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Review of the Assessment Framework for Atlantic Cod in NAFO 3Pn4RS: Treatment of Catch and Individual Weights, and Other Assessment Model Considerations

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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

In 2021, Fisheries and Oceans Canada's Science Branch in the Quebec region initiated a review of the assessment framework for the stock of Atlantic Cod (*Gadus morhua*) in the northern Gulf of St. Lawrence (nGSL; NAFO Subdivision 3Pn and Divisions 4RS). The review was divided into two parts. The first part, which took place in the spring of 2021, reviewed key inputs to the stock assessment. The second part, which took place in May 2022, reviewed proposed analytical models for the nGSL cod stock and additional inputs to those models. This document presents some model inputs which were not reviewed in 2021, and the results of analyses that motivated some important considerations incorporated into the assessment model. First, we review modifications made to the fishery catch-at-age series and proposals for the definition and use of catch bounds in censored catch modelling incorporated into the revised assessment model. Second, we review and revise annual values for the beginning-of-year stock weights also used in the assessment model. Third, we review approaches incorporated into the assessment model to address changes in survey coverage which occurred in the past in two fishery-independent surveys. Fourth, we present evidence that particular calibration factors used to account for a change in vessel and gear in the research vessel survey series may be inadequate for young cod. This evidence motivated explicit estimation of relative catchability in the assessment model for these ages. Fifth, we present evidence for somewhat different trends displayed by groups of abundance indices included in the assessment model, and briefly discuss the possible causes and how these differences could be accounted for in assessment modelling. Finally, we briefly discuss published research findings which had not previously been incorporated into the assessment, but provide useful support in the modelling.

INTRODUCTION

In 2021, Fisheries and Oceans Canada's (DFO) Science Branch in the Quebec region initiated a review of the assessment framework for the stock of Atlantic Cod (*Gadus morhua*) in the northern Gulf of St. Lawrence (nGSL; Northwest Atlantic Fisheries Organization [NAFO] Subdivision 3Pn and Divisions 4RS). The review was divided into two parts. The first part, which took place in the spring of 2021, reviewed key inputs to the stock assessment. Specifically, the meeting reviewed the estimation and compilation of the fishery catch-at-age (Ouellette-Plante et al. 2022a), estimated removals, including retained, discarded and undeclared catch, in directed and non-directed commercial fisheries and removals in the recreational fishery (Benoît et al. 2021; Ouellette-Plante et al. 2022b), and abundance indices estimated from fishery-independent surveys (Benoît et al. 2022). The second part of the review took place from May 24–26, 2022, and reviewed proposed analytical models for the nGSL cod stock and elements relevant to their use in providing relevant and reliable science advice for stock management. Specifically, the terms of reference for the second part of the review aimed to:

- Evaluate potential assessment models to determine whether they provide a sufficient framework for providing scientific advice on the impact of exploitation on 3Pn,4RS cod, in particular estimating the stock size (biomass and abundance), recruitment, fishing mortality, and, potentially, natural mortality in the population.
- Provide direction on projection methods for future catch options.
- Provide direction for an approach to estimating reference points for this stock.
- Discuss whether the assessment methodology has the potential to support quantitative evaluation of harvest control rules.
- Identify uncertainties and knowledge gaps.
- Identify priority short and medium-term research recommendations to improve data sources, assessment model formulation and estimation, and projection methods.

Although many inputs to the stock assessment were reviewed in 2021, other inputs still required some elaboration and subsequent review. This document addresses these inputs.

First, there is some uncertainty regarding the amount of cod removed by commercial fisheries in the nGSL (particularly since the early 2000s) and in the recreational fishery, which is not subject to any formal or regular monitoring. One approach to addressing this type of uncertainty is the use of a censored likelihood function in the assessment model, whereby annual catch is estimated based in part on pre-specified lower and upper bounds (Cadigan 2016a, 2016b; Van Beveren et al. 2017). Although information to support the definition of catch bounds for subsequent modelling was reviewed and discussed in 2021 (Benoît et al. 2021; Ouellette-Plante et al. 2022b), specific values that incorporate different sources of removals were not proposed. Furthermore, the incorporation of discard amounts estimated from at-sea observer data into the assessment was not specifically addressed. Consequently, we begin by suggesting improvements to the fishery catch-at-age series, as well as potential catch bounds for the assessment of nGSL cod. Second, we review the annual values of beginning-of-year stock weights, which are a key input to the assessment and are used in the calculation of spawning stock biomass (SSB). Maturity ogives are another input used in estimating SSB. We evaluated whether the values and approach previously used in the assessment could be improved, and concluded that they could not. Therefore, we do not propose any revisions. Third, we review the approaches incorporated into the assessment model to address changes in survey coverage which were introduced in 1990 in the DFO multispecies bottom-trawl research vessel (RV) survey and in 2003 in the Sentinel bottom-trawl survey (discussed in Benoît et al. 2022). Fourth, we present evidence that RV survey calibrations derived for young cod, ages 2 and 3, which were based on comparative fishing and applied to maintain a constant catchability between the periods of 1984–1989 and 1990–present (Benoît et al. 2022), may be inadequate. This evidence motivated an explicit estimation of relative catchability in the assessment model for these ages. Fifth, we present evidence for somewhat different trends displayed by groups of abundance indices included in the assessment model, and briefly discuss the possible causes and how these differences might be accounted for in the assessment modelling. Finally, we briefly discuss previous published research findings which had not previously been incorporated into the assessment, but provide useful support in the modelling.

CATCH-AT-AGE AND CATCH UNCERTAINTY

Annual fishery catches-at-age for nGSL cod are available beginning in 1974 (Ouellette-Plante et al. 2022a), and currently reflect only catches associated with declared landings for ages three and above (Brassard et al. 2020). The development of a new assessment model for the stock has motivated some revisions to the catches-at-age and how they are used in the model. Justification for these are provided in this section.

INCLUSION OF AGE 2 COD

The assessment for nGSL cod has been based on ages 3 and above since the early 1990s. The last assessment to report fishery catch numbers and individual weights for age 2 was that of Fréchet and Schwab (1992). With the exception of 1983, for which an estimated 116,000 two-year-old cods were caught, 12,000 or fewer were estimated to be caught annually between 1974 and 1991. These amounts are small in absolute terms and negligible with respect to total catches, which were on the order of tens of millions of individuals. A recent revision of fishery catches-at-age since 1993 by Ouellette-Plante et al. (2022a) estimated that catches at age 2 constitute a non-negligible portion of total fishery catches in some years, notably during the first moratorium on fishing in the mid-1990s (Figure 1). Including catches of two-year-old cod in the assessment thus appears relevant. This would also be consistent with the assessments of neighbouring cod stocks in NAFO Divisions 4TVn, 3Ps, and in 2J3KL (Cadigan 2016a; DFO 2021; Swain et al. 2019). Catches of cod aged less than two years in both fisheries and surveys are too small and too variable to contribute meaningfully to the assessments and are therefore not included. For instance, Ouellette-Plante et al. (2022a) report a single one-year-old cod sampled in commercial catches between 1993 and 2020.

TREATMENT OF CATCH IN THE ASSESSMENT MODEL

Fishery catch statistics for cod in NAFO Division 3Ps and for northern cod (NAFO Divisions 2J3KL) are considered unreliable as a result of inadequate catch monitoring (Cadigan et al. 2016a, 2016b; Varkey et al., 2022). The assessments for these stocks treat fishery catch as a censored quantity within an interval which includes the reported catch in some years, or for which reported catch is used as a lower bound, thereby reflecting assumed underreporting (Cadigan 2016b; DFO 2021). The width and location of the catch bounds are assumed based on available evidence and vary across years. On some years, the width of the interval can be considerable, such as an assumed three-fold difference between lower and upper bounds in 1988–1993 for the 3Ps cod assessment (DFO 2021). Total catch is estimated in the assessment model using a censored likelihood approach (details in Cadigan 2016b). Compared to traditional statistical catch-at-age models, which assume that fishery catch is estimated with some variability such that catch over- and underreporting are equally likely, the censored approach can explicitly model catch underreporting, which is often expected to be more likely.

While the censored fishery catch approach can provide modelling which is better aligned with knowledge of the reliability of catch statistics, its implementation in assessment models involves some challenges. First, model output can be quite sensitive to the specified catch bounds (Van Beveren et al. 2017). Second, optimization of the model likelihood when fitting to data can be very sensitive to both the rigidity of the bounds, which is controlled by an assumed model parameter, and to estimated catch values that fall outside of the bounds (Cadigan 2016b). Third, the approach may hinder the estimation of temporal variation in natural mortality, unless additional sources of information are included in the model estimation, such as the results of tagging studies. Given that temporal variation in natural mortality appears to be an important driver of population dynamics in numerous cod stocks in the northwest Atlantic (e.g., Cadigan 2016b; DFO 2021; Rossi et al. 2019; Swain et al. 2019), estimating it for nGSL is a priority. Fourth, it is unclear how to simulate catch bounds, which hinders simulation testing of assessment models involving a censored catch likelihood. In light of these considerations, it appears relevant to evaluate the potential benefits of the censored catch approach before employing it in the assessment model for a given stock.

Information on the reliability of fishery catch statistics was collected as part of the assessment framework review for nGSL cod, based on results from a structured questionnaire provided to current and past harvesters, an estimation of commercial fishery discards using at-sea observer data and estimation of recreational fishery catches using numerous sources of information (Benoît et al. 2021; Ouellette-Plante et al. 2022b). In this section, we provide a summary and synthesis of these results with the aim of quantifying the reliability of catch statistics for the stock and motivating how catch data are treated in the new assessment model.

The recent questionnaire to harvesters aimed to evaluate the contribution of four factors that can affect the quality of catch statistics, including catch underreporting: inadequate monitoring of landings, undeclared personal use of cod by harvesters, discards of cod in fisheries directed at cod and at other species, and landings from the recreational fishery. These factors are discussed separately below based on all available information, with the exception of undeclared personal use which was reported to be trivial in Benoît et al. (2021).

Landings monitoring

A formal landings monitoring program was introduced in this fishery and others in the Gulf of St. Lawrence (e.g., redfish [*Sebastes* spp.], northern shrimp [*Pandalus borealis*]) in 1990 (Benoît and Allard 2009). The majority of commercial fishing trips in the nGSL are monitored under a dockside monitoring program involving third-party weighing of all fishery catches made by arriving vessels. This constitutes one the most rigorous types of landings monitoring available in Canadian fisheries. Complete dockside monitoring of all fishing trips is not available at some wharves. Harvesters landing at these wharves are obligated to report their catches by telephone upon arrival and there is some auditing of fishing trips by independent dockside monitors. The quality of the monitoring of declared landings since 1990 is thus considered high for this fishery (Benoît et al. 2021). Based on results of the questionnaire, there was no reason prior to the recent modelling to suspect important levels of underreporting since 1990.

There was no formal monitoring program for landings in the fishery prior to 1990. Landings were tabulated based on purchase slips. In their responses to the questionnaire, harvesters indicated always having a market for their catch during the 1970s and 1980s (Benoît et al. 2021). This, combined with the fact that domestic landings were below the available total allowable catch during the 1980s (Brassard et al. 2020), suggests few fishery-related incentives to underreport catches or to discard cod (discussed below), although underreporting aimed at reducing declared revenue may have occurred. Importantly, for nGSL cod in 1986–1988, fishing mortality rate estimates derived independently from tagging studies and the stock assessment based on official landings statistics, were found to correspond very well by Myers et al. (1996). This indicates that any catch misreporting at that time was likely not significant.

Discards – general

Based on responses to the questionnaire, discards of cod in the directed fishery were believed to represent values corresponding to less than 1% of landings for all years since the 1960s, while discards of cod in other fisheries were believed to represent a median of about 6% of cod landings annually prior to 1977, 10% between 1977 and 1993, and 3% since then (Benoît et al. 2021). Estimates of total cod discards in the principal groundfish fisheries and the shrimp fishery using at-sea observer data from Ouellette-Plante et al. (2022b), expressed as a percentage of cod landings in weight, correspond generally with the results of the questionnaire. Values from 1987 to 1993 ranged from 1.9–16.6%, averaging 6.1%, while values since 1994, excluding a spike in 1995, ranged from 0.4–5.5%, averaging 1.8% (Figure 2). The availability of markets for different sizes of cod was commonly cited by questionnaire respondents as the reason for the relatively low levels of discarding prior to 1993. Since 1993, discarding of cod has not been authorized, and the amounts reported by respondents, who probably had groundfish fisheries in mind, were said to reflect discarding of spoiled fishery catches. Although a small number of respondents reported second-hand anecdotes of large discarding events occurring prior to 1993, we could not find data or documentation to quantify or substantiate these claims. The results of Myers et al. (1996) mentioned above suggest that such large events were either infrequent and therefore not particularly consequential relative to declared landings, or occurred in years not covered by that study.

The absence of an enforced discard ban prior to 1993 should have provided little incentive for harvesters to avoid discarding when an at-sea observer was present on board a vessel engaged in commercial fishing. To the extent that the discard estimation process used by Ouellette-Plante et al. (2022b) was correct with respect to estimating fishery-scale total discards, those estimates should be representative of discarding in the fisheries. The correspondence with questionnaire results suggests this could be the case.

Overall, we conclude that discard amounts on the order of those estimated from the questionnaire and at-sea observer data are small relative to recorded landings, perhaps with the exception of 1991, and of 1995; the latter occurring when landings were very small due to the moratorium (Figures 2 and 3). There appears to be limited benefits to treating cod fishery catches as censored to accommodate such low levels of discard-related removals. Instead, we propose to simply add the estimated discards to the landings. Length-frequencies for discards from groundfish fisheries presented in Ouellette-Plante et al. (2022b) suggest an age-composition of discards comparable to that of the directed fishery, which we assume for the modelling. However, the age-composition of discards in the shrimp fishery is clearly different and this is discussed below. There are no discard estimates for years prior to 1987, the first year for which data were available to us, although some trips with at-sea observers did occur anteriorly (personal communication, A. Sinclair, retired DFO scientist). Based on mean discard percentages estimated using the questionnaire and the observer data, an assumed value of 6% of the reported landings might be reasonable. Sensitivity to this assumption can be evaluated as part of the modelling, although values of this magnitude are not expected to be consequential. Furthermore, given that the assessment model includes an estimation of trends in natural mortality (M), any misspecifications in catch amounts should be subsumed in estimates of M. This is the case, for example, in models for the neighbouring NAFO Divisions 4TVn cod stock, which does not use a censored likelihood approach for fishery catches. In that assessment, the apparent magnitude of M reflecting unaccounted catch is small compared to that due to other causes like predation, and is restricted to the mid-1980s to mid-1990s, where misattribution of mortality to natural mortality versus fishing mortality is of limited consequence for the contemporary assessment of the stock (Neuenhoff et al. 2019; Swain et al. 2019).

Discards – shrimp-directed fishery

Discards of cod in the shrimp fishery warrant separate treatment because this fishery has selected for younger cod, particularly since 1993, when the Nordmore grate was introduced, allowing for the escape of larger fish (Savard et al. 2013). Estimated annual length frequencies of cod discarded in the shrimp fishery available since 1990 and presented in Ouellette-Plante et al. (2022b) were combined with research survey age-length keys to estimate the annual age composition of cod discards, given the scarcity of ageing data for these smaller sizes in the commercial fishery data. The average estimated age composition for 1990–1992 was applied to estimated discards in the 1987–1989 shrimp fishery. The resulting age-specific estimates show that prior to the introduction of the Nordmore grate, cod discarded in the shrimp fishery were predominately aged less than five years (Figure 4). Since then, thee discards have principally comprised cod two years or younger (based on the size composition in Ouellette-Plante et al. 2022b), although some capture of three-year-old cod is estimated (Figure 5).

Discards in the shrimp fishery have constituted an important component of estimated total fishery catches in all years for age 2 cod, although the average total catch numbers are relatively small (Figure 4). In most years, fewer than 75,000 individuals are estimated to be discarded in the shrimp fishery. Relative to minimum trawlable abundances estimated from the annual August research vessel survey (Benoît et al. 2022), these age 2 removals represent an average age-specific relative exploitation rate of less than 0.5% in most years, and no more than 1.5% annually (Figure 6). Shrimp fishery discards of three- and four-year-old cod also constituted an important component of total catch for these ages prior to 1993 (Figure 4). However, as with the two-year-olds, these catches represented a small relative age-specific relative exploitation rate (Figure 6). Furthermore, for all three age groups, these estimated relative age-specific exploitation rates very likely overestimate true exploitation rates given that cod of these ages are not fully recruited to the survey, and their survey abundance is therefore smaller than true abundance. Given the very small exploitation rates, especially in the most recent years, inclusion of shrimp discards is likely to be inconsequential to the assessment. Nonetheless, we added the age-specific estimates to those for landings and other catches for the sake of completeness and because mortality caused by bycatch in the shrimp fishery is often raised as a concern during cod assessments by participants who are otherwise unaware of the low impact of this component.

In the absence of estimates, assumptions are required for age-specific cod discards in the shrimp fishery for years prior to 1987. Assuming that the capture of cod in the shrimp fishery is truly incidental at the scale of the distribution of nGSL cod, the bycatch harvest rate of cod in that fishery should be proportional to shrimp fishing effort (Paloheimo and Dickie 1964). This appears to be the case for ages 3 and 4 cod for years prior to the introduction of the Nordmore grate, when catches of cod were larger (Figure 7). There appears to be no relationship between exploitation rate and shrimp fishing effort when estimated exploitation rates are small (generally < 0.5%) for all three ages, suggesting that catches in these cases may simply be sporadic. Fishing effort was generally increasing up to the early 1990s as the shrimp fishery developed in the nGSL (Figure 8). Observed fishing effort for 1982–1986 was lower than that for 1990, which was associated with low relative exploitation rates of values around or below 0.5% for all three ages considered (Figure 7). Consistent with a developing fishery, annual shrimp landings scaled with fishing effort (Figure 9). Using reduced major axis (RMA) regression, which assumes errors on both the predictor and responses variables, we estimated fishing effort for years back to 1974 from annual landings to illustrate how fishing effort may have varied in years prior to 1982, when values became available (Bourdages et al. 2020). Although speculative, this suggests that shrimp fishing effort in the mid-1970s may have been smaller than half of the values observed during the late 1980s (Figure 8).

In light of the results above, we used the following approach to approximate annual age-specific total fishery catches for cod ages 2–4 prior to 1987. First, we estimated annual age-specific relative exploitation rates for 1984–1986, using the average of the 1987–1990 values for two-year-old cod, for which there was no apparent relationship between exploitation rate and effort (value 0.201), and using a RMA of log exploitation rate on log effort for the years 1987–1992 for cod ages 3 and 4 (Figure 10). Then, we applied these estimated exploitation rates to the survey abundance estimates to obtain catch amounts for 1984–1986 (Figure 11). In the absence of survey information prior to 1984, we simply use the age-specific averages for these years as the estimate of annual catches for 1974–1983. The values obtained for ages 2 to 4 (in thousands of cod) are 30.6, 75.0 and 199.1, respectively. Given the likely lower values of shrimp fishing effort for those years, and provided that cod abundance for these ages was not much greater than that in the mid-1980s, these catch amounts would represent a maximum number of cod discarded by the shrimp fishery during that time.

Recreational fishery catch

There is no formal monitoring of catches in the recreational cod fishery in the nGSL. Ouellette-Plante et al. (2022b) derived total weight estimates of cod caught in the recreational fishery using five sources of information, including periodic national recreational fishing questionnaire-based surveys (questionnaires), two sets of questions from the recent questionnaire (Benoît et al. 2021) and estimates from the neighbouring northern cod stock. Although there was variability in the estimates derived from the different sources and also in the assumptions made, the authors found consistency in year-specific values since the mid-1990s. This consistency was noticeable in the values derived from different sources: national questionnaires, the northern cod assessment, nGSL specific estimates in 2001, 2002 and 2006 (but not from a poorly documented 2008 estimate), assumptions based on fishing capacity (capture potential) and based on one of the questions from the recent questionnaire (see Figure 14 in Ouellette-Plante et al. 2022b). Correspondence between the different sources of information was particularly good for the period of 1998 to 2005. For the period prior to the 1993 moratorium, questionnaire respondents evaluated recreational fishery catches to be very low, although these catches may not have been evident to them given the large amounts of cod landed from the commercial fishery. National recreational fishery questionnaire results for 1974, 1985 and 1990 ranged from around 700 to 1,200 tons annually, amounts that are considered small compared to fishery landings (< 3%).

Overall, best estimates of recreational fishery catches up to 2005 are relatively small compared to reported landings (Figure 3). This, combined with the consistency between different estimates for the 1998–2005 period, suggests that it may be reasonable to simply add the estimates to reported landings for population modelling. The specific values assumed are reported in Table 1. There is no information on the age or size composition of cod caught in the recreational fishery. Consequently, the annual age composition of recreational catch was assumed to be identical to that of the landings.

Unlike the period prior to 2006, catch estimates for subsequent years are somewhat more variable, and cover a broader range of potential removal values, including some almost as large as reported commercial fisheries landings. Given the range of possible values and the potential magnitude relative to landings, we treated recreational fishery catches for this period as censored values. Ouellette-Plante et al. (2022b) present upper and lower values of potential recreational fishery removals, based on available fishing opportunities and assumptions on the number of recreational fishery participants. The lower values in particular appear to constitute a reasonable lower bound for recreational fishery removals, based on the ensemble of estimates. Furthermore, they have the potential to track interannual variation in removals (Table 1). The sum of landings, estimated discards and recreational fishery catches were therefore treated as a lower catch bound for the model. Specifying an upper value was somewhat more difficult given differences between estimates, some of which produced large values (> 900 t in some years) felt to be highly improbable by participants at the April–May 2021 CSAS review (DFO 2022). Based on averages of different estimates, Ouellette-Plante et al. (2022b) proposed an upper bound on recreational fishery catches of 500 t annually for 2006–2013 and 600 t in subsequent years, which is used hereafter (Table 1).

Summary

The proposed fishery catch-at-age based on the foregoing considerations is summarized in Figure 12. It is clear that for the ages that dominate the catch (ages 5 to 8), the amounts we propose to add for discards and the recreational fishery constitute a small portion of total catch (generally < 10%), except in years since 2010 as a result of estimated recreational fishery catches. This supports our choice of treating catch as an uncensored but uncertain quantity in the assessment model for years prior to 2006. The more elevated and variable recreational fishery catch estimates since 2006 motivate the use of a censored likelihood approach for those years. In contrast, the additional sources of catch constitute a much larger fraction of total catch for cod ages 2 to 4 in at least some years (Figure 12). While these catches are relatively large on an age-specific basis, they are not at the age-aggregated level (e.g., Figure 3) where catch censoring is assumed and applied (Cadigan 2016b). Consequently, we added them on an age-specific basis, such that the age composition of catch, which is relevant to model fitting, more accurately reflects our best estimate of the true composition. However, we reiterate that the consequences of these assumptions are likely to be quite small given the small magnitude of these catches relative to likely abundance-at-age.

The results and proposals for the catch-at-age were derived assuming the revised model would treat the population as comprising individuals aged 2 to an age 13+ group. Subsequently, initial model results suggested high variability of catches at ages 12 and 13+ in both fisheries and surveys. Consequently, the catches at ages 11 to 13+ were grouped into an 11+ category. This involved summing the catches over these ages for the fishery and surveys catches at age, and recalculating fishery cod weights at age 11+. The resulting fishery catch-at-age is presented in Table 2 and the age-specific individual weights are presented in the next section, along with the beginning-of-year stock weights.

AGE-SPECIFIC WEIGHTS

BACKGROUND

There are two sets of year- and age-specific weights used as inputs to most age-based assessment models. The first are beginning-of-year weights, which are used to calculate stock biomass and SSB from the product of assessment estimates of age-specific abundance and weight-at-age, and then summed across ages. They are also used in spawner-per-recruit calculations, a measure of stock productivity that can be used to define reference points (Gabriel and Mace 1999; Gabriel et al. 1989; Morgan et al. 2014). Beginning-of-year weights are sometimes termed stock weights (SW), as they are intended to represent a biological characteristic of the stock. The second set of weights are annual age-specific mean weights in fishery catches (hereafter, catch weights, CW), which are used in the derivation of the fishery catch-at-age. CW are also used in statistical catch-at-age models to derive predicted CW from estimates of abundance at age and age-specific fishing mortality, which is then fitted to model input fishery catch weights. Catch weights are also used to derive some reference points for management, notably in yield-per-recruit analysis (i.e., F_{max} and $F_{0.1}$). Age-specific values of CW will often be greater than those of SW given fishery selectivity towards larger fish, especially at younger ages.

The estimation of SW for nGSL cod was done by first estimating summer weights using the annual length frequency data, age-length keys, and length-weight relationships from the August multispecies RV trawl surveys of 1985–2020 (individual weight values were not available for the 1984 survey). Summer weights were then converted to January 1st equivalents using the approach of Rivard (1982), which employs a geometric mean of weights in adjoining years for individual cohorts. Values of SW for ages 11+ were estimated assuming that cod of these ages were equally catchable by the survey.

Sampling variability, particularly in years when cod were less numerous in August RV survey catches, resulted in variability in SW that was not always consistent with cohort growth, i.e., values at subsequent ages that were equivalent or smaller. Errors in estimates of age-specific SW will contribute to uncertainty in estimates of biomass, and even more so to uncertainty in estimates of SSB, because of the fewer age classes that contribute to SSB compared to biomass. To reduce the potential impact of such errors, we modelled the SW as a function of age, year and cohort effects, using the mixed-effects approach proposed by Cadigan (2023). Although CW for nGSL are also quite variable (Ouellette-Plante et al. 2022a), these were not modelled further and were used directly as inputs in the assessment model to maintain consistency between how the fishery catch-at-age was derived and how catch biomasses are predicted in the assessment model.

While SW could be derived from the RV trawl surveys beginning in 1985, there were no fishery-independent values available for prior years. We could not identify the sources of SW values used previously in the assessment for many of those earlier years (see Brassard et al. 2020), and as we show below, the values assumed for some ages appear to be too large. We therefore derived new SW values for those earlier years using the relationship between SW and CW for the years in which both sets of values were available.

METHODS

The model proposed by Cadigan (2023) is:

$$\log(SW_{ay}) = \beta_a + \delta_y + \delta_c + \delta_{ay} + \varepsilon_{ay}$$

where β_a is the age effect, and δ_y, δ_c, δ_{ay} are random effects for year, cohort, and age-year interactions respectively, and ε_{ay} are sampling measurement errors. The δ_y are assumed to be multivariate normal (MVN) distributed with mean zero and first-order autoregressive, AR(1), covariance with correlation φ_Y and stationary variance σ_Y^2; note the *Y* subscript indicates a parameter for the year effect and does not indicate a specific year. Similarly, δ_c is assumed MVN with mean zero, AR(1) lag one correlation φ_C and stationary variance σ_C^2. The δ_{ay} are MVN with a separable covariance matrix *Σ* with elements:

$$Cov(\Sigma_{ay}, \Sigma_{a-i,y-j}) = \sigma_{AY}^2 \rho_A^{|i|} \rho_Y^{|j|}$$

The ε_{ay} are assumed to have independent normal distributions with mean zero and user-specified variances, $\sigma_{\varepsilon,ay}^2$. Ideally, these variances would be derived from the sampling variances obtained during the surveys. However, deriving these values empirically is somewhat complicated, as it involves accounting for errors occurring at a hierarchy of sampling levels (catch, length frequency, age and weight at length), which was not possible for this report. Similar to Cadigan (2023), we assume that the coefficient of variation in the distribution of length-at-age in the stock is 0.3. This implies that the standard deviation of log-length is approximately 0.3 for each age class in the population. If the slope of log-weight versus log-length is 3, then the standard deviation of log-weight is 0.9 for each age class in the stock, which is an approximation we assume. Hence, if there is no age measurement error and if fish are sampled randomly for age and weight from the survey catches then $\sigma_{\varepsilon,ay} \approx 0.9/n_{ay}$ where n_{ay} is the number of fish sampled in year *y* that were age *a*. Thus $\sigma_{\varepsilon,ay}$ was approximated using n_{ay}values for the survey.

While Cadigan (2023) assumed independent β_a parameters, we assume the age effects are monotonically increasing such that $\beta_{a+x} > \beta_a$ if $x > 0$, consistent with growth dynamics. We freely estimated an effect for age two, and used a monotone regression model for the other ages:

$$\beta_{a_i} = \begin{cases} \exp(\gamma_i), & i = 1, \\ \beta_{a_{i-1}} + \exp(\gamma_i) & i = 2, \ldots, 11. \end{cases}$$

The advantages of using the monotonic model over an assumed parametric growth model (e.g., Von Bertalanffy) to estimate SW (e.g., Cadigan 2016c) include that it can better accommodate SW in the plus group, which are unlikely to conform to a growth model if older cod are abundant, as well as impacts of size-specific mortality, which could cause weights-at-age to deviate from patterns expected from growth alone.

The model described above could have been used to predict SW values for years prior to 1985. However, there was some question as to whether the model would reliably predict decreases in SW that are believed to have occurred over the period from the mid-1960s to the mid-1980s based on changes observed in CW and differences in SW values derived from the summer surveys and those derived from information for years prior to 1967 available in Wiles and May (1968). Instead, we regressed SW values on CW values for the 1985–2020 period using major axis regression and used the estimated parameters to predict annual age-specific SW from CW for the period from 1974–1984.

RESULTS AND DISCUSSION

The age effects account for much of the variation in SW (Figure 13). Year and cohort effects were greater than the year-age interactions (Figure 14), with year effects ranging from -0.067 to 0.056, cohort effects ranging from -0.064 to 0.039 and the interactions ranging from -0.016 to 0.012. This is also indicated by the smaller estimate of σ_{AY} compared to σ_Y and σ_C (Table 3). Estimated correlation parameters were relatively large for each of these effects (Table 3), ranging from around 0.80 for the cohort effect (following inverse logit transformation of the parameter), to around 0.85 for the age and year effects in the interaction. This is why the predicted effects in Figures 13 and 14 vary smoothly.

The model fit the data reasonably well (Figures 15 and 16). Fits were better at ages more commonly sampled in the survey, generally ages 3 to 8. There were no obvious patterns in residuals, although the residual variation was somewhat greater at the youngest and oldest ages (Figures 17 and 18).

Age-specific SW values were correlated with CW values for ages 4 to 10, but not ages 2, 3 and 11+ (Figure 19). Major axis regression was used to model SW values as a function of CW values for the ages where the two were correlated. For ages 9 and 10, the three largest CW values resulted in outliers and were excluded when estimating the regression parameters. The fitted regression model is represented by a blue line in Figure 19. SW and CW values for 1986-1993 correspond with the general pattern for the 1986-2020 period, indicating that there is no reason to suspect a change in the relationship over time and confirming that it is reasonable to use the regression equations to predict SW from CW for years prior to 1985.

For ages 4 to 10, we predicted SW values from the CW values for 1984 and the years prior, using the regression parameters. For 11+ cod, we used the average ratio of SW to CW values for 1985–2020 to predict SW from CW for the prior years. SW values for ages 2 and 3 for years 1984 and prior were simply set at mean age-specific values for the series. The resulting values are presented in Figure 20, along with the formerly used SW values and the CW values derived by Ouellette-Plante et al. (2022a). Unsurprisingly, the former SW values fluctuated much more than the SW estimated using the model of Cadigan (2023). This high frequency variation is difficult to explain from a biological perspective and likely reflected sampling variability. As a result, the modelled SW values appear more appropriate. More surprisingly, the former SWs had values at ages 6 and above that were greater, sometimes much greater (> 75%), than the new proposed SW for the period prior to 1985. These former SW values approached and sometimes exceeded the CW values, which seems unreasonable given that CW are expected to reflect some positive size selectivity in the fishery, and importantly reflect values for mid-season (summer), whereas SW are meant to reflect beginning-of-year values. Because we could not locate documentation for the methods employed to derive these historical values and their justification, we adopted the new SW values for the subsequent modelling.

ADJUSTMENTS FOR CHANGES IN SURVEY COVERAGE AND CATCHABILITY

Multi species trawl surveys were conducted in the nGSL from 1984 to 1990 on the MV *Lady Hammond* using a WIIA trawl, from 1990 to 2005 using the CCGS *Alfred Needler* using a URI trawl and from 2004 to 2022 using the CCGS *Teleost* using a Campelen trawl. As part of their review of fishery-independent survey data relevant to nGSL cod, Benoît et al. (2022) analyzed data from a 1990 comparative fishing experiment to produce a length-dependent calibration function that allowed multispecies trawl survey data for 1984–1990 to be included in producing standardized abundance indices for cod. However, survey data from that earlier period did not include sampling in shallower strata sampled routinely as of 1990, and adjustments for this systematic change in survey coverage are required. There is a similar need for the Sentinel mobile bottom-trawl survey, which began in 1995 and to which a small number of shallow coastal strata were added in 2003. Benoît et al. (2022) provided suggestions to account for the change in coverage in both surveys, but no specific decisions were made. We therefore briefly review the information available to estimate age-dependent factors to account for the changes that occurred in the multispecies survey in 1990 and the Sentinel mobile gear survey in 2003 (Figures 21 and 22). These adjustments were estimated within the assessment model to ensure that the associated uncertainty was propagated to other model parameters that depend on fits to the survey data (details in Benoît et al. 2024[1]).

The length-dependent calibration function for the survey vessel and trawl used up to 1990 was estimated based on an experiment involving a modest number of paired sets. Catches of small

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[1] Benoît, H.P., Cadigan, N., Ouellette-Plante, J., and Brassard, C. In preparation. Review of the Assessment Framework for Atlantic Cod in NAFO 3Pn4RS: Population Modelling and Elements Relevant to a Renewed Precautionary Approach and Rebuilding Plan. DFO Can. Sci. Advis. Sec. Res. Doc.

cod in that experiment (lengths generally < 30 cm, corresponding to ages ≤ 3) were quite variable, resulting in uncertainty in the estimated calibration function at these lengths (Figure 23). We briefly review evidence from the multispecies survey abundance indices that suggest that the calibration factors are likely incorrect for cod ages 2 and 3. This motivated the estimation of catchability adjustment parameters in the assessment model for these two ages, to account for the change in vessel and gear that occurred in 1990.

CHANGES IN SURVEY COVERAGE

As in Benoît et al. (2022), the impact of the change in coverage in both the DFO and Sentinel surveys was evaluated by examining the values of age-specific log abundance values (mean numbers per tow) estimated using data from the reduced suite and the full suite of strata, for the years in which the full suite was sampled. We examined the relationship between the two sets of values using major axis regression and by simply calculating the average difference in log values at each age, which we termed delta values.

Values for age-specific abundance indices in the DFO survey tended to be greater for the full suite of strata relative to estimates based only on the original strata, as reported by Benoît et al. (2022; Figure 21, this document). This reflects the tendency for cod to occur more commonly at intermediate and shallow depths in the nGSL during the summer. For most ages, the major axis slope relating the two sets of indices was not significantly different from a value of one (Table 4). This suggests that interannual changes in cod abundance in the original strata, were generally proportional to those of the strata added in 1990, a conclusion that differs somewhat from the preliminary results reported in Benoît et al. (2022). In line with the results presented here, the average difference in log indices (delta values) provides parsimonious estimates of age-specific factors to correct for the change in survey coverage that occurred in 1990. Values for delta were estimated within the assessment model to allow for their associated uncertainty to be propagated to other estimated parameters in the model. We note that these adjustments are applied only when modelling survey data for 1984 to 1989. Therefore, the impact of possible misspecification is limited to a small portion of the assessment model series.

For the Sentinel mobile gear survey, log abundance index values were generally nearly identical between estimates based only on data from the original and full suite strata (Figure 22). The first exception was for age 2 and, to a lesser extent, age 3, where values for the full suite of strata tended to be a little higher. The other exception was noticeable at older ages in 2007, 2008 and 2018, where catch rates based on the full suite of strata were greater. At all ages, the slope of the major axis regression did not differ statistically from a value of 1, and the estimated intercepts did not differ statistically from a value of 0 for most ages above 3 years old (Table 5). Delta values were calculated using the data from all years, and excluding outlier years identified in Figure 22. Jointly, the results suggest that the change in survey coverage routinely affected only cod ages 2 and (perhaps) 3, albeit to a lesser extent. We therefore estimated correction factors in the model only for ages 2 and 3 in the Sentinel mobile gear survey, noting that these factors are applied only to the indices for 1995–2002.

MULTISPECIES SURVEY CATCHABILITY FOR AGES 2 AND 3

Abundance index values for ages 4 and above during the 1980s reflect the high abundance predicted by the previous assessment model (Brassard et al. 2020) and common perceptions for the stock (Figure 24), and generally track the passage of weak and strong cohorts (Figure 25). In contrast, abundance index values at ages 2 and 3 during the 1980s fluctuated at or below the series mean, even though abundance prior to 1990 must have been much higher in order to sustain the high abundances estimated for the same cohorts at older ages (Figure 24). This result suggests that values for the calibration function used to adjust survey catches at smaller sizes to account for the change in vessel and gear in 1990 may be incorrect, consistent with the high variability described above for those sizes in the comparative fishing experiment (Figure 23). An alternative explanation for the observed patterns is that survival of ages 2 and 3 fish declined considerably after 1990. This explanation seems highly unlikely because older cod and other large groundfish were important predators of smaller/younger cod, and the collapse of these larger fish during the late 1980s and early 1990s should have improved the survival of young cod (Savenkoff et al. 2007). Based on the available evidence, we chose to estimate catchability factors for ages 2 and 3 within the assessment model to account for the change in the survey that occurred in 1990 (details in Benoît et al. In prep.[1]). We note that the factors are applied only to the portion of the DFO survey series that used exclusively the *Lady Hammond* and Western IIA trawl, 1984–1989.

DIVERGENT ABUNDANCE INDEX TRENDS

Trends in fishery-independent survey abundance-at-age have historically differed between the mobile gear surveys (DFO and Sentinel) and the coastal fixed gear Sentinel surveys. Revisions to the manner in which the abundance indices were calculated undertaken by Benoît et al. (2022) have not changed this pattern. To illustrate this, we calculated relativized abundance indices by dividing the estimated annual values by the survey and age-specific means for 1995–2020. This period is common to all five of the major surveys on nGSL cod which are DFO RV, Sentinel bottom-trawl, Sentinel gillnet, Sentinel summer longline sampling (termed Longline 1 herein), and Sentinel fall sampling in and around zone 1 (southwest Newfoundland) of the fixed gear Sentinel program (Longline 2). Plots of these relativized values on log scale reveal that the two longline indices reflect a decrease in the abundance of age 3 and perhaps age 4 cod, beginning around 2010 (Figure 26). For older cod (ages 11 and above), which would reflect the 11+ group, the longline indices were also considerably smaller in relative terms prior to around 2003 and between about 2009 and 2013, and greater in the intervening period. A similar pattern was also observed for older cod in the Sentinel gillnet index relative to the DFO survey, although trends generally matched between the two surveys for younger cod (Figure 27). Trends in the DFO and Sentinel mobile surveys were generally very comparable, although the latter did catch relatively more older cod between 2004 and 2006 (Figure 28).

The diverging yet consistent age-specific patterns for the youngest and older cod in the more offshore mobile gear surveys, compared to the coastal fixed gear surveys, indicates time-varying availability of cod to these surveys. At least two mechanisms could explain these patterns. The first is interannual changes in the distribution of cod with respect to depth and nearshore waters. This hypothesis was previously explored by Cadigan (2004) in some preliminary modelling. The second hypothesis is based on the nature of the fishery and indices. Specifically, since the directed cod fishery was reopened following the 1994–1996 moratorium, it has been limited to fishing by fixed gear, which occurs in coastal waters. If in-season movements of cod inshore and offshore are limited, the fishery may result in in-season depletion of fish as they are captured by the fishery before they are sampled by the Sentinel program. Thus, in years during which the commercial fishery was restricted (e.g., 2003 moratorium, and lower total allowable catches in 2004 and 2011–2016), the number of cod of commercial sizes available to the fixed gear sentinel surveys would have been greater, all else being equal, while the mobile gear surveys should be less affected by in-season depletion. There is some evidence for this in Figures 26 and 27.

In the absence of external information to discriminate the two hypotheses, such as an independent measure of cod distribution across both the offshore and nearshore zones, these hypotheses were explored to a small extent as part of the assessment modelling. This was not undertaken to better understand the spatial dynamics of cod, but rather in an attempt to account for some misspecification in the model, which otherwise treats all abundance indices as representative of the whole population.

OTHER RELEVANT PUBLISHED FINDINGS

During the first part of the framework review, the paper by Wiles and May (1968) was identified as containing highly relevant data and information on the fisheries and biology of nGSL cod. Of note were survey results that helped to inform values for natural mortality for the revised assessment model (Benoît et al. 2022), and data on landings and catch composition (Ouellette-Plante et al. 2022b). As part of the revised model, the paper was further mined for information on age composition in surveys and fishery fleets, growth parameters, and maturity schedule (details in Benoît et al. In prep.[1]). Since the peer review meeting in the spring of 2021, additional published historical information relevant to the assessment was identified. This information is very briefly presented here.

SMALL-MESH BOTTOM-TRAWL SURVEYS, 1973–1976

Minet (1978) presents a summary of the age composition of cod in fall surveys conducted annually from 1973–1976. Although few details are provided for the surveys, the author clearly felt that the derived age composition data were representative of the stock. The age compositions (Figure 29) were incorporated into the revised assessment, thereby extending back to 1973 instead of 1974, and hopefully enhancing the accuracy of age species model abundance estimates, including for recruits. Although limited to four years, the survey data appear to track cohorts born in 1966, 1968 and 1971.

ESTIMATES OF FISHING MORTALITY FROM TAGGING

As part of their review, Ouellette-Plante et al. (2022b) noted the existence of tagging-mark-recapture data for nGSL cod for periods prior to the implementation of the current ongoing tagging program, which began in 1995. However, these data could either not be located or were not available in an interpretable or standardized database format. More generally, it was not possible to re-analyze the contemporary tagging data in time for the review. However, as part of an analysis covering numerous cod stocks, Myers et al. (1996) produced estimates of fishing mortality rates for cod aged approximately 6 years and older for a large number of individual tagging experiments conducted in the nGSL. Their estimates were derived assuming a natural mortality rate (M) of 0.2, although the authors present results of sensitivity analyses that provide adjustment factors to fishing mortality rate values for cases where M differs a little from 0.2. The results from the experiments for which the mid-point occurred in 1986 and 1987, are directly relevant to the new assessment model and were included as a prior on the fishing mortality for cod ages 6 to 9 (details in Benoît et al. In prep.[1]). Meanwhile, the results of experiments in the late 1950s and mid-1960s were used as part of extended modelling of the nGSL stock back to the early 1950s, the results from which were used to inform forthcoming revisions to the precautionary approach and a renewed rebuilding plan for NAFO 3Pn4RS cod.

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TABLES

Table 1. Summary of the proposed assumptions for recreational fishery removals of nGSL cod, either as an assumed single annual value (in t) for years prior to 2006, or assumed lower and upper bounds (in t) for a censored value subsequently.The sources for these values are indicated and details on how the estimates were derived from these sources are available in Ouellette-Plante et al. (2022b).

Year(s)	Value	Lower bound	Upper bound	Source
1974–1993	1,027.5	-	-	Average, ECAN questionnaires (1974, 1985, 1990)
1994–1997	10.0	-	-	Assumed given moratorium, corroborated by 1995 ECAN questionnaire estimate of 16.5 t
1998	294.1	-	-	Derived from northern cod estimate
1999	339.3	-	-	Derived from northern cod estimate
2000	226.2	-	-	Derived from northern cod estimate
2001	395.9	-	-	Derived from northern cod estimate
2002	113.1	-	-	Derived from northern cod estimate
2003	0.0	-	-	No recreational fishing allowed
2004	0.0	-	-	No recreational fishing allowed
2005	40.8	-	-	ECAN questionnaire, noting that there was a moratorium in place and value may have been zero.
2006	-	221.1	500.0	Capture potential estimate / assumed upper bound
2007	-	227.7	500.0	Capture potential estimate / assumed upper bound
2008	-	182.1	500.0	Capture potential estimate / assumed upper bound
2009	-	182.1	500.0	Capture potential estimate / assumed upper bound
2010	-	188.6	500.0	Capture potential estimate / assumed upper bound
2011	-	201.6	500.0	Capture potential estimate / assumed upper bound
2012	-	214.6	500.0	Capture potential estimate / assumed upper bound
2013	-	214.6	500.0	Capture potential estimate / assumed upper bound
2014	-	214.6	600.0	Capture potential estimate / assumed upper bound
2015	-	208.1	600.0	Capture potential estimate / assumed upper bound
2016	-	299.2	600.0	Capture potential estimate / assumed upper bound
2017	-	299.2	600.0	Capture potential estimate / assumed upper bound
2018	-	253.7	600.0	Capture potential estimate / assumed upper bound
2019	-	253.7	600.0	Capture potential estimate / assumed upper bound
2020	-	253.7	600.0	Capture potential estimate / assumed upper bound

Table 2. Catch at age (thousands) for ages 2 to 11+, 1974–2020, used as input to the revised assessment model for nGSL cod.

Year	Age									
	2	3	4	5	6	7	8	9	10	11+
1974	30.7	871.7	4,573.8	10,328.9	14,512.2	5,701.5	7,158.3	3,003.9	1,622.4	922.5
1975	43.5	112.7	4,847.5	8,306.3	5,486.9	7,743.7	3,157.8	2,971.4	1,852.7	1,602.6
1976	33.8	308.0	5,792.9	13,458.4	6,788.8	4,556.6	6,173.6	2,137.7	2,749.7	1,912.2
1977	30.7	90.0	3,068.9	10,873.3	13,700.1	8,530.9	2,822.5	3,516.3	1,179.3	2,035.3
1978	30.7	140.5	3,074	11,587.7	18,911.3	9,975.2	2,322.0	1,142.2	1,353.7	1,689.7
1979	30.7	150.1	3,849.3	15,007.1	13,801.8	13,502.6	5,170.7	1,532.3	773.1	1,374.7
1980	31.7	722.6	3,827.9	18,748.6	21,618.4	12,442.7	7,561.5	1,638.8	517	1,042.6
1981	32.7	413.3	7,360.5	9,634.6	21,470.3	14,957.7	5,064.1	2,306.1	1,005.3	1,150.9
1982	43.4	320.0	3,655.5	20,092.2	13,636.2	14,728.5	9,278.0	3,607.2	2,256.1	1,113.6
1983	154.7	973.6	5,441.9	16,318.7	19,737.6	10,917.7	6,420.5	3,274.4	1242	1,538.3
1984	30.7	125.3	3,351.6	8,272.2	14,433.9	21,657.7	7,909.6	6,084.6	2,241.1	1,709.4
1985	38.1	262.6	2,898.0	17,052.1	14,813.0	11,456.0	10,523.5	3,407.4	2,483.5	1,278.7
1986	42.4	305.5	2,788.5	9,150.1	16,763.8	12,702.3	6,458.9	6,635.8	2,448.9	2,719.1
1987	35.0	278.9	1,668.4	8,912.2	12,846.9	12,358.8	7,507.2	3,802.0	1,918	2,805.5
1988	50.9	520.2	1,626.8	6,468.1	12,067.5	6,398.4	5,404.9	1,592.6	689.1	1,489.5
1989	36.0	683.4	2,188.5	5,424.8	8,050.8	8,771.6	3,976.5	2,545.2	1,018	1,159.3
1990	55.1	807.8	3,227.6	7,145.4	4,970.9	6,273.9	4,476.4	1,927.7	957.7	724.8
1991	303.8	1,658.0	6,213.7	9,192.3	7,226.4	3,764.7	3,074	2,559.9	677.7	809.5
1992	185.8	1,100.6	4,829.0	9,734.4	6,394.8	3,105.9	1,529.5	979.8	742.5	421.6
1993	116.0	519.5	3,546.3	5,734.2	7,373.4	2,912.2	643.6	280.7	153.6	110.9
1994	20.8	100.4	149.0	171.7	78.6	65.5	22.2	10.3	2.7	2.1
1995	42.6	14.7	17.1	17.7	29.0	32.8	31.4	7.0	2.3	0.8
1996	17.5	22.7	22.9	31.5	38.6	38.7	42.6	17.5	9.1	1.2
1997	76.2	278.0	664.5	500.6	739.2	434.2	403.2	212.9	190.9	41.2
1998	18.9	4.8	118.3	429.0	699.2	500.0	214.9	171.9	166.4	76.3
1999	61.9	2.8	263.7	598.8	1,695.7	555.6	768.6	279.3	153.9	126.6
2000	7.6	12.2	224.9	904.9	1,155.7	1,361.6	347.4	284.7	138.6	31.4
2001	20.3	8.9	512.6	647.1	1,093.7	992.3	1,015.5	307.6	111.7	47.9
2002	4.5	5.5	192.3	470.8	962.3	781.7	837.5	536.3	130.8	66.9
2003	53	7.9	7.8	37.5	60.2	50.6	38.0	26.6	8.4	6.3
2004	28	5.3	20.4	237.9	403.7	410.2	303.2	204.8	100.6	59.8
2005	26.3	2.6	26.1	82.8	345.5	781.7	452.6	313.0	119.3	200.8
2006	17.6	3.9	39.4	288.1	666.7	691.6	1,007.9	382.6	153.3	172.9
2007	6.7	15.9	127.6	410.9	663.2	620.9	683.5	554.9	179	147.3
2008	88.1	17.7	414.2	526.0	779.4	727.7	466.0	425.8	167.9	95.9
2009	20	207.6	758.7	1,265.3	779.8	481.0	215.6	163.4	51.1	48.9
2010	14.7	3.1	250.1	411.3	675.2	462.0	242.5	221.4	59.2	39.9
2011	47.7	9.7	70.1	260.1	378.2	353.0	152.5	72.4	34.6	17.6
2012	130.5	6.4	11.4	51.8	193.4	325.3	239.2	68.1	35	18.7
2013	122.4	7.4	47.9	61.8	242.6	256.3	175.2	98.7	19.1	6.0
2014	41.1	10.2	51.4	81.7	130.2	140.6	190.4	136.2	62.7	13.5
2015	12.3	2.7	37.0	91.5	168.1	126.3	215.5	117.1	31.0	13.0
2016	6.4	5.8	34.8	127.8	198.4	196.8	83.0	113.2	43.5	43.2
2017	17.8	3.3	34.0	85.5	279.1	387.7	258.1	159.4	58.7	111.6
2018	18.4	2.1	60.9	158.2	281.3	405.9	275.6	101.3	35.1	39.0
2019	2.8	0.7	7.2	12.3	53.5	112.5	120.1	91.2	18.8	39.3
2020	11.9	3.9	91.2	132.0	50.1	111.6	107.0	85.4	27.9	5.1

Table 3. Parameter estimates (Est), standard errors (SE), and negative loglikelihood gradients (GRD).

Parameter	Est	SE	GRD
γ_2	-2.671	0.042	0.000289
γ_3	0.022	0.037	0.000301
γ_4	-0.319	0.052	0.000022
γ_5	-0.606	0.070	0.000023
γ_6	-1.001	0.104	0.000045
γ_7	-1.369	0.150	0.000041
γ_8	-1.520	0.174	0.000028
γ_9	-1.655	0.200	0.000030
γ_{10}	-1.724	0.214	0.000011
γ_{11+}	-1.223	0.130	-0.000025
$\log(\sigma_Y)$	-3.077	0.534	0.000009
$\log(\sigma_C)$	-3.134	0.414	0.000001
$\log(\sigma_{AY})$	-3.810	2.229	0.000006
$logit(\varphi_Y)$	1.633	0.916	0.000000
$logit(\varphi_C)$	1.389	1.002	-0.000003
$logit(\rho_A)$	1.802	4.231	-0.000001
$logit(\rho_Y)$	1.782	1.562	0.000006

Table 4. Slope and intercept estimates, and associated lower and upper 95% confidence intervals (LCI, UCI respectively) and estimated delta values for the age-specific relationship between multispecies survey catch rates based on the original (reduced) strata set and the regular stratum set.

Age	Intercept			Slope			Delta
	Estimate	LCI	UCI	Estimate	LCI	UCI	
2	0.14	-0.10	0.36	1.09	0.96	1.23	0.29
3	0.26	-0.01	0.5	0.98	0.86	1.11	0.22
4	0.33	0.05	0.57	0.97	0.84	1.12	0.26
5	0.49	0.31	0.65	0.86	0.74	1.01	0.32
6	0.48	0.35	0.59	0.80	0.66	1.00	0.34
7	0.39	0.38	0.4	0.75	0.61	0.92	0.37
8	0.32	0.20	0.47	0.89	0.71	1.12	0.39
9	0.24	0.00	0.54	0.87	0.72	1.07	0.43
10	0.42	-0.06	1.02	0.96	0.76	1.21	0.51
11+	-0.43	-1.04	0.35	0.67	0.53	0.86	0.96

Table 5. Slope and intercept estimates, and associated lower and upper 95% confidence intervals (LCI, UCI respectively), and estimated delta values for the age-specific relationship between Sentinel bottom-trawl survey catch rates based on the original (reduced) strata set and the regular stratum set which includes coastal strata. Delta values were calculated using all data and excluding a small number of outlier sets (Delta.omit).

Age	Intercept			Slope			Delta	Delta omit
	Estimate	LCI	UCI	Estimate	LCI	UCI		
2	0.21	0.12	0.29	1.02	0.90	1.16	0.23	0.06
3	0.09	0.00	0.23	1.05	0.88	1.26	0.13	0.05
4	-0.02	-0.24	0.17	1.05	0.95	1.17	0.08	0.04
5	0.08	-0.07	0.21	0.99	0.89	1.09	0.06	0.04
6	0.11	-0.03	0.23	0.96	0.83	1.1	0.06	0.04
7	0.14	0.05	0.21	0.87	0.71	1.06	0.08	0.03
8	0.08	0.05	0.11	0.95	0.79	1.15	0.09	0.02
9	0.10	-0.03	0.25	1.02	0.87	1.2	0.08	0.02
10	0.14	-0.09	0.42	1.03	0.89	1.19	0.09	0.02
11+	0.08	-0.31	0.56	0.98	0.82	1.16	0.15	0.03

FIGURES

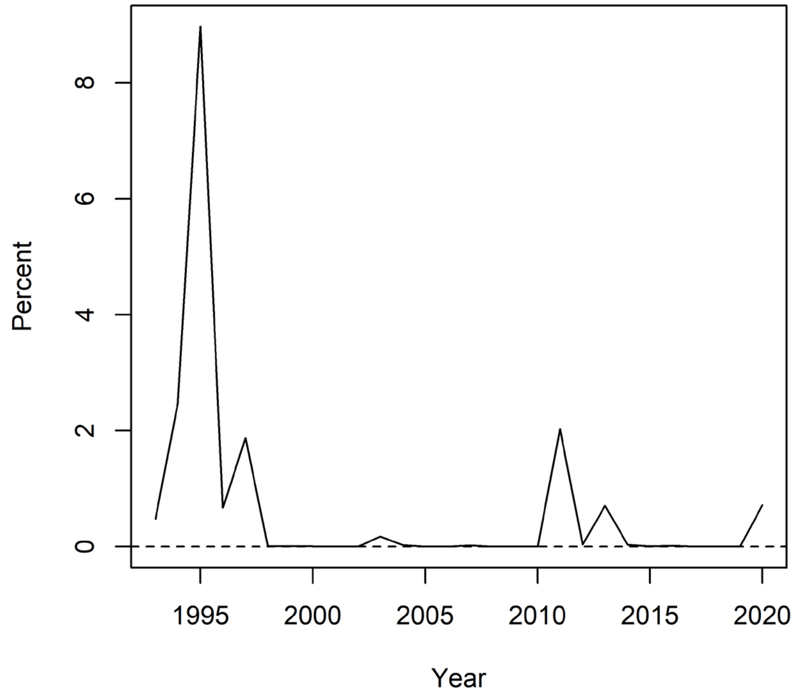

Figure 1. Percent (by number) of annual commercial fishery landings since 1993 comprising two-year-old cod.

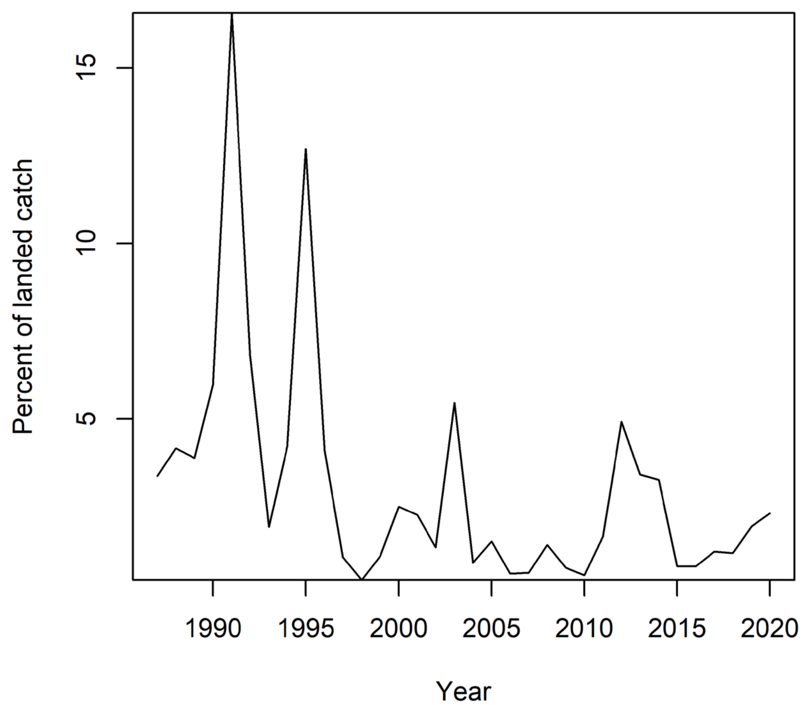

Figure 2. Estimated discards of cod caught commercially in the principal groundfish fisheries and the shrimp fishery from at-sea observer data expressed as a percentage of reported cod landings (by weight).

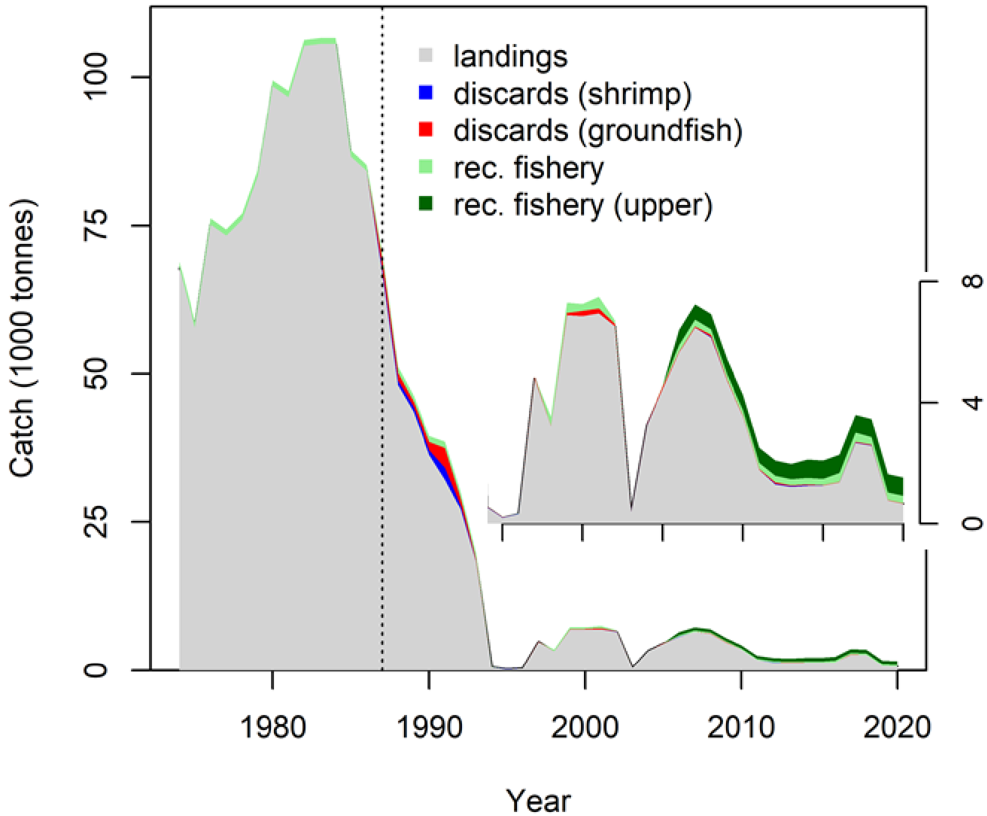

Figure 3. Estimates of annual cod removals in NAFO Divisions 3Pn4RS fisheries from reported landings, estimated discards in shrimp and groundfish fisheries (assuming no post-release survival) and from the recreational fishery. Discard estimates are available only beginning in 1987, indicated by the vertical dotted line. Estimated recreational fishery catches added to landings are indicated in light green, while a proposed censored range for recreational fishery catches as of 2006 is indicated in dark green. The inset provides a magnification for the most recent 25-year period.

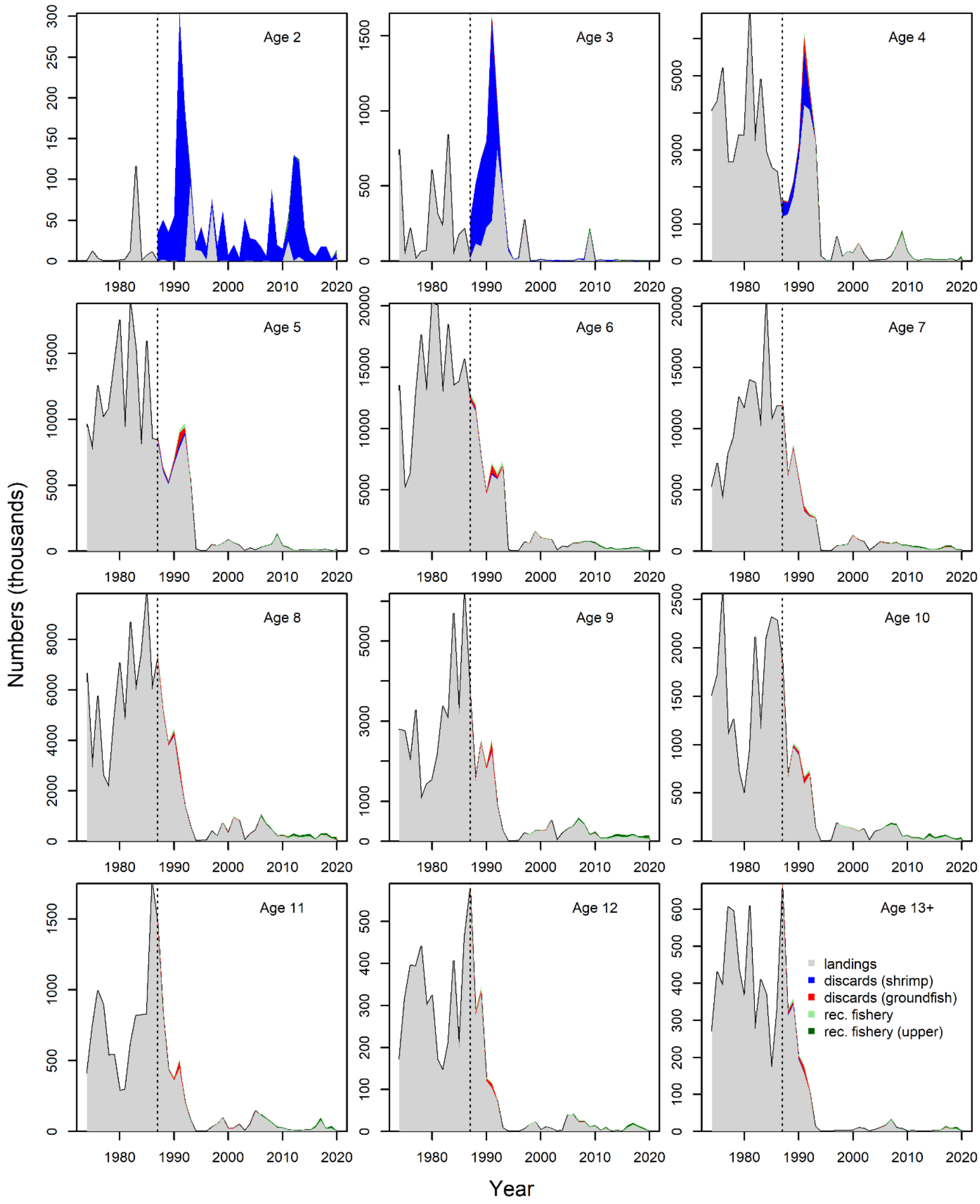

Figure 4. Age-specific estimates of annual cod removals in NAFO Divisions 3Pn4RS fisheries from reported landings, estimated discards in shrimp and groundfish fisheries (assuming no post-release survival), and from the recreational fishery, 1974–2020. Discard estimates are available only beginning in 1987, indicated by the vertical dotted line. Estimated recreational fishery catches proposed to be added to landings are indicated in light green, while a proposed censored range for recreational fishery catches as of 2006 is indicated in dark green.

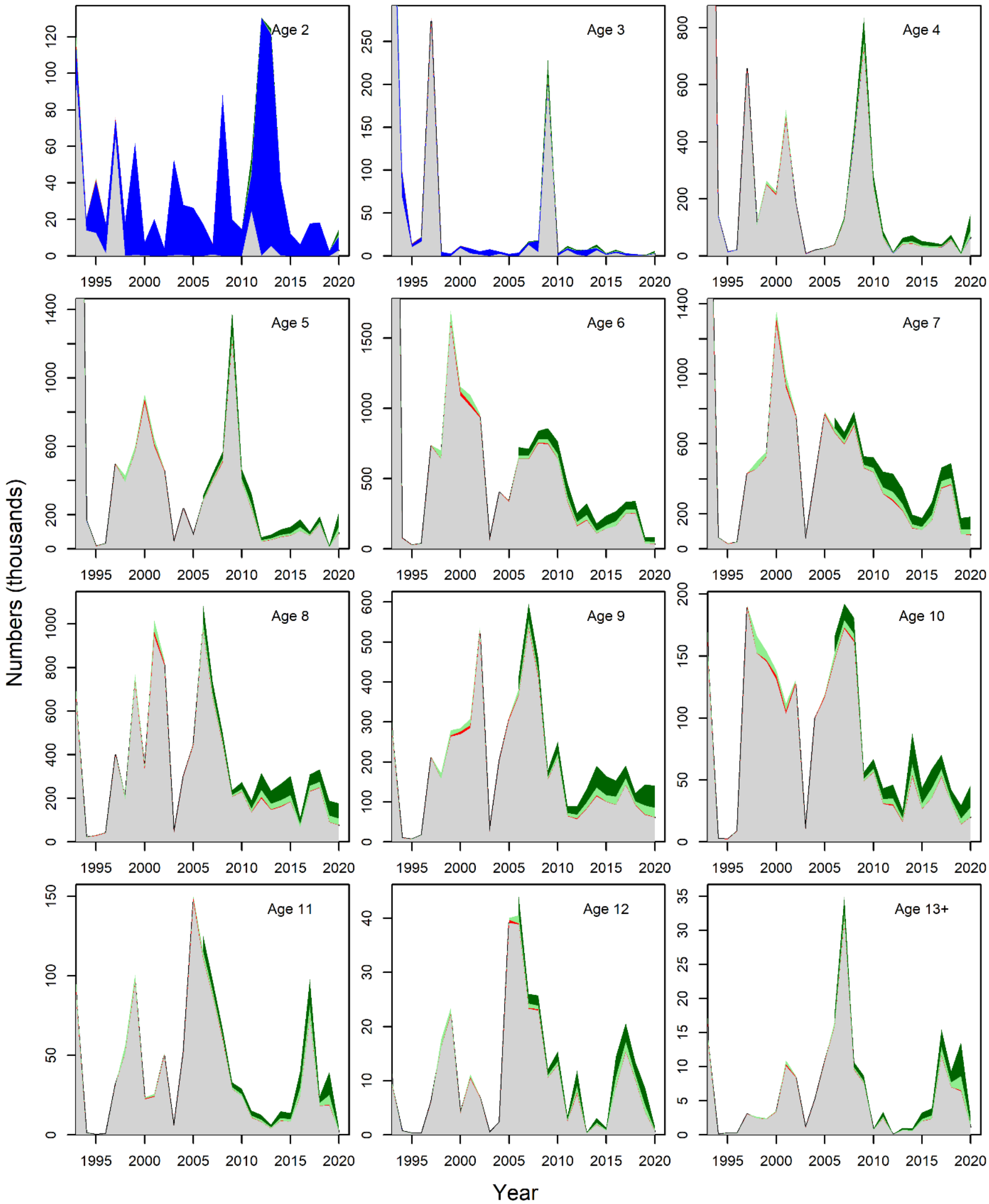

Figure 5. Same results and details as for Figure 4, but focusing on 1994–2020.

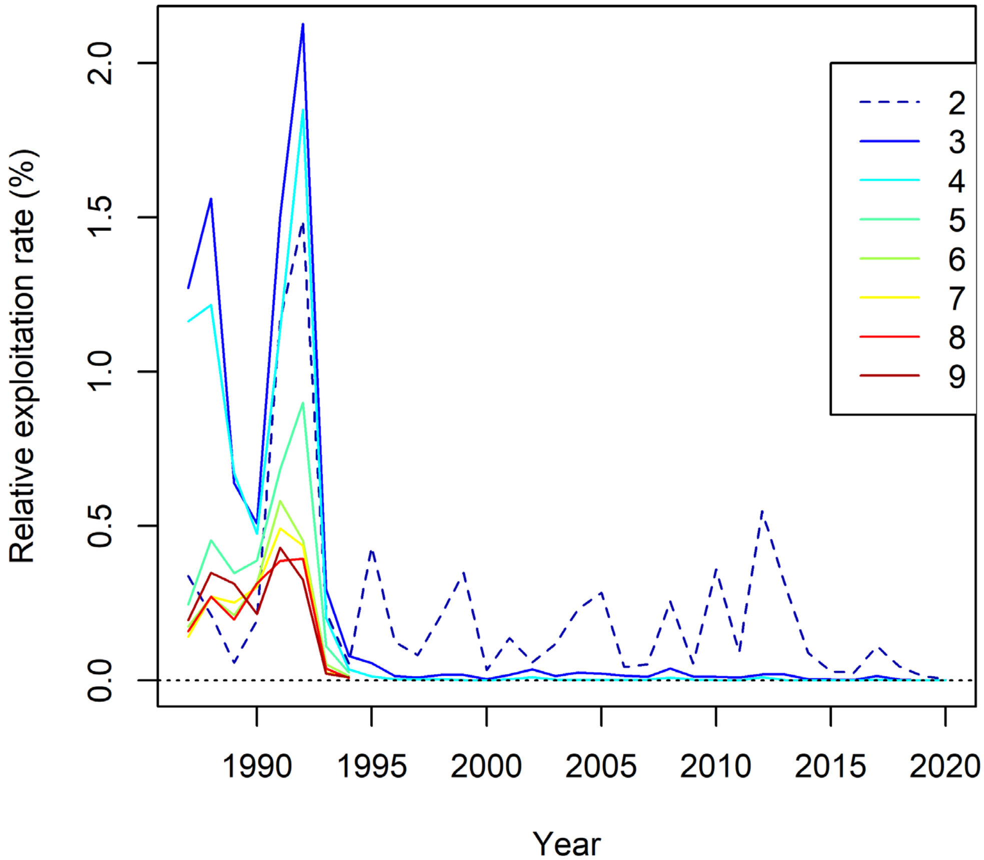

Figure 6. Age-specific relative harvest rates associated with estimated discards in the shrimp fishery, 1987–2020. Relative exploitation rates were calculated as the ratio of estimated discard numbers and minimum trawlable numbers in surveys, expressed as a percentage. Results are only presented for ages two to nine (colour), as amounts were negligeable for older ages.

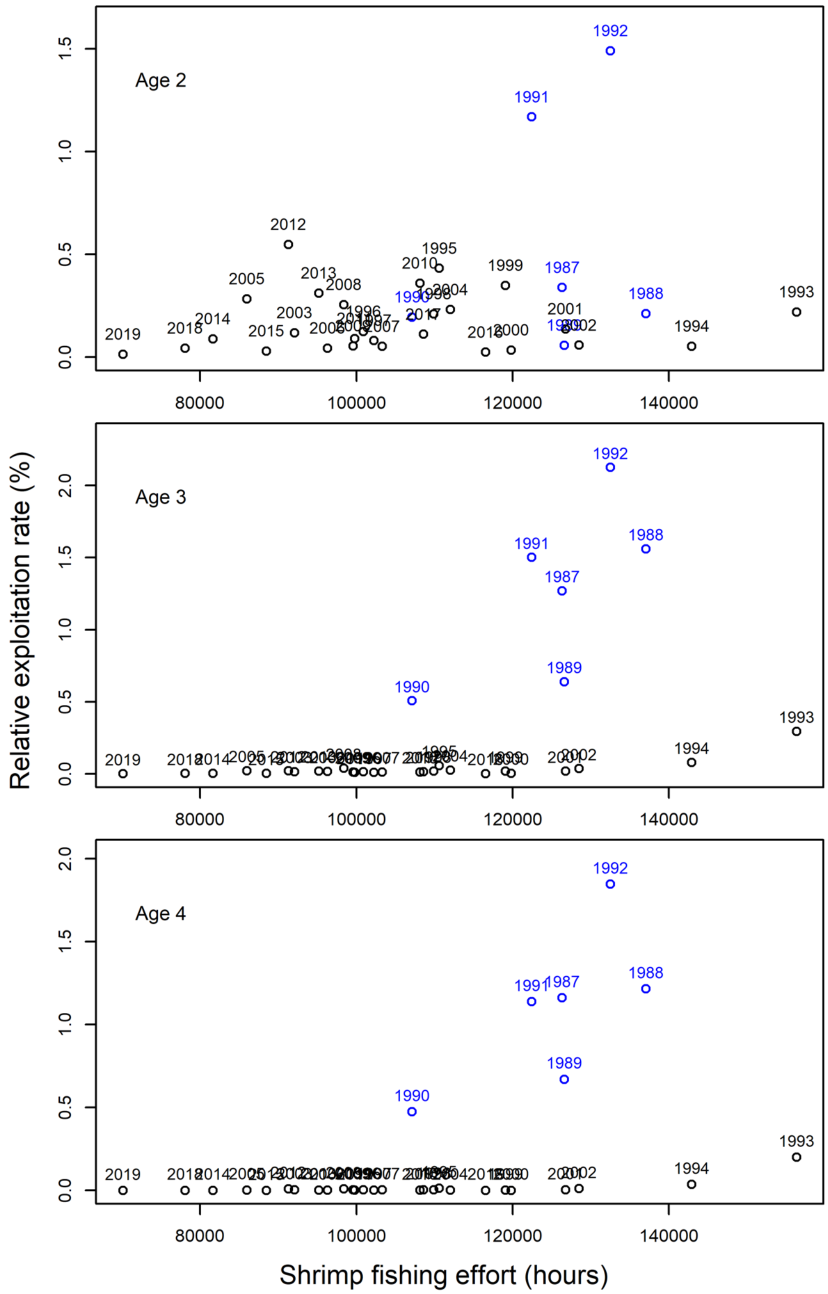

Figure 7. Relationship between shrimp fishing effort in shrimp fishing areas 8 (Esquiman), 9 (Anticosti) and 10 (Sept-Îles) and the estimated relative exploitation rate for cod ages two to four (panels). Values for years prior to the introduction of the Nordmore grate are indicated in blue. Fishing effort values were obtained from Bourdages et al. (2020).

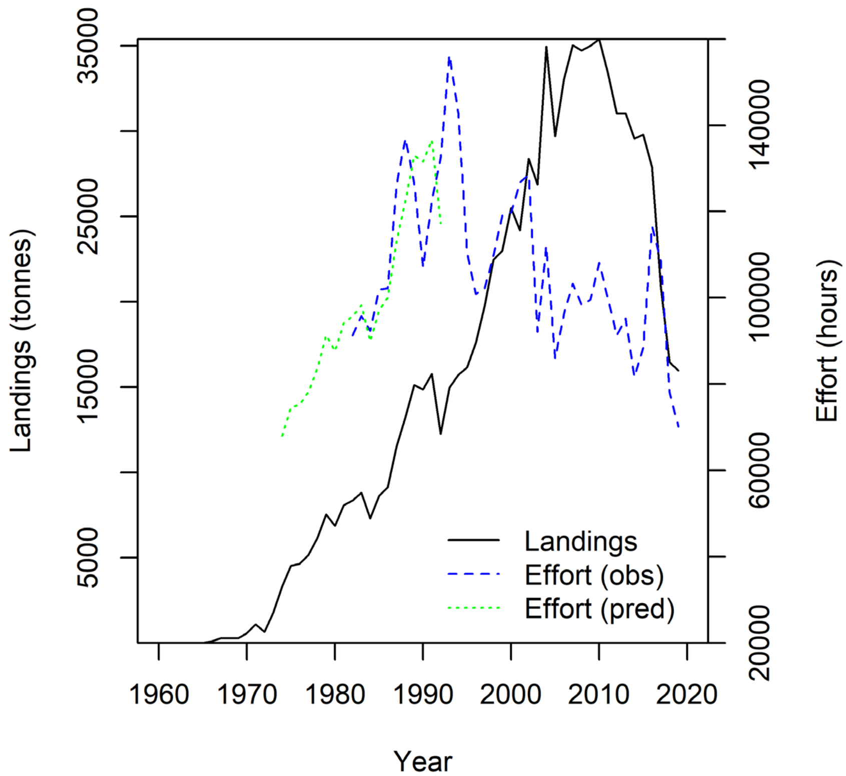

Figure 8. Trends in shrimp landings and observed effort for the shrimp fishery in shrimp fishing areas 8 (Esquiman), 9 (Anticosti) and 10 (Sept-Îles) (from Bourdages et al. 2020). Effort predicted using landings based on major axis regression is shown for illustrative purposes only.

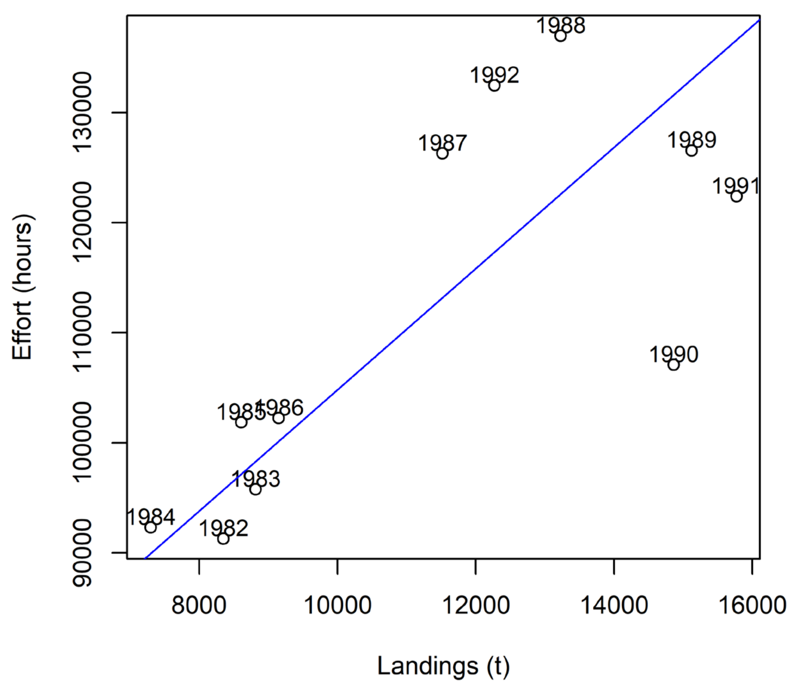

Figure 9. Relationship between shrimp landings and effort for the shrimp fishery in shrimp fishing areas 8 (Esquiman), 9 (Anticosti) and 10 (Sept-Îles) for years prior to the introduction of the Nordmore grate in 1993. The blue line represents the predicted effort based on reduced major axis regression.

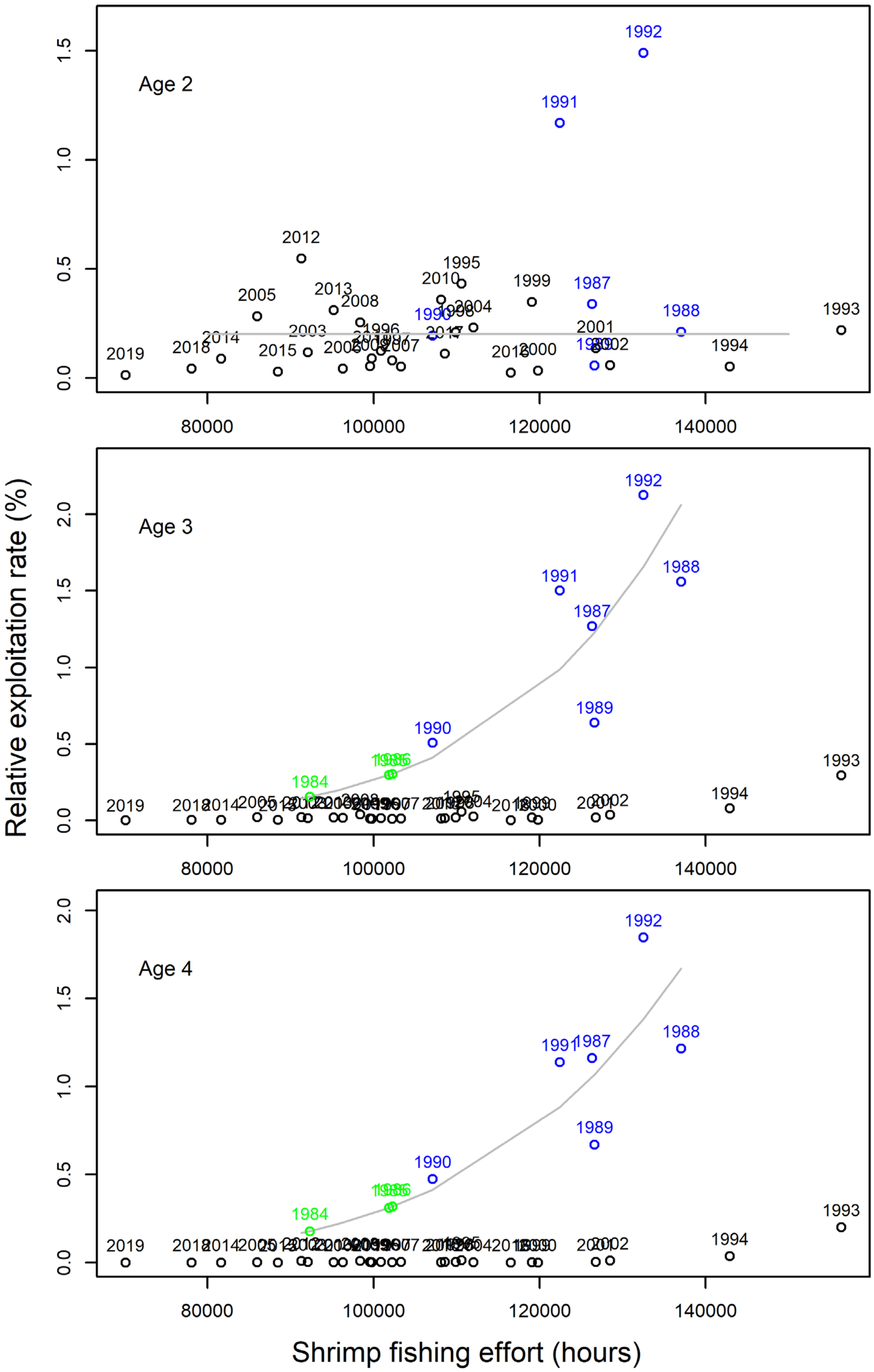

Figure 10. Similar to Figure 7, but with predicted relative exploitation rate (grey line), estimated as an average of 1987–1990 values for age 2 or using reduced major axis regression for ages 3 and 4. Predicted annual values of relative exploitation rate for 1984-1986 are shown in green for ages 3 and 4, noting that the values for 1985 and 1986 overlap considerably given very similar observed fishing effort.

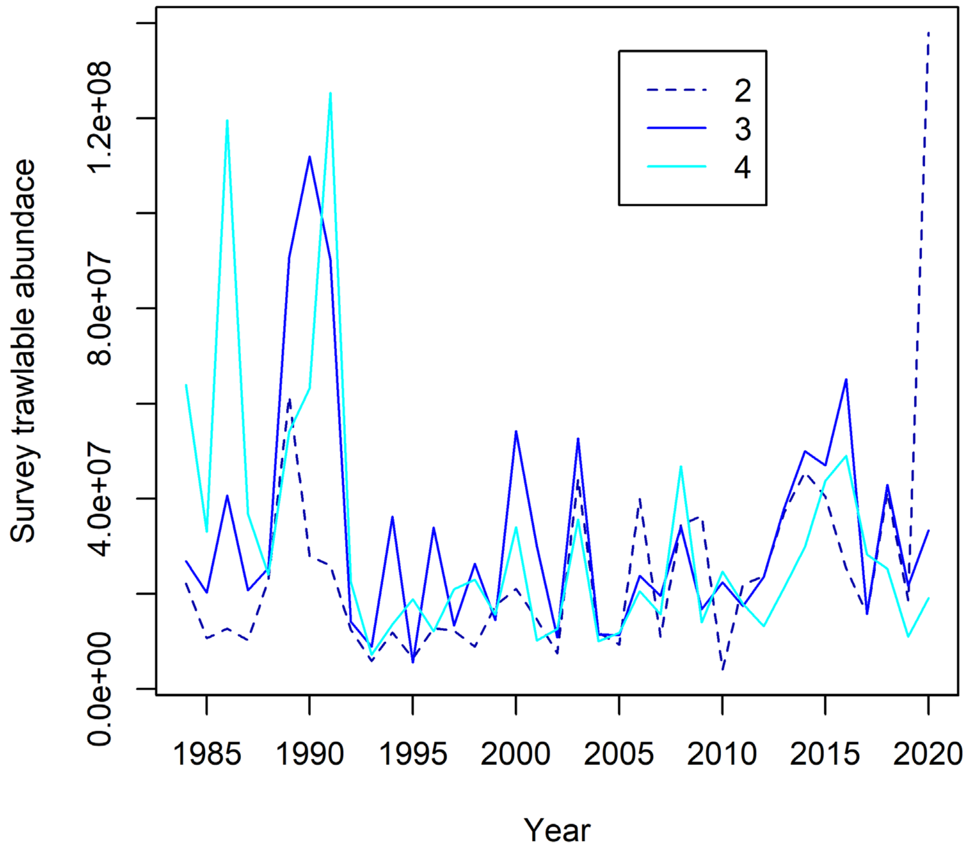

Figure 11. August survey trawlable abundance estimates (numbers) for cod ages 2–4 (from Benoît et al. 2022).

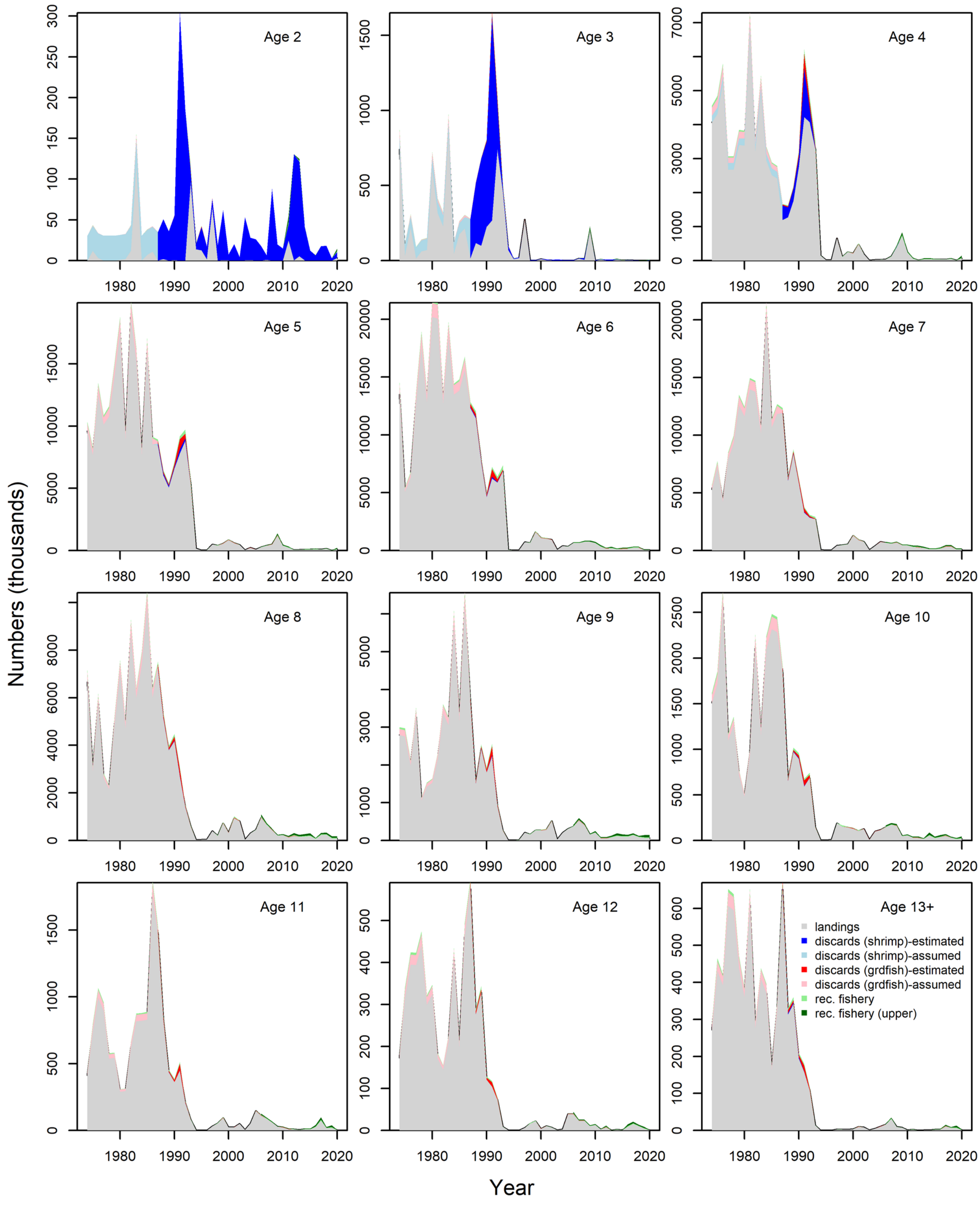

Figure 12. Age-specific estimates of annual cod removals in NAFO Divisions 3Pn4RS fisheries from reported landings, estimated and assumed discards in shrimp and groundfish fisheries (assuming no post-release survival) and estimated catch from the recreational fishery, 1974–2020.

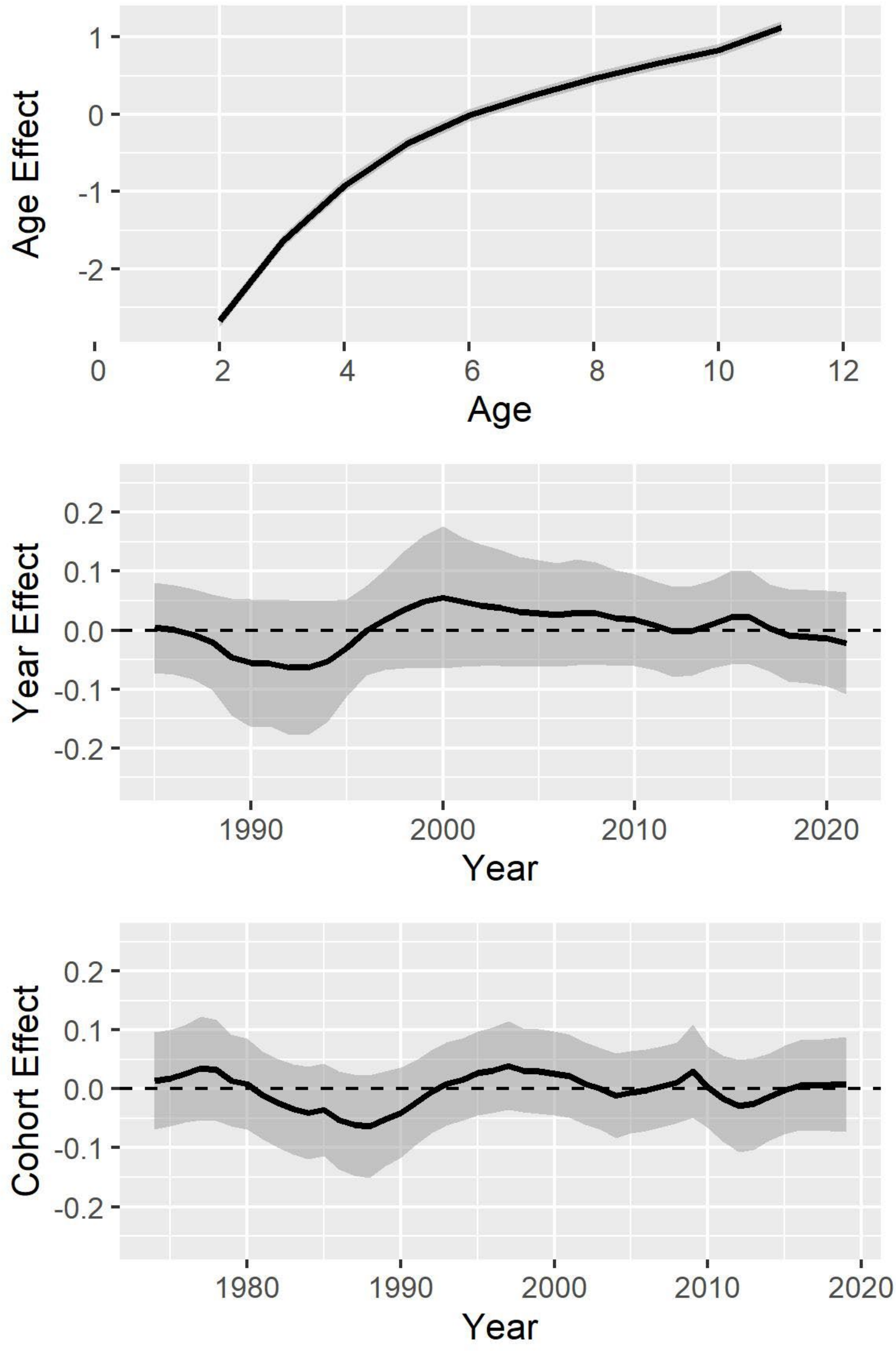

Figure 13. Estimates of the main effects in the weight-at-age model. Shaded regions indicate 95% confidence intervals. Age 11 represents 11+.

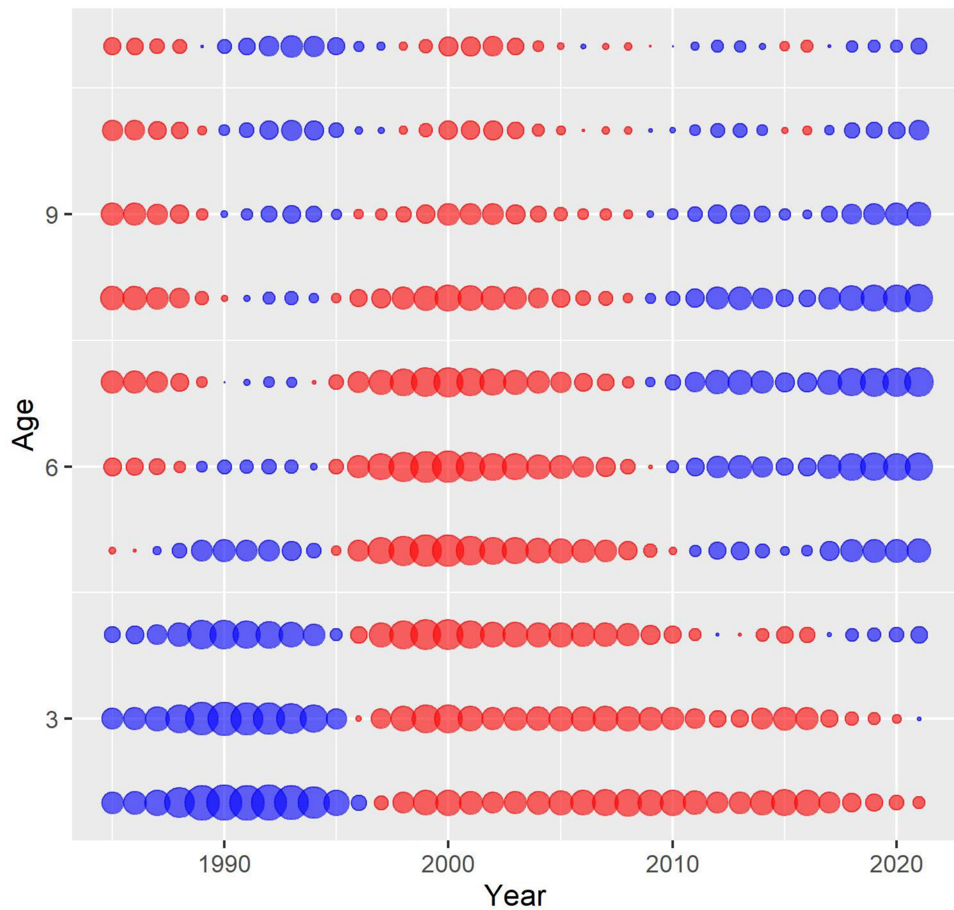

Figure 14. Estimates of the year-age interactions effects. The area of the circles is proportional to the absolute value of the effect, and the color indicates the sign (red +; blue -). Age 11 represents 11+.

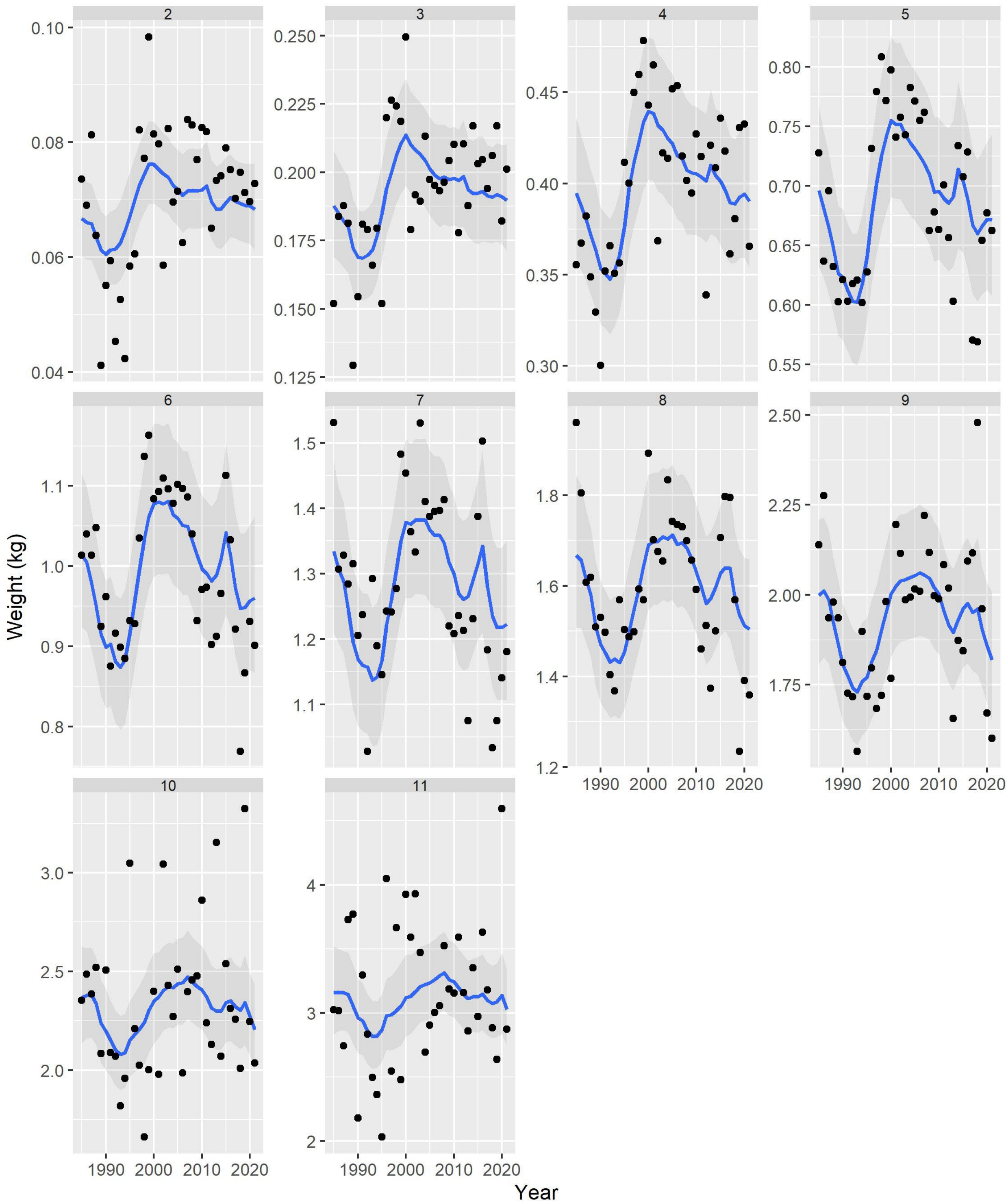

Figure 15. Time-series of observed (points) and model-predicted (lines) average stock weights-at-age. Each panel is for an age class, where 11 represents 11+. Shaded regions indicate 95% confidence intervals.

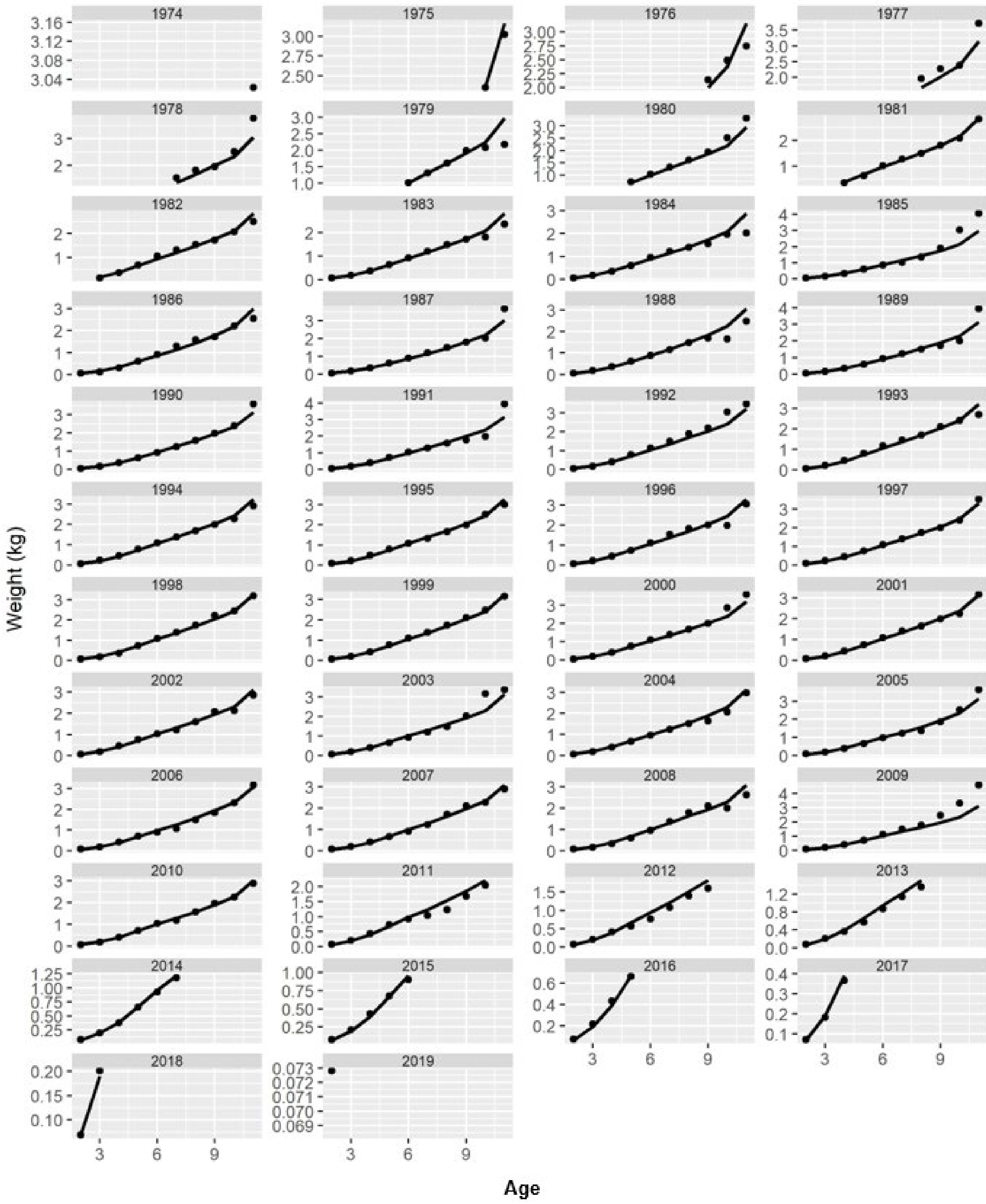

Figure 16. Observed (points) and model-predicted (lines) average stock weights-at-age. Each panel is for a cohort.

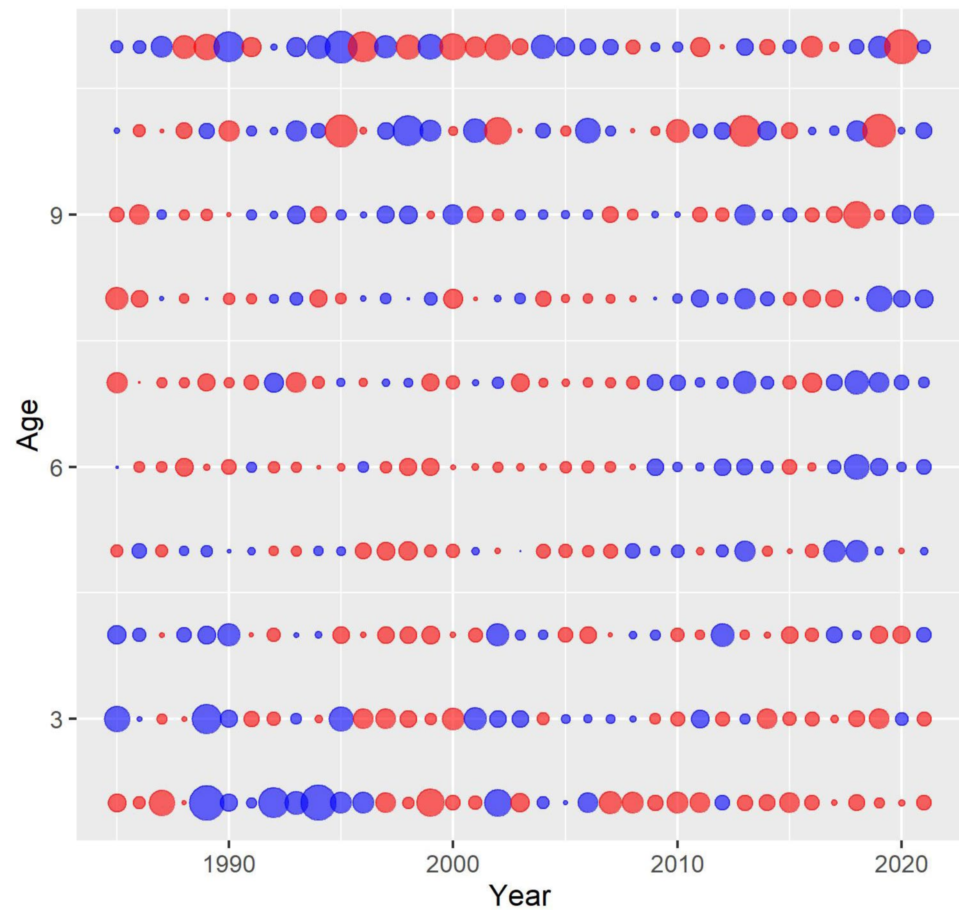

Figure 17. Model standardized residuals. The area of the circles indicates the relative value of the residual and the color indicates the sign (red +; blue -). Age 11 represents 11+.

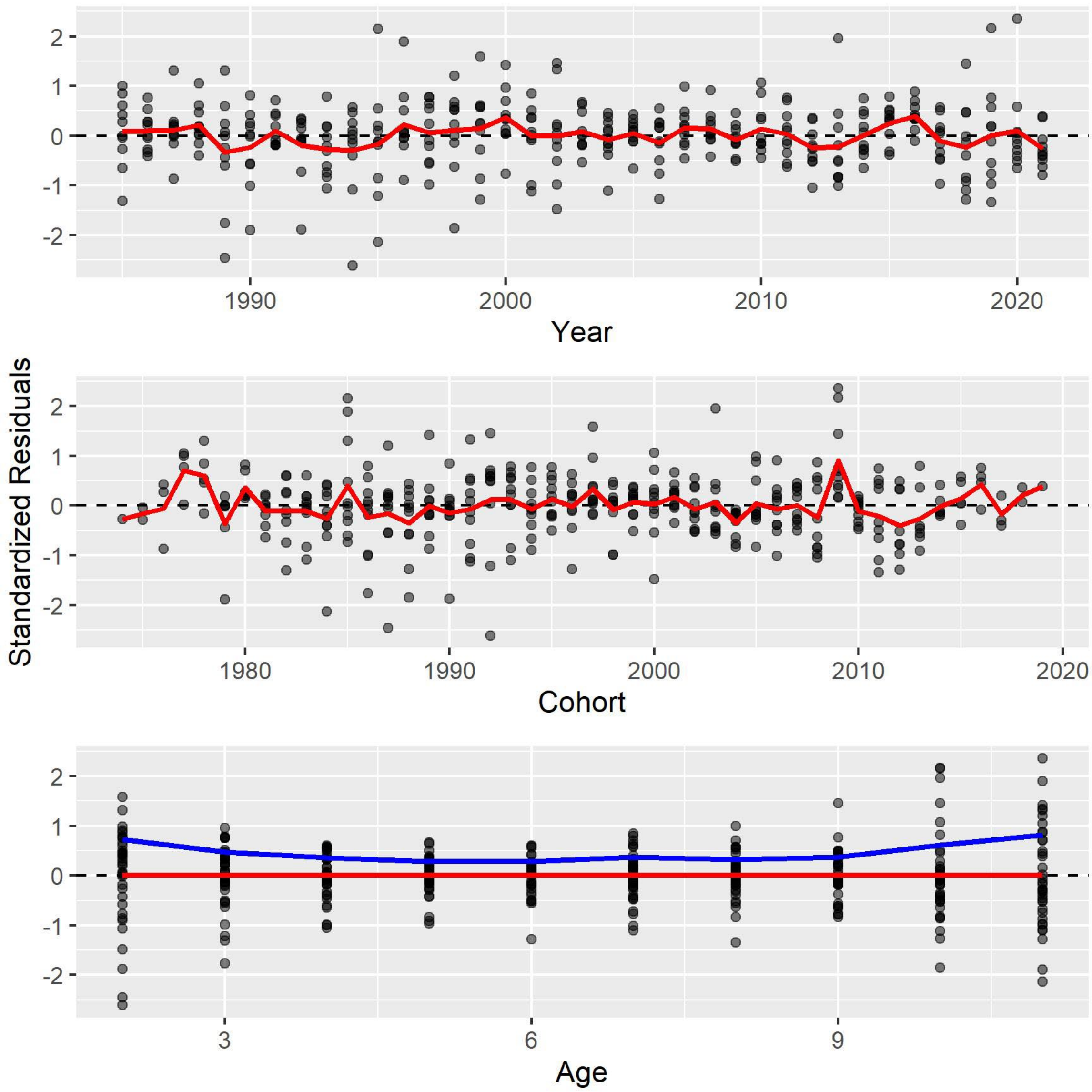

Figure 18. Standardized residuals versus year (top), cohort (middle), and age (bottom). Red lines indicate the average residual, and the blue line indicates the average absolute residual. Age 11 represents 11+.

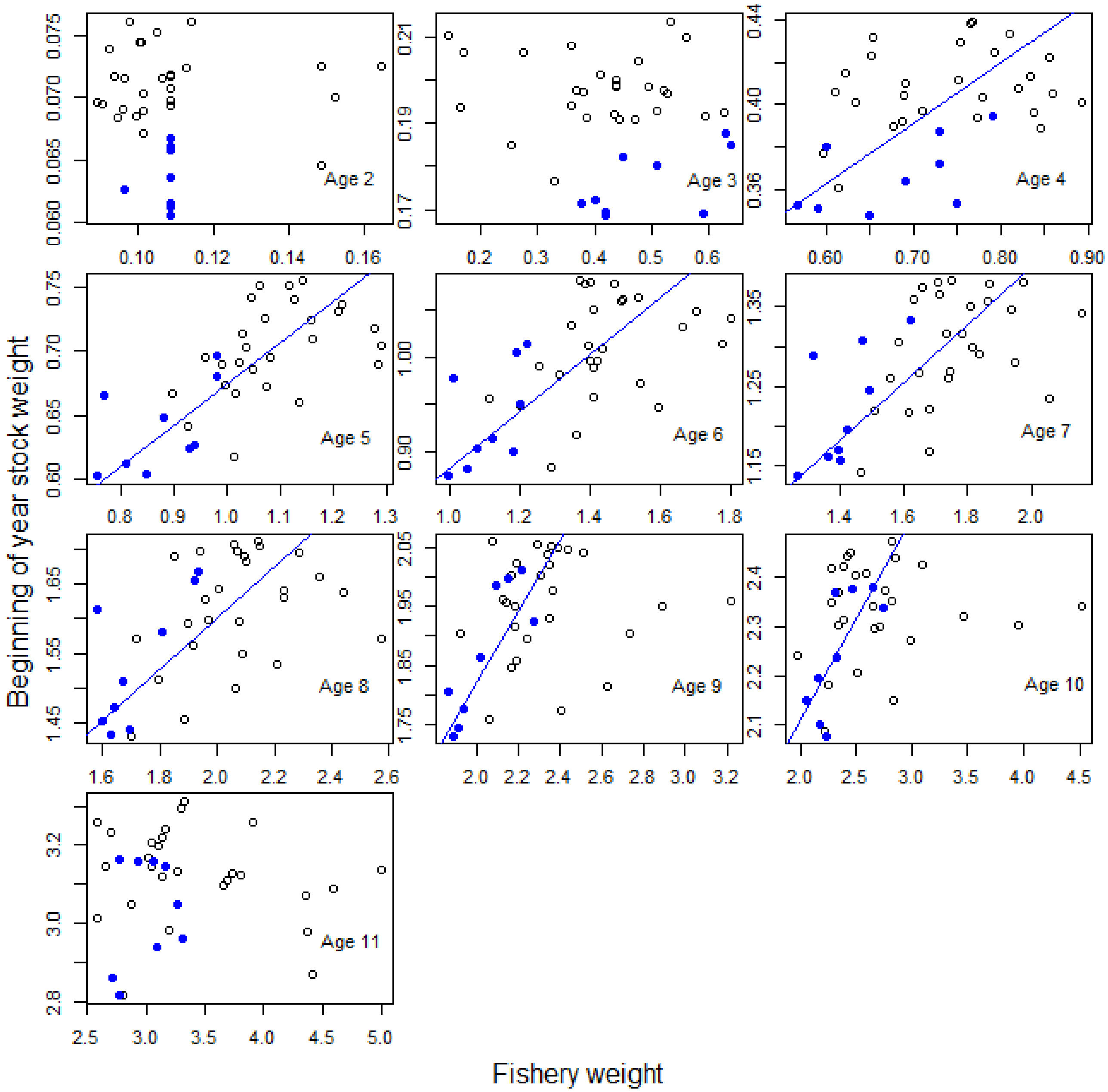

Figure 19. Age-specific annual beginning-of-year stock weights (SW; kg) as a function of fishery weights (CW; kg) for 1985–2020. Values for the 1986–1993 are presented as blue dots to illustrate that these values correspond with the pattern for the whole series. The blue line represents the fit of age-specific major axis regressions. For ages 9 and 10, these regressions excluded the three largest CW values. Age 11 represents 11+.

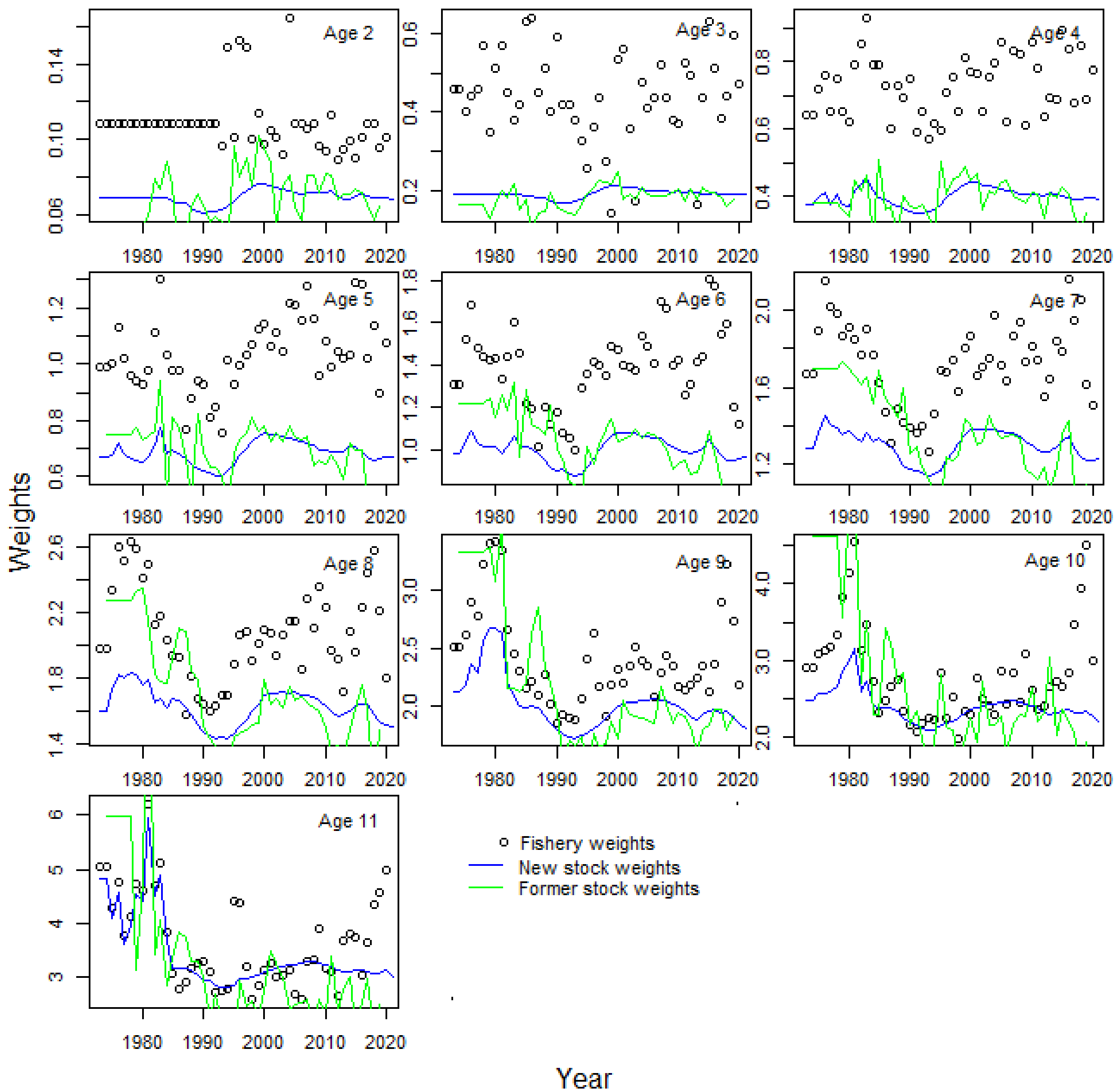

Figure 20. Trends in age-specific individual weight values (in kg) for the fishery (CW, circle), and for the stock (SW). The SW values formerly used in the assessment are from Brassard et al. (2020) and are plotted using a green line, whereas the new stock weighted derived for this report are plotted using a blue line. Age 11 represents 11+.

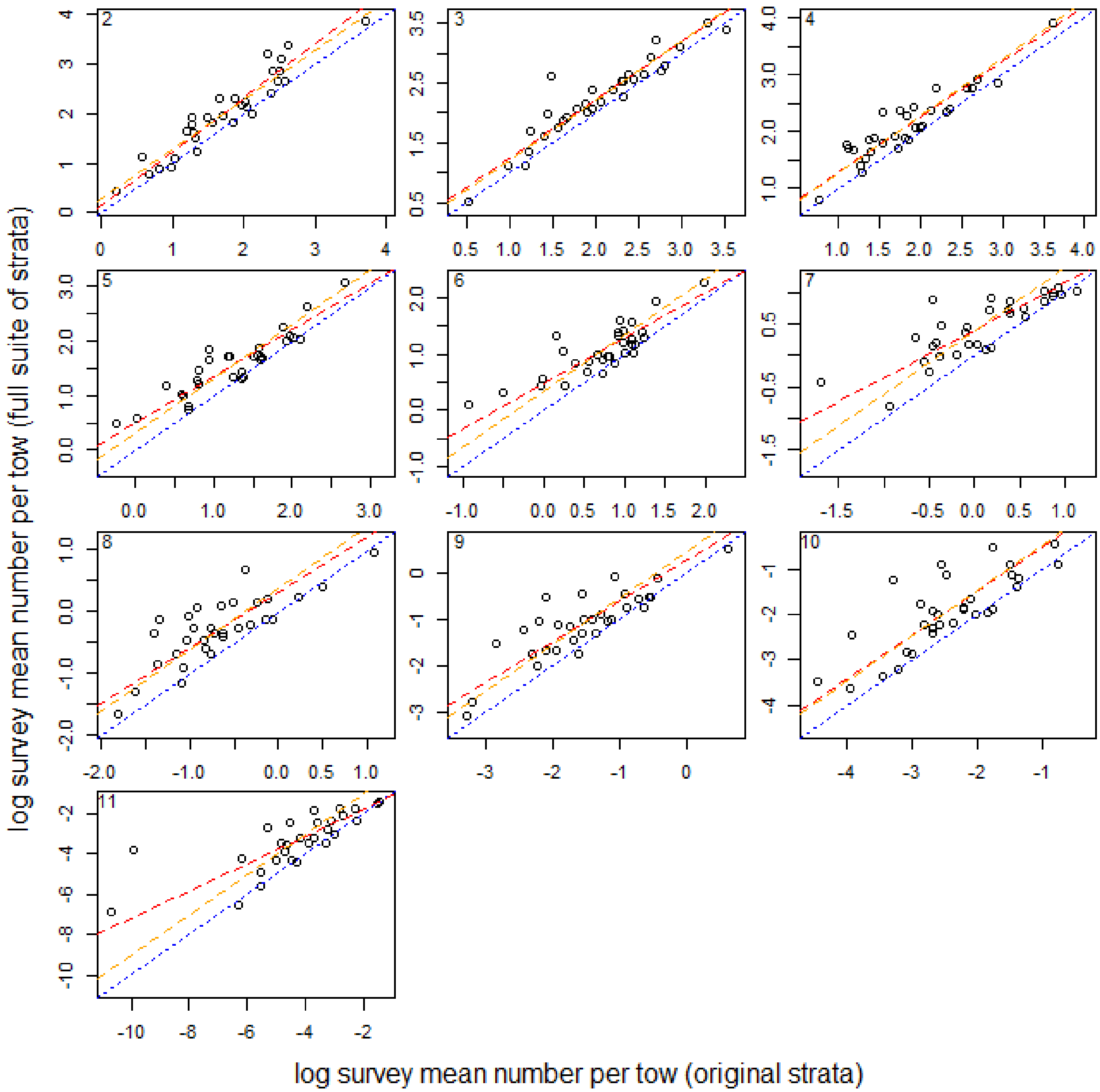

Figure 21. Annual estimates of age-specific (panels) log mean number per tow in the DFO multispecies bottom-trawl RV survey using data restricted to the strata originally sampled during the survey in the 1980s, and the full suite of strata employed since the early 1990s. The dotted blue line is a 1:1 line, the orange dashed line is the mean difference in annual log-estimates and the red dashed line is the fit of a major axis regression. Note that the panel for age 11 represents catches for 11+.

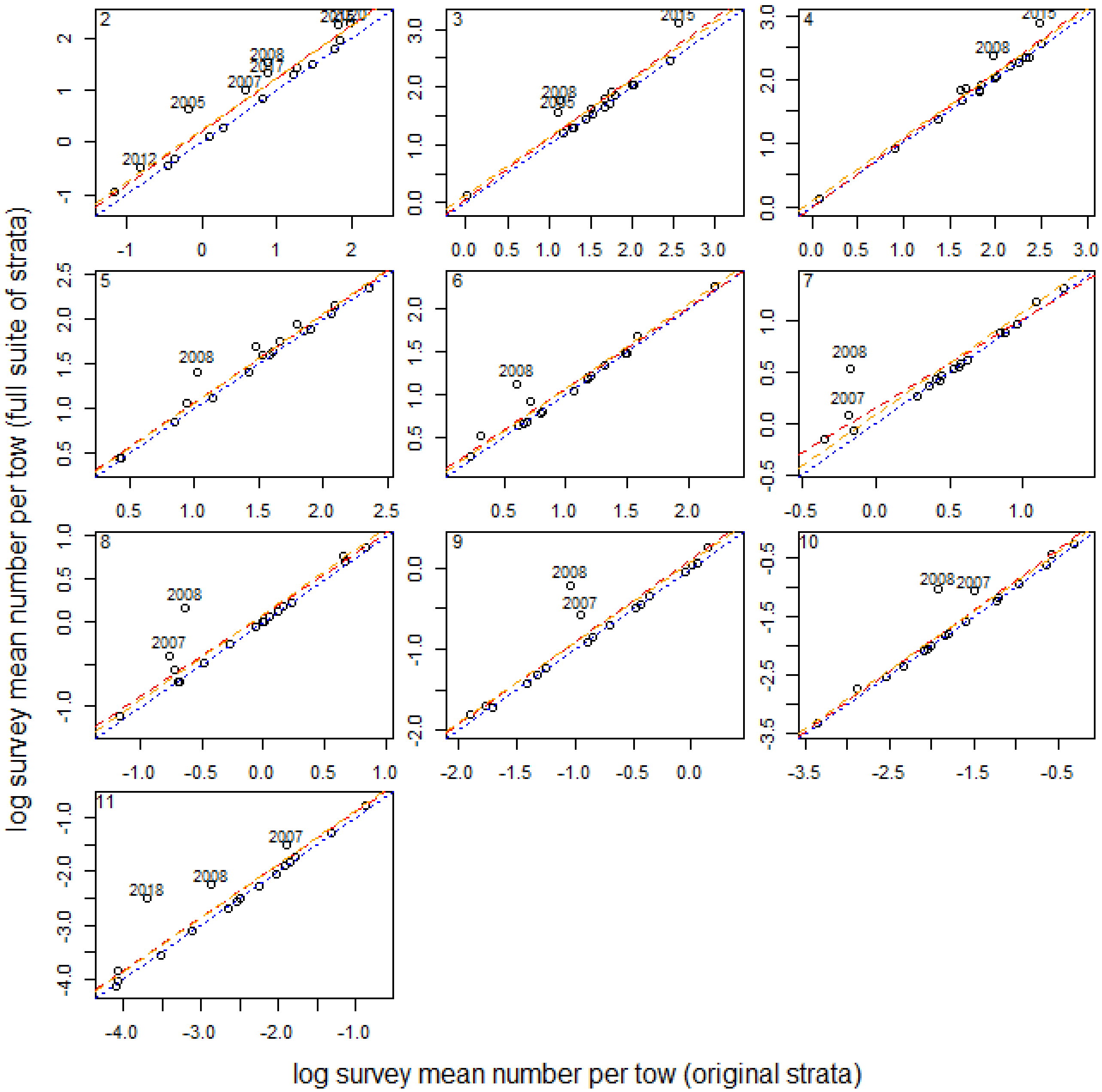

Figure 22. Annual estimates of age-specific (panels) log mean number per tow in the Sentinel bottom-trawl survey using data restricted to the strata originally sampled during the survey until 2002, and the full suite of strata employed since 2003. The dotted blue line is a 1:1 line, the orange dashed line is the mean difference in annual log-estimates and the red dashed line is the fit of a major axis regression. Some outlying years are identified in each panel. Note that the panel for age 11 represents catches for 11+.

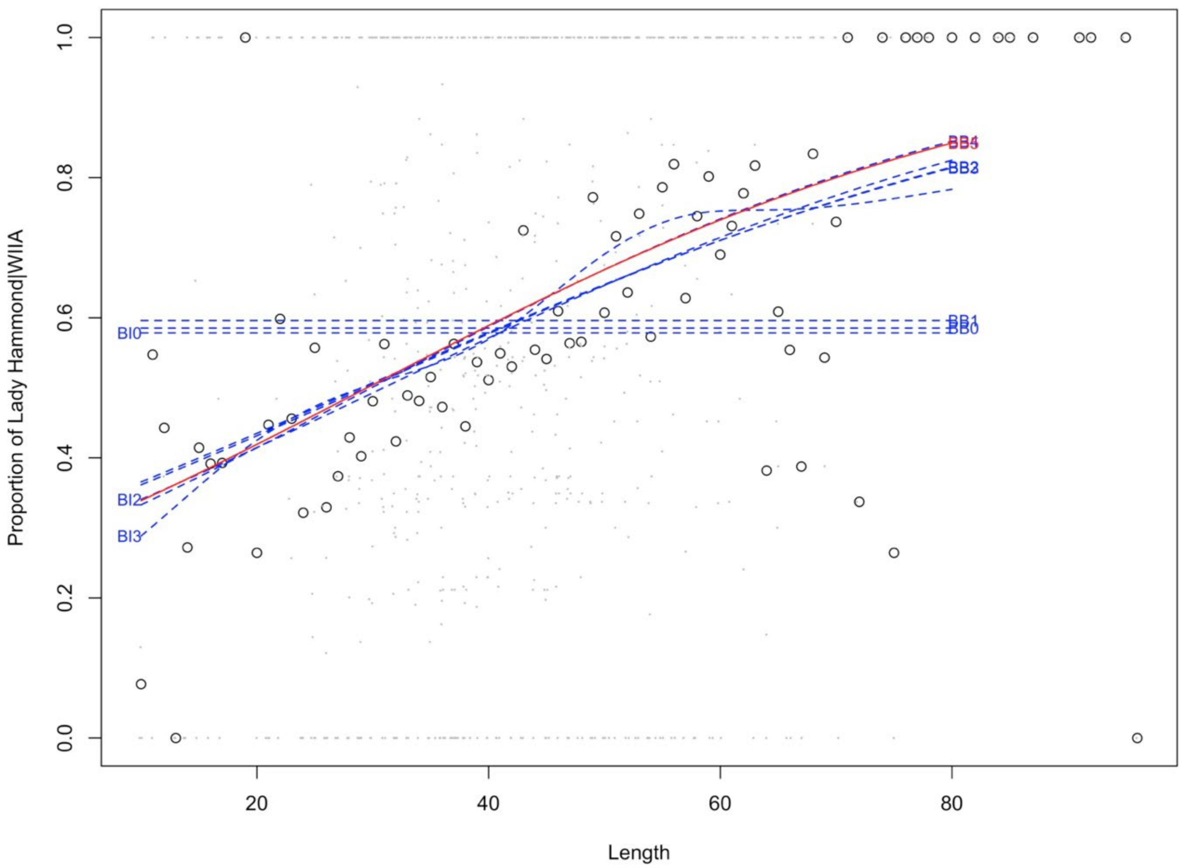

Figure 23. Reproduction of Figure 5 from Benoît et al. (2022), which presented the proportion of cod catch made by the Lady Hammond fishing the WIIA trawl in paired hauls with the Alfred Needler fishing the URI trawl during the 1990 comparative fishing experiment. Proportions are presented as a function of fish length (cm), for individual haul pairs (small light grey dots) and for the length-specific sample average (circles). The solid red line indicates the estimated conversion based on the selected best model, while the blue dashed lines are for other converged models (details in Benoît et al. 2022).

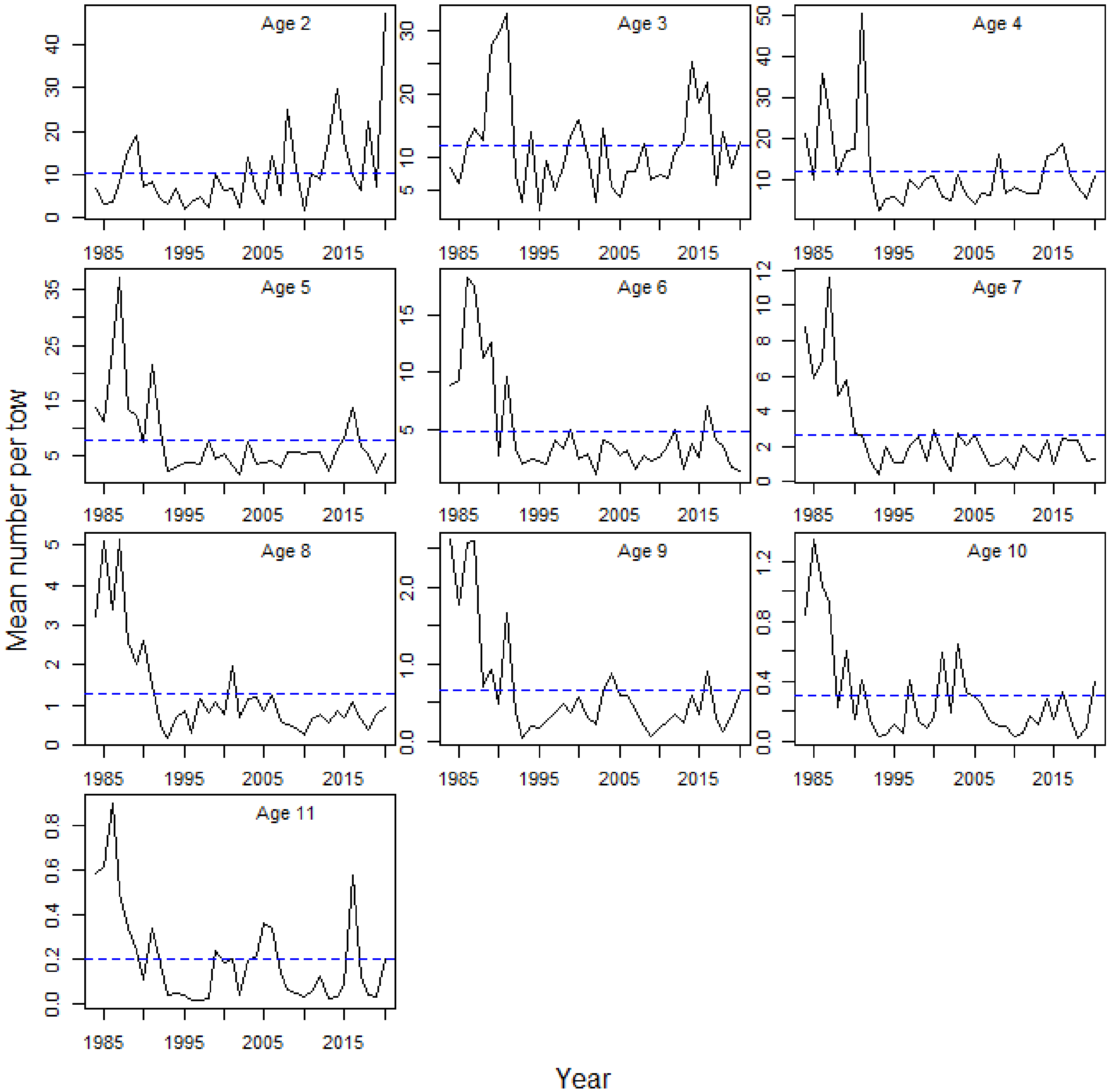

Figure 24. Age-specific abundance index values (mean number per tow) for 1984–2020 in the DFO multispecies bottom-trawl RV survey. The dashed blue line indicates the time series mean value. Note that the panel for age 11 represents mean number per tow for 11+.

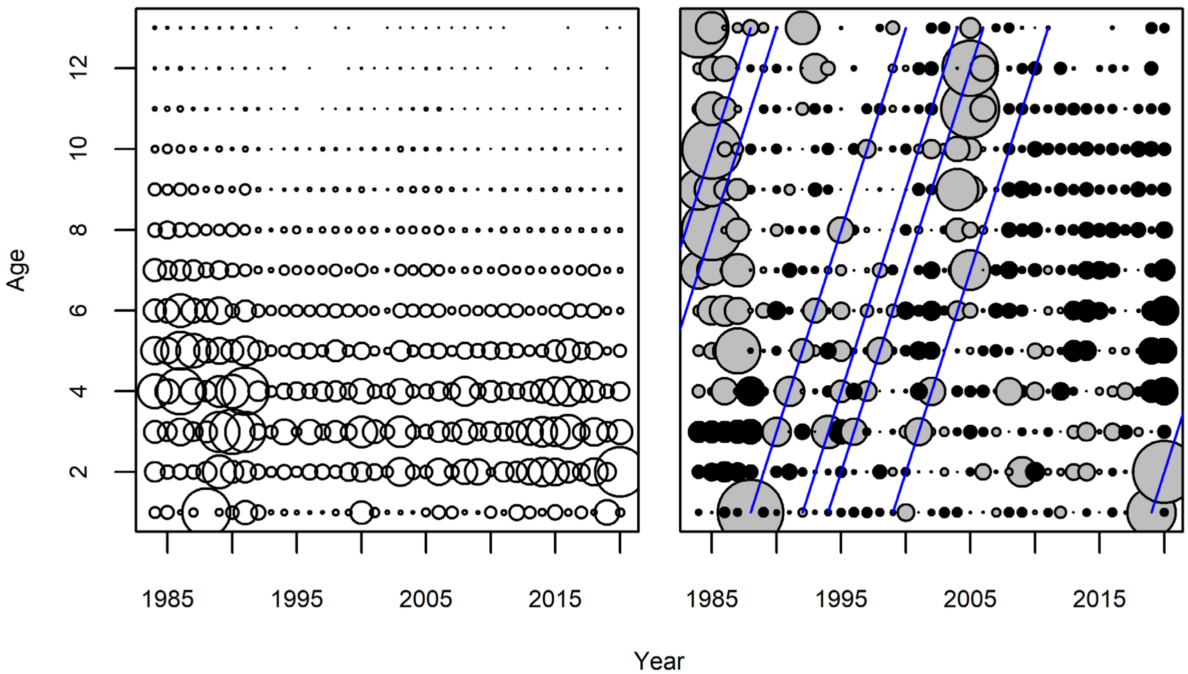

Figure 25. Reprise of Figure 17a from Benoît et al. (2022), showing catch at age in the RV survey for 1984–2020 based on the reduced suite of strata. The left panel shows catch proportional to circle size, while the right panel shows standardized proportions at age and year (SPAY) with grey circles indicating above average catch and black below average. The blue lines indicate some consistently tracked above average cohorts in the survey.

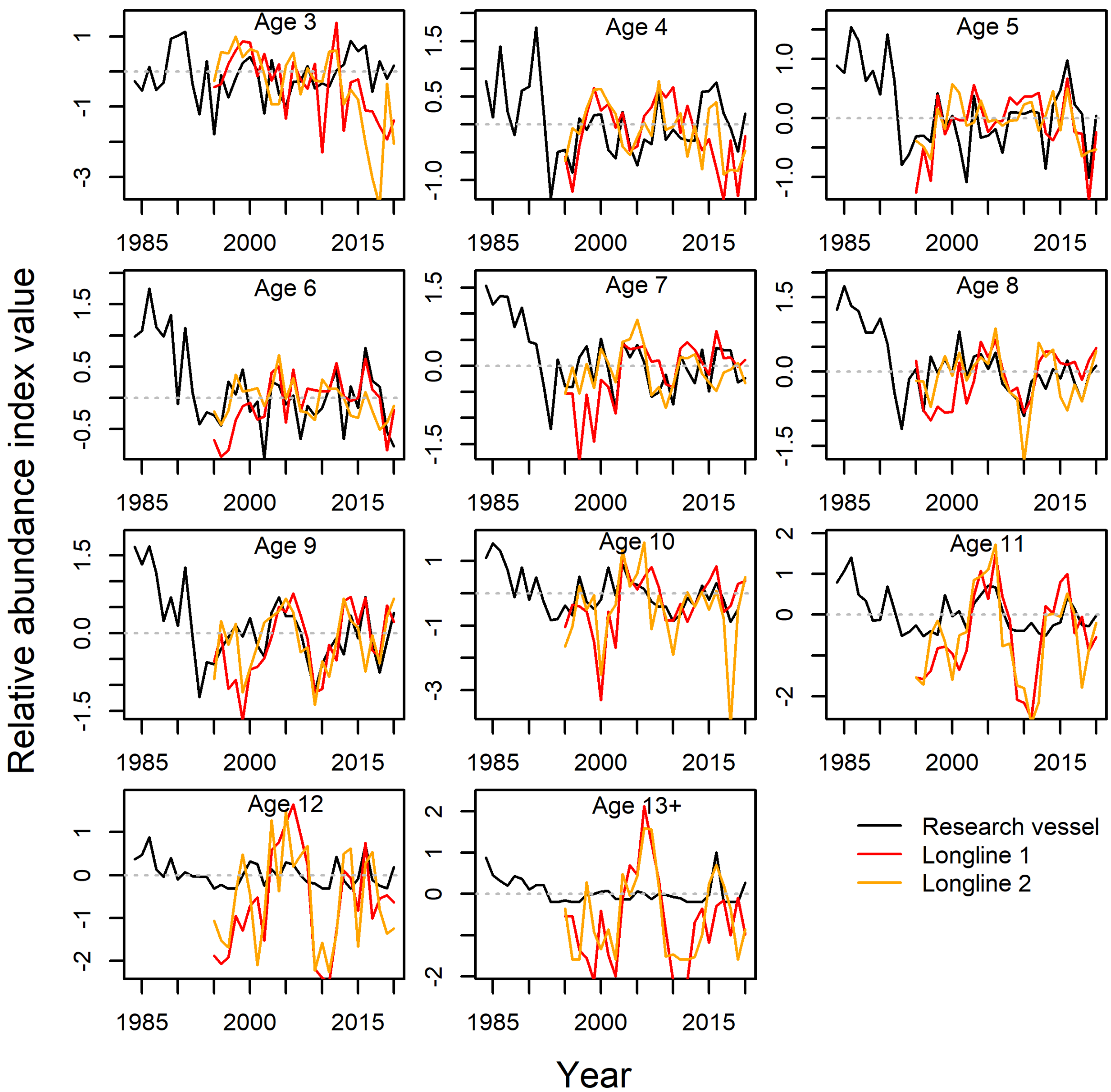

Figure 26. Log relativized abundance index values by age (panels) for the DFO bottom-trawl RV survey and the two Sentinel longline indices. The relativized values were calculated by dividing the abundance indices by survey and age specific mean values for 1995–2020. Results for age 2 are excluded because these cod are not well sampled in the Sentinel fixed gear surveys.

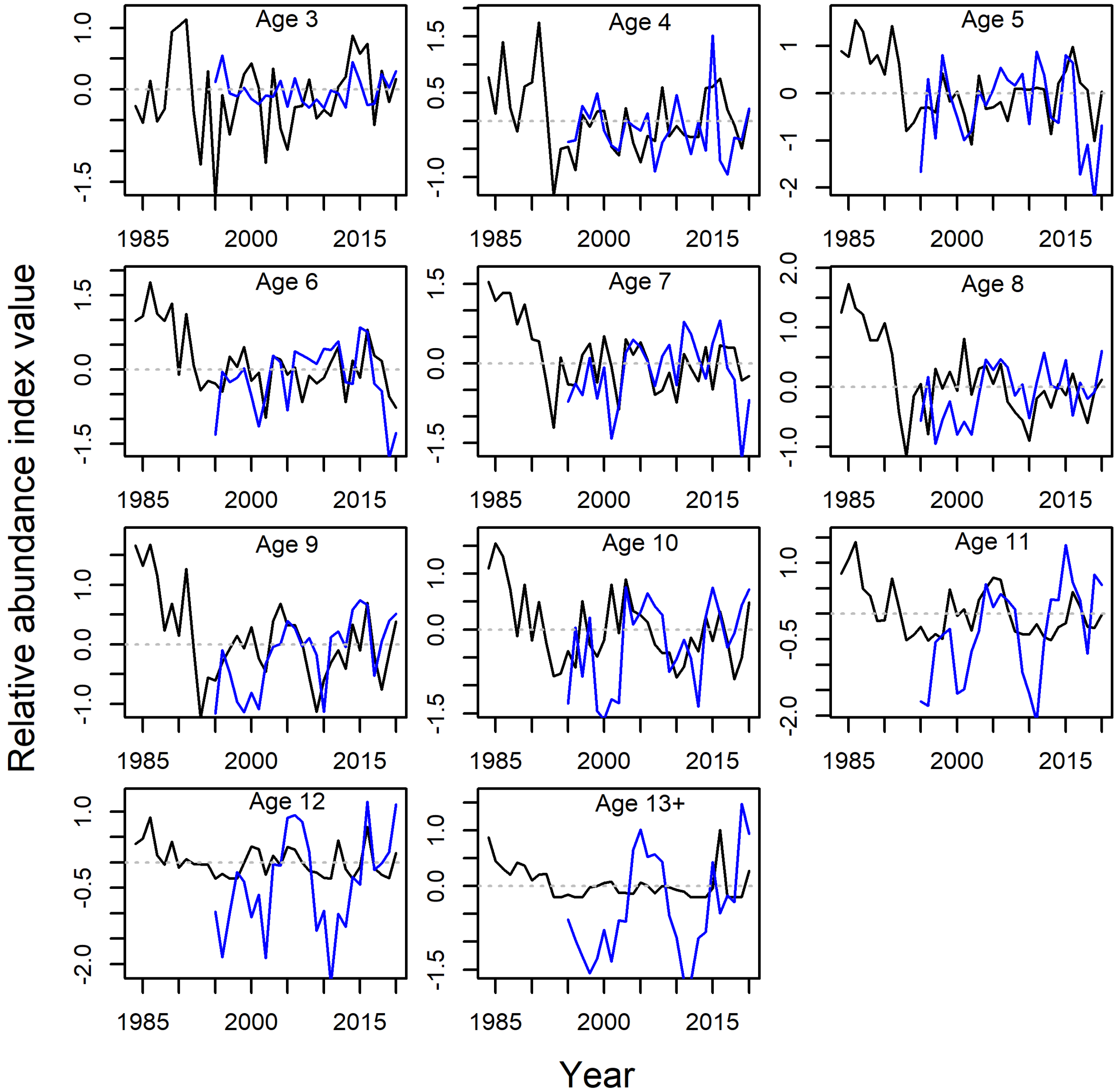

Figure 27. Log relativized abundance index values by age (panels) for the DFO bottom-trawl RV survey (black) and the Sentinel gillnet index (blue). The relativized values were calculated by dividing the abundance indices by survey and age specific mean values for 1995–2020. Results for age 2 are excluded because these cod are not well sampled in the Sentinel fixed gear surveys.

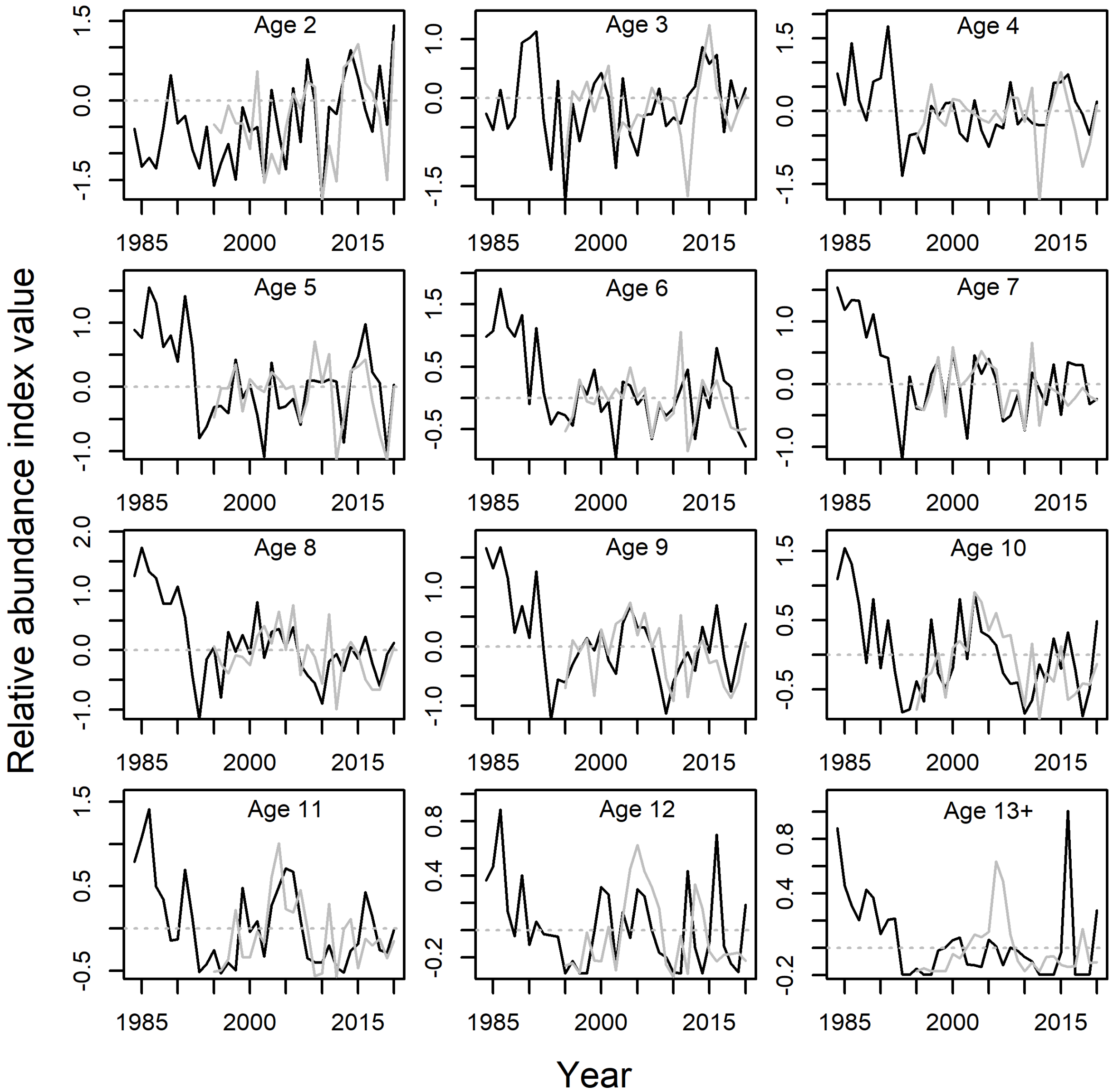

Figure 28. Log relativized abundance index values by age (panels) for the DFO bottom-trawl RV survey (black) and the Sentinel mobile trawl survey index (solid grey). The relativized values were calculated by dividing the abundance indices by survey and age specific mean values for 1995–2020. Results for age 2 are included.

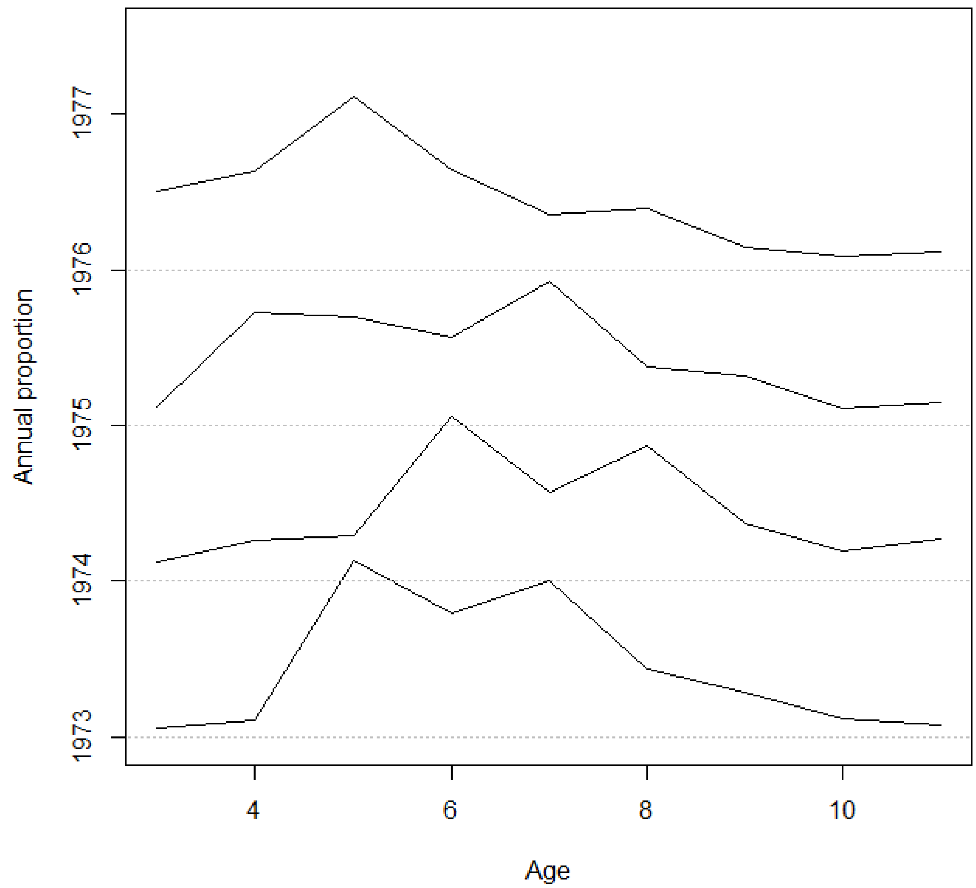

Figure 29. Annual age-specific proportion of cod captured in the 1973–1976 surveys reported by Minet (1978).