.33	4.76	na	na	1.4
2005	na	0.13	0.23	0.45	0.73	1.2	1.7	2.17	3.01	3.79	na	na	na	na	1.13
2006	na	0.15	0.22	0.49	0.8	1.26	1.9	2.55	2.91	4.88	na	na	na	na	1.32
2007	na	0.13	0.24	0.51	0.82	1.39	2.05	2.93	2.74	5.22	4.51	5.38	na	na	1.4
2008	na	0.15	0.34	0.48	0.67	1.21	1.97	3	na	na	na	na	na	na	0.85
2009	na	0.14	0.22	0.48	0.79	1.39	1.85	2.44	3.24	na	na	na	na	na	1.48
2010	na	0.13	0.25	0.51	0.79	1.26	1.77	3.22	2.02	na	na	na	na	na	1.09
2011	na	0.15	0.28	0.5	0.95	1.42	1.95	2.33	2.13	na	na	na	na	na	1.5
2012	na	0.18	0.23	0.51	0.97	1.38	1.86	2.26	4.06	3.68	2.49	na	na	na	1.38
2013	na	0.14	0.22	0.49	0.9	1.3	1.71	2.48	4.25	4.87	6.35	na	na	na	1.46
2014*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.48
2015*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.61
2016*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.54
2017*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.54
2018*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.69
2019*	na	na	0.24	0.49	0.88	1.35	1.83	2.55	3.14	4.33	4.18	na	na	na	1.75

*Average of weight-at-age in 2009 to 2013

[1]Abundance-weighted average

Table 4a. Stratified mean catch rates at age (fish/tow) of White Hake in the southern Gulf of St. Lawrence Research Vessel survey, based on strata 415-439. Values can be converted to trawlable abundance at age (in thousands) by multiplying by 1729.346. Catches at age 15 are not shown. This age was caught only in 1985, at a mean rate of 0.005 fish per tow.

Year	Age (years)														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1971	na	0.018	0.727	0.691	0.788	0.346	0.142	0.038	0.005	0.005	0.012	na	0.027	na	na
1972	na	0.017	0.206	0.217	0.365	0.317	0.365	0.14	0.023	0.015	0.031	na	0.008	na	na
1973	na	0.017	0.448	0.471	2.143	1.833	0.643	0.216	0.033	0.013	0.049	na	na	na	na
1974	na	0.14	1.993	1.529	2.614	2.055	1.382	0.588	0.178	0.044	0.111	na	na	na	na
1975	na	0.08	3.422	2.133	1.481	0.728	0.267	0.072	0.012	0.012	0.031	na	0.02	na	na
1976	na	0.067	3.086	1.98	1.304	0.55	0.187	0.058	0.006	0.006	0.014	na	na	na	na
1977	na	0.02	0.874	1.236	1.456	0.558	0.18	0.067	0.022	0.006	0.02	na	0.008	na	na
1978	na	0.058	2.154	1.499	2.516	2.006	0.982	0.3	0.03	0.021	0.066	na	0.042	na	na
1979	na	na	0.278	2.042	2.077	1.822	1.279	0.484	0.132	0.015	0.025	0.037	0.061	na	na
1980	na	na	0.108	1.11	1.895	2.106	1.308	0.456	0.138	0.008	0.049	0.064	0.046	na	na
1981	na	0.045	0.46	1.112	2.473	3.151	2.392	1.447	0.473	0.232	0.012	0.015	0.012	0.044	0.015
1982	na	0.059	0.265	0.613	0.96	0.786	0.716	0.31	0.137	0.019	0.036	na	na	na	na
1983	na	0.093	0.809	0.824	0.809	0.447	0.285	0.142	0.07	0.067	0.009	na	na	na	na
1984	0.007	0.054	0.477	1.141	1.433	1.128	0.52	0.259	0.156	0.053	0.06	0.009	0.01	na	na
1985	0.001	0.037	0.652	2.591	3.259	1.218	0.809	0.581	0.307	0.273	0.108	0.028	0.042	0.025	0.018
1986	0.045	0.178	1.726	2.998	5.199	3.093	1.014	0.444	0.245	0.116	0.041	0.038	0.035	0.014	na
1987	na	0.039	0.464	2.02	2.581	1.723	0.739	0.214	0.053	0.028	0.026	na	0.025	na	na
1988	0.007	0.146	1.557	2.713	3.232	2.378	0.761	0.297	0.05	0.011	0.013	na	na	na	na
1989	0.118	0.581	1.566	3.428	2.244	1.772	0.915	0.216	0.033	0.026	0.016	0.004	na	0.004	na
1990	0.038	0.152	2.083	3.115	2.35	2.355	0.612	0.353	0.069	0.017	na	na	na	na	na
1991	0.015	0.409	2.12	4.063	2.746	1.853	0.761	0.212	0.064	0.006	0.02	0.02	na	na	na
1992	0.043	0.279	1.499	3.386	2.557	0.77	0.134	0.028	0.006	na	na	na	na	na	na
1993	0.015	0.138	0.826	1.281	1.691	0.856	0.199	0.071	0.002	0.015	na	na	na	na	na
1994	0.061	0.14	0.977	1.068	1.258	0.587	0.144	0.016	0.018	na	na	na	na	na	na
1995	0.105	0.271	1.058	0.673	0.57	0.147	0.066	0.019	0.006	na	na	na	na	na	na
1996	0.066	0.345	1.174	1.123	0.835	0.236	0.057	0.01	0.007	0.002	na	na	na	na	na
1997	0.13	0.42	0.832	0.671	1.039	0.514	0.143	0.029	0.006	na	na	na	na	na	na
1998	0.009	0.382	1.451	0.792	0.678	0.374	0.14	0.021	0.011	na	na	na	na	na	na
1999	0.325	1.037	1.781	1.022	0.933	0.449	0.099	0.02	na	na	na	na	na	na	na
2000	0.068	0.387	4.426	3.406	2.63	0.449	0.05	0.008	na	na	na	na	na	na	na
2001	0.014	0.257	1.218	1.231	1.251	0.443	0.036	0.002	na	na	na	na	na	na	na
2002	0.012	0.588	1.712	0.599	0.601	0.25	0.015	0.006	na	na	na	na	na	na	na
2004	0.009	0.074	0.555	0.547	0.53	0.28	0.038	0.006	na	na	na	na	na	na	na
2005	0.002	0.262	2.508	0.979	1.37	0.364	0.039	0.016	na	na	na	na	na	na	na
2006	0.057	0.136	0.731	0.605	0.573	0.088	na	na	na	na	na	na	na	na	na
2007	0.111	0.441	5.705	3.281	2.45	0.503	0.032	0.01	na	na	na	na	na	na	na
2008	0.058	0.133	1.067	1.249	1.4	0.352	0.025	0.008	na	na	na	na	na	na	na
2009	0.072	0.708	1.601	0.907	1.304	0.501	0.029	na	na	na	na	na	na	na	na
2010	0.004	0.33	2.191	1.062	1.211	0.288	0.032	na	na	na	na	na	na	na	na
2011	na	0.115	1.418	1	1.04	0.141	0.031	na	na	na	na	na	na	na	na
2012	0.021	0.28	1.855	0.888	0.994	0.241	0.025	0.008	na	na	na	na	na	na	na
2013	0.003	0.231	0.697	0.442	0.238	0.234	0.026	na	na	na	na	na	na	na	na
2014	0.025	0.249	3.349	2.704	1.89	0.233	0.03	na	na	na	na	na	na	na	na

Year	Age (years)														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2015	0.08	0.342	1.617	0.839	0.908	0.362	0.04	na	na	na	na	na	na	na	na
2016	0.003	0.224	1.232	0.762	1.025	0.46	0.052	na	na	na	na	na	na	na	na
2017	0.012	0.56	2.891	1.026	0.647	0.423	0.046	na	na	na	na	na	na	na	na
2018	0.002	0.076	0.508	0.563	0.572	0.188	0.022	na	na	na	na	na	na	na	na
2019	0.007	0.769	2.978	1.741	1.209	0.351	0.042	na	na	na	na	na	na	na	na

Table 4b. Mean weight-at-age (kg) of White Hake in the southern Gulf of St. Lawrence Research Vessel survey (strata 415-439).

Year	Age (years)														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1971	na	0.213	0.334	0.484	0.848	1.472	2.129	2.14	2.34	2.34	2.183	na	7.534	na	na
1972	na	0.064	0.314	0.524	1.111	2.094	2.76	2.89	3.684	2.514	2.481	na	7.278	na	na
1973	na	0.123	0.373	0.622	1.097	1.488	1.959	2.611	4.148	2.476	2.062	na	na	na	na
1974	na	0.084	0.257	0.484	0.957	1.701	2.08	2.806	4.712	2.395	2.208	na	na	na	na
1975	na	0.267	0.326	0.423	0.858	1.419	1.951	2.04	2.309	2.309	2.156	na	6.831	na	na
1976	na	0.249	0.31	0.419	0.838	1.421	2.009	2.262	2.462	2.462	2.288	na	na	na	na
1977	na	0.19	0.387	0.525	0.808	1.492	1.812	2.377	4.858	2.36	1.991	na	6.017	na	na
1978	na	0.175	0.255	0.416	0.955	1.532	2.096	2.51	3.398	2.471	2.121	na	8.288	na	na
1979	na	na	0.309	0.449	0.815	1.4	1.839	2.225	2.374	3.172	2.735	5.005	2.736	na	na
1980	na	na	0.437	0.647	0.96	1.378	1.764	2.167	2.829	3.115	4.128	4.688	2.667	na	na
1981	na	0.059	0.247	0.485	0.914	1.405	1.865	2.268	2.984	3.194	3.575	12.275	3.575	9.738	12.275
1982	na	0.099	0.37	0.645	1.072	1.388	1.829	2.408	2.97	3.135	3.631	na	na	na	na
1983	na	0.161	0.337	0.62	1.108	1.907	2.136	3.138	3.876	4.031	5.964	na	na	na	na
1984	0.072	0.15	0.304	0.583	0.933	1.456	2.036	2.483	3.026	2.641	5.755	3.612	6.235	na	na
1985	0.006	0.099	0.234	0.43	0.761	1.258	1.838	2.44	3.298	4.592	3.225	4.25	9.308	8.269	10.06
1986	0.081	0.165	0.254	0.475	0.776	1.226	1.911	2.72	3.284	4.433	6.376	7.126	7.725	10.013	na
1987	na	0.103	0.197	0.432	0.68	1.184	1.982	2.907	3.68	6.485	6.445	na	7.974	na	na
1988	0.052	0.096	0.239	0.419	0.704	1.083	1.737	2.71	3.794	5.917	9.475	na	na	na	na
1989	0.047	0.101	0.224	0.447	0.631	1.064	1.583	2.402	3.435	5.355	6.856	9.162	na	9.162	na
1990	0.036	0.12	0.233	0.363	0.641	0.969	1.417	2.015	3.539	4.102	na	na	na	na	na
1991	0.065	0.201	0.269	0.477	0.674	1.033	1.504	2.12	3.694	4.338	6.55	7.223	na	na	na
1992	0.074	0.174	0.288	0.449	0.613	0.902	1.413	1.814	3.126	na	na	na	na	na	na
1993	0.084	0.154	0.276	0.462	0.666	0.888	1.173	1.381	2.576	4.713	na	na	na	na	na
1994	0.061	0.146	0.259	0.515	0.808	1.1	1.625	2.391	3.14	na	na	na	na	na	na
1995	0.015	0.109	0.249	0.483	0.716	1.078	1.752	3.046	3.698	na	na	na	na	na	na
1996	0.021	0.145	0.262	0.509	0.656	0.952	1.185	1.424	1.101	1.466	na	na	na	na	na
1997	0.044	0.086	0.234	0.44	0.626	0.888	1.254	1.807	1.908	na	na	na	na	na	na
1998	0.071	0.16	0.259	0.436	0.661	1.028	1.56	1.595	2.638	na	na	na	na	na	na
1999	0.049	0.098	0.257	0.46	0.669	1.085	1.727	3.12	na	na	na	na	na	na	na
2000	0.07	0.143	0.25	0.392	0.561	0.915	1.322	1.343	na	na	na	na	na	na	na
2001	0.064	0.185	0.252	0.45	0.617	1.016	1.399	1.308	na	na	na	na	na	na	na
2002	0.022	0.19	0.264	0.514	0.723	1.111	1.059	1.838	na	na	na	na	na	na	na
2004	0.043	0.136	0.227	0.492	0.67	1.078	na	na	na	na	na	na	na	na	na
2005	0.001	0.147	0.285	0.466	0.723	1.154	1.771	2.802	na	na	na	na	na	na	na
2006	0.029	0.188	0.26	0.46	0.615	0.946	1.169	1.509	na	na	na	na	na	na	na
2007	0.136	0.159	0.247	0.458	0.667	1.045	na	na	na	na	na	na	na	na	na
2008	0.025	0.143	0.269	0.391	0.592	0.982	1.367	1.259	na	na	na	na	na	na	na
2009	0.053	0.103	0.262	0.427	0.614	1.079	1.513	1.624	na	na	na	na	na	na	na
2010	0.013	0.087	0.215	0.405	0.593	0.933	0.986	na	na	na	na	na	na	na	na
2011	0.088	0.155	0.246	0.401	0.66	0.973	1.691	na	na	na	na	na	na	na	na
2012	na	0.12	0.214	0.427	0.636	1.112	1.103	na	na	na	na	na	na	na	na
2013	0.02	0.162	0.225	0.419	0.646	1.038	2.303	2.984	na	na	na	na	na	na	na
2014	0.02	0.091	0.243	0.336	0.582	0.918	1.185	na	na	na	na	na	na	na	na
2015	0.006	0.118	0.207	0.345	0.63	1.071	1.146	na	na	na	na	na	na	na	na
2016	0.001	0.128	0.197	0.37	0.68	1.299	1.258	na	na	na	na	na	na	na	na

Year	Age (years)														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2017	0.024	0.133	0.198	0.327	0.683	1.4	1.35	na	na	na	na	na	na	na	na
2018	0.11	0.132	0.202	0.324	0.646	1.266	1.225	na	na	na	na	na	na	na	na
2019	0.038	0.114	0.198	0.313	0.615	1.187	1.15	na	na	na	na	na	na	na	na

Table 5a. Mean number per tow by age for White Hake in the Mobile Sentinel survey conducted in the southern Gulf of St. Lawrence from 2003 to 2019.

Age	1	2	3	4	5	6	7	8	Total
2003	0.497	0.904	0.376	0.415	0.181	0.021	0.004	0.006	2.417
2004	0.114	0.744	0.556	0.707	0.401	0.049	na	na	2.637
2005	0.143	1.35	0.542	0.702	0.209	0.017	0.01	na	2.975
2006	0.252	1.099	0.501	0.372	0.088	0.009	0.006	na	2.334
2007	0.123	0.689	0.309	0.317	0.108	0.019	na	na	1.567
2008	0.058	0.279	0.254	0.214	0.056	0.004	na	na	0.865
2009	0.025	0.371	0.61	0.581	0.231	0.014	0.01	na	1.842
2010	0.147	0.417	0.295	0.219	0.066	0.023	0.005	na	1.174
2011	0.059	0.222	0.214	0.236	0.051	0.002	0.005	na	0.789
2012	0.153	0.2	0.1	0.082	0.031	0.009	na	na	0.75
2013	0.049	0.463	0.098	0.063	0.059	0.007	na	na	0.745
2014	0.021	0.395	0.390	0.318	0.195	0.015	na	na	1.554
2015	0.044	0.665	0.459	0.409	0.522	0.025	na	na	2.481
2016	0.127	2.073	0.605	0.357	0.418	0.026	na	na	3.909
2017	0.127	1.864	0.482	0.174	0.179	0.023	na	na	3.013
2018	0.019	0.515	0.350	0.159	0.123	0.012	na	na	1.329
2019	0.072	1.133	0.592	0.282	0.176	0.005	na	na	2.455

Table 5b. Average weight-at-age (kg) for White Hake in the Mobile Sentinel survey conducted in the southern Gulf of St. Lawrence from 2003 to 2019.

Age	1	2	3	4	5	6	7	8	Weighted
2003	0.14	0.23	0.49	0.76	1.27	1.89	2.14	2.35	0.44
2004	0.11	0.24	0.42	0.73	1.19	1.71	na	na	0.57
2005	0.14	0.21	0.47	0.63	1.12	1.29	1.72	na	0.43
2006	0.15	0.23	0.44	0.63	1.02	1.33	2.47	na	0.37
2007	0.15	0.22	0.42	0.69	1.01	1.46	na	na	0.42
2008	0.15	0.22	0.44	0.65	1.11	2.2	na	na	0.45
2009	0.13	0.22	0.41	0.6	0.99	1.54	2.15	na	0.52
2010	0.14	0.23	0.4	0.69	1.08	1.83	2.77	na	0.44
2011	0.15	0.23	0.44	0.67	1.06	1.94	2.49	na	0.49
2012	0.14	0.21	0.49	0.81	1.13	2.4	na	na	0.31
2013	0.14	0.21	0.37	0.56	1.06	1.9	na	na	0.34
2014	0.16	0.26	0.44	0.61	1.01	2.31	na	na	0.45
2015	0.15	0.22	0.45	0.65	1.09	2.43	na	na	0.51
2016	0.15	0.22	0.38	0.57	1.31	2.52	na	na	0.39
2017	0.15	0.22	0.38	0.54	1.40	2.83	na	na	0.34
2018	0.21	0.26	0.40	0.56	1.31	2.08	na	na	0.42
2019	0.16	0.24	0.41	0.57	0.96	2.28	na	na	0.35

Table 5c. Average length-at-age (cm) for White Hake in Mobile Sentinel survey conducted in the southern Gulf of St. Lawrence from 2003 to 2019.

Age	1	2	3	4	5	6	7	8	Total
2003	26.5	31.2	39.9	46.2	54.6	62.2	65	67	36.2
2004	24.7	31.4	37.9	44.9	52.7	59.4	na	na	39.1
2005	26.7	30.8	39.8	44	53.2	55.9	61.1	na	37.2
2006	27.8	31.4	39.1	43.6	51.2	56.2	68.6	na	35.5
2007	27.4	31	38.2	44.8	50.8	57.2	na	na	36.6
2008	27.5	30.8	38.7	43.7	51.9	65	na	na	37.6
2009	25.7	30.8	37.9	42.9	50.7	58.8	65	na	39.8
2010	26.6	31.3	37.4	44.8	51.7	61.7	71	na	36.6
2011	27.6	31.7	39	44.1	51.2	62	67	na	38.6
2012	26.9	30.4	40.2	47	52.6	66	na	na	27.1
2013	26.4	30.4	36.9	42.3	52.3	64.2	na	na	33.8
2014	27.8	32.8	38.8	43.3	50.9	67.4	na	na	34.4
2015	27.2	30.9	39.4	44.4	52.3	68.0	na	na	35.1
2016	27.8	31.2	37.1	41.7	53.9	66.1	na	na	33.2
2017	27.3	31.1	36.6	40.2	54.0	67.1	na	na	32.3
2018	30.4	32.4	37.5	41.6	54.4	63.8	na	na	33.5
2019	27.9	31.8	38.2	42.3	50.5	67.4	na	na	33.3

Table 6. Risk analysis table for the effects of different levels of bycatch of White Hake on the status of the sGSL White Hake population. Risk estimates are based on 25-year population projections. Two sets of projections were conducted, one sampling from the recruitment rates observed in 2000 to 2019 and one sampling from the recruitment rates observed in 2000 to 2010. Recruitment rates greater than any previously observed occured in the 2011-2019 period. Three statistics are reported: 1) the percent decline in SSB over the 25-year projection, 2) the probability that SSB would be less than 4,000, 2,000 or 1,000 tonnes at the end of the 25-year projection, and 3) the median estimates of SSB in years 5, 10, 15, 20 and 25 of the projections. SSB is reported in kilotonnes (kt). Horizontal lines indicate projections that were not conducted.

Bycatch Level (t)	25-year decline in SSB (%)	Probability (%) SSB25 will be below			Median estimates of SSB (kt) at year				
		4,000 t	2,000 t	1,000 t	2024	2029	2034	2039	2044
Recruitment rates from 2000-2019									
0	38.7	46.2	21.8	7.9	5.9	6.6	5.7	5.0	4.4
20	39.3	46.8	22.4	8.2	5.8	6.6	5.7	5.0	4.3
150	43.0	49.4	25.7	10.2	5.8	6.4	5.5	4.8	4.1
250	45.7	51.3	28.0	12.2	5.7	6.3	5.4	4.6	3.9
350	48.4	53.1	30.2	13.8	5.7	6.3	5.2	4.4	3.7
500	52.0	55.1	33.4	17.7	5.7	6.2	5.2	4.2	3.4
750	57.2	59.0	37.9	20.7	5.6	5.9	4.8	3.8	3.0
1,500	69.9	67.3	49.4	32.4	5.3	5.4	4.1	2.9	2.1
Recruitment rates from 2000-2010									
0	82.3	-	-	-	4.7	4.3	2.8	1.9	1.3
20	82.7	-	-	-	4.7	4.2	2.8	1.8	1.2
150	84.9	-	-	-	4.7	4.1	2.7	1.7	1.1
250	-	-	-	-	-	-	-	-	-
350	-	-	-	-	-	-	-	-	-
500	-	-	-	-	-	-	-	-	-
750	91.5	-	-	-	4.4	3.7	2.2	1.1	0.6
1,500	95.7	-	-	-	4.3	3.4	1.7	0.7	0.2

FIGURES

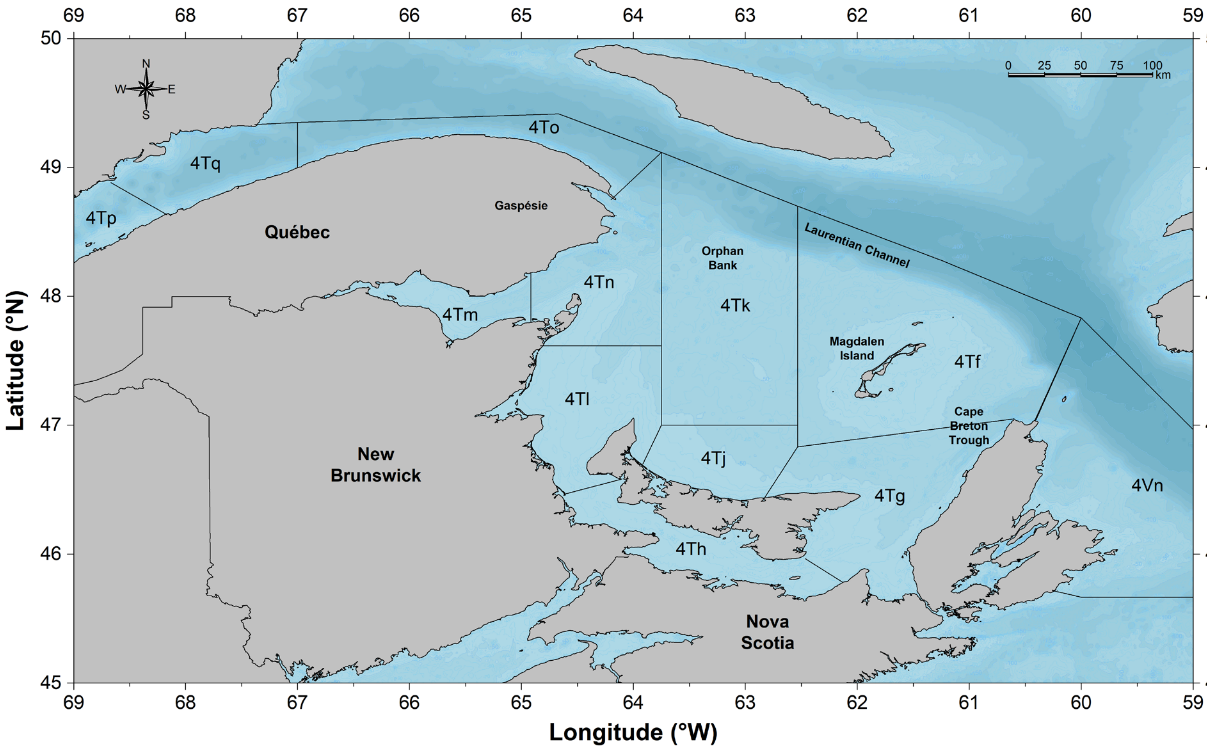

Figure 1. NAFO Divisions in the area of the Gulf of St. Lawrence. Unit areas are indicated for Division 4T.

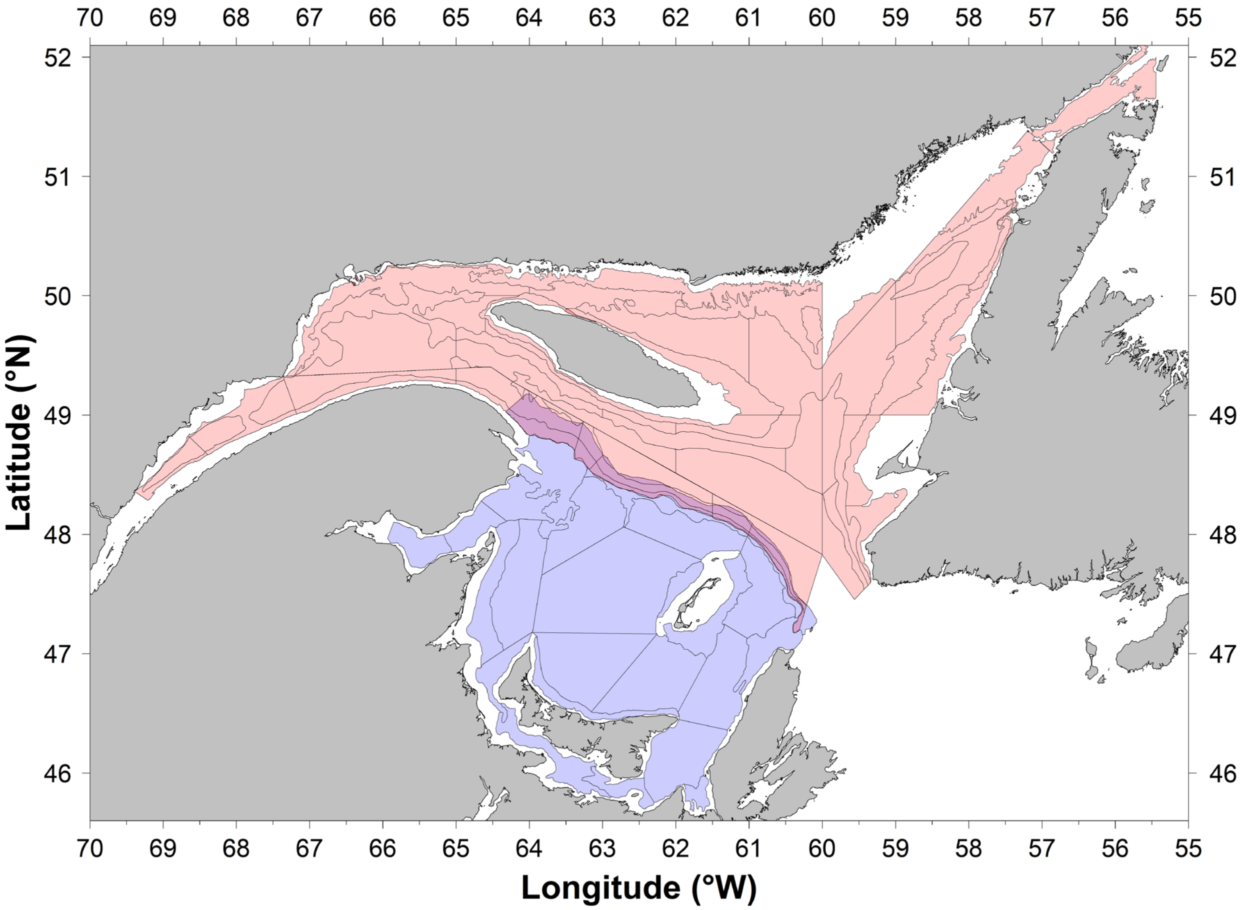

Figure 2. Stratification scheme for the southern (blue) and northern (red) Gulf of St. Lawrence Research Vessel trawl surveys. The area in purple represents the overlap between the two surveys.

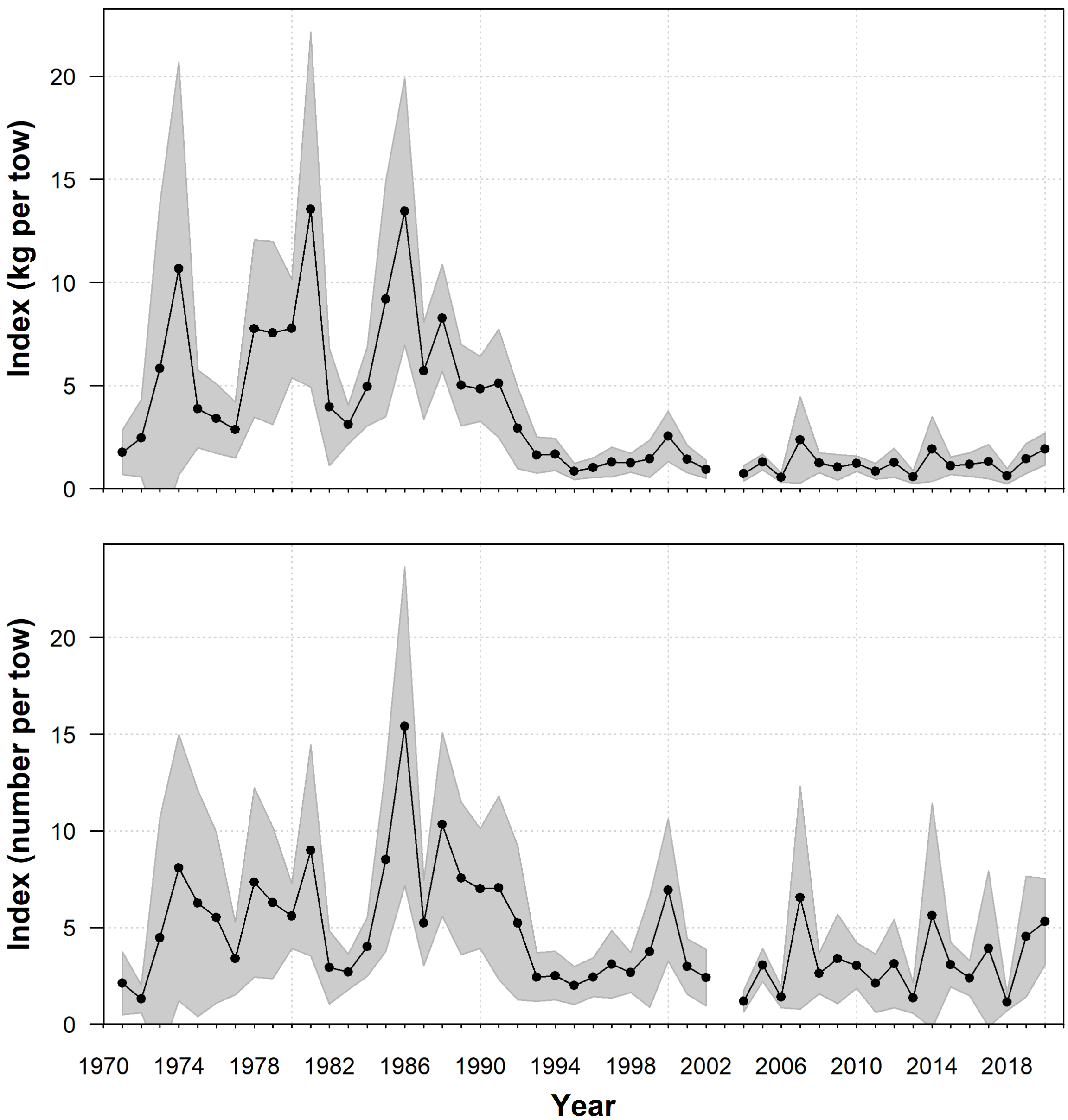

Figure 3. Annual mean catch indices of White Hake in the southern Gulf of St. Lawrence bottom trawl survey (kg per tow, top panel; number per tow, bottom panel). The gray shading denotes approximate 95% confidence limits (± 2 standard errors).

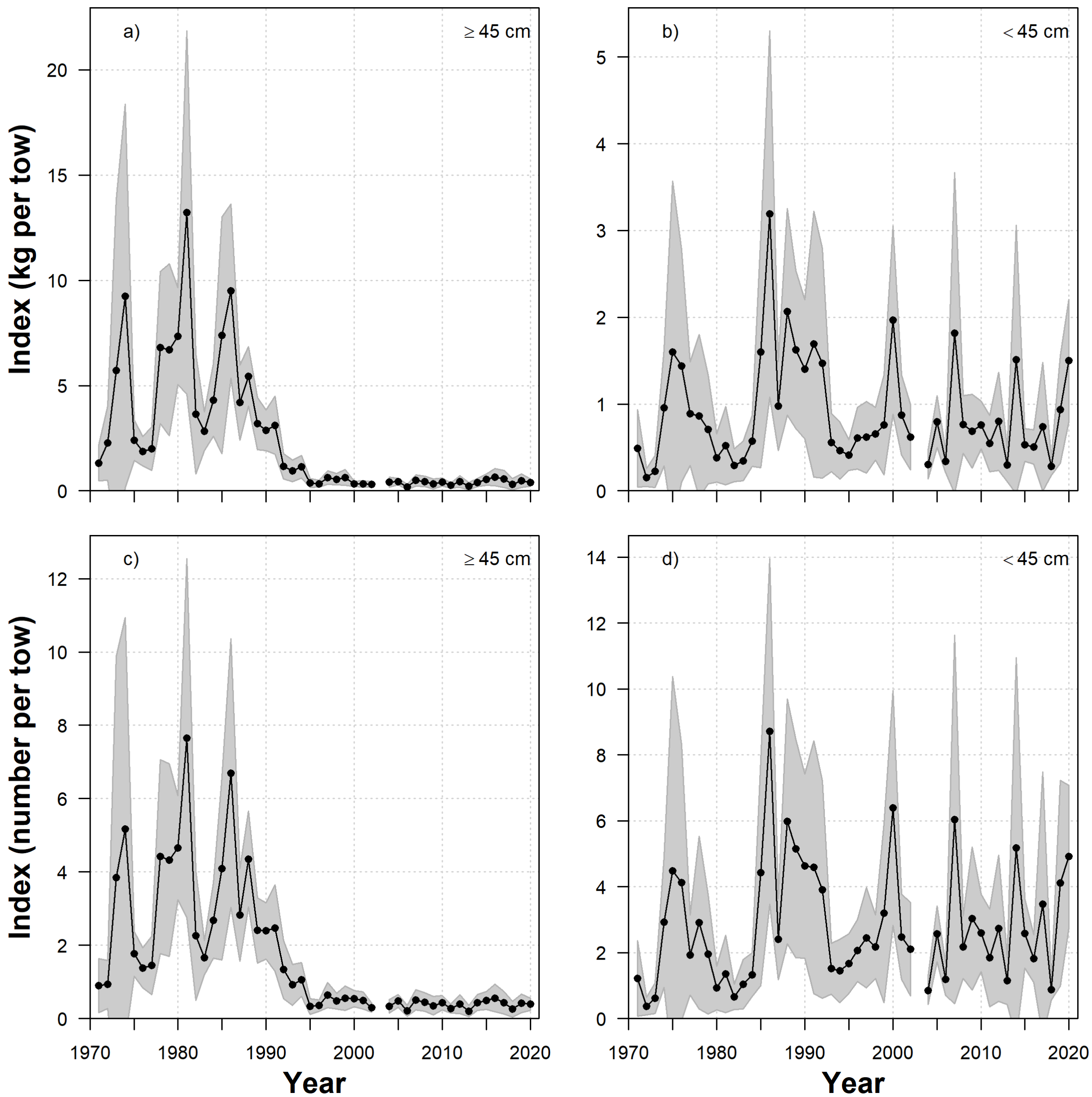

Figure 4. Mean annual catch indices (kg per tow, panels a) and b), number per tow, panels c) and d)) of White Hake ≥ 45 cm in length (a and c) and < 45 cm (c and d) in the southern Gulf of St. Lawrence bottom trawl research vessel survey. The gray shading denote approximate 95% confidence limits (± 2 standard errors).

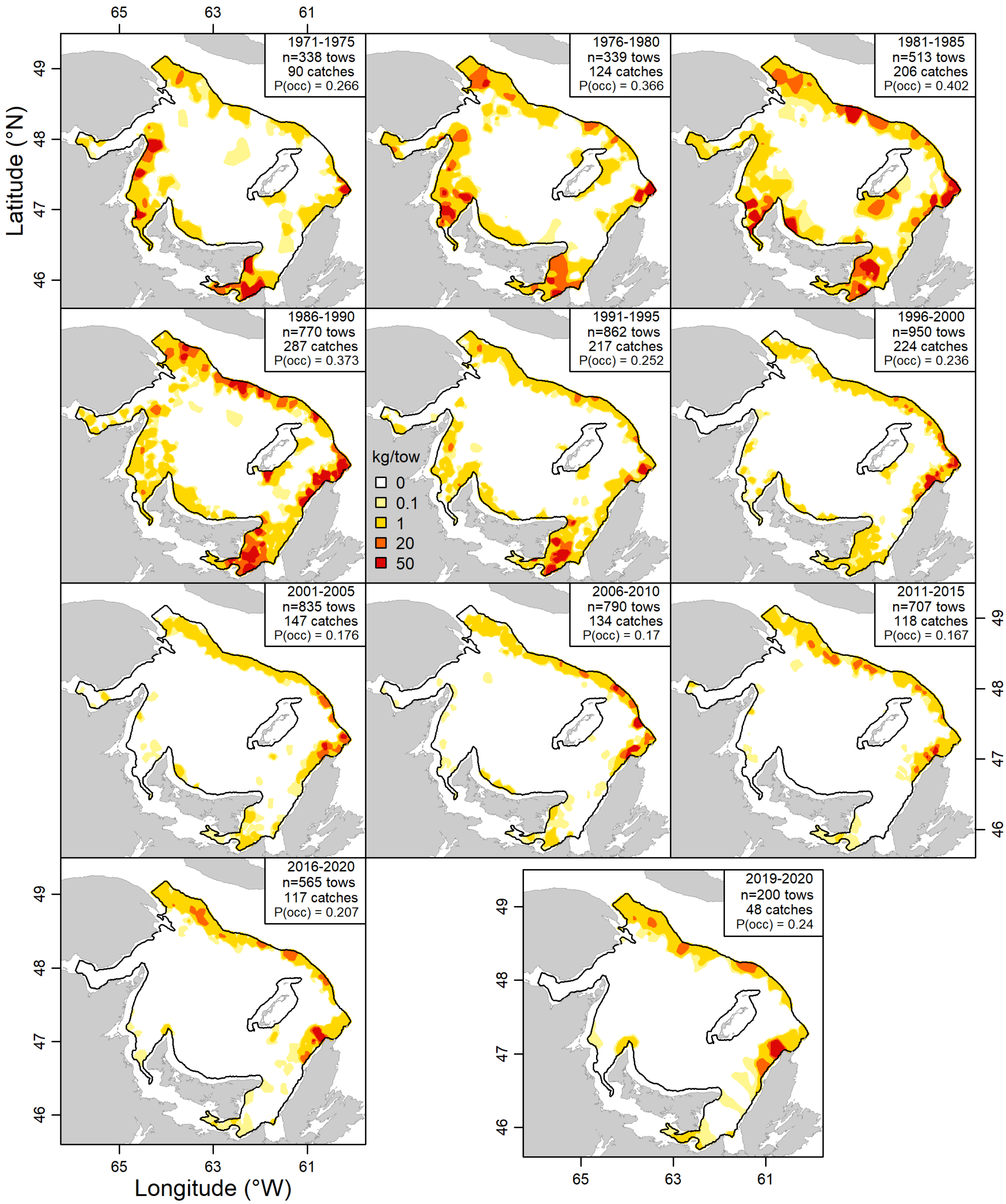

Figure 5. Spatial distribution of White Hake catches by blocks of years in the southern Gulf of St. Lawrence bottom trawl research vessel survey from 1971 to 2020. P(occ) indicates probability of occurrence (the number of tows catching White Hake divided by the total number of tows).

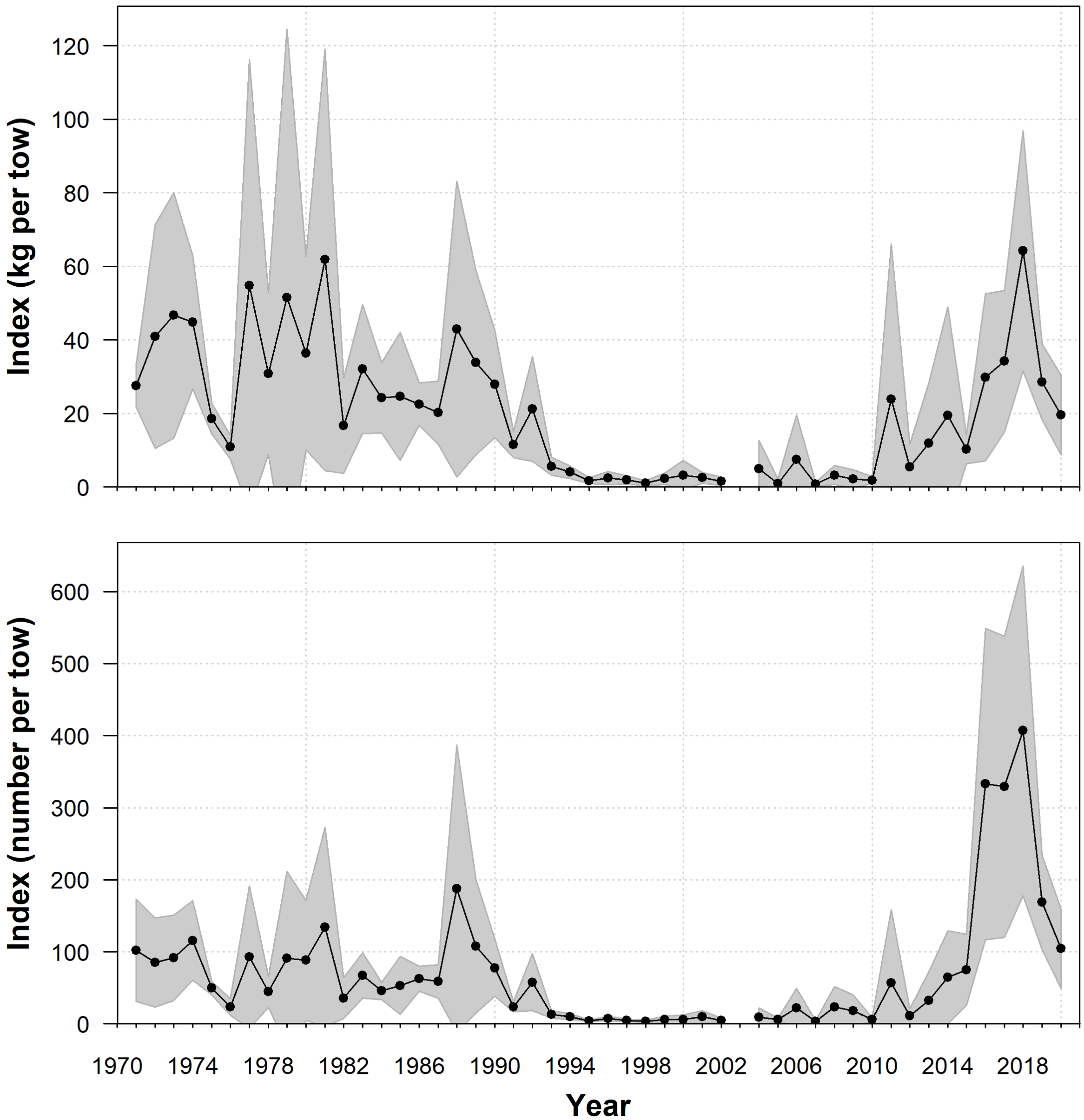

Figure 6. Annual mean catch indices of Redfish in the southern Gulf of St. Lawrence bottom trawl research vessel survey (kg per tow, top panel; number per tow, bottom panel). The gray shading denotes approximate 95% confidence limits (± 2 standard errors).

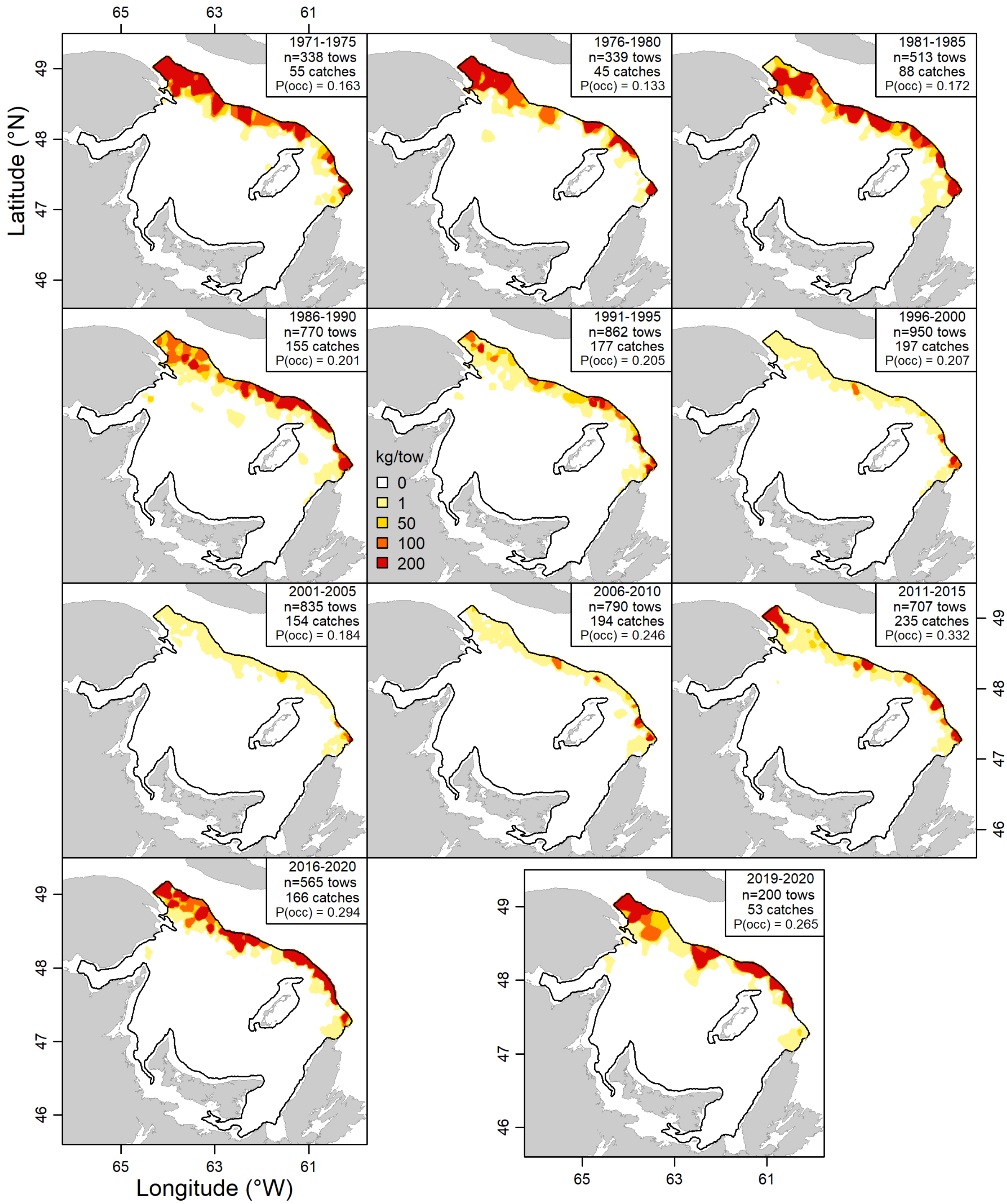

Figure 7. Spatial distribution of Redfish catches by blocks of years in the southern Gulf of St. Lawrence bottom trawl research vessel survey from 1971 to 2020. P(occ) indicates probability of occurrence (the number of tows catching Redfish divided by the total number of tows).

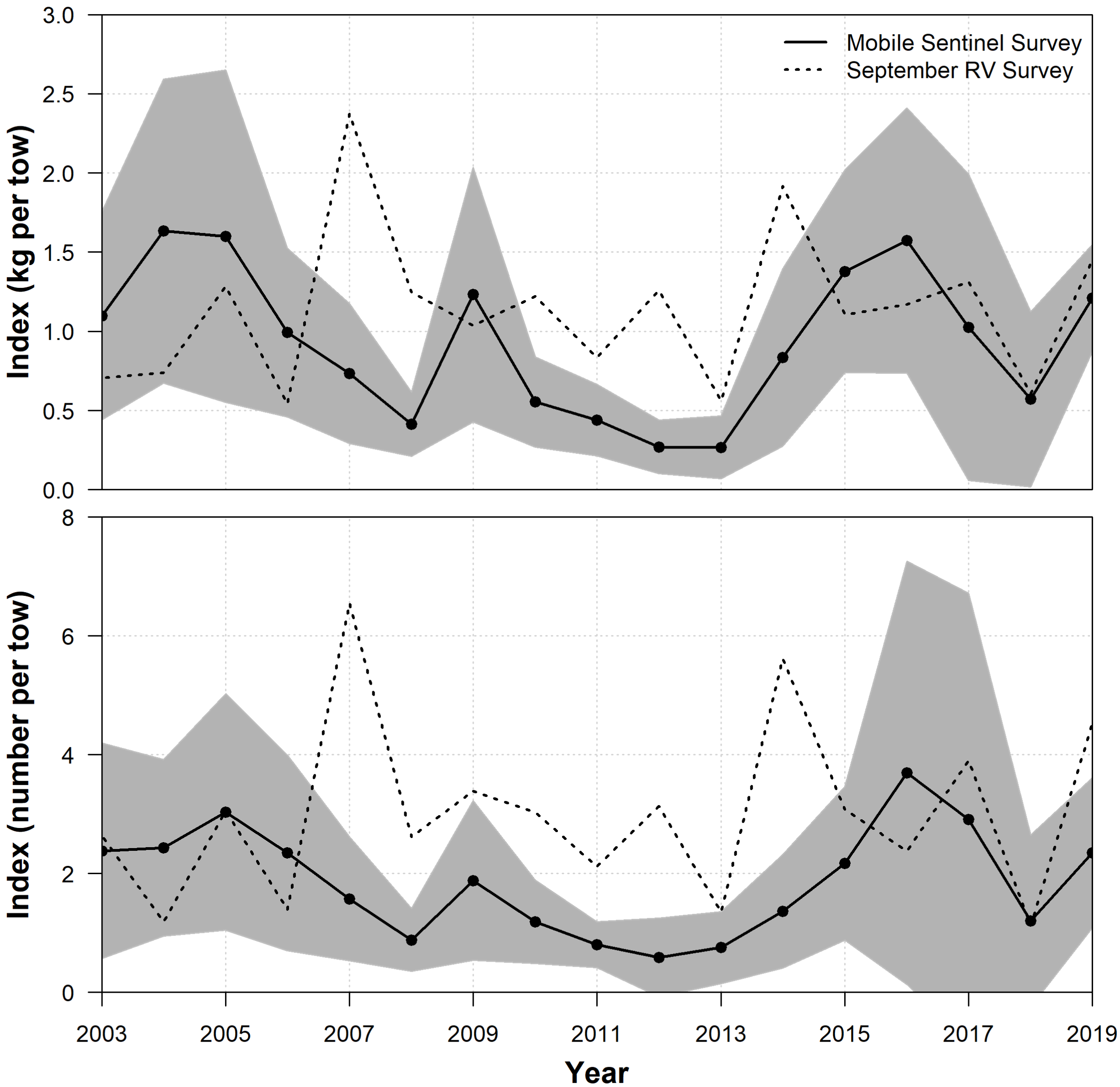

Figure 8. Annual mean catch indices of White Hake caught in the southern Gulf of St. Lawrence mobile Sentinel trawl survey (kg per tow, top panel; number per tow, bottom panel). The gray shading denotes approximate 95% confidence limits (± 2 standard errors). The dashed line represents the same information from the bottom trawl research vessel (RV) survey.

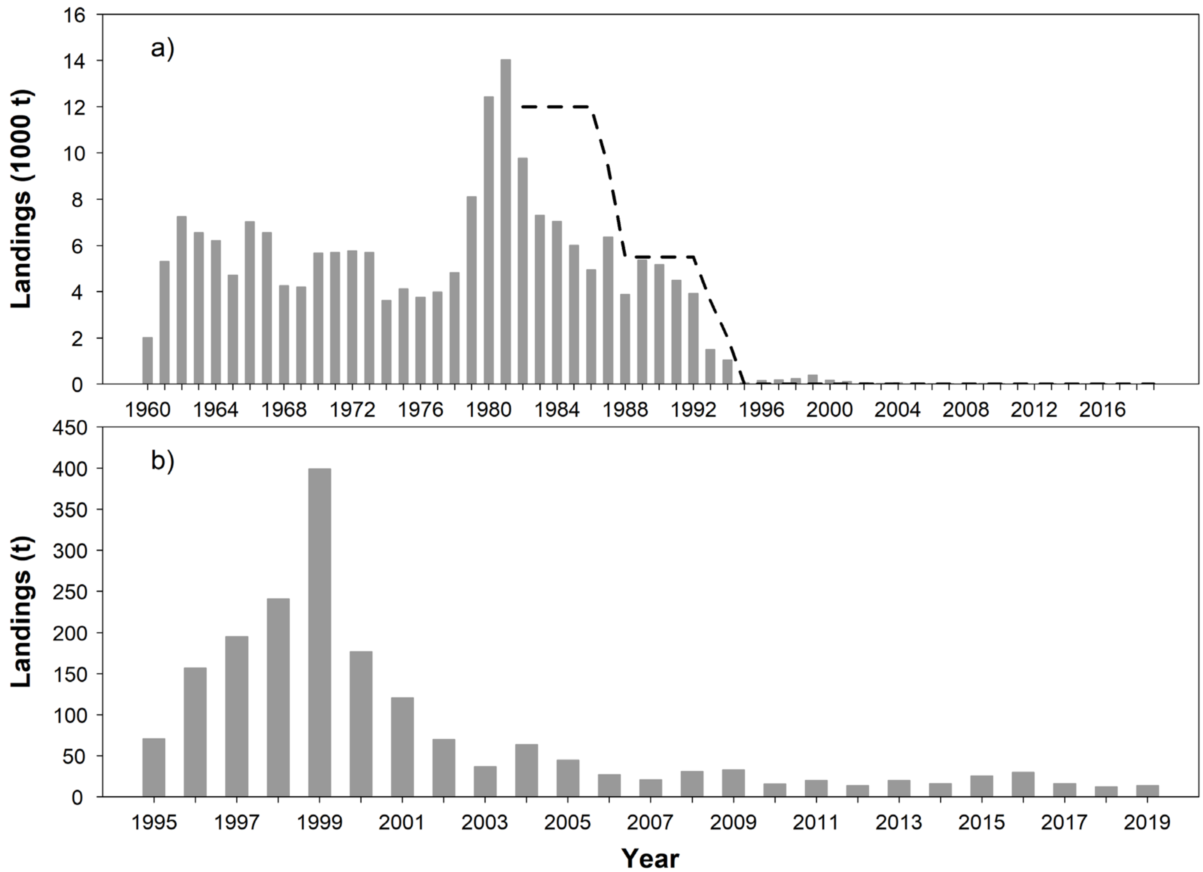

Figure 9. Landings and total allowable catch (TAC) for White Hake in NAFO Division 4T (a - upper panel). B) The bottom panel shows the bycatch landings of White Hake following the moratorium in 1995.

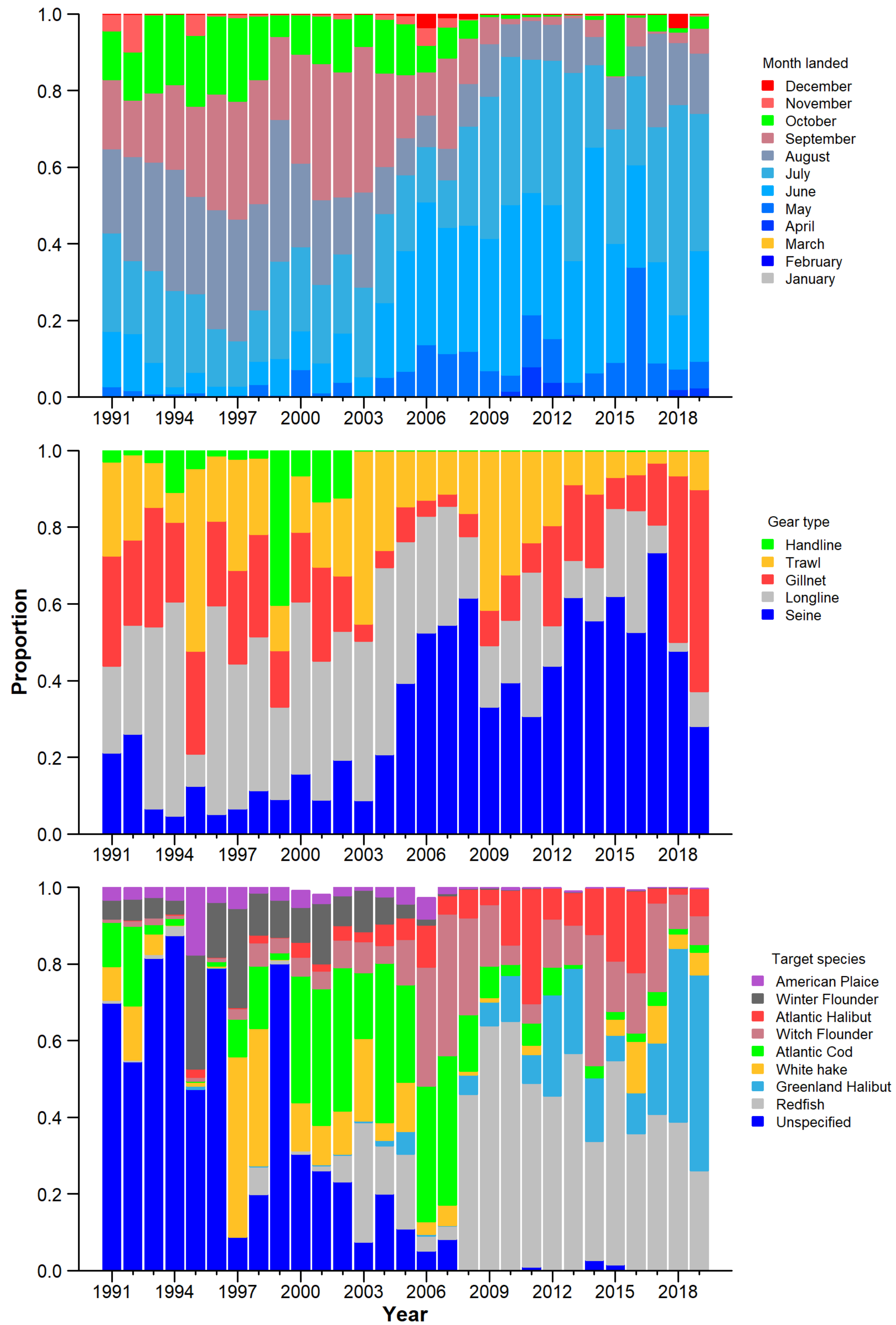

Figure 10. Proportion of annual White Hake landings in NAFO Divisions 4T by month (top panel), by type of fishing gear (middle panel) and by target fishing species (lower panel), 1991 to 2019.

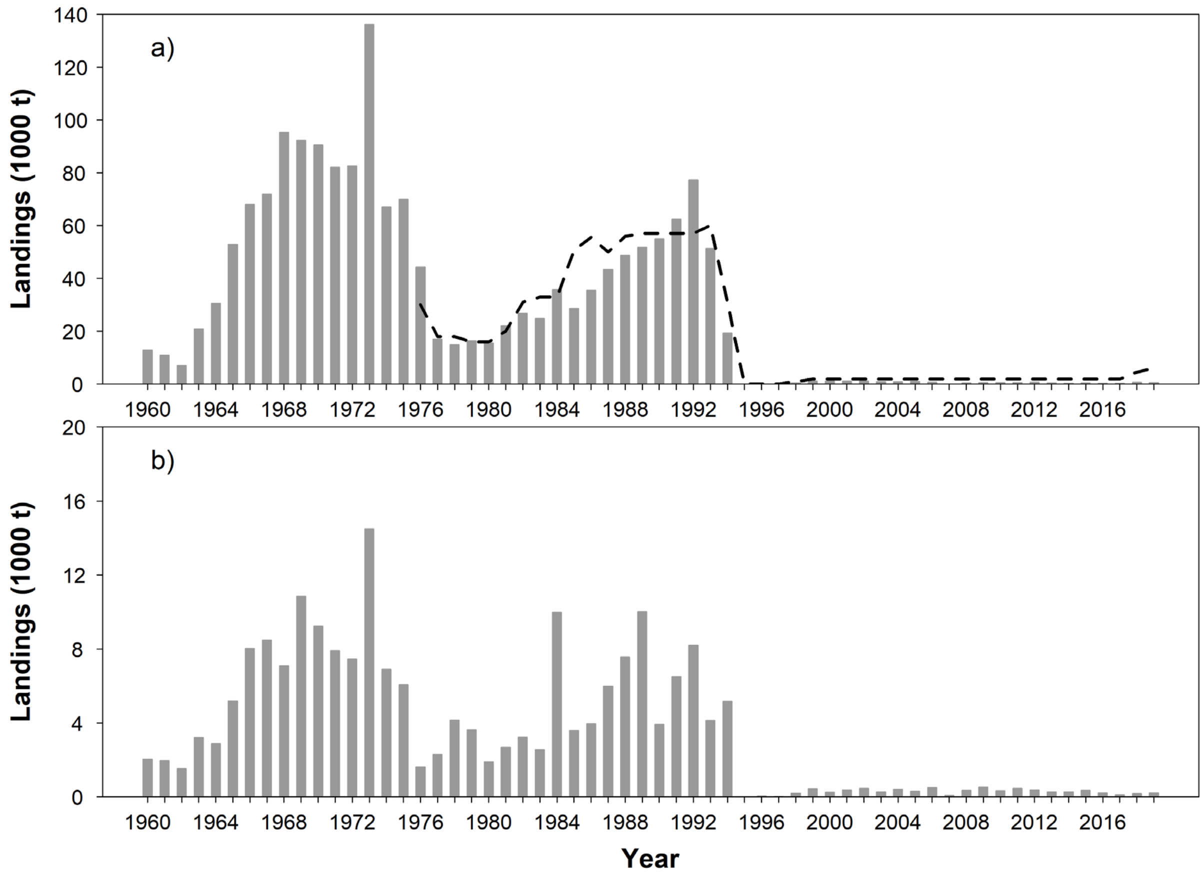

Figure 11. Landings and total allowable catch (TAC) for Redfish spp. in Unit 1 (a – upper panel) and landings in NAFO Division 4T (b – lower panel).

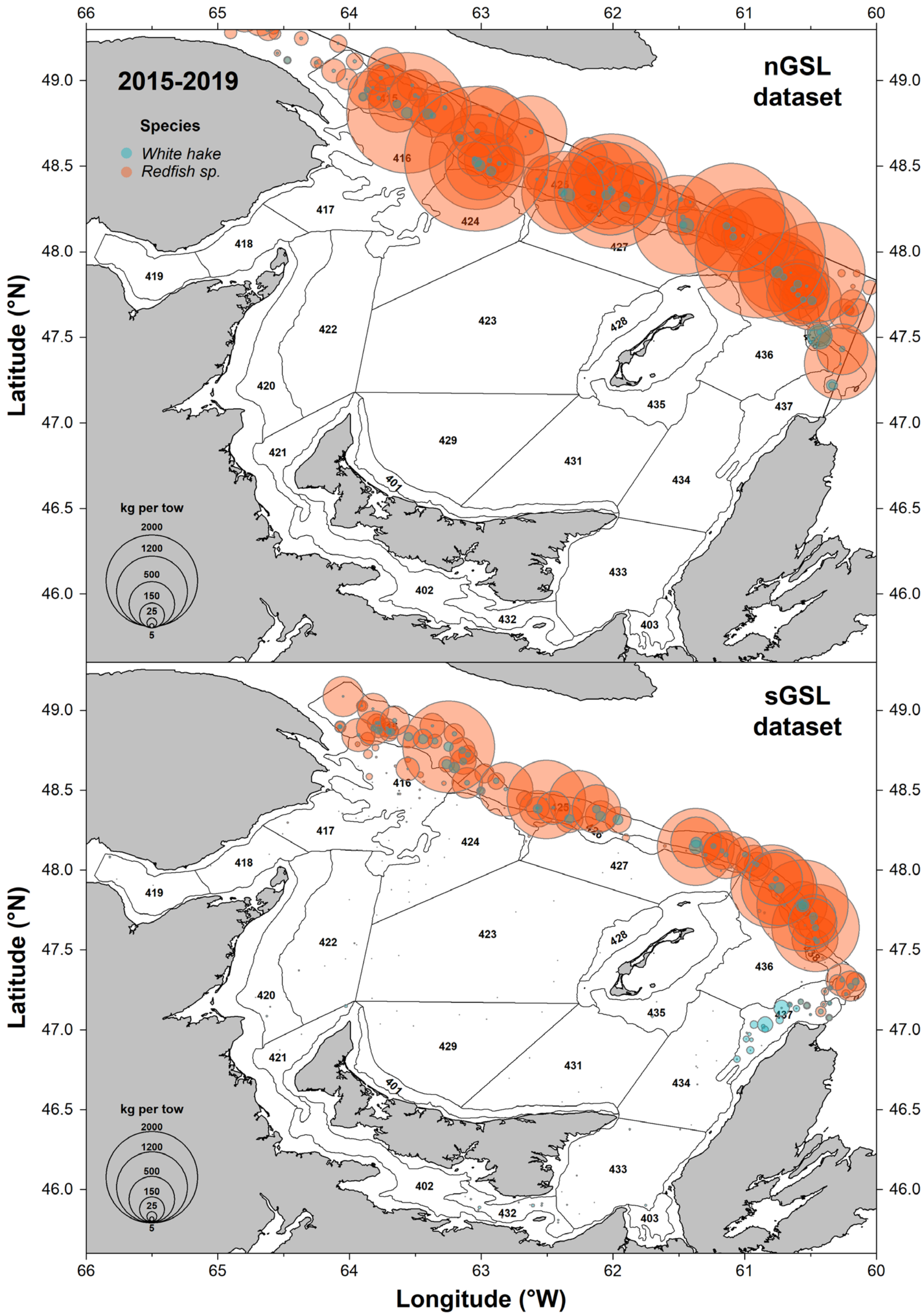

Figure 12. Spatial distribution and abundance (kg per tow) of White Hake and Redfish spp. from the nGSL (upper panel) and the sGSL (lower panel) bottom trawl research vessel survey for 2015 to 2019.

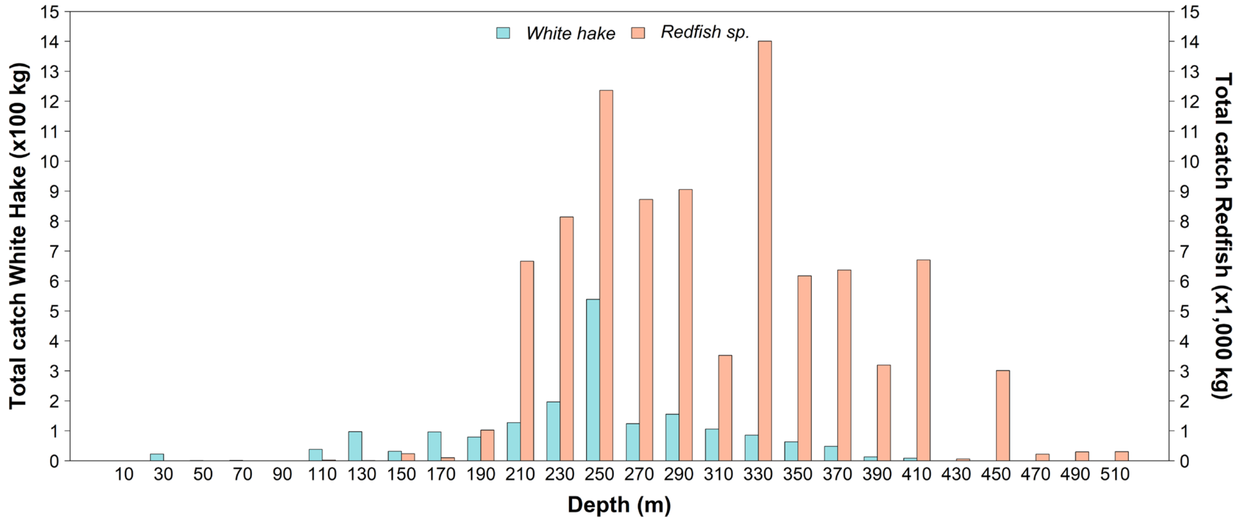

Figure 13. Total catch (kg) of White Hake and Redfish at the average depth of each sets from the bottom trawl research vessel surveys for 2015 to 2019.

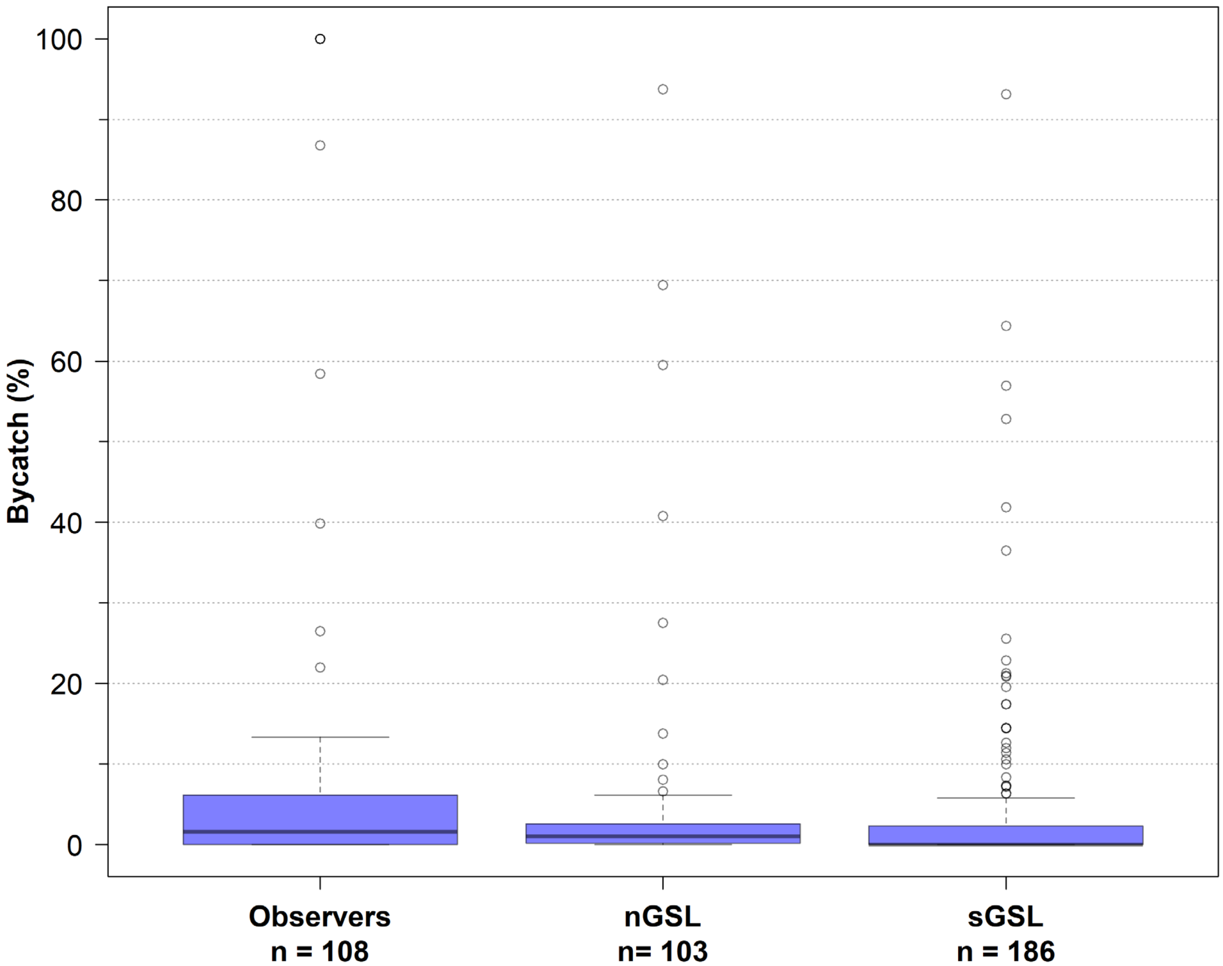

Figure 14. Box plots of bycatch (%) of White Hake from the fishery-dependent dataset (observer), and the fishery-independent datasets (sGSL and nGSL bottom trawl research vessel surveys). The maximum bycatch was set to 250%.

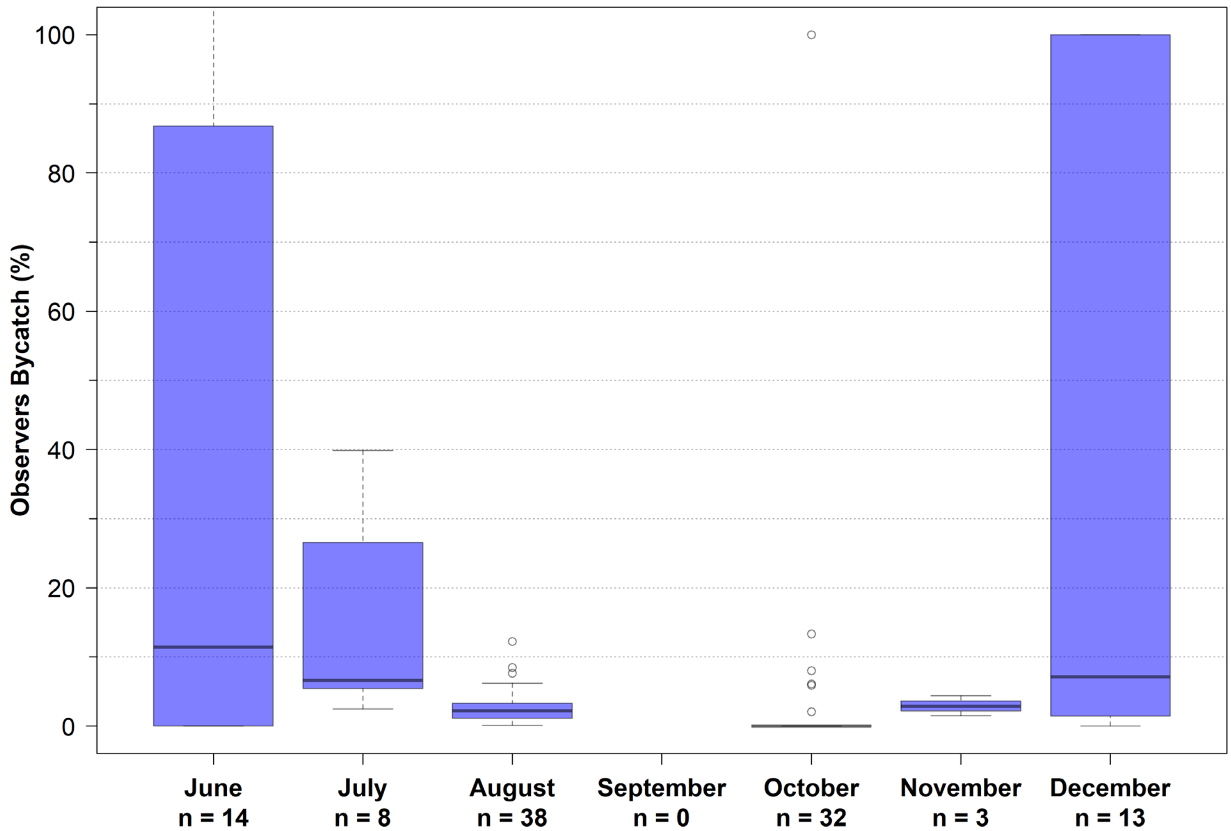

Figure 15. Monthly box plots of bycatch (%) of White Hake from the fishery-dependent observer dataset.

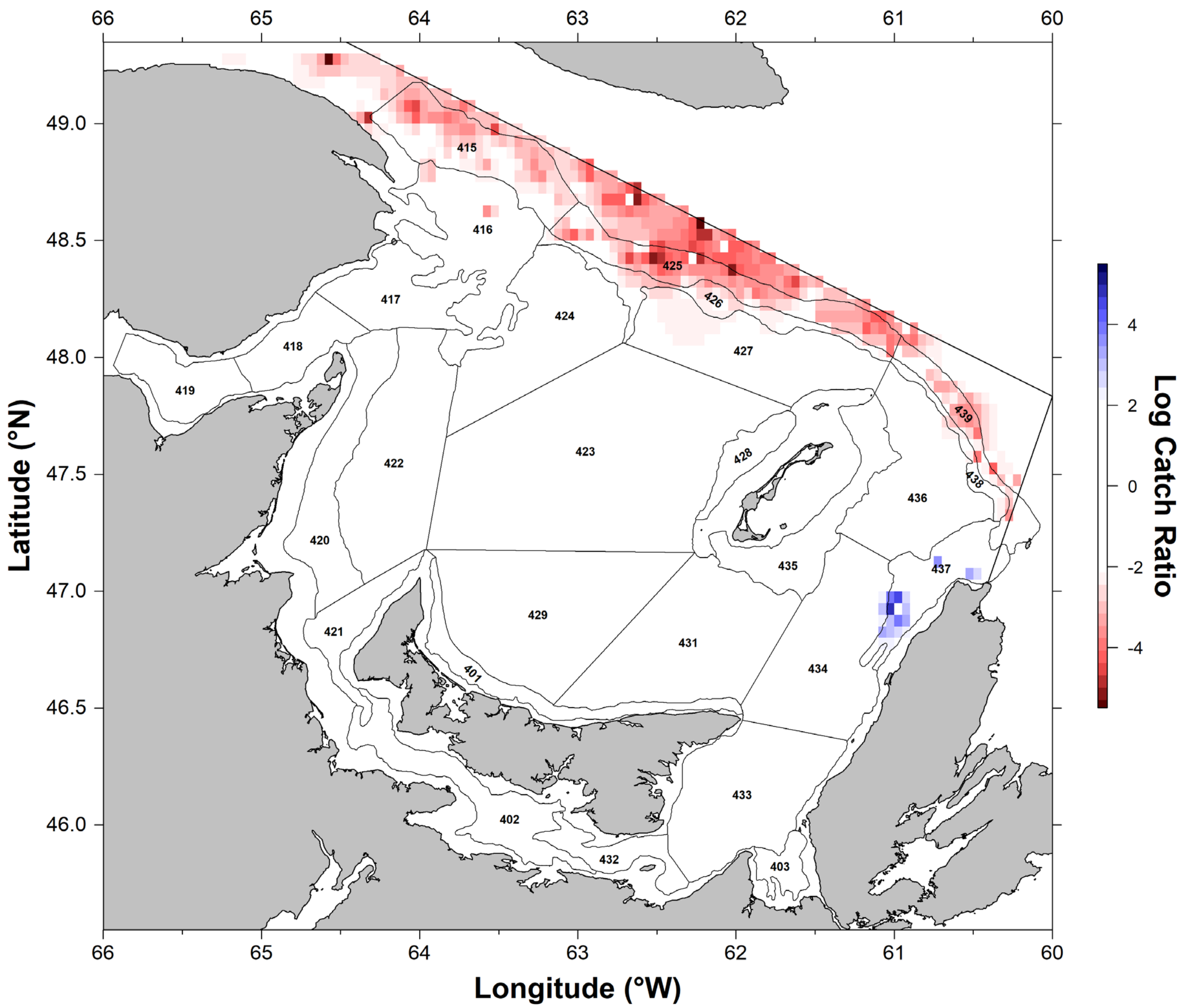

Figure 16. Inverse distance weighting of log-transformed catch ratio of White Hake over Redfish from both the fishery-dependent (2015-2018) and fishery-independent (2015-2019) data sources. The sGSL survey strata are provided alongside with the NAFO Division 4T limit.

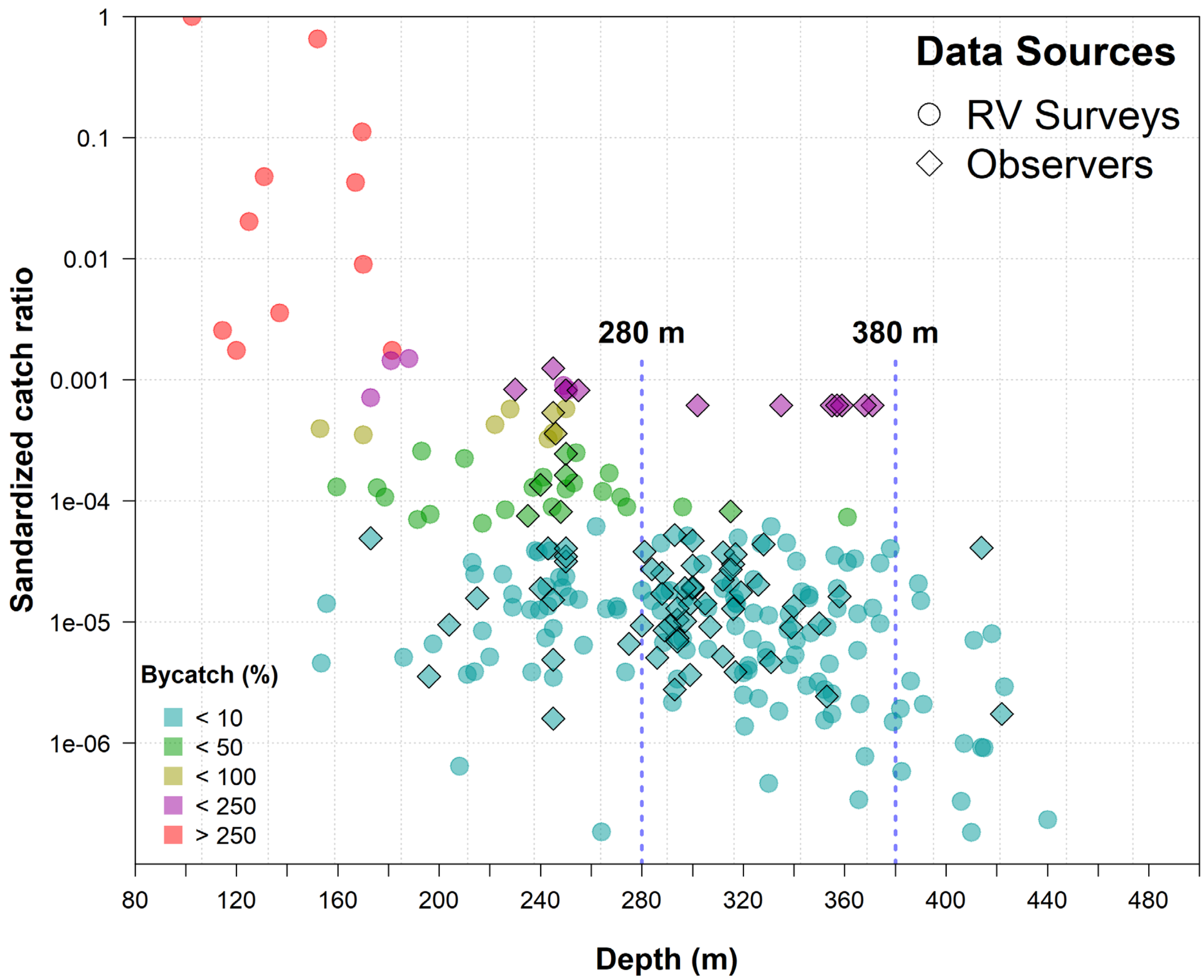

Figure 17. Standardized catch ratio of bycatch of White Hake over Redfish by depth (m) from both the fishery-dependent (2015-2018) and fishery-independent (2015-2019) data sources.

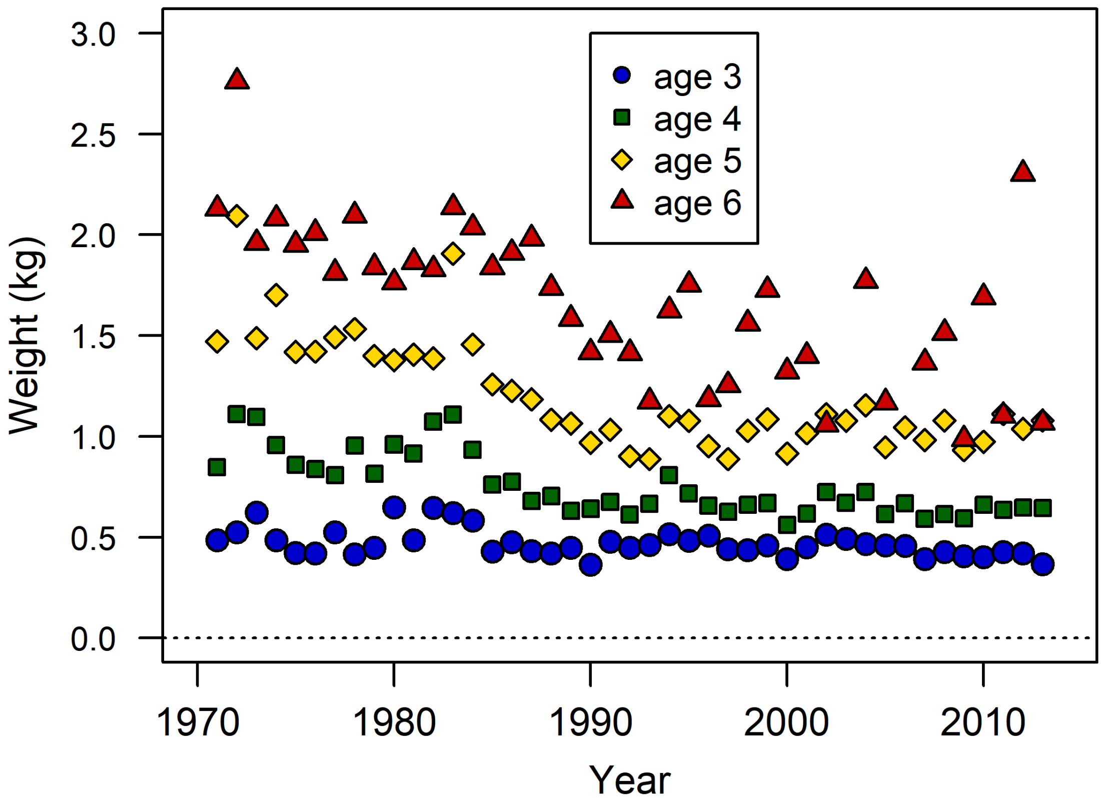

Figure 18. Stratified annual mean weights (kg) at ages 2 to 6 years of White Hake collected during the sGSL Research Vessel survey, 1971 to 2014.

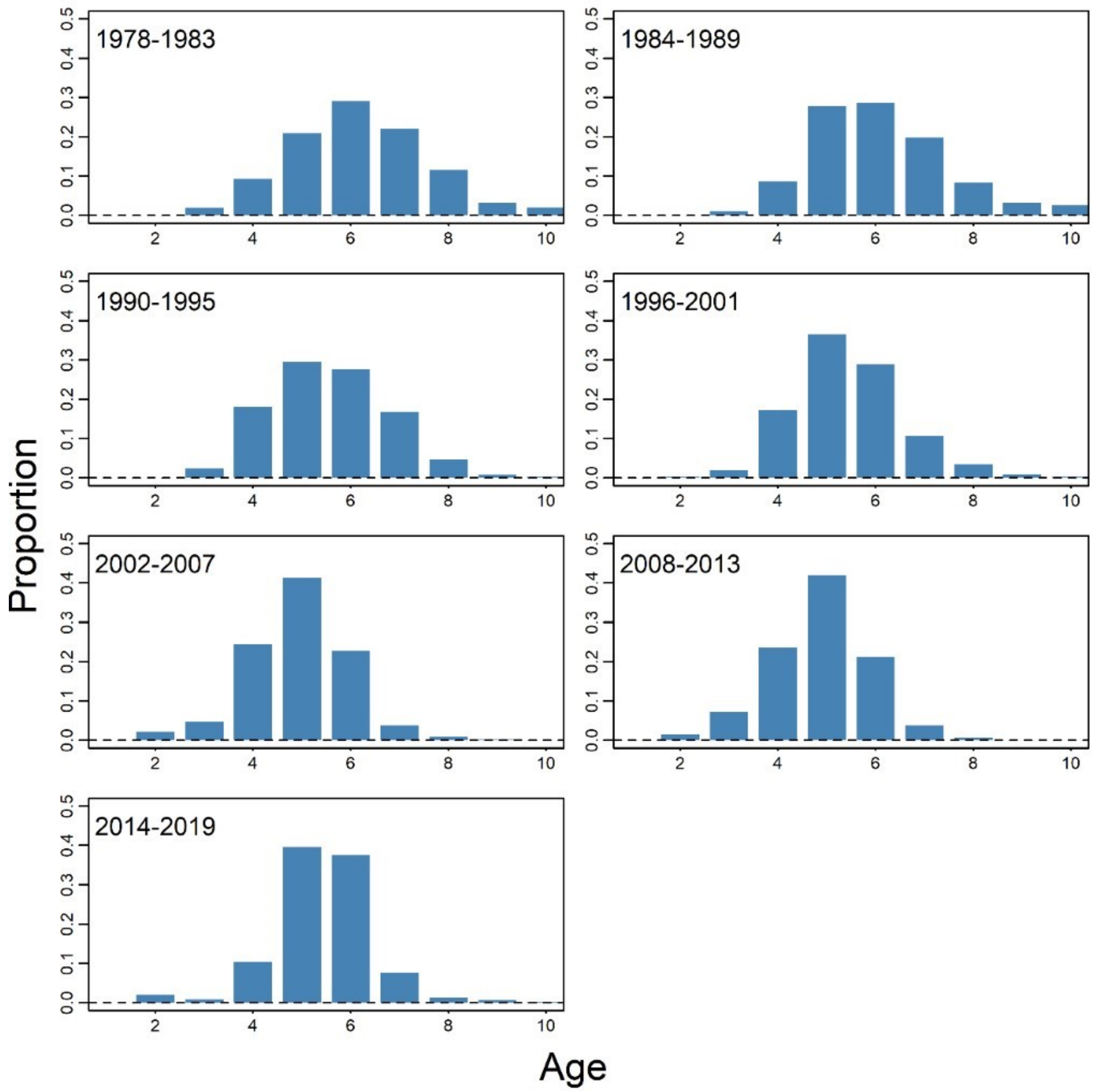

Figure 19. Proportion-at-age in fishery catches of White Hake in the sGSL.

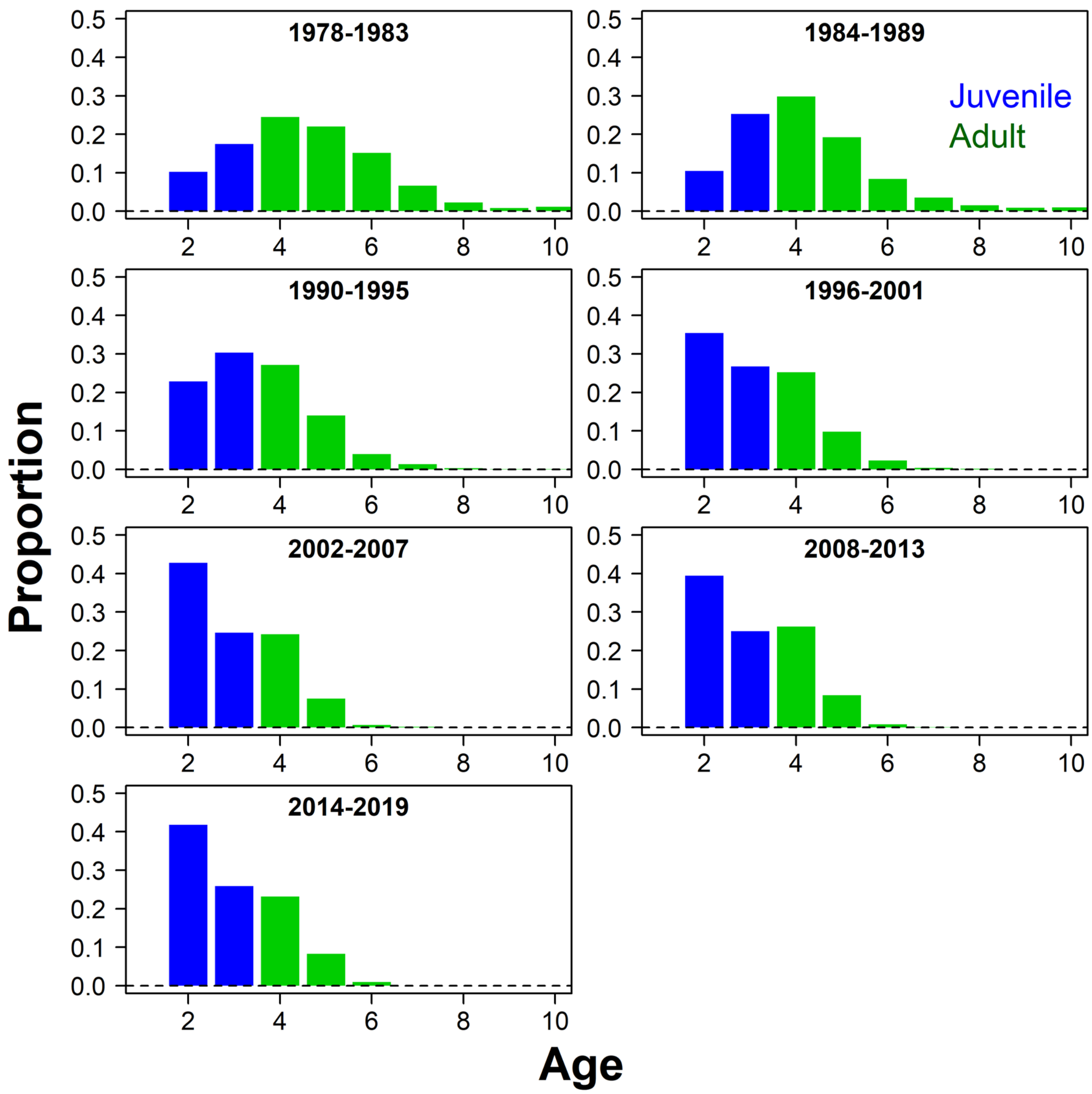

Figure 20. Proportion-at-age of White Hake in sGSL bottom trawl research vessel survey.

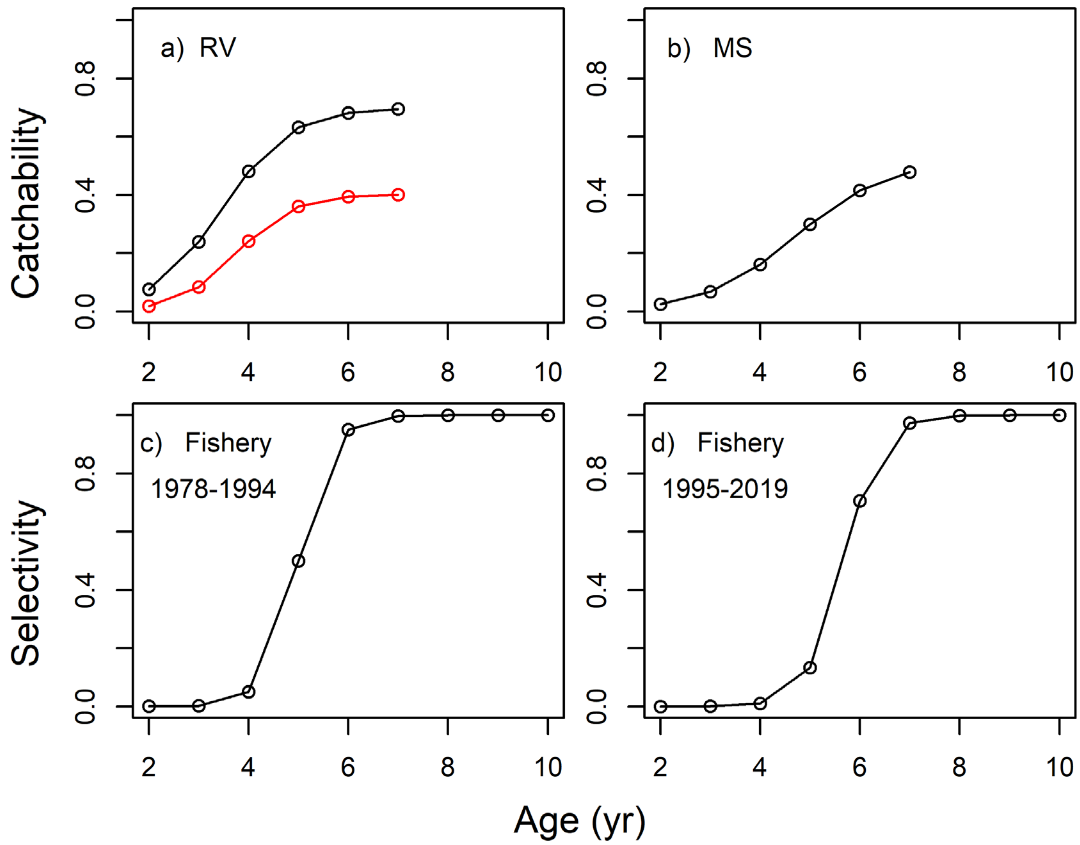

Figure 21. Estimated catchability of White Hake to the southern Gulf of St. Lawrence bottom trawl Research Vessel (RV) survey (a) and Mobile Sentinel (MS) survey (b) in the sGSL and selectivity of fisheries for White Hake in two time periods (c, d). In panel a) the black line indicates catchability in the 1985-2019 period (Western IIa trawl) and the red line indicates catchability in the 1978-1984 period (Yankee 36 trawl).

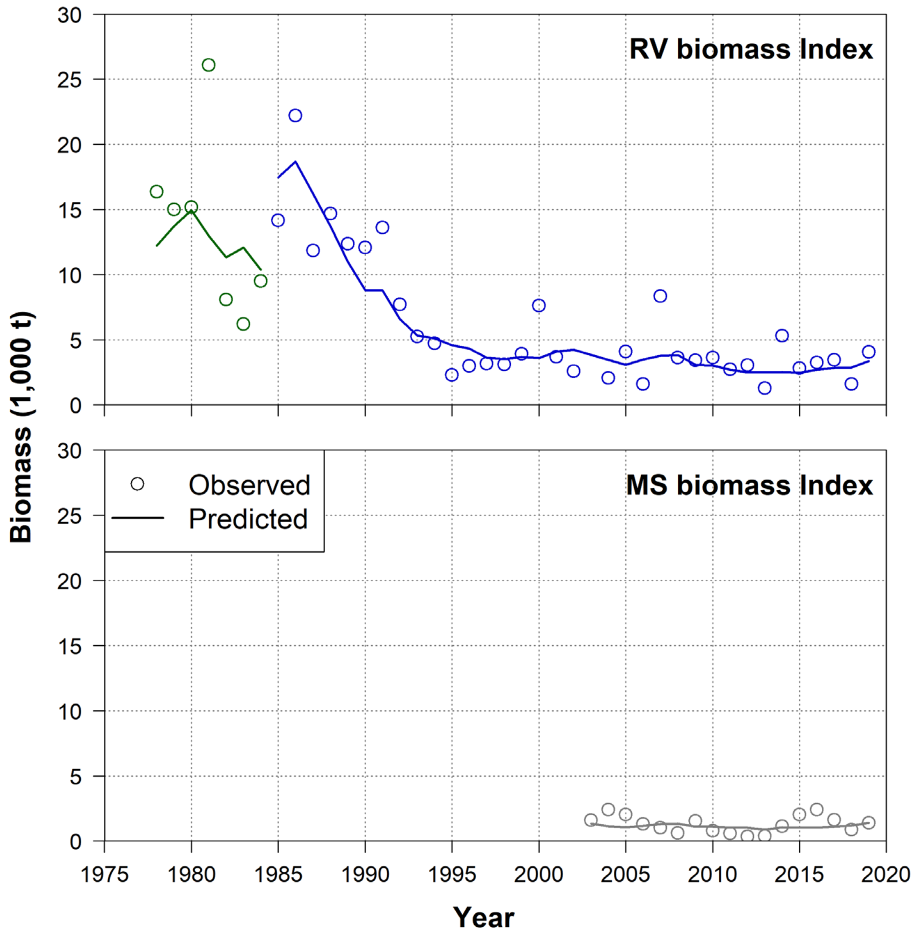

Figure 22. Fit of the predicted biomass indices (line) to those observed (circles) for the southern Gulf of St. Lawrence Research Vessel (RV) survey (upper panel) and Mobile Sentinel (MS) survey (lower panel). The RV indices have been adjusted for the difference in catchability between the 1978-1984 (green) and 1985-2019 (blue) periods.

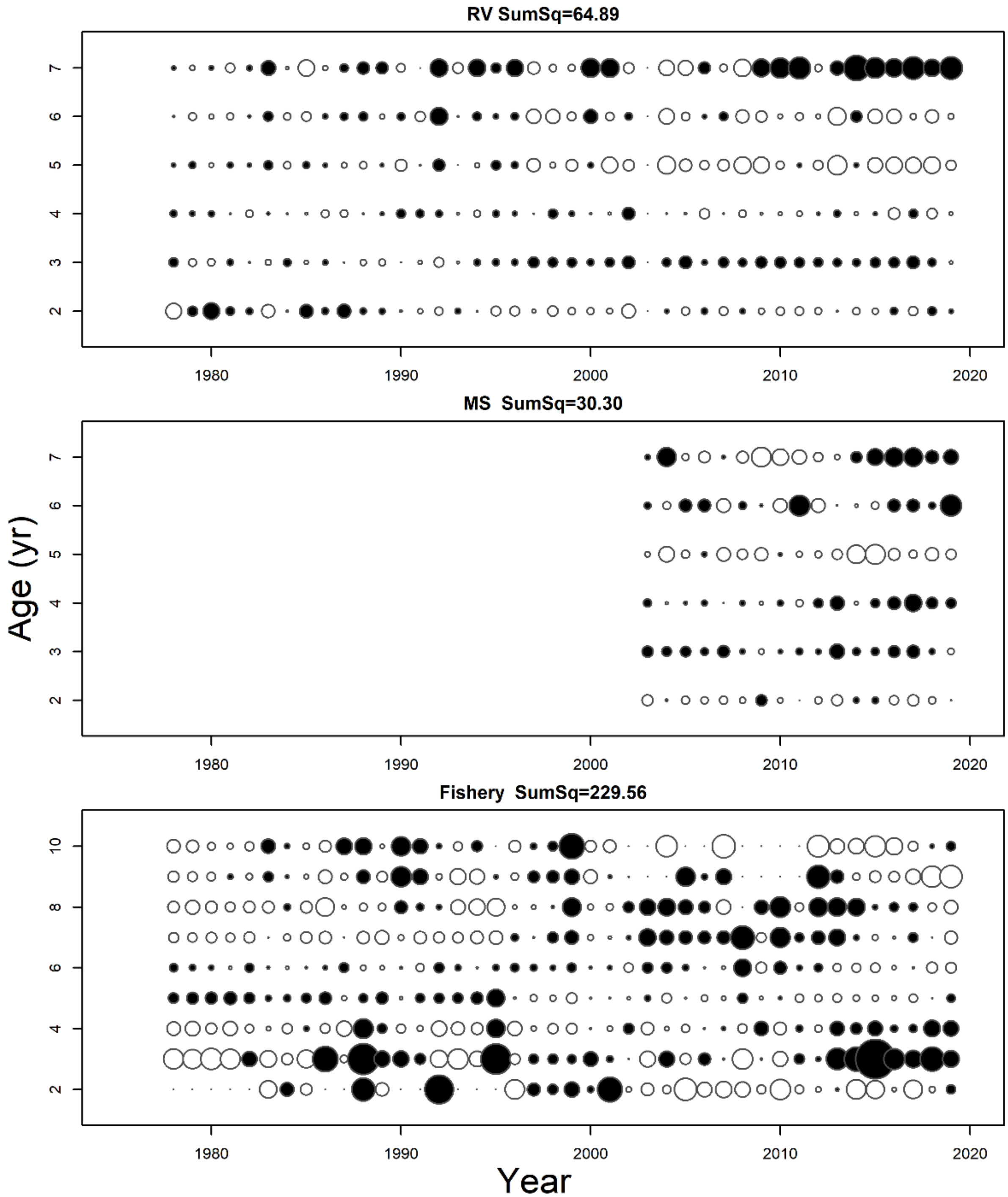

Figure 23. Residuals between observed and predicted proportion-at-age for the southern Gulf of St. Lawrence Research Vessel (RV) survey (upper panel), the Mobile Sentinel (MS) survey (middle panel), and the fishery catch (bottom panel). Circle size is proportional to the magnitude of the residual. Black circles indicate negative residuals (observed < predicted).

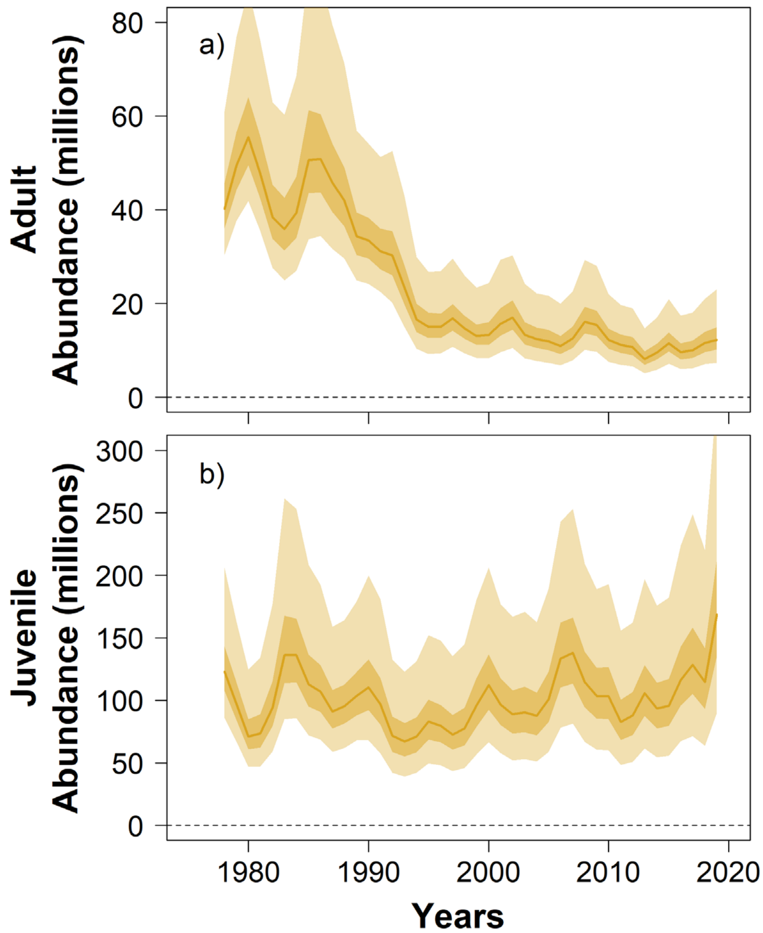

Figure 24. Estimated abundance of adult (a) and juvenile (b) White Hake in the SGSL. Lines are the median estimates of abundance, the heavy shading is the middle 50% of estimates and the light shading shows the 95% confidence limits.

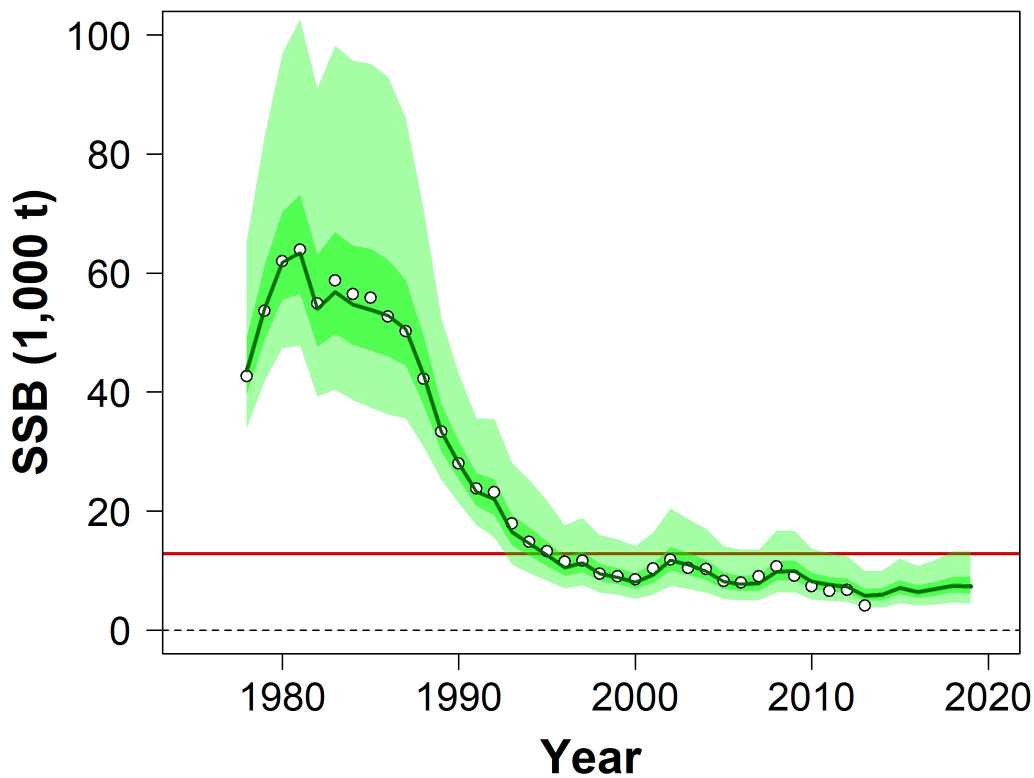

Figure 25. Estimated SSB of White Hake in the sGSL. The line is the median estimate of SSB, the heavy shading is the middle 50% of estimates and the light shading is the 95% confidence limits. The circles show the median estimates of SSB obtained by the 2015 RPA model. The red horizontal line is the LRP of 12,800 t.

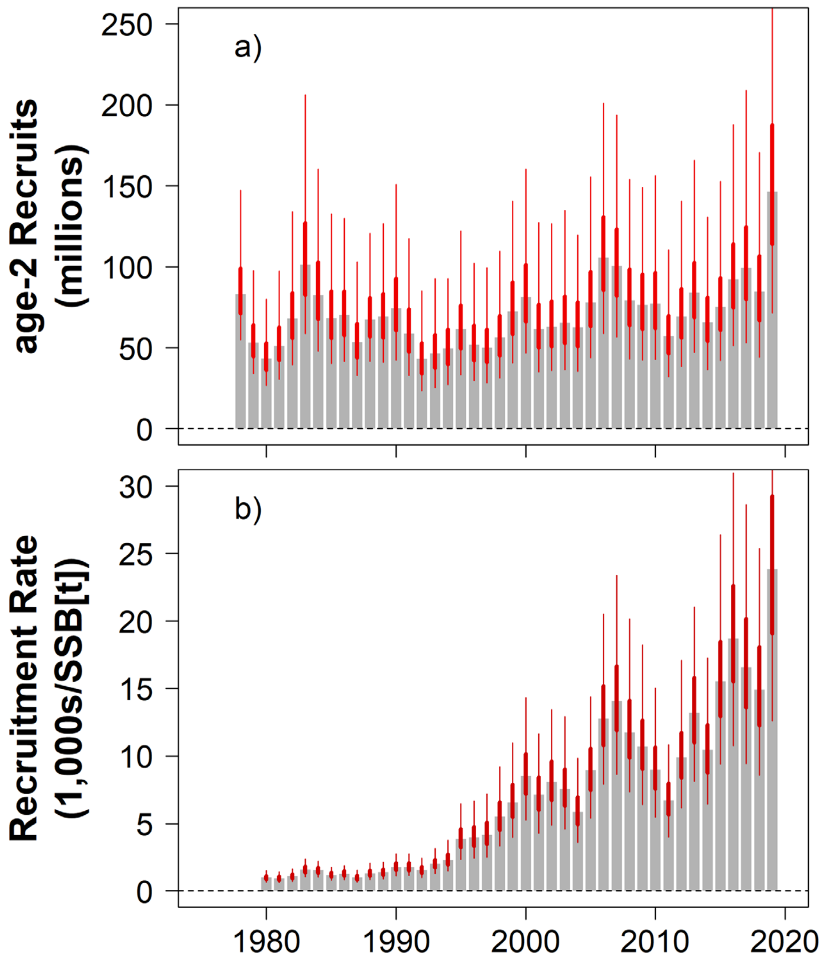

Figure 26. Age-2 recruit abundance (a) and recruitment rate (b) of White Hake in the sGSL. Grey bars show the median estimates, thick red lines show the middle 50% of estimates and thin red lines show the 95% confidence limits.

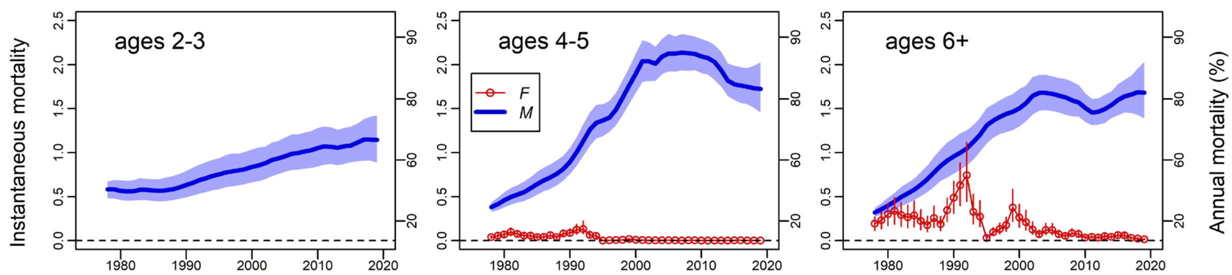

Figure 27. Estimated instantaneous rates of fishing and natural mortality (F and M, respectively) by age group (ages 2-3, ages 4-5, ages 6+). The values shown for F are abundance-weighted averages for each age length group (1978:2006). Blue lines and red circles show the median estimates. Shading and vertical lines show their 95% confidence intervals based on MCMC sampling. The right-hand axis shows the corresponding annual mortality. Average Fs for ages 2 and 3 are not shown since they were negligible (< 0.001 in all years, < 0.00005 since 2000).

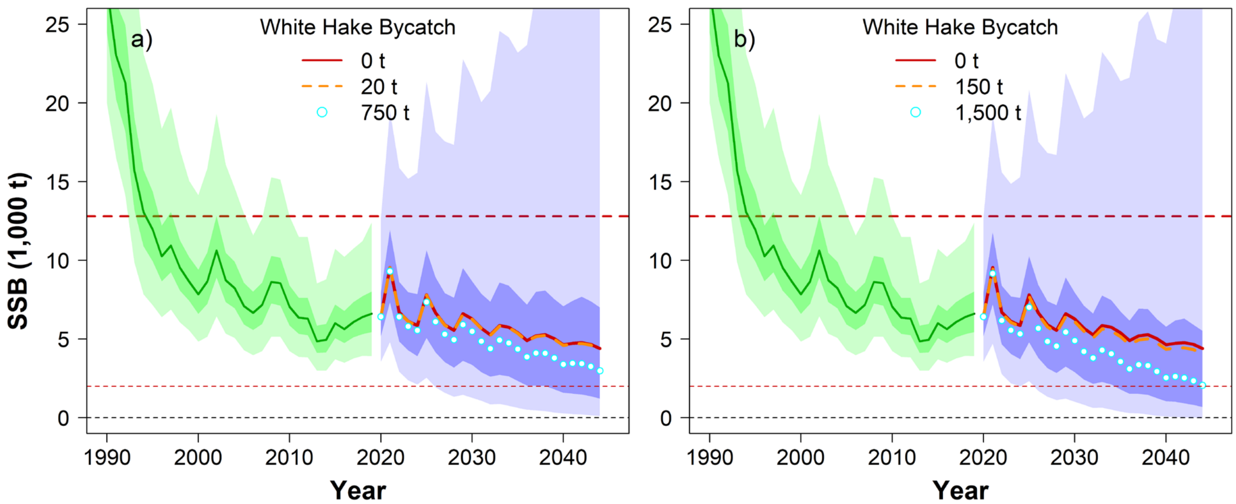

Figure 28. Estimated historical (green) and projected (other colours) SSB of sGSL White Hake at different levels of projected bycatch (0, 20, 150, 750 and 1,500 t). Lines and circles are the median estimate. Shading indicates the 50% (dark) and 95% (light) confidence intervals. These intervals are shown for the historical estimates and the projections at the highest bycatch levels in each panel. For the projections recruitment rates are sampled from the 2000-2019 period. The horizontal dashed lines represent the LRP of 12,800 t and the level of 2,000 t which represents the limit of a very high risk of local extinction.

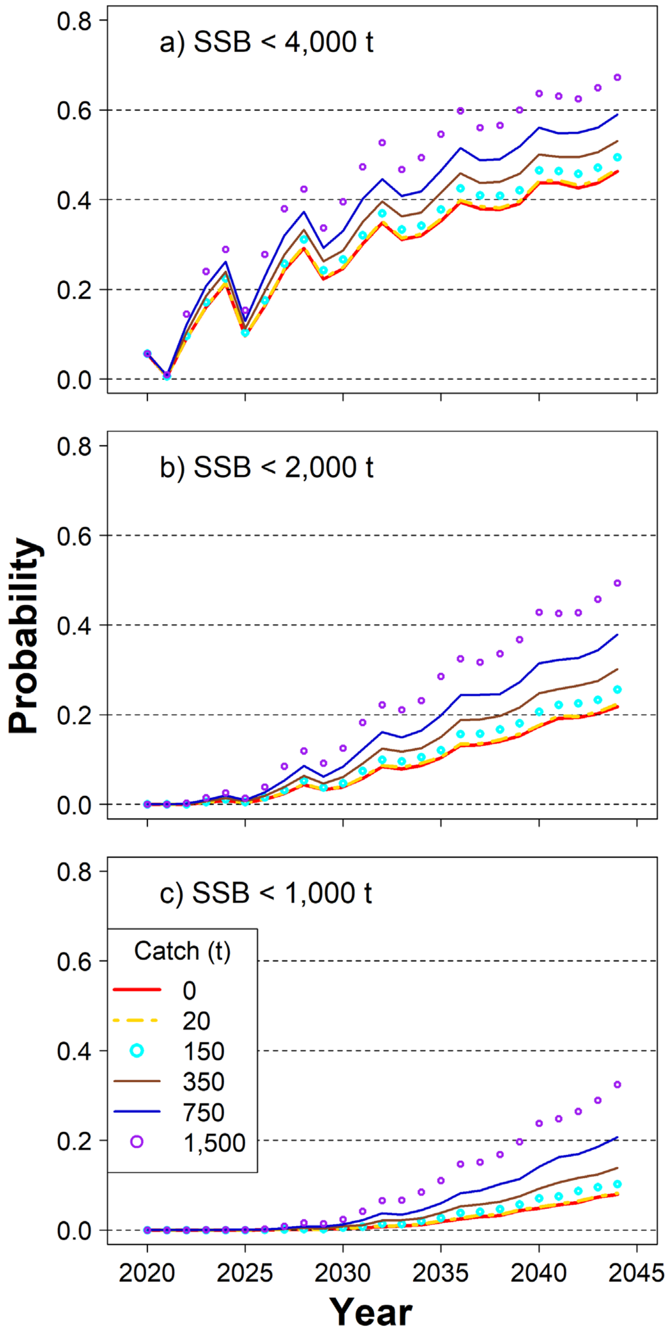

Figure 29. Probability that projected SSB is below 1,000, 2,000 or 4,000 t at different levels of White Hake bycatch (0, 20, 150, 350, 750, and 1,500 t).

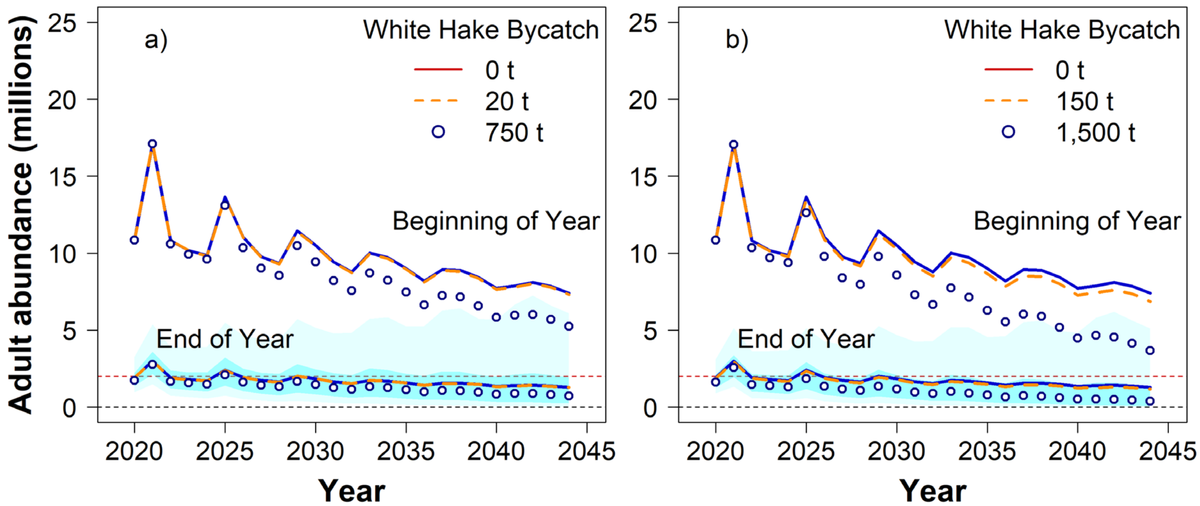

Figure 30. Projected adult abundance of sGSL White Hake at different levels of bycatch (a: 20 t and 750 t, b: 150 t and 1,500 t). Median estimates are shown for both the beginning of the year (upper lines and circles) and the end of the year before recruitment (bottom lines and circles). Shading shows the 50% (dark shading) and 90% (light shading) confidence intervals for the highest bycatch levels (circles) at the end of year.

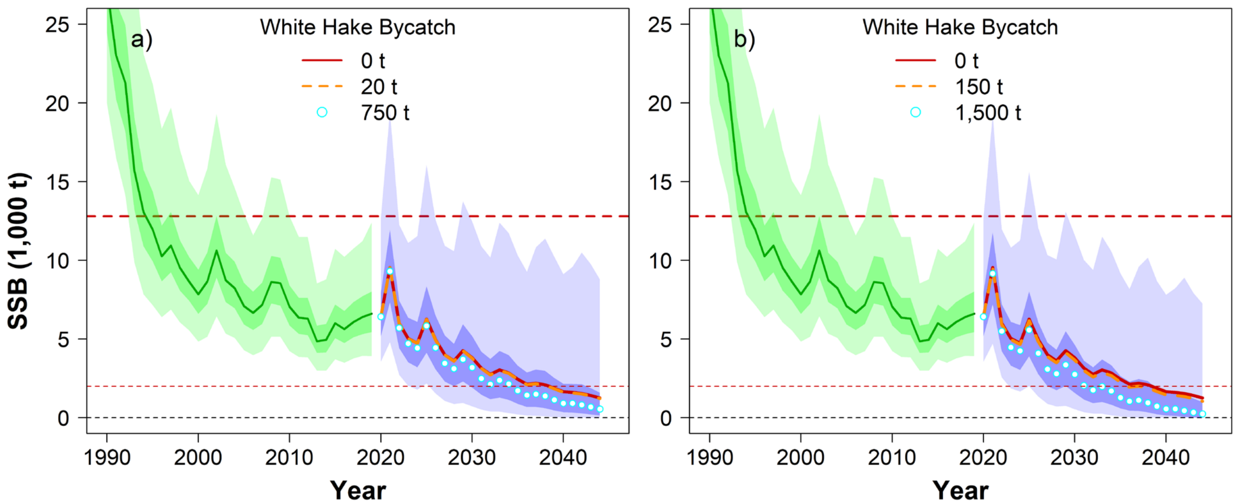

Figure 31. Estimated historical (green) and projected (other colours) SSB of sGSL White Hake at different levels of projected bycatch in the fishery for redfish. Lines and circles are the median estimate. Shading indicates the 50% (dark) and 95% (light) confidence intervals. These intervals are shown for the historical estimates and the projections at the highest bycatch levels in each panel. For the projections recruitment rates are sampled from the 2000-2010 period.

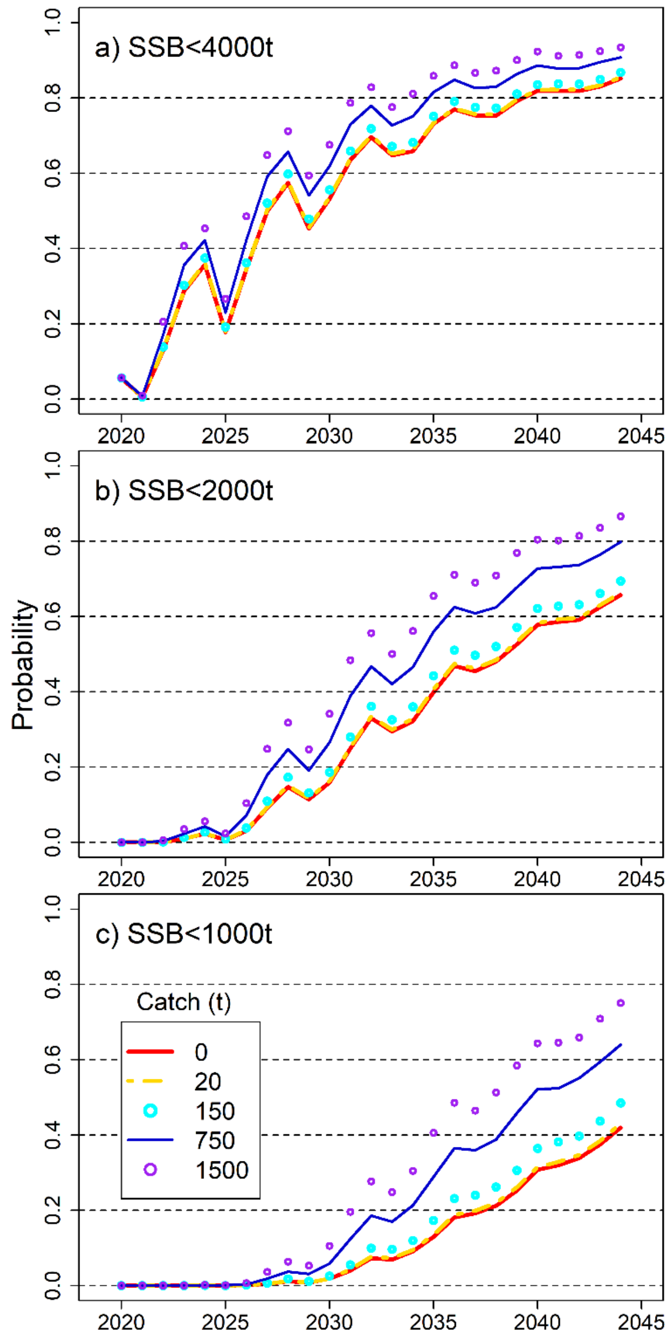

Figure 32. Probability that projected SSB is below 1,000, 2,000 or 4,000 t at different levels of White Hake bycatch. For these projections recruitment rates are sampled from the 2000-2010 period.

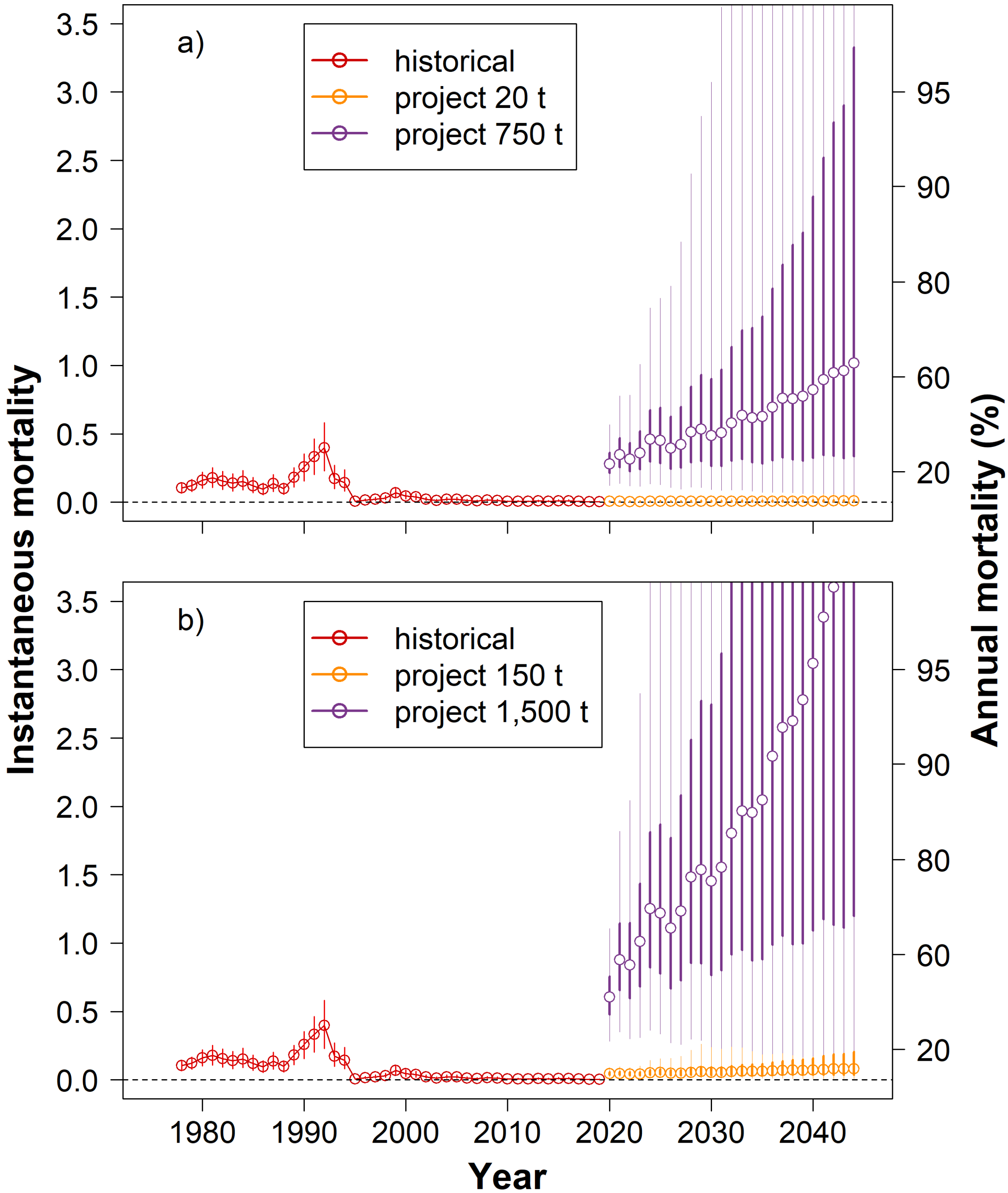

Figure 33. Projected fishing mortality rates during projections at different catch levels. Fishing mortality is shown for age 5 years. Circles show the median estimates. Heavy and light vertical lines show the 50% and 95% confidence intervals.

APPENDIX A. STRATA

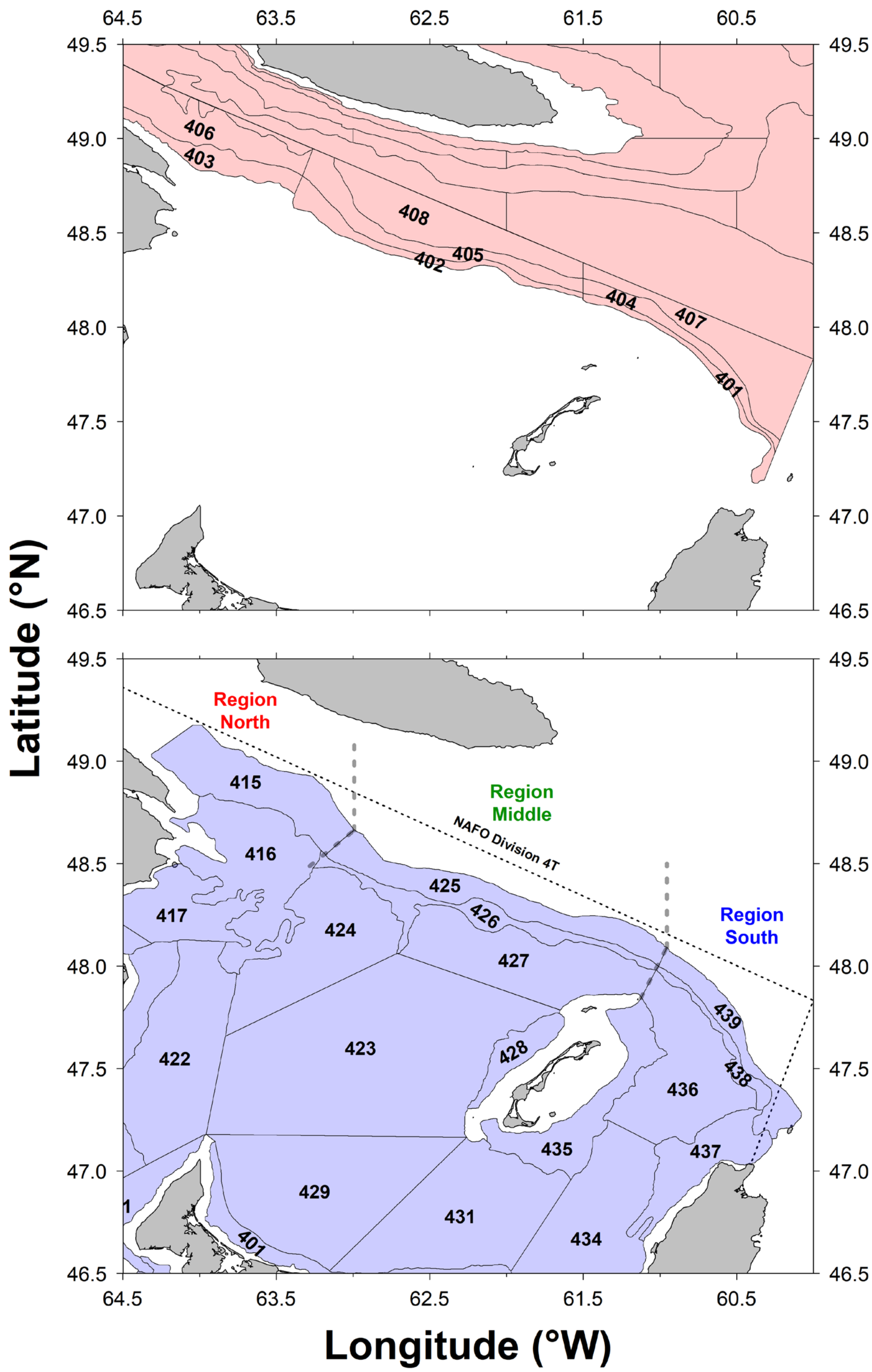

Figure A1. Zoomed in of overlapping strata from the northern (upper panel red) and southern (bottom panel blue) Gulf of St. Lawrence Research Vessel trawl surveys.

APPENDIX B. BYCATCH BY GEAR TYPE AND REGIONS

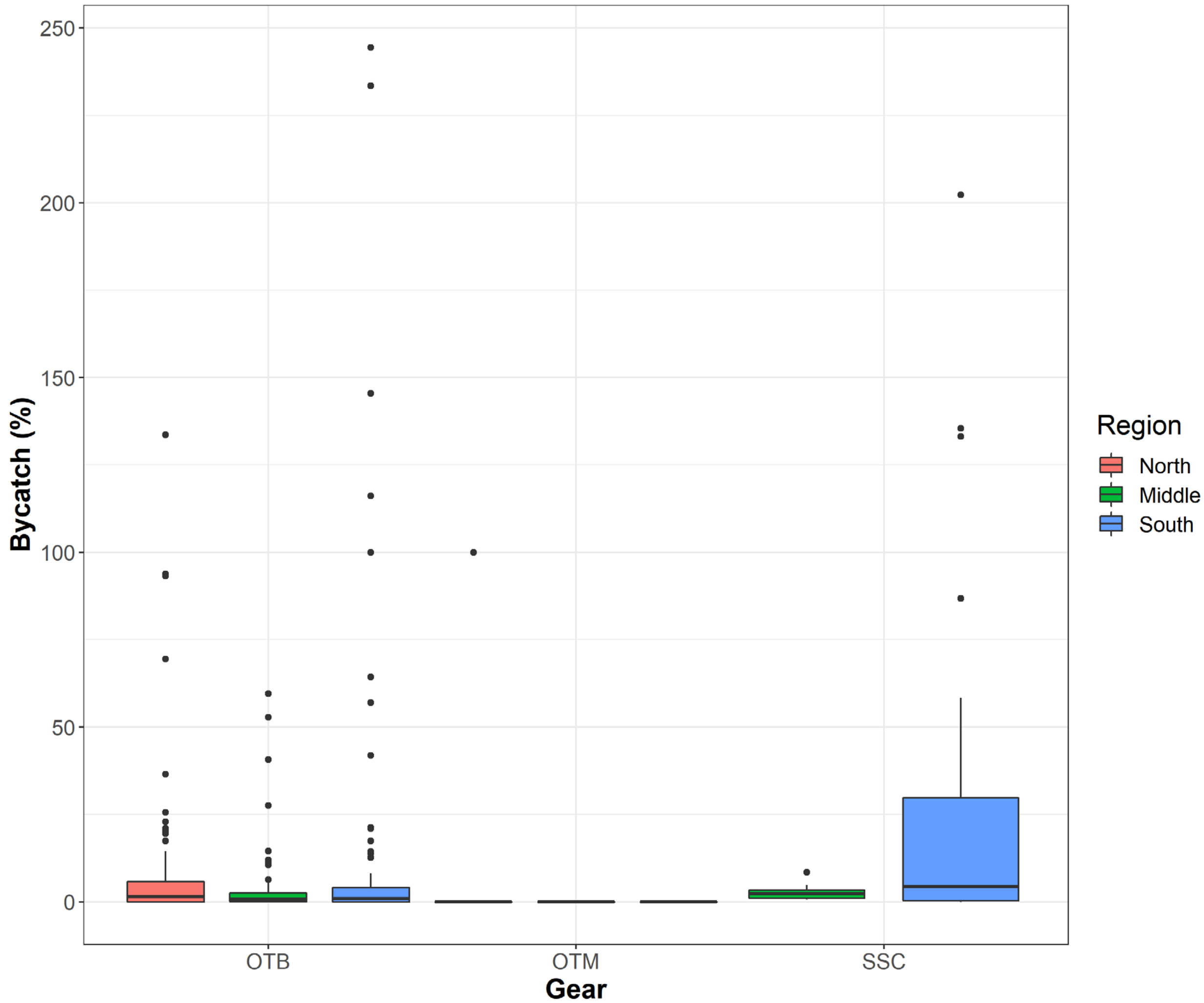

Figure B1. Box plots of bycatch (%) of White Hake by gear type (OTB = Bottom Trawl, OTM = Mid-water trawl and SSC = Scottish seine) and regions.

Table B1: Model selections and there respective AIC

Model type	Parameters	AIC	ΔAIC
Negative-binomial	*White hake bycatch ~ Depth + Region + Gear*	1422.8	2
	White hake bycatch ~ Depth + Region	**1420.8**	**0**
Zero inflated negative binomial	*White hake bycatch ~ Depth + Region + Gear | 1*	1424.8	4
	White hake bycatch ~ Depth + Region | 1	1422.8	2