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Assessing the Productivity of the Georges Bank ‘a’ and Browns Bank North Offshore Scallop Stocks and the Impact of Two-Year Projection Advice

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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

Georges Bank ‘a’ (GBa) and Browns Bank North (BBn) comprise the majority of catches from the Offshore Scallop fishery in the Fisheries and Oceans Canada (DFO) Maritimes Region. Each stock is managed using a total allowable catch (TAC) and has an annual analytical assessment that uses a modified version of a state-space delay-difference population model to provide a one-year biomass projection to inform the setting of the harvest level. However, in 2020, the DFO Science Offshore Scallop survey was cancelled due to challenges associated with the COVID-19 pandemic. In the absence of survey data, two-year model projections are needed to update the stock status for 2021. The objectives of this document are to evaluate the productivity of these stocks based on the population assessment models, to derive two-year model projections to inform the final TAC decisions for 2021, and to evaluate the impact and uncertainty of the two-year model projections. For GBa, the surplus production rate estimates ranged from 0.25 to 0.27, which is consistent with previous estimates. For BBn, the surplus production rate estimates ranged from 0.13 to 0.15, which is higher than previous estimates. The scallop stocks on GBa and BBn demonstrate substantial interannual variability in their productivity such that, relative to the use of one-year projections, use of two-year projections as the basis for management decisions over the long term would result in substantial risk of either loss in potential catch or overharvesting. However, in the context of tactical one-year decision making and in the absence of 2020 survey data, these two-year projections provide context for decision making for the 2021 harvest level. For the two-year projection scenarios evaluated, the probability that the GBa 2021 fully recruited biomass would be above the upper stock reference and in the healthy zone after removing 4,000 mt (the 2021 interim TAC) is at least 0.98; this is predicted to result in an exploitation rate between 0.08 and 0.1 and an expected range of biomass change between −10% and 18%. For BBn, for the two-year projection scenarios, removing 300 mt (the 2021 interim TAC) is predicted to result in an exploitation rate between 0.12 and 0.14 and corresponds to an expected range of biomass change between −14% and 1%.

INTRODUCTION

Georges Bank ‘a’ (GBa) and Browns Bank North (BBn) (Figure 1) comprise the majority of catches from the Offshore Scallop fishery in the Fisheries and Oceans Canada (DFO) Maritimes Region. These two banks comprised > 80% of the total landings of scallop in 2019. The species landed is the sea scallop (*Placopecten magellanicus*) and the fishery for both banks occurs from January 1 through December 31. Each stock is managed using a total allowable catch (TAC) and has an annual analytical assessment that uses a modified version of a state-space delay-difference population model for modelling the population dynamics (Hilborn and Walters 1992). This approach to modelling the population dynamics of sea scallops on Georges Bank was introduced through the GBa scallop framework assessment in 2008 (Jonsen et al. 2009), and was subsequently implemented for BBn in 2011 (Hubley et al. 2011). This approach has been used since 2008 and 2011, respectively, to provide annual harvest advice.

The operational models are used to estimate population biomass, recruitment (to the fishery), exploitation rate, and provide advice on catch levels in the following year. Indices used in the models come from annual survey and commercial catch data. High intensity collaborative joint DFO-Industry surveys occur annually in May for BBn and August for GBa. Survey data collected in spring and summer, respectively, are processed and analyzed, with survey trends provided in the fall at the Offshore Scallop Advisory Committee (OSAC) meeting to inform the setting of interim TACs for January 1st; the start of the fishing season. Formal advice through the Canadian Science Advisory Secretariat (CSAS) is subsequently provided in the spring to inform the setting of final TACs for the year. For each stock, the setting of the final TAC is informed by the one-year projection from the model; thus data up to year *t* are used by the model to forecast fully recruited biomass for year *t+1*. The present time frame between data acquisition from the surveys (May, August year *t*) and operational science advice to set management targets (spring in year *t+1*) means that catch advice is based on one-year projections. This time frame, between data acquisition and operational science advice, enables the broad fisheries objective of maximizing present catches, subject to the constraints of a sustainable harvesting regime, to be achieved.

In 2020, the DFO Science Offshore Scallop survey was cancelled due to challenges associated with the COVID-19 pandemic. In the absence of survey data, two-year model projections are needed to update the stock status for the GBa and BBn Scallop fisheries for 2021. The objectives of this document are to evaluate the productivity of these stocks based on the population assessment models, to derive two-year model projections to inform the final TAC decisions for 2021, and to evaluate the impact and uncertainty of the two-year model projections.

METHODS

DELAY DIFFERENCE MODEL

The operational model for GBa and BBn is a Bayesian state-space modified delay difference assessment model that integrates both fishery and survey data (Hubley et al. 2014). The model is fit to the survey estimates of fully recruited (≥ 95 mm shell height) biomass, recruit (85–94.9 mm shell height) biomass, and fishery catch per unit effort (CPUE, $\frac{kg}{hour \cdot metre}$). The formulation of the process equation is:

$$B_t = [e^{(-m_{fr(t)})} g_{fr(t-1)} (B_{t-1} - C_t) + e^{(-m_{r(t)})} g_{r(t-1)} R_{t-1}] \eta_t$$

Biomass in the current year (B_t) is a function of the previous year fully recruited biomass (B_{t-1}), with gains (inputs) due to recruitment (R_{t-1}) and growth (g_{fr} and g_r), and losses (outputs), due to natural mortality (on fully-recruited (m_{fr}) and recruit size scallop (m_r)) and catch (C). The process error term (η_t) represents the uncertainty in the model dynamics. Growth is the somatic growth of individual animals (meat weight), and recruit size scallop are those that are expected to grow to be fully recruited the following year. The modelled parameters are B, R, m_{fr}, m_r, and η. Note that natural mortality (m_{fr} and m_r) are modelled based on survey observations of empty, hinged scallop shells, called "clappers"; whereas, growth estimates are fixed parameters that are calculated each year (see details in Hubley et al. 2014).

Operational advice to inform harvesting decisions for the following fishing year is derived from projecting the model forward one year. This projection assumes that natural mortality m and process error (η) are unchanged from the most recent model estimates (e.g., $m_{2020} = m_{2019}$). Further, the growth calculations for the one-year projections utilize the size and condition of scallop from the most recent survey (Hubley et al. 2014). This projection is then evaluated for a range of potential catches to derive a catch scenario table. A catch scenario table presents a range of catches, and the associated exploitation rates, probabilities of decline, expected change in biomass, and, in the case of GBa, the probabilities that the biomass will exceed the upper stock reference (USR) and limit reference point (LRP) (e.g., DFO 2020).

PRODUCTIVITY AND SURPLUS PRODUCTION

The productivity of scallop stocks in the Maritimes Region has previously been discussed by Smith and Hubley (2012) in the context of reference points; however, here the drivers of scallop productivity for the GBa and BBn stocks as it relates to informing projections from the operational model are reviewed. The productivity of GBa and BBn scallop stocks is described by the amount or rate of production of new biomass by the stock over a given time frame. The overall productivity of a stock is important to its sustainable management; thus how much can be harvested in a given time frame. In the context of the timing of the monitoring surveys, this time frame corresponds to a year (the time between subsequent surveys). For a population to increase from its current size, gains due to recruitment and growth need to exceed losses due to natural mortality and catch; however, when losses from natural mortality and catch exceed gains from recruitment and growth, a population decrease is observed. Further, a population can remain the same size if gains and losses are equal.

The balance between gains and losses that includes catch, can be used to determine the change in fully recruited biomass (ΔB_{t+1}) between years:

$$\Delta B_{t+1} = B_{t+1} - B_t$$

The percentage biomass change (ΔPB_{t+1}) is defined as:

$$\Delta PB_{t+1} = 100 \times \frac{B_{t+1} - B_t}{B_t}$$

Further, surplus production (SP) for the stock can be defined as the difference between the biomass added to the population through growth and recruitment to the fishery, and the biomass removed by natural mortality. Therefore, at any level of fully recruited biomass, if catch removes less (more) than the biomass added due to surplus production, then the fully recruited biomass will increase (decrease). Walters et al. (2008) succinctly summarized SP as "the change in stock size that would have taken place if there had been no harvesting":

$$SP_t = \Delta B_{t+1} + C_t$$

With the surplus production rate (SP_{rate}) defined by:

$$SP_{rate(t)} = \frac{SP_t}{B_t}$$

To explore the productivity of the GBa and BBn scallop stocks, time series trends were developed for fully recruited biomass (B), recruit biomass (R), fully recruited and recruit natural mortality (m_{fr} and m_r), fully recruited and recruit growth (g_{fr} and g_r), and SP. For all modelled parameters (B, R, m_{fr}, m_r) the posterior medians were used, and the fixed parameter estimates for growth (g_{fr} and g_r) were used; time series medians were calculated using the full time series for each respective parameter. The relationships between SP and B were explored by plotting SP against *B*, while phase plots of fully recruited biomass and exploitation were also evaluated.

A heuristic approach was taken to evaluate how exploitation (e_t) influences changes in fully recruited biomass (ΔPB_t) :

$$\Delta PB_t = \alpha + \beta e_t + \epsilon_t$$

$$\epsilon_t \sim N(0, \sigma^2)$$

The exploitation associated with 0% change in biomass (ΔPB) is estimated from the X-intercept of these models.

The one-year projections (for *t+1*) rely upon observed R in year *t* and assumes that the current year parameter estimates of mortality and growth (m_{fr}, m_r, g_{fr}, g_r) are reliable estimates of these parameters in the following year. An analysis was undertaken to explore if there was any autocorrelation in the main model parameters (B, R, m_{fr}, m_r, g_{fr}, and g_r) or SP. Correlograms were developed using the time series of each of these parameters with the significance of the autocorrelation assessed using the 95% confidence intervals.

TWO-YEAR PROJECTIONS AND IMPACT ASSESSMENT

One-year model projections have been operationalized for harvest advice for GBa and BBn since the current analytical frameworks of the Bayesian state-space delay difference model were implemented (Jonsen et al. 2009, Hubley et al. 2011). These one-year projections assume natural mortality is unchanged from the current year (e.g., that natural mortality in 2020 will be unchanged from 2019), and use the growth of fully recruited (g_{fr}) and recruit (g_r) size scallop calculated from the most recent survey. To evaluate the performance of the one-year model projections, the catch assumption for the one-year model projections was set to the realized catch for each respective year.

Two-year model projection scenarios were informed based on the results from the evaluation of the productivity parameter analyses. To derive two-year model projections, the one-year projections of the fully recruited biomass posteriors (where catch was set to the realized catch for each respective year) were projected forward under 3 scenarios: 1) zero surplus production, 2) median surplus production (for the respective stock), and 3) assuming the same R, m_{fr}, m_r, g_{fr}, g_r and η as the one-year projection (i.e., same conditions as the one-year projection), hereafter referred to as the ‘status quo’ assumption.

The performance of the model’s predictions of biomass in the following year (P_{y1}: one-year projection) and in two years (P_{y2}: two-year projection) were evaluated by comparing model predictions from fits to the data up to year *t* (e.g., 2012) to the posterior distribution of the fully recruited biomass in year *t* based on model fit to year *t−1* (e.g., 2011), and to the posterior distribution of the fully recruited biomass in year *t* based on model fit to year *t−2* (e.g., 2010). The performance of the two-year model projections were compared to the currently operationalized one-year projections by taking the difference in median biomass of the one-year and two-year projections (ΔP_{y2-y1}):

$$\Delta P_{y2-y1} = P_{y2} - P_{y1}$$

The proportional change in the projections between year 2 and year 1 (ΔPP_{y2-y1}) was also calculated using:

$$\Delta PP_{y2-y1} = \frac{P_{y2} - P_{y1}}{P_{y1}}$$

Change was considered different from 0 if it was $> |0.05|$ (i.e., $> |5\%|$).

To evaluate the impact of two-year model projections on harvest advice, the potential maximum catch and the difference in potential maximum catch, derived from the one- and two-year projections were assessed for each year from 2012 to 2020 for a harvest control rule (HCR) scenario for each stock. The HCR scenarios were based on the removal reference (RR) exploitation limit (i.e., associated maximum catch allowed under the RR; for GBa RR = 0.25, see DFO 2021). Since BBn does not have reference points, the exploitation associated with the observed zero change in fully recruited biomass from the productivity analysis was used (0.15).

All analyses were performed in R and the figures were developed using the tidyverse packages (Wickham 2016; R Core Team 2019).

RESULTS

GEORGES BANK ‘A’

Stock Productivity

Fully recruited biomass was above the long-term median (18,452 mt) in 2019 and has been above the long-term median since 2010 (Figure 2). Recruit biomass has been declining since a time series peak in 2009 and was near the long-term median (3,670 mt) in 2019 (Figure 3). Natural mortality of fully recruited and recruit size scallops has declined since 2014 and was below the long-term medians (0.10 and 0.16, respectively) in 2019 (Figure 4). Growth rates of fully recruited and recruit size scallops have displayed substantial interannual variability and in 2019 were below their respective long-term medians (1.27 and 1.52, respectively; Figure 5). Despite large interannual swings in growth, this stock has not observed negative growth (growth rate < 1), unlike other scallop stock areas (e.g., BBn results section and Sameoto et al. 2024). Substantial interannual variability in SP has been observed throughout the time series. The median yearly SP on GBa was 5,016 mt and the corresponding median SP rate was 0.27; however, negative SP has been observed six times between 1986 and 2019 (Figure 6). Correlograms indicated that fully recruited biomass was significantly autocorrelated at a lag of 1 year and marginally significant at lags of 2 years. Recruit biomass and natural mortality of fully recruited scallop also displayed significant autocorrelation at lags of one year, while natural mortality of recruits, growth rates, and SP displayed no autocorrelation between years (Figure 7).

On GBa, low and even negative SP has been observed at large biomass levels, and highly variable SP has been observed across a substantial range of fully recruited biomass levels (Figure 8). Since 2000, exploitation has been below 0.25 and the stock has remained in the healthy zone as defined under current reference points and the DFO Precautionary Approach (Figure 9, DFO 2021). Change in fully recruited biomass was significantly related to exploitation

(p = 0.02) and the exploitation corresponding to zero change in biomass over the time series was 0.25 (Figure 10).

Two-Year Projections

The performance of the model's prediction of biomass for the one- and two-year projections is presented in Figure 11. The two-year biomass projections were evaluated against three scenarios: zero SP, median SP, and the status quo assumption. As measured by the 90% credible interval, there was increased uncertainty in the two-year projection compared to the one-year projections. The two-year projections estimated an increased biomass range relative to the one-year projection in: 8 of 9 years under the zero surplus production scenario, in 9 of 9 years under the median surplus production scenario, and in 8 of 9 years for the status quo scenario. The relative performance of the two-year projection was sensitive to its assumptions and there was no single scenario that consistently improved the two-year model performance (Figure 11).

Georges Bank 'a' reference points are based on 30% and 80% of the mean modelled biomass from 1986 to 2009 (Smith and Hubley 2012, Hubley et al. 2014, DFO 2015). For all three two-year projection scenarios, the probability that the 2021 fully recruited biomass would be above the USR and in the healthy zone after removing 4,000 mt (the 2021 interim TAC) is at least 0.98 (Figure 12, Tables 1–3); this is predicted to result in an exploitation rate between 0.08 and 0.1 and correspond to an expected range of biomass change between −10% and 18%.

The plots of the relative difference in median biomass of the one- and two-year projections are presented in Figure 13, where negative (positive) values indicate that the two-year projected biomass for year *t* was lower (higher) than the one-year projected biomass in year *t*. For the zero SP scenario, the two-year projection was lower than the one-year projection for 8 of 9 years, and higher in 1 of 9 years; this difference ranged from −51% to 68% (−20,800 mt and 11,600 mt; left panel Figure 13). For the median SP scenario, the two-year projection was lower than the one-year projection in 4 of 9 years and higher in 5 of 9 years; the differences ranged from −37% to 120% (−15,200 mt and 19,900 mt; middle panel Figure 13). For the status quo scenario, the two-year projection was lower than the one-year projection for 2 of 9 years, higher in 5 of 9 years, and not different in 2 of 9 years; the differences ranged from −35% to 130% (−14,400 to 21,500 mt; right panel Figure 13).

The impact of using the two-year model projections as harvest advice was quantified through the evaluation of the difference in catch resulting from a one-year projection for year *t* at an exploitation of 0.25, and the resulting catch from a two-year projections for year *t* at an exploitation of 0.25. The catch values associated with an exploitation of 0.25 from the one- and two-year biomass projections from each year from 2012 to 2020 are presented in Figure 14. The relative difference between the one- and two-year catch values associated with an exploitation of 0.25 are shown in Figure 15. Negative (positive) differences indicate that the catch resulting from a two-year projection would be lower (higher) than the catch associated with a one-year projection. For the zero SP scenario, the catch from a two-year projection was lower than that of a one-year projection in 8 of 9 years and higher in 1 of 9 years; the difference in resulting catch ranged from −47% to 63% (−5,550 mt to 3,210 mt). For the median SP scenario, the catch from a two-year projection was lower than that of a one-year projection in 3 of 9 years, higher in 5 of 9 years, and not different in 1 of 9 years; the difference in resulting catch ranged from −33% to 110% (−3,810 mt to 5,520 mt). For the status quo scenario, the catch from a two-year projection was lower than that of a one-year projection in 2 of 9 years, higher in 5 of 9 years, and no different in 2 of 9 years; the difference in resulting catch ranged from −33% to 110% (−3,880 mt to 5,740 mt).

BROWN BANK NORTH

Stock Productivity

Fully recruited and recruit biomass were below their long-term medians (5,401 mt and 503 mt, respectively) in 2019 (Figure 16 and 17); however, the time series of fully recruited biomass is dominated by a single recruitment event that was first observed in the recruit size range in 2000. This recruitment event lasted from 2000 to 2002 and subsequently tripled the fully recruited biomass on BBn from 1999 to 2003 (Figures 16 and 17). There has been substantial interannual variability in the natural mortality of fully recruited and recruit size scallops and both were below their respective long-term medians (0.07 and 0.16) in 2019 (Figure 18). Growth rates of fully recruited and recruit size scallops also demonstrate substantial interannual variability and in 2019 were near their respective long-term medians (1.17 and 1.37); growth rates have generally been positive (i.e., above 1) with the exception of the fully recruited growth rate in 2000 (Figure 19). Substantial interannual variability in SP has been observed throughout the time series (Figure 20). The median yearly SP on BBn was 590 mt and the corresponding median SP rate was 0.13; however, negative SP has been observed seven times between 1991 and 2019 and the SP rate has varied from a minimum of −0.22 in 2005 to a maximum of 1.05 in 1992 (Figure 20). Correlograms indicated that fully recruited biomass was significantly autocorrelated at lags of one and two years, both SP and recruit biomass had significant autocorrelation at lags of one year, while natural mortality and the growth rates displayed no autocorrelation between years (Figure 21).

On BBn, the highest SP rates have been observed at the lowest levels of fully recruited biomass, with substantial variability in SP observed across similar biomass levels. Highly variable SP, including negative rates, has been observed across a substantial range of fully recruited biomass levels (Figure 22). Exploitation on BBn was below 0.15 with the exception of 1995, 1996, 2004, 2008, and 2017 (Figure 23). For 1996, 2008, and 2017, although exploitation was high, the fully recruited biomass did not substantially decline in the following year; this is likely due to the above average SP that occurred during, or immediately following, these higher exploitation years (Figure 20 and 23). Exploitation was significantly related to change in fully recruited biomass ($p < 0.01$) and the exploitation corresponding to zero change in biomass over the time series was 0.15 (Figure 24).

Two-Year Projections

The performance of the model's prediction of biomass for the one- and two-year projections is presented in Figure 25. The two-year biomass projections were evaluated against three scenarios: zero SP, median SP, and the status quo assumption. As measured by the 90% credible interval, there was increased uncertainty in the two-year projection compared to the one-year projection. The two-year projections estimated an increased biomass range relative to the one-year projection in 8 of 9 years under each scenario. The zero SP scenario performed well over the evaluated time period for BBn in comparison to the other two-year scenarios. There are currently no adopted reference points for BBn. Removing 300 mt (the 2021 interim TAC) is predicted to result in an exploitation rate between 0.12 and 0.14 for the three two-year projection scenarios evaluated, and corresponds to an expected range of biomass change between −14% and 1% (Figure 26, Tables 4–6).

The plots of the relative difference in median biomass of the one- and two-year projections are in Figure 27, where negative (positive) values indicate that the two-year projected biomass for year *t* was lower (higher) than the one-year projected biomass in year t. For the zero SP scenario, the two-year projection was lower than the one-year projection for 3 of 9 years, higher in 3 of 9 years, and not different in 3 of 9 years; this difference ranged from −44% to 21% (−1,810 mt and 768 mt; left panel Figure 27). For the median SP scenario, the two-year projection was lower than the one-year projection in 2 of 9 years, higher in 6 of 9 years, and not different in 1 of 9 years; the differences ranged from −36% to 37% (−1,500 mt and 1,490 mt; middle panel Figure 27). For the status quo scenario, the two-year projection was lower than the one-year projection for 2 of 9 years, 6 of 9 years were higher, and not different in 1 of 9 years; the differences ranged from −39 to 62% (−1,610 to 3,980 mt; right panel Figure 27).

The impact of using the two-year model projections as harvest advice was quantified through the evaluation of the potential difference in catch resulting from a one- and two-year projection for year *t* at an exploitation of 0.15. The catch values associated with an exploitation of 0.15 from the one- and two-year biomass projections from each year from 2012 to 2020 are presented in Figure 28. The relative difference between the one- and two-year catch values associated with an exploitation of 0.15 are shown in Figure 29. Negative (positive) differences indicate that the catch resulting from a two-year projection would be lower (higher) than the catch associated with a one-year projection. For the zero SP scenario, the catch from a two-year projection was lower than that of a one-year projection in 3 of 9 years, higher in 3 of 9 years, and no different in 3 of 9 years; the difference in resulting catch ranged from −42% to 22% (−290 mt to 148 mt). For the median SP scenario, the catch from a two-year projection was lower than that of a one-year projection in 2 of 9 years, higher in 6 of 9 years, and not different in 1 of 9 years; the difference in resulting catch ranged from −35% to 37% (−240 mt to 245 mt). For the status quo scenario, the catch from a two-year projection was lower than that of a one-year projection in 2 of 9 years, higher in 6 of 9 years, and no different in 1 of 9 years; the difference in resulting catch ranged from −39% to 55% (−267 mt to 603 mt).

CONCLUSION

The scallop stocks on GBa and BBn demonstrate substantial interannual variability in their productivity and this is reflected in the lack of autocorrelation in the primary model parameters and in SP beyond a one-year lag. Relative to the use of one-year projections, use of two-year projections as the basis for management decisions over the long term would result in substantial risk of either loss in potential catch or overharvesting. Further, the evaluations of the two-year projection performance should be considered as independent trials and not as a time series. For example, had a two-year projection been used to decide the harvest level for GBa in year *t*, and the two-year biomass projection overestimated the one-year biomass by 100%, twice as much catch could be taken in that year and the consequences of this potential overharvesting would be carried forward into the following year(s). This analysis only evaluates the potential difference in harvest within a given year using a two-year projection, and not the future follow-on effects that may have occurred had this decision been taken. In the context of tactical one-year decision making and in the absence of 2020 survey data, these two-year projections provide context for decision making on the 2021 harvest levels.

For GBa, the median long-term SP rate (0.27) and the results of the zero-change in biomass analyses (0.25) are in agreement with previous analyses of this stock. Jonsen et al. (2009) reported 0.27 as the exploitation rate that resulted in no change in biomass (1981 to 2007) and the industry proposed the mean exploitation of 0.25 as the RR for the Precautionary Approach, which was subsequently adopted by DFO (Smith and Hubley 2012, DFO 2021). Although there was autocorrelation in some parameters, the cumulative effect of these parameters in the resulting surplus production showed no significant autocorrelation. This was reflected by the variable interannual surplus production observed and there being no clear ‘best’ scenario to assume for the two-year projection. Although no two-year projection scenario assuming negative surplus production was evaluated, it is acknowledged that negative surplus production has been observed 18% of the time in this stock. For all three two-year projection scenarios, the probability that the 2021 fully recruited biomass would be above the USR and in the healthy zone after removing 4,000 mt (the 2021 interim TAC) is at least 0.98; this is predicted to result in an exploitation rate between 0.08 and 0.1 and correspond to an expected range of biomass change between −10% and 18%.

For BBn, the median long-term SP rate (0.13) and the results of the zero-change in biomass analyses (0.15) supports a higher surplus production rate than reported previously for this stock. Smith and Hubley (2012) reported 0.09 as the exploitation rate that resulted in no change in biomass (1991 to 2010). There was significant autocorrelation in the surplus production and recruit biomass time series at one-year lags and in fully recruited biomasses at one- and two-year lags. However, this two-year autocorrelation did not translate to reliable two-year projections under the scenarios evaluated in this analysis. The status quo and median SP scenarios for the two-year projection tended to overestimate the fully recruited biomass compared to the one-year projection. The zero SP scenario tended to provide better two-year projections than these other scenarios because there have not been any major fluctuations in fully recruited biomass during the evaluated time period (large fluctuations in fully recruited biomass were observed pre-2010). Although no two-year projection scenario assuming negative surplus production was evaluated, it is acknowledged that negative surplus production has been observed 25% of the time in this stock. For all three two-year projection scenarios, removing 300 mt (the 2021 interim TAC) is predicted to result in an exploitation rate between 0.12 and 0.14 and correspond to an expected range of biomass change between −14% and 1%.

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TABLES

Table 1. Catch scenarios for Georges Bank ‘a’ in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass and exceeding the upper stock reference (USR) and limit reference point (LRP). These probabilities account for uncertainty in the biomass forecasts and are presented assuming zero surplus production from 2020 to 2021.

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)	Probability biomass will exceed LRP	Probability biomass will exceed USR
1,800	0.05	0.56	−5.0	> 0.99	0.98
2,300	0.06	0.57	−6.0	> 0.99	0.98
2,700	0.07	0.59	−7.1	> 0.99	0.98
3,100	0.08	0.60	−7.9	> 0.99	0.98
3,600	0.09	0.61	−9.1	> 0.99	0.98
4,000	0.10	0.63	−10.1	> 0.99	0.98
4,400	0.11	0.64	−10.8	> 0.99	0.98
4,900	0.12	0.65	−12.0	> 0.99	0.98
5,200	0.13	0.66	−13.2	> 0.99	0.98
5,700	0.14	0.68	−14.0	> 0.99	0.97
6,100	0.15	0.69	−15.1	> 0.99	0.97
6,600	0.16	0.70	−15.9	> 0.99	0.97
7,000	0.17	0.72	−17.2	> 0.99	0.97
7,400	0.18	0.73	−18.1	> 0.99	0.97
7,800	0.19	0.74	−19.0	> 0.99	0.97
8,300	0.20	0.75	−20.2	> 0.99	0.96
8,700	0.21	0.77	−21.3	> 0.99	0.97
9,200	0.22	0.77	−21.7	> 0.99	0.96
9,600	0.23	0.79	−23.3	> 0.99	0.96
10,000	0.24	0.80	−24.3	> 0.99	0.96
10,500	0.25	0.81	−24.9	> 0.99	0.96

Table 2. Catch scenarios for Georges Bank 'a' in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass and exceeding the upper stock reference (USR) and limit reference point (LRP). These probabilities account for uncertainty in the biomass forecasts and are presented assuming the time series median surplus production (0.27) from 2020 to 2021.

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)	Probability biomass will exceed LRP	Probability biomass will exceed USR
2,400	0.05	0.28	20.9	> 0.99	0.99
3,000	0.06	0.29	19.9	> 0.99	0.99
3,500	0.07	0.30	18.6	> 0.99	0.99
4,100	0.08	0.31	17.6	> 0.99	0.99
4,600	0.09	0.33	16.0	> 0.99	0.99
5,200	0.10	0.34	14.5	> 0.99	0.99
5,700	0.11	0.36	13.1	> 0.99	0.99
6,300	0.12	0.36	12.5	> 0.99	0.99
6,900	0.13	0.37	11.1	> 0.99	0.99
7,300	0.14	0.39	9.2	> 0.99	0.99
8,000	0.15	0.40	8.5	> 0.99	0.99
8,400	0.16	0.42	7.2	> 0.99	0.99
9,000	0.17	0.43	5.8	> 0.99	0.99
9,600	0.18	0.44	4.7	> 0.99	0.99
10,100	0.19	0.46	2.9	> 0.99	0.99
10,700	0.20	0.48	2.0	> 0.99	0.99
11,200	0.21	0.49	0.8	> 0.99	0.99
11,700	0.22	0.51	−0.8	> 0.99	0.99
12,300	0.23	0.52	−1.9	> 0.99	0.99
12,800	0.24	0.54	−3.2	> 0.99	0.98
13,300	0.25	0.56	−4.7	> 0.99	0.98

Table 3. Catch scenarios for Georges Bank 'a' in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass and exceeding the upper stock reference (USR) and limit reference point (LRP). These probabilities account for uncertainty in the biomass forecasts and are presented assuming the status quo assumption (same recruitment, mortality, and growth as for the 2020 projection).

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)	Probability biomass will exceed LRP	Probability biomass will exceed USR
2,400	0.05	0.28	20.9	> 0.99	> 0.99
3,000	0.06	0.29	20.1	> 0.99	> 0.99
3,500	0.07	0.30	18.7	> 0.99	> 0.99
4,100	0.08	0.31	17.2	> 0.99	> 0.99
4,600	0.09	0.33	16.0	> 0.99	> 0.99
5,200	0.10	0.33	15.1	> 0.99	> 0.99
5,700	0.11	0.35	13.5	> 0.99	0.99
6,200	0.12	0.36	12.7	> 0.99	0.99
6,800	0.13	0.38	10.9	> 0.99	0.99
7,400	0.14	0.38	10.2	> 0.99	0.99
7,900	0.15	0.40	8.7	> 0.99	0.99
8,400	0.16	0.41	7.6	> 0.99	0.99
9,000	0.17	0.43	6.1	> 0.99	0.99
9,600	0.18	0.44	4.7	> 0.99	0.99
10,100	0.19	0.46	3.6	> 0.99	0.99
10,600	0.20	0.47	2.3	> 0.99	0.99
11,200	0.21	0.49	1.0	> 0.99	0.99
11,800	0.22	0.51	−0.4	> 0.99	0.99
12,300	0.23	0.52	−1.6	> 0.99	0.99
12,800	0.24	0.53	−2.7	> 0.99	0.99
13,400	0.25	0.55	−4.3	> 0.99	0.99

Table 4. Catch scenarios for Browns Bank North in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass. These probabilities account for uncertainty in the biomass forecasts and are presented assuming zero surplus production from 2020 to 2021.

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)
60	0.08	0.62	−7.8
100	0.09	0.63	−8.9
140	0.10	0.65	−9.9
180	0.11	0.66	−11.0
220	0.12	0.68	−11.7
260	0.13	0.69	−12.8
300	0.14	0.71	−14.1
350	0.15	0.73	−14.9
390	0.16	0.73	−16.0
430	0.17	0.75	−17.0
470	0.18	0.76	−17.9
510	0.19	0.78	−18.9
550	0.20	0.79	−20.3
590	0.21	0.80	−21.0
630	0.22	0.81	−22.1
670	0.23	0.82	−23.0
720	0.24	0.83	−23.7
750	0.25	0.85	−25.0

Table 5. Catch scenarios for Browns Bank North in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass. These probabilities account for uncertainty in the biomass forecasts and are presented assuming the time series median surplus production (0.13) from 2020 to 2021.

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)
100	0.08	0.44	4.2
150	0.09	0.46	2.6
190	0.10	0.48	1.3
240	0.11	0.49	0.9
280	0.12	0.51	−0.7
330	0.13	0.52	−1.6
380	0.14	0.54	−3.0
420	0.15	0.56	−4.1
470	0.16	0.58	−5.3
510	0.17	0.59	−6.4
560	0.18	0.61	−7.5
610	0.19	0.63	−8.5
660	0.20	0.65	−10.2
700	0.21	0.66	−10.6
740	0.22	0.68	−12.1
800	0.23	0.69	−12.7
840	0.24	0.71	−14.5
880	0.25	0.73	−15.5

Table 6. Catch scenarios for Browns Bank North in 2021 in terms of exploitation and expected changes in fully recruited biomass. Potential catches in 2021 are evaluated in terms of the probability of a decline in biomass. These probabilities account for uncertainty in the biomass forecasts and are presented assuming the status quo assumption (same recruitment, mortality, and growth as for the 2020 projection).

Catch (mt)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)
110	0.08	0.42	5.9
150	0.09	0.44	4.6
200	0.10	0.46	3.0
250	0.11	0.47	2.3
290	0.12	0.48	1.1
340	0.13	0.51	−0.4
380	0.14	0.53	−1.8
440	0.15	0.53	−2.1
480	0.16	0.55	−3.7
530	0.17	0.56	−4.3
580	0.18	0.59	−5.9
620	0.19	0.61	−7.5
670	0.20	0.62	−7.9
720	0.21	0.63	−9.1
770	0.22	0.65	−10.2
810	0.23	0.67	−11.5
860	0.24	0.69	−12.8
910	0.25	0.70	−13.6

FIGURES

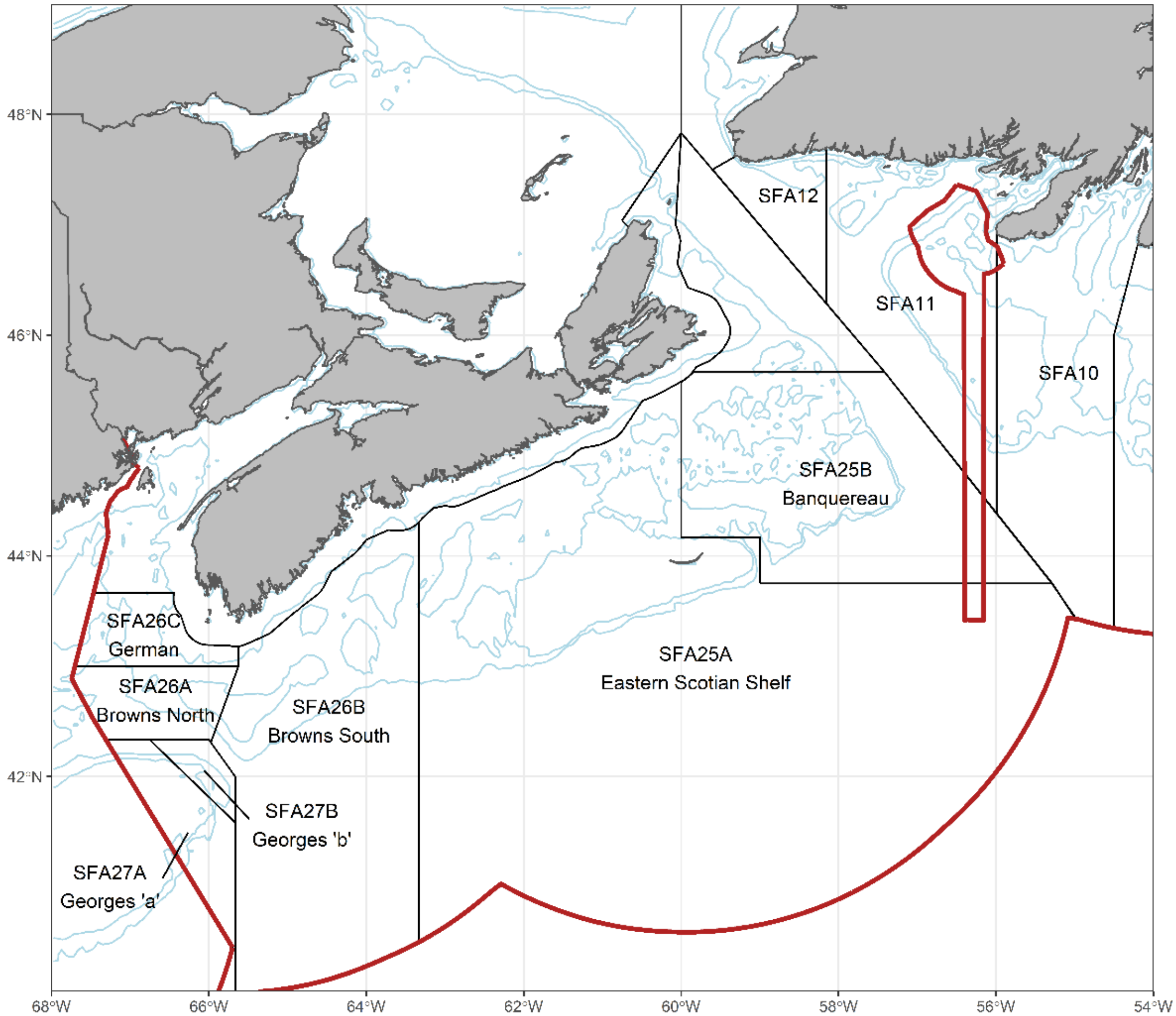

Figure 1. Map of Offshore Scallop Fishing Areas (SFAs) used for management purposes in the Maritimes Region. Note the division of Browns Bank North as a subarea of SFA 26 and of Georges Bank 'a' as a subarea of SFA 27.

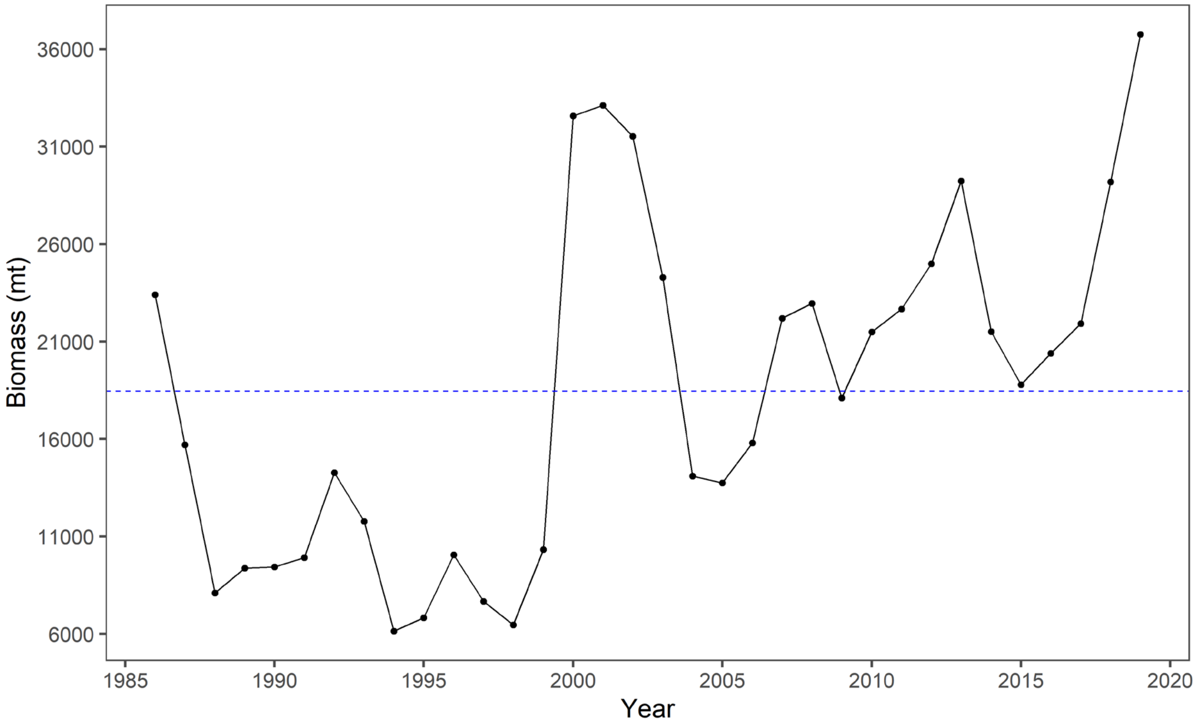

Figure 2. Time series of median biomass (meats, tonnes) estimates of fully recruited scallops from the stock assessment model fit to Georges Bank 'a.' The blue dashed line represents the long-term median (1986–2019).

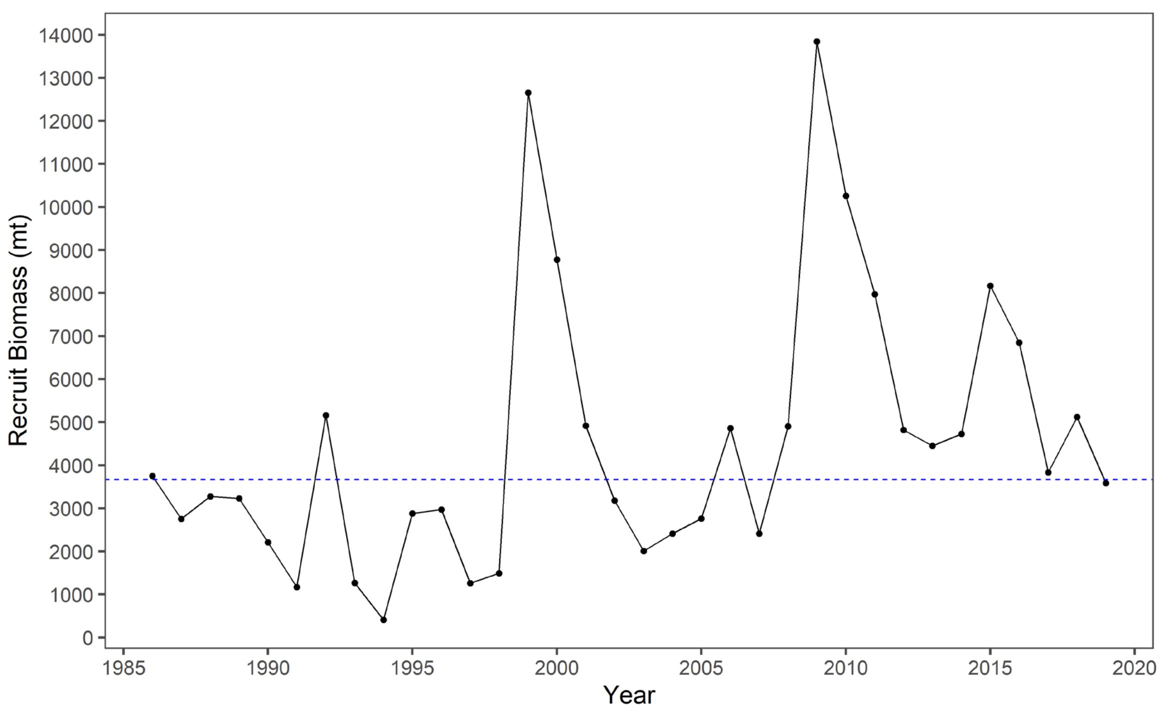

Figure 3. Time series of median biomass (meats, tonnes) estimates of recruit scallops from the stock assessment model fit to Georges Bank 'a.' The blue dashed line represents the long-term median (1986–2019).

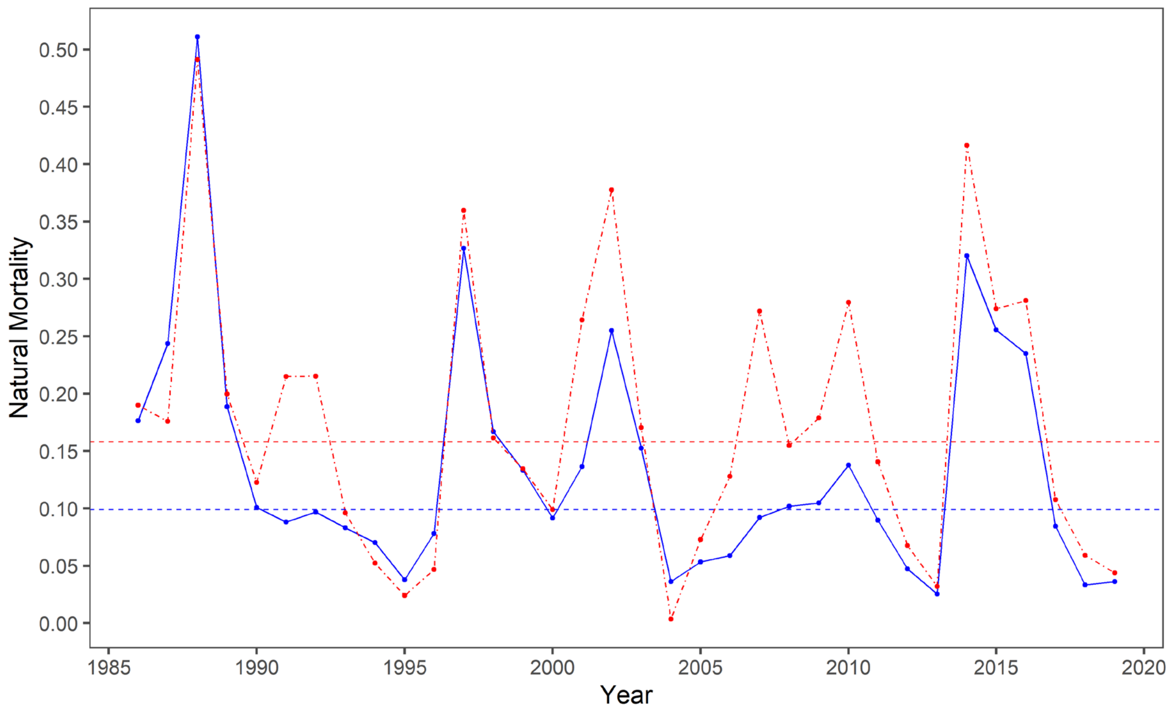

Figure 4. Time series of median natural mortality (proportion) estimates for fully recruited (blue) and recruit (red) scallop from the stock assessment model fit to Georges Bank 'a.' The blue and red dashed lines represents the long-term medians (1986–2019) for fully recruited and recruit scallops, respectively.

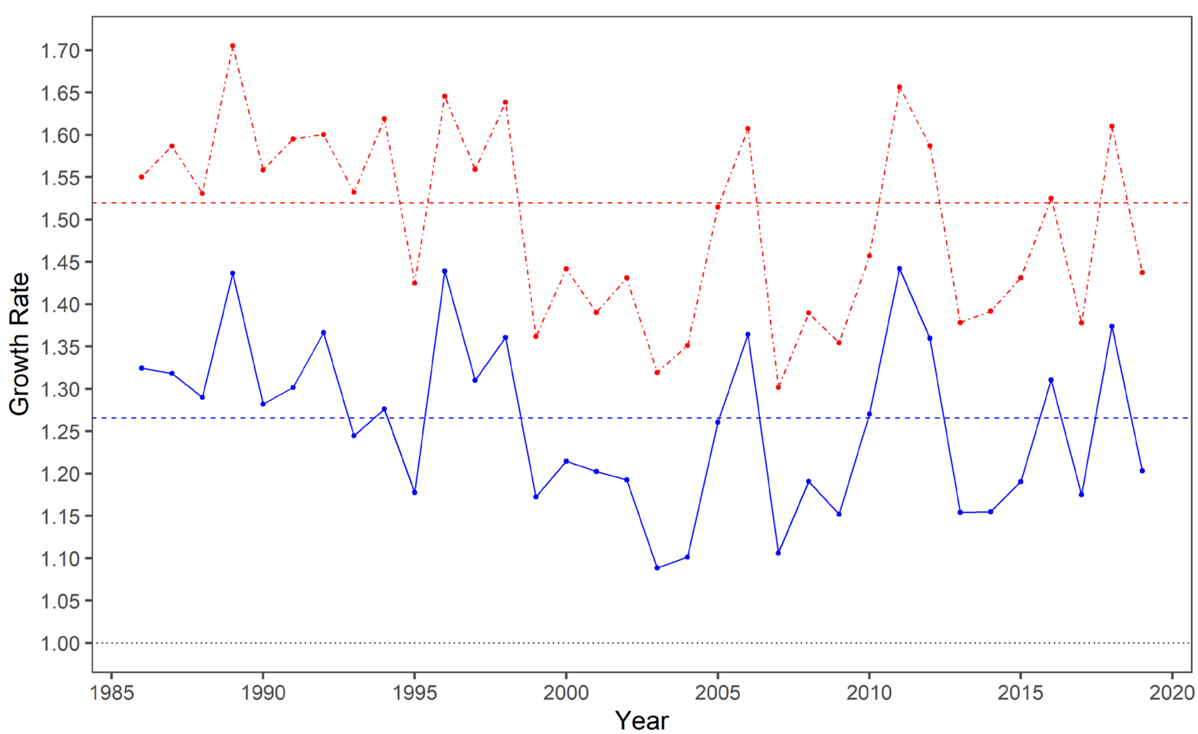

Figure 5. Time series of fully recruited growth rate (blue) and recruit growth rate (red) for Georges Bank 'a.' The blue and red dashed lines represents the long-term medians (1986–2019) for fully recruited and recruit scallops, respectively.

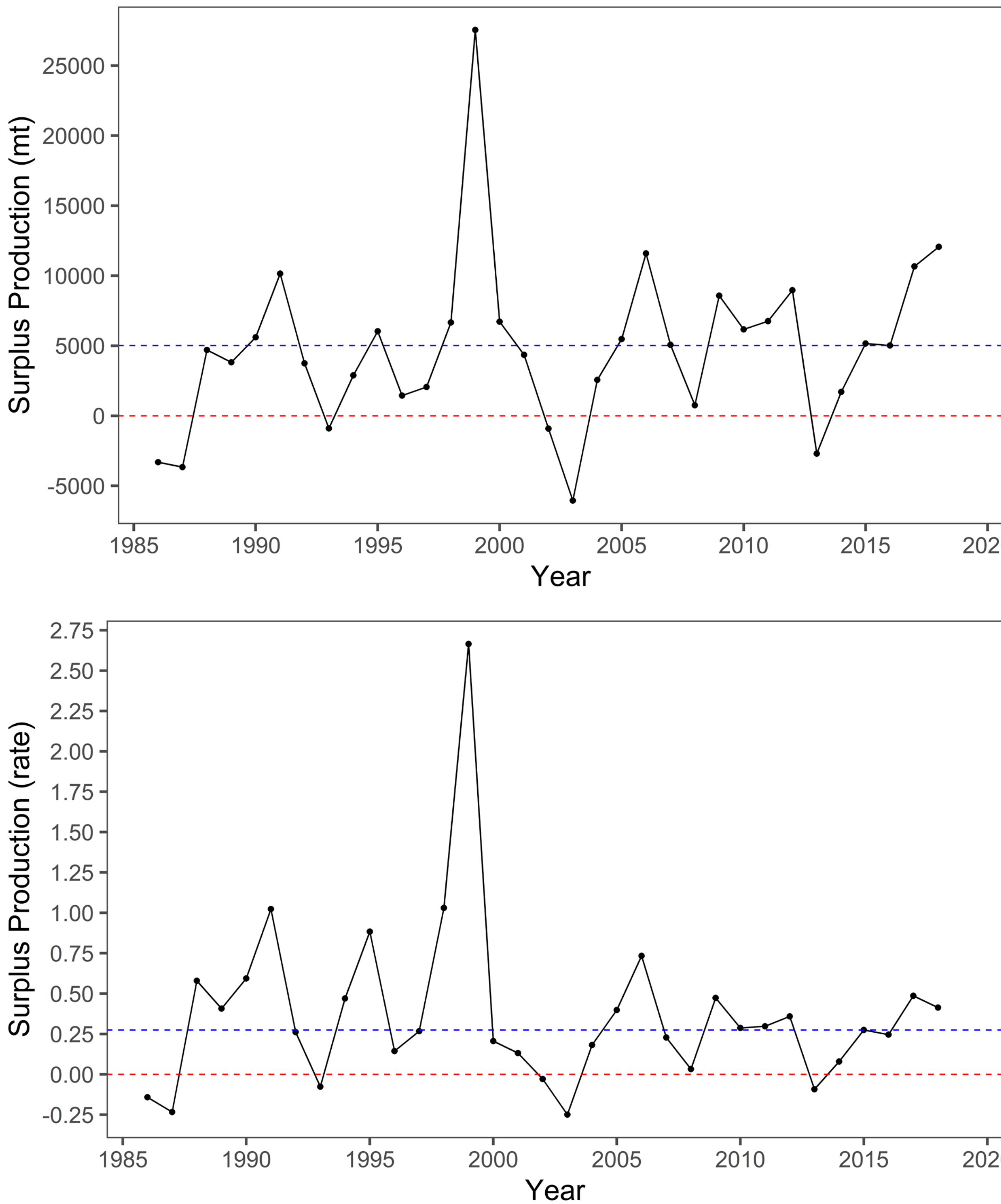

Figure 6. Time series of surplus production (meats, tonnes) (top panel) and surplus production rate (bottom panel) of fully recruited biomass for Georges Bank 'a.' The blue dashed lines represents the long-term medians (1986–2019) and the red dashed lines represent zero surplus production.

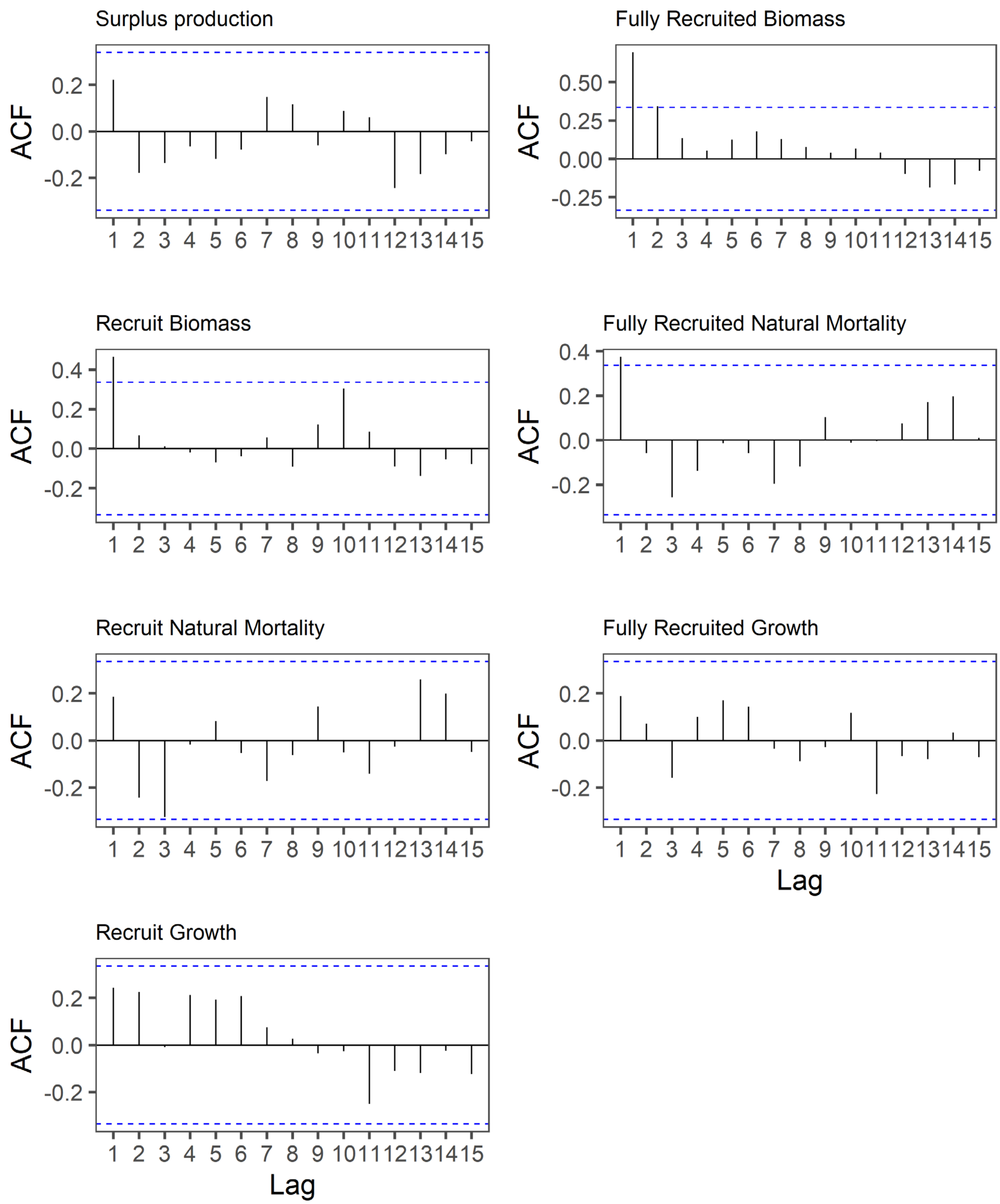

Figure 7. Autocorrelation (ACF) in the assessment model parameters and surplus production time series for Georges Bank 'a.' The blue dashed lines represent the 95% confidence intervals.

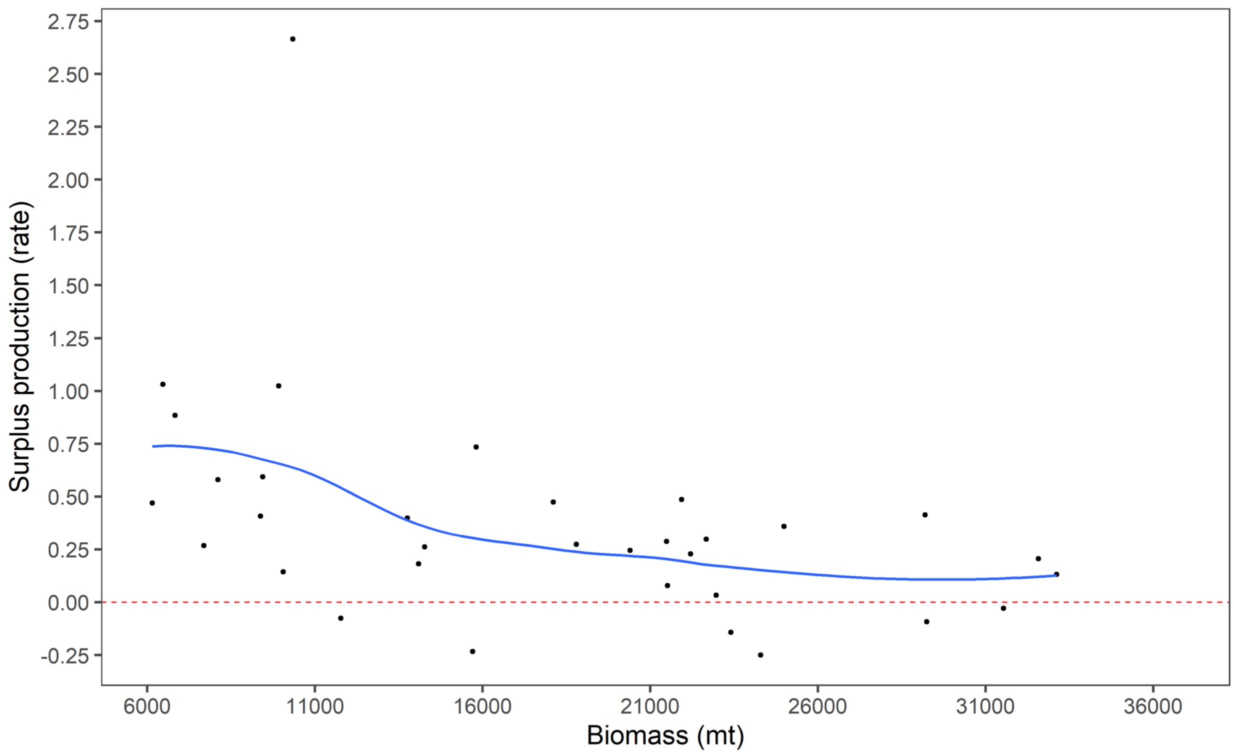

Figure 8. Surplus production (rate) of fully recruited biomass for Georges Bank 'a.' The red dashed line represent zero surplus production. The blue line represents a loess curve added to detect trend.

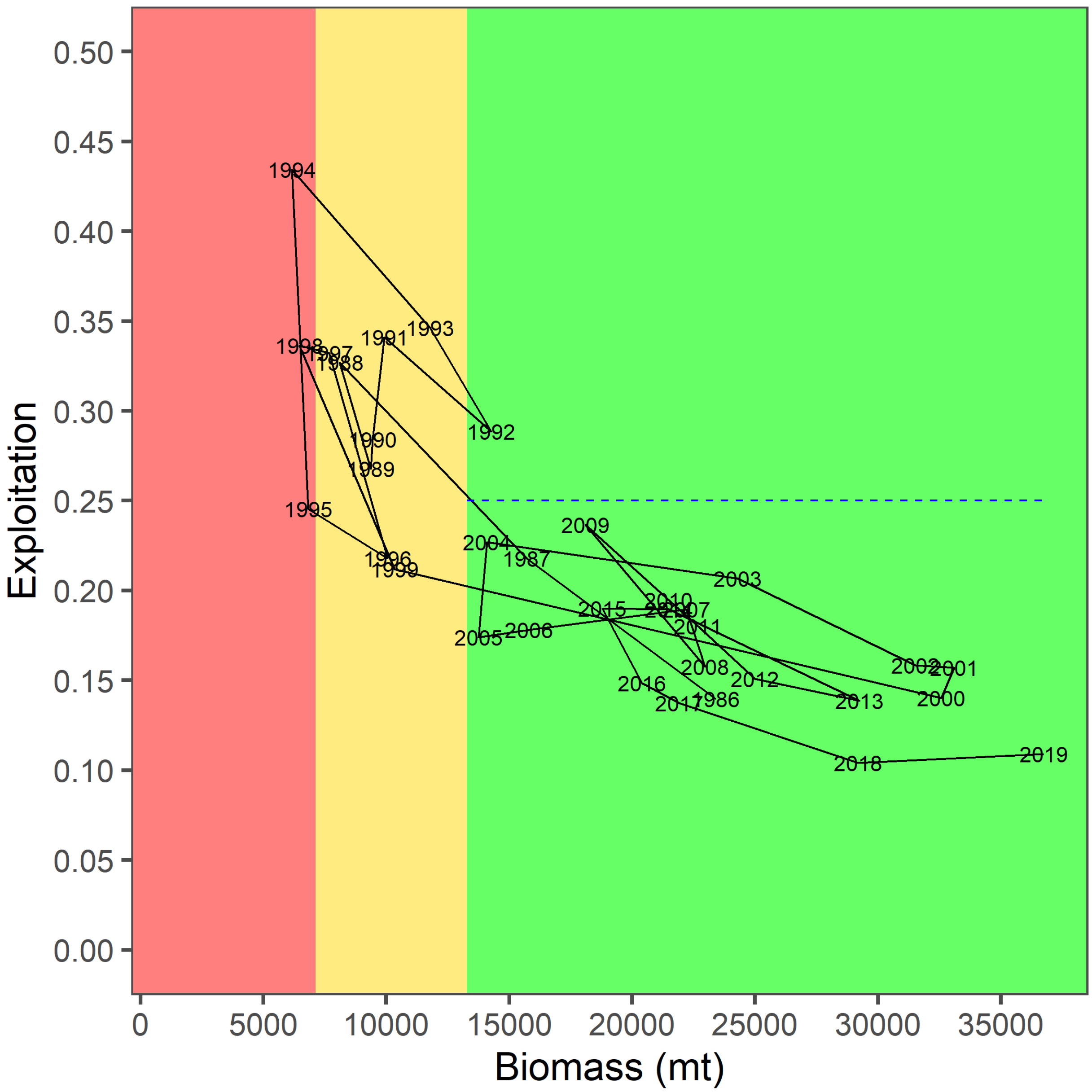

Figure 9. Phase plot of fully recruited biomass (meats, tonnes) and exploitation for Georges Bank 'a.' Labels refer to year of the survey. The green shaded area represents the healthy zone, the yellow shaded area represents the cautious zone, and the red shaded area represents the critical zone.

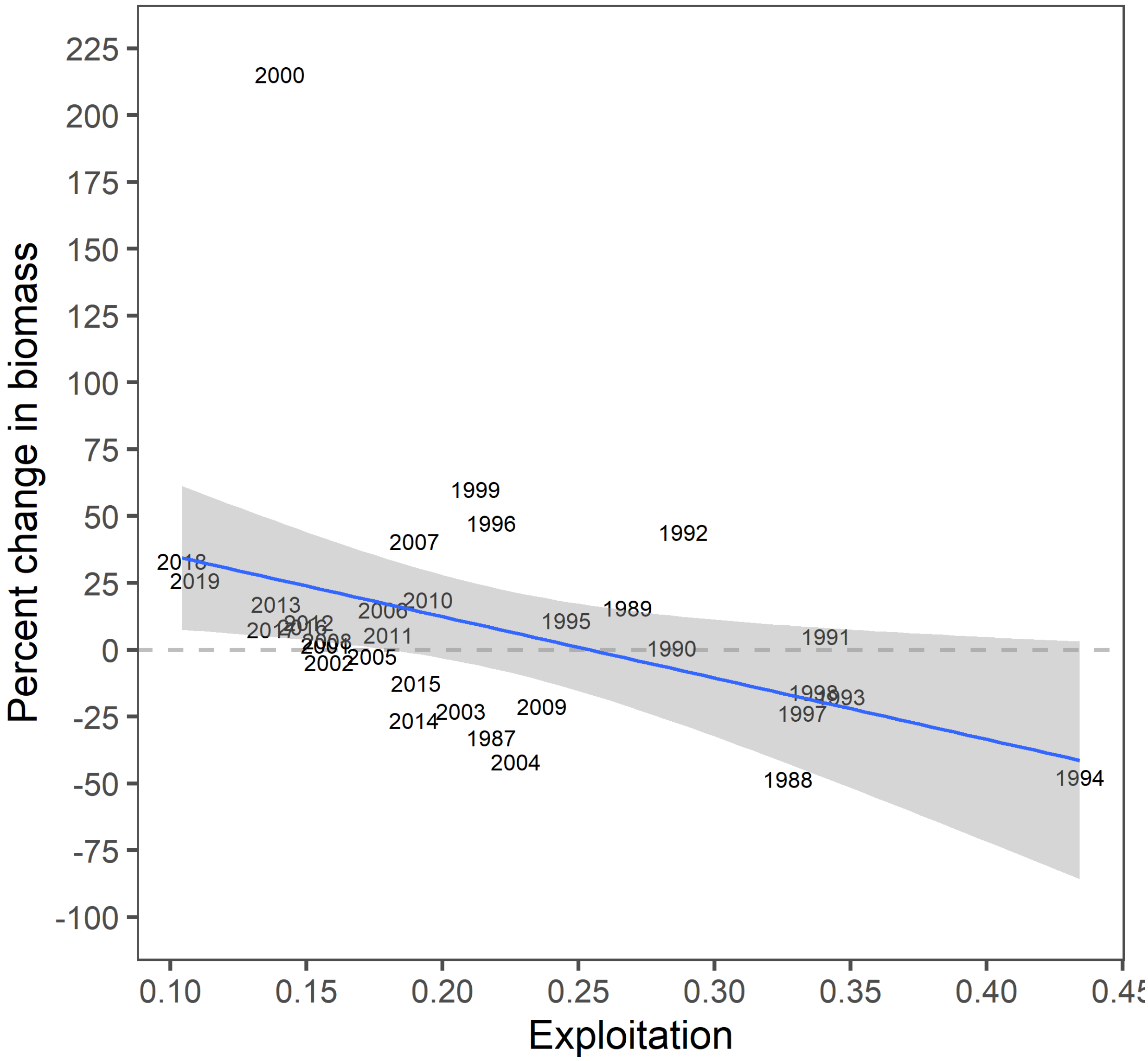

Figure 10. Comparison of exploitation rate versus percent change in fully recruited biomass for Georges Bank 'a.' Labels of year t represent change from year $t-1$ to t. The exploitation rate at zero biomass change is shown based on a linear model (blue line) with a 95% CI (gray ribbon).

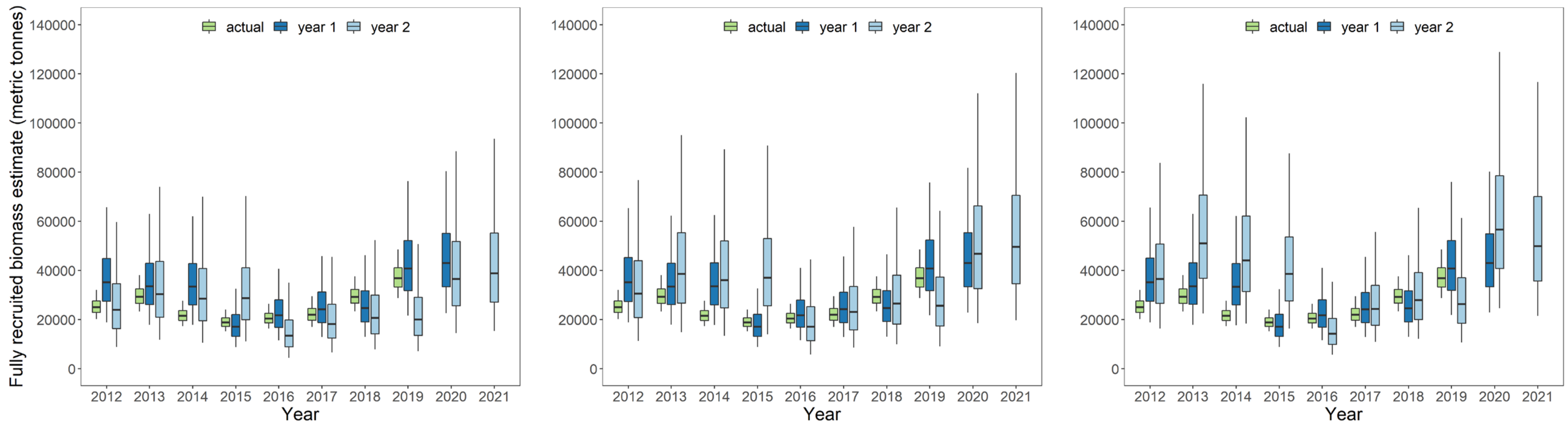

Figure 11. Evaluation of the model projection performance from 2012 to 2021 on Georges Bank 'a.' Green box and whisker plots summarize the posterior distribution of the fully recruited biomass in year t using data up to and including year t (e.g., 2012 predictions based on data up to and including 2012). Dark blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-1$ (e.g., 2012 predictions based on data up to and including 2011). Light blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-2$ (e.g., 2012 predictions based on data up to and including 2010). Box plots show median (horizontal line), 50% credible limits (box), and 90% credible limits (whiskers). The projections for 2020 assumes landings of 4,096 mt is caught, and for 2021 the interim total allowable catch of 4,000 mt is caught. Prediction evaluations presented for three two-year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one−year projection in year $t-1$; right panel).

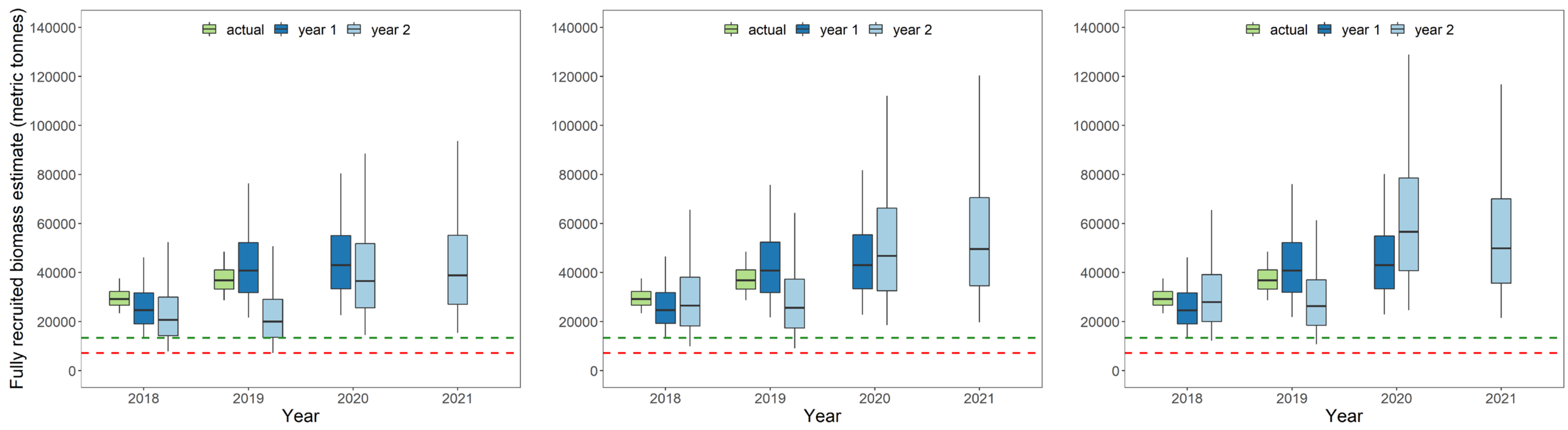

Figure 12. Evaluation of the model projection performance from 2018 to 2021 on Georges Bank 'a' relative to the upper stock reference (USR; green dashed line) and limit reference point (LRP; red dashed line). Green box and whisker plots summarize the posterior distribution of the fully recruited biomass in year t using data up to and including year t (e.g., 2012 predictions based on data up to and including 2012). Dark blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-1$ (e.g., 2012 predictions based on data up to and including 2011). Light blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-2$ (e.g., 2012 predictions based on data up to and including 2010). Box plots show median (horizontal line), 50% credible limits (box), and 90% credible limits (whiskers). The projections for 2020 assumes landings of 4,096 mt is caught, and for 2021 the interim total allowable catch of 4,000 mt is caught. Prediction evaluations presented for three two-year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one-year projection in year $t-1$; right panel).

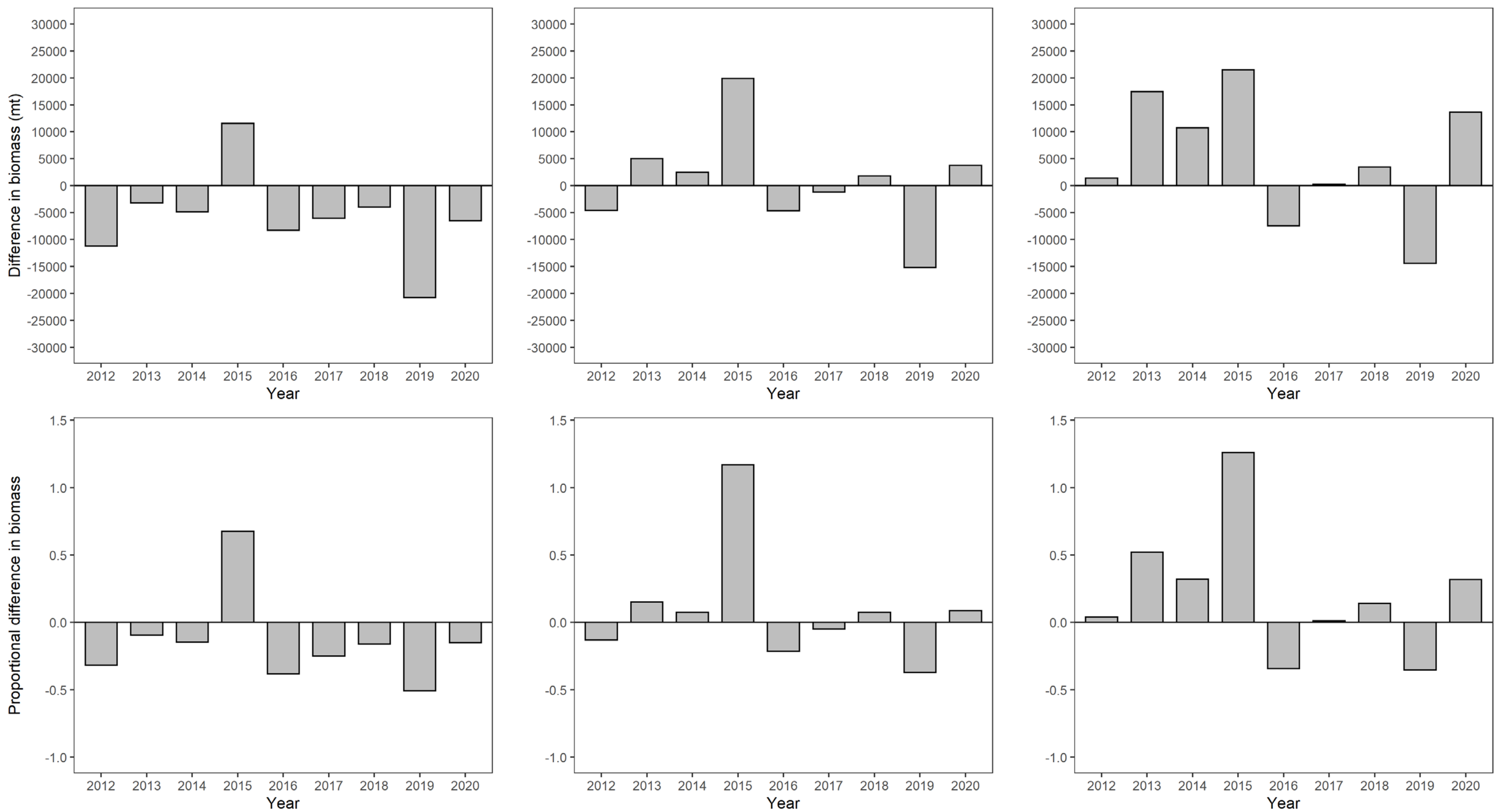

Figure 13. Difference in fully recruited biomass between two-year and one-year projections for each year (t) from 2012 to 2020 for Georges Bank 'a.' Top panel in tonnes (mt) of meats and bottom panel as a proportion. Positive values indicate that the two-year projected fully recruited biomass for year t exceeded the one-year projected estimate of fully recruited biomass in year t. Negative values indicate that the two-year projected fully recruited biomass for year t was lower than the one-year projected estimate of fully recruited biomass in year t.

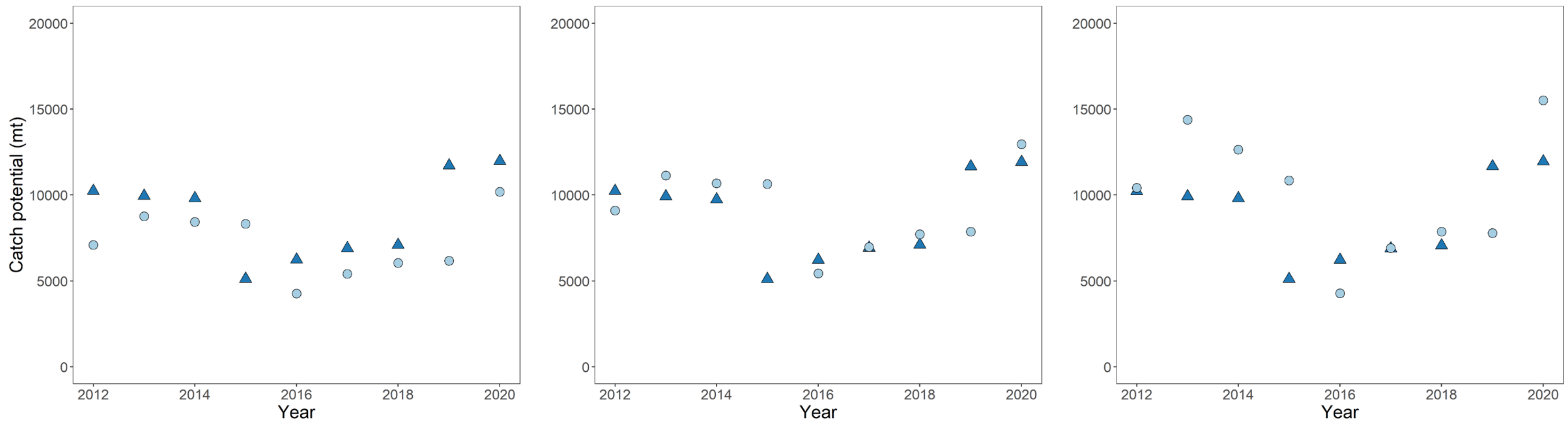

Figure 14. Catch from one-year and a two-year projections for year t where exploitation is 0.25 for Georges Bank 'a' for three two-year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one-year projections in year $t-1$; right panel). The dark blue triangles represent the one-year projection and the light blue circles represent the two-year projection.

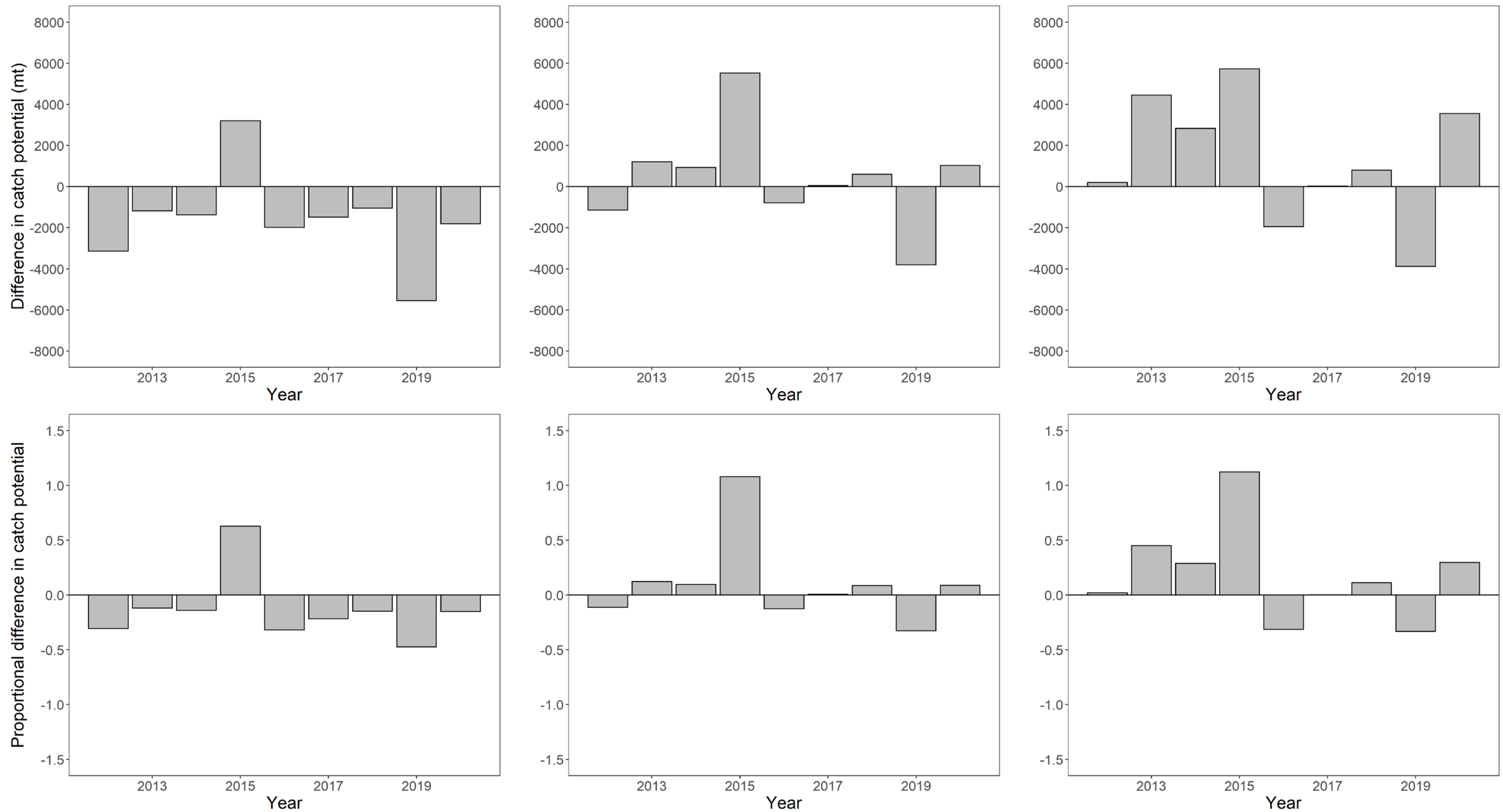

Figure 15. Difference in catch between using a one-year projection for year t and a two-year projection for year t using an exploitation of 0.25 for Georges Bank 'a.' Top panels in tonnes (mt) and bottom panel as a proportion. Positive values indicate the associated catch limit is higher using the two-year projection than a one-year projection in year t. Negative values indicate the associated catch limit is lower using the two-year projection than a one-year projection in year t. Two-year projections conducted for three scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one−year projections in year $t-1$; right panel).

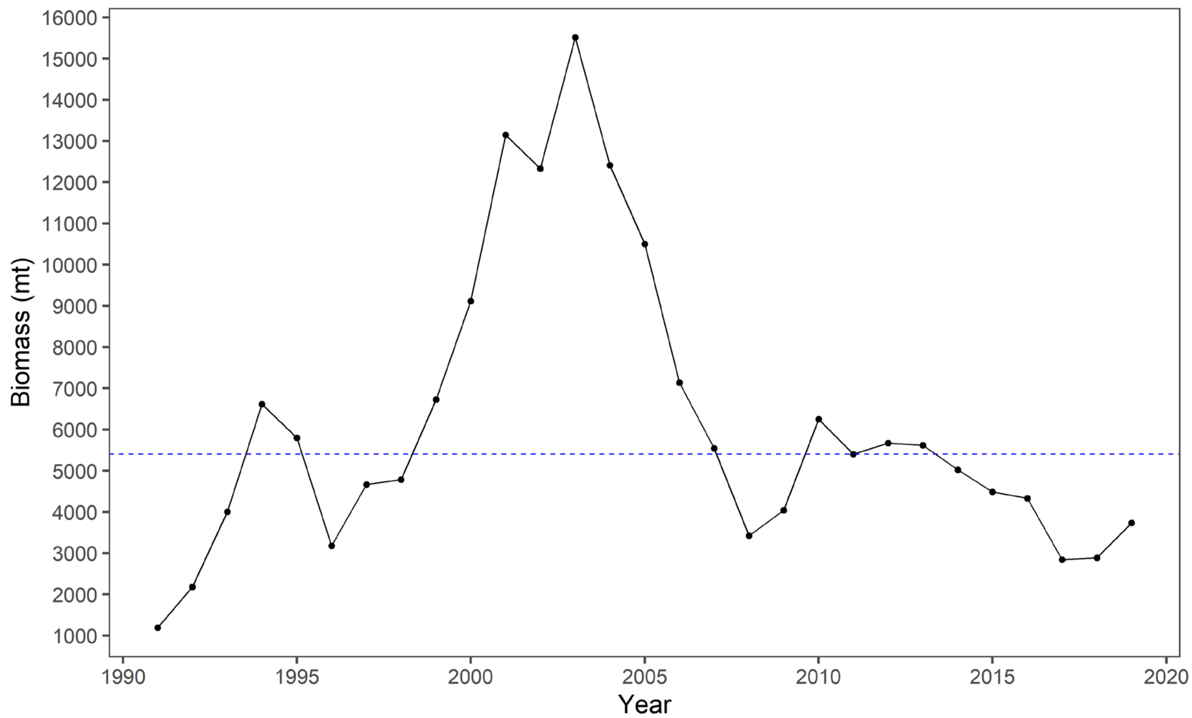

Figure 16. Time series of median biomass (meats, tonnes) estimates of fully recruited scallops from the stock assessment model fit to Browns Bank North. The blue dashed line represents the long-term median (1991–2019).

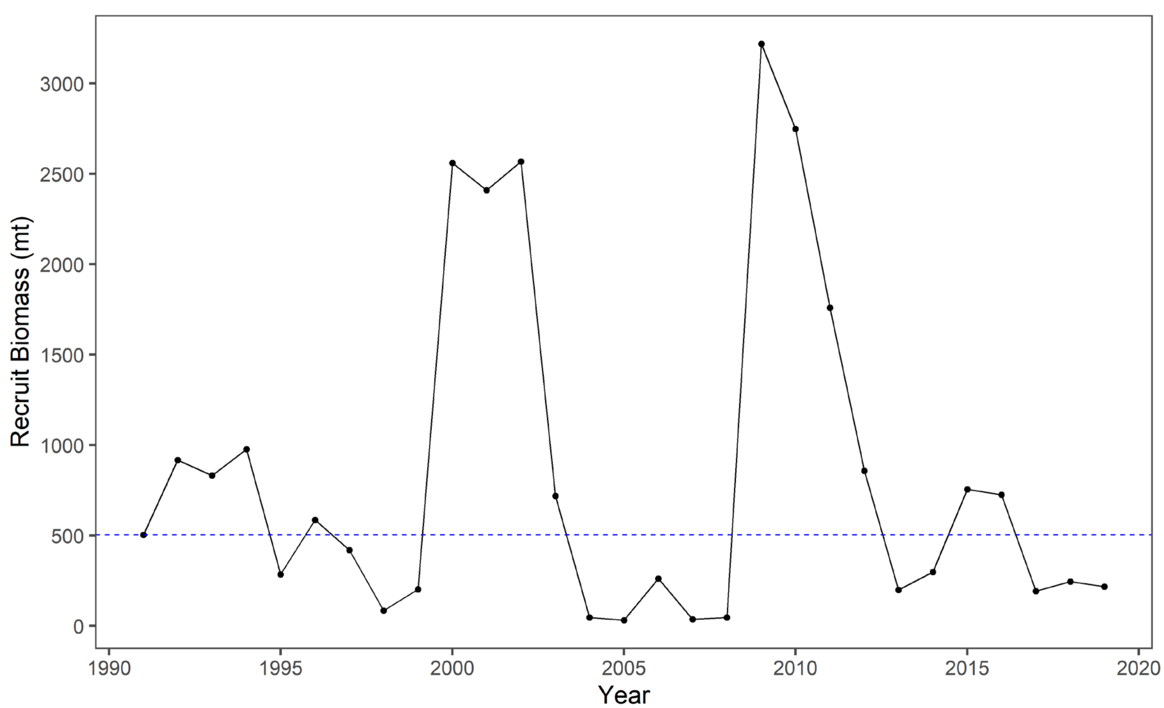

Figure 17. Time series of median biomass (meats, tonnes) estimates of recruit scallops from the stock assessment model fit to Browns Bank North. The blue dashed line represents the long-term median (1991–2019).

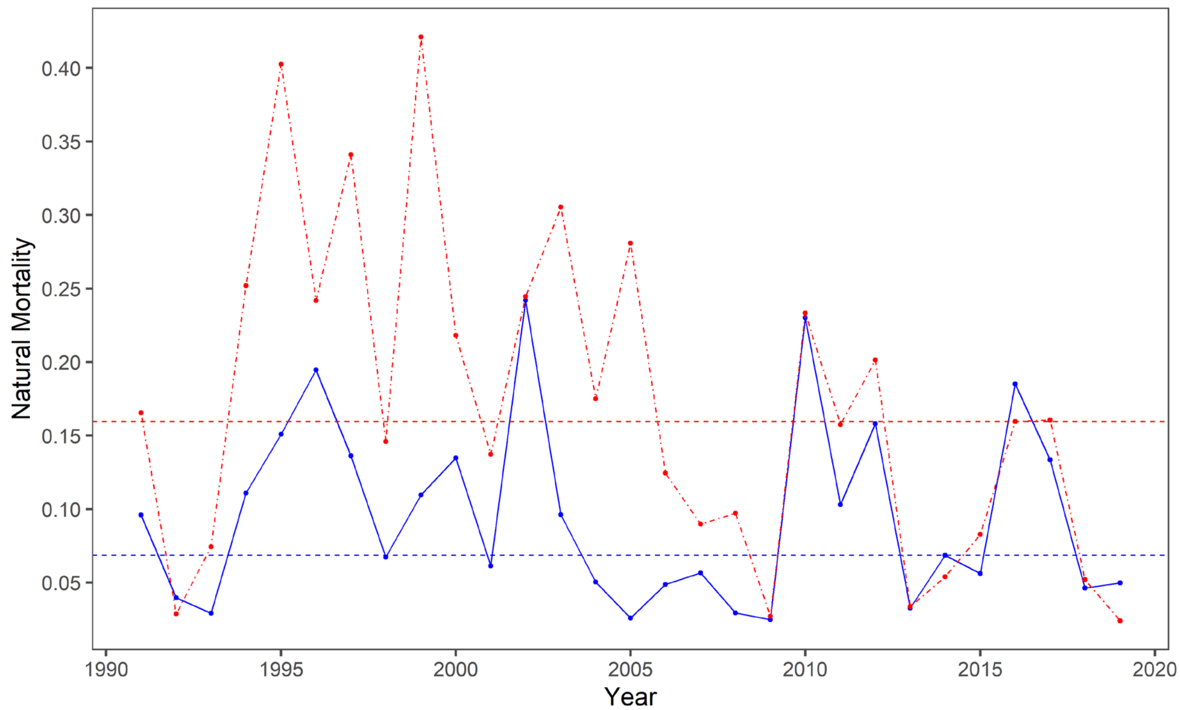

Figure 18. Time series of median natural mortality (proportion) estimates for fully recruited (blue) and recruit (red) scallop from the stock assessment model fit to Browns Bank North. The blue and red dashed lines represent the long-term medians (1991–2019) for fully recruited and recruit scallops, respectively.

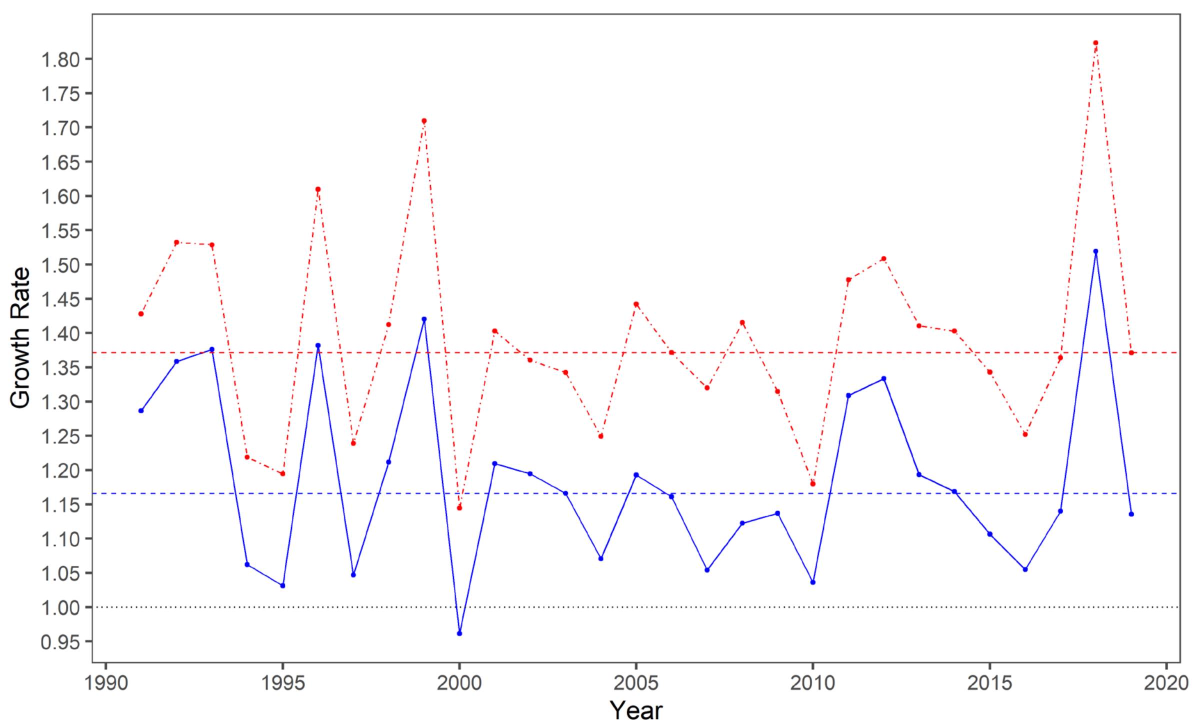

Figure 19. Time series of fully recruited growth rate (blue) and recruit growth rate (red) for Browns Bank North. The blue and red dashed lines represent the long-term medians (1991–2019) for fully recruited and recruit scallops, respectively.

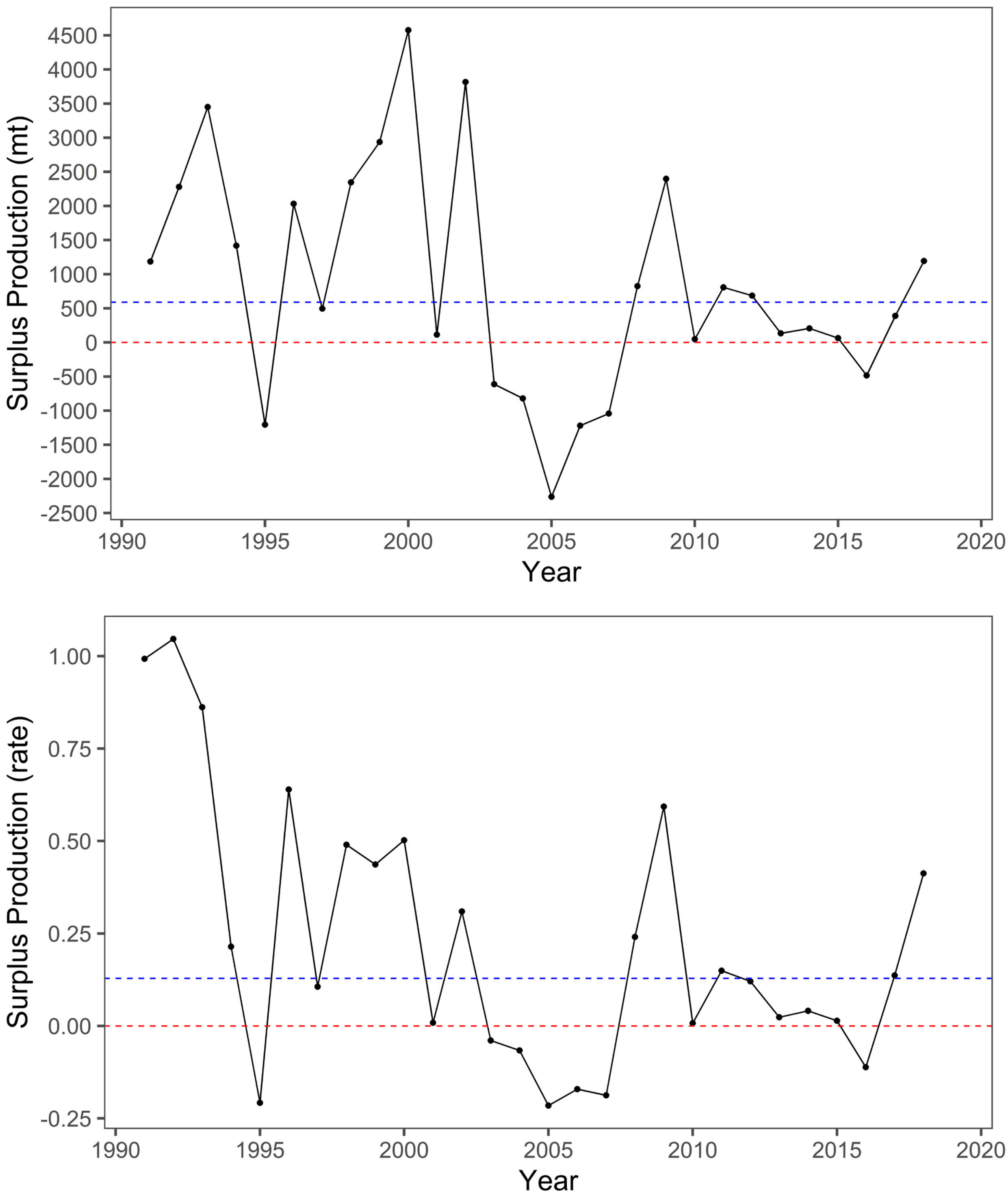

Figure 20. Time series of surplus production (meats, tonnes) (top panel) and surplus production rate (bottom panel) of fully recruited biomass for Browns Bank North. The blue dashed lines represent the long-term medians (1991–2019) and the red dashed lines represent zero surplus production.

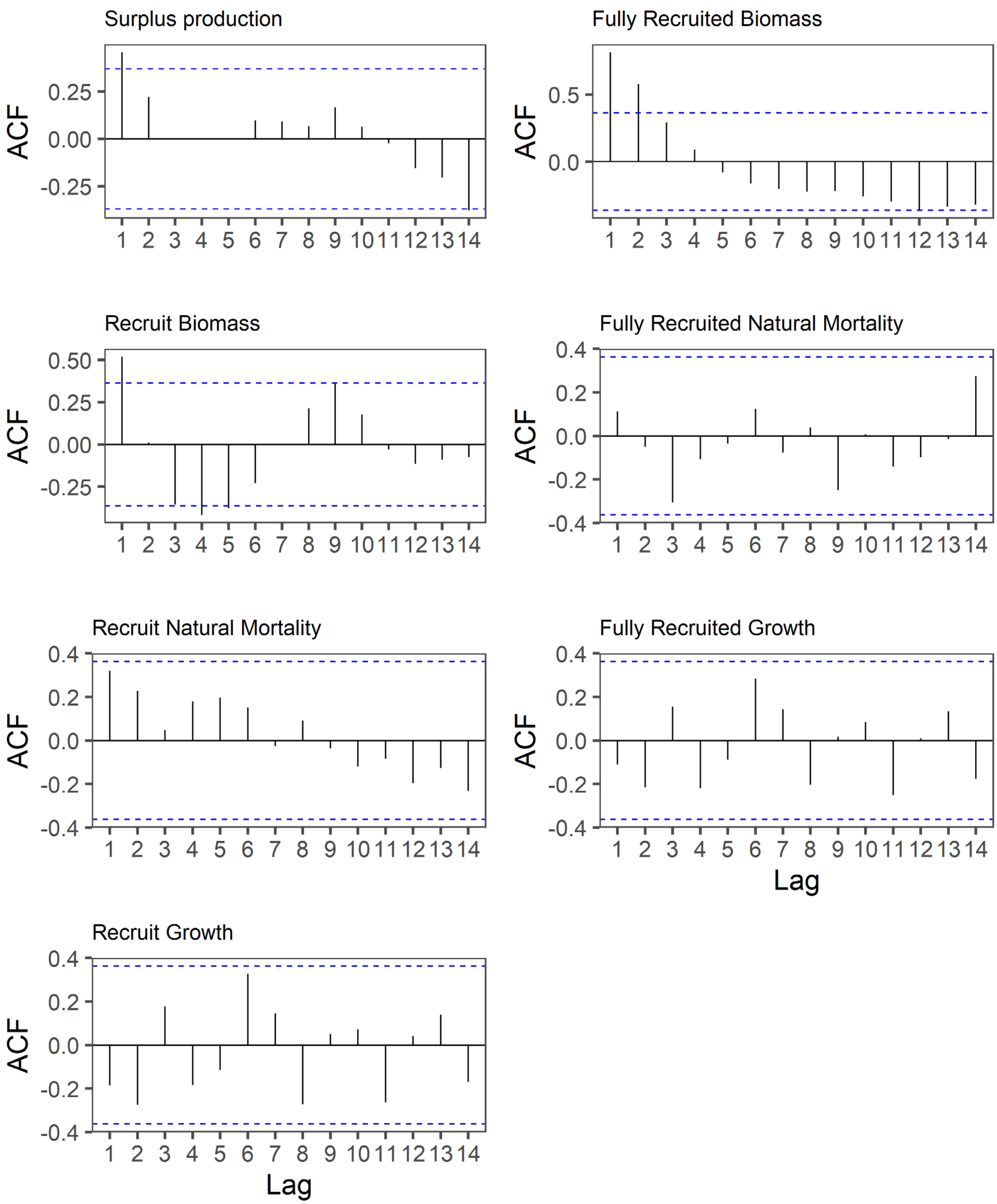

Figure 21. Autocorrelation (ACF) in the assessment model parameters and surplus production time series for Browns Bank North. The blue dashed lines represent the 95% confidence intervals.

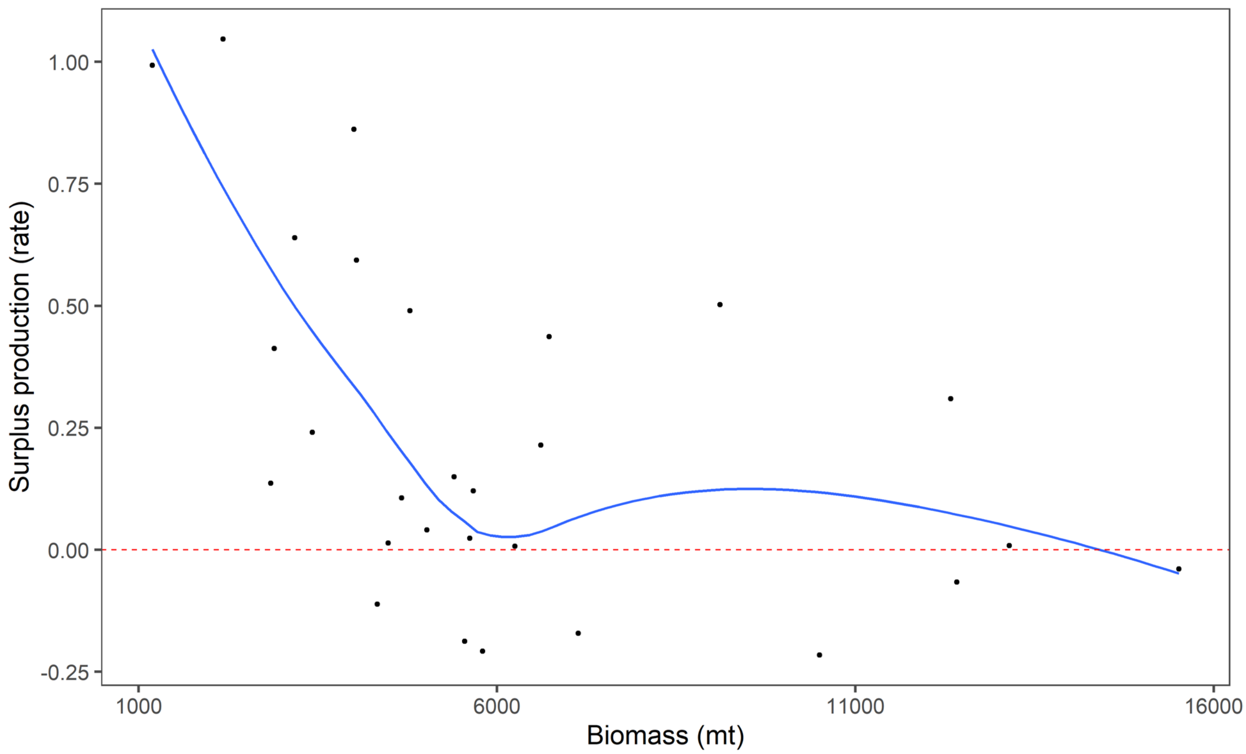

Figure 22. Surplus production (rate) of fully recruited biomass (meats, tonnes) for Browns Bank North. The red dashed line represent zero surplus production. The blue line represents a loess curve added to detect trend.

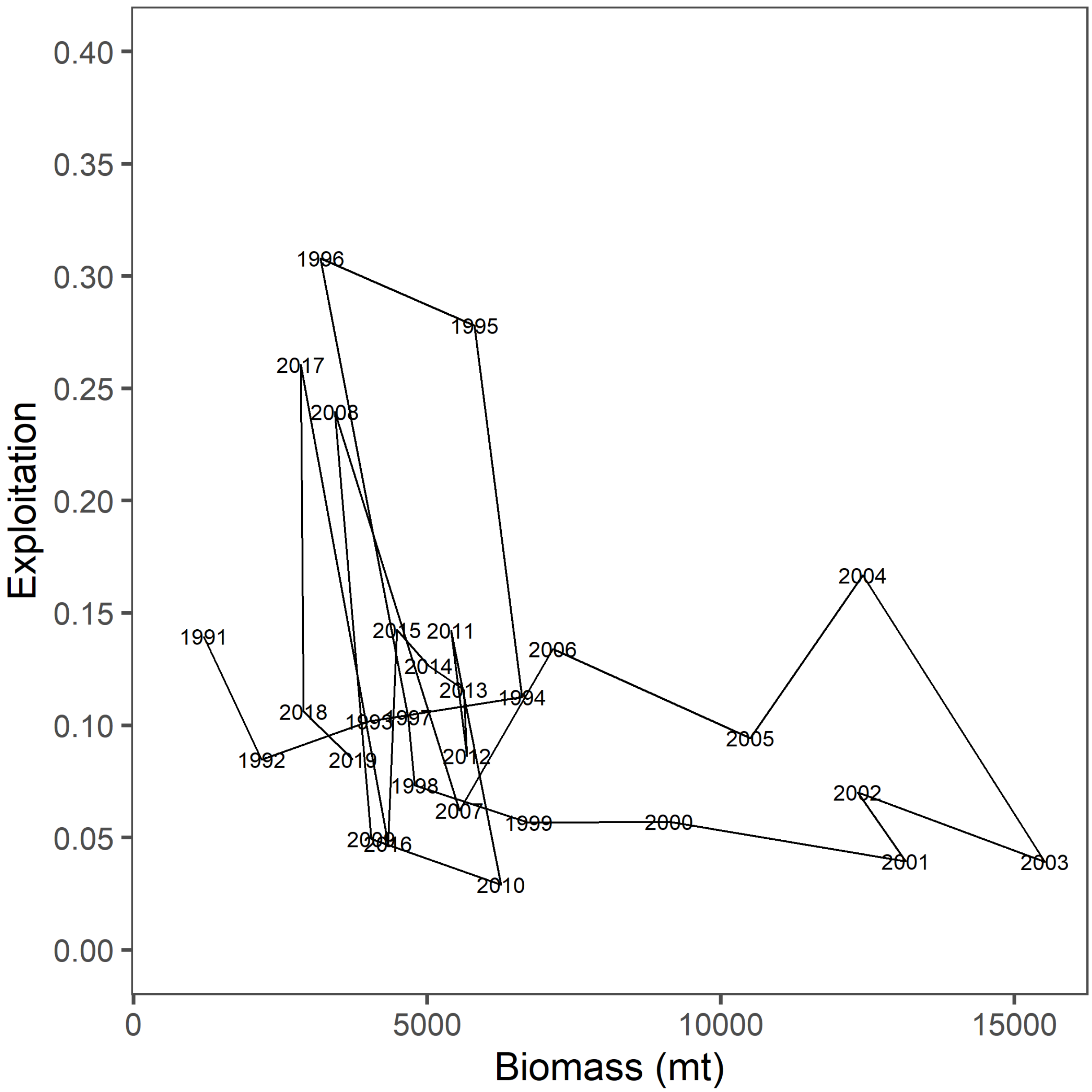

Figure 23. Phase plot of fully recruited biomass (meats, tonnes) and exploitation for Browns Bank North. Labels refer to year of the survey.

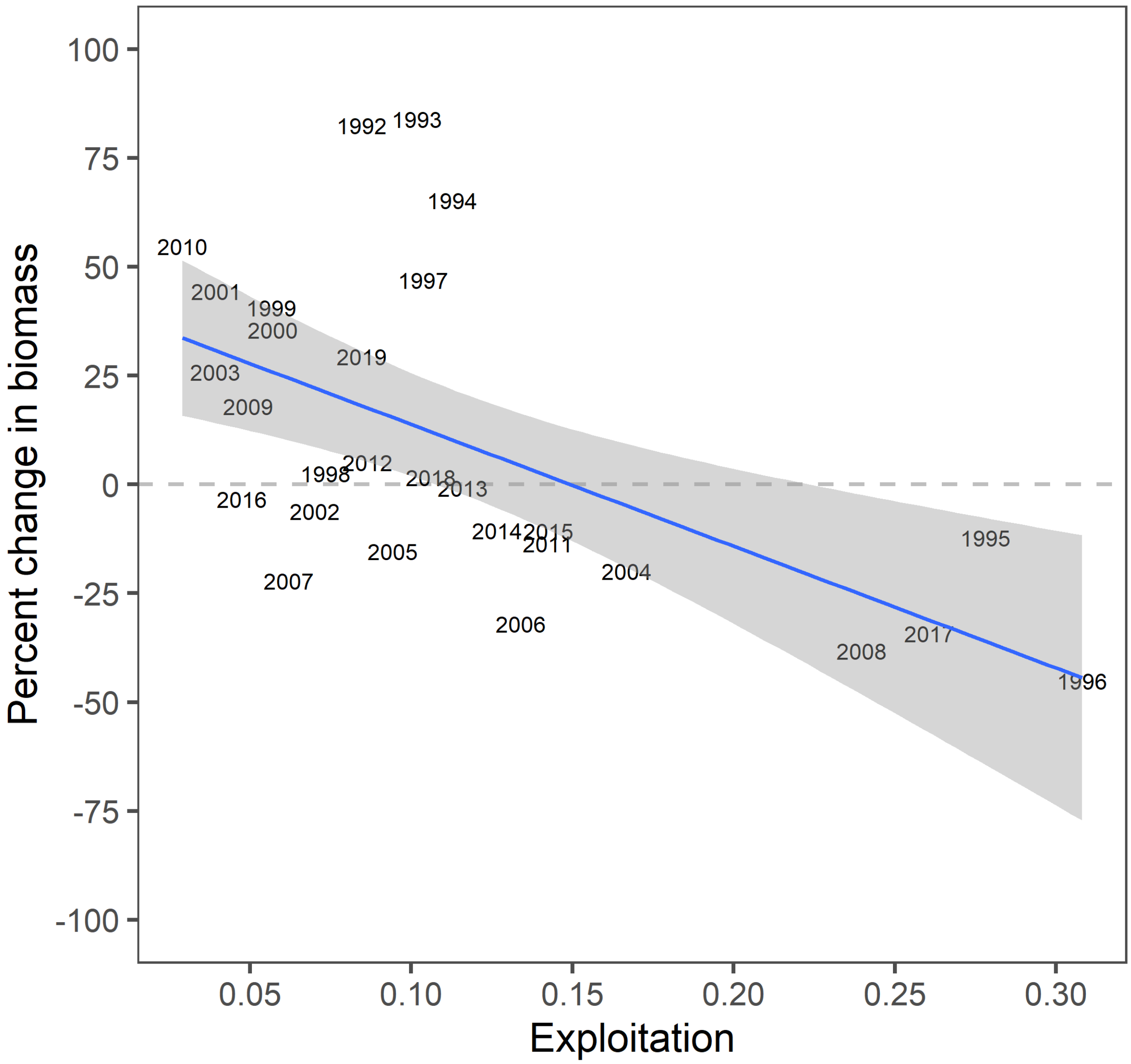

Figure 24. Comparison of exploitation rate versus percent change in fully recruited biomass for Browns Bank North. Labels of year t represent change from year $t-1$ to t. The exploitation rate at zero biomass change is shown based on a linear model (blue line) with a 95% CI (gray ribbon).

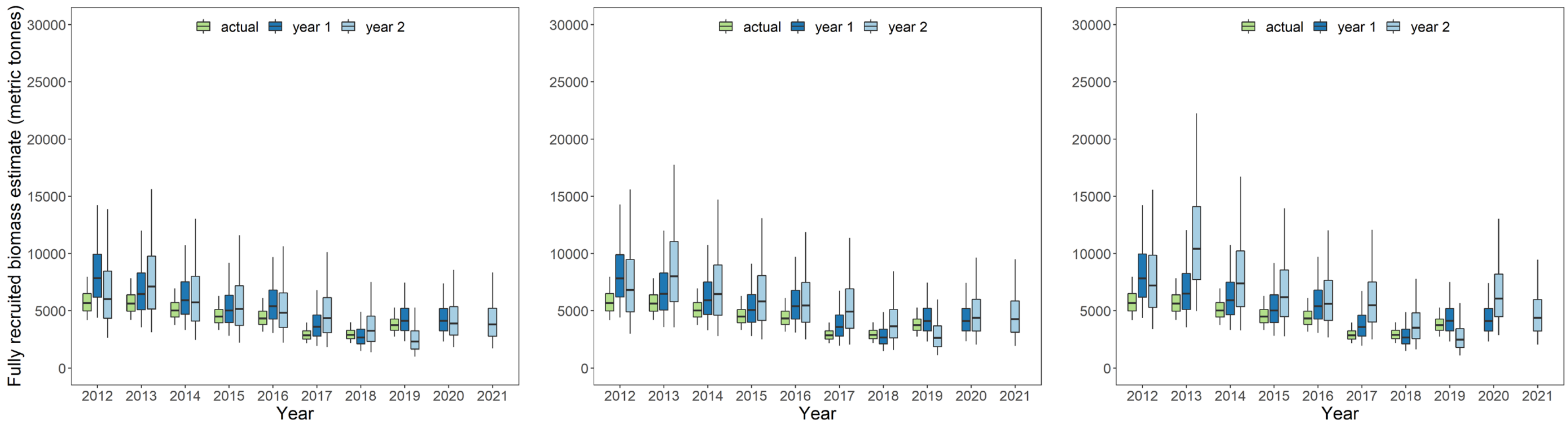

Figure 25. Evaluation of the model projection performance from 2012 to 2021 on Browns Bank North. Green box and whisker plots summarize the posterior distribution of the fully recruited biomass in year t using data up to and including year t (e.g., 2012 predictions based on data up to and including 2012). Dark blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-1$ (e.g., 2012 predictions based on data up to and including 2011). Light blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-2$ (e.g., 2012 predictions based on data up to and including 2010). Box plots show median (horizontal line), 50% credible limits (box), and 90% credible limits (whiskers). The projections for 2020 assumes landings of 211 mt is caught, and for 2021 the interim total allowable catch of 300 mt is caught. Prediction evaluations presented for three two-year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the recent year assumption (i.e., same conditions as the one−year projection in year $t-1$; right panel).

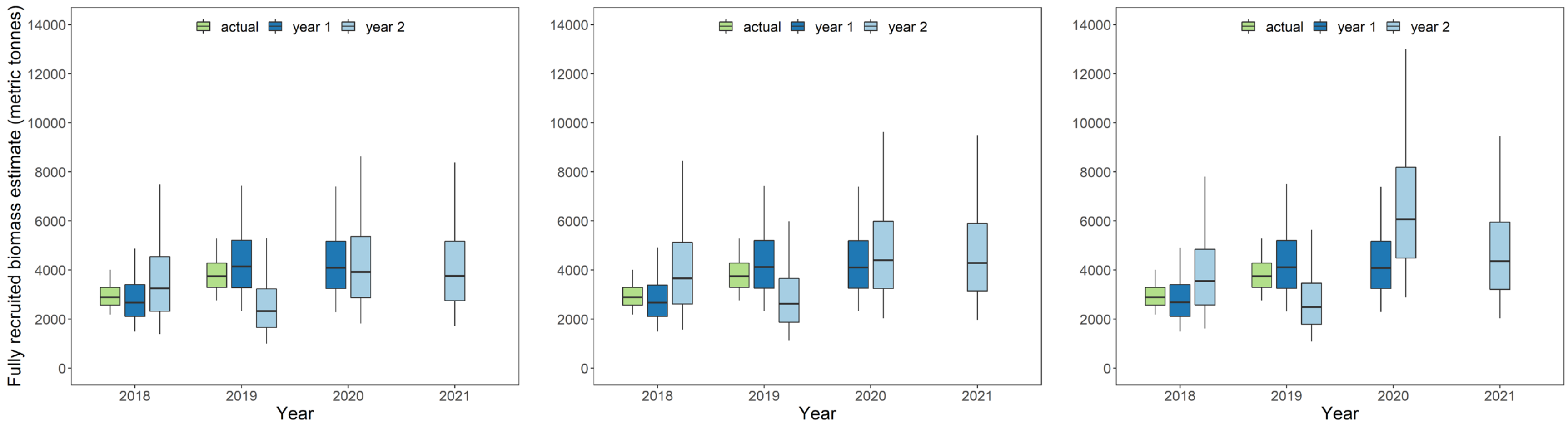

Figure 26. Evaluation of the model projection performance from 2018 to 2021 on Browns Bank North. Green box and whisker plots summarize the posterior distribution of the fully recruited biomass in year t using data up to and including year t (e.g., 2012 predictions based on data up to and including 2012). Dark blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-1$ (e.g., 2012 predictions based on data up to and including 2011). Light blue box and whisker plots summarize posterior distributions of fully recruited biomass in year t based on model fit to year $t-2$ (e.g., 2012 predictions based on data up to and including 2010). Box plots show median (horizontal line), 50% credible limits (box), and 90% credible limits (whiskers). The projections for 2020 assumes landings of 211 mt is caught, and for 2021 the interim total allowable catch of 300 mt is caught. Prediction evaluations presented for three two−year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the recent year assumption (i.e., same conditions as the one−year projection in year $t-1$; right panel).

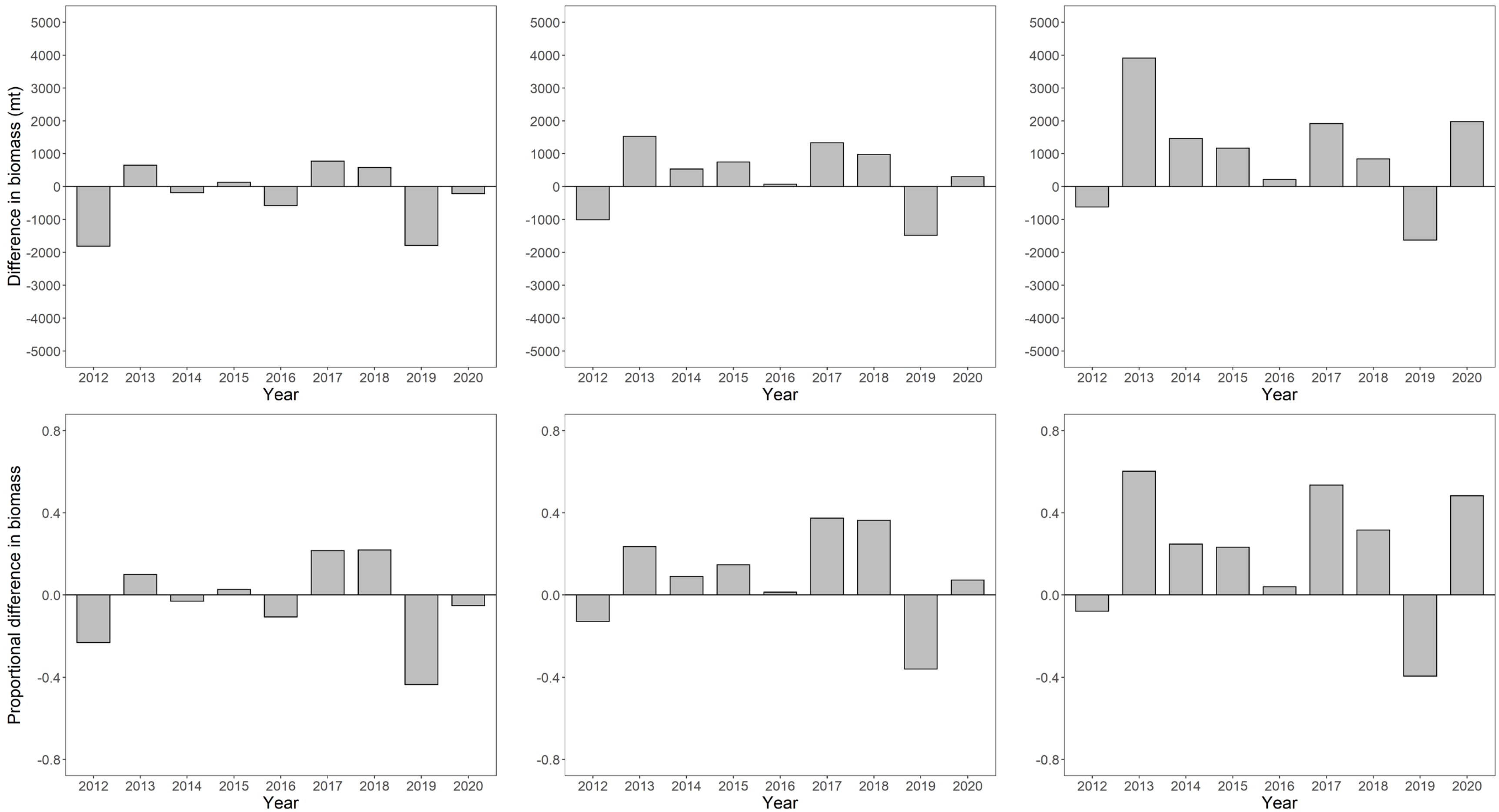

Figure 27. Difference in fully recruited biomass between two-year and one-year projections for each year from 2012 to 2020 for Browns Bank North. Top panel in tonnes (mt) of meats and bottom panel as a proportion. Positive values indicate that the two-year projected fully recruited biomass for year t exceeded the one-year projected estimate of fully recruited biomass in year t. Negative values indicate that the two-year projected fully recruited biomass for year t was lower than the one-year projected estimate of fully recruited biomass in year t.

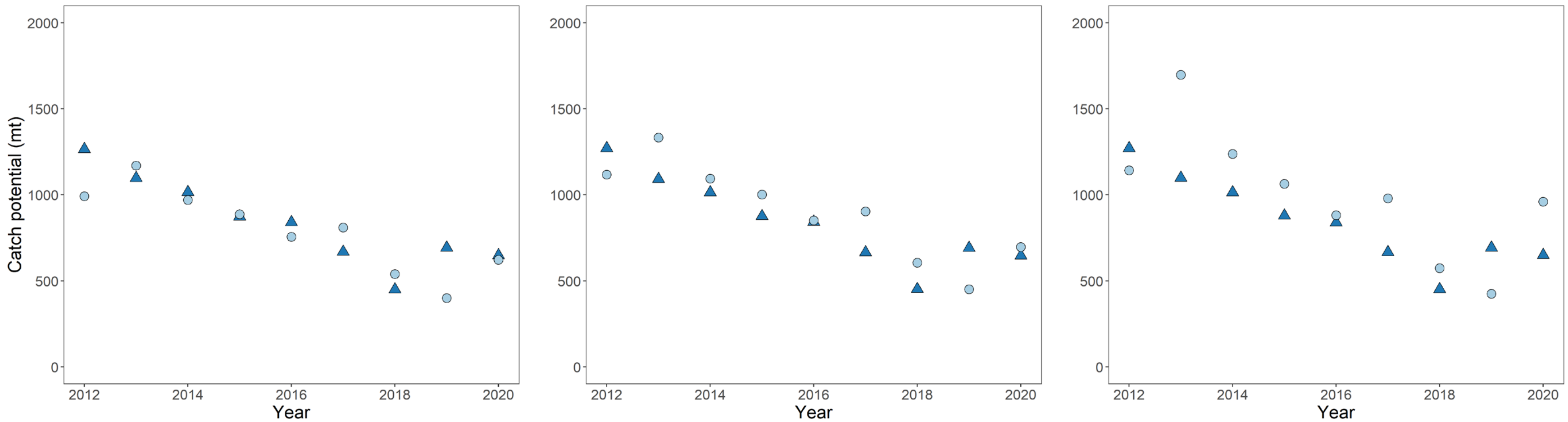

Figure 28. Catch from one-year and a two-year projections for year t using an exploitation of 0.15 for Browns Bank North for three two-year projection scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one-year projections in year $t-1$; right panel). The dark blue triangles represent the one-year projection and the light blue circles represent the two-year projection.

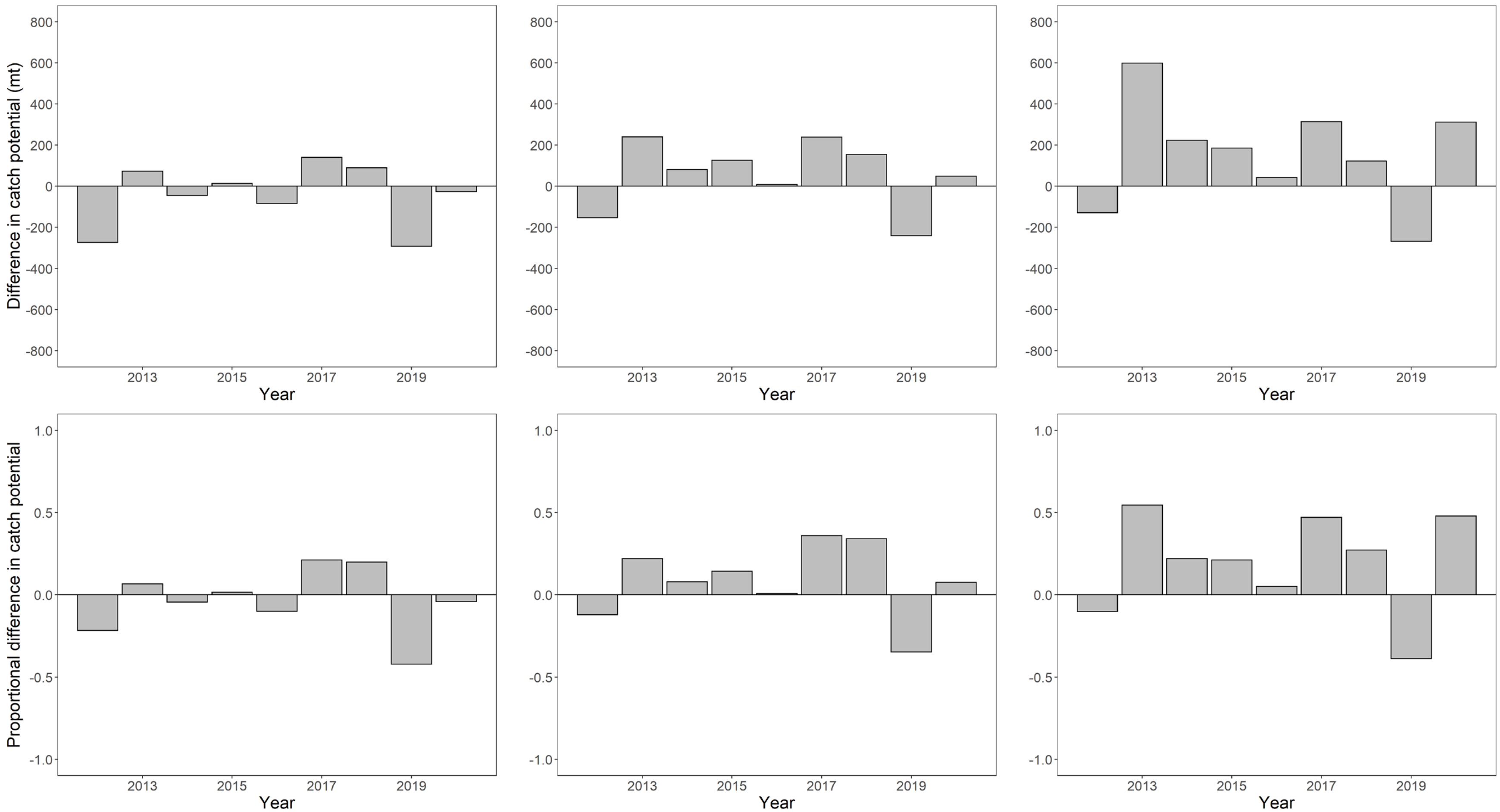

Figure 29. Difference in catch between using a one-year projection for year t and a two-year projection for year t using an exploitation of 0.15 for Browns Bank North. Top panels in tonnes (mt) and bottom panel as a proportion. Positive values indicate the associated catch limit is higher using the two-year projection than a one-year projection in year t. Negative values indicate the associated catch limit is lower using the two-year projection than a one-year projection in year t. Two-year projections conducted for three scenarios; zero surplus production (left panel), median surplus production (middle panel), and the status quo assumption (i.e., same conditions as the one-year projections in year $t-1$; right panel).