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Stock assessment of the coastwide population of Shortspine Thornyhead (*Sebastolobus alascanus*) in 2015 off the British Columbia coast

Paul J. Starr[1] and Rowan Haigh[2]

[1]Canadian Groundfish Research and Conservation Society
1406 Rose Ann Drive
Nanaimo, BC V9T 4K8

[2]Pacific Biological Station
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

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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

A new stock assessment is presented for coastwide (Pacific Marine Fisheries Commission areas 3 and 5 combined) Shortspine Thornyhead (SST) based on a delay-difference production model fit to five fishery-independent surveys, a CPUE series derived from commercial catch rates, and an annual mean weight series derived from unsorted commercial catch samples. Growth rates, natural mortality and selectivity were assumed externally from the model. The stock assessment was characterised by considerable uncertainty associated with conflicting growth models and a range of plausible natural mortality estimates and sizes for full recruitment. In addition, there was conflict in the fitted index series, with the biomass indices generally showing little contrast while the mean weight at age series showed increases after a sharp initial drop. The stock assessment was conducted in a Bayesian framework, where the best fit to the data was used as the starting point for a search across the joint posterior parameter distributions using the Monte Carlo Markov Chain (MCMC) procedure. A composite reference scenario (model average) was selected to represent this stock, consisting of 12 model runs which spanned plausible hypotheses with respect to growth, either based on age-length pairs from the Department of Fisheries and Oceans (DFO) biological database or based on a published growth model from the US National Marine Fisheries Service (NMFS). The composite reference scenario also included three values for instantaneous natural mortality M (0.03, 0.06, 0.08) as well as a range of lengths at which knife-edge recruitment (k) to the fishery occurred (k = 29, 24, 21 cm). Three of the 12 runs assumed the DFO growth model in conjunction with three M values and k=29 cm. The remaining nine runs were based on the NMFS growth model and included three values of M and three values for knife-edge recruitment (k=29, 24, 21 cm). An MCMC posterior for the composite scenario was constructed by pooling 1000 MCMC samples from each of the selected runs to give a posterior of 12,000 samples, thus giving equal weight to each run. The composite reference scenario was evaluated against two B_{MSY}-based reference points consistent with the DFO Precautionary Approach policy and the exploitation rate at B_{MSY} (u_{MSY}). The model-average median estimates of current stock status (B_{2016}/ B_0) ranged from 40% to 141% B_0 with a median estimate of 79%, indicating that current biomass is well above all reference points. Three-year projections at the level of current removals resulted in a biomass decline which remained above reference levels. The stock assessment provides a decision table which evaluates the probability of the model average case staying above three reference points across a range of 11 constant catches. However, because the six abundance index series show little contrast, the stock assessment is unable to resolve productivity uncertainties, with similar fits to the data across the investigated range of natural mortality and age-at-knife-edge recruitment parameters. Therefore, this assessment was unable to provide advice on the absolute size of the stock and the level of equilibrium yield.

Évaluation du stock de sébastolobe à courtes épines (*Sebastolobus alascanus*) sur l'ensemble de la côte de la Colombie-Britannique en 2015

RÉSUMÉ

Une nouvelle évaluation du stock est présentée pour la population de sébastolobe à courtes épines sur l'ensemble de la côte (zones 3 et 5 de la Commission des pêches maritimes du Pacifique), en fonction d'un modèle de production de type différence-délai adapté à cinq relevés indépendants de la pêche, d'une série chronologique sur les prises par unité d'effort (CPUE) dévirée des taux de capture commerciale, et d'une série chronologique annuelle de poids moyen tirée d'échantillons de prises commerciales non triées. Le modèle n'a pas été utilisé pour prévoir le taux de croissance, la mortalité naturelle et la sélectivité. L'évaluation du stock était caractérisée par une incertitude considérable concernant les modèles de croissance conflictuels et une variété d'estimations plausibles de la mortalité naturelle et de la taille pour un recrutement complet. En outre, la série d'indices adaptés contenait des incohérences; les indices de biomasse montraient généralement peu de contraste, tandis que le poids moyen selon la série sur l'âge indiquait des augmentations après un déclin initial abrupt. L'évaluation du stock a été effectuée à l'aide d'un cadre bayésien, la solution qui correspond le mieux aux données étant utilisée comme point de départ d'une recherche dans les distributions conjuguées a postériori des paramètres à l'aide de la procédure de Monte Carlo par chaîne de Markov (MCCM). Un scénario de référence composite (moyenne du modèle) a été choisi pour représenter ce stock. Il comprend 12 exécutions de modèle ayant donné lieu à des hypothèses plausibles concernant la croissance, fondées soit sur des paires âge-longueur de la base de données biologiques de Pêches et Océans Canada (MPO), soit sur un modèle de croissance publié par le National Marine Fisheries Service des États-Unis (NMFS). Le scénario de référence composite comprenait également trois valeurs pour la mortalité naturelle instantanée *M* (0,03; 0,06; 0,08), ainsi qu'une variété de longueurs auxquelles la sélectivité marquée pour le recrutement (*k*) se produisait dans le cadre de la pêche (*k* = 29, 24, 21 cm). Trois des 12 exécutions laissaient supposer que le modèle de croissance du MPO, combiné aux trois valeurs *M* et à *k*, égalait 29 cm. Les neuf autres exécutions étaient fondées sur le modèle de croissance du NMFS et incluaient trois valeurs *M* et trois valeurs de sélectivité marquée pour le recrutement (*k* = 29, 24, 21 cm). On a construit une distribution a posteriori de la méthode de MCCM pour le scénario composite en réunissant 1 000 échantillons MCCM à partir de chacune des exécutions choisies afin d'obtenir une distribution a posteriori de 12 000 échantillons, ce qui a donné un poids équivalent à chaque exécution. Le scénario de référence composite a été évalué par rapport à deux points de référence fondés sur B_{RMS}, conformément à l'approche de précaution du MPO et au taux d'exploitation à B_{RMS} (u_{RMS}). Les estimations médianes de la moyenne du modèle de l'état du stock actuel (B_{2016}/ B_0) variaient de 40 % à 141 % B_0, et l'estimation de la médiane était à 79 %, ce qui indique que la biomasse actuelle est bien au-dessus de tous les points de référence. Des projections sur trois ans au niveau actuel de retraits ont indiqué un déclin de la biomasse, qui est demeurée au-dessus des niveaux de référence. L'évaluation du stock fournit un tableau de décisions qui permet d'évaluer la probabilité que la moyenne du modèle reste au-dessus des trois points de référence sur une fourchette de 11 prises constantes. Cependant, étant donné que les six séries d'indices d'abondance montrent peu de contraste, l'évaluation du stock ne permet pas d'atténuer les incertitudes relatives à la productivité. Les correspondances avec les données sont similaires dans toute la fourchette évaluée des paramètres relatifs à la mortalité naturelle et à l'âge de la sélectivité marquée pour le recrutement. Par conséquent, cette évaluation n'a pas permis de formuler un avis sur la taille absolue du stock et le niveau de rendement d'équilibre.

1 INTRODUCTION

This stock assessment is for the British Columbia (BC) coastwide stock of Shortspine Thornyhead (*Sebastolobus alascanus*) that occurs in the combined Pacific Marine Fisheries Commission (PMFC) major areas 3CD (west coast Vancouver Island), 5AB (Queen Charlotte Sound), 5CD (Hecate Strait and Dixon Entrance), and 5E (west coast Haida Gwaii). The modelling approach used a delay-difference model developed by Forrest et al. (2015) for Pacific Cod (*Gadus macrocephalus*).

Thornyheads (genus *Sebastolobus*) are relatively small fish that are represented by two species along the BC coast – Shortspine (*S. alascanus*) and Longspine Thornyhead (*S. altivelis*). The latter species has been assessed by DFO several times over the last 15 years (Starr and Haigh 2000, Starr 2001, Schnute et al. 2004, Haigh et al. 2005), and its development as a target species was documented by Haigh and Schnute (2003). Shortspine Thornyhead, on the other hand, is characterised more as a bycatch species due its shallower distribution and its concurrence with numerous other TAC (total allowable catch) species. The last stock assessment to review Shortspine Thornyhead occurred in 1999 (Schnute et al. 1999).

The Fisheries Management Branch of DFO requested that the Shortspine Thornyhead coastwide stock be assessed relative to reference points that are consistent with the DFO Precautionary Approach (DFO 2009), and that decision tables be produced to forecast the impacts of varying harvest levels on stock status. The Terms of Reference objectives include the following:

- Use reference points consistent with the DFO Precautionary Approach. Include the biological considerations and rationale used.
- Evaluate the current status of the *Sebastolobus alascanus* coastwide BC stock relative to the reference points.
- Provide reasons if formal assessment is not possible.
- Evaluate the consequences of varying constant catches on future population status, providing decision tables and figures of projected biomass.

The main document presents background information, an overview of the assessment model and input data, the main model results, and the advice to managers. Further technical details are given in the relevant Appendices.

1.1 BIOLOGICAL BACKGROUND

The name *Sebastolobus alascanus* (Bean 1890) is derived from the Greek *sebastos* (magnificent) and *lobos* (lobe – pectoral fin), and place of first capture by scientists – Alaska (Hart 1973). Colloquial names include “idiot” and “channel rockfish” (Love et al. 2002).

The early development of Shortspine Thornyhead is described by Pearcy (1962) and Moser (1974). Spawning likely occurs between March and May, and eggs are released in gelatinous masses that float to the surface (Pearcy 1962). The eggs are characterised by a distinctive oil globule, while larvae feature pigmentation patterns that differentiate them from other larval Scorpaenids (Pearcy 1962). In California, the larvae and juveniles remain in the pelagic zone for 14-15 months (Moser 1974). The exact timing of spawning and duration of pelagic residency in BC is not known, but is thought to be similar. The juveniles settle into the benthic zone when they are 22-27 mm in length (Moser 1974).

Adults are characterised by a bright orange-to-red colour with white patches in various places on the body, occasional black pigmentation on fins, spiny ridges on the forehead and cheeks, and 15 or more dorsal spines without the elongated third spine featured by *S. altivelis* (Love et al. 2002).

1.2 RANGE AND DISTRIBUTION

The geographic range of Shortspine Thornyhead is extensive, occurring from the Sea of Japan, through the Aleutian Islands and down along the west coast of North America to Baja California (Love et al. 2002). In BC, the highest CPUE densities observed by the trawl fishery (Figure 1) occur off northwest Haida Gwaii, in Moresby Gully, in the Tide Marks region, and west of Nootka Island (on the west coast of Vancouver Island).

The depth range for this species in BC also varies widely (down to 1570 m, Brian Krishka, DFO, Nanaimo, B.C., pers. comm., Krishka et al. 2005) but the species is found most often between 150 and 450 m depth (Figure 2, regional variations appear in Appendix D), with spawning aggregations reportedly occurring in the oxygen minimum zone (600-1000 m, Jacobson and Vetter 1996). Shortspine Thornyhead larvae and juveniles spend just over one year in the pelagic zone before settling onto the shelf at ~100 m depth (Moser 1974). As this species gets older and bigger, it migrates into deeper water (Jacobson and Hunter 1993). This is thought to be an adaptation to reduce the risk of newly settled juveniles being eaten by larger thornyheads of both species (Jacobson and Vetter 1996). At depths greater than 600 m, Shortspine Thornyhead adults are nine times heavier than adults of Longspine Thornyhead, and are known to prey on the smaller but more abundant, congener (Jacobson and Vetter 1996).

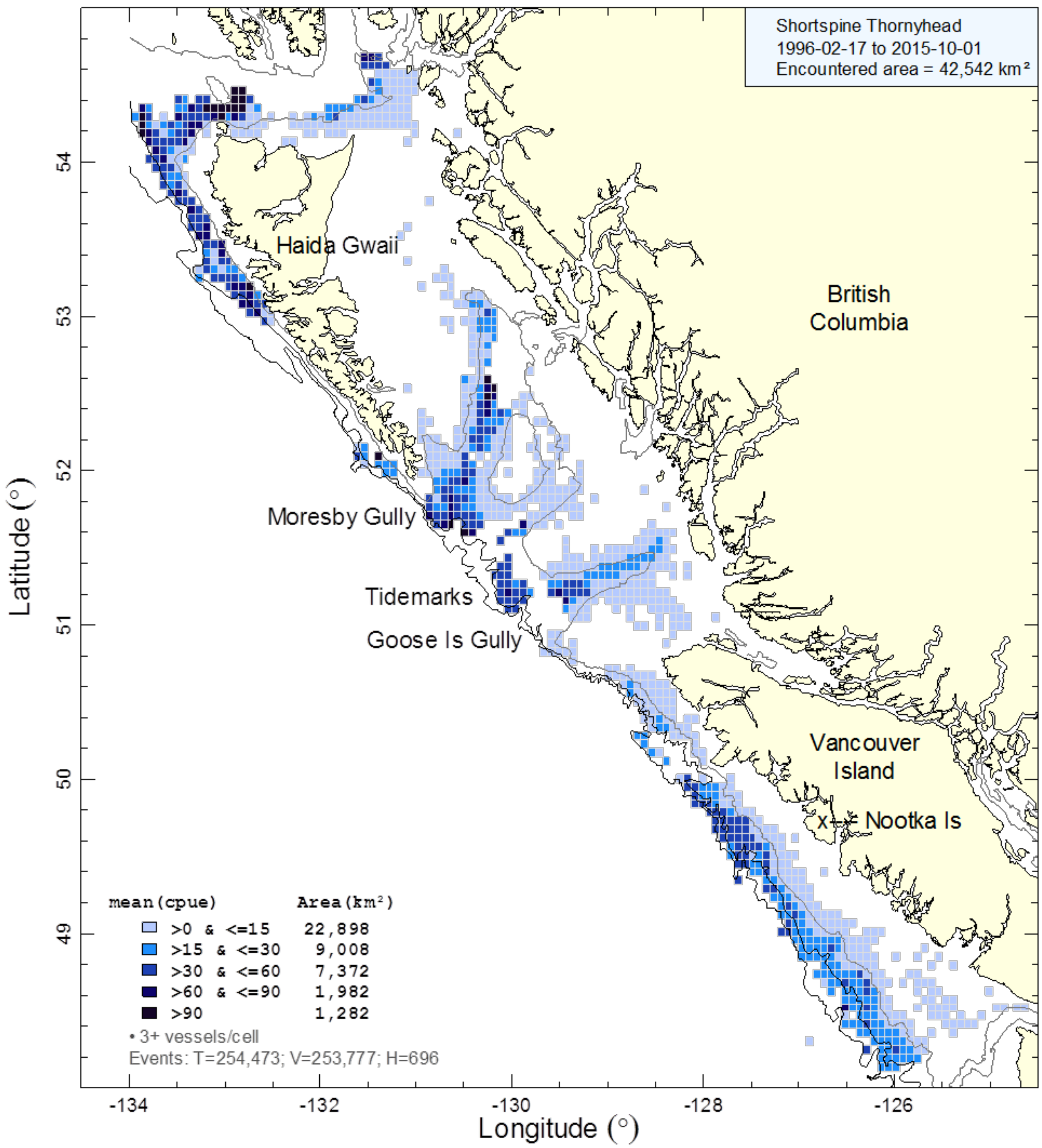

Figure 1. Mean catch-per-unit effort (CPUE: kg/h) of Shortspine Thornyhead in grid cells 0.075° longitude by 0.055° latitude (roughly 32.5 km^2 each) . The shaded grid cells give an approximation of the area where this species was encountered by fishing events from the groundfish trawl fleet from February 1996 to September 2015. Only those grid cells with three or more fishing vessels are displayed, where T = total number of fishing events available, V = number of events summarised by the display, and H = number of events hidden by absent grid cells. Legend colours divide the distribution of CPUE into 25%, 50%, 75%, 90% and 95% quantiles.

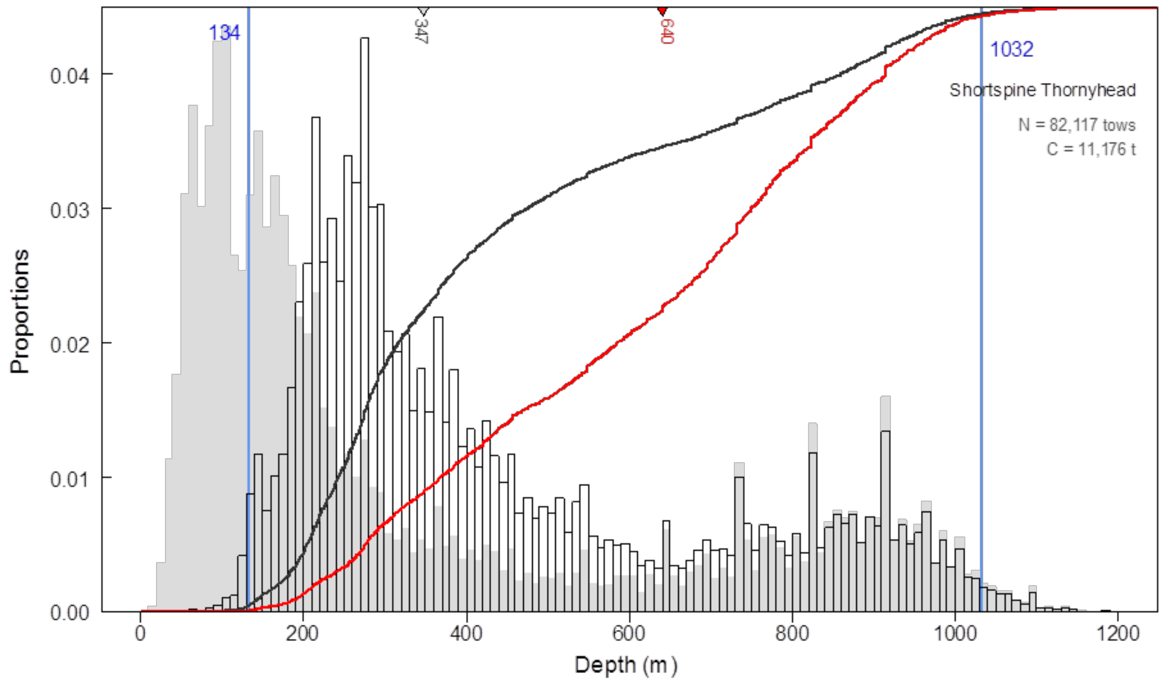

Figure 2. Depth frequency of bottom tows that capture Shortspine Thornyhead (SST) from commercial trawl logs (1996-2007 in PacHarvest, 2007-2015 in GFFOS, where 2015 records are incomplete) in PMFC major areas 3CD + 5A-E (transparent histogram). The vertical solid lines denote the 1% and 99% percentiles. The black curve shows the cumulative frequency of tows that encounter SST while the red curve shows the cumulative catch of SST at depth (scaled from 0 to 1). The median depths of cumulative catch (inverted red triangle) and of SST encounters (inverted grey triangle) are indicated along the upper axis. 'N' reports the total number of tows; 'C' reports the total catch (t). The shaded histogram in the background reports the relative trawl effort on all species at all depths.

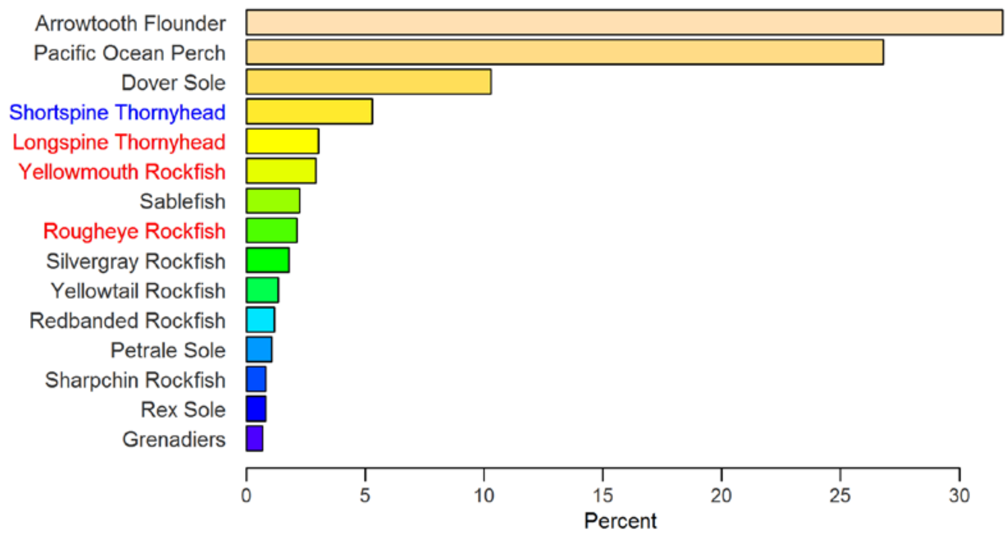

Figure 3. Distribution of catch weights summed over the period February 1996 to September 2015 for important finfish species in bottom tows that caught at least one Shortspine Thornyhead. Coastwide tows were selected over a depth range between 134 and 1032 m (the 1% and 99% range in Figure 2). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Shortspine Thornyhead is indicated in blue font on the y-axis; species of interest to SARA are indicated in red font.

2 CATCH DATA

Most British Columbia rockfish stock assessments conducted in recent years have attempted to reconstruct historical (pre-1996) catches because recorded rockfish catches during this period were either reported as combined species catches or the reported catch by species was inaccurate (Haigh and Yamanaka 2011). The general approach adopted in these stock assessments was to use modern (i.e., post-1996 – after the introduction of compulsory observer coverage) estimates of species distribution in the catch to disaggregate pre-1996 rockfish catches (e.g., Edwards et al. 2014a, Edwards et al. 2014b). However, after initial attempts to apply this approach to Shortspine Thornyhead catches, it was deemed inappropriate because the specialised nature of the modern fishery led to biased estimates of historical catch when the method was applied to historical bulk landings (see Appendix A for a summary of these results).

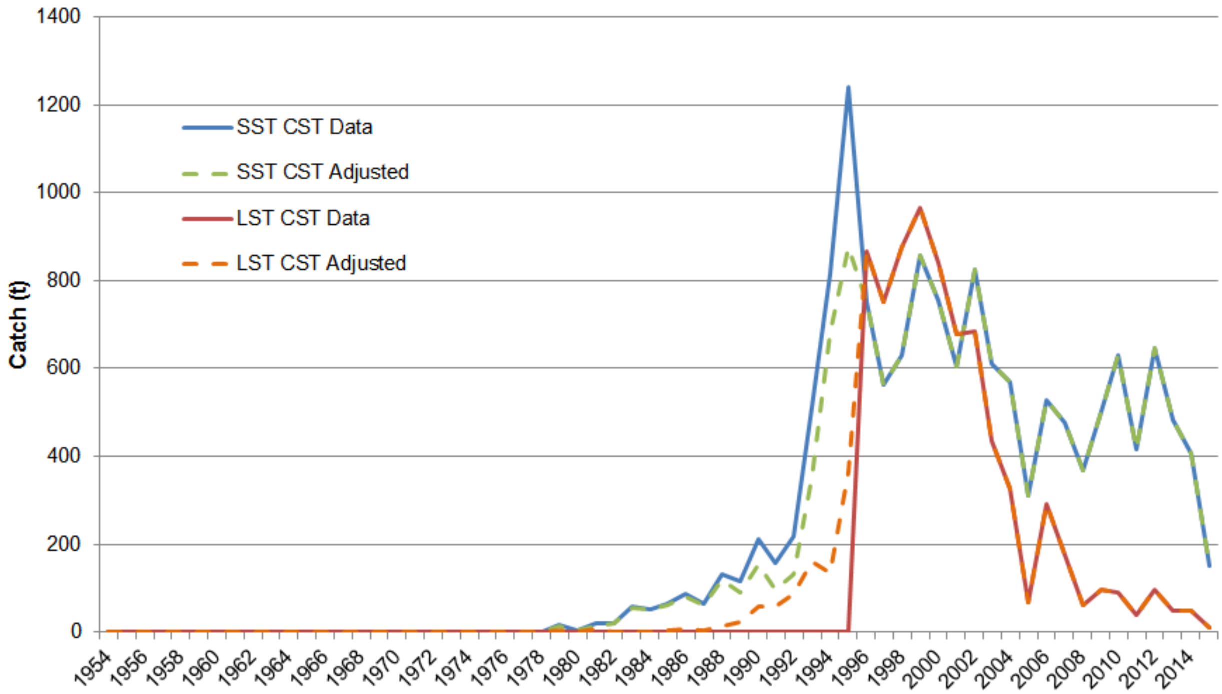

Figure 4. Trawl catch history of Shortspine (SST) and Longspine Thornyhead (LST) along the BC coast. Solid lines indicate the catches (landings + releases) reported in DFO databases; dashed lines indicate the adjusted catch histories after disaggregating the pre-1996 WCVI SST catch using proportions in Table A.6. Trawl catch data for the adjusted SST from 1980 on were used in the assessment.

After discussions with the BC trawl industry, represented by Brian Mose (Commercial Industry Caucus – trawl branch) and Bruce Turris (Canadian Groundfish Research and Conservation Society), the authors were advised that thornyheads were likely not captured by the domestic fleet before 1980, nor by the foreign offshore fleet that targeted Pacific Ocean Perch from the mid-1960s to the mid-1970s. Additionally, reporting of thornyhead landings by species did not occur until after 1996, with the sudden appearance of Longspine Thornyhead catches coinciding with the introduction of compulsory observer coverage. Industry advised that thornyhead landings (all coded SST in the available databases) before 1996 should be disaggregated into catch by species for each PMFC region using the ratios of the two species in the observer catch records during the early years of the observed fishery, when species identification was reliable and the fishery most closely resembled fleet activity in the early 1990s. The resulting catch history for SST is reported in Table A.7 and plotted in Figure 4.

3 FISHERIES MANAGEMENT

The history of fisheries management of Shortspine Thornyhead is detailed in Appendix A. Total allowable catches (TACs) for this species have only been in place since 1996 and have remained fairly stable since then (~730-770 t/y). Starting in management year 2001, a coastwide TAC of 771 t was established with formal allocation between the trawl (95.4%) and hook and line sectors (4.6%). The latter subdivided the 4.6% allocation between the Outside ZN (2.27%) and Halibut (2.33%) fisheries. In 2006, the Groundfish Hook and Line Sub Committee (GHLSC) agreed to set aside 5% of the ZN allocation for research purposes (~1 t/y). In 2013, the Groundfish Trawl industry agreed to trawl TAC offsets to account for unavoidable mortality during groundfish trawl multi-species surveys; for Shortspine Thornyhead this offset = 1.7 t per year.

4 SURVEY DESCRIPTIONS

Five fishery-independent surveys were used to describe Shortspine Thornyhead abundance in the stock assessment model (details in Appendix B, including justification for inclusion or exclusion of surveys). These surveys cover the period from 1980 to 2015, which is the same period included in the delay-difference stock assessment model. The five surveys are:

1. a transect-design trawl survey covering the lower half of Vancouver Island and most of the Washington State coast south of Juan de Fuca Strait. This survey was operated by the US National Marine Fisheries Service (NMFS), and was repeated seven times in Canadian waters using 11 vessels over the period 1980 to 2001. This survey is referred to as the “US Triennial” survey series.
2. a random-stratified “synoptic” trawl survey covering the west coast of Vancouver Island (WCVI). This survey has been repeated six times between 2004 to 2014 using the same vessel and a consistent design, including targeting a wide range of finfish species. The series is referred to as the “WCVI synoptic” survey series.
3. a random-stratified “synoptic” trawl survey covering all of Queen Charlotte Sound (QCS). This survey has been repeated eight times between 2003 to 2015 using three vessels and a consistent design, including targeting a wide range of finfish species. This series is referred to as the “QCS synoptic” series.
4. a random-stratified “synoptic” trawl survey covering all of Hecate Strait (HS) and extending into Dixon Entrance and across the top of Graham Island. This survey has been repeated six times between 2005 to 2015 using two vessels and a consistent design, including targeting a wide range of finfish species. This series is referred to as the “HS synoptic” series.
5. a random-stratified “synoptic” trawl survey covering the west coast of Graham Island in Haida Gwaii (HG) and western part of Dixon Entrance. This survey has been repeated five times between 2006 to 2012 using three vessels and a consistent design, including targeting a wide range of finfish species. This series is referred to as the “WCHG synoptic” series.

These relative biomass survey series were used as input data to the stock assessment model along with the associated relative error for each index value.

5 CPUE ABUNDANCE SERIES

Commercial catch and effort data were used to generate indices of abundance for SST in this stock assessment. This was done for several reasons, with the primary reason being the lack of long-term abundance information for use in this data-moderate model. In addition, it was hoped that the nature of this fishery, with the majority of SST catches being non-targeted while targeting other rockfish (Figure 3) or as a specialised target fishery where tows were long and indiscriminate as to species captured, would result in an index series that was relatively unaffected by economic considerations. Similar work on the congener species Longspine Thornyhead (Starr and Haigh 2000; Starr 2001) had also yielded apparently credible CPUE index series.

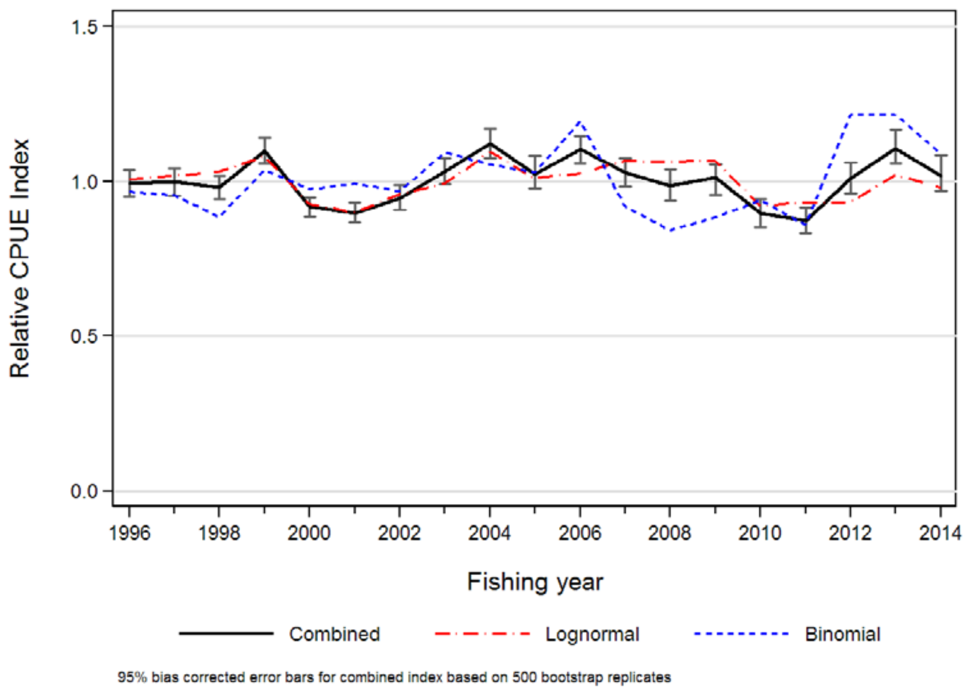

Figure 5. Combined, lognormal and binomial models for Shortspine Thornyhead in PMFC areas 3CD + 5ABCDE, based on commercial trawl catch and effort data. The error bars for the combined model were estimated by a bootstrap procedure sampling 500 times with replacement.

The theoretical basis for the analysis is described in Appendix C, Section C.2. The analysis (Sections C.3 and C.4) is based on coastwide (PMFC areas 3 and 5) tow-by-tow data which reported Shortspine Thornyhead landings or discards or which operated in a depth range where SST would be expected to be caught. The period analysed was from 1996, when compulsory onboard observer coverage began, to 2014, the last available complete year of data. Three analyses were performed:

a. a regression analysis on all positive catch records which assumed a log-normal distribution, where the effect on catch rates by fishing depth, 0.1°degree latitude bands, hours fished and vessel were estimated and removed from the trend, leaving a standardised annual abundance trend;

b. a similar analysis using the presence/absence of SST in the data set, which assumed a binomial distribution and which removed the effects of depth, DFO locality and hours fished, resulting in an alternative annual abundance trend; and

c. an analysis which combined the log-normal and binomial series using the delta-lognormal method of Vignaux (1994; see Equation C.4).

It is this final series (Figure 5) that was used as input to the SST stock assessment model. Model sensitivity runs which dropped this series or used it alone were made to investigate the impact of this CPUE series in the stock assessment.

6 BIOLOGICAL INFORMATION

6.1 GROWTH PARAMETERS

DFO growth parameters were estimated from approximately 700 Shortspine Thornyhead length and age data pairs available from biological samples collected primarily in 1995, 1996 and 2003 by research surveys (see Appendix D). This ageing had been done using the “break & burn” method which potentially underestimates the number of growth rings compared to using the “thin-section” method when applied to a species with this level of age estimation difficulty (Stephen Wischniowski, DFO, Nanaimo, B.C., pers. comm. see Section D.6). A test sample of SST otoliths (*n*=60) had been recently prepared at the PBSSL using the above two preparation methods which had been read independently by four experienced readers. An analysis of the resulting data suggested that the two preparation methods did not, on average, estimate significantly different ages for the same otoliths (see Table D.4 and the associated text in Appendix D). However this unpublished trial should not be considered definitive because the power to detect bias from this simple experiment is likely to be low due to the small number of observations and the exploratory nature of the study.

A sex-specific growth model (termed DFO) was estimated as a three-parameter von Bertalanffy model from these ages and then combined into a single-sex averaged growth function (see Figure D.4) for use in the single-sex delay difference model. Parameters for allometric weight-length relationship for both sexes combined were estimated for SST using research survey data (see Section D.1). These two functions were combined to estimate a Walford plot (see Figure D.7) which is the function used to specify growth in a delay-difference model (see Equation E.1).

A second growth model (termed NMFS) was developed based on the growth parameters published in Taylor and Stephens (2013, see Section D.1.3 for details). This growth model estimated a combined-sex L_∞=71.2 cm, which was much higher than the equivalent parameter estimated by the DFO growth model (combined-sex L_∞=47.3 cm) and a lower intrinsic growth rate (K=0.018 compared to the DFO K=0.038). The weight-length allometric relationship used by Taylor and Stephens (2013) was nearly identical to the one derived from the Canadian data, and these two functions were combined to generate a Walford plot specific to the NMFS growth function for use in model runs.

6.2 SELECTIVITY AND MEAN WEIGHT

In excess of 30,000 length observations were available from the combined 3CD+5A-E trawl fisheries (see Appendix D) covering an 18-year period extending from 1997 to 2014. Only observations from unsorted samples collected by on-board observers in the commercial fishery were used to estimate weighted length distributions based on the sample weight within a three-month quarter and using the commercial catch to weight the combined annual sample across quarters.

These data were used in two ways:

a. to calculate proportional cumulative frequency distributions for each year by one-centimetre length bin (see Section D.1.3). The median length across all these distributions was then used to estimate an age (based on back-calculating from the final von-Bertalanffy growth model) for knife-edge selectivity to the fishery. The resulting median length of 29 cm equated to a 16-year old SST, using the DFO growth model and to 21 years using the NMFS growth model. Because of the high mean age associated with 29 cm when using NMFS growth, alternative values of 24 cm (16 years) and 21 cm (13 years) were used in model runs based on NMFS growth.

b. to estimate annual mean weights for use as an input data series in the stock assessment model (see Section D.3). Delay-difference models use this information as absolute estimates of population mean weight which serve as a major source of information in the model for estimating recruitment deviations. An additive GLM regression model was fit to the sample data to estimate a series of annual mean weights after removing trends resulting from depth, longitude, latitude and month of capture for each sample.

6.3 MATURITY

Maturity is not used as input into a delay-difference model. Instead, the age at knife-edge recruitment is assumed to also define maturity, resulting in a model which assumes that all recruited fish are also mature. However, a maturity ogive based on a subset of the break and burn age data described in Section 6.1 was constructed to test the consistency of the available data with the assumption that all fish from the knife-edge age were mature (see Section D.2).

The resulting analysis indicated that the median age at maturity for SST lay between ages 8 and 9 for both males and females (using the DFO growth model, see Figure D.10) or between lengths 20 and 22 cm (Figure D.11). These values are below any of the ages or lengths used in this stock assessment as candidates for knife-edge recruitment (the lowest investigated age was 12 y which was a model that seemed to be at the lower limit of plausible ages for this parameter). Therefore, it is likely that all recruited SST are mature.

6.4 NATURAL MORTALITY

Understanding natural mortality for SST was made difficult because of the contradictory nature of the available information. While the literature suggested that *M* should be low (around 0.04 to 0.06, e.g., Butler et al. 1995, Kastelle et al. 2000), the DFO GFBio database held few old females (maximum age=95, see Table D.2) and the majority of the available SST ages were young (mean age 19 years, *n*=1144). Most of these ages were collected in the mid-1990s, near the beginning of the exploitation history when it would be expected that the population would contain the older fish associated with a low *M*. Given that the available data held fewer older SST than would be expected from a low *M*, we considered a number of hypotheses to explain this observation:

a. the ageing was biased low;

b. the older SST were not available to the fishery; or

c. natural mortality *M* may be greater than suggested by the literature.

Although we couldn't rule out hypothesis a, the availability of a limited test sample of SST otoliths (*n*=60) (see Section 6.1 above) prepared using the two methods and read independently by four readers suggested that the age estimates were, on average, not significantly different among preparation methods. Hypothesis b was not easily testable but could be true, given that SST are thought to migrate deeper as they get older (Jacobson and Hunter 1993). Finally, hypothesis c could not be ruled out. We considered that the lone observation of a 95-year old female set a lower bound of about *M*=0.05 for this species in BC waters (see Section D.4), while the available ageing data were most consistent with *M*=0.10, given the relatively young mean age for the available age estimates. We settled *M*=0.08 as the most plausible estimate for *M* that was consistent with the DFO growth rate model and investigated model sensitivity across five fixed values of *M*, ranging from 0.03 to 0.12. Similarly, we investigated three values of *M* (0.03. 0.06 and 0.08) using model runs based on the NMFS growth model.

6.5 STEEPNESS

A Beverton-Holt (BH) stock-recruitment function was used to generate average recruitment estimates in each year, based on the biomass of recruited SST (Equation E.22). Recruitment deviations from this average (Equation E.23) were estimated to improve the fit to the model data. The BH function was parameterised using a "steepness" parameter, *h,* which specified the proportion of the maximum recruitment that was available at 0.2 B_0. The parameter *h* was estimated in the model, constrained by a prior that took the form of a beta distribution with mean 0.7 and standard deviation 0.15. These values are very similar to the prior developed for west coast rockfish by Forrest et al. (2010; mean=0.67; standard deviation=0.168).

7 DELAY-DIFFERENCE MODEL

Delay difference models represent an intermediate approach between aggregated surplus production models and age-structured models. The delay-difference structure tracks the effects of recruitment, survival and growth on biomass, without requiring an age-structured framework, and can perform well as long as its major assumptions are met (Hilborn and Walters 1992). Difference equations, which allow for a time-delay between spawning and recruitment, are used to build population models in discrete time-steps (generally 1 year), in which the surviving biomass for next year is predicted from the surviving biomass from the previous year, after adjusting for growth and mortality and adding next year's recruitment. An advantage of delay difference models over some simpler production models is that they do not assume constant recruitment over time.

The key assumptions of the delay difference model are:

- Growth in mean body weight follows the linear relationship described by the Ford-Walford equation (E.1).
- Knife-edge selectivity, i.e., all fish aged *k* and older, are equally vulnerable to the fishing gear. A corollary to the assumption of knife-edge selectivity is that maturity is also knife-edge and the same as selectivity. This means that all fish in the model are mature and fully selected.
- Constant mortality at age, i.e., all fish aged *k* and older, have the same mortality rate.

This model is described with equations in Appendix E. The model was fit to the annual catch data, five survey series described in Appendix B, a series of CPUE biomass indices described in Appendix C, and a series of fishery mean weights described in Section D.3. We did not attempt to alter the relative weighting of the component data series, instead using the observation error CVs estimated by the surveys without modification. An arbitrary CV=0.3 was used for the CPUE data and CV=0.15 for the mean weight data. Sensitivity to the variance components of the model was explored through runs which arbitrarily raised and lowered the overall model error or which changed the relative mean weight error.

7.1 RUNS BASED ON DFO GROWTH MODEL

Initial model runs were made based on the DFO growth model. These model runs were assumed to start at equilibrium from B_0 in 1980. While there were minor amounts of SST landings before 1980, reported landings for this species did not exceed 100 t/year until the early

1990s (Table A.7 and Figure 4). Preliminary fits using starting years earlier than 1980 led to implausible biomass trajectories. Starting the model in 1980 allowed the use of all seven observations from the NMFS Triennial survey while still giving sufficient time for the model to move away from the initial equilibrium assumption. Sensitivity to start years after 1980, once the fishery was more established, was explored through runs which assumed that the stock was at equilibrium with the fishing mortality rate in the first year. A description of the fixed parameters assumed for one example run based on the DFO growth model can be found in Table E.1.

All model runs were made in a Bayesian context, starting from the MPD (mode of the posterior distribution). This “best fit” to the available data was found by minimising a function that summed the negative log-likelihoods arising from fit of the model predictions to each data set (relative abundance, catch, mean weight), the deviations from mean recruitment, the penalties from the informed prior for steepness, and penalties used to ensure that the catch data were fit. The MPD was used as the starting point for a Bayesian search across the joint posterior distributions of the parameters using the Monte Carlo Markov Chain (MCMC) procedure. The MCMC chain length was 50,000,000, with a sample taken every 50,000 to give a posterior of 1,000 samples. An initial chain of 1,500,000 was run as a “burn-in” as well as allowing the MCMC search to rescale to obtain an appropriate sampling rate. The initial samples (including the MPD start) were discarded and the final posterior contained 1000 samples which were used to estimate parameters and quantities of interest, including stock status by year and the probabilities of being above reference points.

Table 1. List of sensitivity runs made for the SST delay-difference stock assessment, based on the DFO growth model and ordered by sensitivity grouping. The description shows the changed assumptions for each sensitivity run; all remaining assumptions remain as described in Table E.1.

Sensitivity number	Description	Label	Sensitivity grouping
S00	M=0.08, k=16	M.08	0
S01	M=0.03, k=16	M.03	1
S02	M=0.06, k=16	M.06	1
S03	M=0.10, k=16	M.10	1
S04	M=0.12, k=16	M.12	1
S05	M=0.08, k=12	k12	2
S06	M=0.08, k=14	k14	2
S07	M=0.08, k=18	k18	2
S08	M=0.08, k=20	k20	2
S09	M=0.08, k=16, σ_O =0.3; σ_R =0.8	sig0.3|sigR.8	3
S10	M=0.08, k=16, σ_O =0.1; σ_R =0.4	sig0.1|sigR.4	3
S11	M=0.08, k=16, σ_W =0.05	wgtsig.05	3
S12	M=0.08, k=16, start year=1990	syr=1990	4
S13	M=0.08, k=16, start year=1996	syr=1996	4
S14	M=0.08, k=16, no CPUE	noCPUE	5
S15	M=0.08, k=16, only CPUE	onlyCPUE	5
S16	M=0.08, k=16, no Triennial	noTriennial	5
S17	M=0.10, k=12	M.10+k12	2
S18	M=0.10, k=14	M.10+k14	2
S19	M=0.10, k=18	M.10+k18	2
S20	M=0.10, k=20	M.10+k20	2
S21	M=0.10, k=16, σ_O =0.3; σ_R =0.8	M.10+sig0.3|sigR.8	3
S22	M=0.10, k=16, σ_O =0.1; σ_R =0.4	M.10+sig0.1|sigR.4	3

Sensitivity number	Description	Label	Sensitivity grouping
S23	M=0.10, k=16, σ_W =0.05	M.10+wgtsig.05	3
S24	M=0.10, k=16, start year=1991	M.10+syr=1991	4

An important component to this stock assessment was testing the sensitivity of the results and the associated advice to key uncertainties in the underlying stock assessment model. Therefore, we made 25 runs based on the DFO growth model (Table 1) that tested the robustness of the results and advice to uncertainties in:

- natural mortality (*M*);
- age at knife-edge recruitment (*k*);
- observation, recruitment and mean weight error (σ_O , σ_R , and σ_W);
- model start year;
- use of CPUE index series.

We particularly focussed on uncertainties in *M* and *k*, reasoning that these parameters will have the greatest impact on model results and advice and will be poorly informed by the available data. Fewer variations were explored for other uncertainties because we felt there was less impact to the advice from these assumptions.

MCMC posterior distributions were generated for each sensitivity run using the procedure described for the example run.

Results from these model runs are described in Section F.3.

7.2 RUNS BASED ON NMFS GROWTH MODEL

The NMFS growth model was developed for this stock assessment in recognition of the uncertainty associated with ageing this species (see Section 6.1 and Section D.1.3). The ages used in the NMFS growth model were also determined using the “break and burn”' methodology, but the available data included older and larger specimens than those observed from BC waters.

Nine model runs were made using the NMFS growth model. These explored three possible fixed values for M (0.03, 0.06, 0.08) across three options for age at knife-edge recruitment: 21 years (corresponding to 29 cm), 16 years (corresponding to 24 cm) and 13 years (corresponding to 21 cm). All runs started at equilibrium in 1980 and used the 5 survey series and the CPUE index series. It was felt that model sensitivities to alternative error assumptions, different starting year assumptions and the effect of removing specific data sets had already been adequately explored using the DFO growth model. MCMC posterior distributions were generated for each run using the procedure described for the example run.

Results from these model runs are described in Section F.4.

7.3 COMPOSITE REFERENCE SCENARIO (MODEL AVERAGE)

We adopted a composite reference scenario (sometimes referred to as the “Model Average”) to evaluate this stock because of the uncertainty with respect to many key assumptions that cannot be resolved from the available data. This composite scenario incorporated a range of assumptions that span the uncertainty in the underlying assumptions, including two growth functions, which represent two possible hypotheses on SST life history. The first, represented by the NMFS growth model, adopts published analyses that characterise Shortspine

Thornyhead as a slow-growing species with many old fish in the population, while the second, represented by the DFO growth model, adopts the available BC Shortspine Thornyhead age data which suggest that BC had few old or large specimens. See Sections F.3 and F.4 for details regarding the model runs used for the model average.

Uncertainty due to growth, natural mortality, and the age of knife-edged selectivity was included in this composite scenario by selecting 12 model runs from the 34 model runs for inclusion in the final averaged scenario (Table 2). These 12 model runs spanned hypotheses deemed plausible by the peer review process with respect to growth (options DFO and NMFS), instantaneous natural mortality M (0.03, 0.06, 0.08) and a range of lengths for knife-edge (*k*) recruitment to the fishery occurred (k = 29, 24, 21 cm). The selection of runs to include in the composite reference scenario included three values for M and one value of k (29 cm) used with the DFO growth model. The remaining nine runs were based on the NMFS growth model and included three values of M and three values for knife-edge recruitment (k=29, 24, 21 cm). The lower values for k in conjunction with the NMFS growth model were selected in recognition that the 29 cm length was probably at the upper end of plausibility, given the slower growth model. An MCMC posterior for the composite reference scenario was constructed by pooling 1000 MCMC samples from each of the selected runs to give a pooled total of 12,000 samples. This pooled posterior was then used to give advice with respect to stock status and projections, with each individual model run contributing equally to the model average scenario.

Table 2. Twelve scenario options adopted for model averaging. DFO growth: L_∞=47.257cm, K=0.0385, t0=-8.456; NMFS growth: L_∞=84.99cm, K=0.0178, t0=-2.88; M= natural mortality; (k_L, k_A)= length and age at knife-edge recruitment. Each scenario contributes 1000 MCMC samples.

Scenario	Growth	M	k_L (cm)	k_A (y)	Model Run
1	DFO	0.03	29	16	22
2	DFO	0.06	29	16	12
3	DFO	0.08	29	16	5
4	NMFS	0.03	29	21	24
5	NMFS	0.03	24	16	25
6	NMFS	0.03	21	13	26
7	NMFS	0.06	29	21	27
8	NMFS	0.06	24	16	28
9	NMFS	0.06	21	13	29
10	NMFS	0.08	29	21	33
11	NMFS	0.08	24	16	34
12	NMFS	0.08	21	13	35

8 MODEL RESULTS

8.1 RUNS BASED ON DFO GROWTH MODEL

Results for an example model run which assumed M=0.08 and k=29 cm (=16 years old, based on the DFO growth model) (run S00, Table 1) are presented to illustrate model behaviour, particularly in how these models fit the available data, the shape of the biomass trajectory and the predictions of stock status. This comparison could be done using many of the plausible model runs as the example run, regardless of the assumptions made regarding key productivity parameters, because the available data are not informative with respect to productivity, resulting in reasonable fits to the data across a fairly wide range of assumptions.

The MPD fits in the example model run to the survey and CPUE indices are generally reasonable although the model is incapable of fitting the abrupt changes in some series (Figure 6). The model is also not capable of fitting the generally increasing trend in mean weight that follows an initial drop in 1998 (Figure 7). Instead it remains fairly constant near the mean of the series, ignoring the upward trend in the data. Model runs which attempted to improve the fit to this index series by increasing the relative series weight showed little improvement in the fit while substantially deteriorating the fit to the biomass indices. Fits to the catch data are not presented because the model is parameterised to always fit these data.

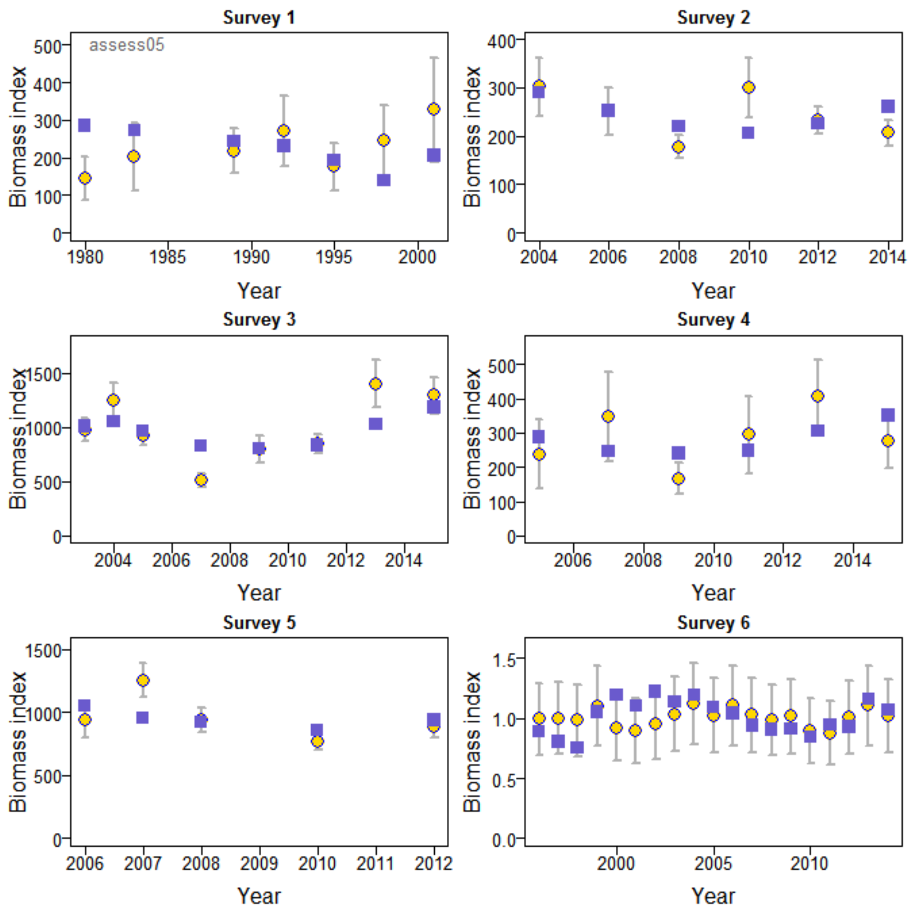

Figure 6. MPD fits to the five survey abundance series and to the CPUE index series by example model run S00.

The MCMC diagnostics for the example model run are acceptable, with the posterior chain showing good mixing and no sign of drifting (see Figures F.3 and F.4). Autocorrelation in the leading parameters is low (Figure F.5) and correlations between parameters are acceptable and follow predictable patterns (Figure F.6).

A plot of spawning biomass depletion (B_t/B_0 ; Figure 8, left panel), based on the MCMC posterior, shows a declining trend once catch started to increase in the early to mid-1990s, and then started to increase until the present. The median value for depletion in 2015 is 1.22, which is well above all proposed reference points. The MPD trend is similar but lies at the lower edge of the MCMC posterior distribution. This result is likely caused by the MCMC search giving plausibility to larger biomass levels than were obtained by the MPD best fit. The model estimates a strong recruitment in 1999 (Figure 8, right panel), possibly as a response to the increased catches but more likely to fit the drop in mean weight observed between 1998 and 1999. The declining biomass trend reverses with this recruitment pulse and in response to a lower fishing mortality from reduced catch levels after 2000 (see Figure A.2). Fishing mortality peaks in 1999 (Figure F.9) at a median value of 0.165 and declines until it reaches 0.053 in 2015.

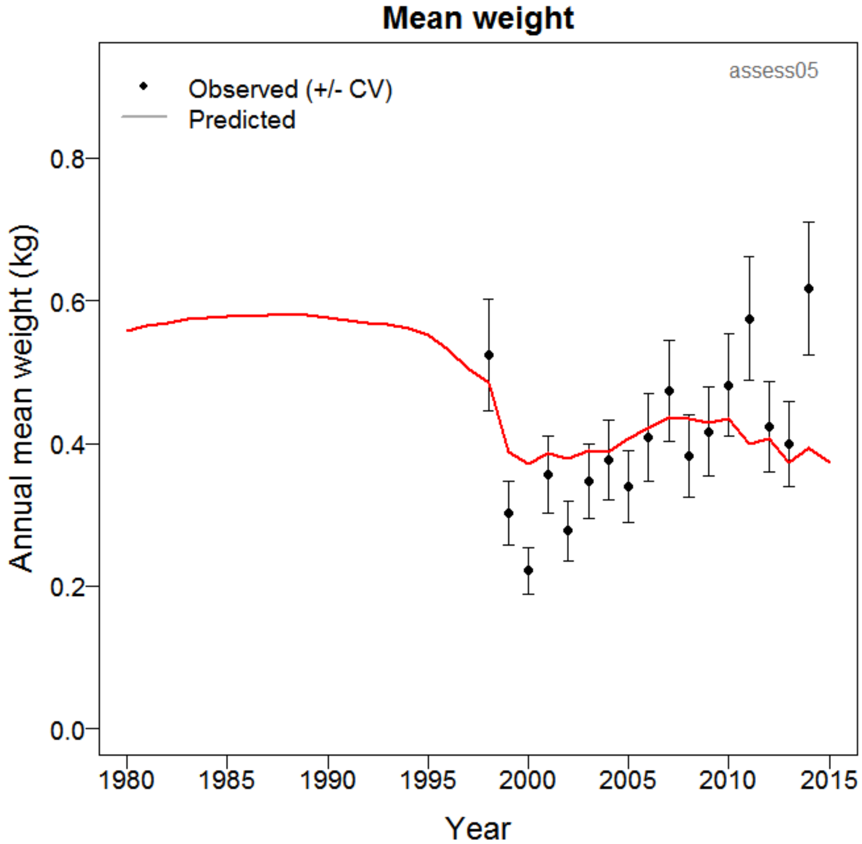

Figure 7. MPD fit to the mean weight data by example model run S00.

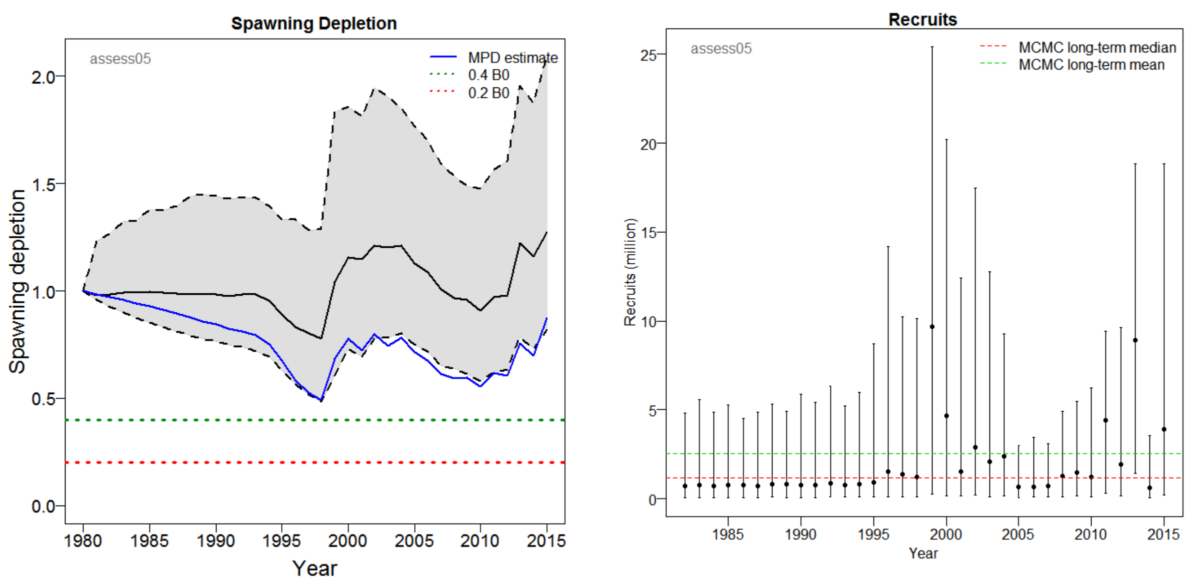

Figure 8. Example model run S00 : [left panel]: time trend of depletion (Bt /B0), showing the median (heavy line), 5% and 95% quantiles (dashed lines) from the posterior distribution, as well as showing the MPD trend and the DFO provisional LSR and USR; [right panel]: time trend of recruitment showing 95% credibility intervals.

Plots which show the MPD fits to three data series (Figure F.13 – mean weight, Figure F.14 – CPUE, and Figure F.15 – QC Sound synoptic survey) across all the sensitivity runs demonstrate that this model has little power to distinguish among hypotheses on the basis of these fits. Table F.3, which gives the negative log-likelihoods for comparable model fits, provides a more quantitative basis to make the same comparison. This table shows that while there are differences in the fits to the data among the sensitivity runs, they are not large and there is no consistent pattern among hypotheses to use these likelihoods as criteria for model selection. This leads to the conclusion that the available data have little power to distinguish between the uncertainties associated with *M* and *k*. This is not surprising because these parameters usually require age or length data for estimation and are often problematic to estimate even when such data are available. Apart from the observation that the trends in the mean weight data and survey abundance indices are in conflict, which means that fitting more closely one set deteriorates the fit in the other set, there seems to be little in the actual fits to the data to aid in model selection.

The behaviour of the MCMC traces with respect to this range of sensitivity hypotheses is interesting and possibly informative. Models with age=12 and age=14 at knife-edge recruitment, assuming the DFO growth model, showed more unstable MCMC behaviour than the older ages for *k* (see Figure F.16), which was true for the two values of M (0.08 and 0.10) which explored lower ages for knife-edge recruitment. However, the top row of Figure F.16 shows little difference in the trace plots for the full range of M values (from 0.03 to 0.12). Unsurprisingly, the models with increased variance showed more evidence of MCMC non-convergence than the example case or the models with reduced variance. While these observations have no theoretical basis for use in distinguishing among hypotheses, they do lead to the feeling that the range of hypotheses included in Table 1 likely span a reasonable range of parameters and that the more extreme values of *k* and *M* tested in this group may be less plausible than those in the centre of the range, given the assumption of the DFO growth model.

Median estimates for current biomass lie well above the B_{MSY} and 0.4 B_0 target reference points across the full range of sensitivity runs (Table 3). Only when *k*=20 is there even a suggestion that median current biomass is dropping to levels that might approach the 0.4 B_0 reference level and is in all cases well above B_{MSY}. Table F.5 shows that, while the estimates of current stock status are somewhat independent of the underlying model hypothesis, the estimates of long-term yield are highly dependent on the underlying hypotheses, with median estimates of MSY varying from around 200 t/year for the runs where variance or *M* are low to greater than 1000 t/year for the models where *k* is low or *M* is high.

The primary determinants for stock status and yield are, unsurprisingly, *M* and *k*, with lower values of *M* giving lower long-term yields and lower stock status while the lower values for *k* result in very strong stock status and high yields. Other considerations (such as the size of the variance component, the use of CPUE data and the model start year) appear to be much less influential that are the two primary sources of uncertainly.

The S14 sensitivity run, which dropped the CPUE abundance index series, showed poorer MCMC convergence characteristics (see Figure F.16) but its parameter estimates are similar to those for the example case (Table 3; Figure F.21). This leads to the conclusion that the CPUE series is reasonably consistent with the other abundance index series and that the long uninterrupted nature of this series helps stabilise model behaviour.

Table 3. Median values for select MCMC-derived parameters and quantities for the 21 runs described in Table 1. Projections to 2019 were made assuming TAC=600 t, a value near to the 2010-2014 average catch of 572 t.

Sensitivity run	Label	h	B_0	B_{2016}/B_0	B_{2019}/B_0	P[B_{2019}> B_{2016}]	B_{2016}/ B_{MSY}	u_{MSY}	u_{2016}/ u_{MSY}
S00	M.08+k16 (DFO Ref)	0.775	7,338	1.219	0.998	0.001	3.56	0.139	0.361
S01	M.03	0.784	6,118	0.977	0.746	0	2.56	0.039	1.78
S02	M.06	0.782	6,761	1.110	0.880	0	3.16	0.095	0.622
S03	M.10	0.772	8,628	1.374	1.140	0.007	4.14	0.189	0.203
S04	M.12	0.773	10,676	1.524	1.300	0.022	4.55	0.252	0.118
S05	k12	0.763	37,029	1.843	1.740	0.048	5.062	0.113	0.054
S06	k14	0.771	11,960	1.590	1.430	0.010	4.535	0.131	0.189
S07	k18	0.783	5,436	0.915	0.633	0	2.841	0.156	0.565
S08	k20	0.784	4,338	0.558	0.235	0	1.732	0.173	1.031
S09	sig0.3|sigR.8	0.787	9,179	0.876	0.725	0.036	2.537	0.156	0.371
S10	sig0.1|sigR.4	0.776	4,282	1.740	1.320	0	5.626	0.139	0.449
S11	wgtsig.05	0.776	5,371	1.817	1.470	0	5.465	0.139	0.326
S12	syr=1990	0.766	8,644	0.936	0.780	0.009	2.796	0.139	0.402
S13	syr=1996	0.833	26,143	0.390	0.400	0.512	1.32	0.173	0.276
S14	noCPUE	0.778	6,897	1.750	1.440	0	5.285	0.148	0.265
S15	onlyCPUE	0.765	7,039	0.734	0.540	0.005	2.98	0.112	0.779
S16	noTriennial	0.781	7,312	1.12	0.902	0.005	4.68	0.118	0.479
S17	M.10+k12	0.765	95,031	1.888	1.760	0.058	5.320	0.156	0.016
S18	M.10+k14	0.774	20,128	1.776	1.610	0.031	5.109	0.181	0.072
S19	M.10+k18	0.783	5,568	0.993	0.711	0.003	3.158	0.213	0.378
S20	M.10+k20	0.774	4,239	0.667	0.328	0	2.087	0.221	0.691
S21	M.10+sig0.3|sigR.8	0.789	10,892	0.978	0.839	0.078	2.893	0.213	0.212
S22	M.10+sig0.1|sigR.4	0.771	4,521	1.950	1.480	0	6.327	0.181	0.282
S23	M.10+wgtsig.05	0.772	6,108	2.019	1.640	0	6.238	0.189	0.191
S24	M.10+syr=1991	0.773	9,980	1.022	0.882	0.036	3.106	0.197	0.237

8.2 COMPOSITE REFERENCE SCENARIO (MODEL AVERAGE)

Selected MPD results from the 12 model runs contributing to the composite reference scenario are presented in Figures F.24 to F.26. Generally, the fits through the mean weight data are better for the NMFS growth scenarios but these models tend to exaggerate the unfished equilibrium mean weight (Figure F.24). It seems unlikely that the mean weight of SST would have declined from over 2 kg to 0.5 kg in the space of a few years with all the large individuals disappearing (as observed in the available sampling data). The models using DFO growth do not fit the mean weight data very well even though estimated equilibrium mean weight appears to be more plausible. The model fits to the Queen Charlotte Sound Synoptic survey index data are good for the DFO growth scenarios but poor for the NMFS growth scenarios that use lower *k* values (Figure F.25). All scenarios appear to have little trouble fitting the commercial CPUE except for the run which assumes DFO growth with M=0.03 (Figure F.26).

Trace plots for the 12 contributing model runs are generally well behaved (Figure F.27). Biomass trajectories for the runs using the DFO growth model are largely flat while those runs which use the NMFS growth model show steep declines under lower M assumptions (Figure F.28). Biomass projections (2016-2019) are downward under all scenarios, with the NMFS M=0.03 scenarios suggesting unrealistic stock collapse. Biomass depletion is flat for the runs using the DFO growth model while the NMFS growth model runs show declines with lower M values and higher k values (Figure F.29). Depletion appears to be more heavily influenced by changes in M than changes in k. All runs other than NMFS M=0.03 show that the stock largely remains above the DFO biomass reference points outlined in Section 9.1 (Figure F.29). The scenarios also differ on how biomass and fishing mortality compare to various candidate reference points (Figure F.30). Phase plots show how the biomass and harvest rate trajectories have behaved under the different scenarios (Figure 31). All scenarios largely remain in the DFO Healthy Zone with respect to B_{MSY}; however, the harvest rates have frequently exceeded u_{MSY}.

The composite reference scenario biomass depletion (B_t/B_0, Figure 9) suggests that the stock has remained above the upper stock reference $0.8B_{MSY}$ since 1980, with a probability of 0.0078 that it dropped below 0.4 B_{MSY} in 1999. However, since that time, the stock is estimated to have increased to levels well above both reference points, coinciding with a decrease in catches in the early 2000s. Figure 9 (right panel) details the trajectory of biomass B_t and harvest rate u_t in B_{MSY} and u_{MSY} space, respectively, from 1980 to 2016. Median equilibrium biomass before fishing (B_0 or B_{1980}) appears to be roughly 2.5 times the biomass required to generate MSY.

Figure 10 shows the current stock status, represented as B_{2016}/B_{MSY}, for the model average scenario as well as each of the 12 contributing scenarios, shown for contrast only. The probability that the stock lies above the USR (in the DFO "healthy zone") is 0.98. The median B_{2016}/B_{MSY} = 2.26 (1.59, 3.48), where values in parentheses represent the 5th and 95th percentiles. Quantities of interest for the composite reference scenario appear in Table 4.

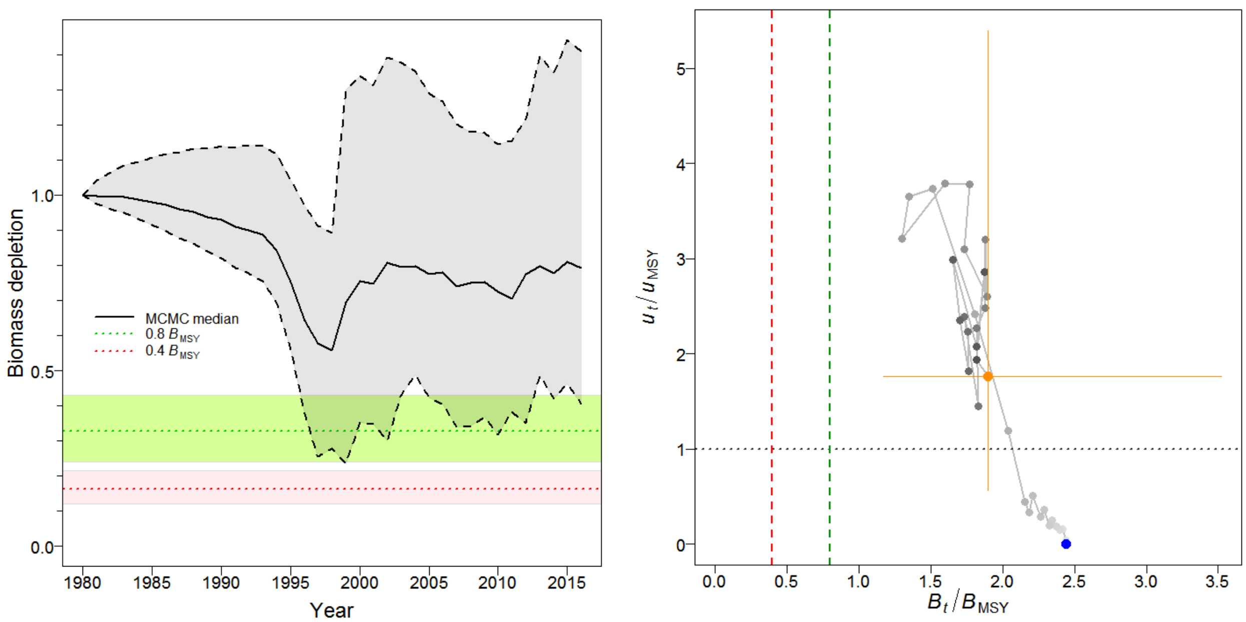

Figure 9. Left: Median estimates (solid black line) and 90% credibility intervals (black dashed lines, grey fill) for the composite reference scenario B_t/B_0 (biomass in year t relative to that in 1980) for SST. Also shown are the MSY-based reference points (Limit Reference Point, LRP = $0.4B_{MSY}$ shown as a red band and line; Upper Stock Reference, USR = $0.8B_{MSY}$ shown as a green band and line) relative to B_0. Right: Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the harvest rate in year t relative to u_{MSY}) for the model average. Blue filled circle is the starting year 1980. Years then proceed from light grey through to dark grey with the final year 2016 as a filled orange circle with limit lines represent the 0.1 and 0.9 quantiles of the posterior distributions for the final year. Vertical dashed lines indicate the Precautionary Approach provisional limit (red) and upper stock reference (green) points (0.4, $0.8B_{MSY}$), and horizontal dotted line indicates u at MSY.

Table 4. The 5th, 50th, and 95th percentiles of MCMC-derived quantities from 12,000 MCMC samples contributing to the composite reference scenario. Definitions: B_0 – unfished equilibrium biomass, B_{2016} – biomass at the start of 2016, u_{2015} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2015, B_{MSY} – equilibrium biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

	5%	50%	95%
Model-based			
$0.2B_0$	889	1,316	1,963
$0.4B_0$	1,777	2,632	3,926
B_0	4,443	6,580	9,815
B_{2016}	1,965	5,548	10,946
B_{2016}/B_0	0.404	0.793	1.41
u_{2015}	0.0434	0.0828	0.212
MSY-based			
$0.4B_{MSY}$	641	1,068	1,809
$0.8B_{MSY}$	1,282	2,137	3,618
B_{MSY}	1,602	2,671	4,522
B_{MSY}/B_0	0.299	0.410	0.538
B/B_{MSY}	0.926	1.85	4.16
MSY	55.9	154	354
u_{MSY}	0.0198	0.0582	0.148
u/u_{MSY}	0.366	1.67	6.69

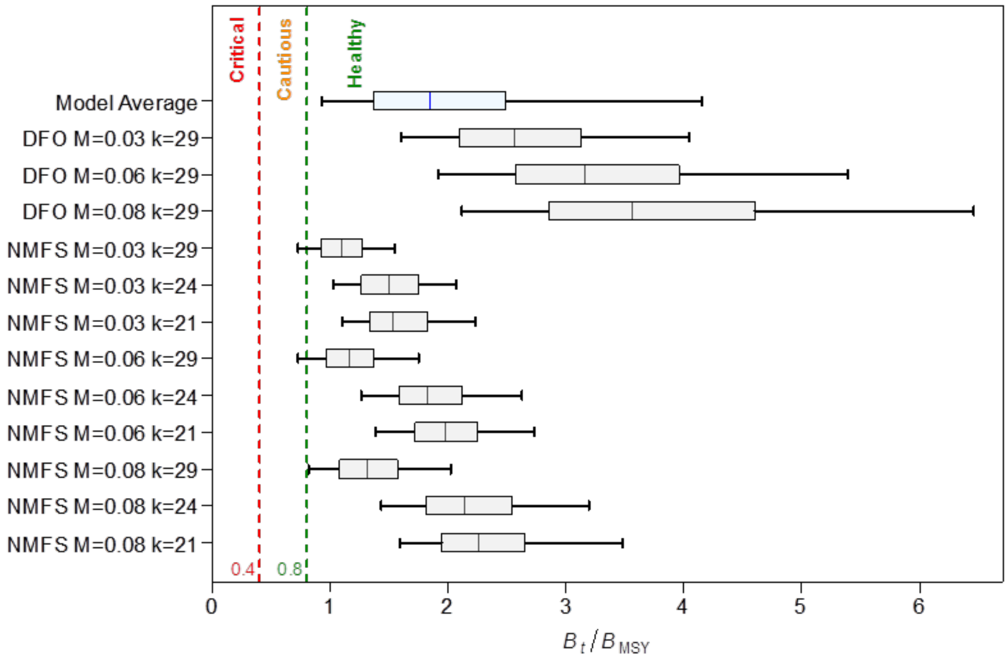

Figure 10. Current status of the coastwide BC Shortspine Thornyhead stock relative to the DFO Precautionary Approach provisional reference points of 0.4B_{MSY} and 0.8B_{MSY}. The value of B_t/B_{MSY} uses t=2016. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. The model average (top boxplot in blue) summarises the 12 model runs represented in the grey boxplots below the model average (see Table 2 for run definitions). DFO = Canadian Fisheries and Oceans; NMFS = US National Marine Fisheries Service; M = natural mortality (y^{-1}); k = length (cm) at knife-edge selectivity.

9 ADVICE FOR MANAGERS

9.1 REFERENCE POINTS

Management targets have not been set for Shortspine Thornyhead so we are using MSY-based reference points consistent with the provisional recommendations contained in the DFO Fishery Decision-making Framework Incorporating the Precautionary Approach (PA) policy (DFO 2009). This policy specifies three reference points:

i. a reference removal rate,

ii. an upper stock reference point (USR), and

iii. a limit reference point (LRP).

Provisional values of USR=0.8B_{MSY} and LRP=0.4B_{MSY} are suggested by the policy when there is insufficient information to estimate stock-specific MSY-based reference points. The Framework specifies that the reference removal rate should not exceed F_{MSY}, which implies a maximum reference removal rate of F_{MSY} and a target biomass level of B_{MSY}. We therefore report three reference points linked to the DFO PA Policy in decision tables:

- Limit Reference Point (LRP): 0.4 B_{MSY}
- Upper Stock Reference (USR): 0.8 B_{MSY}
- u_{MSY} $\left(1-e^{-F_{MSY}}\right)$

Four additional reference points are mentioned in Table 4; however, we do not provide harvest advice for these:

- B_{MSY}
- 0.2 B_0: a limit reference point used in some other jurisdictions;
- 0.4 B_0: a target reference point used in some other jurisdictions;
- B_{2016}: reports the probability of an increase or decrease

9.2 DECISION TABLE

A decision table of probabilities (Table 5), based on the composite reference (model average) scenario, forms the basis of the advice to managers. Note that the probabilities in this table for 2016 cannot change as the 2015 catch has already been taken. The probability that the estimated biomass in 2016, B_{2016}, is greater than the estimated upper stock reference is 0.98, and B_{2016} is always greater than the limit reference point. The estimated harvest rate u_{2015} has a probability of 0.72 of being greater than the estimated harvest rate at maximum sustainable yield.

The average harvest level in the last five years (2010-2014) is estimated to be 572 t coastwide, which is close to the constant catch policy of 600 t listed in Table 5. Three-year projections indicate that annual catches of 200 t or greater will cause the stock to decline from current levels. At 600 t/year, the probability that the biomass in 2019 will be greater than the upper stock reference point, P(B_{2016} > 0.8B_{MSY}), is 0.76 and P(B_{2019} > 0.4B_{MSY}) is 0.88. At fixed annual catches of 600 t, the probability that the harvest rate will exceed the harvest rate at maximum sustainable yield, u_{MSY}, is 0.84.

Table 5. Decision table for the composite reference (model average) scenario for three reference points – the upper stock reference point 0.8B_{MSY}, the limit reference point 0.4B_{MSY}, and the harvest rate at maximum sustainable yield u_{MSY} – for end-year biomass B_{2016} and mid-year harvest rate u_{2015} and their respective 3-year projections for a range of constant catch strategies (in tonnes). Each value is the probability that current or projected biomass or harvest rate is greater than the indicated reference point. The probabilities are the proportion of the 12 pooled MCMC samples for which B_t > 0.8B_{MSY}, B_t > 0.4B_{MSY}, and u_t > u_{MSY}. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

TAC	P(B_{2016} > 0.8B_{MSY})	P(B_{2019} > 0.8B_{MSY})	P(B_{2016} > 0.4B_{MSY})	P(B_{2019} > 0.4B_{MSY})	P(u_{2015} > u_{MSY})	P(u_{2018} > u_{MSY})
0	0.9792	0.9964	1	1	0.72	0
100	0.9792	0.9867	1	1	0.72	0.1412
200	0.9792	0.9604	1	0.9998	0.72	0.4002
300	0.9792	0.9158	1	0.9963	0.72	0.5630
400	0.9792	0.8571	1	0.9799	0.72	0.6884
500	0.9792	0.8043	1	0.9388	0.72	0.7758
600	0.9792	0.7605	1	0.8795	0.72	0.8370
700	0.9792	0.7245	1	0.8259	0.72	0.8816
800	0.9792	0.6874	1	0.7849	0.72	0.9135
900	0.9792	0.6463	1	0.7570	0.72	0.9346
1000	0.9792	0.6025	1	0.7318	0.72	0.9526

9.3 IUCN RED LIST

Shortspine Thornyhead was listed as “Endangered” by the IUCN (International Union for Conservation of Nature and Natural Resources) in 2000 based on an unpublished 1999 report (Bell, T. and Guttman, A. 1999. Species Assessment for the Shortspine Thornyhead

(*Sebastolobus alascanus*) (Unpublished report). Cited in Bell and Guttman 2000). The justification read:

> *"Commercial exploitation of S. alascanus began in 1967. Since then, a valuable market has developed for the species. Populations have declined in all areas assessed. Overall it has declined by 53% from the estimated unfished biomass to the biomass in 1998."*

No link is provided to the unpublished report, nor is it summarised on the IUCN webpage, so it is not possible to evaluate the information that has led to this listing or to the above justification. There is no obvious way to treat this listing other than to alert managers to its existence. The above justification implies that the 1998 spawning biomass population (presumably in Canada, the Russian Federation, and the United States of America combined) sits at $0.47B_0$. The IUCN website report noted that this assessment needs updating.

10 DISCUSSION AND CONCLUSIONS

The median estimate for current stock status (B_{2016}/B_0) is estimated to be 79% of B_0 for the composite scenario (Table 4). The stock is expected to decline over the next three years at a level of catch consistent with the 2010-2014 average catch (600 t/year). However, the model average prediction is that the decline will stay well above the highest reference point with high probability (0.76, Table 5).

This stock assessment is less capable of giving advice on equilibrium levels of yield or the absolute stock size, given that the available data can be fit reasonably well across a wide range of stock production hypotheses. Therefore, it is not possible to predict what is the most likely level of the equilibrium yield, given that the MSY estimates span a wide range (see Table F.6). This is because the application of the delay-difference model to this data set is hampered by the lack of contrast in the abundance index series and the upward trend in the mean weight series, which is inconsistent with the flat abundance trend. Given that this is a production model with limited flexibility, it is unable to fit both sets of series adequately. Sensitivity runs S11 and S23 demonstrate that the fit to the mean weight data series only improves marginally when the associated σ_W is decreased while there is a clear deterioration in the fit to the abundance series at the same time. S23 had the poorest fits among the 20 comparable runs for the QC Sound and Hecate Strait surveys while S11 was the worst for the WCHG survey and the CPUE data (Table F.4).

The composite reference scenario estimates that the stock maintained its size over the period covered by this stock assessment (Figure 9), a reflection of the lack of trend in all the available biomass index series. This observation implies that productivity has been adequate to balance removals over the reconstruction period. However, the stock assessment projections indicate that that recent catches will reduce the biomass over the next three years once the information from biomass indices is no longer available. This immediate drop indicates that stock abundance has been maintained in the past through good recruitment generated by the model or that the assumed levels of stock productivity are too low. For these reasons, the three year projection probabilities presented in Table 5 should be considered less reliable than the stock reconstruction presented in Figure 9.

While the advice stemming from this stock assessment may not be as definitive as could be obtained from a well-fitted age-structured model, we are aware that the assessment of this species has a number of important limitations. These include an uncertain capacity to age the otoliths reliably coupled with an expected large cost associated with the thin-section otolith preparation methodology. Consequently there was a serious risk that committing large amounts of resources to ageing this species could result in an equally uncertain outcome. The application of delay-difference production models to rockfish species has not yet been attempted in BC although this type of model has been used for Pacific Cod, Rock Sole, English Sole and Petrale Sole. We hope that the outcome of this stock assessment will encourage the continued use of this approach in situations where there are limitations to the application of more sophisticated age- or length-structured models.

Available BC Shortspine Thornyhead biological sampling data do not hold many large or old fish (less than 2% of all available samples are greater than 50 cm). This was notable because stock assessments for this species both to the north and to the south of BC used growth functions and an assumed natural mortality (*M*) value that implied that the species lives longer and grows larger than appeared to be the case in BC waters. This difference is reflected in the published data in the most recent stock assessment from the west coast of the United States (Taylor and Stephens 2013). Figure 25 of Taylor and Stephens (2013) shows a much larger proportion of the commercial trawl catch comprising Shortspine Thornyhead greater than 50 cm compared to the equivalent proportion from the BC trawl fishery. The peer review participants did not agree on the cause of this lack, with some stating that the anomaly was most likely a sampling issue, with the fishery and research surveys operating in regions where the preponderance of large, old Shortspine Thornyhead was small. Others noted that a large proportion of the length observations were from random trawl surveys, several of which went to very deep depths expressly to sample *Sebastolobus*. However, the existence of a sub-population of large and less vulnerable fish implies that there is a reservoir of spawners which will reduce the risk of over-fishing for the fished population. It is notable that Taylor and Stephens (2013, see Figure 16) allow declining right-hand limb selectivity functions for the trawl fleet and for the trawl surveys to account for the lack of older fish in the fishery and the surveys, which is a by-product of their assumption that M=0.05.

11 RESEARCH RECOMMENDATIONS

1. Establish the most appropriate otolith preparation methodology for production ageing of SST (e.g., thin-sectioning).
2. Confirm ageing accuracy for SST by extending the size of the existing trial beyond current number of 60 otoliths.
3. Collect length-stratified biological samples from the commercial fishery and from research surveys to ensure that age structures represent the full size range of SST in BC.
4. Reassess the growth curve for BC SST when reliable ages become available.

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APPENDIX A. CATCH DATA

A.1. BRIEF HISTORY OF THE FISHERY

Haigh and Schnute (2003) describe the development of the Longspine Thornyhead (*Sebastolobus altivelis* – LST) fishery along the BC coast. A deep-water fishery started in the early 1990s due to increasing market demand from Japan; however, *S. alascanus* (Shortspine Thornyhead – SST) had been landed as incidental catch back to 1980. While LST emerged as an independent target species, primarily due to its depth and isolation from other TAC (total allowable catch) species, SST was largely a non-directed catch due to its prevalence along the BC coast at a wider range of depths and its consequent concurrence with numerous other rockfish species at mid-depth ranges.

In Japan, whole thornyheads are used in wedding ceremonies and the frozen flesh is considered a delicacy. This demand caused depletion of the Japanese Broadbanded Thornyhead (*S. macrochir*) stocks (Rogers et al. 1997) and a strong increase in BC landings of thornyhead species in 1993 (Haigh and Schnute 2003). The Japanese shortage drove prices up for thornyheads on world markets, which further accelerated the expansion of BC trawl fishery (including the introduction of onboard freezer technology).

At roughly the same time, DFO started introducing various control programs – dockside monitoring (1994), mandatory onboard trawl observers (1996), and individual (transferrable) vessel quotas (1997). The observer program was instrumental in resolving species identification in the catch, which meant that after 1996 Longspine Thornyhead was identified as a separate species for the first time in BC landings data. According to industry, this species was being landed earlier but was simply lumped in with Shortspine landings (Brian Mose, Canadian Groundfish Research and Conservation Society, Nanoose Bay, BC, pers. comm.).

The history of TACs for Shortspine Thornyhead started in 1996 coincident with the establishment of the compulsory onboard observer program for the offshore trawl fleet (Table A.2). During the transition to an IVQ (individual vessel quota) system in 1997, the trawl fishery was managed by quarter limits. These periods determined the initial IVQ allocation depending on vessel masters' trawling activity.

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges by the British Columbia groundfish bottom trawl fishery. These measures were developed jointly by industry and environmental non-governmental organizations, and include limiting the footprint of groundfish bottom trawl activities (DFO 2013). These measures reduced the contribution of Shortspine Thornyhead catch from outside the footprint from 10.7% of total catch over the period 1996 to 2012 to 0.7% in the period 2012 to 2015 (Table A.1, Figure A.1).

Table A.1. Trawl footprint effects on Shortspine Thornyhead effort (# sets) and catch (t) before and after the freezing (April 2012) of allowable bottom areas for trawling. Statistics compiled by Norm Olsen (DFO, Nanaimo BC) from DFO databases PacHarvest and GFFOS (accessed Dec 14, 2015).

	Before (1996-2012)		**After (2012-2015)**	
Footprint	**# Sets**	**Catch (t)**	**# Sets**	**Catch (t)**
Inside	67,195	8,242	10,167	1,764
Outside	4,988	990	86	13
Total (In + Out)	72,183	9,232	10,253	1,776
Percent Out	6.9%	10.7%	0.8%	0.7%

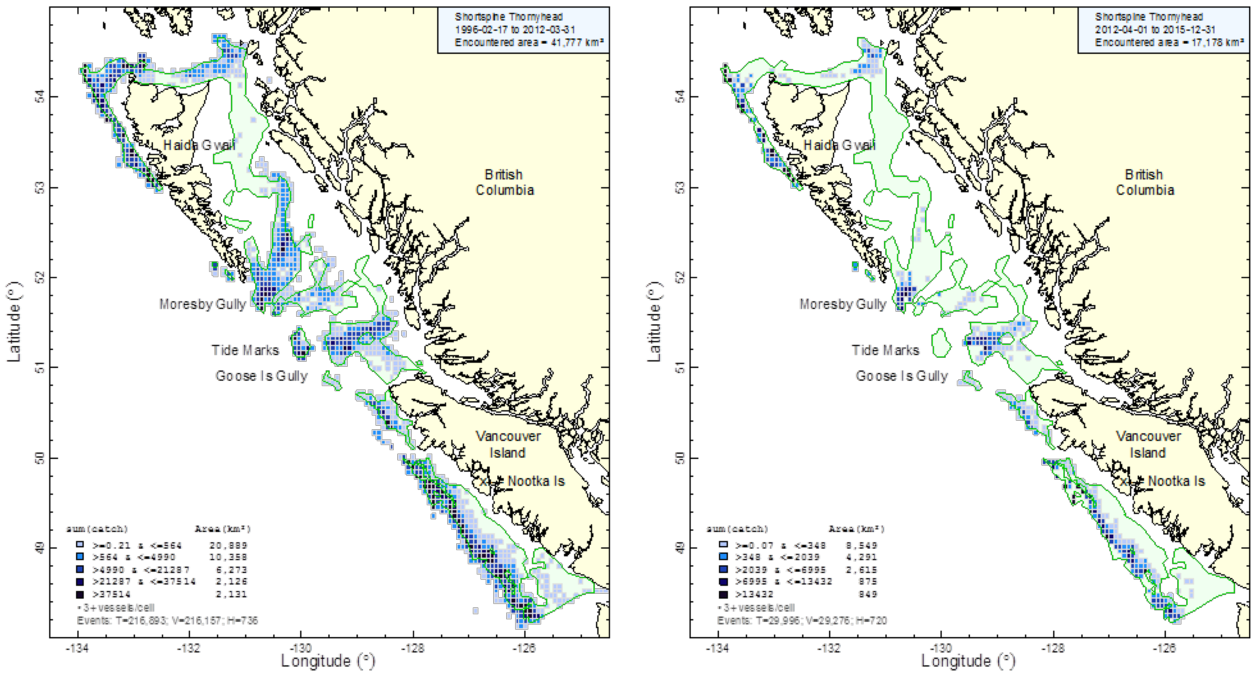

Figure A.1. Aerial distribution of accumulated Shortspine Thornyhead catch before (left) and after (right) the introduction of the trawl footprint in April 2012 limiting areas in which trawl vessels can operate. Note that cells with <3 fishing vessels are not displayed.

Table A.2. Annual total allowable catches (TACs) in tonnes for Shortspine Thornyhead coastwide ('Coast'), which are allocated to various fishing sectors ('Trawl', 'HL' = Outside ZN hook and line, and 'Halibut' longline) and 'Research' surveys. Fishing years comprise various time periods (see columns marked 'Start' and 'End'). See Table A.3 for details in the 'Notes' column.

Year	Start	End	Coast	Trawl	HL	ZN	Halibut	Research	Notes
1996	2/6/1996	5/31/1996	263	263	-	-	-	-	a,b
1996	6/1/1996	9/15/1996	226	226	-	-	-	-	a,b
1996	9/16/1996	12/31/1996	263	263	-	-	-	-	a,b
1997	1/1/1997	3/31/1997	196	196	-	-	-	-	c
1997	4/1/1997	3/31/1998	748	748	-	-	-	-	c
1998	4/1/1998	3/31/1999	749	749	-	-	-	-	d
1999	4/1/1999	3/31/2000	732	732	-	-	-	-	-
2000	4/1/2000	3/31/2001	733	733	-	-	-	-	e,f
2001	4/1/2001	3/31/2002	771	736	-	18	18	-	-
2002	4/1/2002	3/31/2003	771	736	-	18	18	-	g
2003	4/1/2003	3/31/2004	771	736	-	18	18	-	-
2004	4/1/2004	3/31/2005	771	736	-	18	18	-	-
2005	4/1/2005	3/31/2006	771	736	-	18	18	-	-
2006	4/1/2006	3/31/2007	771	736	-	17	18	1	h,i,j,k,l
2007	3/10/2007	3/31/2008	771	736	-	17	18	1	m
2008	3/8/2008	2/20/2009	771	736	-	17	18	1	-
2009	2/21/2009	2/20/2010	771	736	-	17	18	1	-
2010	2/21/2010	2/20/2011	771	736	-	17	18	1	-
2011	2/21/2011	2/20/2013	771	736	-	17	18	1	-
2013	2/21/2013	-	771	734	-	17	18	2.6	n,o
2014	2/21/2014	-	771	734	-	17	18	2.6	-
2015	2/21/2015	-	771	734	-	17	18	2.6	-

Table A.3. Codes to notes on management actions and quota adjustments that appear in Table A.2. Abbreviations that under 'Management Actions': SST = Shortspine Thornyhead, LST = Longspine Thornyhead, DMP = dockside monitoring program, H&L = hook and line, IVQ = individual vessel quota, WCVI = west coast of Vancouver Island, lbs = pounds (0.4536 kg/lb).

	Year	Management Action
a	1996	Started 100% onboard observer program for offshore Trawl fleet.
b	1996	Started DMP for H&L fleet.
c	1997	Started IVQ system for Trawl *Total Allowable Catch* (TAC) species (April 1, 2007)
d	1998	H&L Aggregate 4 (includes SST) Option A: a quantity of Aggregates 2 to 5 and 7 combined not to exceed 100% of the total of Aggregate 1 per landing; an overage of Aggregate 1 and 6 up to a maximum of 10% per fishing period which shall be deducted from the vessel's succeeding fishing period limit. Option B: a quantity of Aggregates 2 to 7 combined not to exceed 100% of the Yelloweye Rockfish per landing. Option C: 20,000 pounds of Aggregate 4 per fishing period; an overage for each of the Aggregates 3 to 5 and, Aggregates 6 and 7 combined, up to a maximum of 20% per fishing period which shall be deducted from the vessel's succeeding fishing period limit.
e	2000	Implemented formal allocation of rockfish species between Halibut and H&L sectors.
f	2000	DFO cut LST TAC off WCVI to 404 t and set a conditional TAC of 425 t for an exploratory fishery north of 230° true from Lookout Is.
g	2002	Managers created five LST management zones coastwide (WCVI, Triangle, Tidemarks, Flamingo, Rennell); zones north of WCVI were designated "experimental".
h	2006	Introduced an *Integrated Fisheries Management Plan* (IFMP) for most groundfish fisheries.
i	2006	Started 100% at-sea electronic monitoring for H&L.
j	2006	Implemented mandatory retention of rockfish for H&L.
k	2006	To support rockfish research the Groundfish Hook and Line Sub Committee (GHLSC) agreed to set aside 5% of the ZN allocations for research purposes.
l	2006	Annual non-directed species caps on SST by fishery: Dogfish = 0.05% Dogfish IVQ, Outside ZN = 1881 lbs., Halibut = 8000 lbs., Sablefish = 10,512 lbs.)
m	2007	Amendment to Halibut IVQ cap for SST -- reallocations can only occur in blocks up to 4000 lbs or until the vessel species cap is met. Once the first 4000 lbs has been caught additional IVQ can be reallocated onto the licence up to 4000 lbs. This can continue until the vessel species cap is met.
n	2012	Freeze the footprint of where groundfish bottom trawl activities can occur (all vessels under the authority of a valid Category "T" commercial groundfish trawl license selecting Option A as identified in the IFMP.
o	2013	To support groundfish research the Groundfish Trawl Industry agreed to the trawl TAC offsets to account for unavoidable mortality incurred in during the 2013 DFO and Trawl industry agreed upon Groundfish Trawl Multi-species surveys: SST=1.7 t.

A.2. CATCH RECONSTRUCTION

In this assessment, we use calendar year for population models, requiring catch estimates to be made by calendar year. As with the previous rockfish assessments, we use "official" catch numbers whenever they have been prepared in the various modern catch databases (see Edwards et al. 2014 and Yamanaka et al. in revision[1]) for the latest details.

Shortspine Thornyhead catch by fishery sector was compiled using a combination of these seven DFO databases:

- PacHarv3 sales slips (from 1982 to 1995) – hook and line only,
- GFCatch – trawl and trap,
- PacHarvest observer trawl – trawl,
- PacHarvHL merged data table – halibut, Dogfish+Lingcod, H&L rockfish,
- PacHarvSable fisherlogs – Sablefish,
- GFFOS groundfish subset from Fishery Operation System – all fisheries and modern surveys, and
- GFBio joint-venture hake and research survey catches – multiple gear types.

Starting in 2015, all official catch tables from databases above (except PacHarv3) have been merged into one catch table called "GF_MERGED_CATCH", which is available in DFO's GFFOS database.

A.2.1. Initial reconstructions considered but not used

We first attempted to build catch reconstructions from the official landings using the methodology outlined in Haigh and Yamanaka (2011) and modified by Yamanaka et al. (in revision[1]). We present a brief summary of these findings, even though the resulting reconstructions were rejected by the technical working group they concluded that modern catch ratios were not applicable to the historical time period when the thornyhead fishery was not active.

First, a reminder of the definition of terms:

Fisheries: there are five fisheries in the reconstruction:

- groundfish trawl (bottom + midwater),
- Halibut longline,
- Sablefish trap/longline.
- Schedule II (mostly Lingcod and Dogfish longline),
- hook and line rockfish (now ZN).

ORF: acronym for "other rockfish" (= total rockfish − POP), landed catch aggregated by year, fishery, and PMFC (Pacific Marine Fisheries Commission) major area.

SST: Shortspine Thornyhead, L =landed catch, D =releases (formerly called "discards").

TAR: Target species landed catch.

[1] Yamanaka, K.L., McAllister, M. K., Etienne, M.-P., Edwards, A., and Haigh, R. (in revision). Stock assessment for the outside population of Yelloweye Rockfish (*Sebastes ruberrimus*) for British Columbia, Canada in 2014. CSAS Working 2013GRF09

gamma: mean of annual ratios, $\sum_i \mathrm{SST}_i^L / \mathrm{ORF}_i$, grouped by major PMFC area and fishery using reference years i = 1997-2005.

delta: mean of annual ratios, $\sum_i \mathrm{SST}_i^D / \mathrm{TAR}_i$, grouped by major PMFC area and fishery using reference years i = 1997-2006 for the trawl fishery and 2000-2004 for all other fisheries. Observer records were used to gather data on releases.

The reconstruction runs are detailed in Table A.4. The outcomes of these reconstruction runs differ substantially (Figure A.2), with the effect of applying the modern catch ratios to the combined rockfish catches from the foreign fleet resulted in catch estimates that were clearly biased high (Run01). Run02, which dropped the foreign fleet and used only the domestic fleet, is lower, but still appears to be biased high because it seems unlikely that there would have been such large catches of SST in the late 1970s/early 1980s, followed by nothing after 1982. Run03 tries to get around the lack of catch in the 1980s and early 1990s by continuing the reconstruction right up to 1995. It is the same as Run02 before 1983 and it estimates a very large catch of SST during the decade between 1985 and 1996, with catches considerably greater than those observed when the thornyhead fishery was at its peak in the late 1990s. These high catches appeared to be driven by the depth-weighted gamma ratios, as catches in the 1985-1995 decade dropped considerably for Run04, which used an unweighted gamma (and delta). Note that the actual recorded catches for 1995 are greater than the estimated 1995 catch for Run04 (otherwise this run is the most credible of the four reconstructions).

Table A.4. Catch reconstruction runs considered by the technical working group but rejected for the assessment.

Run	Description
01	Uses ORF from offshore foreign fishing fleet; estimates 'gamma' for shelf localities only, weighted by catch in 100 m depth bins; reconstruction ends: trawl=1982, halibut=1985, sablefish=1999, dogfish/lingcod=1986, ZN=1985
02	Same as Run01, except uses ORF from domestic fleet only (drops foreign fishing fleet)
03	Same as Run02, except that reconstruction ends in 1995 for all five fisheries
04	Same as Run03, except that `gamma' is a non-weighted (by depth) average for each PMFC area and fishery
05	"raw" catch (landings+releases) from DFO catch databases (no reconstruction)

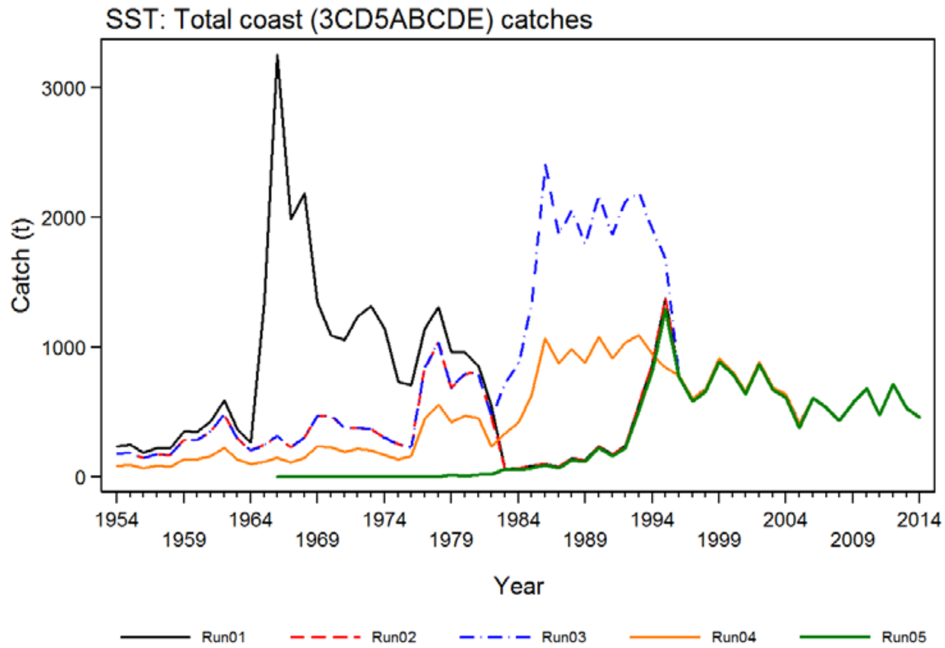

Figure A.2. Annual total catch trajectories for SST (summed across the five defined fisheries) for each of the five reconstruction "runs" defined above, from 1954 to 2014. Run05 is the "raw" catch data from the DFO catch databases. The majority of the catch comes from the 'trawl' fishery.

The 'gamma' ratios seem very high in some of the PMFC areas (Table A.5). For instance, the ratios are 0.15 in 3C and 3D and 0.17 for 5E, which mean that nearly 15–17% of the ORF catch in those areas will be SST. The ratios drop a lot for these areas when the algorithm does not take into account the distribution of tows by depth (to 6% in 3CD and 8% in 5E), but these may still be high for this species.

The 'delta' ratios are low (all under 10% and most under 5%, Table A.5), which indicates that, in the modern (post-1996) fisheries, most SST were retained. However, this may not have been the case in the historical period, when there was no established market for this species.

Table A.5. Estimated 'gamma' and 'delta' ratios for each fishery and PMFC area for the four reconstructions runs defined in Table A.4.

PMFC	Run01	Run02	Run03	Run04	Run01	Run02	Run03	Run04
	Trawl -- gamma				Trawl -- delta			
3C	0.151	0.151	0.151	0.064	0.089	0.089	0.089	0.070
3D	0.148	0.148	0.148	0.056	0.055	0.055	0.055	0.036
5A	0.041	0.018	0.018	0.010	0.089	0.089	0.089	0.091
5B	0.097	0.045	0.045	0.031	0.057	0.057	0.057	0.062
5C	0	0.067	0.067	0.039	0.051	0.051	0.051	0.033
5D	0.189	0.058	0.058	0.084	0.012	0.012	0.012	0.016
5E	0.172	0.172	0.172	0.079	0.051	0.051	0.051	0.039
	Halibut -- gamma				Halibut -- delta			
3C	0.026	0.026	0.026	0.077	0	0	0	0
3D	0.027	0.027	0.027	0.054	0.001	0.001	0.001	0.001
5A	0.036	0.036	0.036	0.050	0.001	0.001	0.001	0.001
5B	0.039	0.039	0.039	0.051	0.001	0.001	0.001	0.003
5C	0.015	0.015	0.015	0.013	0	0	0	0
5D	0.047	0.047	0.047	0.068	0.001	0.001	0.001	0.001
5E	0.111	0.111	0.111	0.092	0	0	0	0

PMFC	Run01	Run02	Run03	Run04	Run01	Run02	Run03	Run04
	Sablefish -- gamma				Sablefish -- delta			
3C	0	0	0	0.035	0.005	0.005	0.005	0.003
3D	0	0	0	0.023	0.005	0.005	0.005	0.004
5A	0	0	0	0.027	0.006	0.006	0.006	0.004
5B	0	0	0	0.013	0.002	0.002	0.002	0.002
5C	0	0	0	0.012	0	0	0	0
5D	0	0	0	0.014	0	0	0	0
5E	0	0	0	0.029	0.001	0.001	0.001	0.001
	Dogfish+Lingcod -- gamma				Dogfish+Lingcod -- delta			
3C	0	0	0	0.021	0	0	0	0
3D	0.003	0.003	0.003	0.008	0	0	0	0
5A	0	0	0	0.001	0	0	0	0
5B	0	0	0	0	0	0	0	0
5C	0	0	0	0	0	0	0	0
5D	0	0	0	0.009	0	0	0	0
5E	0.001	0.001	0.001	0.001	0	0	0	0
	H&L Rockfish -- gamma				H&L Rockfish -- delta			
3C	0.003	0.003	0.003	0.007	0	0	0	0
3D	0.017	0.017	0.017	0.024	0	0	0	0
5A	0.003	0.003	0.003	0.006	0.035	0.035	0.035	0.188
5B	0.003	0.003	0.003	0.006	0.019	0.019	0.019	0.007
5C	0	0	0	0.001	0	0	0	0
5D	0	0	0	0.008	0	0	0	0
5E	0.013	0.013	0.013	0.017	0.099	0.099	0.099	0.080

These catch reconstruction runs will have a different impact on the SST stock assessment, with each Run having different underlying catch totals (Table A.6). Models using these catch reconstructions will estimate different levels of productivity, proportional to the sum of the total catches, with the most productive models having the larger catch history. Even Run04, which appears to be the most credible of the four reconstructions, implies a near doubling of productivity relative to a model based only on the reported catches (compare totals for Run04 and Run05 in Table A.6).

Table A.6. Total SST catch (t) from 1954-2014 by reconstruction 'Run' descriptor (see Table A.4).

Run descriptor	Sum of Catch (t)
Run01	42,826
Run02	27,498
Run03	46,356
Run04	29,110
Run05	15,751

A.2.2. Reconstruction used in the assessment

After discussions with the BC trawl industry, represented by Brian Mose (Commercial Industry Caucus – trawl branch) and Bruce Turris (Canadian Groundfish Research and Conservation Society), we were advised that thornyheads were likely not captured by the domestic fleet before 1980, nor by the foreign offshore fleet that targeted Pacific Ocean Perch (POP) from the mid-1960s to the mid-1970s. Additionally, the reporting of two thornyhead species in the landings reports did not occur until after 1996, with the sudden appearance of Longspine Thornyhead reported catches coinciding with the introduction of compulsory observer coverage. Industry advised that thornyhead landings (all called SST in the available databases) before 1996 should be disaggregated by PMFC region based on the ratio of the two species in the observer catch records during the early years of the observed fishery when species identification was good and the fishery most closely resembled what was going on in the early 1990s (Table A.7).

Table A.7. Thornyhead catch and proportions using observer trawl records from 1996 to 1999. SST = sum of Shortspine Thornyhead catch (t), LST = sum of Longspine Thornyhead catch (t), 3CD =WCVI, 5ABCDE = BC coast north of WVCI, CST = coastwide, p = proportion, and subscripts L, D, and C denote catch components: landed, released (discarded), and total catch (C=L+D). The cells highlighted in green give the proportions used to disaggregate the pre-1996 catch of WCVI thornyheads.

	$p(SST_L/[SST_L+LST_L])$			$p(SST_D/[SST_D+LST_D])$			$p(SST_C/[SST_C+LST_C])$			$p(SST_D/SST_L)$	
Year	3CD	5ABC 5DE	CST	3CD	5ABC 5DE	CST	3CD	5ABC 5DE	CST	3CD	5ABC 5DE
1996	0.320	0.993	0.476	0.209	0.916	0.298	0.312	0.990	0.464	0.0541	0.0365
1997	0.325	0.958	0.447	0.143	0.860	0.238	0.308	0.952	0.429	0.0448	0.0596
1998	0.345	0.941	0.441	0.171	0.855	0.237	0.324	0.935	0.418	0.0671	0.0684
1999	0.430	0.941	0.490	0.186	0.866	0.252	0.410	0.936	0.470	0.0388	0.0678
1996-97	0.323	0.975	0.461	0.176	0.888	0.268	0.310	0.971	0.446	0.0495	0.0480
1996-98	0.330	0.964	0.455	0.174	0.877	0.258	0.315	0.959	0.437	0.0553	0.0548
1996-99	0.355	0.958	0.463	0.177	0.874	0.256	0.338	0.953	0.445	0.0512	0.0581

The WCVI ratios of SST to SST+LST remained fairly consistent over the entire 1996-1999 period; we used the 1996 SST landed catch proportions in 3CD and all of PMFC 5 (Table A.7) to disaggregate catches of SST before 1996. There were only small landings of LST (36.4 t) and releases (7.6 t) in PMFC 5 from 1996-99 which was thought to accurately represent what had gone on this region before 1996.

Using the ratios of landed SST in 3CD (0.320) and PMFC 5 (0.993) in the pre-1996 landings records, and the calculated SST discard ratios in 3C (0.0541) and PMFC 5 (0.0365), we adjusted the official trawl catch to extend the LST catch history back before 1996 and reduce the corresponding SST catch (Figure 4).

$$SST_i = 0.320\ SST_{Li}\,(1{+}0.0541) + 0.993\ SST_{Li}\,(1{+}0.0365) \qquad \text{(A.1)}$$

$$LST_i = 0.680\ SST_{Li}\,(1{+}0.0967) + 0.007\ SST_{Li}\,(1{+}0.4526) \qquad \text{(A.2)}$$

where i = years 1980-1995 and L refers to landed catch.

The annual SST adjusted trawl catch and catches from the non-trawl fisheries appear in Table A.8.

Table A.8. Catches (landings + releases) of SST used in the model (Total only). The trawl catches from 1980 to 1995 were adjusted using Eq. A.1. Entries marked '0' denote true zero catch while '0.0' denotes a small catch (<0.05 t). The Total catch is the amount used in the model. As the final year (2015) was incomplete, the previous year's catch value was used.

Year	Trawl	Halibut	Sablefish	Dogfish+ Lingcod	H&L Rockfish	Total
1980	2.1	0	0	0	0	2.1
1981	9.5	0	0	0	0	9.5
1982	14.0	0	0	0	0	14.0
1983	55.0	0.5	0	0.5	0	55.9
1984	53.1	0	0	0	0	53.1
1985	63.4	0.8	0	0	0.2	64.4
1986	83.3	2.8	0	0	0	86.1
1987	63.6	2.3	0	1.1	0.8	67.8
1988	121.8	0.5	0	0.0	0.5	122.9
1989	94.2	1.2	0	0.0	0.0	95.4

Year	Trawl	Halibut	Sablefish	Dogfish+ Lingcod	H&L Rockfish	Total
1990	155.7	1.2	0	4.5	5.1	166.6
1991	102.0	2.1	0	0.1	1.6	105.8
1992	138.5	1.0	0	0.0	2.6	142.1
1993	366.7	2.3	0	0.0	0.3	369.3
1994	703.2	5.6	0	0.1	2.5	711.5
1995	909.8	9.1	0.3	6.5	32.2	957.9
1996	750.2	6.4	0.5	0.2	10.6	767.9
1997	562.9	10.1	0.6	0.3	8.3	582.2
1998	629.7	11.2	0.0	0.2	13.2	654.4
1999	857.4	17.5	0	0.2	13.2	888.2
2000	756.2	21.8	0.1	0.3	14.6	792.9
2001	605.5	26.6	0.0	0.1	7.7	639.9
2002	823.5	36.0	0.4	0.0	7.1	867.0
2003	612.4	42.2	1.7	0	12.7	669.1
2004	568.0	42.2	0.3	0	6.3	616.9
2005	312.2	44.6	0.2	0.0	18.9	375.9
2006	528.6	66.1	11.9	0.0	4.2	610.8
2007	476.5	41.7	15.9	0.0	0.9	535.0
2008	369.0	45.6	18.8	0.1	1.7	435.2
2009	501.6	36.9	28.3	0.0	1.9	568.7
2010	629.8	33.9	16.4	0.1	3.2	683.3
2011	416.8	36.3	17.4	0.0	4.0	474.5
2012	645.7	42.4	22.0	0.0	2.8	713.0
2013	483.1	30.3	13.6	0.0	2.2	529.2
2014	405.9	34.5	17.1	0.0	2.6	460.0
2015	405.9	34.5	17.1	0.0	2.6	460.0

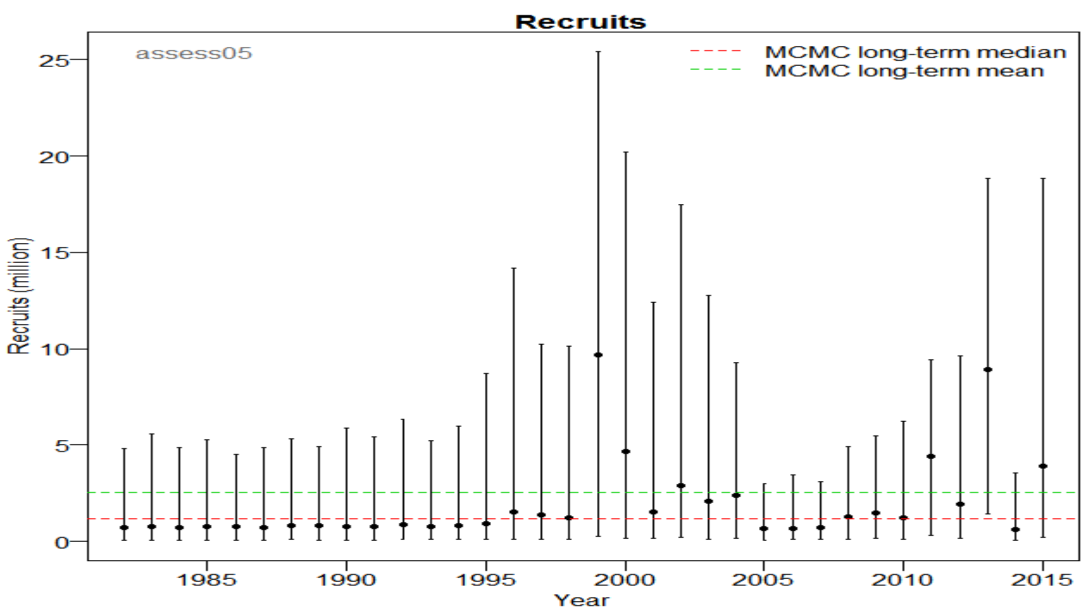

Figure A.3. Trawl catch history of Shortspine (SST) and Longspine Thornyhead (LST) along the BC coast. Solid lines indicate the catches (landings + releases) reported in DFO databases; dashed lines indicate the adjusted catch histories after disaggregating the pre-1996 WCVI SST catch using proportions in Table A.7. Trawl catch data for the adjusted SST from 1980 on were used in the stock assessment.

A.3. REFERENCES – CATCH

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APPENDIX B. SURVEYS

B.1. INTRODUCTION

This appendix summarises the derivation of relative Shortspine Thornyhead (SST) abundance indices from the following bottom trawl surveys:

- National Marine Fisheries Service (NMFS) Triennial survey operated off the lower half of Vancouver Island (Section B.3);
- Hecate Strait synoptic survey (Section B.4);
- Queen Charlotte Sound synoptic survey (Section B.5);
- west coast Vancouver Island synoptic survey (Section B.6);
- west coast Haida Gwaii synoptic survey (Section B.7).

Only surveys which were used in the SST stock assessment are presented. The historic GB Reed Queen Charlotte Sound survey series has been omitted because six of the eight available indices were obtained before the model start year of 1980. The WCVI and QC Sound shrimp surveys were omitted because their depth range stops near the beginning of the depth range where SST are taken in the commercial trawl fishery. Finally, the Hecate Strait Multispecies survey was omitted for the same reason: its main area of coverage was in the part of Hecate Strait where SST have not been taken by the replacement synoptic survey.

B.2. ANALYTICAL METHODS

Catch and effort data for strata i in year y yield catch per unit effort (CPUE) values U_{yi}. Given a set of data $\left\{C_{yij}, E_{yij}\right\}$ for tows $j = 1,\dots,n_{yi}$,

Eq. B.1 $$U_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{E_{yij}},$$

where C_{yij} = catch (kg) in tow j, stratum i, year y;
E_{yij} = effort (h) in tow j, stratum i, year y;
n_{yi} = number of tows in stratum i, year y.

CPUE values U_{yi} convert to CPUE densities δ_{yi} (kg/km^2) using:

Eq. B.2 $$\delta_{yi} = \frac{1}{vw} U_{yi},$$

where v = average vessel speed (km/h);
w = average net width (km).

Alternatively, if vessel information exists for every tow, CPUE density can be expressed

Eq. B.3 $$\delta_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{D_{yij} w_{yij}},$$

where C_{yij} = catch weight (kg) for tow j, stratum i, year y;

D_{yij} = distance travelled (km) for tow j, stratum i, year y;

w_{yij} = net opening (km) for tow j, stratum i, year y;

n_{yi} = number of tows in stratum i, year y.

The annual biomass estimate is then the sum of the product of CPUE densities and bottom areas across m strata:

Eq. B.4 $$B_y = \sum_{i=1}^{m} \delta_{yi} A_i = \sum_{i=1}^{m} B_{yi} ,$$

where δ_{yi} = mean CPUE density (kg/km^2) for stratum i, year y;

A_i = area (km^2) of stratum i;

B_{yi} = biomass (kg) for stratum i, year y;

m = number of strata.

The variance of the survey biomass estimate V_y (kg^2) follows:

Eq. B.5 $$V_y = \sum_{i=1}^{m} \frac{\sigma_{yi}^2 A_i^2}{n_{yi}} = \sum_{i=1}^{m} V_{yi} ,$$

where σ_{yi}^2 = variance of CPUE density (kg^2/km^4) for stratum i, year y;

V_{yi} = variance of the biomass estimate (kg^2) for stratum i, year y.

The coefficient of variation (CV) of the annual biomass estimate for year y is

Eq. B.6 $$CV_y = \frac{\sqrt{V_y}}{B_y} .$$

B.3. NMFS TRIENNIAL TRAWL SURVEY

B.3.1. Data selection

Tow-by-tow data from the US National Marine Fisheries Service (NMFS) triennial survey covering the Vancouver INPFC (International North Pacific Fisheries Commission) region were provided by (Mark Wilkins, NMFS, Seattle, WA., pers. comm.) for the seven years that the survey worked in BC waters (Table B.1; 1980: Figure B.1; 1983: Figure B.2; 1989: Figure B.3; 1992: Figure B.4; 1995: Figure B.5; 1998: Figure B.6; 2001: Figure B.7). These tows were assigned to strata by the NMFS, but the size and definition of these strata have changed over the life of the survey (Table B.2). The NMFS survey database also identified in which country the tow was located. This information was plotted and checked against the accepted Canada/USA marine boundary: all tows appeared to be appropriately located with respect to country, based on the tow start position (Figure B.1 to Figure B.7). The NMFS designations were accepted for tows located near the marine border.

All usable tows had an associated median net width (with 1-99% quantiles) of 13.4 (11.3-15.7) m and median distance travelled of 2.8 (1.4-3.5) km, allowing for the calculation of the area swept by each tow. Biomass indices and the associated analytical CVs for Shortspine Thornyhead were calculated for the total Vancouver INPFC region and for each of the Canadian- and US-Vancouver sub-regions, using appropriate area estimates for each stratum and year (Table B.2). Strata that were not surveyed consistently in all seven years of the survey were dropped from the analysis (Table B.1; Table B.2), allowing the remaining data to provide a comparable set of data for each year (Table B.3).

Table B.1. Number of tows by stratum and by survey year for the NFMS triennial survey. Strata coloured grey have been excluded from the analysis due to incomplete coverage across the seven survey years or were from locations outside the Vancouver INPFC area (Table B.2).

Stratum	**1980**		**1983**		**1989**		**1992**		**1995**		**1998**		**2001**	
No.	**CDN**	**US**	**CDN**	**US**	**CDN**	**US**	**CDN**	**US**	**CDN**	**US**	**CDN**	**US**	**CDN**	**US**
10	-	17	-	7	-	-	-	-	-	-	-	-	-	-
11	48	-	-	39	-	-	-	-	-	-	-	-	-	-
12	-	-	38	-	-	-	-	-	-	-	-	-	-	-
17N	-	-	-	-	-	8	-	9	-	8	-	8	-	8
17S	-	-	-	-	-	27	-	27	-	25	-	26	-	25
18N	-	-	-	-	1		1	-	-		-	-	-	-
18S	-	-	-	-	-	32		23	-	12	-	20	-	14
19N	-	-	-	-	58	-	53	-	55	-	48	-	33	-
19S	-	-	-	-	-	4	-	6	-	3	-	3	-	3
27N	-	-	-	-	-	2	-	1	-	2	-	2	-	2
27S	-	-	-	-	-	5	-	2	-	3	-	4	-	5
28N	-	-	-	-	1	-	1	-	2	-	1	-	-	-
28S	-	-	-	-	-	6	-	9	-	7		6	-	7
29N	-	-	-	-	7	-	6	-	7	-	6	-	3	-
29S	-	-	-	-	-	3	-	2	-	3	-	3	-	3
30	-	4	-	2	-	-	-	-	-	-	-	-	-	-
31	7	-	-	11	-	-	-	-	-	-	-	-	-	-
32	-	-	5	-	-	-	-	-	-	-	-	-	-	-
37N	-	-	-	-	-	-	-	-	-	1	-	1	-	1
37S	-	-	-	-	-	-	-	-	-	2	-	1	-	1
38N	-	-	-	-	-	-	-	-	1	-	-	-	-	-
38S	-	-	-	-	-	-	-	-	-	2	-	-	-	3
39	-	-	-	-	-	-	-	-	6	-	4	-	2	-
50	-	5	-	1	-	-	-	-	-	-	-	-	-	-
51	4	-	-	10	-	-	-	-	-	-	-	-	-	-
52	-	-	4	-	-	-	-	-	-	-	-	-	-	-
Total	**59**	**26**	**47**	**70**	**67**	**87**	**61**	**79**	**71**	**68**	**59**	**74**	**38**	**72**

The stratum definitions used in the 1980 and 1983 surveys were different than those used in subsequent surveys, particularly in Canadian waters (Table B.3). Therefore, the 1980 and 1983 indices were scaled up by the ratio (9166 km^2 / 7399 km^2 = 1.24) of the total stratum areas relative to the 1989 and later surveys so that the coverage from the first two surveys would be comparable to the surveys conducted from 1989 onwards. The tow density was much higher in US waters although the overall number of tows was approximately the same for each country (Table B.3). This occurs because the size of the total area fished in the INPFC Vancouver area was about twice as large in Canadian waters than in US waters (Table B.3). Note that the northern extension of the survey has varied from year to year (Figure B.1 to Figure B.7), but this difference has been compensated for by using a constant survey area for all years and assuming that catch rates in the unsampled areas were the same as in the sampled area.

Table B.2. Stratum definitions by year used in the NMFS triennial survey to separate the survey results by country and by INPFC area. Stratum definitions in grey are those strata which have been excluded from the final analysis due to incomplete coverage across the seven survey years or because the locations were outside the Vancouver INPFC area.

Year	Stratum No.	Area (km^2)	Start	End	Country	INPFC area	Depth range (m)
1980	10	3537	47°30	US-Can Border	US	Vancouver	55-183
1980	11	6572	US-Can Border	49°15	CDN	Vancouver	55-183
1980	30	443	47°30	US-Can Border	US	Vancouver	184-219
1980	31	325	US-Can Border	49°15	CDN	Vancouver	184-219
1980	50	758	47°30	US-Can Border	US	Vancouver	220-366
1980	51	503	US-Can Border	49°15	CDN	Vancouver	220-366
1983	10	1307	47°30	47°55	US	Vancouver	55-183
1983	11	2230	47°55	US-Can Border	US	Vancouver	55-183
1983	12	6572	US-Can Border	49°15	CDN	Vancouver	55-183
1983	30	66	47°30	47°55	US	Vancouver	184-219
1983	31	377	47°55	US-Can Border	US	Vancouver	184-219
1983	32	325	US-Can Border	49°15	CDN	Vancouver	184-219
1983	50	127	47°30	47°55	US	Vancouver	220-366
1983	51	631	47°55	US-Can Border	US	Vancouver	220-366
1983	52	503	US-Can Border	49 °15	CDN	Vancouver	220-366
1989&after	17N	1033	47°30	47°50	US	Vancouver	55-183
1989&after	17S	3378	46°30	47°30	US	Columbia	55-183
1989&after	18N	159	47°50	48°20	CDN	Vancouver	55-183
1989&after	18S	2123	47°50	48°20	US	Vancouver	55-183
1989&after	19N	8224	48°20	49°40	CDN	Vancouver	55-183
1989&after	19S	363	48°20	49°40	US	Vancouver	55-183
1989&after	27N	125	47°30	47°50	US	Vancouver	184-366
1989&after	27S	412	46°30	47°30	US	Columbia	184-366
1989&after	28N	88	47°50	48°20	CDN	Vancouver	184-366
1989&after	28S	787	47°50	48°20	US	Vancouver	184-366
1989&after	29N	942	48°20	49°40	CDN	Vancouver	184-366
1989&after	29S	270	48°20	49°40	US	Vancouver	184-366
1995&after	37N	102	47°30	47°50	US	Vancouver	367-500
1995&after	37S	218	46°30	47°30	US	Columbia	367-500
1995&after	38N	66	47°50	48°20	CDN	Vancouver	367-500
1995&after	38S	175	47°50	48°20	US	Vancouver	367-500

Table B.3. Number of usable tows performed and area surveyed in the INPFC Vancouver region separated by the international border between Canada and the United States. Strata 18N, 28N, 37, 38 and 39 (Table B.2) were dropped from this analysis as they were not consistently conducted over the survey period. All strata occurring in the Columbia INPFC region (17S and 27S; Table B.2) were also dropped.

Survey year	Number of tows			Area surveyed (km^2)		
	CDN waters	US waters	Total	CDN waters	US waters	Total
1980	59	26	85	7,399	4,738	12,137
1983	47	70	117	7,399	4,738	12,137
1989	65	55	120	9,166	4,699	13,865
1992	59	50	109	9,166	4,699	13,865
1995	62	35	97	9,166	4,699	13,865
1998	54	42	96	9,166	4,699	13,865
2001	36	37	73	9,166	4,699	13,865
Total	382	315	697	–	–	–

B.3.2. Methods

The data were analysed using the equations in Section B.1. When calculating the variance for this survey, it was assumed that the variance and CPUE within any stratum was equal, even for strata that were split by the Canada/USA border. The total biomass $\left(B_{y_i}\right)$ within a stratum that straddled the border was split between the two countries $\left(B_{y_{i_c}}\right)$ by the ratio of the relative area within each country:

Eq. B.7 $$B_{y_{i_c}} = B_{y_i} \frac{A_{y_{i_c}}}{A_{y_i}},$$

where $A_{y_{i_c}}$ = area (km^2) within country *c* in year *y* and stratum *i*.

The variance $V_{y_{i_c}}$ for that part of stratum *i* within country *c* was calculated as being in proportion to the ratio of the square of the area within each country *c* relative to the total area of stratum *i*. This assumption resulted in the CVs within each country stratum being the same as the CV in the entire stratum:

Eq. B.8 $$V_{y_{i_c}} = V_{y_i} \frac{A^2_{y_{i_c}}}{A^2_{y_i}}.$$

The partial variance $V_{y_{i_c}}$ for country *c* was used in Eq. B.5 instead of the total variance in the stratum V_{y_i} when calculating the variance for the total biomass in Canadian or American waters. CVs were calculated as in Eq. B.6.

The biomass estimates Eq. B.4 and the associated standard errors were adjusted to a constant area covered using the ratios of area surveyed provided in Table B.3. This was required to adjust the Canadian biomass estimates for 1980 and 1983 to account for the smaller area surveyed in those years compared to the succeeding surveys. The 1980 and 1983 biomass estimates from Canadian waters were consequently multiplied by the ratio 1.24 (= 9166 km^2 / 7399 km^2) to make them equivalent to the coverage of the surveys from 1989 onwards.

Biomass estimates were bootstrapped for 1000 random draws with replacement to obtain bias-corrected (Efron 1982) 95% confidence intervals for each year and for three area categories (total Vancouver region, Canadian-Vancouver only and US-Vancouver only) based on the distribution of biomass estimates and using the above equations.

B.3.3. Results

Shortspine Thornyhead (SST) are characterised by frequent and consistent catches along the shelf edge and particularly in the deep gully entering Juan de Fuca Strait (e.g., Figure B.1 and Figure B.2). Coverage by depth has been consistent for all seven years of the survey after the exclusion of the deep strata that were not covered in the earlier surveys (Figure B.8). The latter plot shows that this species was mainly found between 113 and 466 m (1 and 99% quantiles of [`bottom_depth`]), with observations at deeper depths frequent as the survey design changed by incorporating deeper strata starting in 1995. Note that these deep strata were not used in the biomass estimation because they were not consistently sampled over the survey period.

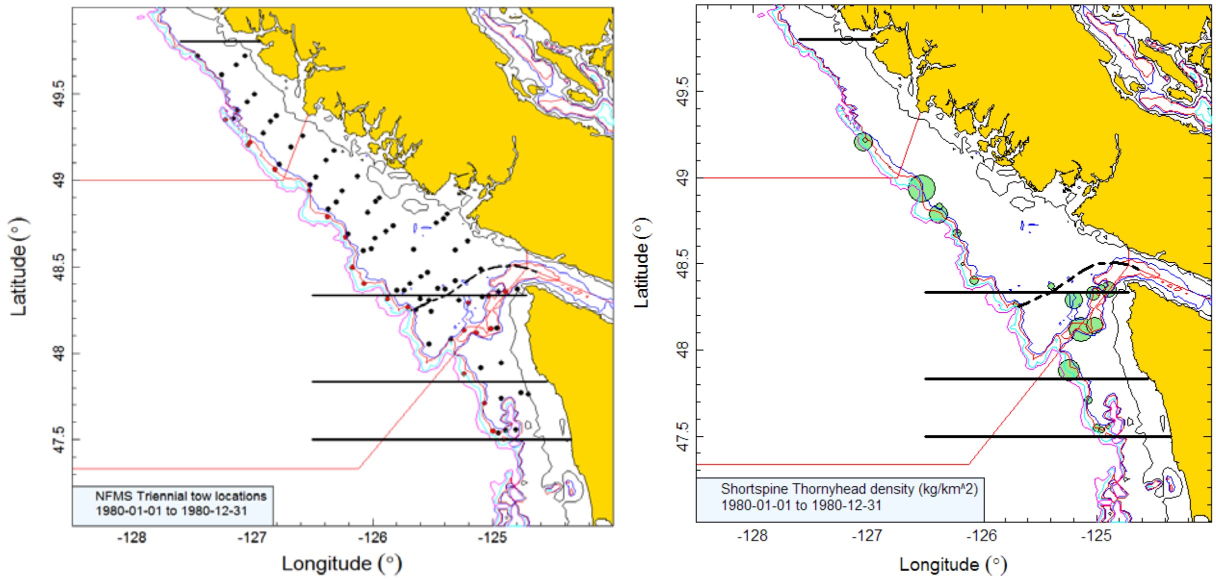

Figure B.1. [left panel]: plot of tow locations in the Vancouver INPFC region for the 1980 NMFS triennial survey in US and Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m; grey=367-500m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'. Tows south of the 47°30' line were not included in the analysis. [right panel]: circle sizes in the density plot are scaled across all years (1980, 1983, 1989, 1992, 1995, 1998, and 2001), with the largest circle = 1409 kg/km^2 in 1995. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D.

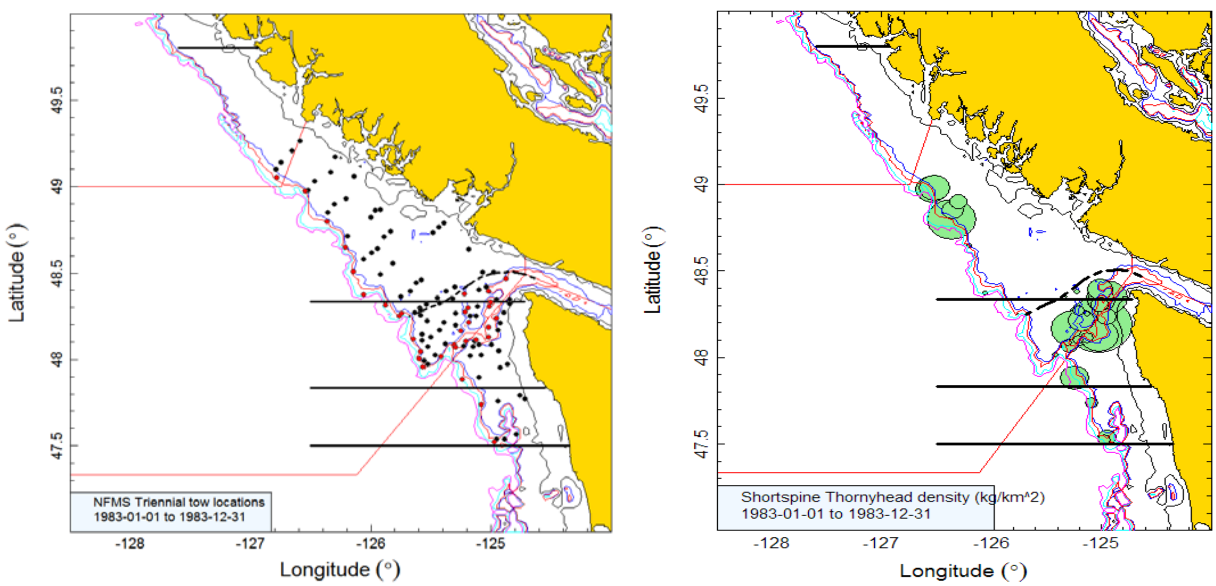

Figure B.2. Tow locations and density plots for the 1983 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

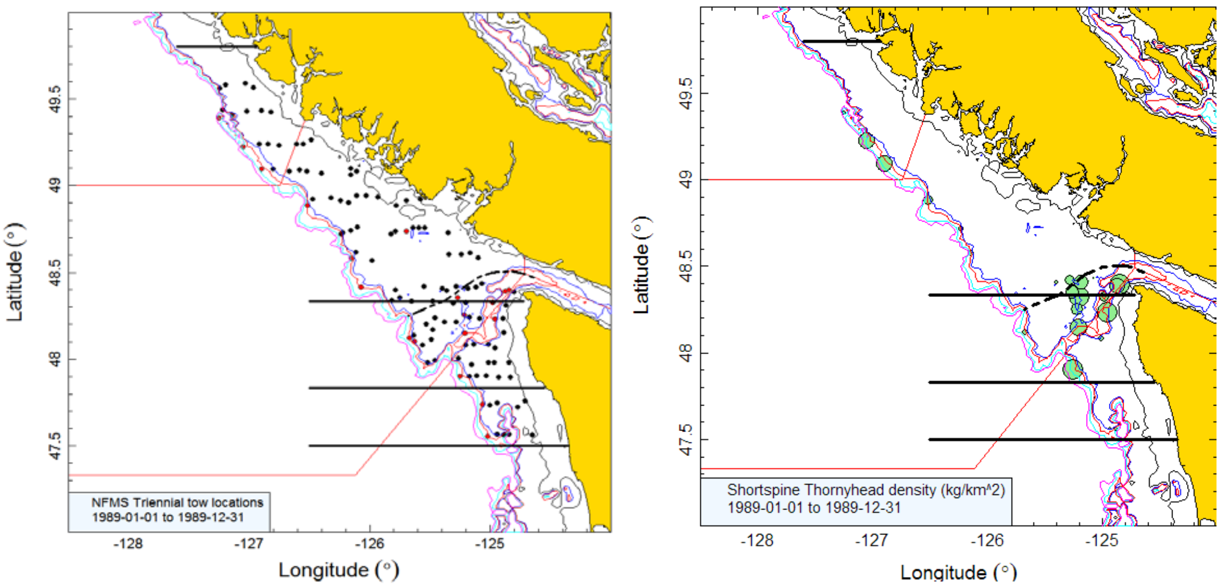

Figure B.3. Tow locations and density plots for the 1989 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

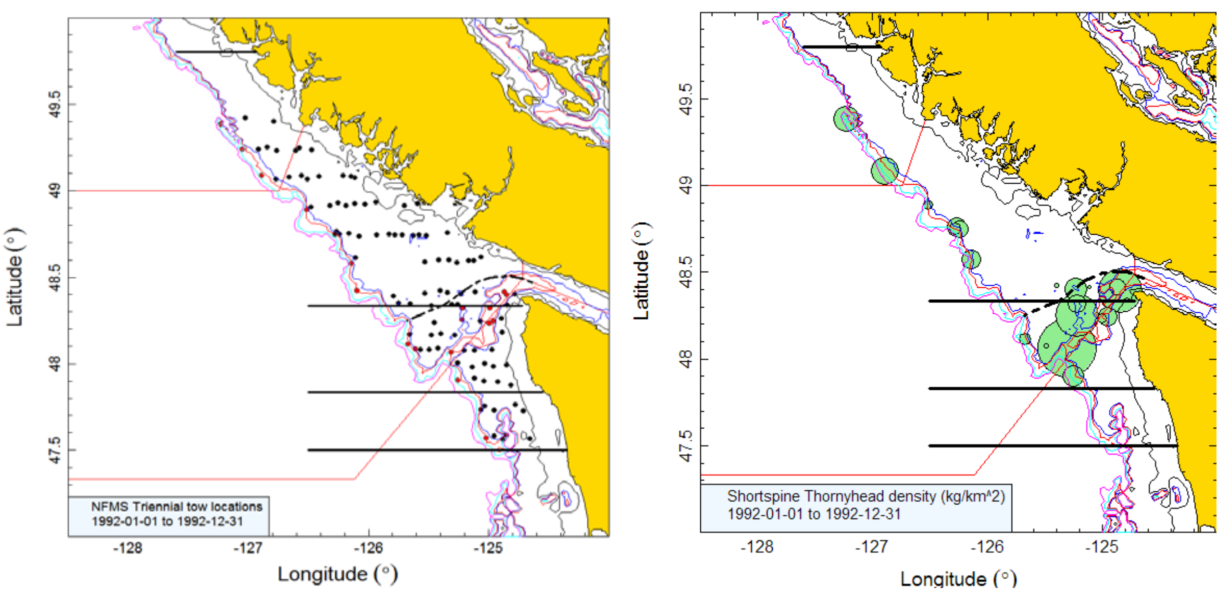

Figure B.4. Tow locations and density plots for the 1992 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

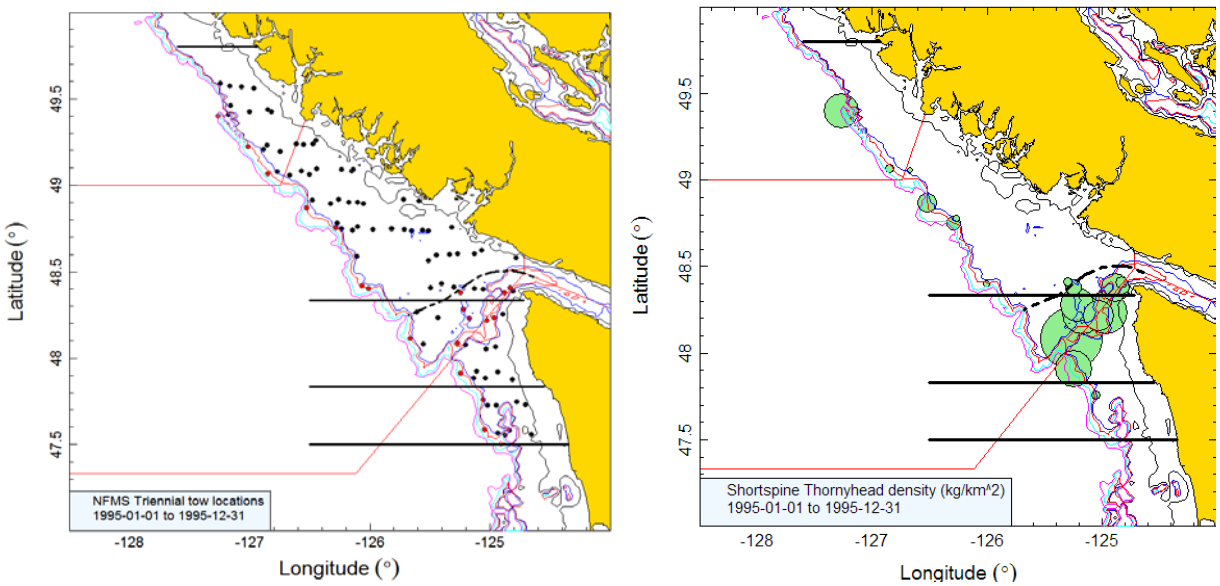

Figure B.5. Tow locations and density plots for the 1995 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

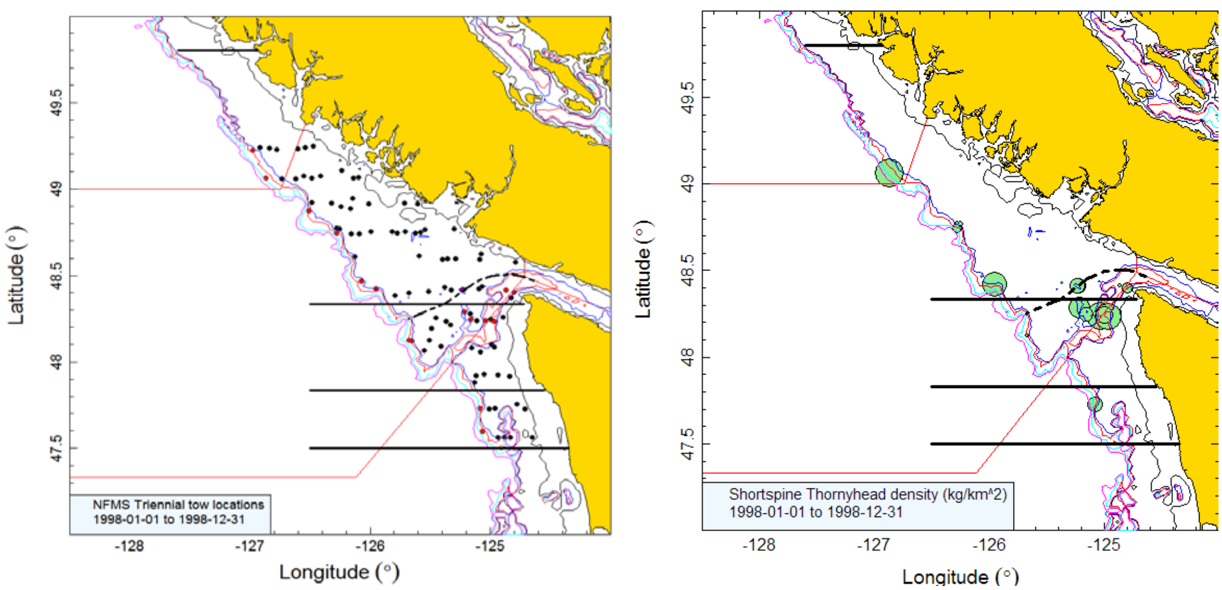

Figure B.6. Tow locations and density plots for the 1998 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

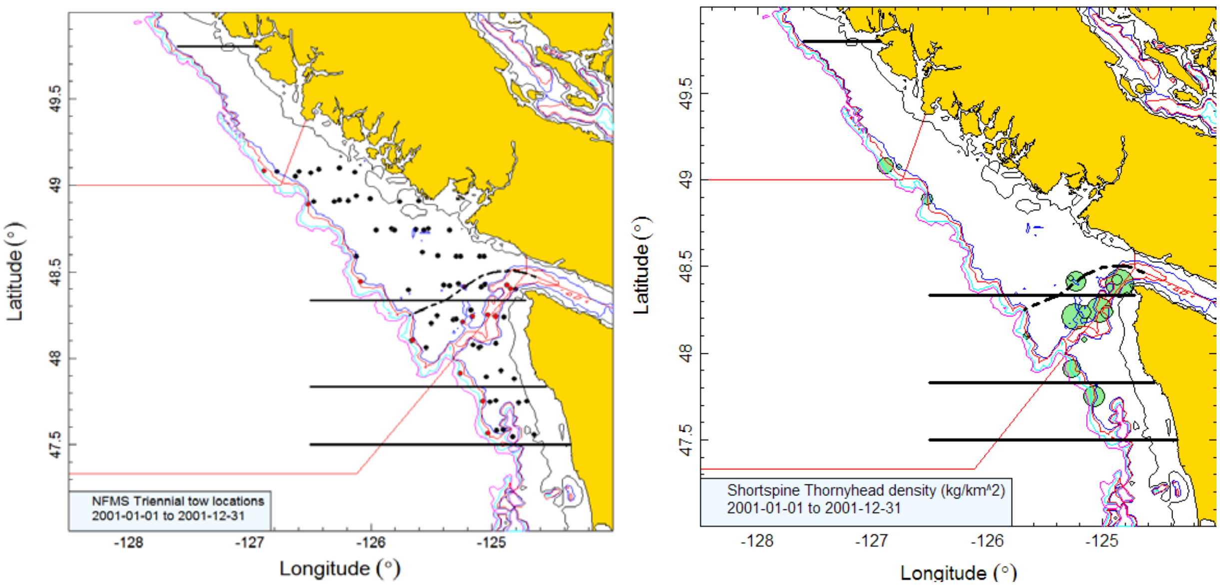

Figure B.7. Tow locations and density plots for the 2001 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

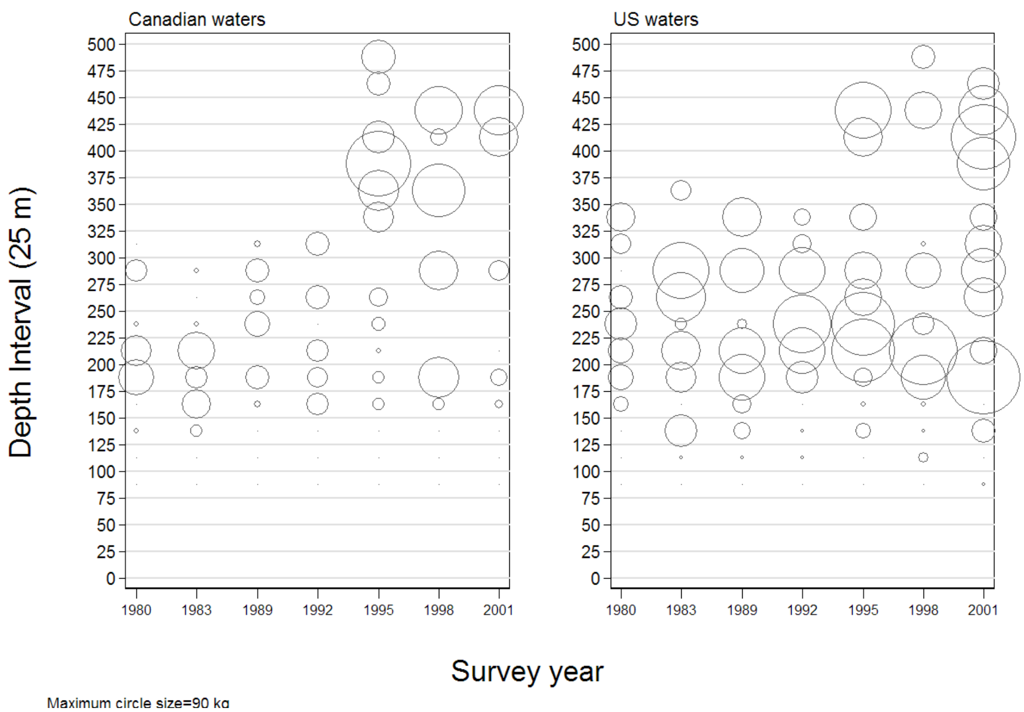

Figure B.8. Distribution of Shortspine Thornyhead catch weights for each survey year summarised into 25 m depth intervals for all tows (Table B.2) in Canadian and US waters of the Vancouver INPFC area. Catches are plotted at the mid-point of the interval. Note that the deep strata introduced in 1995 (see Table B.2) have been included in this plot but were not used in the biomass estimation.

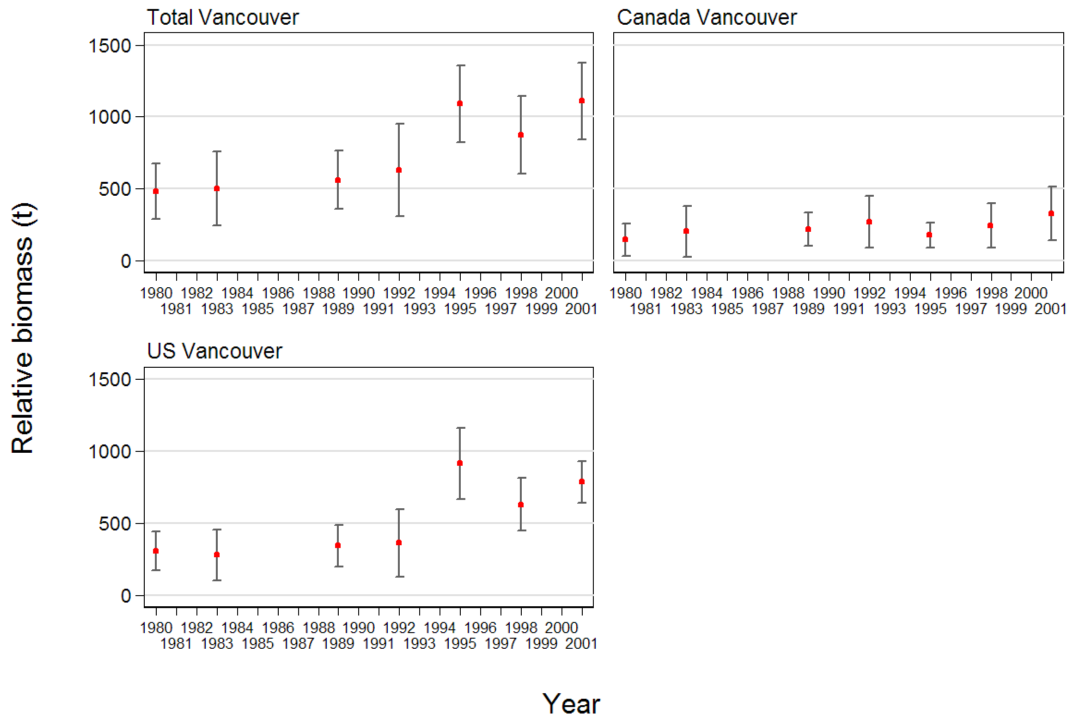

Figure B.9. Biomass estimates for three series of Shortspine Thornyhead in the INPFC Vancouver region (total region, Canadian waters only, and US waters only) with 95% error bars estimated from 1000 bootstraps.

Table B.4. Biomass estimates for Shortspine Thornyhead in the Vancouver INPFC region (total region, Canadian waters only, and US waters only) with 95% confidence bounds based on the bootstrap distribution of biomass.. Bootstrap estimates are based on 1000 random draws with replacement.

Estimate series	Year	Biomass (Eq. B.4)	Mean bootstrap biomass	Lower bound biomass	Upper bound biomass	CV bootstrap	CV Analytic (Eq. B.6)
Total Vancouver	1980	483.8	481.2	292.7	674.8	0.202	0.205
	1983	502.8	492.2	245.1	760.4	0.267	0.270
	1989	559.9	505.6	357.0	762.7	0.204	0.191
	1992	631.2	554.5	307.7	954.7	0.297	0.272
	1995	1,090.2	599.9	822.1	1,358.3	0.228	0.169
	1998	873.4	505.9	604.8	1,142.0	0.271	0.215
	2001	1,111.8	505.4	845.2	1,378.4	0.269	0.211
Canada Vancouver	1980	144.7	147.3	31.4	257.9	0.392	0.410
	1983	201.7	199.3	26.5	376.8	0.448	0.458
	1989	218.4	216.8	102.7	334.2	0.272	0.269
	1992	270.8	267.8	89.9	451.7	0.344	0.341
	1995	176.6	123.9	89.9	263.3	0.357	0.267
	1998	244.1	202.5	87.9	400.3	0.393	0.344
	2001	327.5	223.5	140.5	514.5	0.426	0.294
US Vancouver	1980	306.7	302.4	169.7	443.8	0.231	0.237
	1983	277.3	270.0	98.4	456.2	0.338	0.333
	1989	341.4	288.8	194.6	488.2	0.259	0.237
	1992	360.4	286.7	124.0	596.8	0.420	0.359
	1995	913.7	476.0	665.9	1,161.4	0.265	0.183
	1998	629.3	303.5	447.7	811.0	0.305	0.232
	2001	784.3	282.0	639.8	928.8	0.261	0.227

Shortspine Thornyhead biomass estimates in both US waters were characterised by an increasing trend in US waters from 1980 to 2001 while the indices from the Canadian waters tended to be flat (Figure B.9; Table B.4). The relative error estimates are moderate, with the lowest relative error occurring at 0.20 in 1980 for Total Vancouver and the greatest at 0.45 in 1983 for the Canada Vancouver (Table B.4). The relative error estimates for the sub-divided national strata tend to be higher than for Total Vancouver in the same years. Note that the bootstrap estimates of relative error do not include any uncertainty with respect to the ratio expansion required to make the 1980 and 1983 survey estimates comparable to the 1989 and later surveys. Therefore, it is likely that the true uncertainty for this series is even greater than estimated.

One hundred and fifty-four tows of the nearly 700 valid tows captured SST (22%), with nearly three-quarters of the tows that captured SST having less than 10 kg. The largest tow was 49 kg in 1983. The proportion of tows which contained Shortspine Thornyhead was higher in US waters than in Canadian waters, with the US proportions by year ranging from 26 to 42% (mean=32%) while the equivalent Canadian values were 11–20% with a mean value of 15% (Figure B.10). The incidence of SST in Canadian waters for this survey is lower than for the synoptic survey operating in the 2000s off the west coast of Vancouver Island, with the latter survey having over 26% (range: 21-32%) of the tows containing SST.

The seven Triennial survey indices from the Canada Vancouver region spanning the period 1980 to 2001 were used as a series of abundance indices for use in the stock assessment model (described in Appendix E).

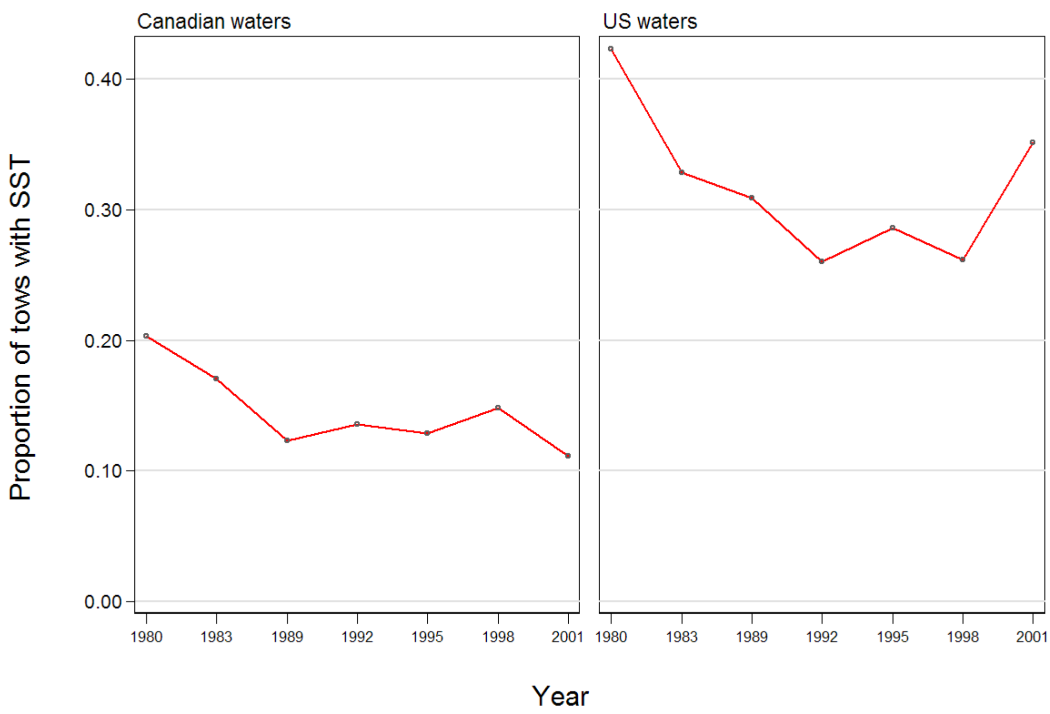

Figure B.10. Proportion of tows with Shortspine Thornyhead by year for the Vancouver INPFC region (Canadian and US waters).

B.4. HECATE STRAIT SYNOPTIC SURVEY

B.4.1. Data selection

This survey has been conducted over six alternating years over the period 2005 to 2015 in Hecate Strait (HS) between Moresby and Graham Islands and the mainland and in Dixon Entrance at the top of Graham Island (all valid tow starting positions by survey year are shown in Figure B.11 to Figure B.16). This survey treats the full spatial coverage as a single areal stratum divided into four depth strata: 10–70 m; 70–130 m; 130–220 m; and 220–500 m (Table B.5).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Shortspine Thornyhead (SST) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`] X [`tow duration`]) can be used for this variable if [`distance travelled`] is missing, but there were no instances of this occurring in the 6 trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (217 values over all years: Table B.6).

Table B.5. Number of usable tows for biomass estimation by year and depth stratum for the Hecate Strait synoptic survey over the period 2005 to 2013. Also shown is the area of each depth stratum and the vessel conducting the survey by survey year.

		Depth stratum				Total
Year	**Vessel**	**10-70**	**70-130**	**130-220**	**220-500**	**tows**
2005	Frosti	79	88	26	9	202
2007	W.E. Ricker	48	43	36	7	134
2009	W.E. Ricker	53	43	48	12	156
2011	W.E. Ricker	70	51	50	14	185
2013	W.E. Ricker	74	42	43	16	175
2015	W.E. Ricker	47	46	40	15	148
Area (km^2)		5,958	3,011	2,432	1,858	13,259[1]

[1] total area for survey

Table B.6. Number of missing doorspread values by year for the Hecate Strait synoptic survey over the period 2005 to 2015 as well as showing the number of available doorspread observations and the mean doorspread value for the survey year.

Year	Number tows with missing doorspread [1]	Number tows with doorspread observations [2]	Mean doorspread (m) used for tows with missing values [2]
2005	7	217	64.4
2007	98	37	59.0
2009	93	70	54.0
2011	13	186	54.8
2013	6	169	51.7
2015	0	151	59.4
Total	217	830	57.6

[1] valid biomass estimation tows only
[2] includes tows not used for biomass estimation

Table B.7. Biomass estimates for Shortspine Thornyhead from the Hecate Strait synoptic trawl survey for the survey years 2005 to 2015. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2005	237.9	237.6	84.1	487.7	0.426	0.415
2007	346.9	348.6	151.0	656.5	0.379	0.361
2009	166.8	165.7	101.4	280.9	0.267	0.256
2011	294.0	291.9	137.5	582.8	0.382	0.382
2013	406.2	408.3	220.9	639.4	0.262	0.269
2015	277.2	276.2	162.9	489.9	0.288	0.298

B.4.2. Results

Catches of SST from this survey are seen in the waters north of Graham Island and in the eastern reaches of Dixon Entrance, as well as in the upper reaches of the Moresby Gully (Figure B.11 to Figure B.16). SST were mainly taken at depths from 124 to 336 m (5–95% quantiles), but there were sporadic observations to depths up to 400 m and down to about 20 m (Figure B.17).

Estimated SST doorspread biomass from this trawl survey showed no overall trend over the period 2005 to 2015, with the highest estimates recorded in 2007 and 2013 and the lowest estimate in 2009 (Table B.7; Figure B.18). The estimated relative errors were moderate, ranging from 26 to 43% (Table B.7). On average, 19% of the survey tows captured SST (ranging from 0.09 to 0.29 by year) (Figure B.19). Overall, 188 of the 1000 valid survey tows contained SST with a low median catch weight for positive tows (around 3 kg/tow) and a maximum catch weight across all six surveys of 98 kg (in 2011).

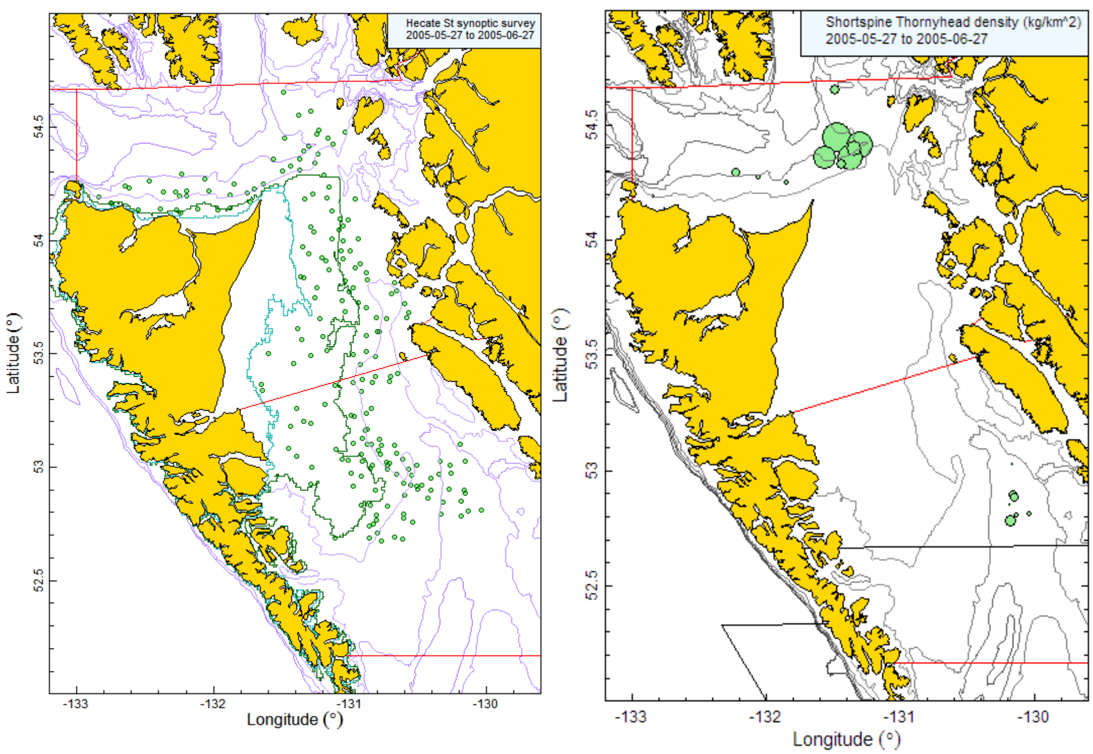

Figure B.11. Valid tow locations and density plots for the 2005 Hecate Strait synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2005, 2007, 2009, 2011, 2013, 2015), with the largest circle = 849 kg/km^2 in 2011. Red lines indicate boundaries for PMFC major areas 5C, 5D and 5E.

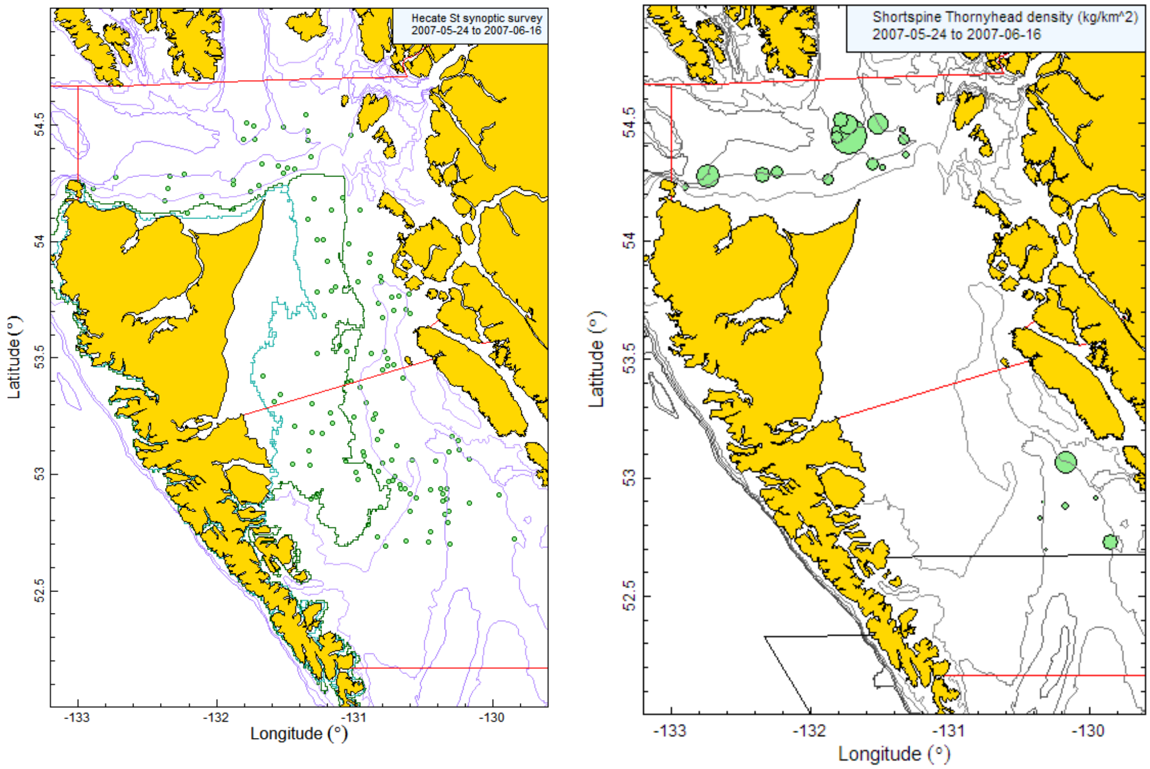

Figure B.12. Tow locations and density plots for the 2007 Hecate Strait synoptic survey (see Figure B.11 caption).

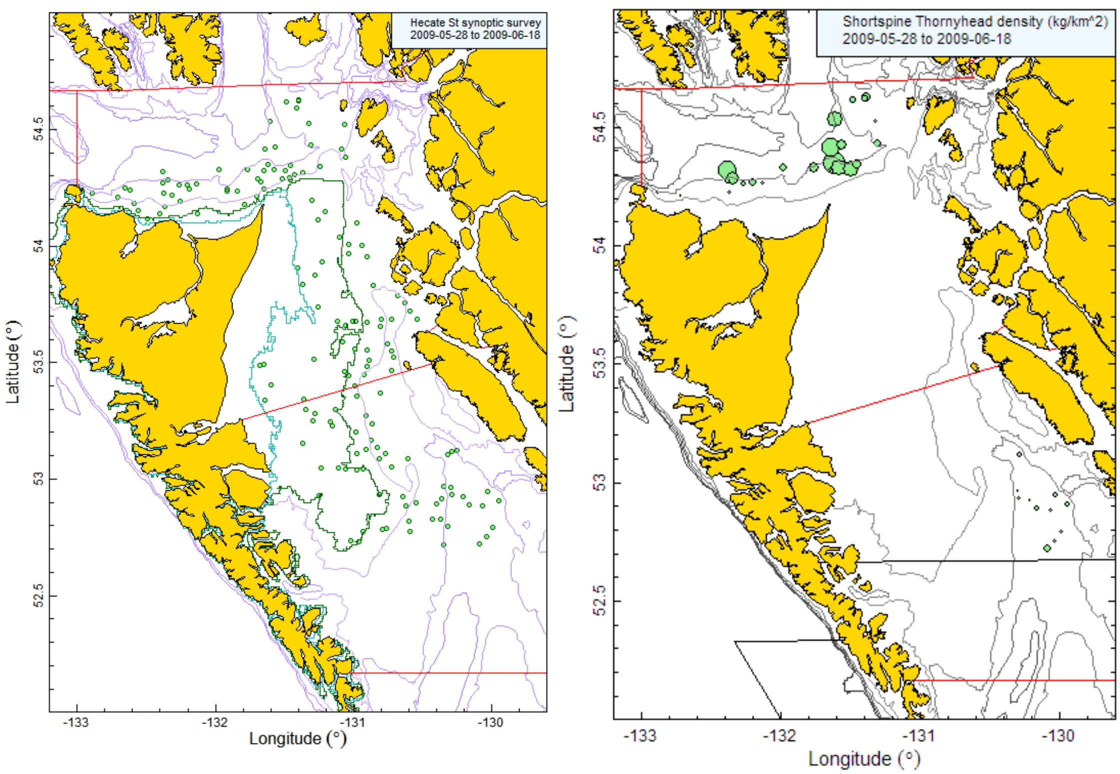

Figure B.13. Tow locations and density plots for the 2009 Hecate Strait synoptic survey (see Figure B.11 caption).

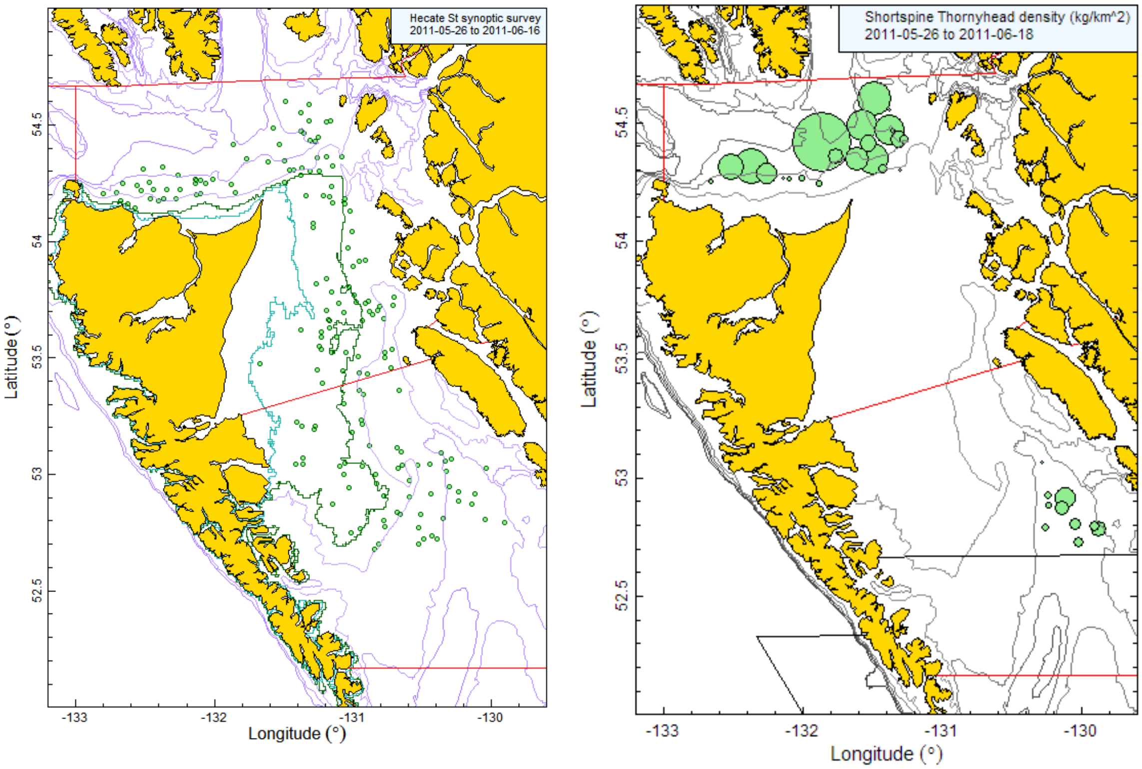

Figure B.14. Tow locations and density plots for the 2011 Hecate Strait synoptic survey (see Figure B.11 caption).

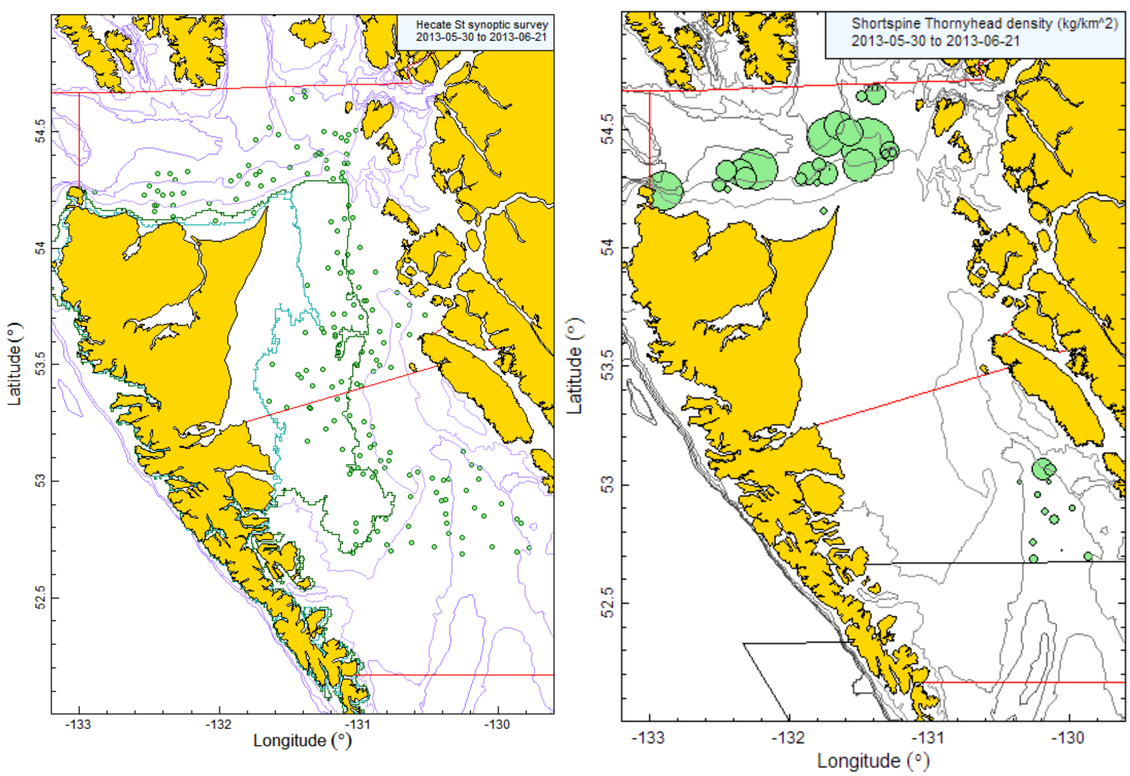

Figure B.15. Tow locations and density plots for the 2013 Hecate Strait synoptic survey (see Figure B.11 caption).

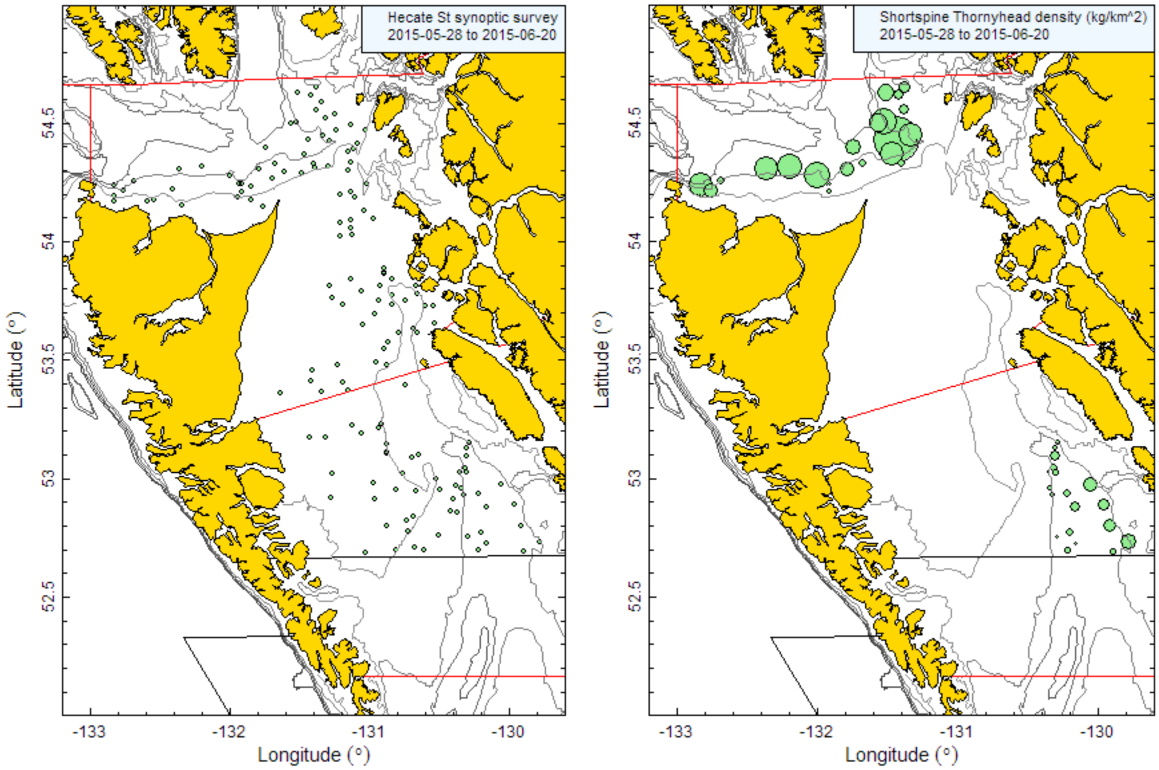

Figure B.16. Tow locations and density plots for the 2013 Hecate Strait synoptic survey (see Figure B.11 caption).

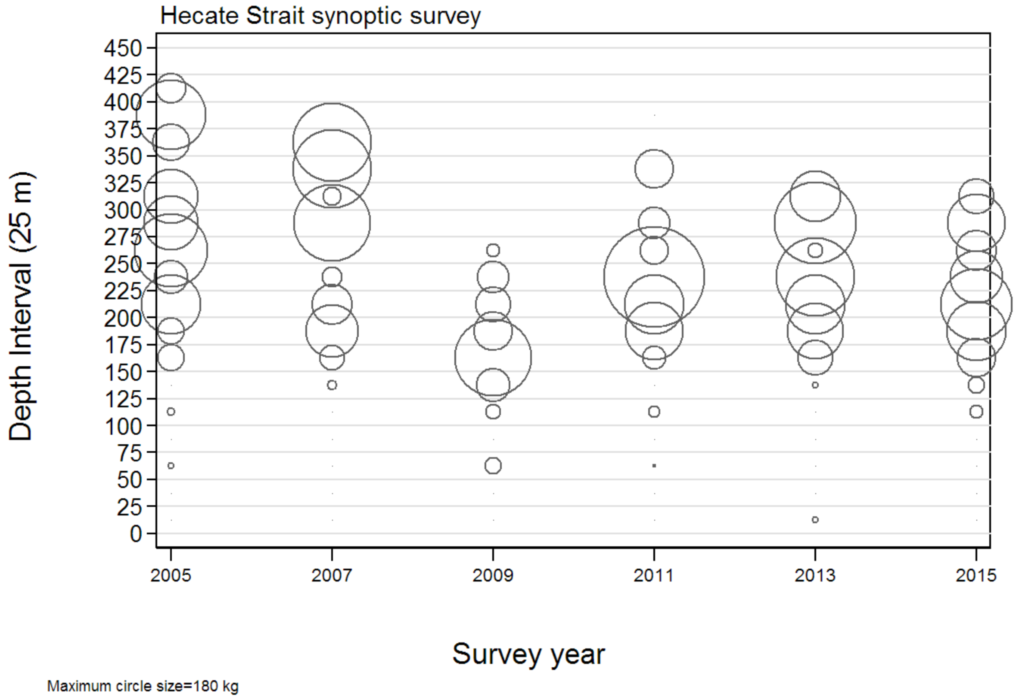

Figure B.17. Distribution of observed catch weights of SST for the Hecate Strait synoptic survey (Table B.5) by survey year and 25 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (180 kg) in the 225–250 m interval in 2011. The 1% and 99% quantiles for the SST empirical start of tow depth distribution= 64 m and 378 m respectively.

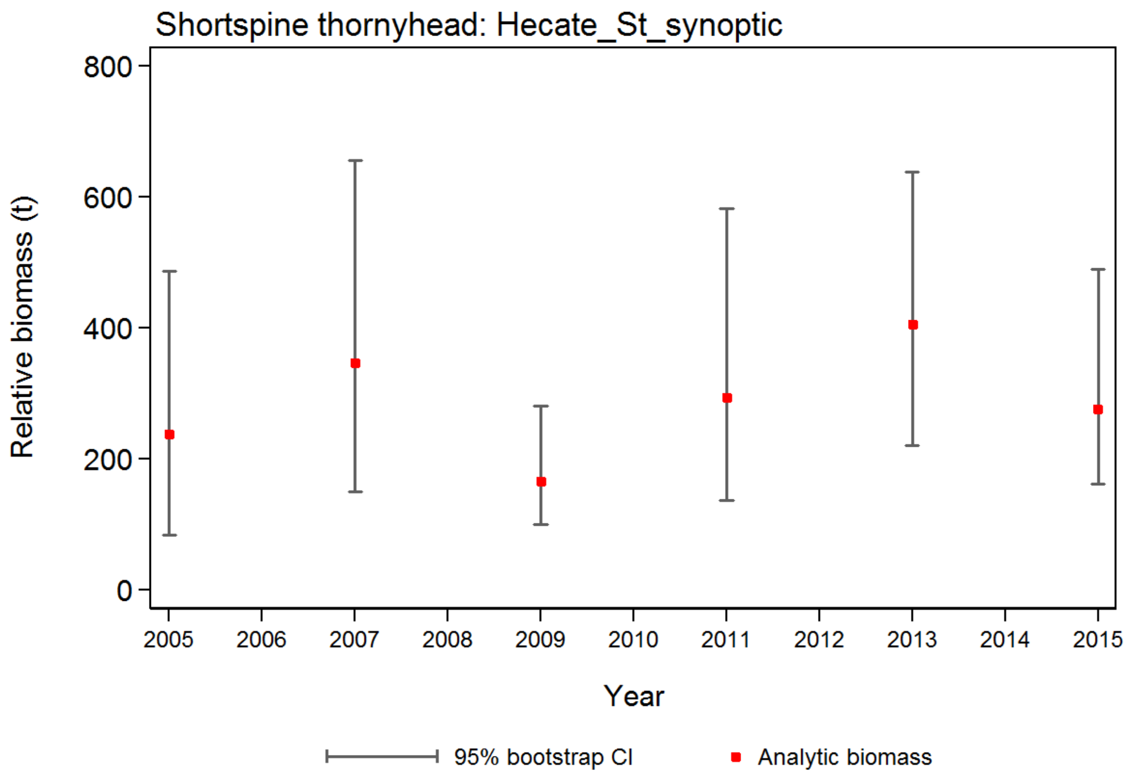

Figure B.18. Plot of biomass estimates for Shortspine Thornyhead (values provided in Table B.7) from the Hecate Strait synoptic survey over the period 2005 to 2015 . Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

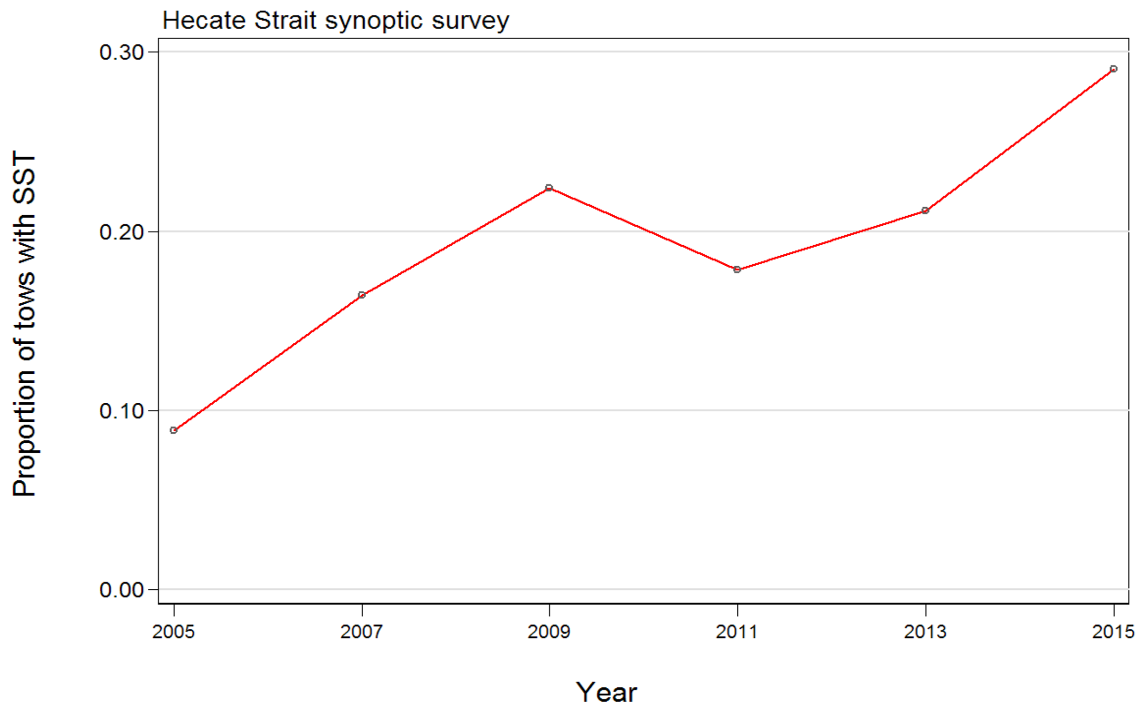

Figure B.19. Proportion of tows by year which contain Shortspine Thornyhead from the Hecate Strait synoptic survey over the period 2005 to 2013.

B.5. QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

B.5.1. Data selection

This survey has been conducted in eight years over the period 2003 to 2015 in Queen Charlotte Sound (QCS), which lies between the top of Vancouver Island and the southern portion of Moresby Island and extends into the lower part of Hecate Strait between Moresby Island and the mainland. The design divided the survey into two large areal strata which roughly correspond to the PMFC regions 5A and 5B while also incorporating part of 5C (all valid tow starting positions are shown by survey year in Figure B.20 to Figure B.27). Each of these two areas was divided into four depth strata: 50–125 m; 125–200 m; 200–330 m; and 330–500 m (Table B.8).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Shortspine Thornyhead (SST) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`] X [`tow duration`]) can be used for this variable if [`distance travelled`] is missing, but there were only two instances of this occurring in the 8 trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (140 values over all years: Table B.9).

Table B.8. Number of usable tows for biomass estimation by year and depth stratum for the Queen Charlotte Sound synoptic survey over the period 2003 to 2015. Also shown is the area of each stratum and the vessel conducting the survey by survey year.

		South depth strata				North stratum				Total
Year	**Vessel**	**50-125**	**125-200**	**200-330**	**330-500**	**50-125**	**125-200**	**200-330**	**330-500**	**tows**
2003	Viking Storm	29	56	29	6	5	39	50	19	233
2004	Viking Storm	42	48	31	8	20	38	37	6	230
2005	Viking Storm	29	60	29	8	8	45	37	8	224
2007	Viking Storm	33	62	24	7	19	57	48	7	257
2009	Viking Storm	34	60	28	8	10	44	43	6	233
2011	Nordic Pearl	38	67	25	8	10	51	45	8	252
2013	Nordic Pearl	32	66	29	10	9	46	44	5	241
2015	Frosti	30	65	26	4	12	50	44	8	239
Area (km^2)		5,072	5,432	2,712	548	1,804	4,060	3,748	1,252	24,628

Table B.9. Number of missing doorspread values by year for the Queen Charlotte Sound synoptic survey over the period 2003 to 2015 as well as showing the number of available doorspread observations and the mean doorspread value for the survey year.

Year	**Number tows with missing doorspread** [1]	**Number tows with doorspread observations** [2]	**Mean doorspread (m) used for tows with missing values** [2]
2003	13	236	72.1
2004	8	267	72.8
2005	1	258	74.5
2007	5	262	71.8
2009	2	248	71.3
2011	30	242	67.0
2013	42	226	69.5
2015	0	249	70.5
Total	101	1,988	71.2

[1] valid biomass estimation tows only; [2] includes tows not used for biomass estimation

Table B.10. Biomass estimates for Shortspine Thornyhead from the Queen Charlotte Sound synoptic trawl survey for the survey years 2003 to 2015. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2003	976.5	976.3	791.8	1,192.1	0.109	0.109
2004	1,246.3	1,244.7	990.0	1,606.0	0.129	0.123
2005	916.9	917.3	761.9	1,069.2	0.084	0.089
2007	508.8	509.6	393.8	624.6	0.115	0.124
2009	799.2	793.2	599.6	1,118.4	0.154	0.155
2011	848.4	843.7	696.6	1,027.6	0.098	0.097
2013	1,400.5	1,387.4	1,012.6	1,882.4	0.157	0.151
2015	1,291.3	1,286.9	1,009.1	1,670.2	0.130	0.128

B.5.2. Results

Catch densities of SST from this survey were similar in the two strata, with some high density tows recorded in both strata (Figure B.20 to Figure B.27). Based on the distribution of catch densities in these figures, it appears that SST are taken along the outer shelf edge and well into all three gullies (Moresby, Mitchell and Goose). SST were mainly taken at depths from 179 to 401 m (5–95% quantiles), but there were sporadic observations up to depths greater than 600 m and down to about 100 m (Figure B.28).

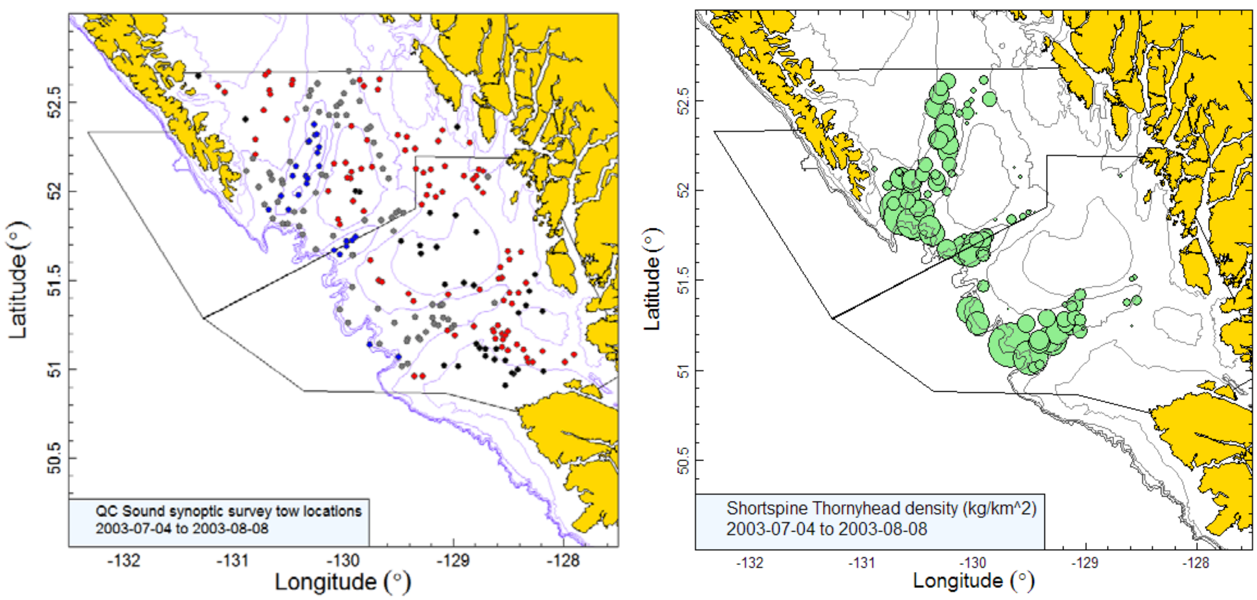

Figure B.20. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 Queen Charlotte Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013, 2015), with the largest circle = 1083 kg/km^2 in 2004. Boundaries delineate the North and South areal strata.

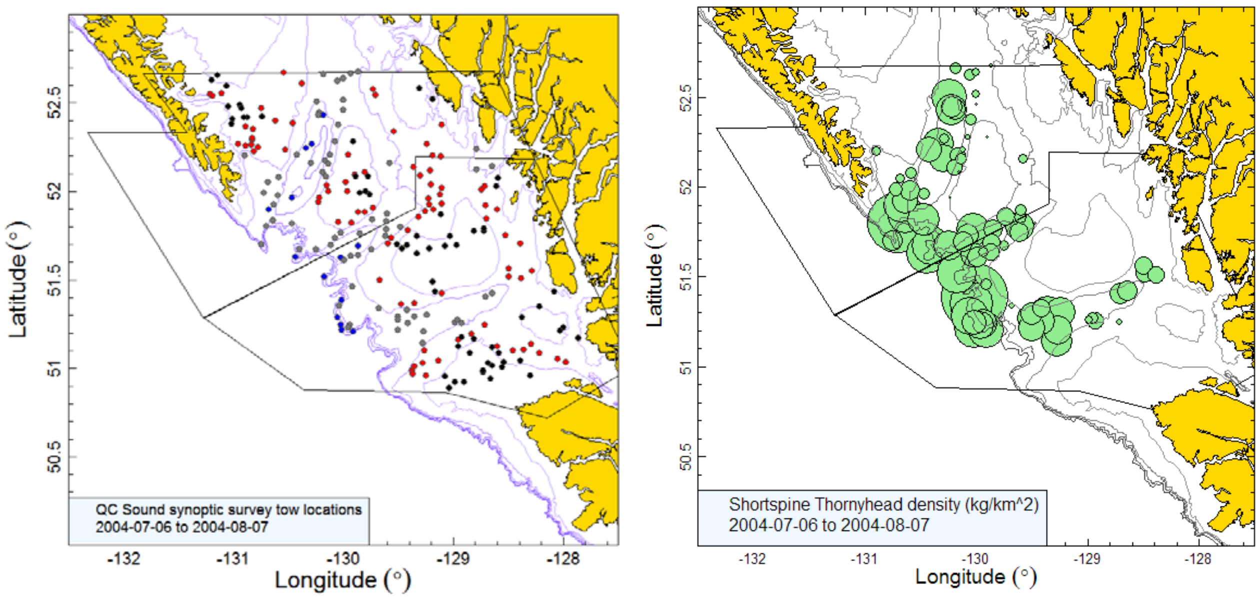

Figure B.21. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

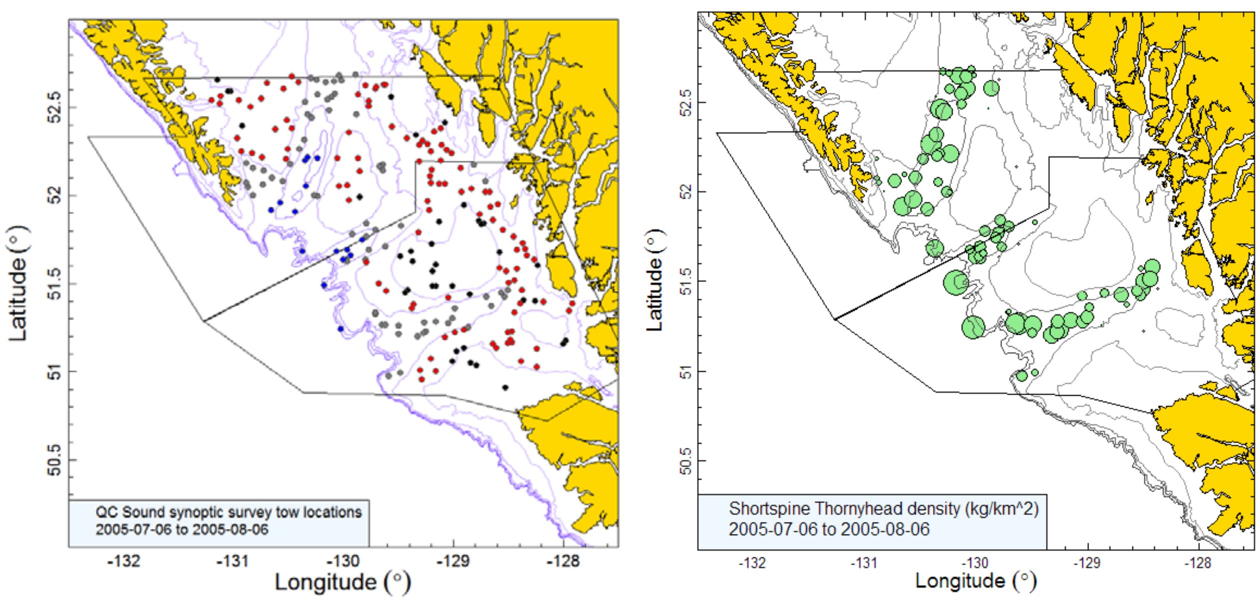

Figure B.22. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

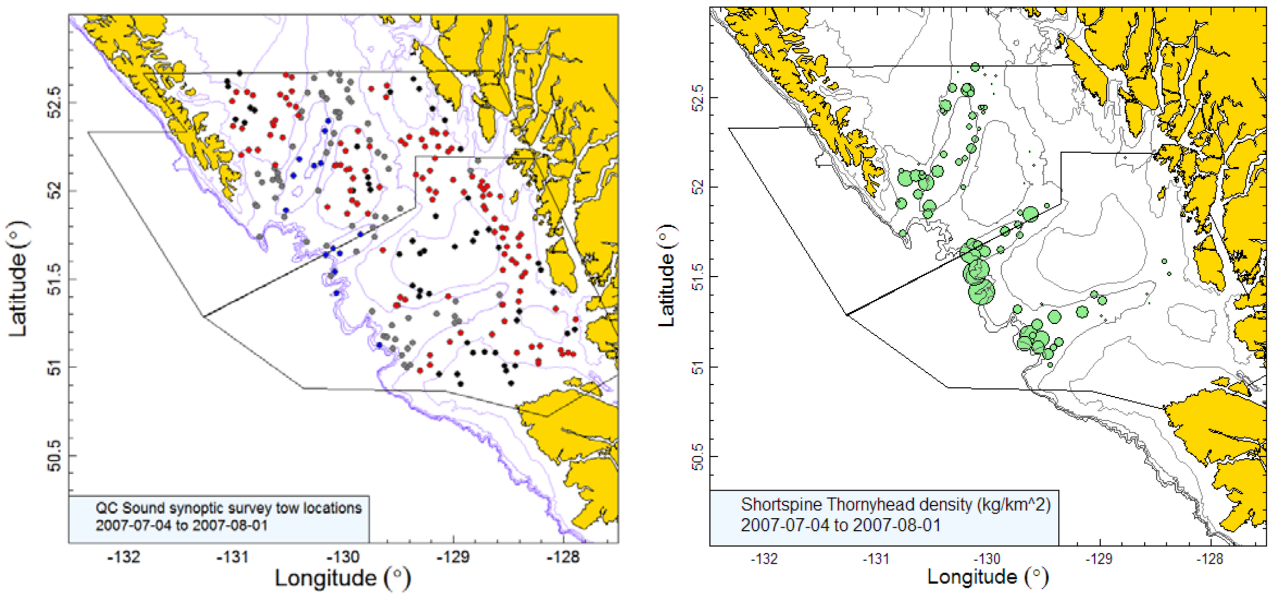

Figure B.23. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

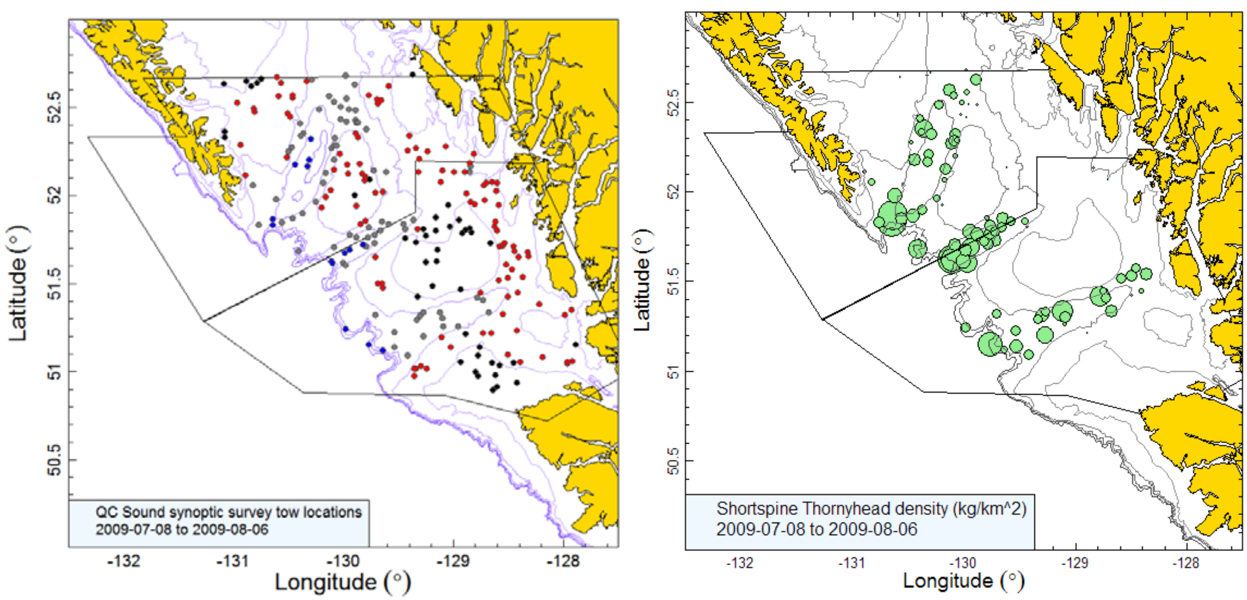

Figure B.24. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

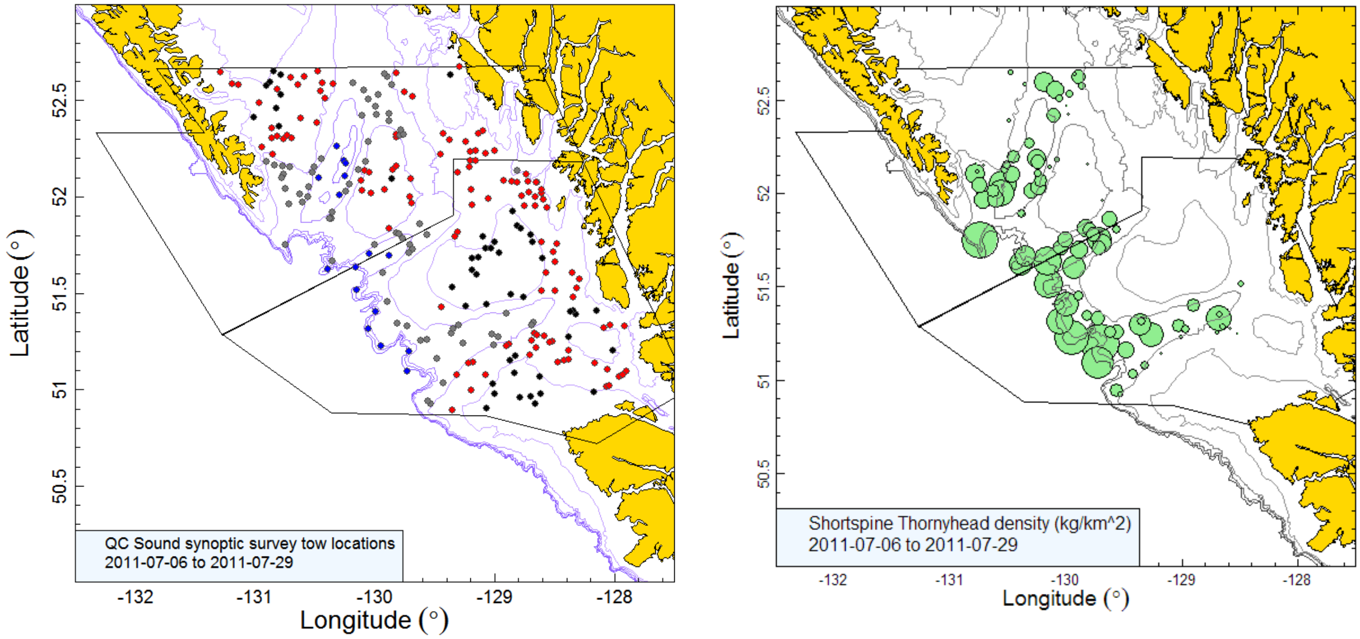

Figure B.25. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

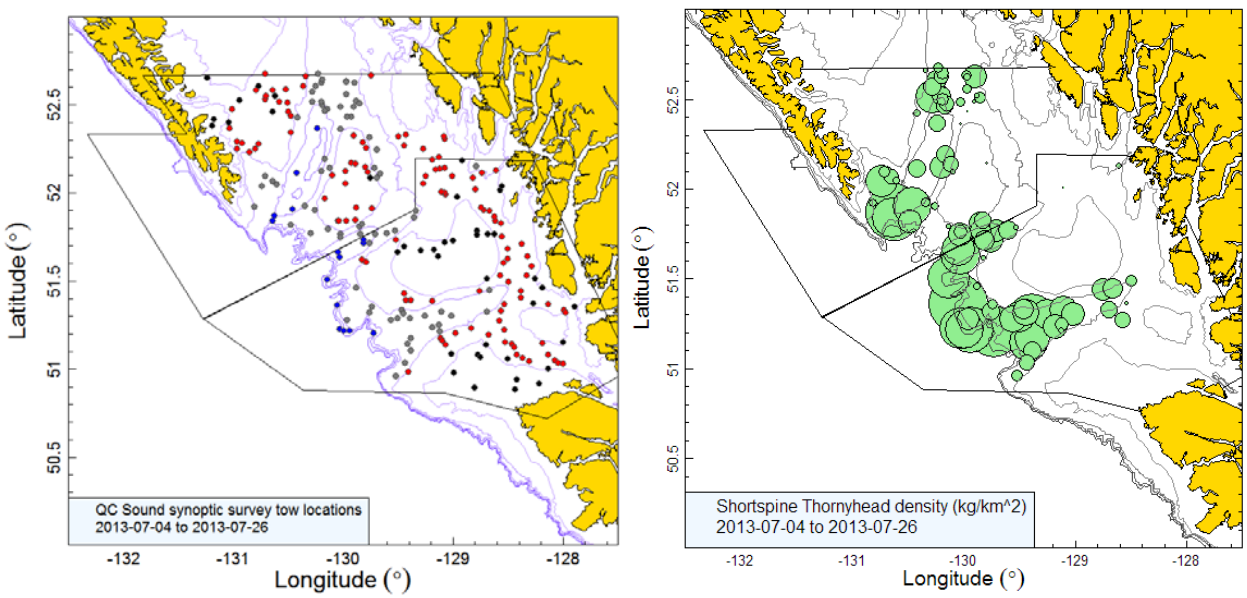

Figure B.26. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

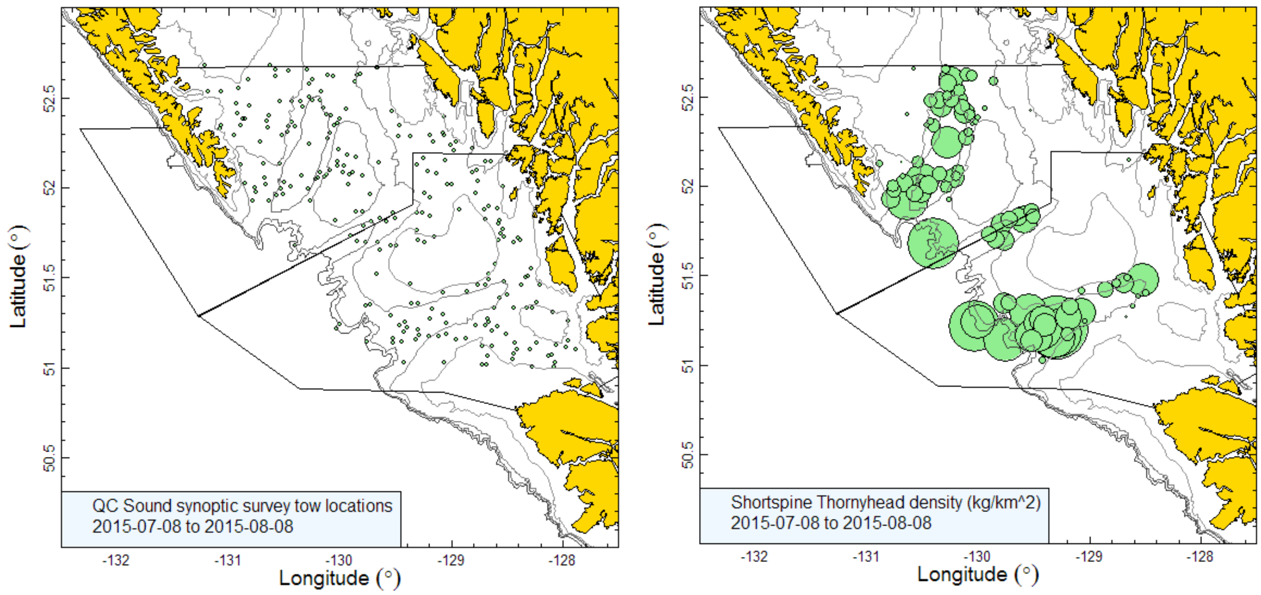

Figure B.27. Tow locations and density plots for the 2015 Queen Charlotte Sound synoptic survey (see Figure B.20 caption).

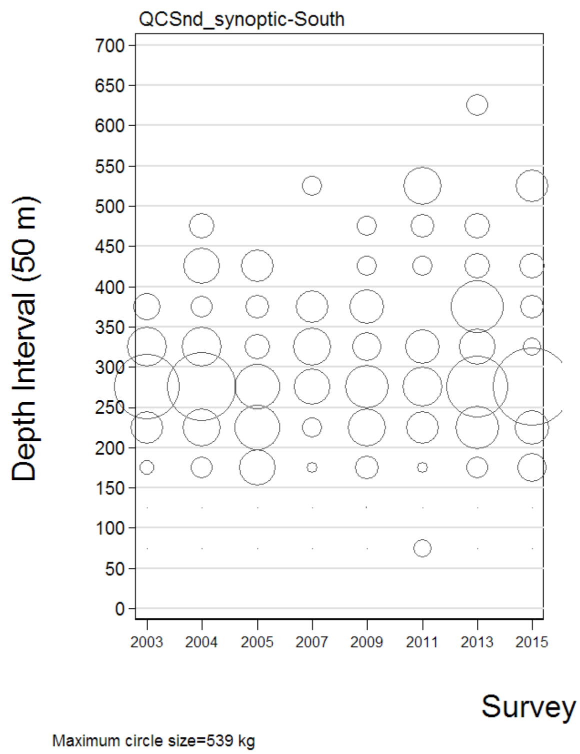

Figure B.28. Distribution of observed catch weights of Shortspine Thornyhead for the two main Queen Charlotte Sound synoptic survey areal strata (Table B.8) by survey year and 50 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (539 kg) in the 250–300 m interval in the 2015 southern stratum. The 1% and 99% quantiles for the SST empirical start of tow depth distribution= 153 m and 481 m respectively.

Estimated SST doorspread biomass from this trawl survey showed no overall trend from 2003 to 2015, with high estimates at both the beginning and the end of the survey series (Table B.10;

Figure B.29). The estimated relative errors were low for this species, lying between 8 and 16% (Table B.10). Between 26 and 34% of the South stratum tows and 41 to 56% of the North stratum tows captured some SST (Figure B.30). Overall, 721 of the 1909 valid survey tows (38%) contained SST, with the North stratum having a 46% average proportion non-zero tows while the equivalent South stratum proportion was 31%. Although this species occurs frequently in this survey, catch weights tend to be low, with the median catch weight for positive tows around 10 kg/tow across all 8 surveys and the maximum catch weight at 151 kg in the 2004 survey.

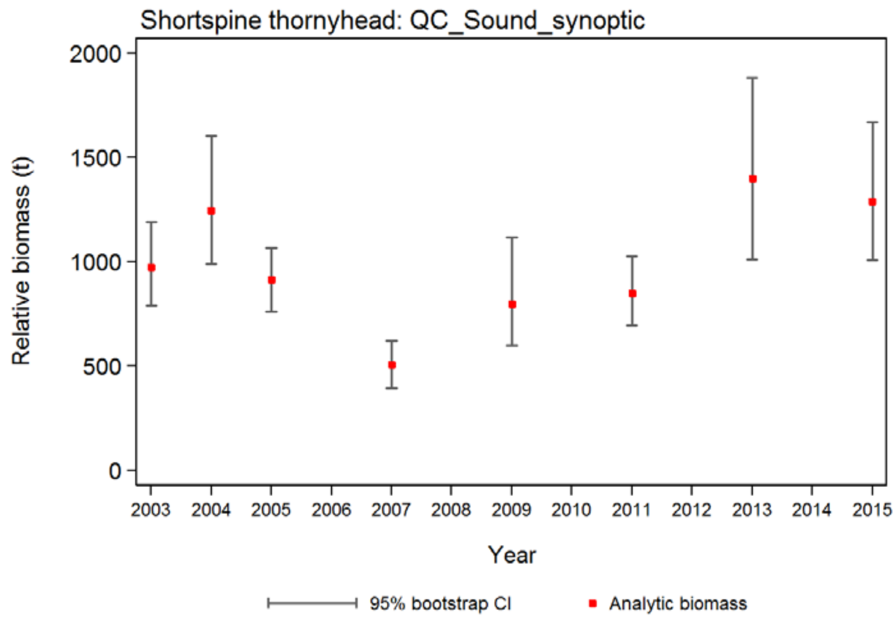

Figure B.29. Plot of biomass estimates for SST (values provided in Table B.10) from the Queen Charlotte Sound synoptic survey over the period 2003 to 2015. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

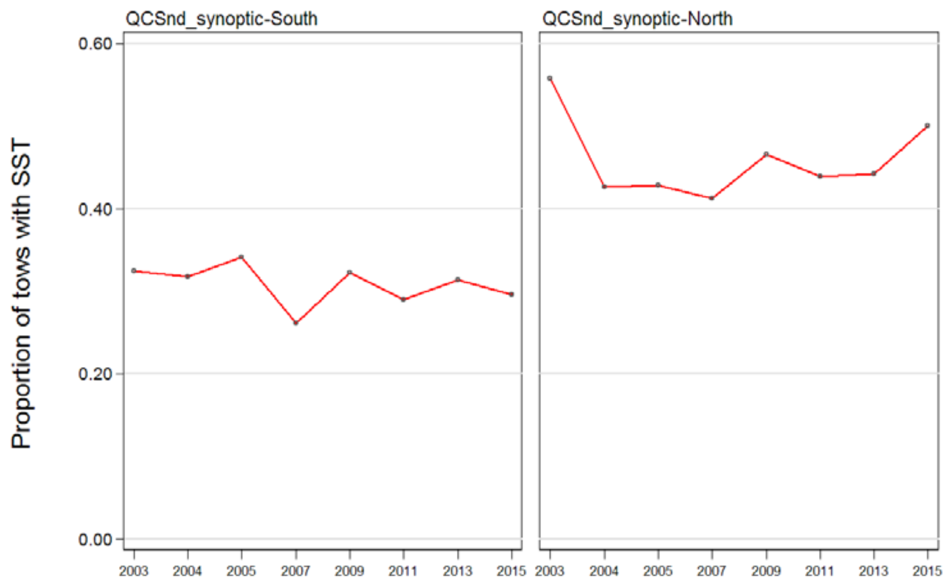

Figure B.30. Proportion of tows by stratum and year which contain SST from the Queen Charlotte Sound synoptic survey over the period 2003 to 2015.

B.6. WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY

B.6.1. Data selection

This survey has been conducted six times in the period 2004 to 2014 off the west coast of Vancouver Island by RV W.E. Ricker. It comprises a single areal stratum, separated into four depth strata: 50-125 m; 125-200 m; 200-330 m; and 330-500 m (Table B.11). Approximately 150 to 180 2-km^2 blocks are selected randomly among the four depth strata when conducting each survey (Olsen et. al. 2008).

Table B.11. Stratum designations, number of usable and unusable tows, for each year of the west coast Vancouver Island synoptic survey. Also shown is the area of each stratum and the start and end dates for each survey.

Survey	Stratum depth zone				Total	Unusable	Start	End
year	50-125 m	125-200 m	200-330 m	330-500 m	Tows[1]	tows	date	date
2004	35	34	13	8	89	16	26-May-04	09-Jun-04
2006	62	63	28	13	164	10	24-May-06	18-Jun-06
2008	54	51	34	24	159	15	27-May-08	21-Jun-08
2010	58	47	22	10	136	7	08-Jun-10	28-Jun-10
2012	61	46	26	20	153	4	23-May-12	15-Jun-12
2014	55	49	29	14	147	6	29-May-14	20-Jun-14
Area (km^2)	5,872	3,844	720	624	11,060[2]	–	–	–

[1] GFBio usability codes=0,1,2,6
[2] Total area (km^2) for 2014 synoptic survey

A “doorspread density” value was generated for each tow based on the catch of Shortspine Thornyhead, the mean doorspread for the tow and the distance travelled (Eq. B.3). The distance travelled was provided as a data field, determined directly from vessel track information collected during the tow. There were only two missing values in this field which were filled in by multiplying the vessel speed by the time that the net was towed. There were a large number of missing values for the doorspread field, which were filled in using the mean doorspread for the survey year or a default value of 64.4 m for the three years with no doorspread data (Table B.12). The default value is based on the mean of the observed doorspread from the net mensuration equipment.

Table B.12. Number of tows with and without doorspread measurements by survey year for the WCVI synoptic survey. Mean doorspread values for those tows with measurements are provided.

	Number tows		Mean
	Without doorspread	With doorspread	doorspread (m)
2004	89	–	–
2006	96	69	64.3
2008	58	107	64.5
2010	136	–	–
2012	153	–	–
2014	14	139	64.3
All surveys	546	315	64.4

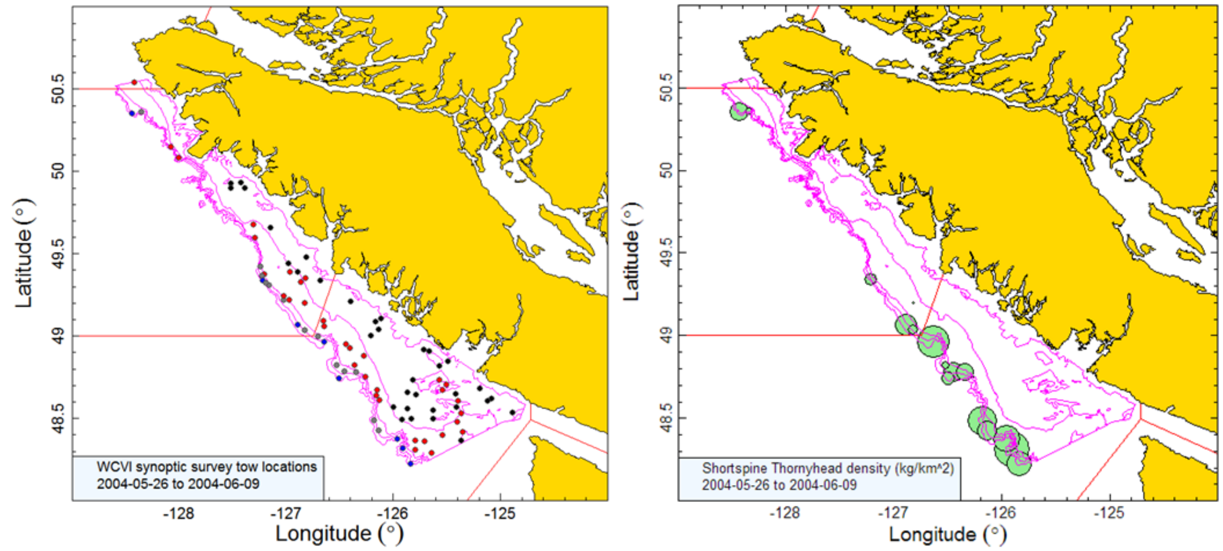

Figure B.31. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2004 west coast Vancouver Island synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2004, 2006, 2008, 2010, 2012, 2014), with the largest circle = 1362 kg/km^2 in 2006. The red solid lines indicate the boundaries for PMFC areas 3C, 3D and 5A.

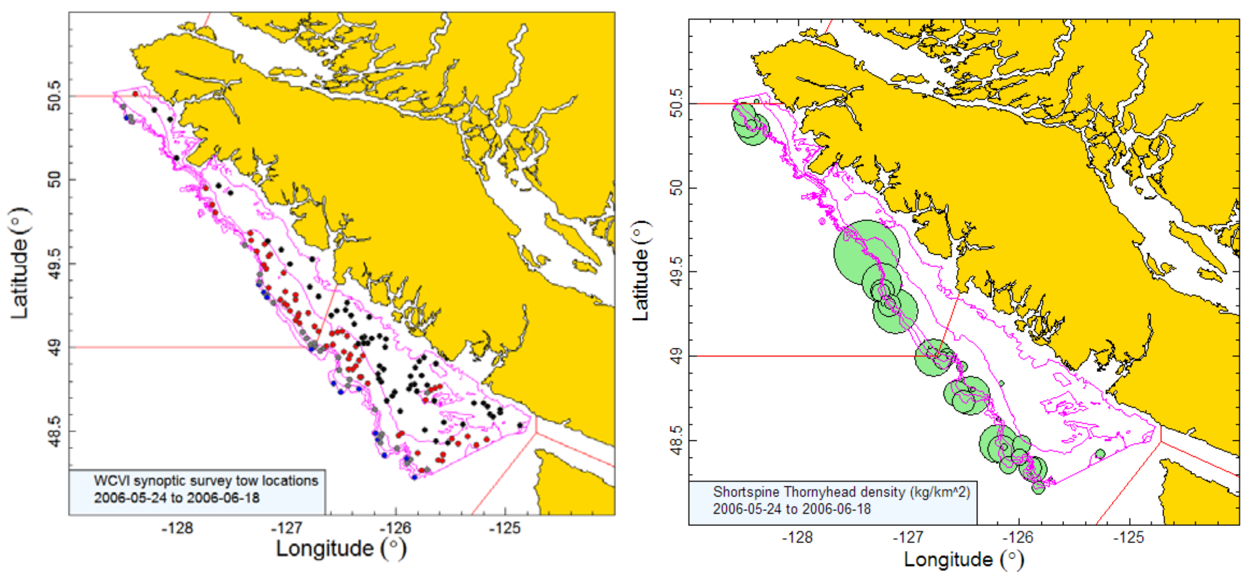

Figure B.32. Tow locations and density plots for the 2006 west coast Vancouver Island synoptic survey (see Figure B.31 caption).

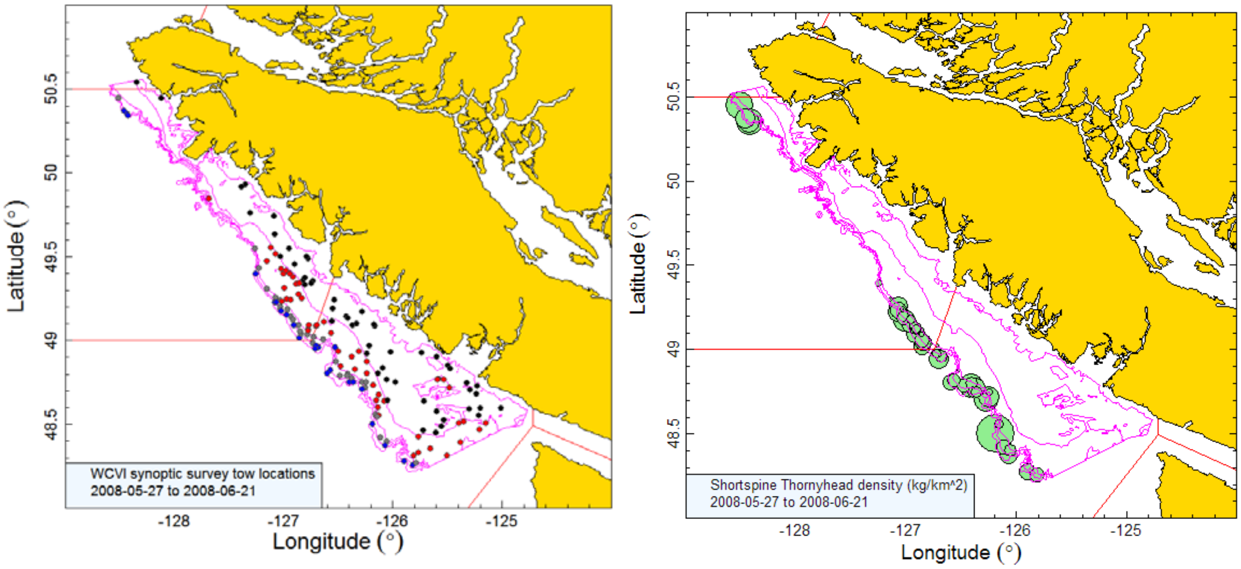

Figure B.33. Tow locations and density plots for the 2008 west coast Vancouver Island synoptic survey (see Figure B.31 caption).

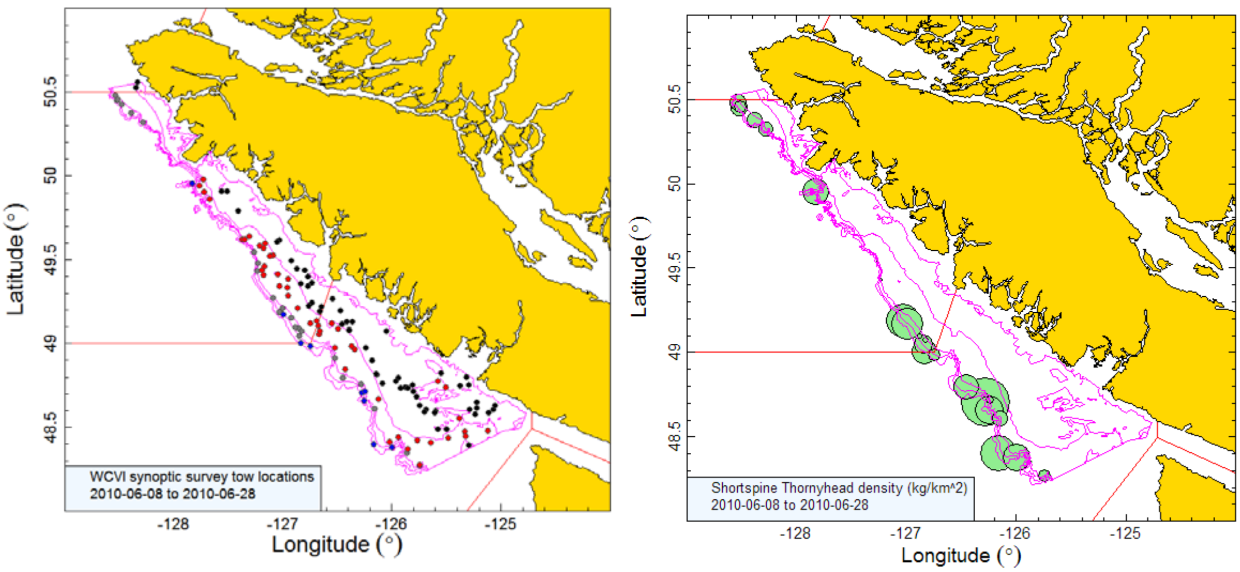

Figure B.34. Tow locations and density plots for the 2010 west coast Vancouver Island synoptic survey (see Figure B.31 caption).

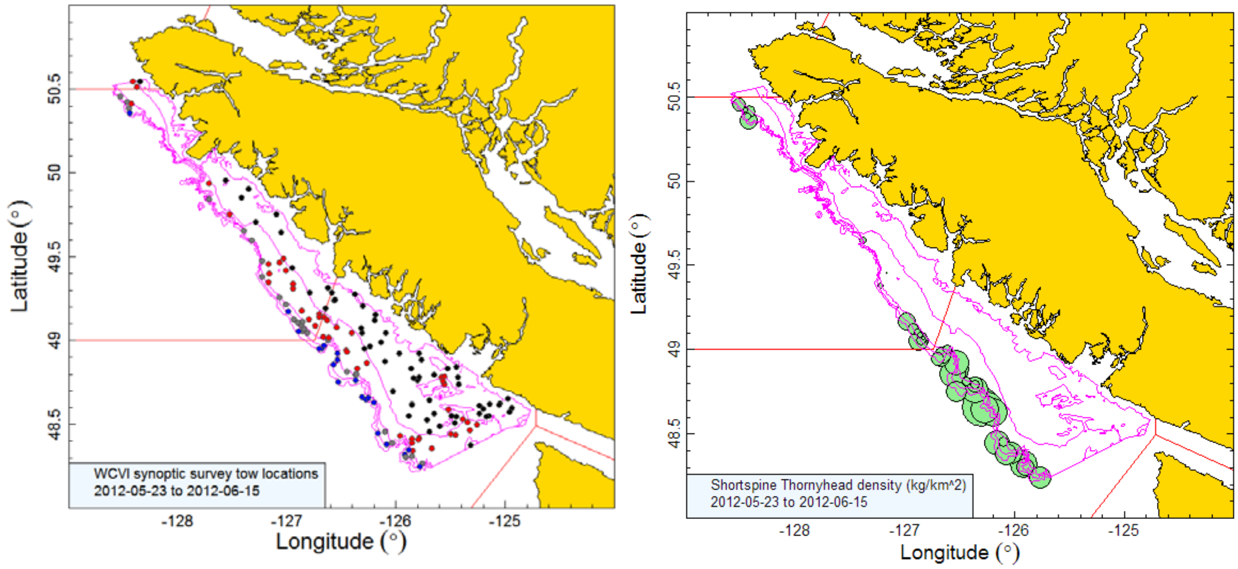

Figure B.35. Tow locations and density plots for the 2012 west coast Vancouver Island synoptic survey (see Figure B.31 caption).

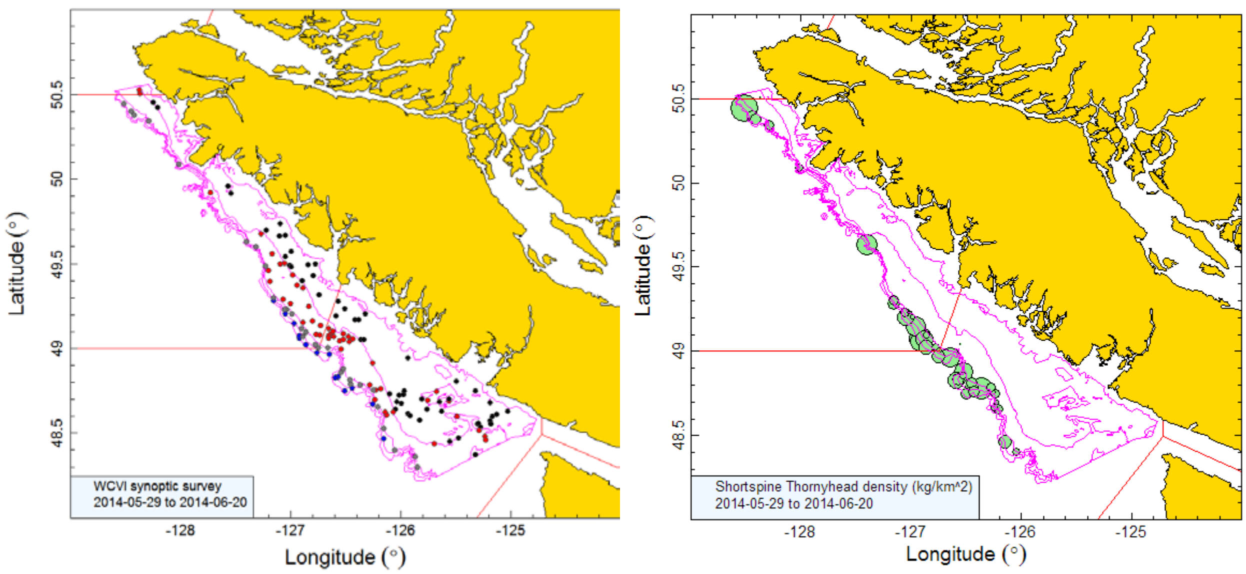

Figure B.36. Tow locations and density plots for the 2014 west coast Vancouver Island synoptic survey (see Figure B.31 caption).

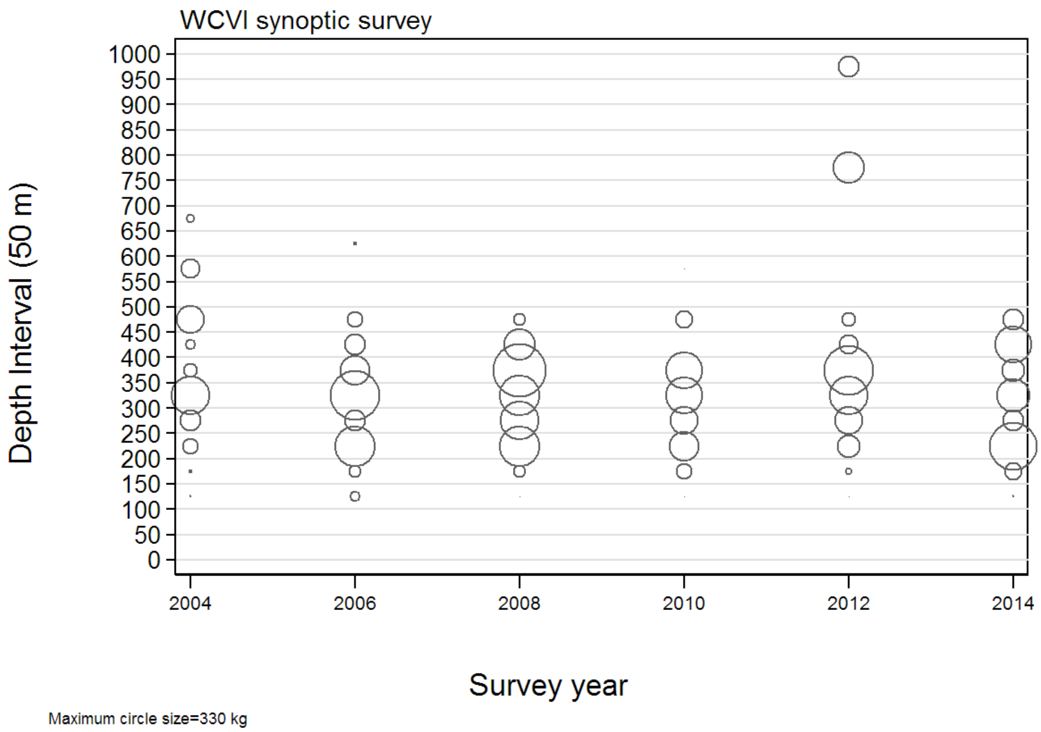

Figure B.37. Distribution of observed weights of Shortspine Thornyhead by survey year and 50 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (330 kg) in the 350-400 m interval in 2008. The 1% and 99% quantiles for the SST empirical start of tow depth distribution= 143 m and 764 m respectively.

B.6.2. Results

Shortspine Thornyhead are found at the shelf drop-off along the entire west coast of Vancouver Island, although abundance seems to be greater in the lower part of Vancouver Island's west coast (Figure B.31 to Figure B.36). Shortspine Thornyhead were mainly taken at depths from 165 to 461 m (5–95% quantiles), but there were many observations at depths greater than 500 m (it may be that the very deep observations at 764 and 988 m are errors; Figure B.37). Estimated biomass levels for Shortspine Thornyhead from this trawl survey show no overall trend, with low relative errors which range from 12 to 21% across the six surveys (Figure B.38; Table B.13).

The proportion of tows capturing Shortspine Thornyhead ranged between 21 and 32% for the six surveys, with a mean value of 26% (Figure B.39). About one quarter of the tows from this survey contain SST, but as in the QC Sound synoptic survey, the median catch weight for positive tows was relatively low (around 13 kg/tow) and the maximum catch weight across all six surveys was 100 kg (in 2006).

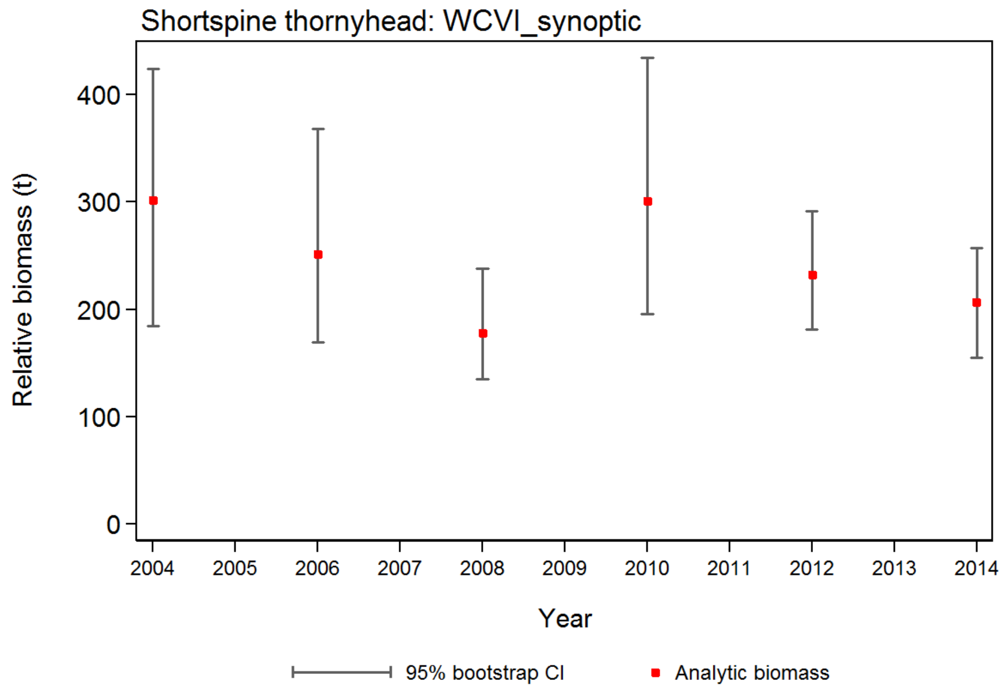

Figure B.38. Plot of biomass estimates for Shortspine Thornyhead from the 2004 to 2014 west coast Vancouver Island synoptic trawl surveys (Table B.11). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

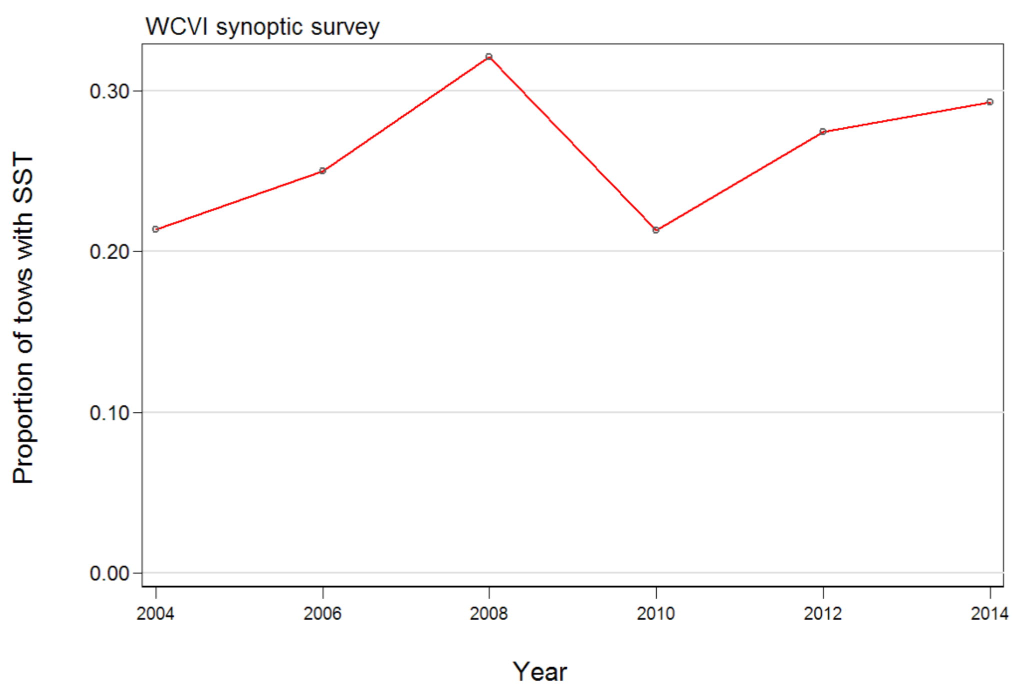

Figure B.39. Proportion of tows by stratum and year capturing Shortspine Thornyhead in the WCVI synoptic trawl surveys, 2004–2014.

Table B.13. Biomass estimates for Shortspine Thornyhead from the WCVI synoptic trawl survey for the survey years 2004 to 2014. Bootstrap bias-corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2004	301.8	303.3	184.7	423.5	0.201	0.198
2006	251.2	246.7	169.8	368.1	0.198	0.193
2008	177.9	176.6	135.4	237.8	0.140	0.140
2010	300.5	297.3	196.1	433.8	0.207	0.211
2012	232.2	231.7	181.1	291.4	0.119	0.119
2014	207.0	207.6	154.8	257.4	0.128	0.128

The six WCVI synoptic survey indices spanning the period 2004 to 2014 were used as a abundance index series for use in the stock assessment model (described in Appendix E).

B.7. WEST COAST HAIDA GWAII SYNOPTIC TRAWL SURVEY

B.7.1. Data selection

The west coast Haida Gwaii (WCHG) survey has been conducted five times in the period 2006 to 2012 off the west coast of Haida Gwaii. A sixth survey conducted in 2014 did not complete a sufficient number of tows for it to be considered completed. The survey comprises a single areal stratum extending from 53°N to the BC-Alaska border and east to 133°W (e.g., Olsen et al. 2008). The 2006 survey used a different depth stratification scheme compared to the later synoptic surveys: 150–200 m, 200–330 m, 330–500 m, 500–800 m, and 800–1300 m (Workman et al. 2007). All tows from this survey were re-stratified into the four depth strata used from 2007 onwards: 180–330 m; 330–500 m; 500–800 m; and 800–1300 m, based on the mean of the beginning and end depths of each tow (Table B.14). Plots of the locations of all valid tows by year and stratum are presented in Figure B.40 (2006), Figure B.41 (2007), Figure B.42 (2008), Figure B.43 (2010) and Figure B.44 (2012). Note that the depth stratum boundaries for this survey differ from those used for the Queen Charlotte Sound (Edwards et al. 2012) and west coast Vancouver Island (Edwards et al. 2014) synoptic surveys due to the considerable difference in the seabed topography of the area being surveyed. The deepest stratum (800–1300 m) was omitted from this analysis because of lack of coverage in 2007.

Table B.14. Stratum designations, vessel name, number of usable and unusable tows, for each year of the west coast Haida Gwaii synoptic. Also shown are the area of each stratum and the dates of the first and last survey tow in each year.

		Depth stratum							
Survey year	Vessel	180-330m	330-500m	500-800m	800-1300m	Total tows[1]	Unusable tows	Minimum date	Maximum date
2006	Viking Storm	54	27	18	11	110	13	30-Aug-06	22-Sep-06
2007	Nemesis	68	34	9	–	111	5	14-Sep-07	12-Oct-07
2008	Frosti	71	31	8	8	118	9	28-Aug-08	18-Sep-08
2010	Viking Storm	82	29	12	5	128	3	28-Aug-10	16-Sep-10
2012	Nordic Pearl	75	29	10	15	129	12	27-Aug-12	16-Sep-12
Area (km^2)		1104	1028	956	2248	5336[3]	–	–	–

[1] GFBio usability codes=0,1,2,6; [2] excludes 2 tows S of 53°N; [3] Total area (km^2)

A "doorspread density" value (Eq. B.4) was generated for each tow based on the catch of Shortspine Thornyhead, the mean doorspread for the tow and the distance travelled for both the WCHG. The distance travelled was determined directly by measuring the tow path for all six surveys. There were no missing values in the distance travelled field for these six surveys, but there were some missing doorspread values in valid tows from the five synoptic surveys, which had mean doorspread values that ranged from 69 m to 81 m (Table B.15). Missing doorspread values were replaced with the mean doorspread for the survey year.

Table B.15. Number of valid tows with doorspread measurements, the mean doorspread values (in m) from these tows for each survey year and the number of valid tows without doorspread measurements.

Year	Tows with doorspread	Tows missing doorspread	Mean doorspread (m)
2006	93	30	77.7
2007	113	3	68.5
2008	123	4	80.7
2010	129	2	79.1
2012	92	49	73.8
Total/Average	550	88	76.6[1]

[1] average 2006–2010: all observations

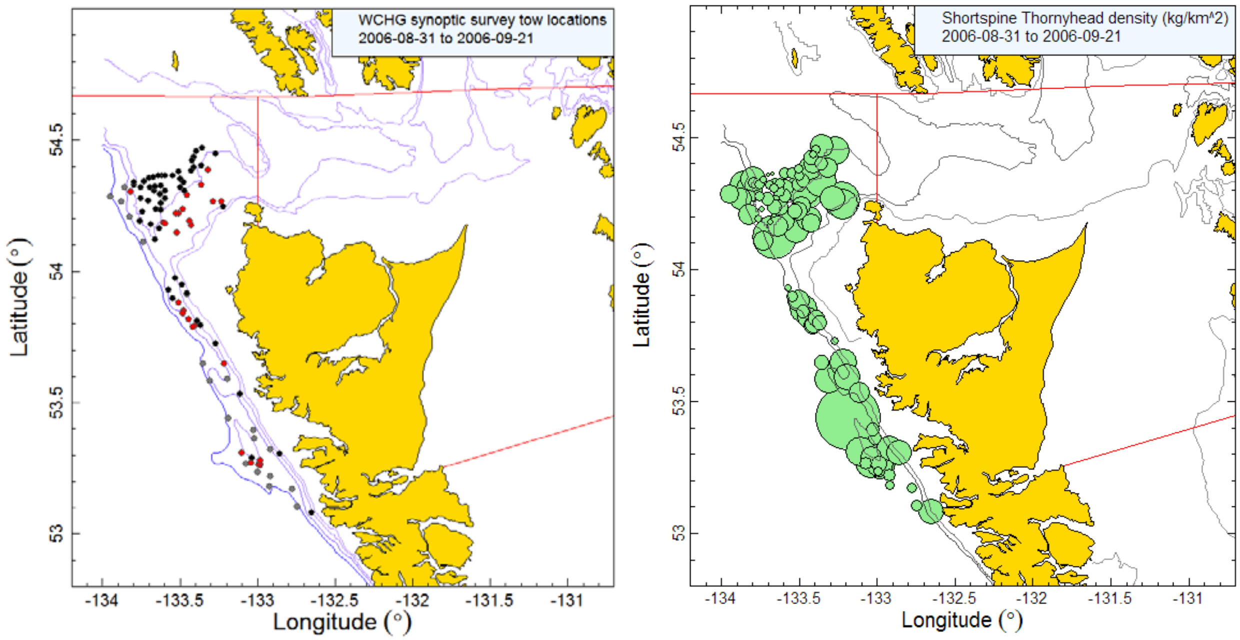

Figure B.40. Valid tow locations (180-330m stratum: black; 330-500m stratum: red; 500-800m stratum: grey) and density plots for the 2006 Viking Storm synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2006–2012), with the largest circle =2628 kg/km^2 in 2006. The red lines show the Pacific Marine Fisheries Commission 5E and 5D major area boundaries.

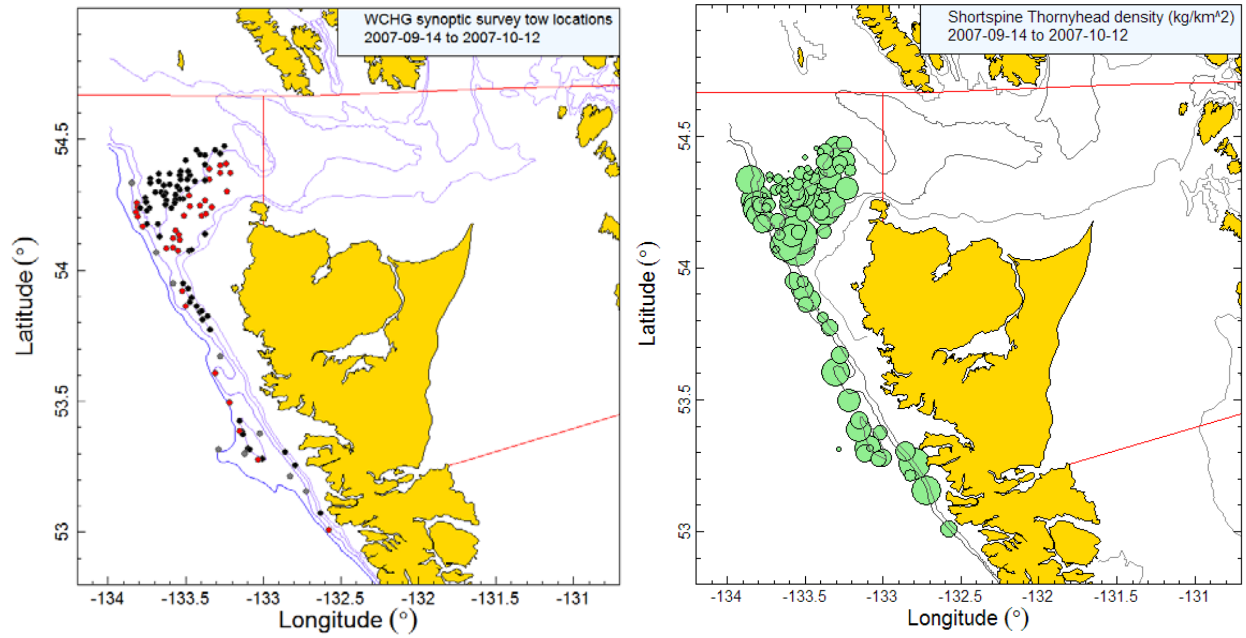

Figure B.41. Tow locations and density plots for the 2007 Nemesis synoptic survey (see Figure B.40 caption).

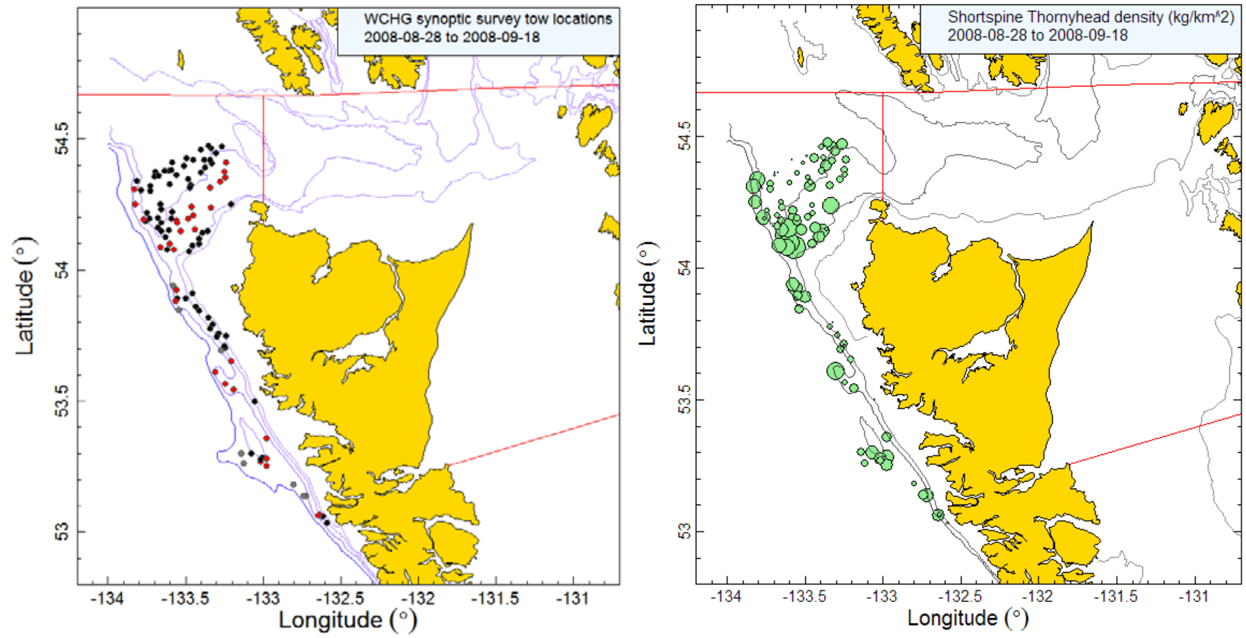

Figure B.42. Tow locations and density plots for the 2008 Frosti synoptic survey (see Figure B.40 caption).

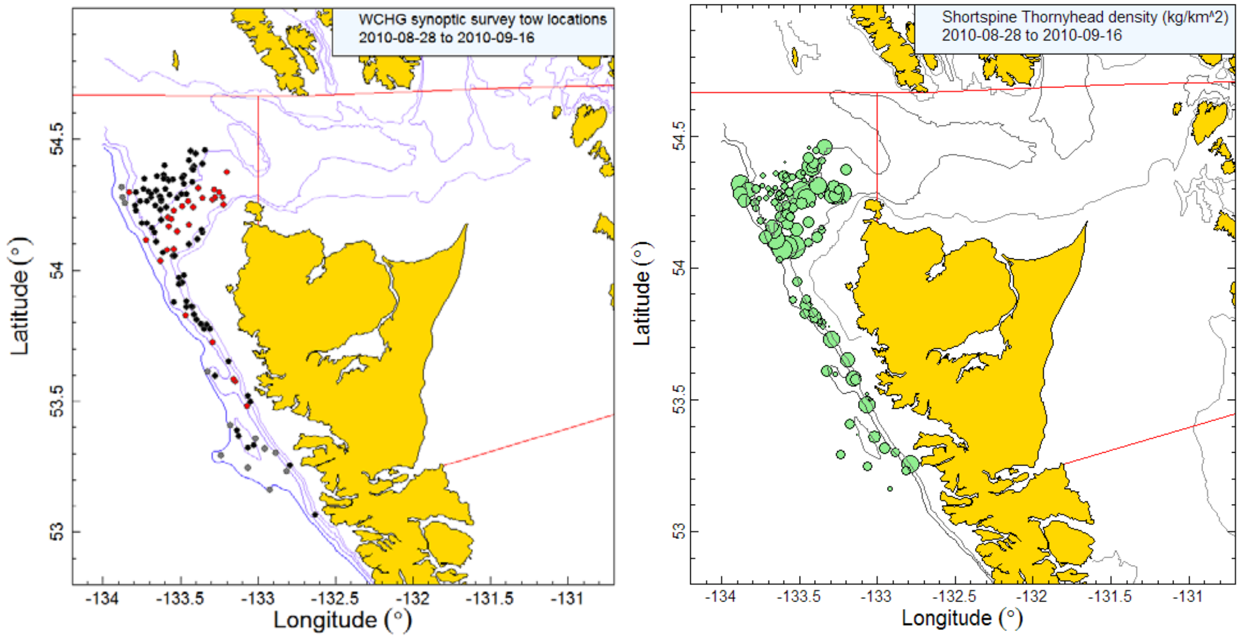

Figure B.43. Tow locations and density plots for the 2010 Viking Storm synoptic survey (see Figure B.40 caption).

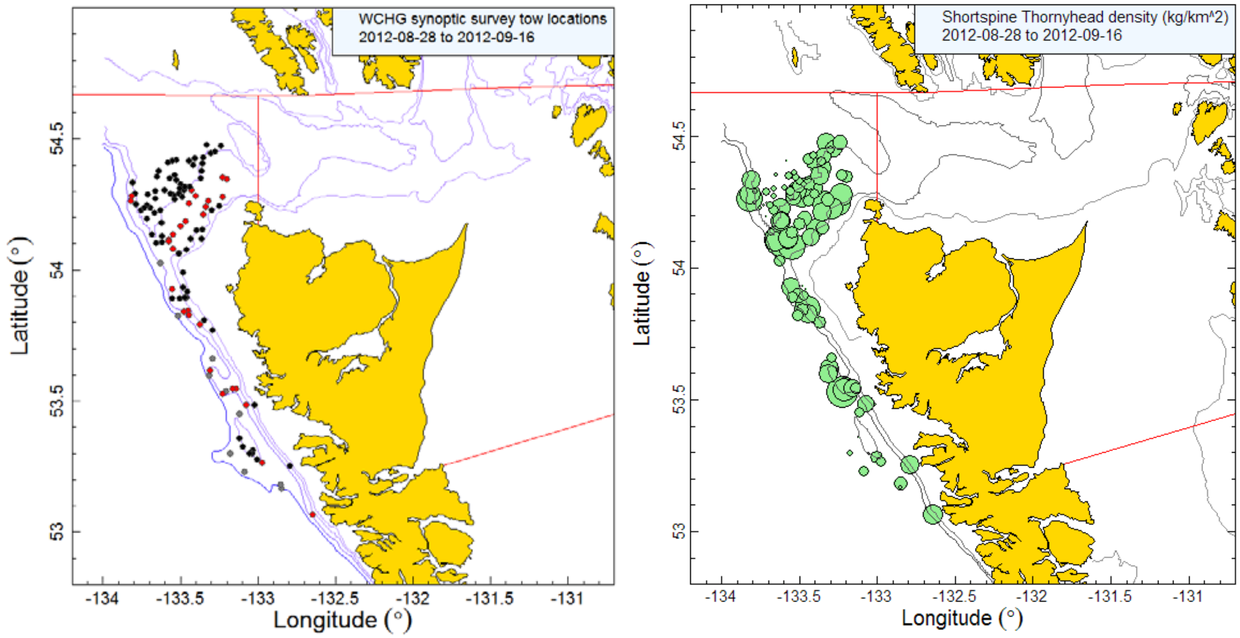

Figure B.44. Tow locations and density plots for the 2012 Viking Storm synoptic survey (see Figure B.40 caption).

B.7.2. Results

Catch densities of Shortspine Thornyhead from this survey series were distributed ubiquitously along the northwest shelf and into the western part of Dixon Entrance [Figure B.40 (2006), Figure B.41 (2007), Figure B.42 (2008), Figure B.43 (2010), Figure B.44 (2012)]. Shortspine Thornyhead were mainly taken at depths from 226 to 646 m (5 to 95% quantiles), with the majority of the observations lying between 200 and 500 m depth (Figure B.45).

Table B.16. Biomass estimates for Shortspine Thornyhead from the five west coast Haida Gwaii synoptic surveys. Bootstrap bias-corrected confidence intervals and coefficients of variation (CVs) are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2006	942.9	945.8	736.9	1329.0	0.154	0.151
2007	1254.0	1251.1	1005.3	1532.3	0.105	0.106
2008	938.6	937.1	780.8	1145.0	0.098	0.103
2010	765.3	764.0	655.3	912.5	0.084	0.085
2012	880.2	879.5	719.9	1060.0	0.098	0.098

Estimated biomass levels for Shortspine Thornyhead from these trawl surveys were consistent (ranging from 765 t in 2010 to 1254 t in 2007) with no trend over the five survey years (Figure B.46; Table B.16). The estimated relative errors for these surveys were low, ranging from 8 to 15% (Table B.16).

The proportion of tows that captured Shortspine Thornyhead ranged from 88 to 95% of the valid tows over the five synoptic survey years, with an overall mean of 91% (Figure B.47). SST occurred frequently in this survey (much more frequently than in the other synoptic surveys) and the median catch weight for positive tows was, at 30 kg/tow, greater than in any of the other synoptic surveys for this species. The maximum catch weight across all six surveys was 254 kg (in 2008).

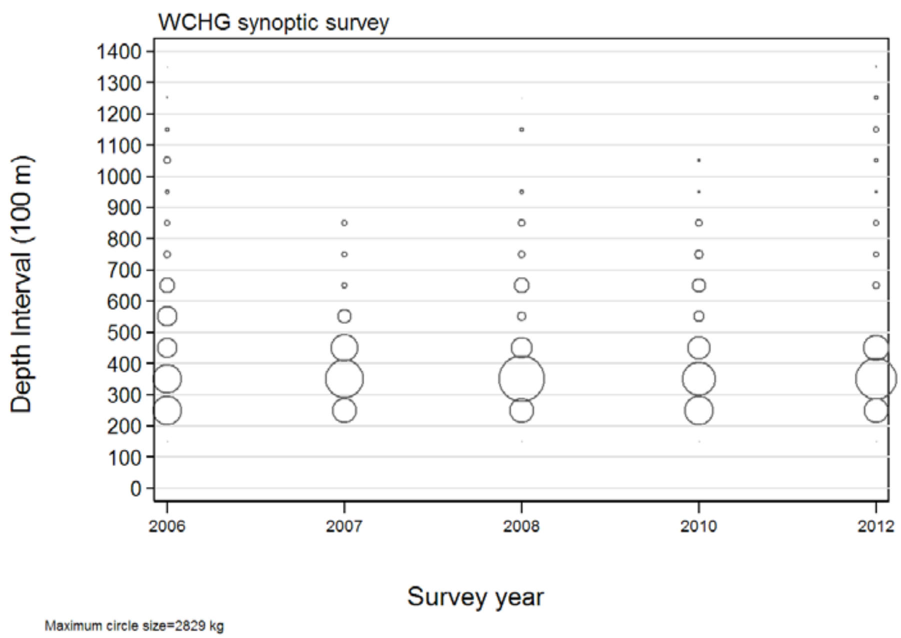

Figure B.45. Distribution of observed weights of Shortspine Thornyhead by survey year and 100 m depth zone intervals. Catches are plotted at the mid-point of the interval and circles in the each panel are scaled to the maximum value (2829 kg – 300-400 m interval in 2008). Minimum and maximum depths observed for SST: 193 m and 1329 m, respectively. Depth is taken at the start position for each tow.

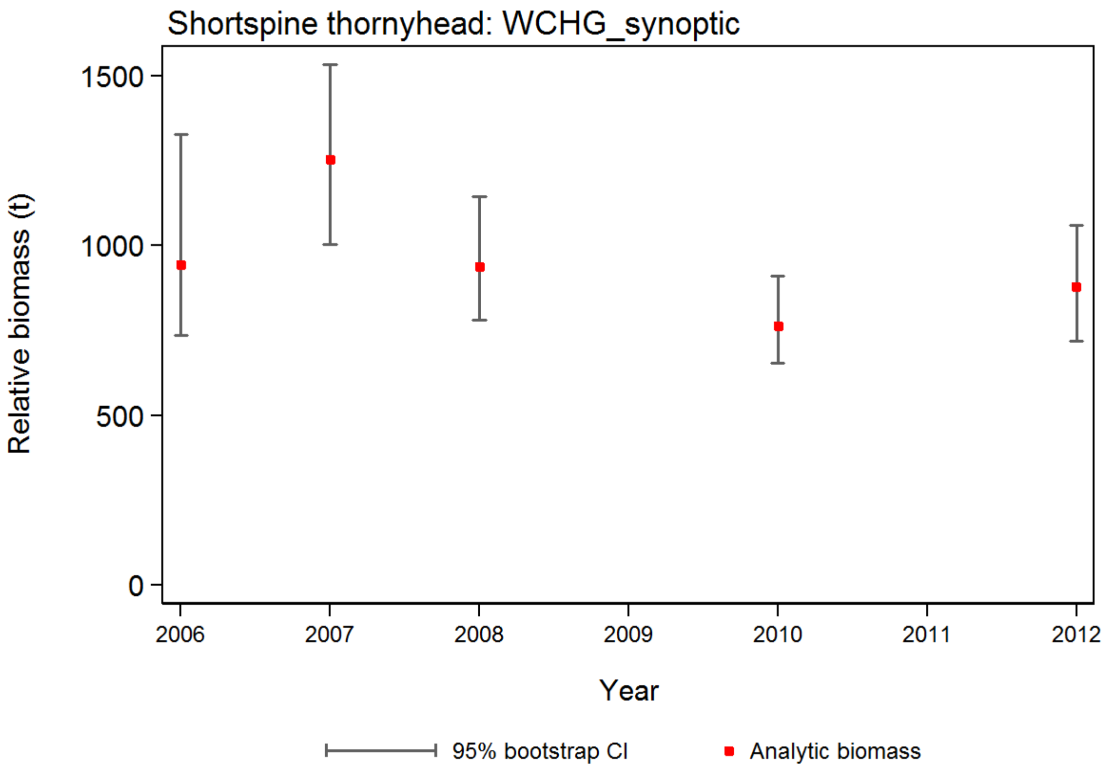

Figure B.46. Biomass estimates for Shortspine Thornyhead from the five west coast Haida Gwaii synoptic surveys (Table B.16). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

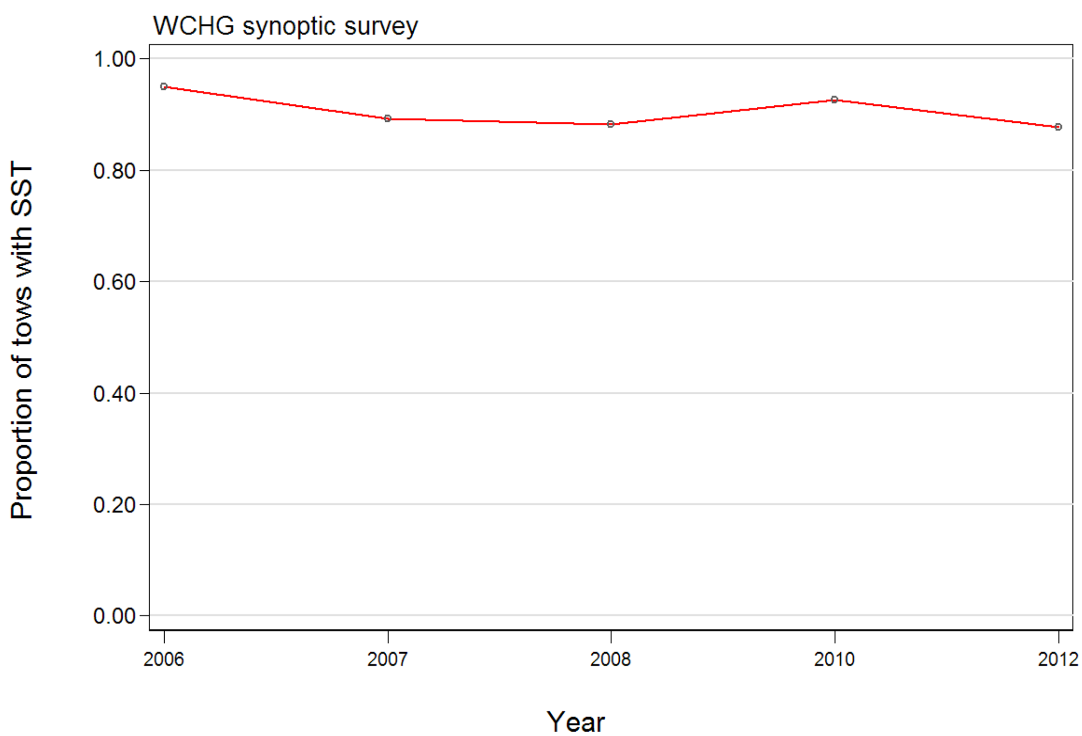

Figure B.47. Proportion of tows by year that contain Shortspine Thornyhead for the five west coast Haida Gwaii synoptic surveys.

B.8. REFERENCES – SURVEYS

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APPENDIX C. STANDARDISATION OF COMMERCIAL TRAWL CPUE

C.1. INTRODUCTION

Commercial catch and effort data have been used to generate indices of abundance in several ways. The simplest indices are derived from the arithmetic mean or geometric mean of catch divided by an appropriate measure of effort (Catch Per Unit Effort or CPUE) but such indices make no adjustments for changes in fishing practices or other non-abundance factors which may affect catch rates. Consequently, methods to standardise for changes to vessel configuration, the timing or location of catch and other possible effects have been developed to remove potential biases to CPUE that may result from such changes. In these models, abundance is represented as a “year effect” and the dependent variable is either an explicitly calculated CPUE represented as catch divided by effort, or an implicit CPUE represented as catch per tow or catch per record. In the latter case, additional effort terms can be offered as explanatory variables, allowing the model to select the effort term with the greatest explanatory power. It is always preferable to standardise for as many factors as possible when using CPUE as a proxy for abundance. Unfortunately, it is often not possible to adjust for factors that might affect the behaviour of fishers, particularly economic factors, resulting in indices that may not entirely reflect the underlying stock abundance.

C.2. METHODS

C.2.1. Arithmetic and Unstandardised CPUE

Arithmetic CPUE ($\widehat{A_y}$) in year *y* was calculated as the total catch for the year divided by the total effort in the year using Eq. C.1:

Eq. C.1
$$\widehat{A_y} = \frac{\sum_{i=1}^{n_y} C_{i,y}}{\sum_{i=1}^{n_y} E_{i,y}}$$

where $C_{i,y}$ is the [catch], $E_{i,y} = T_{i,y}$ ([*tows*]) or $E_{i,y} = H_{i,y}$ ([*hours_fished*]) for record i in year y, and n_y is the number of records in year y.

Unstandardised (geometric) CPUE assumes a log-normal error distribution. An unstandardised index of CPUE ($\widehat{G_y}$)) in year y was calculated as the geometric mean of the ratio of catch to effort for each record i in year y, using Eq. C.2:

Eq. C.2
$$\widehat{G_y} = \exp\left[\sum_{i=1}^{n_y} \ln\left(\frac{C_{i,y}}{E_{i,y}}\right) \Big/ n_y\right]$$

C.2.2. Standardised CPUE

These models are preferred over the unstandardised models described above because they can account for changes in fishing behaviour and other factors which may affect the estimated abundance trend, as long as the models are provided with adequate data. In the models described below, catch per record is used as the dependent variable and the associated effort is treated as an explanatory variable.

C.2.3. Lognormal Model

Standardised CPUE assumes a lognormal error distribution, with explanatory variables to used represent changes in the fishery. A standardised CPUE index (Eq. C.3) is calculated from a generalised linear model (GLM) (Quinn and Deriso 1999) using a range of explanatory variables including [*year*], [*month*], [*depth*], [*vessel*] and other available factors:

Eq. C.3 $$\ln\left(I_i\right) = B + Y_{y_i} + \alpha_{a_i} + \beta_{b_i} + \ldots + f\left(\chi_i\right) + f\left(\delta_i\right) + \ldots + \varepsilon_i$$

where I_i = C_i or catch;

B = the intercept;

Y_{y_i} = year coefficient for the year corresponding to record i;

α_{a_i} and β_{b_i} = coefficients for factorial variables a and b corresponding to record i;

$f\left(\chi_i\right)$ and $f\left(\delta_i\right)$ are polynomial functions (to the 3rd order) of the continuous variables χ_i and δ_i corresponding to record i;

ε_i = an error term.

The actual number of factorial and continuous explanatory variables in each model depends on the model selection criteria. Because each record represents a single tow, C_i has an implicit associated effort of one tow. Hours fished for the tow is represented on the right-hand side of the equation, usually as a continuous (polynomial) variable.

Note that calculating standardised CPUE with Eq. C.3 without additional explanatory variables is equivalent to using Eq. C.2, provided the same definition for $E_{i,y}$ is used.

Canonical coefficients and standard errors were calculated for each categorical variable (Francis 1999). Standardised analyses typically set one of the coefficients to 1.0 without an error term and estimate the remaining coefficients and the associated error relative to the fixed coefficient. This is required because of parameter confounding. The Francis (1999) procedure rescales all coefficients so that the geometric mean of the coefficients is equal to 1.0 and calculates a standard error for each coefficient, including the fixed coefficient.

Coefficient-distribution-influence plots (CDI plots) are visual tools to facilitate understanding of patterns which may exist in the combination of coefficient values, distributional changes, and annual influence (Bentley et al. 2011). CDI plots were used to illustrate each explanatory variable added to the model.

C.2.4. Binomial Logit Model

The procedure described by Eq. C.3 is necessarily confined to the positive catch observations in the data set because the logarithm of zero is undefined. Observations with zero catch were modelled by fitting a logit regression model based on a binomial distribution and using the presence/absence of Shortspine Thornyhead as the dependent variable (where 1 is substituted for $\ln(I_i)$ in Eq. C.3 if it is a successful catch record and 0 if it is not successful) and using the same data set. Explanatory factors are estimated in the model in the same manner as described in Eq. C.3. Such a model provides an alternative series of standardised coefficients of relative annual changes that is analogous to the series estimated from the lognormal regression.

C.2.5. Combined Model

A combined model, integrating the two sets of relative annual changes estimated by the lognormal and binomial models, can be estimated using the delta distribution, which allows zero and positive observations (Vignaux 1994). Such a model provides a single index of abundance which integrates the signals from the positive (lognormal) and binomial series. This approach uses the following equation to calculate an index based on the two contributing indices:

Eq. C.4 $$^{C}Y_y = \frac{^{L}Y_y}{\left(1 - P_0\left[1 - \frac{1}{^{B}Y_y}\right]\right)}$$

where $^{C}Y_y$ = combined index for year *y,* $^{L}Y_y$ = lognormal index for year *y,* $^{B}Y_y$ = binomial index for year *y*, and P_0 = proportion zero for base year 0.

Francis (2001) suggests that a bootstrap procedure is the appropriate way to estimate the variability of the combined index. Therefore, confidence bounds for the combined model were estimated using a bootstrap procedure based on 500 replicates, drawn with replacement.

C.3. PRELIMINARY INSPECTION OF THE DATA

The analysis reported in this Appendix is based on tow-by-tow total catch (landings + discards) data collected over the period 1996–2014 for which detailed positional data for every tow are available and there is an estimate of discarded catch for the tow because of the presence of an observer on board the vessel. These data are held in the DFO PacHarvestTrawl (PacHarv) and GFFOS databases (Fisheries and Oceans Canada, Pacific Region, Groundfish Data Unit);

Tow-by-tow catch and effort data for Shortspine Thornyhead from the BC bottom trawl fishery operating from Juan de Fuca Strait to the Dixon Entrance from 1996 to 2014 were selected using the following criteria:

- Tow start date between 1 January 1996 and 31 December 2014
- Bottom trawl type (includes soft and hard bottom trawl types after 2006) (includes 'unknown' gear)
- Fished in PMFC regions: 3C, 3D, 5A, 5B, 5C, 5D or 5E
- Fishing success code <=1 (code 0= unknown; code 1= useable)
- Catch of at least one fish or invertebrate species (no water hauls or inanimate object tows)
- Valid depth field
- Valid latitude and longitude co-ordinates

- Valid estimate of time towed that was greater than 0 hours and less than or equal to 24 hours

Each record represents a single tow, which results in equivalency between the number of records and number of tows. Catch per record can therefore be used to represent CPUE, because each record (tow) has an implicit effort component. The empirical 1 and 99% quantiles of the distribution of successful catch records data ranged from 133 m to 1033 m, with sporadic observations at deeper depths (Figure C.1). It is possible that the deeper recorded depths are in error or document tows that passed through a wide range of depths. Valid tows were binned by depth in 50 m increments, between 125 and 1075 m.

There were a total of113 trawl vessels in the 3CD+5A-E data set which recorded a catch of Shortspine Thornyhead at least once in the 19 year period. Vessel qualification criteria based on number of trips per year and number of years fishing were developed to avoid including vessels which only occasionally fished in 3CD+5A-E or which did not fish Shortspine Thornyhead (Figure C.2). Qualified vessels were those which had fished at least five trips for a minimum of five years. Once a vessel was selected, all data for the qualifying vessel were included, regardless of the number of trips in a year.

The analysis was based on a core fleet of 50 qualified vessels, responsible for 88% of the total catch in the data set. The vessel overlap across years was good, with a number of vessels operating across in most of the available 19 years of data (Figure C.3). Only tows which were less than 24 hours long were used in the analysis. This criterion dropped very little data because only 6 of the qualifying tows were greater than 24 hours in length. The final data set is large, with over 70,000 successful tows and nearly 10,000 t of Shortspine Thornyhead catch (Table C.1). Mean catch rates for successful tows in the data set are 141 kg/tow and 41 kg/h.

The following explanatory variables were offered to the model, based on the tow-by-tow information in each record:

Variable	**Number of Categories**
Year (1 January–31 December)	19 categories
Hours fished	continuous: 3rd order polynomial
Month	12 categories
DFO locality (Rutherford 1995)	50 categories plus a final aggregated category
Latitude separated in 0.1° bands beginning with 48°N	50 categories plus a final aggregated category
Vessel	50 categories
Depth aggregated into 40 m depth bands	19 categories
DFO Major region (5C or 5D)	7 categories

C.4. RESULTS

C.4.1. Lognormal Positive Model

A standardised lognormal General Linear Model (GLM) analysis was performed on positive catch records from a tow-by-tow data set generated as described in Section C.3. Eight explanatory variables (described in Section C.3 above) were offered to the model and *ln(catch)* was used as the dependent variable, where catch is the total by weight of landed plus discarded Shortspine Thornyhead in each record (tow) (Eq. C.3). The resulting CPUE index series is presented in Table C.2 and Figure C.4.

The `[Year]` categorical variable was forced as the first variable in the model without regard to its effect on the model deviance. The remainder of the variables were offered sequentially, with a stepwise acceptance of the remaining variables with the best AIC. This process was continued until the improvement in the model R^2 was less than 1% (Table C.3). This model selected 4 of the 7 remaining explanatory variables, including `[DFO locality]`, `[Depth band]`, `[0.1° Latitude bands]`, `[Hours fished]`, and `[Vessel]` in addition to `[Year]`. The final lognormal model accounted for 56% of the total model deviance (Table C.3), with the year variable explaining less than 1% of the model deviance.

Model residuals appeared to be consistent with the underlying lognormal distributional assumption, with some deviation at the tails of the residual distribution (Figure C.5).

A stepwise plot of the year indices as each explanatory variable was introduced into the model shows relatively little impact from the standardisation procedure, except at the two peaks observed in 2005 and 2011 (Figure C.6).

CDI plots of the four explanatory variables introduced to the model in addition to `[Year]` show some overall trends (Figure C.7 to Figure C.10). For instance, the variable [depth] had the greatest explanatory power, with the CDI plot suggesting that tows catching SST have become shorter over time, which is consistent with the decline of the Longspine Thornyhead fishery as the cost of fuel increased and the Japanese markets diminished. Interestingly, neither the month of catch or the locality of capture added any explanatory power to the analysis.

The year indices show little contrast and no trend in this series over the 19 years of data (Figure C.6).

C.4.2. Binomial Logit Model

The same variables used in the lognormal model were offered sequentially to this model, beginning with the year categorical variable, until the improvement in the model R^2 was less than 1% (Table C.4). This model also produced a series with little or no overall trend, although there was a period of higher incidence of SST from the mid- to late 2000s (Figure C.11). CPUE from this series has since returned to somewhat higher levels (Figure C.11).

C.4.3. Combined Model

Figure 5 shows that the effect of adding the binomial series to the lognormal series to produce a combined series (Eq. C.4) is relatively small, most likely because the binomial series resembles the lognormal series with each series showing little contrast and no trend. This can be interpreted either as the fishery is having little effect on the abundance of this species in BC waters or that operators have no difficulty in maintaining consistent catch rates that are not affected by changes in abundance.

C.5. REFERENCES – CPUE

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Table C.1. Summary data for the Shortspine Thornyhead fishery in 3CD+5A-E by year for the core data set (after selection of core vessels and applying all data filters).

Year	Number vessels[1]	Number trips[1]	Number tows[1]	Number records[1]	Number records[2]	% zero records[2]	Total catch (t)[1]	Total hours[1]	CPUE (kg/h) (**Eq. C.1**)
1996	47	476	4,699	4,699	8,129	42.2	544.7	15,497	35.1
1997	45	471	4,042	4,042	8,082	50.0	424.4	13,438	31.6
1998	44	580	4,843	4,843	9,452	48.8	560.7	18,229	30.8
1999	44	630	5,191	5,191	9,701	46.5	781.9	22,091	35.4
2000	45	651	5,439	5,439	10,625	48.8	701.9	21,122	33.2
2001	46	602	4,869	4,869	9,837	50.5	548.9	18,850	29.1
2002	44	690	5,050	5,050	10,271	50.8	768.4	21,810	35.2
2003	43	660	4,186	4,186	9,162	54.3	567.0	15,746	36.0
2004	43	607	3,835	3,835	8,802	56.4	528.7	13,786	38.3
2005	44	596	3,041	3,041	8,469	64.1	299.4	8,588	34.9
2006	40	601	3,685	3,685	7,839	53.0	484.8	12,692	38.2
2007	38	467	2,924	2,924	6,873	57.5	438.0	10,239	42.8
2008	38	443	2,423	2,423	6,085	60.2	345.1	7,278	47.4
2009	39	473	2,794	2,794	6,536	57.3	468.1	9,025	51.9
2010	37	459	2,975	2,975	6,585	54.8	609.8	10,366	58.8
2011	35	417	2,515	2,515	5,760	56.3	400.2	8,127	49.3
2012	34	394	2,815	2,815	5,408	47.9	616.4	11,362	54.3
2013	31	387	2,646	2,646	5,249	49.6	444.6	9,218	48.2
2014	30	357	2,078	2,078	4,643	55.2	369.6	7,771	47.6

[1] calculated for tows with Shortspine Thornyhead catch >0
[2] calculated for all tows

Table C.2. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal, binomial, and combined models of non-zero catches of Shortspine Thornyhead in 3CD+5A-E . All indices are scaled so that their geometric means equal 1.0. Upper and lower 95% confidence bounds and associated standard error (SE) are presented for the lognormal model, while bootstrapped upper and lower 95% confidence bounds are presented for the combined model.

Year	Arithmetic Index	Unstandardised Index	Lognormal				Binomial Index	Combined		
			Index	Lower bound	Upper bound	SE		Index	Lower bound	Upper bound
1996	0.877	1.137	1.007	0.975	1.040	0.017	0.967	0.994	0.952	1.037
1997	0.788	1.015	1.018	0.984	1.054	0.017	0.955	1.000	0.953	1.041
1998	0.767	1.039	1.032	1.000	1.065	0.016	0.885	0.979	0.944	1.018
1999	0.883	1.103	1.081	1.049	1.115	0.015	1.037	1.100	1.058	1.141
2000	0.829	1.039	0.926	0.900	0.954	0.015	0.975	0.918	0.885	0.949
2001	0.726	0.928	0.900	0.873	0.927	0.016	0.993	0.898	0.867	0.933
2002	0.879	1.018	0.958	0.930	0.988	0.015	0.968	0.947	0.907	0.988
2003	0.898	0.961	0.993	0.961	1.025	0.017	1.093	1.031	0.991	1.074
2004	0.956	1.134	1.096	1.059	1.133	0.017	1.055	1.122	1.074	1.172
2005	0.870	0.881	1.010	0.973	1.049	0.019	1.028	1.024	0.976	1.082
2006	0.953	0.967	1.027	0.992	1.063	0.018	1.195	1.104	1.059	1.145
2007	1.067	1.081	1.066	1.026	1.108	0.020	0.918	1.029	0.983	1.075
2008	1.183	0.958	1.063	1.019	1.109	0.021	0.841	0.986	0.936	1.040
2009	1.294	1.083	1.067	1.026	1.109	0.020	0.885	1.013	0.956	1.056
2010	1.467	0.974	0.921	0.886	0.958	0.020	0.939	0.898	0.851	0.942
2011	1.228	0.953	0.933	0.895	0.973	0.021	0.859	0.874	0.832	0.917
2012	1.353	0.973	0.933	0.897	0.971	0.020	1.215	1.010	0.961	1.061
2013	1.203	0.953	1.021	0.980	1.064	0.021	1.217	1.106	1.059	1.167
2014	1.186	0.859	0.980	0.936	1.025	0.023	1.091	1.017	0.969	1.085

*Table C.3. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of Shortspine Thornyhead by core vessels in 3CD+5A-E (based on the vessel selection criteria of at least five trips in five or more years) with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are marked with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5	6
Year*	**0.0092**					
Depth bands*	0.3966	**0.4006**				
0.1° Latitude bands*	0.2076	0.2118	**0.4855**			
Hours fished*	0.3844	0.3872	0.4792	**0.5367**		
Vessel*	0.1992	0.2032	0.4243	0.5114	**0.5572**	
DFO locality	0.2585	0.2611	0.4850	0.4989	0.5488	0.5659
Month	0.0276	0.0341	0.4273	0.4954	0.5427	0.5630
Major PMFC area	0.0936	0.1014	0.4483	0.4898	0.5396	0.5609
Improvement in deviance	0.0000	0.3914	0.0850	0.0512	0.0204	0.0087

*Table C.4. Order of acceptance of variables into the binomial model of presence/absence of Shortspine Thornyhead by core vessels in 3CD+5A-E (based on the vessel selection criteria of at least five trips in five or more years) with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are marked with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5
Year*	**0.0077**				
Depth bands*	0.3587	**0.3601**			
DFO locality*	0.1679	0.1704	**0.4125**		
Hours fished*	0.1394	0.1424	0.3752	**0.4239**	
Vessel	0.0720	0.0782	0.3760	0.4228	0.4330
Month	0.0016	0.0089	0.3740	0.4214	0.4319
0.1° Latitude bands*	0.0581	0.0662	0.4057	0.4179	0.4289
Major PMFC area	0.0318	0.0404	0.3874	0.4138	0.4257
Improvement in deviance	0.0000	0.3524	0.0524	0.0114	0.0091

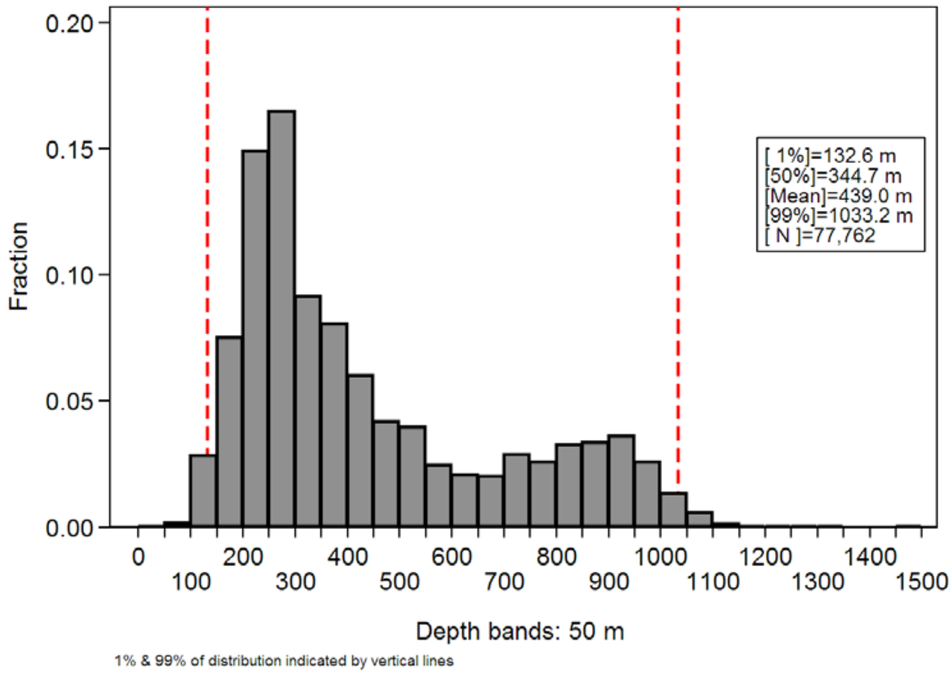

Figure C.1. Depth distribution of Shortspine Thornyhead for tows with landed plus discarded catch in Area 3CD+5A-E from 1996 to 2014 in 50 m intervals. Each bin interval is labelled with the upper bound of the interval. Vertical lines indicate the following quantiles: 1%=133 m; 99%=1033 m. Mean depth=439 m; median depth=345 m.

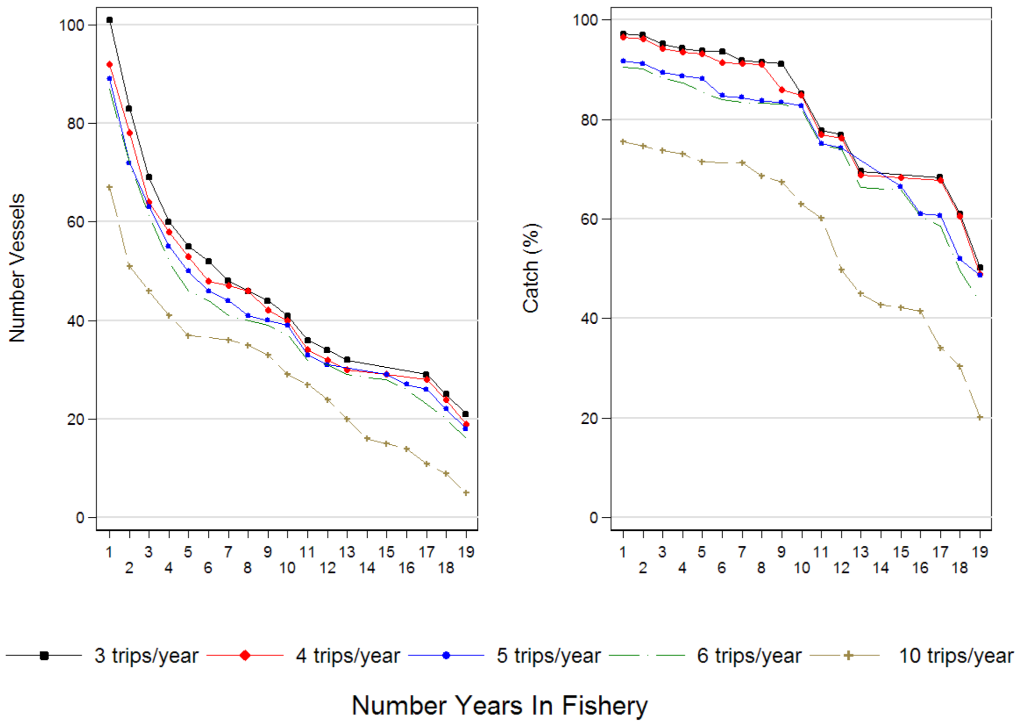

Figure C.2. Plots showing the relationship of number of trawl vessels [left panel] or percentage of total Shortspine Thornyhead catch [right panel] with the number of trips per year and the number of years in the Areas 3CD+5A-E fishery from 1996 to 2014. Each plotted point relates the number of years that vessels participated in the fishery while recording at least the indicated minimum number of trips per year.

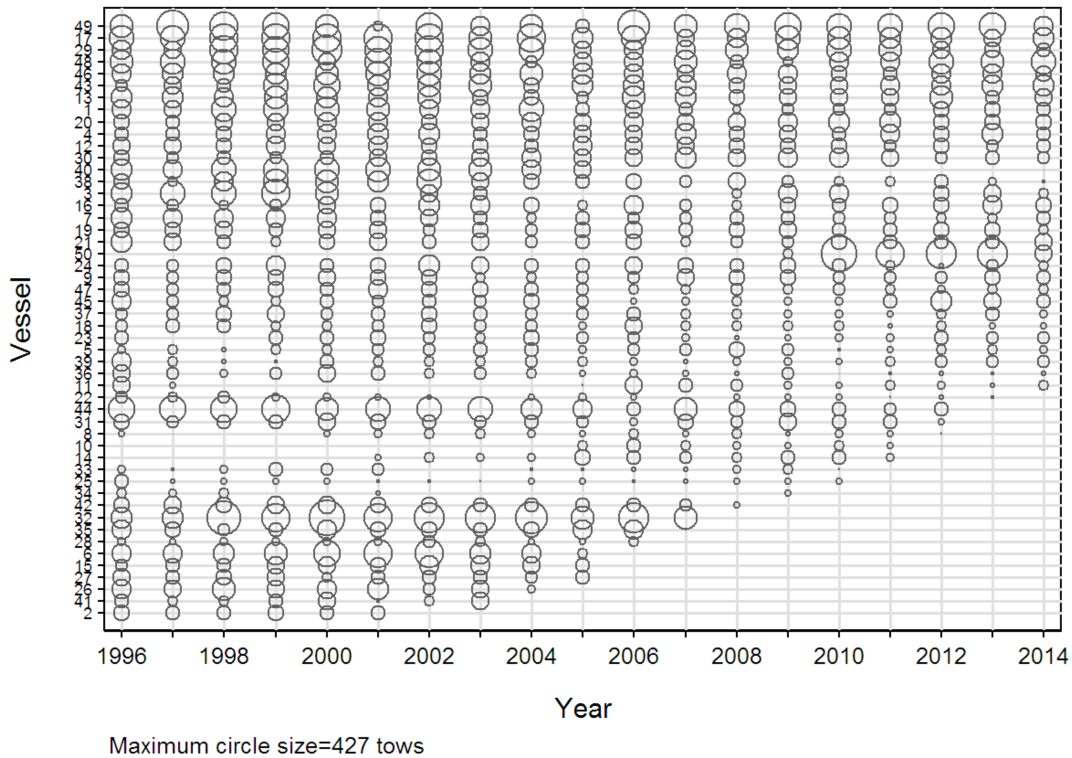

Figure C.3. Bubble plot showing vessel participation (number tows) by the 3CD+5A-E core fleet in each year. Vessels are coded in ascending order total catch.

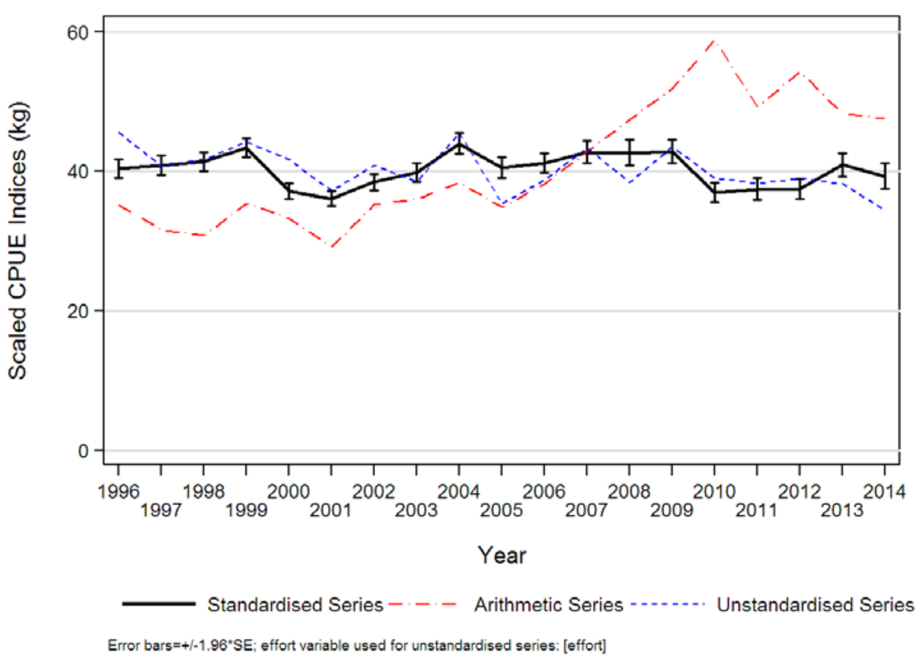

*Figure C.4. Three CPUE series for Shortspine Thornyhead from 1996 to 2014 in 3CD+5A-E. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (**Eq. C.1**) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.*

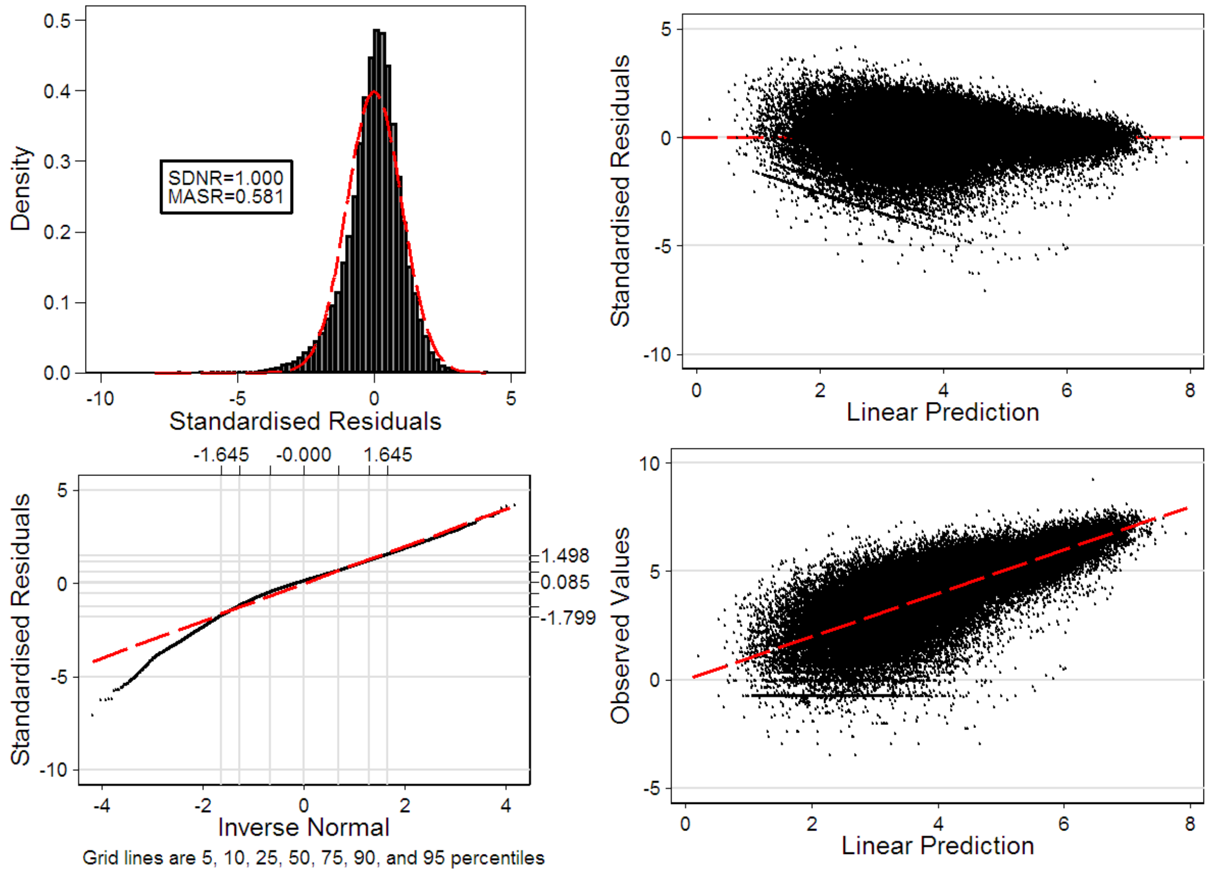

Figure C.5. Residual diagnostic plots for the GLM lognormal analysis for Shortspine Thornyhead in 3CD+5A-E. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised residuals). Lower left: Q-Q plot of the standardised residuals with the outside horizontal and vertical lines representing the 5th and 95th percentiles of the theoretical and observed distributions. Upper right: standardised residuals plotted against the predicted CPUE. Lower right: observed CPUE plotted against the predicted CPUE.

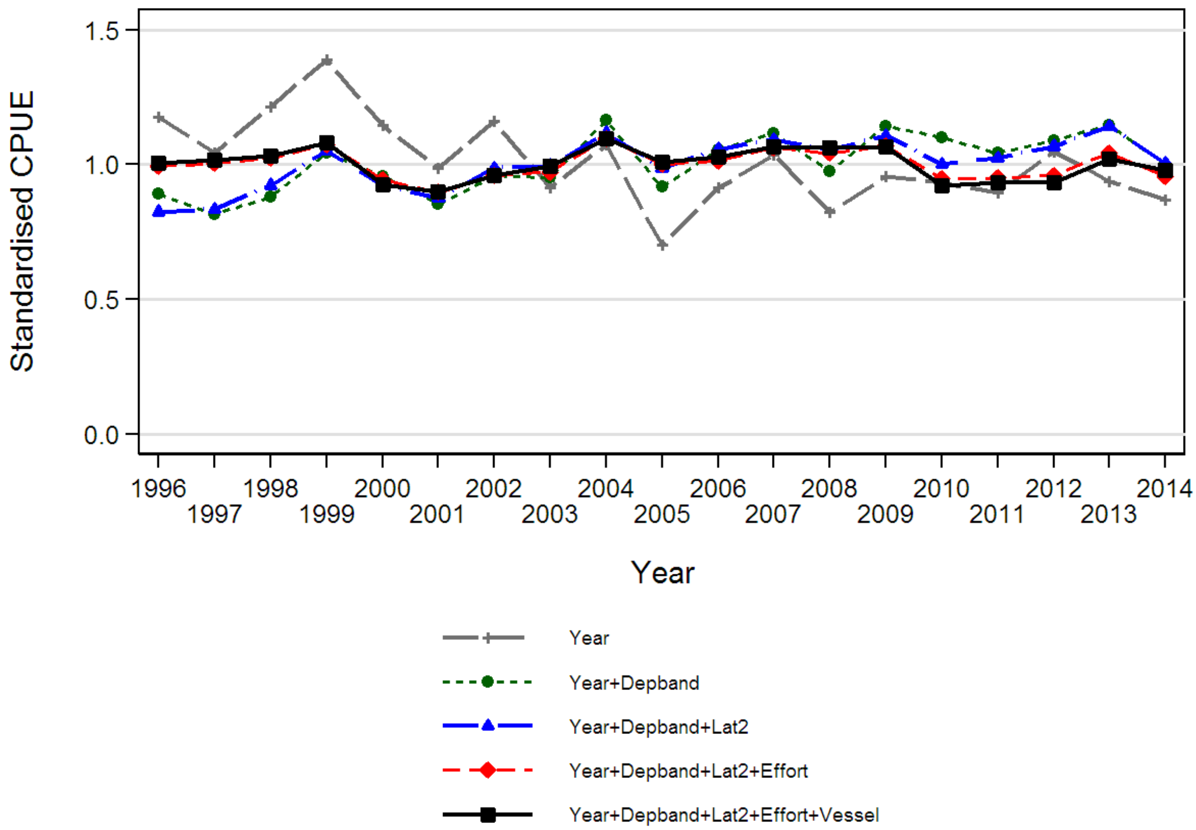

Figure C.6. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for Shortspine Thornyhead in 3CD+5A-E. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

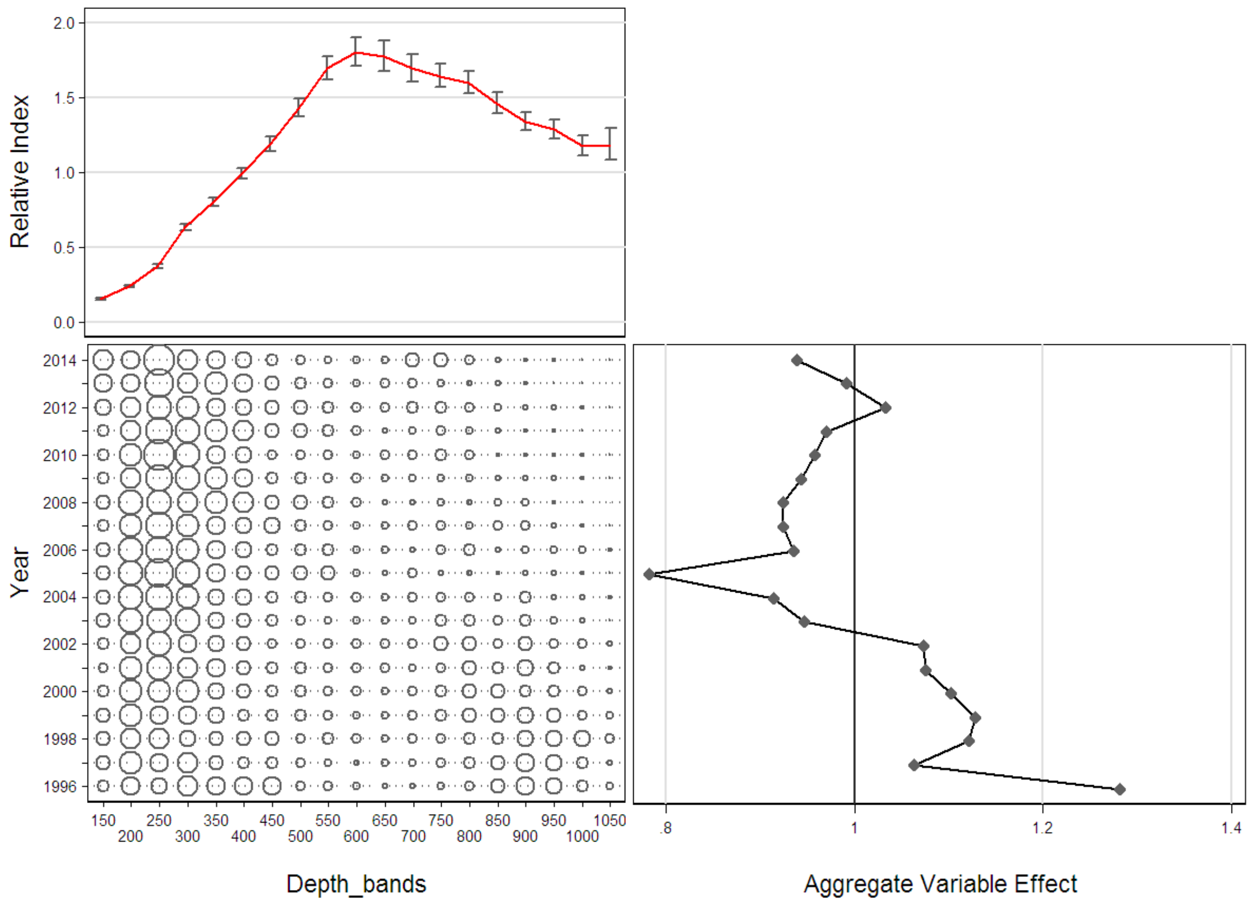

Figure C.7. CDI plot showing the effect of introducing the categorical variable [`depth_band`] to the lognormal regression model for Shortspine Thornyhead in 3CD+5A-E. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

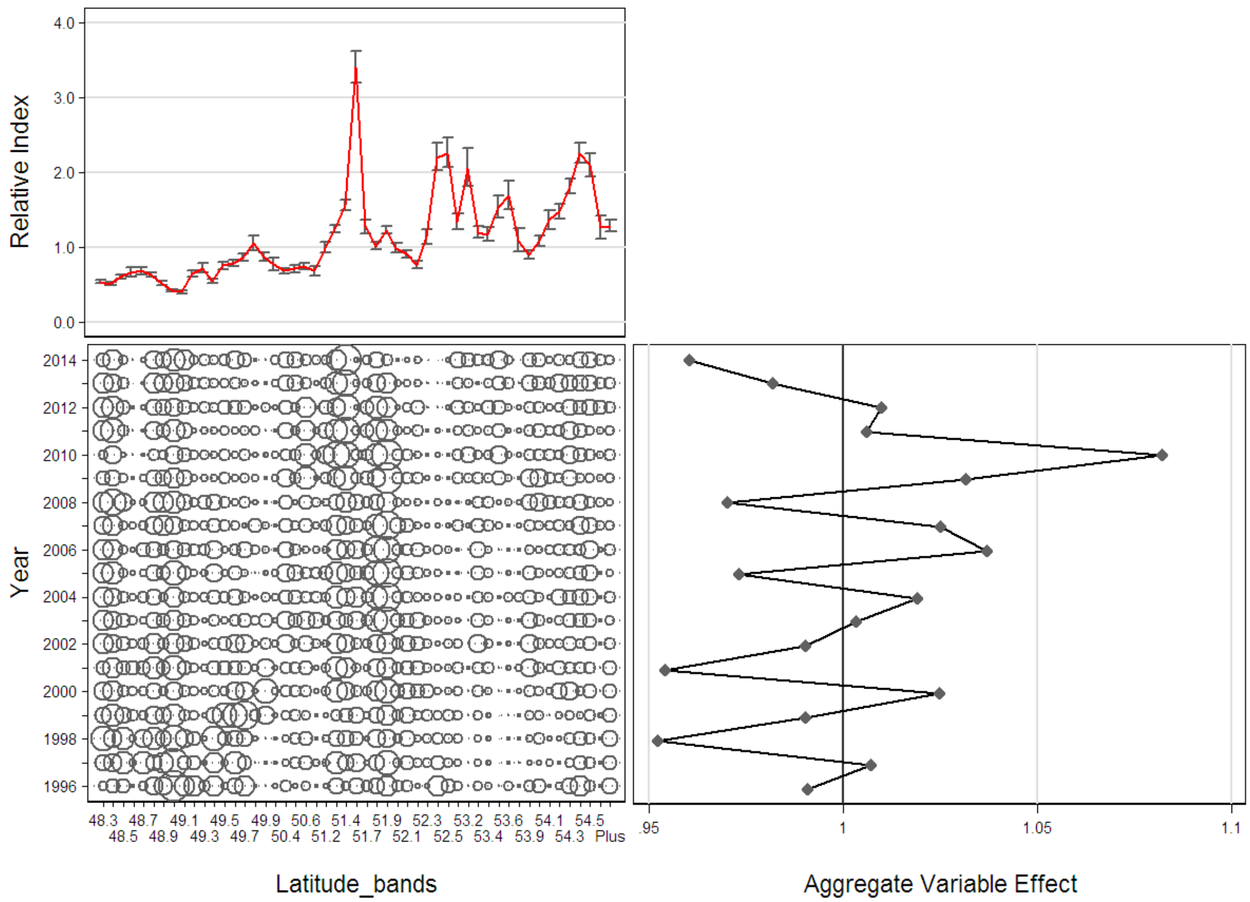

Figure C.8. CDI plot showing the effect of introducing the categorical variable [`Latitude_bands`] to the lognormal regression model for Shortspine Thornyhead in 3CD+5A-E. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

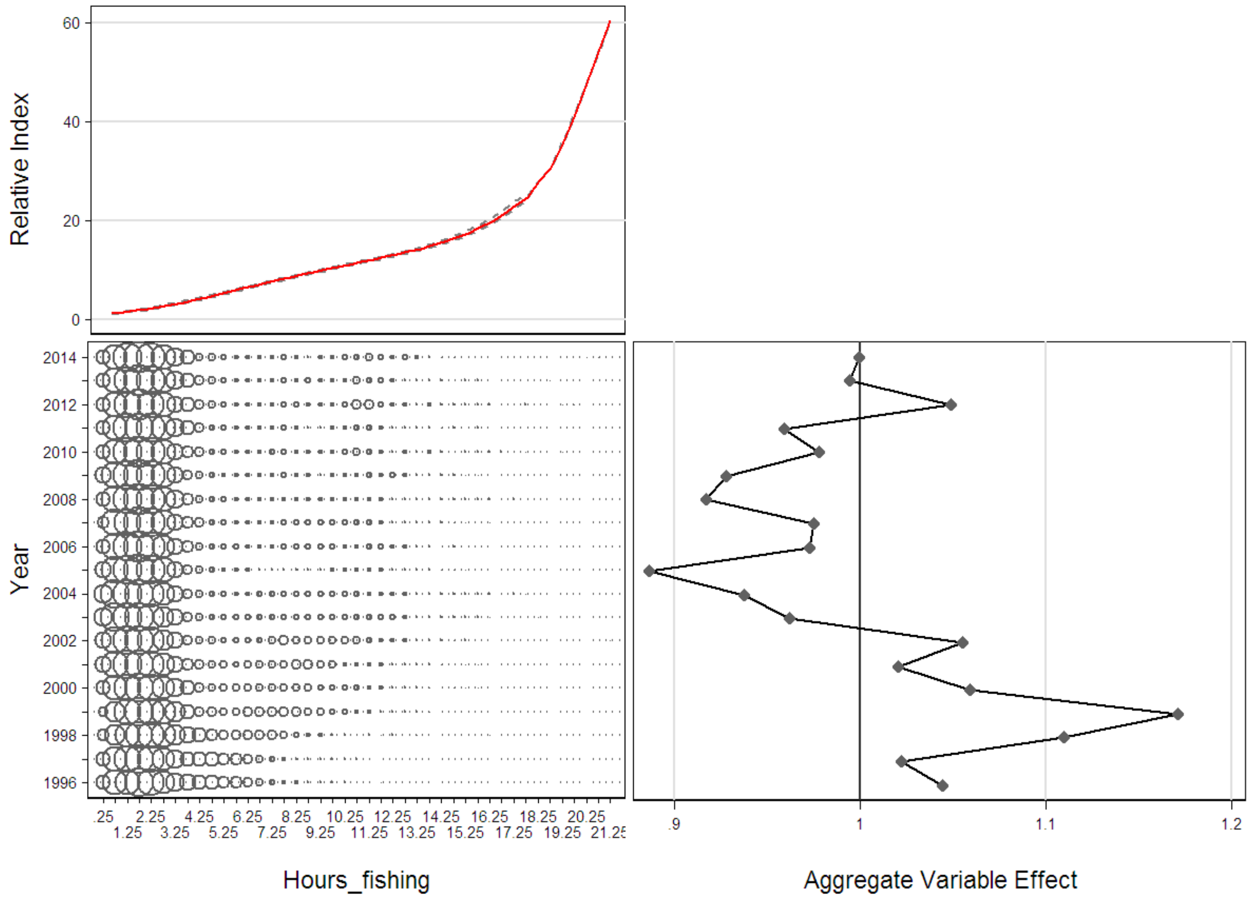

Figure C.9. CDI plot showing the effect of introducing the continuous variable [`Hours_fishing`] to the lognormal regression model for Shortspine Thornyhead in 3CD+5A-E. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

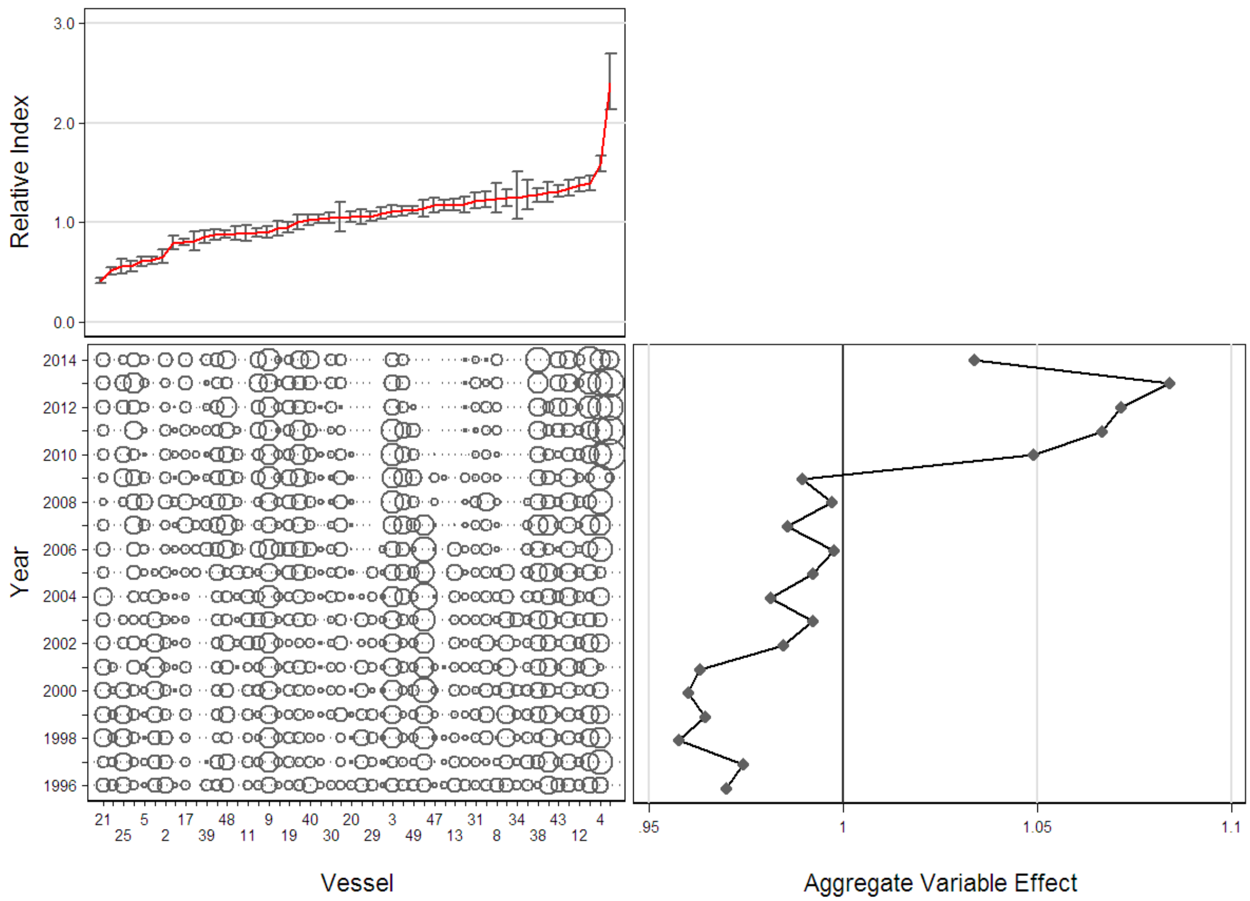

Figure C.10. CDI plot showing the effect of introducing the categorical variable [`Vessel`] to the lognormal regression model for Shortspine Thornyhead in 3CD+5A-E. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right). Vessel numbers have been coded and are ordered from left to right in terms of the relative index value

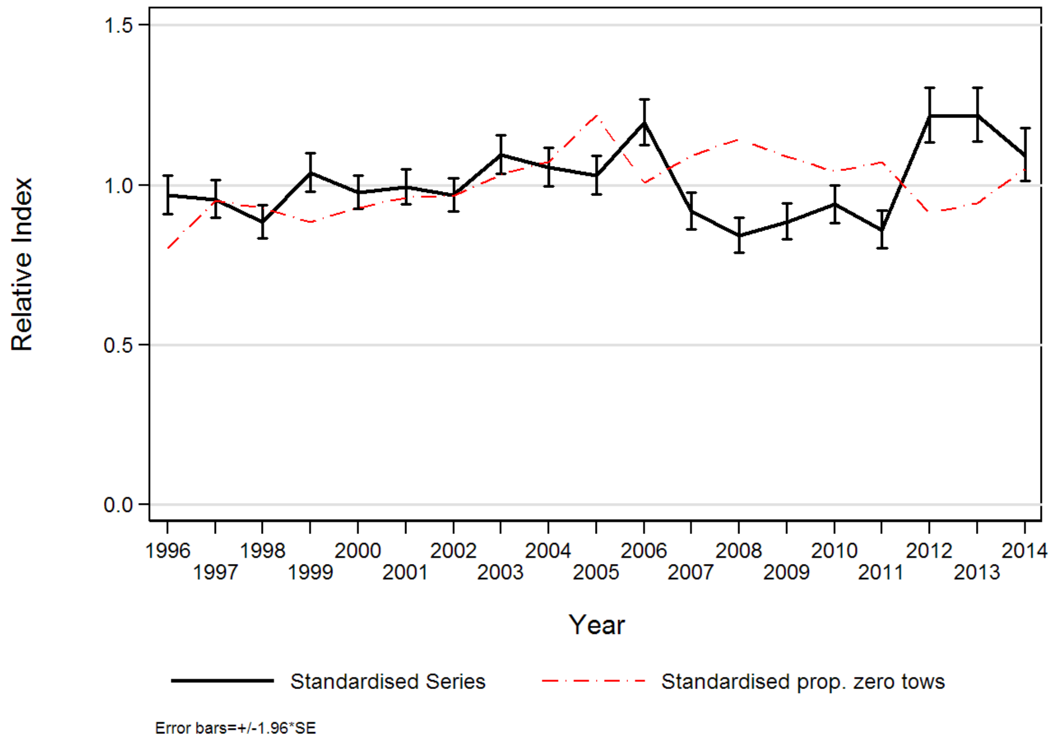

Figure C.11. Year effects from a standardised binomial logit model fit to the presence/absence of Shortspine Thornyhead in the 3CD+5A-E trawl fishery, using the same dataset that provided the lognormal regression model. Also shown is the relative proportion of tows with zero Shortspine Thornyhead by year (mean=0.471). Each series has been normalised so that the geometric mean=1.0.

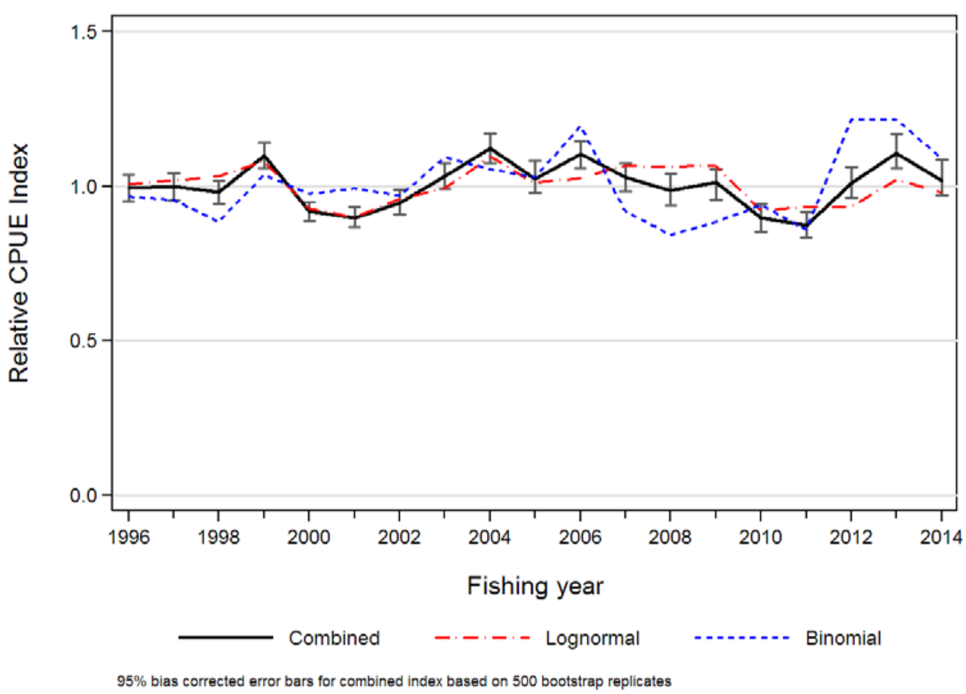

Figure C.12. Combined, lognormal and binomial models for Shortspine Thornyhead in 3CD+5A-E, based on commercial trawl catch and effort data. The error bars for the combined model were estimated by a bootstrap procedure replicated 500 times with replacement.

APPENDIX D. BIOLOGICAL DATA

D.1. GROWTH

This appendix describes the derivation of the length-weight relationship, von Bertalanffy growth relationship, maturity schedule and Walford parameters used in the Shortspine Thornyhead (SST) delay-difference stock assessment model. These analyses are based on Shortspine Thornyhead biological data extracted from the Fisheries and Oceans Canada (DFO) Groundfish database "*GFBio"* on 05 August 2015 (115,531 records). Data selection criteria are summarized in Table D.1. The ageing method and maturity criteria were applied only when required by a given analysis. The length-weight analysis did not enforce the sex criterion.

Table D.1. Data selection criteria for analyses of Shortspine Thornyhead biological data for growth and length-weight analysis.

Field	Criterion	Notes
Trip type	[trip_type]==2|[trip_type]==3	Definition of research observations.
Ageing method	[agemeth]==3|(==0&[year]>=1980))	Break & burn ageing method, or unknown from 1980 onwards.
Sample type	[sample_type]==1|==2|==6|==7	Only random or total samples.
Species category code	[SPECIES_CATEGORY_CODE]==1	Unsorted samples only
Month	[month]>=`startmonth'&[month]<=`endmonth'	Valid month observation in range.
Sex code	[sex]==`sex'	Valid sex observation (1=male or 2=female).
Maturity code	[maturity]>=1&[maturity]<=7	Valid maturity observation from 1 to 7.
Area code	select valid area observations	Based on outside PMFC regions (3CD and 5A-E).
Tow status	select [Not_available_reason_code]=NULL	Not rejected, valid tow.

D.1.1. Length-Weight

A log-linear relationship with additive errors was fitted without reference to sex to all valid weight and length data pairs i, $\left\{W_i\ ,L_i\right\}$:

$$\ln\left(W_i\ \right)=b\ \ln\left(L_i\right)+a\ +\varepsilon \tag{D.1}$$

where a and b are the intercept and slope parameters. The paired observations were drawn from samples obtained during research or charter trips from PMFC areas 3CD and 5A-E. Visual inspection of an initial model fit to all data showed outliers which were resolved by excluding observations with standardised (Pearson) residuals greater than three (Figure D.1).

Table D.2. Length-weight parameter estimates, standard errors (SE) and number of observations (n) for Shortspine Thornyhead (combined sexes) for all research or charter samples operating in PMFC Areas 3CD and 5A-E from 1989 to 2014. $\bar{W}$: mean weight (in kg) from the fitted data set.

Restrictions	Excluded data Residuals	*n*	a	b	$\mathrm{SE}\left(a\right)$	$\mathrm{SE}\left(b\right)$	$\bar{W}$ (kg)
|Pearson residuals| >3 dropped	236	24310	-11.8647	3.1658	0.006904	0.002085	0.3698

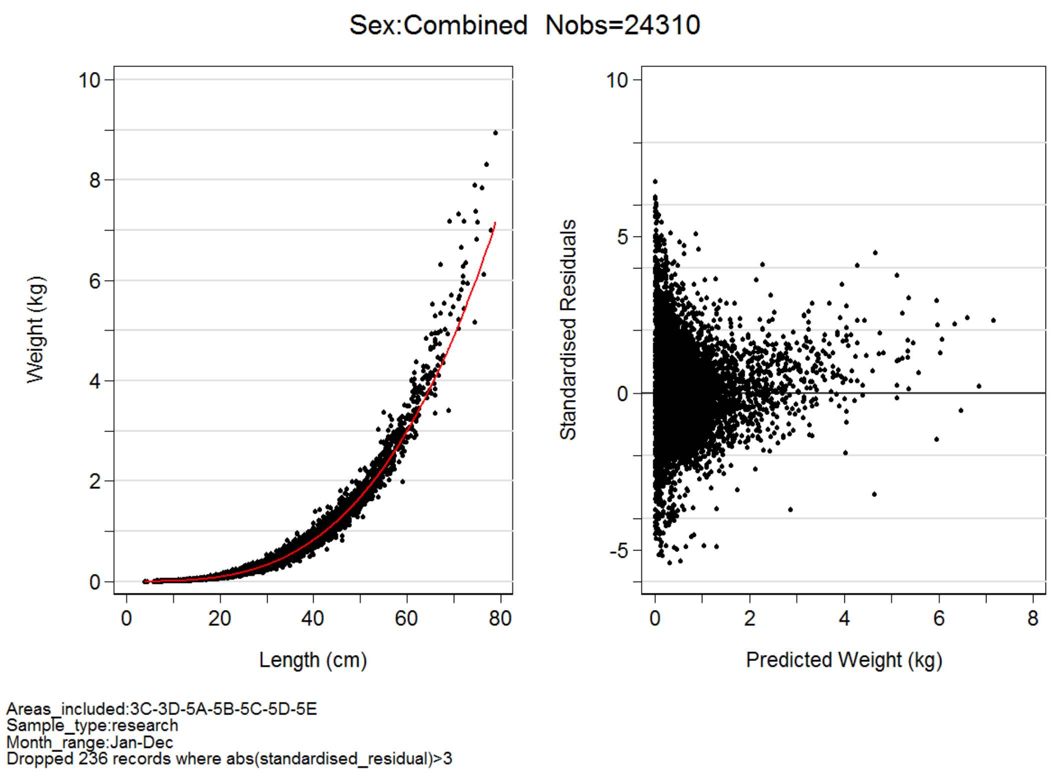

Figure D.1. Length-weight relationship for combined sexes Shortspine Thornyhead from research surveys for areas 3CD and 5A-E. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped.

D.1.2. von Bertalanffy Growth

There was concern that the age information available for SST might be biased low, given that the available ageing had been done using the "break & burn" method which is thought to underestimate the number of growth rings compared to using the "thin-section" method when applied to a species with this level of age estimation difficulty (Stephen Wischniowski, Pacific Biological Station Sclerochronology Laboratory, Nanaimo, BC, pers. comm.). A recent unpublished trial was conducted by staff at the Pacific Biological Station Sclerochronology Laboratory where 60 otoliths were prepared using both methods (thin section and break & burn) and were subsequently read independently by four experienced readers. The mean age of these otoliths (when averaged across the four readers) ranged from 11 to 55 for the break & burn readings and from 14 to 71 for the thin-section readings, indicating that these otoliths spanned a reasonable range of ages and sizes. Simple linear regressions were fitted to the paired ages for each reader as well as the average of the paired ages across all four readers. Examination of the residuals from these fits did not show any systematic bias with increasing age. Based on the averaged results from this comparative trial (the estimate of the slope ~1.0 and the intercept estimate was not significantly different from zero; Table D.3, Figure D.2), it was concluded that the available break & burn ages could be used to specify the growth curve for Shortspine Thornyhead. However this unpublished trial should not be considered definitive because the power to detect bias from this simple experiment is likely to be low due to the small sample size.

Thornyhead otoliths are notoriously difficult to age, which is highlighted by among-reader variation in age determination in the pilot study above (individual reads not shown here). This stems partly from prior experience in assessing thornyhead otoliths but also from the physical attributes of the otoliths themselves (see Section D.6 for more details).

Table D.3. Regression statistics for a simple model relating thin-section otolith reading with break & burn readings for 60 otoliths read by four independent readers. The final model regressed the average reading across all four readers.

	Slope			Intercept		
	Estimate	**Lower**	**Upper**	**Estimate**	**Lower**	**Upper**
Reader 1	0.97	0.60	1.33	11.7	3.9	19.5
Reader 2	0.83	0.63	1.02	6.7	0.5	12.9
Reader 3	0.68	0.39	0.97	14.3	6.5	22.1
Reader 4	0.59	0.29	0.88	17.9	8.8	27.0
Average	1.04	0.80	1.29	5.1	-1.5	11.7

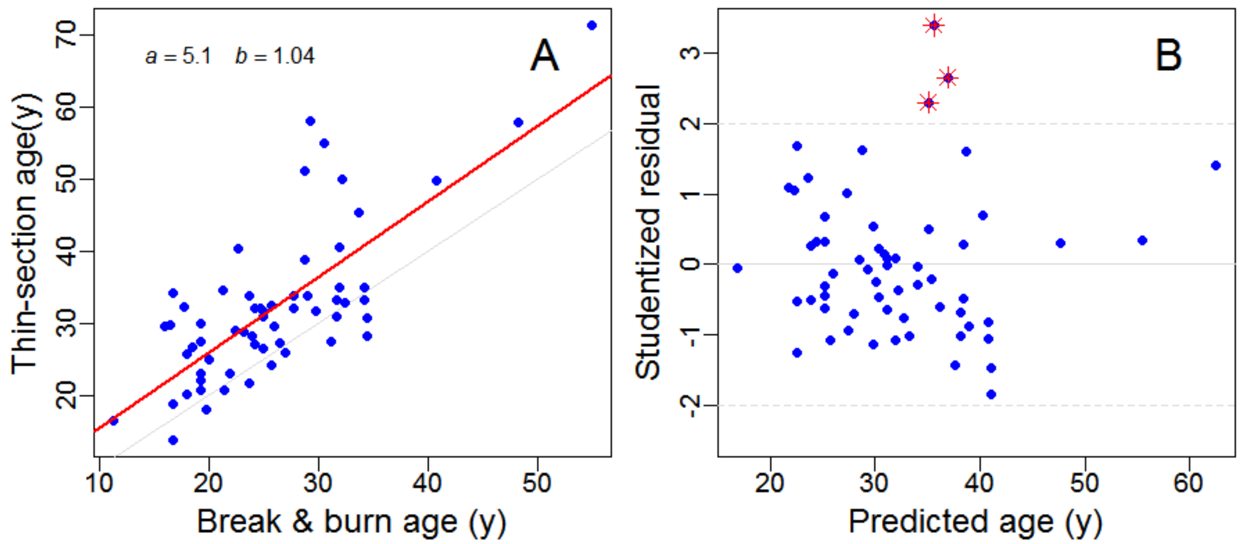

Figure D.2. Linear least-squares fit of average thin-section otolith age as a function of average break and burn otolith age. (A) Red line shows the best fit (intercept a and slope b coefficients indicated in upper left); the 1:1 line is also displayed as a grey line, (B) Studentized residuals vs. predicted ages, with values outside two standard deviations indicated by red asterisks.

Paired observations i of length and age by sex, $\{L_{is}, a_{is}\}$, for $s = 1,2$ (males, females) were extracted from research samples collected from PMFC areas 3CD and 5A-E. Ages were included in the data extraction if they were read using

a) the burnt-otolith cross section method (MacLellan 1997), or

b) unknown method after 1980 when all ageing was performed by burnt-otolith cross-section.

Maximum observed ages for male and female SST are 65 and 95 years, respectively (Table D.4). There were only about 1100 otoliths with available ages read, most of which came from the mid-1990s when the fishery was still very new.

Growth was formulated as a von Bertalanffy model where lengths by sex, L_{is}, for fish $i = 1,\ldots,n_s$ are given by:

$$L_{is} = L_{\infty s} e^{\left(-\kappa_s \left[a_{is} - t_{0s}\right]\right)} \quad \text{(D.2)}$$

where for each sex, s, $L_{\infty s}$ is the average length at maximum age of an individual, κ_s is the growth rate coefficient, and t_{0s} is the age at which the average size is zero.

Table D.4. Number of paired length and age observations by origin and sex. The maximum observed age is shown by sex for each origin type. All determined from otoliths prepared using the break & burn method.

		Sex				Maximum age	
Year	**Description**	**Males**	**Females**	**Unknown**	**Total**	**Male**	**Female**
1995	Unknown research	23	27	0	50	40	42
1995	QC Sound Rockfish	206	147	14	367	50	31
1995	Unobserved domestic	101	67	55	223	44	48
1996	Observed domestic	76	67	0	143	65	50
1996	WCVI Rockfish	93	124	0	217	47	62
2003	WCVI Longspine	80	62	1	143	47	95
2006	WCHG synoptic	–	1	0	1	–	45
	All	579	495	70	1144	65	95

Initial fits to the age-length data gave implausibly large estimates for L_∞ for female SST (Figure D.3; Table D.5). These estimates were not credible and it was determined that three observations were responsible for the poor behaviour of the female model (Table D.6). Model fits to the male age-at-length data gave plausible estimates for L_∞ regardless of data selection (Table D.5).

A range of options were explored to see if the female SST von-Bertalanffy model would provide more credible estimates. These included

a) constraining the estimation to research-only observations;

b) calculating the von-Bertalanffy model with equal weighting between each age class; and

c) successively dropping the three outlier observations identified in Table D.6.

The model which gave equal weighting to each age class while dropping all three observations was selected for use in the SST delay-difference model (highlighted in grey in Table D.5, Figure D.4). The models for each sex were averaged by giving equal weight to each sex to create a growth function that could be used in the single-sex SST delay-difference stock assessment model (Figure D.5).

Table D.5. Summary of L_∞ estimates (cm) for male (M) and female (F) SST over a range of trial fits where data were summarised to one observation/age or treating each age observation independently. R+C = research and commercial observations; R only = research observations only. The influential female observations (see Table D.6) were treated as described in the second column. The models highlighted in grey were selected for use in the SST delay-difference stock assessment (see Figure D.5).

Data source	**Drop old female observations**	**1 observation/age**		**All observations**	
		M	**F**	**M**	**F**
R+C	no	42.8	243.3	42.8	119.0
R only	no	45.4	148.0	43.7	147.7
R+C	drop age=95			42.8	80.9
R only	drop age=95			43.7	198.7
R only	drop age=62 & 95	45.4	414.6		
R+C	drop all 3 obs			42.2	58.7
R only	drop all 3 obs	**45.4**	**49.1**	43.7	64.5

Table D.6. Characteristics of three influential female age-length observations

Year	Survey	PMFC	Sex	Age	Length (cm)	Weight (kg)	Maturity
1996	WCVI Rockfish	3C	F	62	56.5	2.74	Resting
2003	WCVI Longspine	3C	F	55	67.9	5.54	Maturing
2003	WCVI Longspine	3C	F	95	72.1	7.18	Maturing

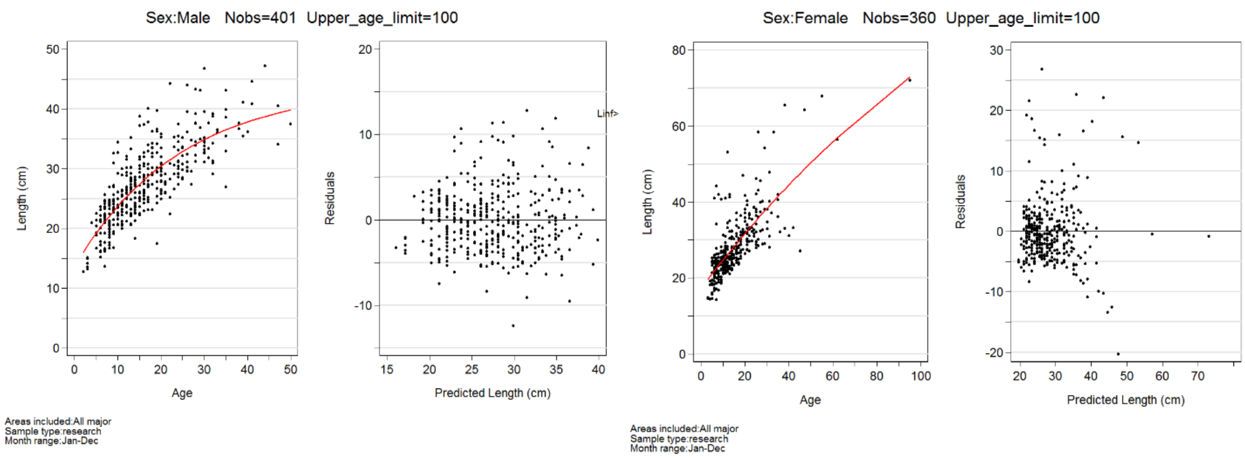

Figure D.3. Growth model fits for male [left panel] and female [right panel] Shortspine Thornyhead to combined 3CD and 5A-E samples, treating all research age observations independently and retaining the three influential female observations (see Table D.6).

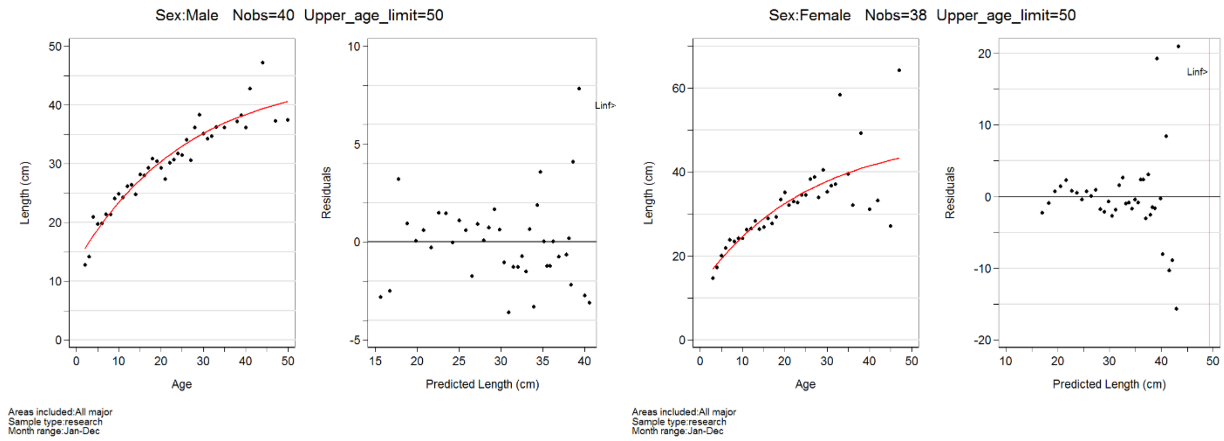

Figure D.4. Growth model fits for male [left panel] and female [right panel] Shortspine Thornyhead to combined 3CD and 5A-E samples, using one observation for each age (research ages only) and dropping the three influential female observations (see Table D.6).

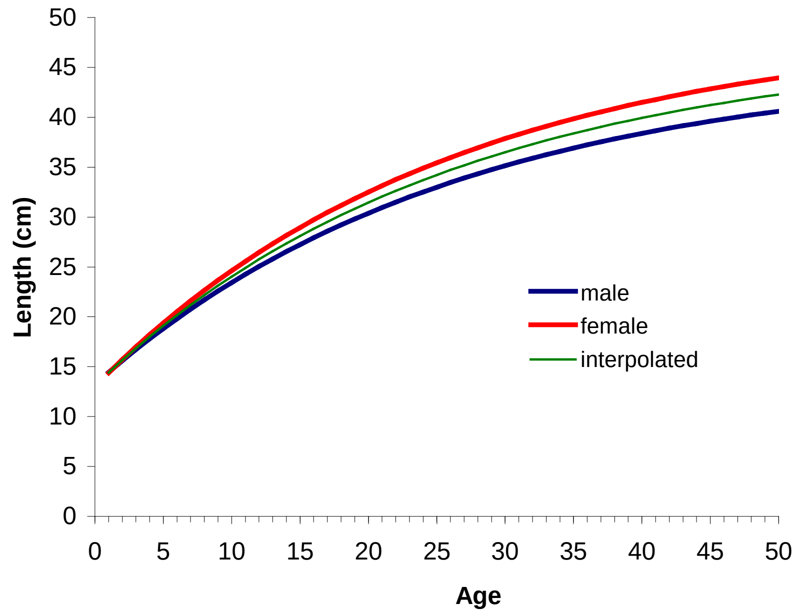

Figure D.5. Interpolated von-Bertalanffy function used for calculating the Walford plot that determines growth in the single-sex SST delay-difference stock assessment model. Parameter values for the interpolated model: $L_\infty = 47.257$; $\kappa = 0.0385$; $t_0 = -8.456$

D.1.3. Taylor-Stephens Growth Function

Taylor-Stephens (2013) used the Schnute parameterisation (Schnute 1981, Eq. 15; Quinn and Deriso 1999, Eq. 4.31) of the von Bertalanffy growth model to describe predicted size at age *t*:

$$L_t = L_1 + \left(L_2 - L_1\right) \frac{\left(1 - e^{(-\kappa[t-\tau_1])}\right)}{\left(1 - e^{(-\kappa[\tau_2-\tau_1])}\right)} \tag{D.3}$$

where τ_1 = age of a young fish, τ_2 = age of an older fish, L_1 and L_2 are mean lengths at ages τ_1 and τ_2 respectively, and κ is the growth rate coefficient. Equation (D.3) assumes that the incremental relative rate γ of the relative growth rate is set to 1 (and therefore is factored out). Taylor and Stephens (2013) and Jacobson (1991) did not specify the value of γ used in their growth models, so we assumed that they used γ=1 as well. The parameter values given in Table 8 (Taylor-Stephens 2013) were:

	males	females	single-sex
τ_1	2	2	2
τ_2	100	100	100
L_1	7 cm	7 cm	7 cm
L_2	67.5 cm	75 cm	71.5 cm
κ	0.018	0.018	0.018
a	4.7707×10^{-6}	4.7707×10^{-6}	4.7707×10^{-6}
b	3.2630	3.2630	3.2630

The final column shows how the model was revised for use in the single-sex delay difference model, with only the parameter L_2 requiring adjustment to the mean of the L_2 values for males and females, while the other parameters were the same for both sexes. The final two rows from Table 8 (Taylor-Stephens 2013) show the length weight parameters *a* and *b* (Eq. D.1) were specified without reference to sex. These parameters describe a function that is nearly identical to the one estimated in Section D.1.1 (Figure D.6). However, the Taylor-Stephens (2013) growth function predicts much slower growth up to about age 30 and the growth model specified in Section D.1.2 estimates a much smaller maximum size compared to the Taylor-Stephens model (Figure D.7).

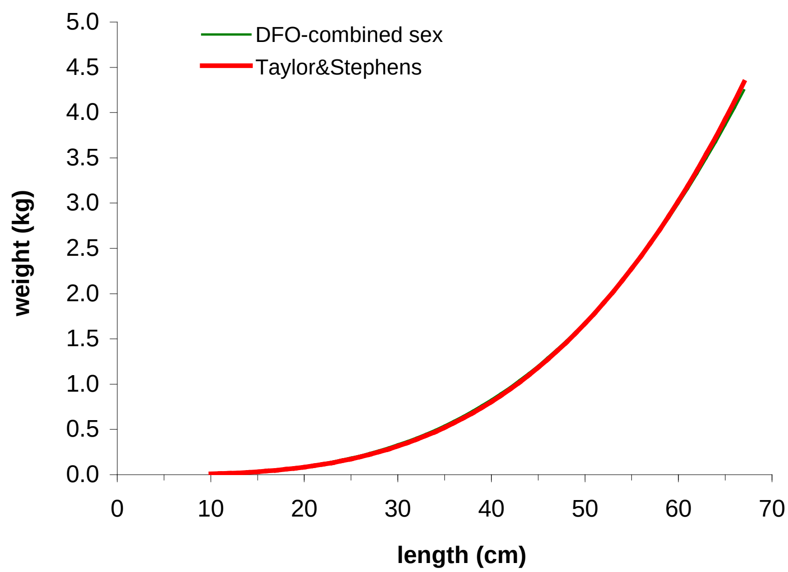

Figure D.6. Comparison of weight at length based on the parameters estimated in Section D.1.1 and those provided in Table 8 of Taylor-Stephens (2013).

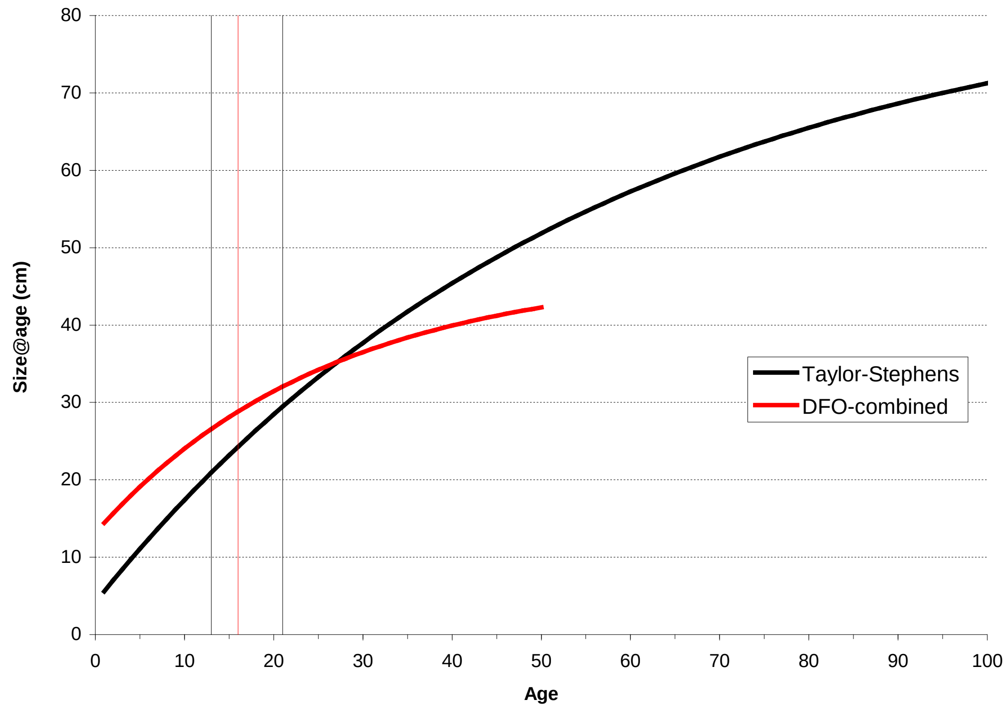

Figure D.7. Comparison of the growth functions estimated in Section D.1.2 with the Taylor-Stephens (2013) growth function.

D.1.4. Knife-edge Selectivity and Walford Plot

Length information from unsorted samples taken from the commercial trawl fishery were summarised by year as cumulative frequency distributions (Figure D.8). The median length by year from these distributions ranged from 26 to 35 cm, with the median from all 18 years being 29 cm (Table D.7). Based on the von-Bertalanffy parameters estimated in Section D.1.2, this mean length corresponds to an average age of 16 y for SST. This age of knife-edge recruitment was used to prepare a Walford plot (Figure D.9) to obtain the parameter values used as input to the SST delay-difference model. The Walford parameters are calculated from the recruitment age to 49 y for the Section D.1.2 growth model and to 114 y for the Section D.1.3 growth model. The Walford parameters will vary slightly with changing age assumptions at knife-edge recruitment for both growth models. Table D.8 presents the Walford parameters used in the stock assessment for both growth models along with the mean length and mean weight associated with each of the knife-edge age at recruitment assumptions. Equilibrium mean weights assuming *M*=0.08 are also presented for comparative purposes.

Table D.7. 5%, 50% 95% percentiles of length (cm) by year from the Figure D.8 cumulative distributions, weighted by the number of observations at each length bin.

Year	5%	Median	95%	Year	5%	Median	95%
1997	23	36	54	2006	19	27	41
1998	20	31	58	2007	21	30	41
1999	20	26	40	2008	18	29	39
2000	14	27	40	2009	21	30	39
2001	19	27	45	2010	18	33	41
2002	15	26	40	2011	23	35	45
2003	17	26	38	2012	20	33	41
2004	18	29	40	2013	21	31	42

Year	5%	Median	95%	Year	5%	Median	95%
2005	20	28	38	2014	20	35	44
				All data	17	**29**	42

Table D.8. Age varying biological parameters used in the SST delay-difference stock assessment using two growth models.

	Age at knife-edge recruitment							
	Section D.1.2 growth model					Section D.1.3 growth		
	12	**14**	**16**	**18**	**20**	**13**	**16**	**21**
α_g	0.027	0.029	0.030	0.031	0.032	0.051	0.054	0.059
ρ_g	0.989	0.987	0.986	0.984	0.983	1.003	1.002	1.001
length (cm) at W_k	25.8	27.3	28.8	30.2	31.5	20.9	24.3	29.5
W_k (kg)	0.206	0.249	0.294	0.340	0.388	0.097	0.158	0.297
$\bar{W}_0$ (kg)[1]	0.472	0.514	0.557	0.599	0.641	0.731	0.826	1.019

[1] assumes M=0.08 for comparative purposes.

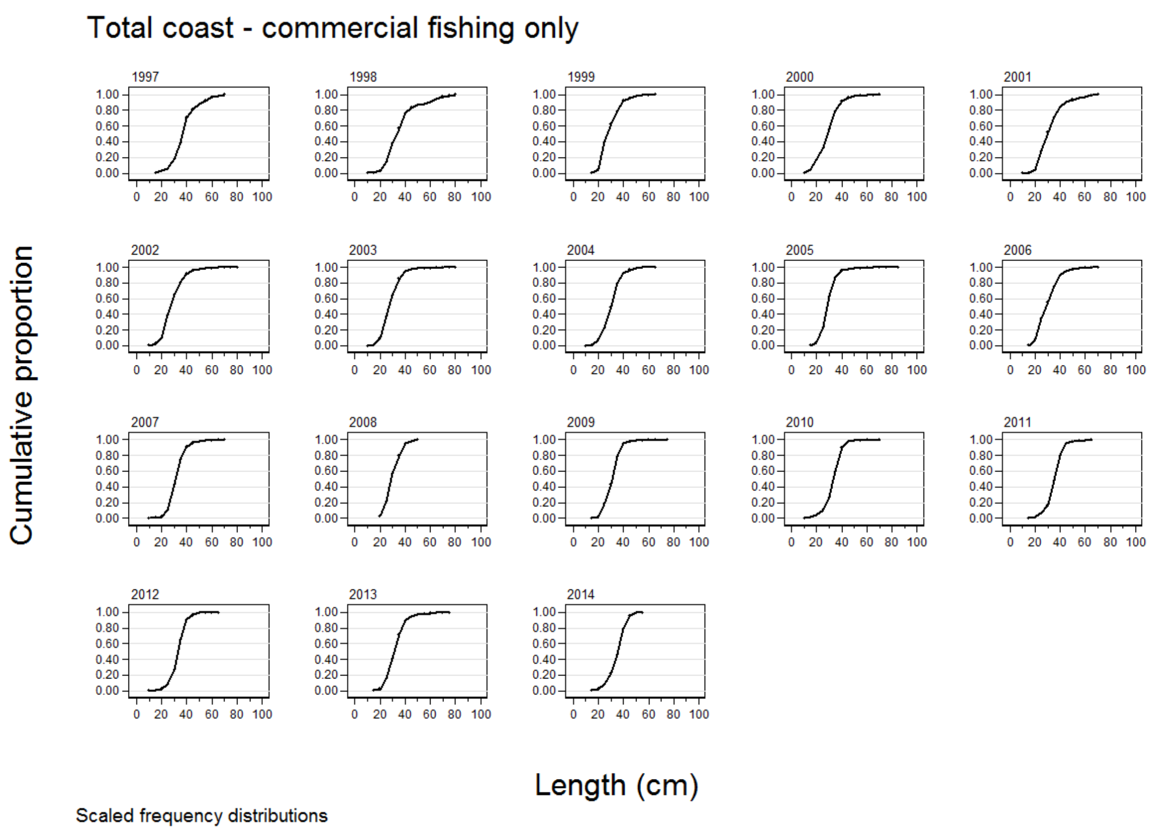

Figure D.8. Annual cumulative proportion for SST by 1-cm length bin in unsorted samples taken from commercial catch. Proportions are weighted by the sample catch weight within each year.

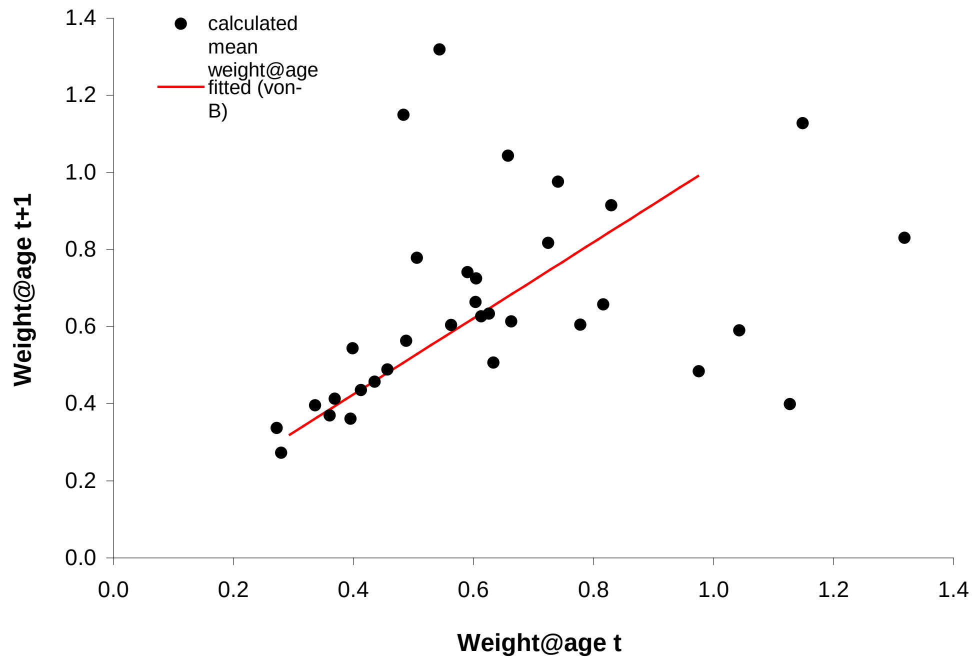

Figure D.9. Walford plot for SST using age=16y as the knife-edge recruitment assumption. The mean weights-at-age are calculated using the mean length-at-age from the 1,144 aged SST documented in Table D.4.

D.2. MATURITY

Maturity data for this stock assessment were obtained and filtered as described in Table D.1. Specifically, the data used to calculate a maturity ogive were collected from two survey series:

- GFBio survey series 9 – 1996 West Coast VI Rockfish, and
- GFBio survey series 10 – 1995 QC Sound Rockfish.

The 1995 survey provided 183 maturities in 5AB (113 ♂, 70 ♀) and the 1996 survey provided 207 maturities in 3CD (91 ♂, 116 ♀), all from random samples.

Using stage 3 and up to denote mature fish, we constructed a maturity ogive (Figure D.10) using a double-normal model:

$$m_{as} = \begin{cases} e^{-(a-\nu_s)^2/\rho_{sL}}, & a \le \nu_s \\ 1, & a > \nu_s \end{cases} \tag{D.4}$$

where, m_{as} = maturity at age a for sex s,

ν_s = age of full maturity for sex s,

ρ_{sL} = variance for the left limb of the maturity curve for sex s.

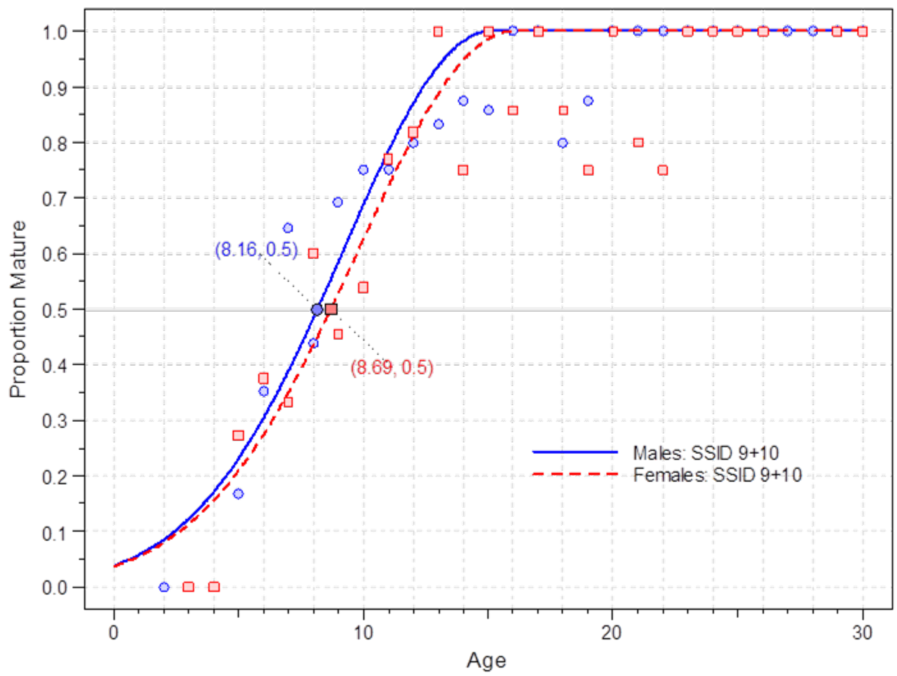

Figure D.10. Maturity ogives by age for BC Shortspine Thornyhead (data from combined rockfish surveys – 1995 5AB and 1996 3CD, GFBioSQL). Solid blue line shows the double-normal fit to data on males where maturity is defined by stages ≥ 3; red dashed line indicates fit to stage 3+ females. The age at 50% maturity is similar (8-9 years) for both sexes.

The proportion of mature individuals is calculated (Table D.9, Figure D.10) and the age of 50% maturity is estimated at 8.16 y for males and 8.69 y for females using the growth model estimated in Section D.1.2. The binomial logit fit is included in Table D.9 for comparison purposes only. The maturity schedule is not used in this assessment because the knife-edge selectivity assumption used by this model also assumes that maturity matches selectivity, i.e.: all recruited fish are mature. This analysis shows that the median age at maturity for Shortspine Thornyhead is lower than any of the knife-edge recruitment assumptions investigated in this stock assessment (see Table D.8).

Alternative maturity ogives by length are shown in Figure D.11. Length data are more abundant than age data. The estimated length at 50% maturity from the groundfish synoptic surveys is ~21-22 cm while that from the earlier rockfish surveys is ~22-24 cm. These are well below the length at knife-edge selectivity (k_L=29 cm) estimated in Section D.1.3. The lengths in Figure D.11 correspond to ages 8–9 using the Section D.1.2 growth model and ages 13–14 using the Section D.1.3 growth model.

Pearson and Gunderson (2003) found age-at-maturity for Shortspine Thornyhead at 18.2 cm along the US west coast, which Hamel (2005) ascribed to ages 8-10 y. Taylor and Stephens (2013) noted differences in maturity with latitude (higher maturity rates in the north than the south) and depth (higher proportions mature at shallow depths), suggesting that ontogenetic migration might be the main reason behind these differences.

Table D.9. Proportion of Shortspine Thornyhead mature at each age (m_a) up to age 20y. In this assessment, maturity stages 1 and 2 describe immature fish while stages 3 to 7 are considered mature. Model fits are presented for the binomial logit (BL, comparison only) and the double normal (DN), used in this stock assessment.

	Males				**Females**			
Age	#Fish	Obs. m_a	BL fit	DN fit	#Fish	Obs. m_a	BL fit	DN fit
1	0	0	0.1119	0.0577	0	0	0.1382	0.0550
2	1	0	0.1471	0.0851	0	0	0.1701	0.0798
3	5	0	0.1910	0.1222	2	0	0.2077	0.1130
4	1	0	0.2443	0.1704	3	0	0.2511	0.1558
5	6	0.1667	0.3068	0.2310	11	0.2727	0.3002	0.2094
6	17	0.3529	0.3773	0.3042	24	0.375	0.3542	0.2744
7	17	0.6471	0.4534	0.3893	21	0.3333	0.4123	0.3505
8	16	0.4375	0.5317	0.4842	10	0.6	0.4729	0.4363
9	13	0.6923	0.6085	0.5852	11	0.4545	0.5343	0.5293
10	12	0.75	0.6803	0.6873	13	0.5385	0.5947	0.6260
11	8	0.75	0.7444	0.7845	13	0.7692	0.6524	0.7216
12	10	0.8	0.7995	0.8701	11	0.8182	0.7059	0.8108
13	12	0.8333	0.8452	0.9378	9	1	0.7543	0.8879
14	8	0.875	0.8820	0.9823	8	0.75	0.7970	0.9477
15	7	0.8571	0.9109	0.9998	3	1	0.8339	0.9861
16	5	1	0.9333	1	7	0.8571	0.8653	1.0000
17	4	1	0.9504	1	3	1	0.8915	1
18	5	0.8	0.9633	1	7	0.8571	0.9131	1
19	8	0.875	0.9729	1	4	0.75	0.9307	1
20	14	1	0.9801	1	3	1	0.9450	1

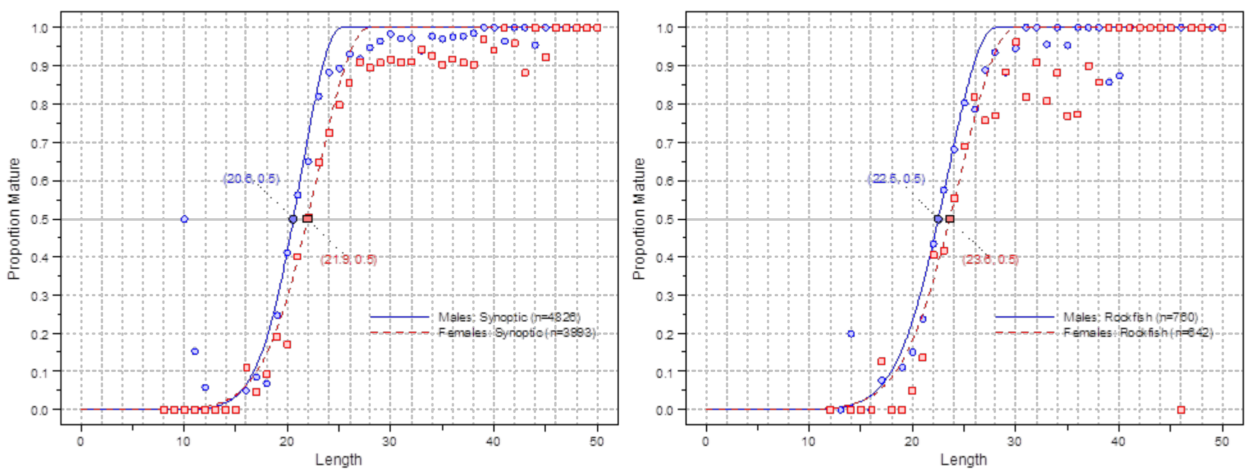

Figure D.11. Maturity ogives by length for BC Shortspine Thornyhead (GFBioSQL data from combined surveys – left: all groundfish synoptic surveys (2003-2015), right: rockfish surveys (1995 QCS, 1996 WCVI, 1997 WCHG). Solid blue line shows the double-normal fit to data on males where maturity is defined by stages ≥ 3; red dashed line indicates fit to stage 3+ females.

D.3. MEAN WEIGHT

Data used to estimate the mean weight by year for this stock assessment were selected following the relevant guidelines in Table D.1. The initial extract of biological data for SST from the GFBio database yielded 115,531 records which were filtered as follows:

• year = 1998:2014		102,132 records
• trip type = c(1,4)	{commercial}	49,744 records
• sample type = c(1,2,6,7)	{random}	49,537 records
• spp. category = 1	{unsorted}	32,233 records
• major PMFC = 3:9	{coastwide}	32,233 records
• gear type = 1	{bottom trawl}	31,628 records

This process resulted in 31,628 biological records, all containing length data but no weight data. Therefore weights were calculated from the measured lengths using the length-weight regression described in Section D.1.1 (see Figure D.1 and Table D.2). The 1997 data were discarded because the small sample size (3) and only 138 fish measured yielded a mean weight (~0.7 kg) that was implausible and inconsistent with the rest of the series.

D.3.1. GLM Method

To remove some of the variance due to influential factors in the data, an additive lognormal model (Schnute et al. 2004) was used to adjust the annual index of fish weight for depth, longitude, latitude, and month:

$$\log_2 w_{ijklmn} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \lambda_m + \sigma\varepsilon_{ijklmn} \tag{D.5}$$

where, μ = the overall mean,

α_i = year effect (1998 to 2014 every calendar year),

β_j = depth effect (zones 125 m to 1075 m every 75 m),

γ_k = longitude effect (-134°W to -126°W every 1°),

δ_l = latitude effect (48°N to 54°N every 0.5°),

λ_m = month effect (1 to 12 every 1 month),

n = number of fish weight values, and

ε_{ijklmn} = independent residuals assumed to be standard normal N(0,1).

The restrictions placed on the data by the limits of the factors reduced the number of records from 31,628 to 30,850 (see Table D.10 for annual reductions). The fitted model had a residual standard error of 1.146 on 30,791 degrees of freedom (multiple R^2 = 0.1658, adjusted R^2 = 0.1642, Figure D.12).

The main purpose of the GLM fit was to adjust for trend in the annual indices of weight; however, the process rendered the scale of the indices relative. To transform the relative indices back to absolute, they were multiplied by the ratio of the geometric mean of the non-standardised annual indices (0.3947 kg/fish) to the geometric mean of the standardised indices (0.2963 kg/fish); see results in Table D.10.

$$w_{ai} = w_{si}\left[\left(\prod_{i=1998}^{2014} w_{ui}\right)^{1/17} \Big/ \left(\prod_{i=1998}^{2014} w_{si}\right)^{1/17}\right] \tag{D.6}$$

where, i = annual index (17 years from 1998 to 2014),

w_{ui} = unstandardized annual mean weights (kg/fish),

w_{si} = GLM-standardized annual mean weights (kg/fish), and

w_{ai} = adjusted GLM-standardized annual mean weights (kg/fish).

Table D.10. Annual mean weight (kg) per Shortspine Thornyhead caught by commercial bottom trawlers coastwide: w_{ui} = non-standardized (non-std), w_{si} = GLM-standardized (glm-std), w_{ai} = adjusted GLM-standardized (adj glm-std); number of fish used for (non-std) and (glm-std) calculations are also reported.

Year	# fish (non-std)	# fish (glm-std)	Fish weight (non-std)	Fish weight (glm-std)	Fish weight (adj glm-std)
1998	2345	2083	0.638189	0.393528	0.524251
1999	1199	1019	0.307458	0.226793	0.302129
2000	4495	4455	0.325338	0.166269	0.2215
2001	4241	4241	0.401662	0.267652	0.356561
2002	2831	2636	0.307356	0.208282	0.277469
2003	1596	1596	0.300652	0.260394	0.346892
2004	2699	2699	0.376527	0.282904	0.37688
2005	1791	1791	0.31007	0.254768	0.339397
2006	1845	1845	0.39283	0.306848	0.408777
2007	1661	1607	0.395606	0.355533	0.473634
2008	69	22	0.344442	0.28679	0.382055
2009	1747	1747	0.37452	0.312305	0.416047
2010	729	729	0.457554	0.361753	0.481921
2011	550	550	0.551864	0.431467	0.574792
2012	1287	1287	0.462434	0.317571	0.423062
2013	1914	1914	0.412753	0.299664	0.399207
2014	629	629	0.511964	0.463234	0.61711

The standardization (D.4) removed spatial effects but the review panel expressed concern over whether the annual mean weight pattern (Figure D.12) adopted for the coastal stock was consistently representative of the various regions (north, central, and south coasts). This concern stemmed from the possible northward movement of the fleet, primarily by vessels targeting Longspine Thornyhead (Haigh and Schnute 2003), which might manifest as increasing mean weight despite GLM standardization (e.g., through an interaction effect). The delay-difference model assumes that signals in mean weight trend result from recruitment, not spatial movement of the fishery.

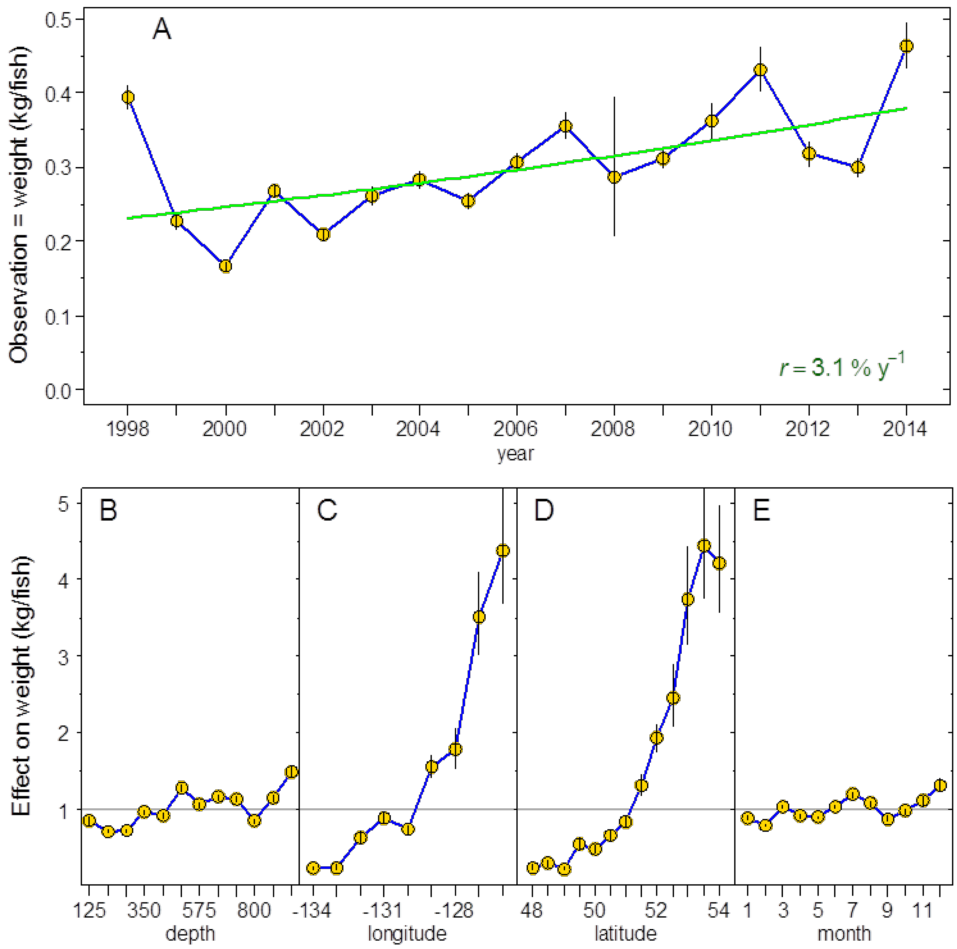

Figure D.12. Mean weight (kg/fish) of SST estimated from (D.4) as $\log_2 w$ from coastwide data: (A) year as $2^{\mu+\alpha_i}$, (B) depth zone as 2^{β_j}, (C) 1° longitude bands as 2^{γ_k}, (D) 0.5° latitude bands as 2^{δ_l}. and (E) month as 2^{λ_m}. Vertical error bars indicate 95% confidence limits. Green line in (A) shows the back-transformed linear fit through α_i, implying an annual increase of 3.1% per year.

To resolve some of the concern, we re-analysed the weight data using (D.4) in three separate regions – north coast (represented by PMFC 5DE and labelled 'WCHG'), central coast (represented by PMFC 5ABC and labelled 'QCS'), and south coast (represented by PMFC 3CD and labelled 'WCVI'). The annual indices of mean weight show that WCVI and WCHG both show increasing mean weight while the trend in QCS is negative but essentially flat (Figure D.13). The coastwide mean weight trend used in the assessment appears to be very similar to that in the WCVI region and is mirrored in the north, which supports a recruitment event coastwide. Additionally, the observed mean weights in the south and north were very similar (0.43 kg/fish). The central coast, on the other hand, appears to be anomalous with no trend and an observed mean weight of only 0.28 kg/fish. The depth distribution of length samples in these regions show that mean length did not increase very much with increasing depth (Figure D.14). The figure also illustrates that the majority (~84%) of the 10,360 length samples in PMFC area 5ABC were taken from depths between 200 and 400 m, and therefore may not represent the majority of the SST population in this region. Further exploration in future assessments using spatial modelling techniques (not yet developed) might resolve issues such as these.

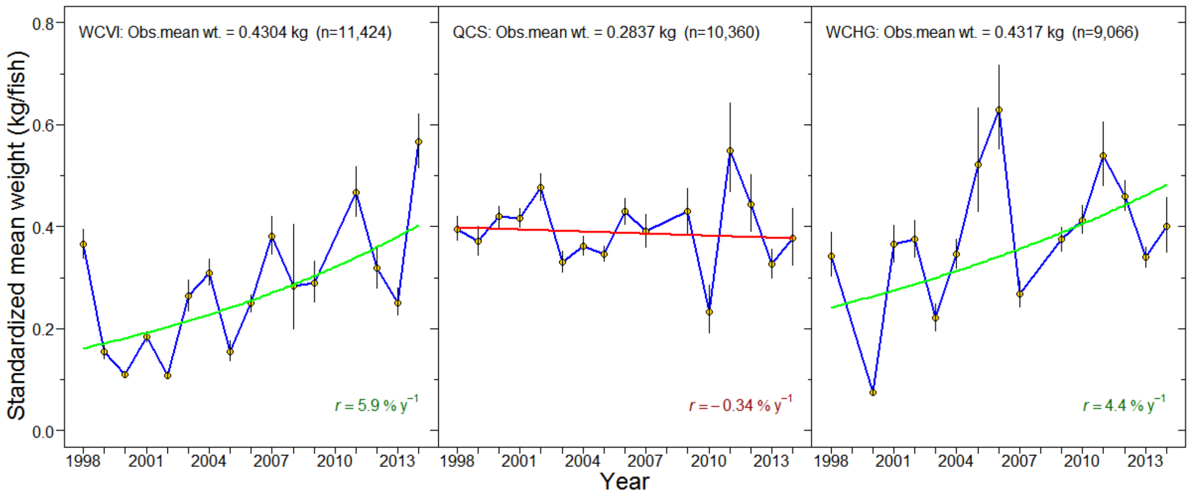

Figure D.13. Standardized mean weight (kg/fish) in three BC regions – west coast Vancouver Island (WCVI), Queen Charlotte Sound and Hecate Strait (QCS), and west coast of Haida Gwaii and Dixon Entrance (WCHG). Observed mean weights of the three series are displayed at top. Other details provided in caption for Figure D.1.

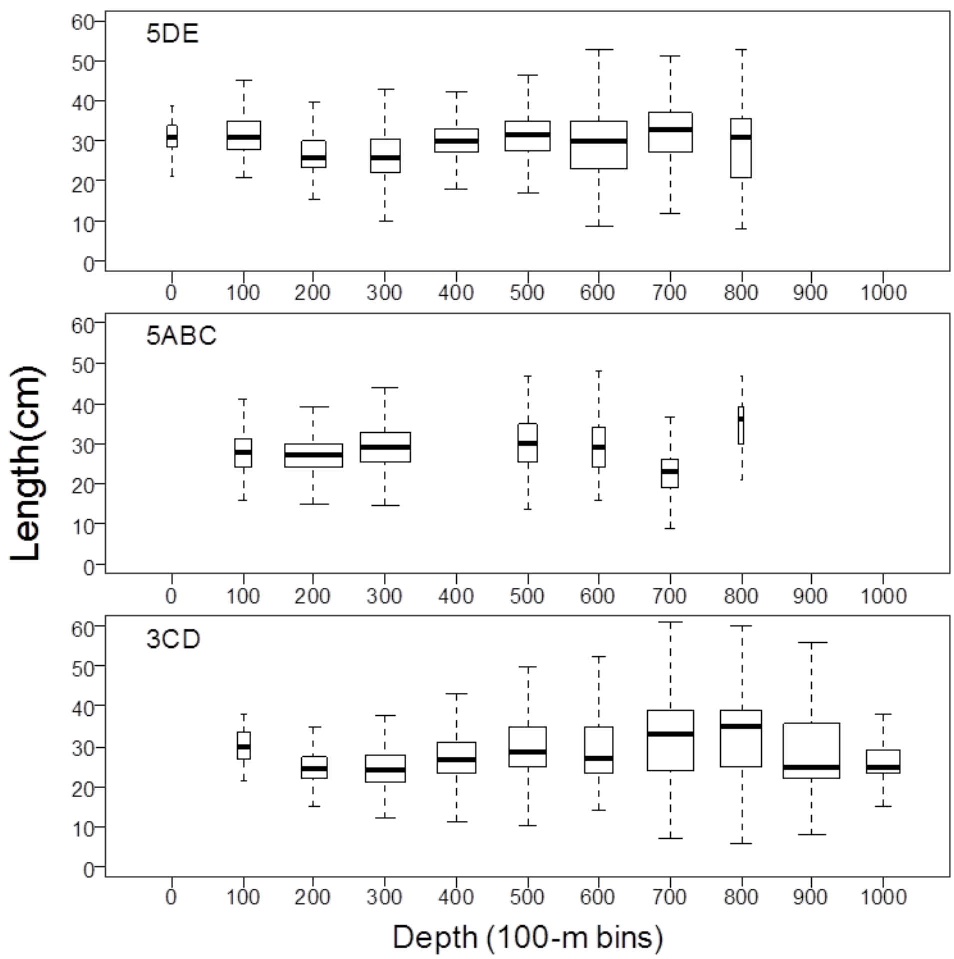

Figure D.14. Length (cm) of SST by depth (100m bin, where the label indicates the minimum depth in the bin) in three BC coastal areas – 3CD (west coast Vancouver Island), 5ABC (Queen Charlotte Sound and lower Hecate Strait), 5DE (west coast Haida Gwaii and Dixon Entrance). Note: box widths are proportional to the square root of the number of observations and outliers are excluded.

D.4. NATURAL MORTALITY

Ageing Shortspine Thornyhead otoliths is difficult because the otoliths are thin and the growth rings, particularly near the origin, are often ambiguous (Butler et al. 1995). The more usual break & burn preparation methodology may be potentially biased with this species and it is considered that a thin-sectioning technique is potentially more robust (Stephen Wischniowski, Sclerochronology Laboratory, PBS Nanaimo, pers. comm.). However, preliminary unpublished results from the PBS Sclerochronology Lab where the two methodologies were directly compared across four independent readers indicated no detectable bias when comparing ages determined by the two methods (see Table D.3). However, it is likely that the power to detect bias was low. Future studies will look at this more closely for both Thornyhead species.

In the DFO database GFBio (see Table D.4), the maximum age is 95 for a female specimen caught at 732 m in PMFC area 3C; however the mean age is only 18.7 y (n=1144) and the 0.99 quantile is 47 y. Bechtol (2000) reported that ages in Prince William Sound, Alaska, ranged from 5 to 89 with an average of 39.5 (n=50). Off California, Kline (2000) found maximum ages at ~80 y. Various laboratories using radiochemical techniques suggest that Shortspine Thornyheads might live to ages of ~100 y (Butler et al. 1995, Kastelle et al. 2000).

The current assessment does not use catch-at-age information as the data are insufficient and potentially biased by the ageing methodology. However, we do estimate natural mortality (*M*) using Quinn and Deriso (1999, p.361) based on Hoenig (1983):

$$M = -\ln(0.01)/t_m \tag{D.7}$$

where, t_m = maximum observed age reach by 1% of the population.

Using the maximum age observed in the DFO database t_m = 95 y, *M* = 0.048, which provides a lower bound on *M*, while an upper bound is calculated using t_m = 47 y (0.99 quantile), *M* = 0.098. Hoenig (1983) also mentions that sample size affects the maximum age observed and provides an equation for t_m that can be re-arranged to calculate total mortality *Z*:

$$Z = \frac{\ln(2n+1)}{(t_m - t_c)} \tag{D.8}$$

where *n* = sample size and t_c =youngest age fully represented in the catch. For our data, *n*=1144 and if we assume that t_c = 2y then *Z* = 0.083.

Given the above, our reference case fixes *M* = 0.08, which is higher than that used by US assessments of Shortspine Thornyhead (*M* = (0.03, 0.06) Rogers et al. 1997, *M* = (0.04, 0.06) Piner and Methot 2001, *M* = 0.05 Hamel 2005, *M* = 0.0505 Taylor and Stephens 2013).

D.5. HABITAT

Shortspine Thornyhead is ubiquitous along the BC coast, with an estimated area of occupancy ranging from ~42,500 km^2 using trawl occurrence (Figure 1) to ~50,500 km^2,using bathymetry limits (Figure D.15). The estimated bathymetry limits come from this species capture in 98% of bottom trawl tows that span depths 134 to 1032 m (Figure 2). The wide range of depths that it occupies is likely a function of its life cycle – juveniles settle into shallow water and migrate deeper as they grow bigger (Jacobsen and Hunter 1993). See Section 1.2 for more details. This species reportedly eats shrimps, amphipods, fishes, crabs, and other invertebrates; juveniles are often eaten by bigger Shortspines, while adults are eaten by marine mammals (Love et al. 2002).

Regional variations in depth distributions occur along the BC coast. Below we present three PMFC combinations that are typically used in stock assessments – 3CD (west coast Vancouver Island), 5ABC (Queen Charlotte Sound), and 5DE (west coast Haida Gwaii and Dixon Entrance).

The west coast of Vancouver Island (WCVI) has traditionally been fished to great depths due to favourable bathymetry (Figure D.16). The effort of the trawl fleet (shaded bars) along the WCVI appears to have three depth modes, with the shallowest being the highest. The effort on Shortspine Thornyhead has little in common with the first mode but increasingly matches fleet effort as depth increases. The species that occur in trawls catching Shortspine Thornyhead between 164 m and 1065 m appear in Figure D.17. The dominants are flatfish – Arrowtooth Flounder (*Atheresthes stomias*, 45.7% of total catch) and Dover Sole (*Microstomus pacificus*, 13.8%). Shortspine Thornyhead only accounts for 5.9% of the total catch in these tows.

The central coast comprises primarily Queen Charlotte Sound (QCS), which contains three important rockfish gullies – Goose Island Gully, Mitchell's Gully, and Moresby Gully. The effort of the trawl fleet in QCS is appears to be limited to depths shallower than 400 m (Figure D.18), whereas the effort on Shortspine Thornyhead shows a mode at ~300 m. This region is highly important to the Pacific Ocean Perch (POP, *Sebastes alutus*) fishery, and not surprisingly Figure D.19 shows a preponderance of POP (45.5% of total catch) in tows that catch Shortspine Thornyhead (only 2.5% of total catch).

The west coast of Haida Gwaii (WCHG), Dixon Entrance, and upper Hecate Strait are clearly dominated by shallow trawl effort (Figure D.20), which presumably indicates the targetting of flatfish in Hecate Strait. Trawls that capture Shortspine Thornyhead occur deeper than this and are dominated by catches of Pacific Ocean Perch (28.4% of total catch), Arrowtooth Flounder (19.7%), and Dover Sole (13.4%, Figure D.21). This region also sees the highest percentage (10.0% of catch weight) of Shortspine Thornyhead in depths where it's caught.

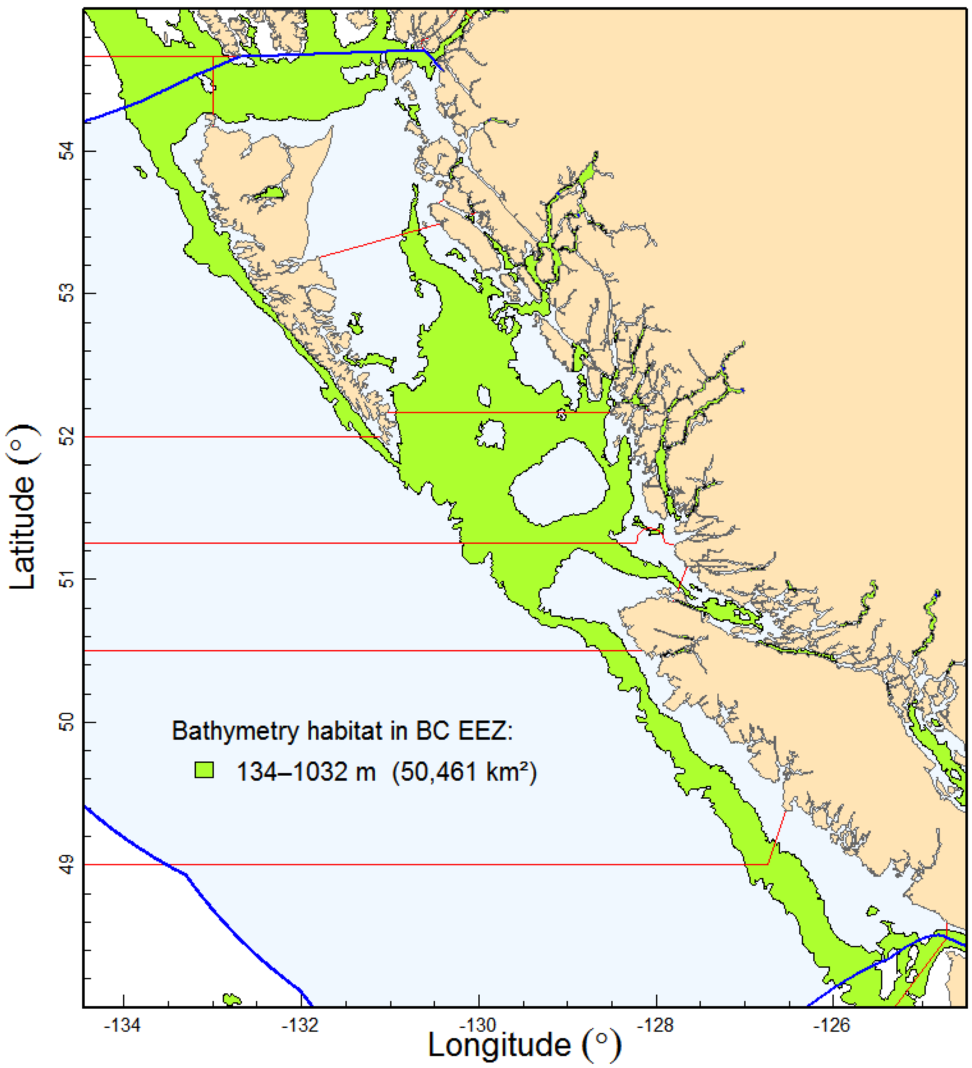

Figure D.15. Highlighted bathymetry (green) between 134 and 1032 m serves as a proxy for benthic habitat for Shortspine Thornyhead along the BC coast. The green highlighted region in Canada's exclusive economic zone (EEZ, blue highlighted area) covers 50,461 km^2. The boundaries in red delimit the PMFC areas.

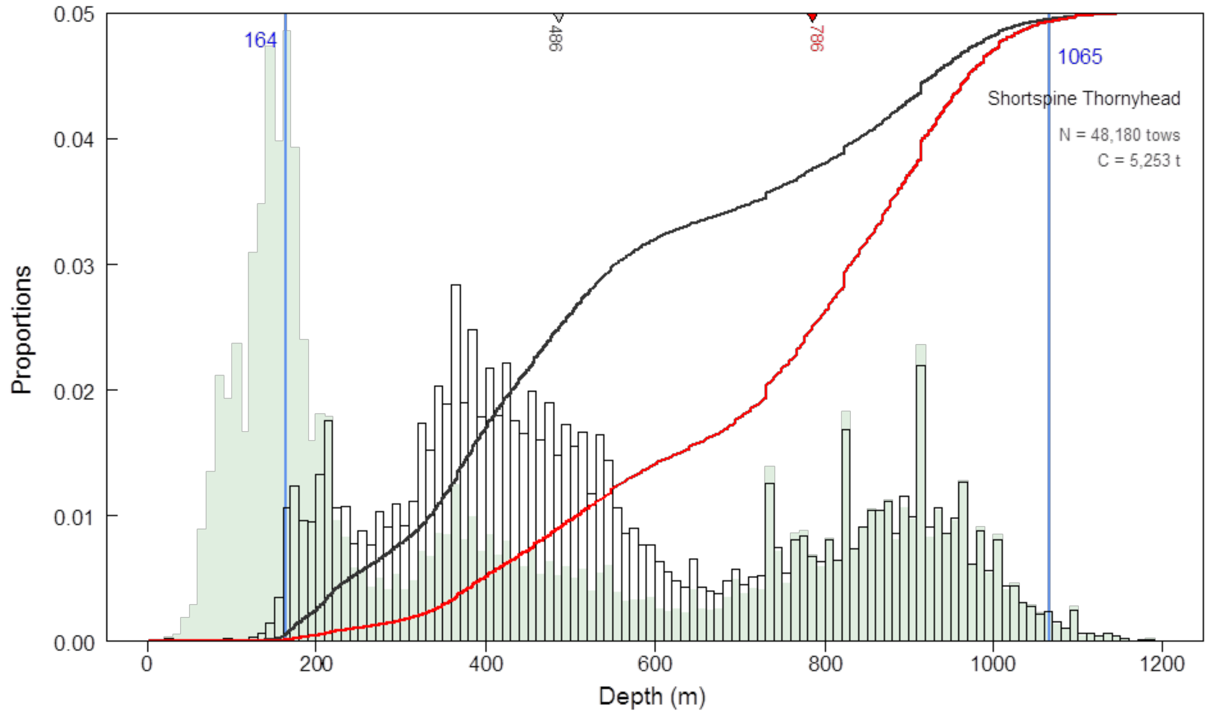

Figure D.16. Depth frequency of bottom tows that capture Shortspine Thornyhead (SST) from commercial trawl logs (1996-2007 in PacHarvest, 2007-2015 in GFFOS, where 2015 records are incomplete) in PMFC major areas 3CD (transparent histogram). The vertical solid lines denote the 1% and 99% percentiles. The black curve shows the cumulative frequency of tows that encounter SST while the red curve shows the cumulative catch of SST at depth (scaled from 0 to 1). The median depths of cumulative catch (inverted red triangle) and of SST encounters (inverted grey triangle) are indicated along the upper axis. 'N' reports the total number of tows; 'C' reports the total catch (t). The shaded histogram in the background reports the relative trawl effort on all species at all depths in 3CD (WCVI).

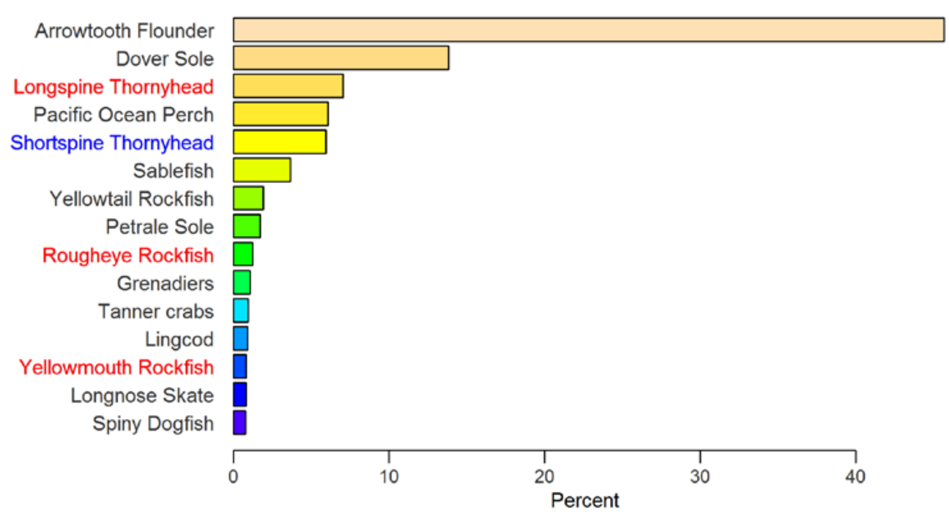

Figure D.17. Distribution of catch weights in 3CD summed over the period February 1996 to September 2015 for important finfish species in bottom tows that caught at least one Shortspine Thornyhead . Coastwide tows were selected over a depth range between 164 and 1065 m (the 1% and 99% quantile range). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Shortspine Thornyhead is indicated in blue on the y-axis; other species of interest to SARA are indicated in red.

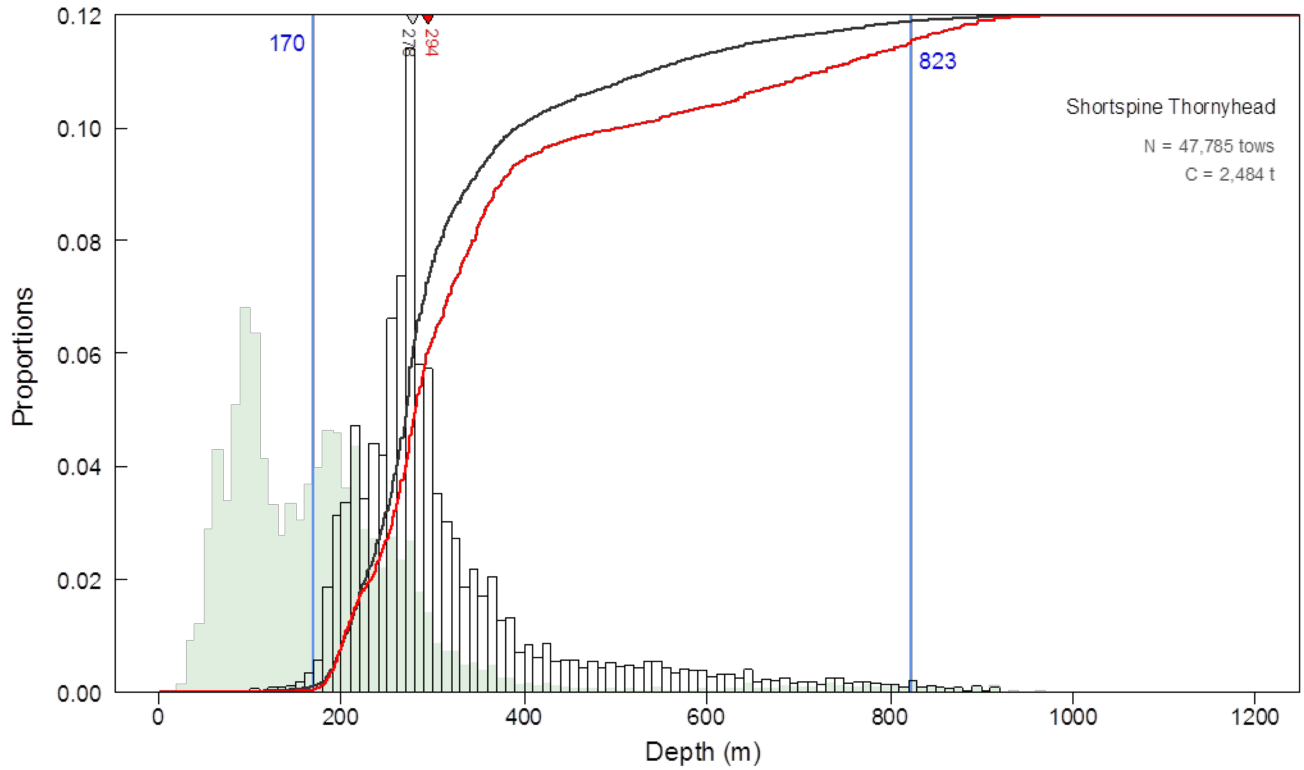

Figure D.18. Depth frequency of bottom tows that capture Shortspine Thornyhead (SST) from commercial trawl logs (1996-2007 in PacHarvest, 2007-2015 in GFFOS, where 2015 records are incomplete) in PMFC major areas 5ABC (transparent histogram). The shaded histogram in the background reports the relative trawl effort on all species at all depths in 5ABC (QCS). Plot details appear in Figure D.16.

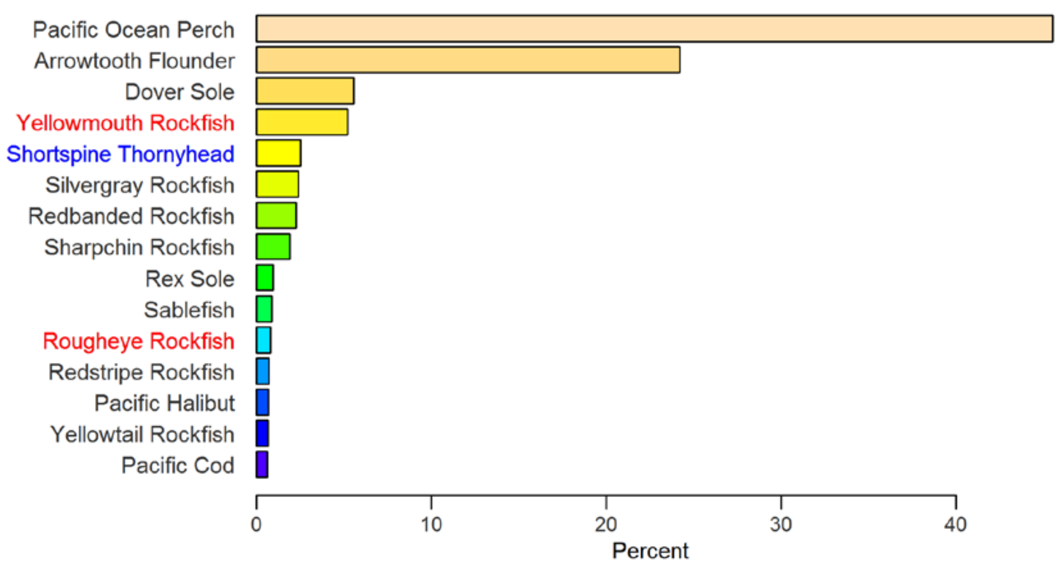

Figure D.19. Distribution of catch weights in 5ABC summed over the period February 1996 to September 2015 for important finfish species in bottom tows that caught at least one Shortspine Thornyhead . Coastwide tows were selected over a depth range between 170 and 823 m (the 1% and 99% quantile range). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Shortspine Thornyhead is indicated in blue on the y-axis; other species of interest to SARA are indicated in red.

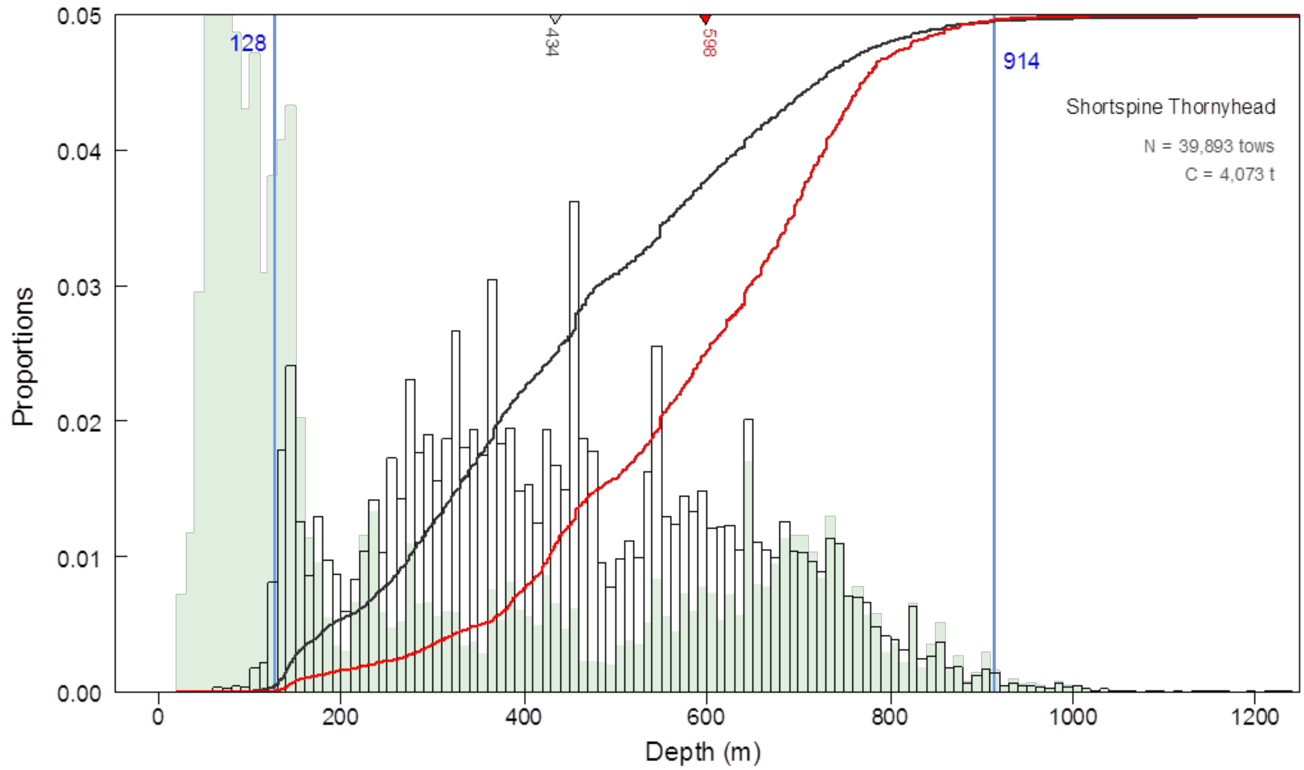

Figure D.20. Depth frequency of bottom tows that capture Shortspine Thornyhead (SST) from commercial trawl logs (1996-2007 in PacHarvest, 2007-2015 in GFFOS, where 2015 records are incomplete) in PMFC major areas 5DE (transparent histogram). The shaded histogram in the background reports the relative trawl effort on all species at all depths in 5DE (WCHG). Plot details appear in Figure D.16.

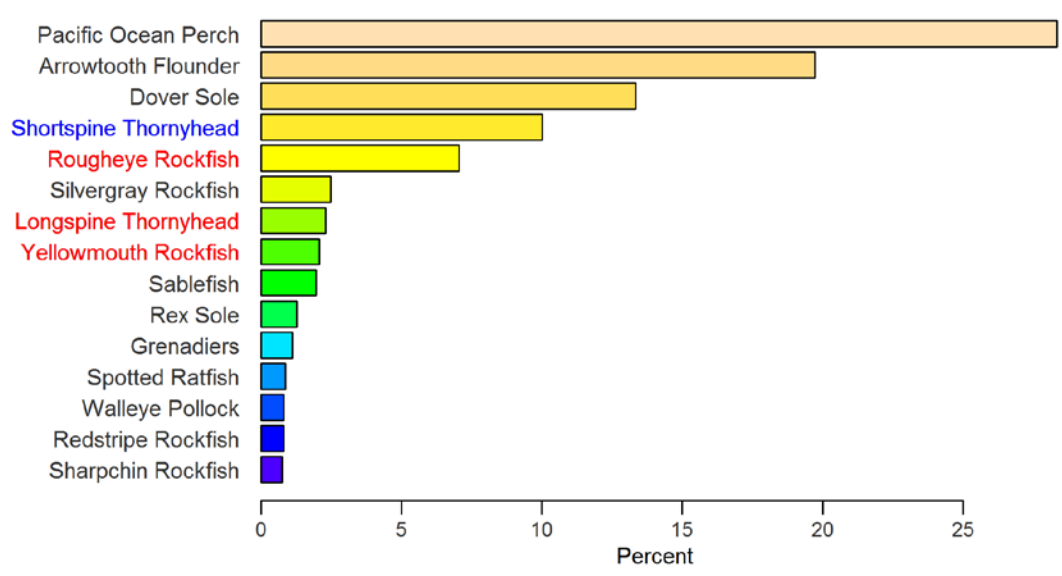

Figure D.21. Distribution of catch weights in 5CD summed over the period February 1996 to September 2015 for important finfish species in bottom tows that caught at least one Shortspine Thornyhead . Coastwide tows were selected over a depth range between 128 and 914 m (the 1% and 99% quantile range). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Shortspine Thornyhead is indicated in blue on the y-axis; other species of interest to SARA are indicated in red.

D.6. AGEING DIFFICULTIES

The following text was provided by Stephen Wischniowski from the Sclerochronology Lab at the Pacific Biological Station, Nanaimo BC. and modified by the authors for clarity only.

The process of age estimation for any species is dependent on the criteria developed to identify the characteristics that are unique to not only the species in question, but the structure selected and the technique(s) developed to estimate ages from that structure. An annulus is characterized by the ease with which it can be followed continuously from the sulcal groove to either the dorsal or ventral tips. The strength and uniformity of the summer and winter growth zones (annuli) coupled with the expected spacing between these annuli in reference to the earlier growth is used to determine an ageing pattern, and used to differentiate true annuli from checks. Checks are defined as growth zones, or parts of growth zones, that do not form annually, and reflect various environmental or physiological pressures encountered by the individual. As individuals undergo maturation and migrate with respect to latitude and depth, the width of annuli, and the spacing in-between these annuli, begin to decrease in a pattern reflective of the rate of change of these movements. Age estimation criteria must take all this, and more, into consideration.

The difficulties encountered with estimating the ages of Shortspine Thornyhead for the 2015 Groundfish assessment are as follows:

1. The thornyhead complex has not been historically aged in the Sclerochronology Lab. The historic ages generated to date (i.e., 1995, 1997, 2006) were exploratory in nature – to determine the plausibility of creating criteria for a future age requests. Ultimately, it was determined that the development of criteria would require several years to complete because of the difficultly in ageing this species. Subsequently, the original request was dropped as was the development of any ageing criteria.
2. No ageing criteria currently exist for Shortspine Thornyhead.
3. The 2014 age request for Shortspine Thornyhead did not provide enough lead time to pick up from the historic study.
4. The 2015 review of the historic documentation and subsequent “Break and Burn” (BB) review of newly selected structures determined:
    a. difficulty in producing quality burns;
    b. the lack of quality burns resulted in vague patterns due to poor contrast between summer/winter growth zones;
    c. difficulty in locating the first three years;
    d. many split/double annuli in the first 15 years made identification of the transitional growth zone from juvenile to the adult phase difficult to interpret;
    e. uneven growth patterns in the mature stages of life (>20 y).
5. The lack of older specimens (>50 y) in the 1995, 1997 and 2006 ages, together with validated (Radiometric and Bomb Carbon) longevity (up to 100 years) of SST suggests that a different otolith preparatory methodology should be considered. A thin-sectioning (TS) technique was employed based on its ability to resolve the fine micro-structure of older specimens. Some issues regarding TS include:
    a. the sulcal groove was determined to be the most promising reading plane, yielding superior results compared to BB samples;
    b. difficulty in determining the first year;

c. many fine checks, which may or may not be annuli;

d. uneven growth pattern in the mature stages of life (>20 y).

Comparison of Break-Burn and Thin-Section Methods

The comparison study of the BB and TS techniques indicated:

1. Coefficient of variation (CV) and average percent error (APE) between agers for the BB technique were very poor and resulted in a very high averaged net bias (unpublished analysis).
2. CV and APE between agers for the TS technique, although high, were lower than those for the BB technique. The averaged net bias was substantially lower than for the BB, indicating agers were better at identifying winter annuli (unpublished analysis).
3. Maximum ages were higher for the TS technique, indicating that this methodology is better suited for interpreting annuli in otoliths for this long-lived species.
4. Overall precision comparisons, although not great, were better with the TS technique indicating agers had better agreements when structures were thin-sectioned.
5. Although the TS technique produces better age estimates than does BB, ageing criteria still need to be established for Shortspine Thornyhead using this technique.

D.7. REFERENCES – BIOLOGY

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APPENDIX E. DELAY-DIFFERENCE MODEL

E.1. INTRODUCTION

The software used in this stock assessment is a variant of the integrated Statistical Catch Age Model (iSC∀M), developed by Steven Martell (Martell, 2010) and modified by Robyn Forrest (DFO PBS, pers. comm.) to run a delay-difference (DD) model for Pacific Cod (*Gadus macrocephalus*) on the west code of Canada (Forrest et al., 2015). The DD model was written in AD Model Builder template code (Fournier et al., 2012) and was compiled using the PBSadmb package (Schnute et al., 2015).

E.2. DELAY-DIFFERENCE MODEL

Delay difference models represent an intermediate approach between aggregated surplus production models and age-structured models. The delay-difference structure tracks the effects of recruitment, survival and growth on biomass, without requiring an age-structured framework, and can perform well as long as its major assumptions are met (Hilborn and Walters, 1992). Difference equations, which allow for a time-delay between spawning and recruitment, are used to build population models in discrete time-steps (generally 1 year), in which the surviving biomass for next year is predicted from the surviving biomass from last year, after adjusting for growth and adding next year's recruitment. An advantage of delay difference models over simpler production models is that they do not assume constant recruitment over time.

The key assumptions of the delay difference model are:

- Growth in mean body weight W_a follows the linear relationship described by the Ford-Walford equation (E.1); see Section D.1.4.

$$W_a = \alpha_g + \rho_g W_{a-1} \tag{E.1}$$

- Knife-edge selectivity, i.e., all fish aged k and older, are equally vulnerable to the fishing gear. A corollary to the assumption of knife-edge selectivity is that maturity is also knife-edge and the same as selectivity. This means that all fish in the model are mature and fully selected; and
- Mortality at age remains constant, i.e., all fish aged k and older have the same mortality rate.

The delay difference model collapses all the equations needed to fully describe the population's age structure into equations for the total numbers (N_t), biomass (B_t), and survival (S_t) at time t:

$$B_t = S_{t-1}(\alpha_g N_{t-1} + \rho_g B_{t-1}) + w_k R_t \tag{E.2}$$

$$N_t = S_{t-1} N_{t-1} + R_t \tag{E.3}$$

$$S_t = e^{-(M+F_t)}, \tag{E.4}$$

where:

S is the survival rate;
M is natural mortality;
F is the estimated instantaneous fishing mortality rate;
α_g and ρ_g are the intercept and slope of the Ford-Walford equation for all ages $\geq k$, where k is the age at which fish are assumed to become fully vulnerable to fishing;
w_k is the weight at age k; and
R_t is the assumed stock-recruit function, here constrained to conform to a Beverton-Holt relationship with constants a and b (E.26).

We assume that recruitment to the fishery and surveys occurs at age 16 (i.e., k = 16y) in the reference case.

A list of model parameters is given in Table E.1. Equilibrium and dynamic equations are given in Tables E.2 and E.3, respectively. Variance parameters and likelihood components of the objective function are given in Table E.4.

E.2.1. Objective function components

Variance parameters and objective function components are listed in Table E.4. The objective function $f(\theta)$ in the delay-difference model contains five major components:

1. the negative log-likelihood for the relative abundance data (E.33);
2. the negative log-likelihood for the catch data (E.35);
3. the negative log-likelihood for the mean weight data (E.37);
4. the prior distributions for model parameters, and
5. three penalty functions that:
   a. constrain the estimates of annual recruitment to conform to a Beverton-Holt stock-recruit function;
   b. weakly constrain the log recruitment deviations to a normal distribution; and
   c. weakly constrain estimates of log fishing mortality to a normal distribution, N (ln(0.2), 4.0), to prevent estimates of catch from exceeding estimated biomass.

E.2.2. Variance components and weighting of index data

The iSC∀M modelling framework (Martell, 2010) partitions the variance using an errors in variables approach. Total variance ϕ^{-2} can be fixed or estimated, and was fixed for the SST delay-difference model. Total variance is partitioned by the model into observation and process error components using the parameter ρ, which represents the proportion of the total variance that is due to process error (Punt and Butterworth, 1993; Deriso et al., 2007). This parameter was also fixed in the SST model and sensitivities to these two components were examined through runs that fixed these two parameters at alternative values.

The standard deviation used when fitting the survey and CPUE abundance index data is given in equation (E.27), with each index value weighted by the inverse of the CV associated with that index, as shown in equation (E.29). The index variance is added to the total likelihood as shown in (E.33). Five surveys and one CPUE index series were fitted in this model. The relative sampling error (CV$_{jt}$) associated with each survey index value was used without adding additional process error. A relative error of 0.3 was assumed for each CPUE index value. We did not attempt to alter the relative weights of the component data series (Francis, 2011), instead using the observation error CVs estimated by the surveys without modification. The process error component of the total variance is given in equation (E.28) and is applied to the estimated recruitments as shown in equation (E.39).

E.3. REFERENCES POINTS, PROJECTIONS AND ADVICE TO MANAGERS

Advice to managers is given with respect to three reference points based on the maximum sustainable yield (MSY).The provisional reference points of the DFO Precautionary Approach (DFO, 2006), namely $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$ comprise the primary benchmarks for advice, where B_{MSY} is the estimated equilibrium spawning biomass at MSY. The third reference point is u_{MSY}, the harvest rate at MSY, and is derived from instantaneous fishing mortality at MSY: $u_{\mathrm{MSY}} = (1 - e^{-F_{MSY}})$.

B_{MSY} was estimated by projecting the model forward across a range (0.01 to 0.40 in increments of 0.01) of constant fishing mortlity rates (F_t) for 200 years, allowing sufficient time to reach equilibrium. MSY was defined as the largest equilibrium yield found in this search, with the associated exploitation rate being F_{MSY} and the associated biomass being B_{MSY}. This calculation was done for each of the 1,000 MCMC samples, resulting in marginal posterior distributions for MSY, F_{MSY}, and B_{MSY}.

The probability P$(B_{2016} > 0.8B_{\mathrm{MSY}})$ is calculated as the proportion of the 1,000 MCMC samples for which $B_{2016} > 0.8B_{\mathrm{MSY}}$ (and similarly for the other reference points).

Projections were made for only 3 years due to the model's inherent uncertainty and its lack of associated age structure, starting with the biomass calculated for the start of 2016, across a range of constant catch strategies. For each strategy, projections were performed for each of the 1,000 MCMC samples (resulting in posterior distributions of future spawning biomass).

Recruitments for the projections were randomly generated from lognormal recruitment deviations applied to the deterministic recruitment estimate from the B-H stock-recruitment function, using randomly generated values of $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. For each of the 1,000 MCMC samples a time series of $\{\epsilon_t\}$ was generated. For each MCMC sample, the same time series of $\{\epsilon_t\}$ was used for each catch strategy so that, for a given MCMC sample, all catch strategies experience the same recruitment stochasticity.

Table E.1. Notation for the delay-difference model.

Symbol	Description	DFO case
	Indices (subscripts)	
t	Model year, where $t = 1980, 1981, ..., 2015$;	
	and $t = 1980$ represents unfished equilibrium conditions	
j	Gear (fishery or index of abundance)	1–7
g	Ford-Walford identifier	
v	von Bertalanffy identifier	
	Fixed input parameters	
k	Age at knife-edge recruitment	16
L_∞	Theoretical maximum length (cm)	47.257
κ	von Bertalanffy growth rate	0.0385
t_0	Theoretical age at length = 0 cm	-8.456
a_v	Scaling parameter of the length-weight relationship	7.035e-6
b_v	Exponent of the length-weight relationship	3.166
α_g	Intercept of the Ford-Walford plot, for all ages > k	0.0297
ρ_g	Slope of the Ford-Walford plot, for all ages > k	0.9859
W_k	Weight at age of recruitment k	0.2939
M	Natural mortality (in natural log space)	ln(0.08)
	Annual input data	
C_{jt}	Catch (metric tonnes) for gear j=1 (total commercial) at time t	
W_t	Mean weight (kg) of individuals in population at time t	
I_{jt}	Indices of abundance for gear j at time t, where	
	j=2 – National Marine Fisheries Service Triennial survey series	
	j=3 – West Coast Vancouver Island synoptic survey series	
	j=4 – Queen Charlotte Sound synoptic survey series	
	j=5 – Hecate Strait synoptic survey series	
	j=6 – West Coast Haida Gwaii synoptic survey series	
	j=7 – commercial SST CPUE (catch per unit effort) series	
CV$_{jt}$	Annual coefficients of variation for I_{jt}	
	Time-invariant parameters	
R_0	Equilibrium unfished age-0 recruits (est. as natural logarithm)	
h	Steepness of the stock-recruit relationship	
χ	Recruitment compensation ratio (CR)	
a	Slope of the stock-recruit function at the origin	
b	Scaling parameter of the stock-recruit function	
N_0	Equilibrium unfished number of fish	
B_0	Equilibrium unfished biomass (t)	
S_0	Equilibrium unfished survival rate	
$\overline{W}_0$	Equilibrium unfished mean weight (kg)	

Symbol	Description	DFO case
	Time-varying parameters (at time t)	
ω_t	Ln-recruitment deviations (in log space)	
F_t	Fishing mortality (in log space) by the commercial fishery	
S_t	Survival rate	
N_t	Numbers of fish	
R_t	Recruits (1000s fish)	
B_t	Biomass (tonnes)	
$\overline{W}_t$	Predicted mean weight (kg)	
	Likelihood components	
σ_O	Overall standard deviation of observation residuals	0.2
σ_R	Standard deviation of ln-recruitment deviations	0.6
σ_W	Standard deviation of mean weight	0.15
σ_{jt}	Annual standard deviation of observation residuals for each survey	
σ_C	Standard deviation of catch	
ϕ^{-2}	Inverse of the total variance (total precision)	
ρ	Proportion of total variance due to observation error	
q_j	Constant of proportionality in indices of catchability (in log space)	
d^2_{jt}	Residual log difference for I_{jt} indices of abundance	
$d^2_{C_t}$	Residual log difference for catch data	
$d^2_{W_t}$	Residual log difference for mean weight data	
	Fishery reference points	
MSY	Maximum sustainable yield (t)	
B_{MSY}	Long-term fixed spawning biomass at MSY	
F_{MSY}	Long-term fixed fishing mortality that produces MSY	
u_{MSY}	Long-term fixed harvest rate that produces MSY $(1 - e^{-F_{\mathrm{MSY}}})$	

Table E.2. Summary of equilibrium equations for the delay-difference model.

Description	Equations	
Initialization at equilibrium with $F = 0$		
Unfished survival	$S_0 = e^{-M}$	(E.5)
Unfished mean weight	$\bar{W}_0 = \dfrac{S_0 \alpha_g + W_k(1 - S_0)}{1 - \rho_g S_0}$	(E.6)
Unfished numbers	$N_0 = \dfrac{R_0}{1 - S_0}$	(E.7)
Unfished biomass	$B_0 = N_0 \bar{W}_0$	(E.8)
Recruitment compensation ratio (CR)	$\chi = \dfrac{4h}{1 - h}$	(E.9)
Stock-recruit parameters	$a = \chi \dfrac{R_0}{B_0}; \quad b = \dfrac{\chi - 1}{B_0}$	(E.10)
Initialization at equilibrium with $F_e > 0$		
Survival at F_e	$S_e = e^{-(M+F_e)}$	(E.11)
Mean weight at F_e	$\bar{W}_e = \dfrac{S_e \alpha_g + W_k(1 - S_e)}{1 - \rho_g S_e}$	(E.12)
[1]Biomass at F_e	$B_e = -\dfrac{\left(-\bar{W}_e + S_e \alpha_g + S_e \rho_g \bar{W}_e + W_k a \bar{W}_e\right)}{b\left(-\bar{W}_e + S_e \alpha_g + S_e \rho_g \bar{W}_e\right)}$	(E.13)
Fisheries reference points at equilbrium fishing mortality F_e		
Fishing mortalities	$\gamma = \{0.01, 0.02, ..., 0.40\}$	
Years to equilibrium	$t = \{2016, ..., T\}$, where $T = 2016 + 200$	
Biomass	$B_{\gamma t} = S_{\gamma,t\text{-}1} \rho_g B_{\gamma,t\text{-}1} + \alpha_g N_{\gamma,t\text{-}1} + W_k R_{\gamma t}$	(E.14)
Numbers	$N_{\gamma t} = S_{\gamma,t\text{-}1} N_{\gamma,t\text{-}1} + R_{\gamma t}$	(E.15)
Survival	$S_{\gamma t} = e^{-(M+\gamma)}$	(E.16)
Long-term yield	$Y_{\gamma T} = \quad 1 - e^{-\gamma} \quad B_{\gamma T}$	(E.17)
MSY	$Y_e = \max\{Y_{\gamma T}\}$	(E.18)
Biomass at MSY	$B_e = B_{\gamma T}, \quad \text{for } \gamma \text{ when } Y_e = Y_{\gamma T}$	(E.19)
Fishing mortality at MSY	$F_e = F_{\gamma T}, \quad \text{for } \gamma \text{ when } Y_e = Y_{\gamma T}$	(E.20)

[1] Steven Martell (Sea State Inc., Seattle WA, pers. comm.)

Table E.3. Time-dynamic equations and likelihood components for the delay-difference model.

Description	Equations	
Time-dynamic equations		
Survival rate	$S_t = e^{-M+F_t}$	(E.21)
Biomass	$B_t = S_{t-1}\left(\alpha_g N_{t-1} + \rho_g B_{t-1}\right) + W_k R_t$	(E.22)
Recruits	$R_t = R_0\ e^{\omega_t - 0.5\sigma_R^2}$	(E.23)
Predicted variables used in objective function		
Predicted catch	$\widehat{C}_t = B_t \frac{F_t}{(F_t + M)}\left(1 - e^{-(F_t+M)}\right)$	(E.24)
Predicted mean weight	$\widehat{W}_t = \frac{B_t}{N_t}$	(E.25)
Predicted recruits	$\widehat{R}_t = \frac{aB_{t-k+1}}{1 + bB_{t-k+1}}$	(E.26)

Table E.4. Calculation of variance parameters, residuals, and likelihoods.

Description	Equations	
Variance parameters (SD = standard deviation)		
SD of abundance index residuals	$\sigma_O = \sqrt{\frac{\rho}{\phi^{-2}}}$	(E.27)
SD of recruitment residuals	$\sigma_R = \sqrt{\frac{1-\rho}{\phi^{-2}}}$	(E.28)
SD of abundance index observations	$\sigma_{jt} = \sigma_O \mathrm{CV}_{jt}$	(E.29)
Indices of abundance		
Residuals	$z_{jt} = \log\left(I_{jt}\right) - \log\left(\widehat{B}_t\right)$	(E.30)
	$\bar{z}_j = \frac{1}{n_j} \sum_t^{n_j} z_{jt}$	(E.31)
	$d_{jt} = z_{jt} - \bar{z}_t$	(E.32)
Natural log likelihood	$L_{jt} = \log \quad \sigma_{jt}^2 \quad + \frac{d_{jt}^2}{2\sigma_{jt}^2}$	(E.33)
Catch		
Residuals	$d_{C_t} = \log\left(C_t\right) - \log\left(\widehat{C}_t\right)$	(E.34)
Ln likelihood	$L_t = \log \quad \sigma_C^2 \quad + \frac{d_{C_t}^2}{2\sigma_C^2}$	(E.35)
Mean weight		
Residuals	$d_{W_t} = \log\left(\overline{W}_t\right) - \log\left(\widehat{\overline{W}}_t\right)$	(E.36)
Ln likelihood	$L_t = \log \quad \sigma_W^2 \quad + \frac{d_{W_t}^2}{2\sigma_W^2}$	(E.37)
Recruitment		
Residuals	$d_{R_t} = \log\left(R_t\right) - \log\left(\widehat{R}_t\right)$	(E.38)
Ln likelihood	$L_t = \log \quad \sigma_R^2 \quad + \frac{d_{R_t}^2}{2\sigma_R^2}$	(E.39)

E.4. REFERENCES – MODEL EQUATIONS

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APPENDIX F. MODEL RESULTS

F.1. INTRODUCTION

This appendix describes the results from the mode of the posterior distribution (MPD) (to compare model estimates to observations), diagnostics of the Markov chain Monte Carlo (MCMC) results, and the MCMC results for the estimated parameters and derived parameters for 34 model runs. All final advice and major outputs are based on the MCMC results. Estimates of major quantities and advice to management (such as decision tables) are also presented in the main document.

Biological data from DFO sources suggest a BC productivity regime different from those to the north (Alaska) and to the south (Washington, Oregon, and California) for Shortspine Thornyhead. Specifically, there appear to be a lack of old and large fish off BC's coast. Whether this situation represents the ecological situation in these waters or is simply the result of unrepresentative sampling is not known at present. Regardless, the DFO data generate growth curves that are significantly different from those derived by the US National Marine Fisheries Service (NFMS) (e.g., Taylor and Stephens 2013). Our best estimate of natural mortality (M=0.08) based on fish ages is also different from those in the US (M=0.05), but this, in part, may be due to ageing error. For these reasons, there is substantial uncertainty in specifying the productivity of this stock as well as other key assumptions, such as age at full knife-edge recruitment, that go into the delay difference model. Unfortunately, because the available data, which consist of biomass index series which show little contrast and a mean weight index series that is increasing, are uninformative with respect to these assumptions, it was not possible to objectively rule out a wide range of alternate hypotheses for key model parameters Consequently, we have adopted a "model averaging" approach to this assessment, where 12 contributing model runs which represent the range of plausible hypotheses, are used to construct a "composite reference scenario" for providing advice to managers (Section F.4.4.).

F.2. EXAMPLE MODEL RUN USING DFO GROWTH MODEL

This example model run using the DFO growth model included the following elements:

- M fixed at 0.08;
- knife-edge recruitment at age k = 16;
- GLM mean weight annual indices scaled to the arithmetic mean weight;
- observation error σ_O = 0.2;
- recruitment error σ_R = 0.6;
- mean weight error σ_W = 0.15;
- uniform priors on q with bounds -10 to 0;
- catch series based on 1996 proportions for SST to allocate pre-1996 catch (use 1996 ratios in strata 3CD and 5ABCDE: SST$_L$/ (SST$_L$ + LST$_L$) and SST$_D$/SST$_L$, where L= landed and D= discarded);
- h beta prior (mean=0.7, SD=0.15);
- equilibrium start in 1980.

F.2.1. MPD results - example

The mode of the posterior distribution (MPD) for each estimated parameter (reported in Table F.1) is estimated by minimising the objective function (components summarised in Section E.2.1). The results here are presented to show the fits by the model to the observed data and are used as the starting point for the MCMC simulations. MPD fits are shown for the abundance indices (Figure F.1) and the mean weights (Figure F.2). The fits to the survey and CPUE indices are generally reasonable although the model is incapable of fitting the abrupt changes in some series. The model is not capable of fitting the generally increasing trend in mean weight that follows an initial drop in 1998 (Figure F.2). Instead it remains fairly constant near the mean of the series, effectively ignoring the upward trend in the data. Model runs that attempted to improve the fit to this index series by reducing the CV from 0.15 to 0.05 showed some improvement in the fit to mean weight; however, fits to the biomass indices deteriorated. Fits to the catch data are not presented because the model is parameterised so that it always fits the catch closely.

F.2.2. MCMC results - example

The MCMC procedure performed 51,500,000 iterations, sampling every 5,000 to give 1,030 MCMC samples. The initial chain of 1,500,000 was run as a "burn-in" as well as allowing the MCMC search to rescale to obtain an appropriate sampling rate. These initial samples were discarded (including the MPD start point) and the final posterior contained 1000 samples which were used to estimate parameters and quantities of interest, including stock status by year and the probabilities of being above reference points.

MCMC traces show good convergence properties (no trend with increasing sample number) for the leading estimated parameters (Figure F.3), as does a diagnostic analysis that splits the samples into three segments, checking for consistency along the length of the chain (Figure F.4). Autocorrelation appears to be minimal (Figure F.5). Pairs plots of the estimated parameters (Figure F.6) show no undesirable correlation between the two primary parameters, ln(R_0) and h, though all the q parameters were highly correlated with ln(R_0), as would be expected. MCMC quantiles for parameters, biomass, and maximum sustainable yield (MSY) are summarised in Table F.1.

Marginal posterior distributions along with the corresponding priors for the estimated parameters are shown in Figure F.7. Only the steepness parameter used an informative prior, with its posterior distribution shifting a small amount away from the prior. This indicates that there was relatively little information in this model to inform this parameter and it is unlikely that it could be estimated without using a prior.

The plot of biomass (Figure F.8) shows an expected decline once catch started to increase in the early to mid-1990s. This model run estimates a strong recruitment pulse in 1999 (Figure F.9), possibly as a response to the increased catches but more likely to fit the drop in mean weight observed in 1998 and 1999. The decline in biomass reverses with this recruitment pulse, as well as in response to lower fishing mortality which is associated with reduced catch levels after 2000 (see Figure A.2). Fishing mortality peaks in 1995 (Figure F.10) at a median F value of 0.165 y^{-1} and declines until it reaches 0.053 y^{-1} in 2015. The median value (and the 5th and 95th percentiles in parentheses) for the estimated level of biomass depletion (B_t/B_0) at the end of the final year of the reconstruction is 1.22 (0.84, 1.85), with the MPD value of 0.84 lying at the lower end of the posterior distribution of this quantity (Figure F.10). This result is caused by the MCMC search giving plausibility to larger biomass levels than were obtained by the MPD best fit to the data observations.

Table F.1. The 5th, 50th, and 95th percentiles of MCMC-derived parameter estimates and quantities from 1,000 MCMC samples for the example model run. Some fixed parameters are reported as MPD only. See Appendix E for paramater definitions. Subscripts 1-5 on q refer to the fishery-independent surveys, subscript 6 refers to the commercial trawl CPUE series. Other definitions: B_0 – unfished equilibrium biomass (mature females), B_{2016} – biomass at the start of 2016, u_{2015} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2015, B_{MSY} – equilibrium biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

	5%	50%	95%	MPD
Parameters				
R_0	706	1,013	1,492	1,149
h	0.539	0.775	0.939	0.823
M				0.08
q_1	0.0221	0.0322	0.0433	0.0357
q_2	0.0193	0.0332	0.0491	0.0465
q_3	0.0737	0.123	0.182	0.169
q_4	0.0218	0.0368	0.0543	0.0504
q_5	0.0794	0.137	0.206	0.194
q_6	0.000084	0.00014	0.000205	0.000191
Model-based				
0.2B_0	1,023	1,468	2,161	1,664
0.4B_0	2,045	2,935	4,321	3,329
B_0	5,114	7,338	10,803	8,322
B_{2016}	5,662	8,940	15,437	7,013
B_{2016}/B_0	0.831	1.22	1.85	0.843
u_{2015}	0.0295	0.0512	0.0798	0.0659
MSY-based				
0.4B_{MSY}	572	998	1,687	1,026
0.8B_{MSY}	1,143	1,996	3,375	2,051
B_{MSY}	1,429	2,495	4,219	2,564
B_{MSY}/B_0	0.212	0.344	0.496	0.308
$B_{2016}/B_{\mathrm{MSY}}$	2.12	3.56	6.46	2.73
MSY	237	356	532	422
u_{MSY}	0.0769	0.139	0.267	0.165
$u_{2015}/u_{\mathrm{MSY}}$	0.164	0.361	0.745	0.4

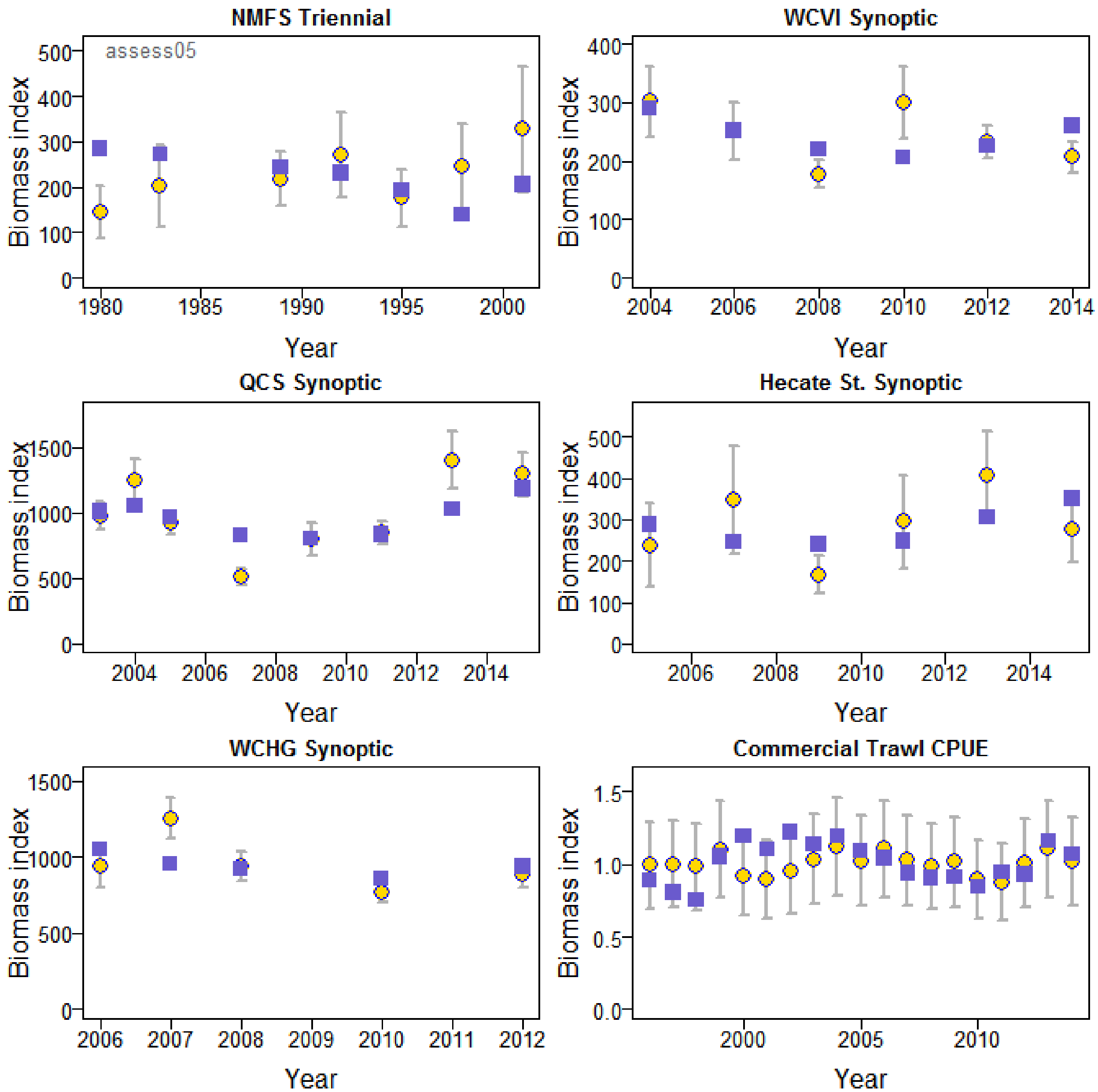


Figure F.1. Example model run: MPD index fits for relative abundance indices. Circles represent observed indices with associated CVs; squares represent the model fit. Surveys: (1) NMFS (US National Marine Fisheries Service) Triennial, (2) WCVI (west coast Vancouver Island) Synoptic, (3) QCS (Queen Charlotte Sound) Synoptic, (4) HS (Hecate Strait) Synoptic, and (5) WCHG (west coast Haida Gwaii) Synoptic; CPUE: (6) commercial trawl catch per unit effort of Shortspine Thornyhead.

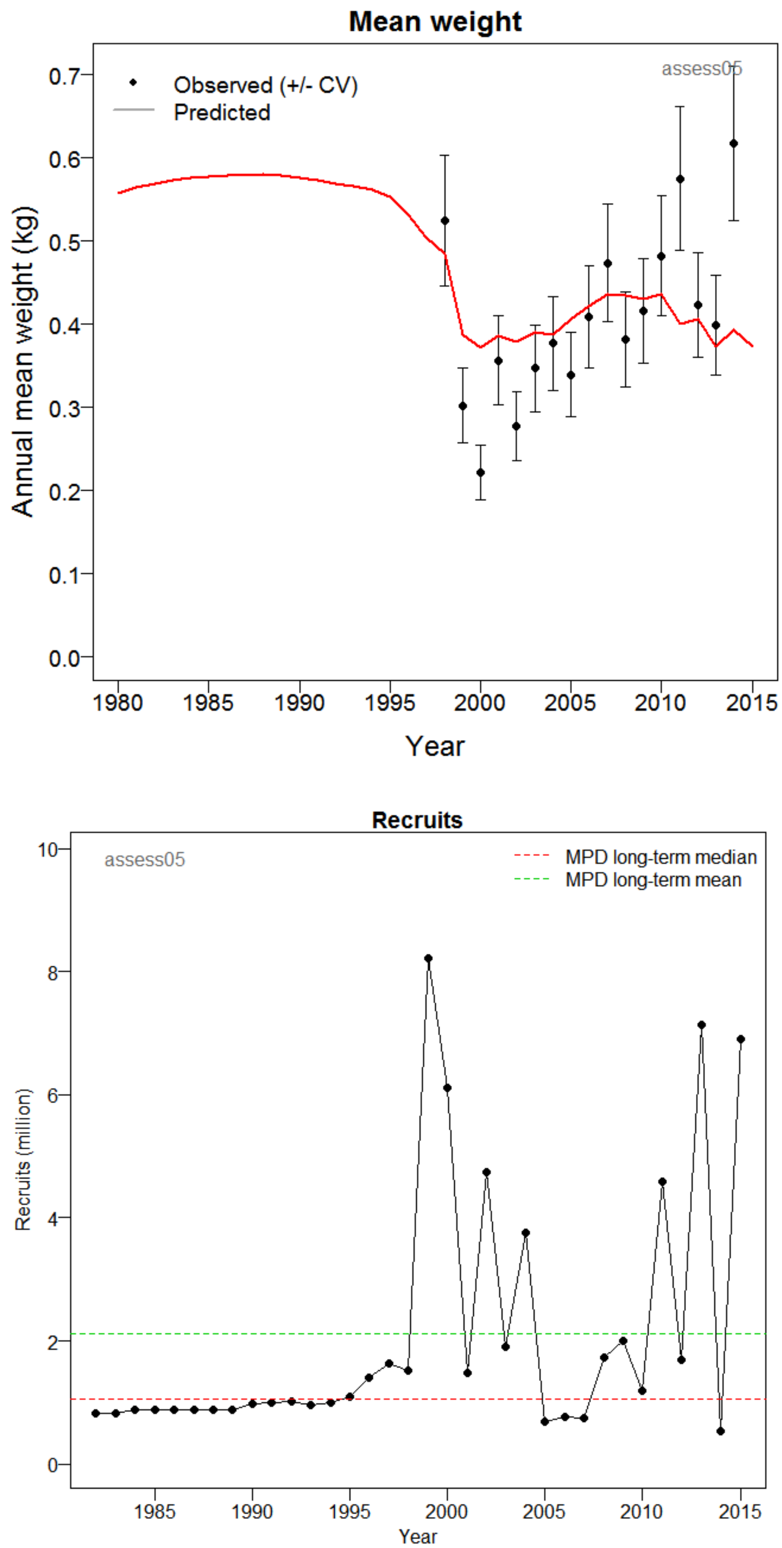


*Figure F.2. **Top:** Example model run: MPD fit to the mean weight data. Predicted mean weights are shown as a red line and observations are shown as points. Error bars on mean weight observations represent a fixed CV using σ_W = 0.15. **Bottom:** Example model run: MPD recruitment in thousands of age-16 individuals in year t.*

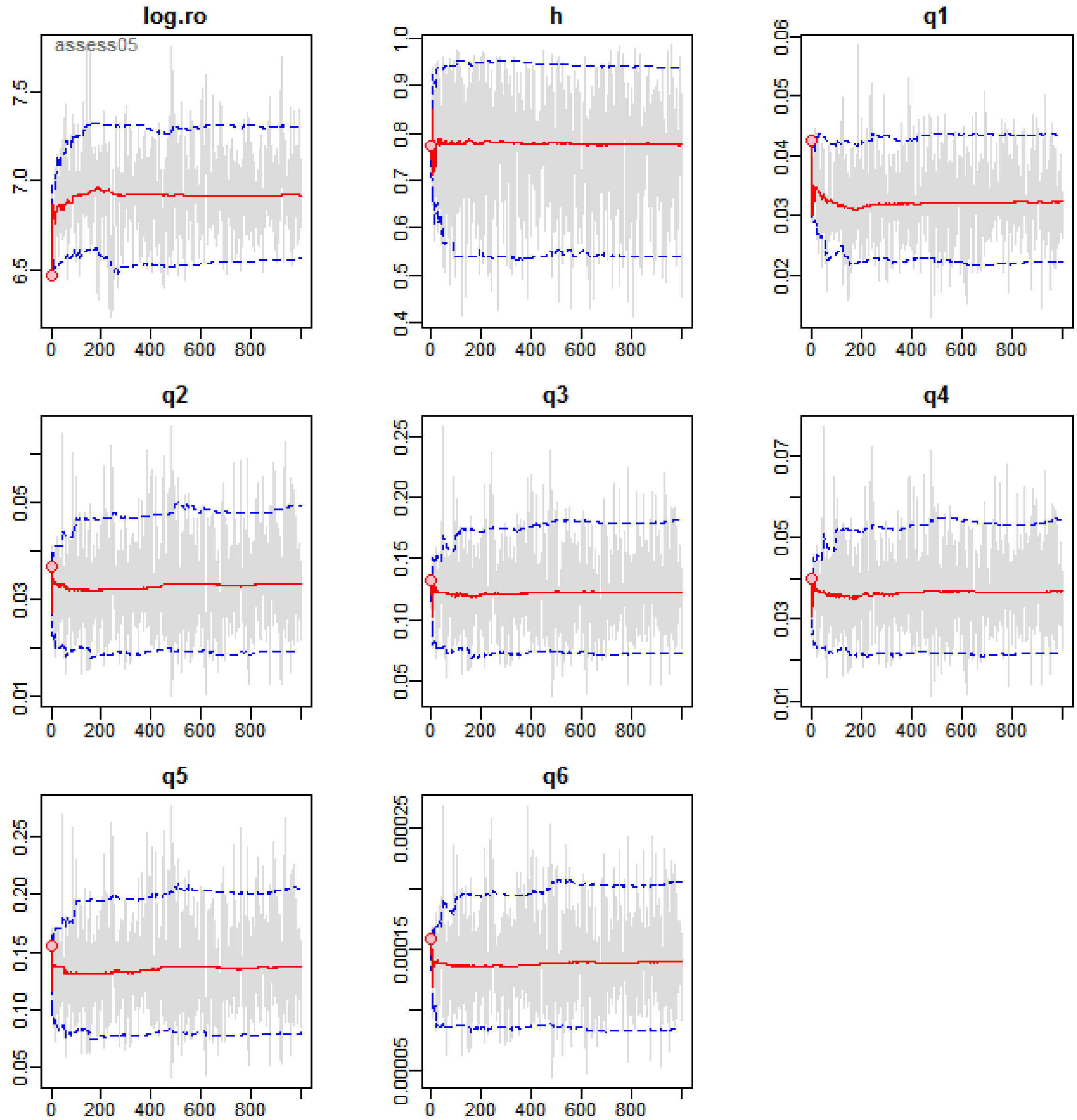


Figure F.3. Example model run: trace plots for MCMC output of estimated parameters in the reference model. The MCMC run had chain length 51.5 million, with a burn-in period of 1.5 million and a sample taken at every 50,000$^{\mathrm{th}}$ *iterations to yield 1,000 MCMC samples. Parameters log.ro (natural log of unfished equilibrium recruitment), h (steepness), and qj (catchability) where j=1: NMFS Triennial, j=2: WCVI Synoptic, j=3: QCS Synoptic, j=4: HS Synoptic, j=5: WCHG Synoptic, j=6: SST CPUE.*

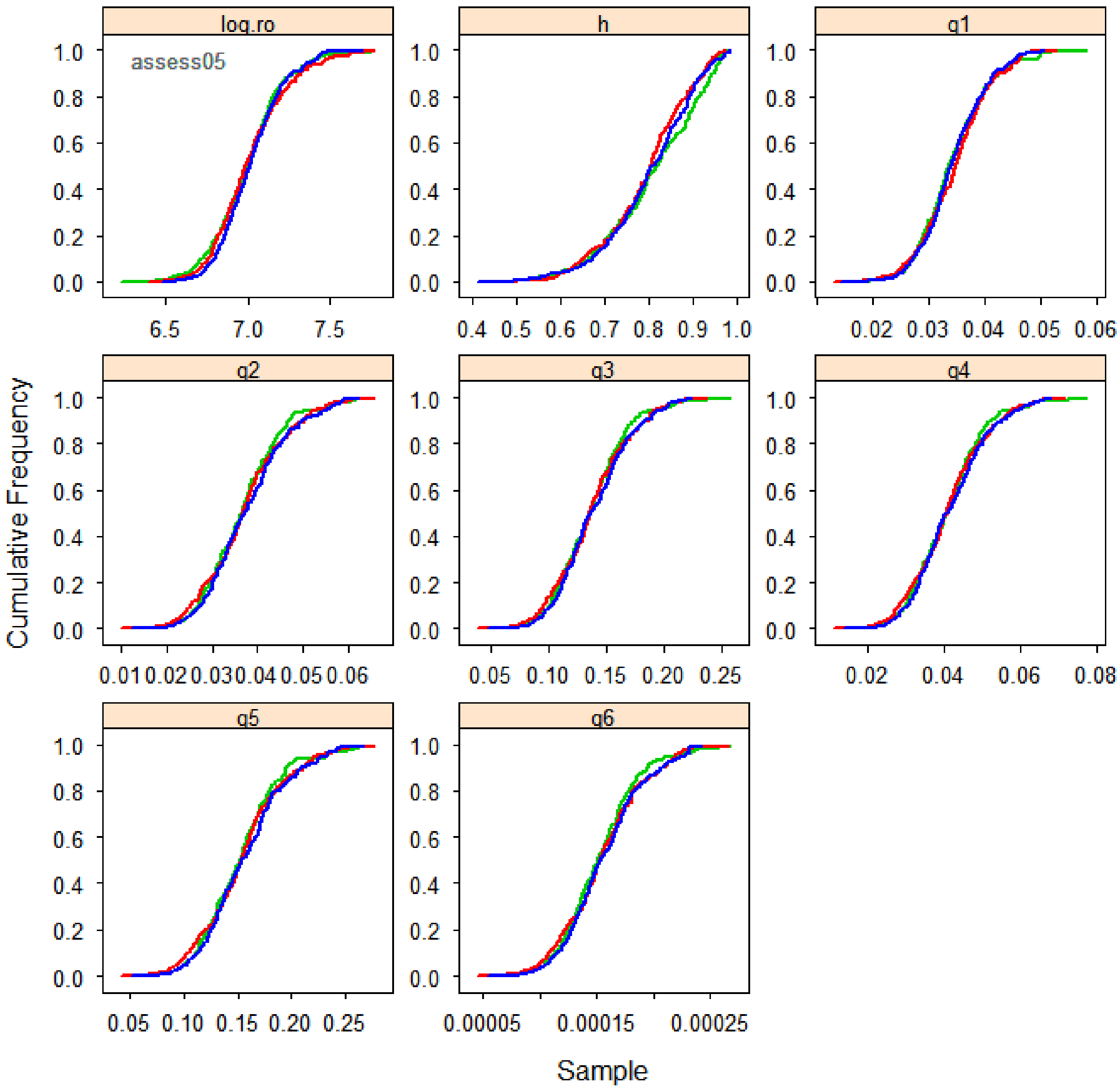


Figure F.4. Example model run: diagnostic plot obtained by dividing the MCMC chain of 1000 samples into three segments, an overplotting the cumulative distributions ofthe first segment (green), second segment (red), and final segment (blue).

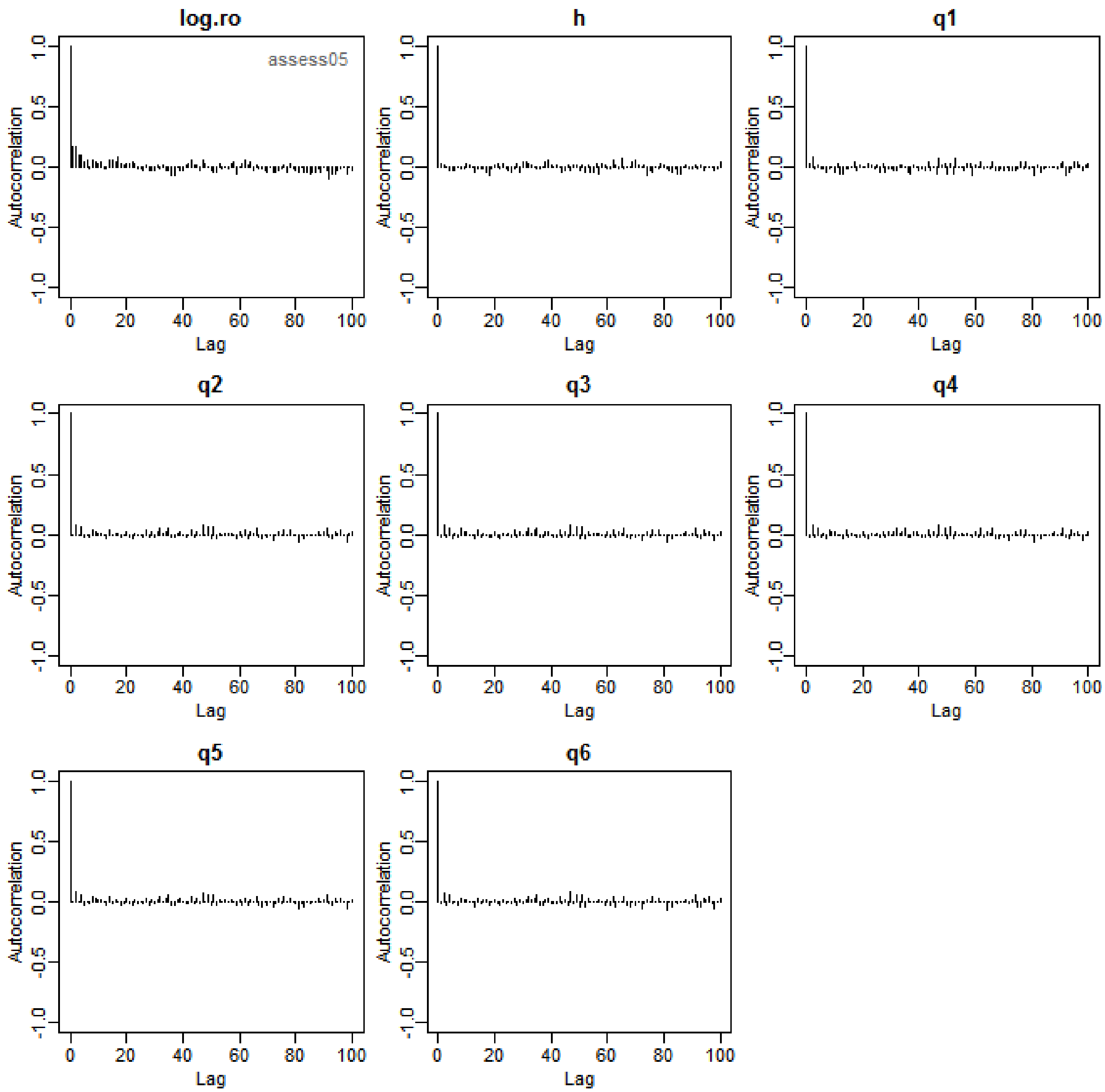


Figure F.5. Example model run: autocorrelation plots for MCMC output of estimated parameters in the reference model. See Figure F.3 for parameter descriptions.

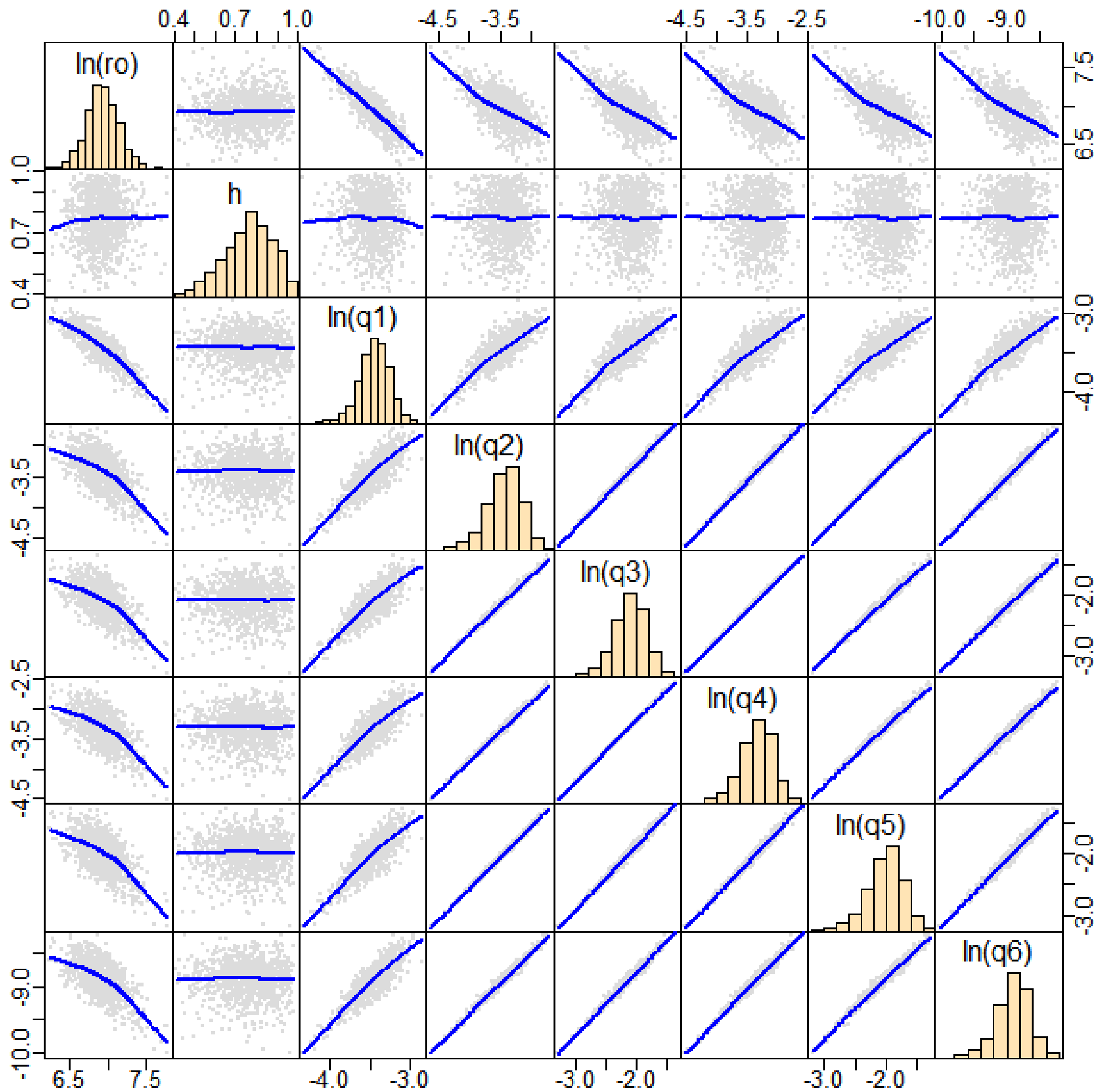


Figure F.6. Example model run: pairs plot coastwide of 1000 MCMC samples for the estimated parameters.

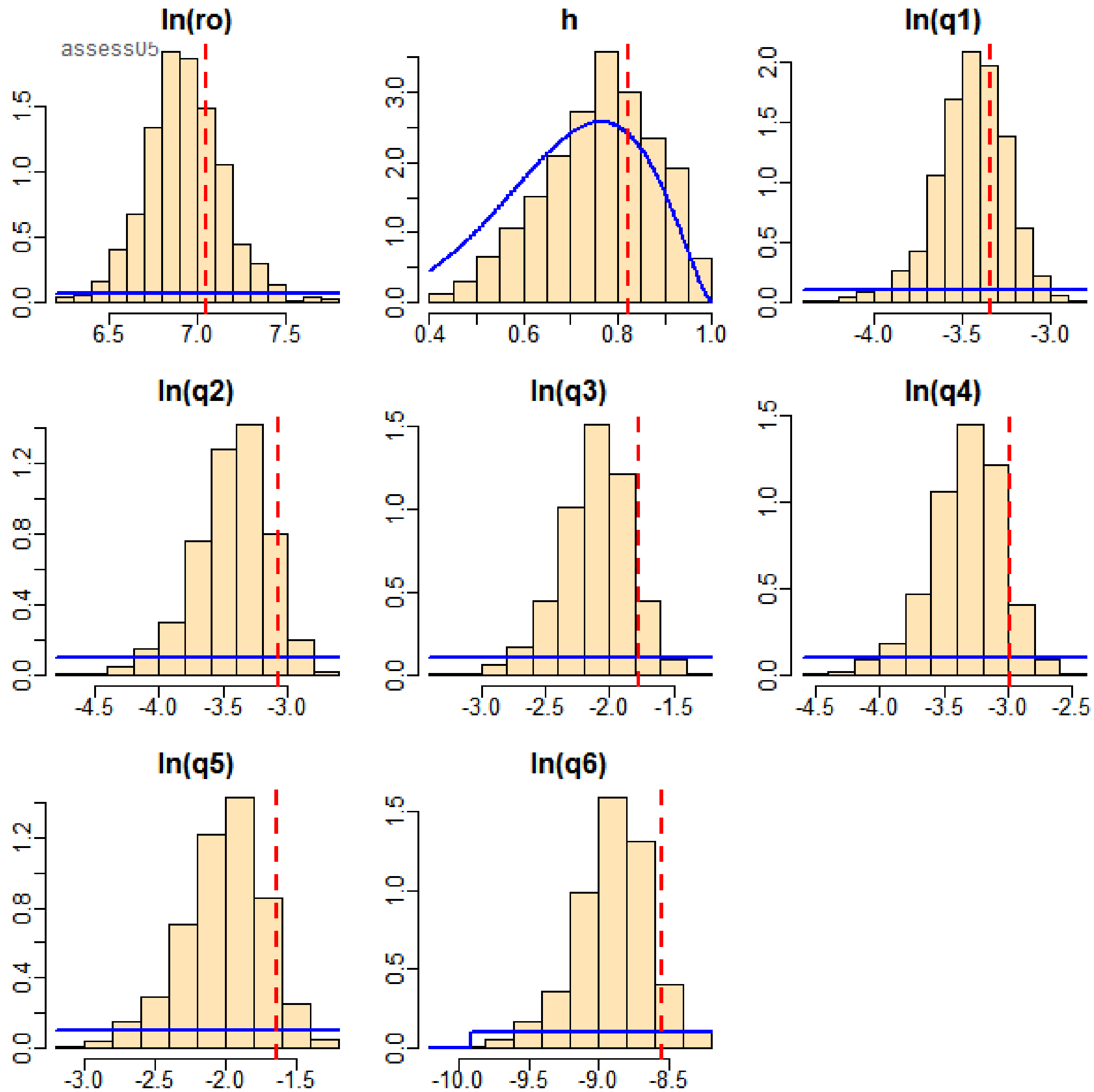


Figure F.7. Example model run: prior probability distributions (blue lines) used in the reference model and the comparative posterior histograms. Parameters qk represent catchability of the various surveys k as defined in Figure F.3. The dashed red vertical lines show the MPD estimates.

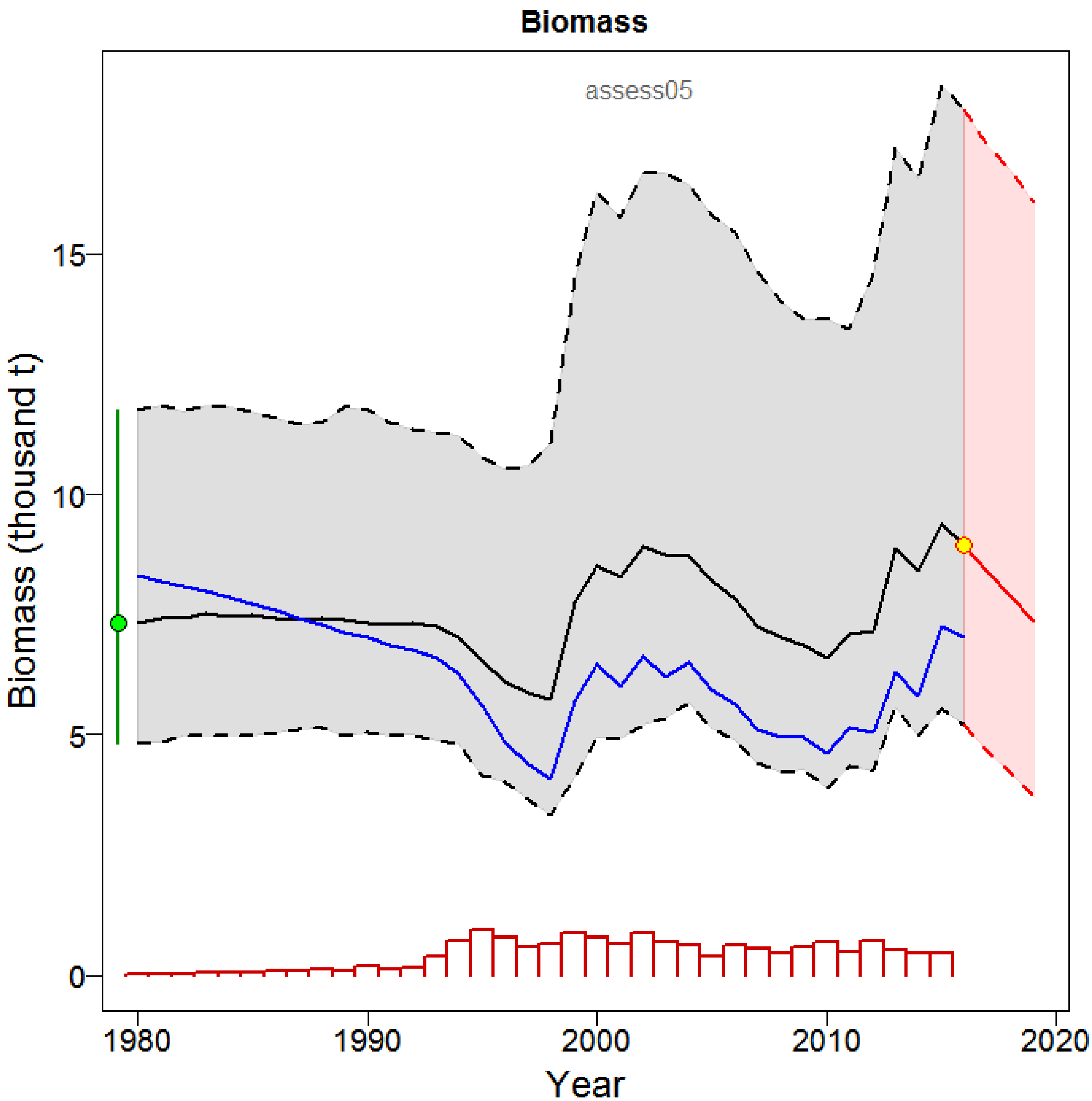
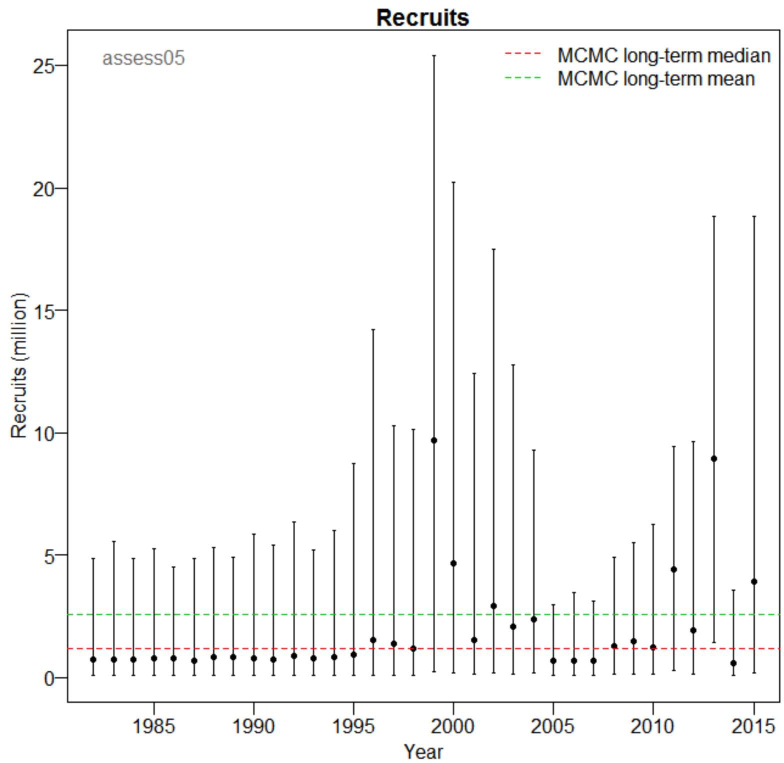


Figure F.8. Example model run: posterior estimates of biomass (1000 t) for the reference model with 95% credibility intervals in grey. The current year biomass (2016, yellow point) and projected biomass (2017-2019, red line), assuming a constant catch policy of 600 t/y, are enclosed by a 95% credibility interval shaded pink. The median posterior estimate of B_0 is shown as a green point (with 95% credibility range) to the left of the time series. The MPD estimate is shown as a blue line. The total catch is shown along the bottom as red bars.



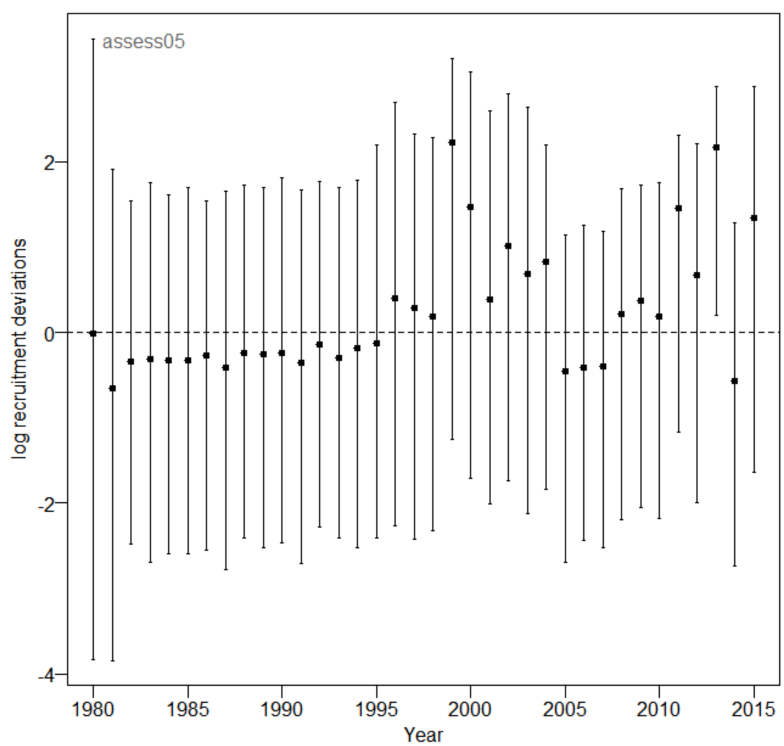


*Figure F.9. Example model run: posterior estimates of age-16 recruits (**top**) and log recruitment deviations (**bottom**) for the reference model with 95% credibility intervals.*

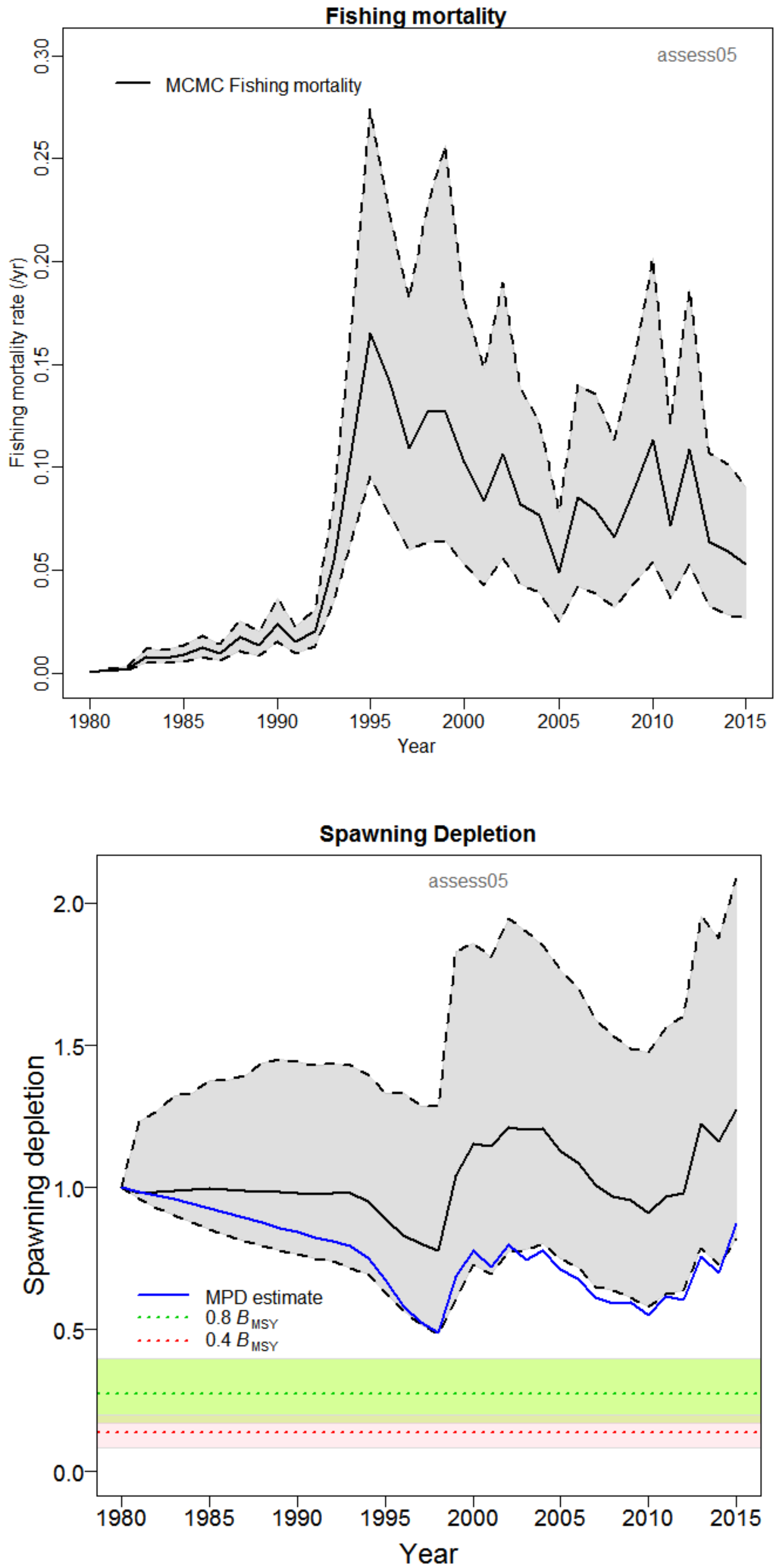


*Figure F.10. Example model run: posterior estimates of fishing mortality (**top**) and biomass depletion, i.e. B_t/B_0, (**bottom**) for the reference model with 95% credibility intervals. Also displayed on the depletion figure is the MPD estimate (blue line) and the reference points 0.2B_0 (red dashed line) and 0.4B_0 (green dashed line).*

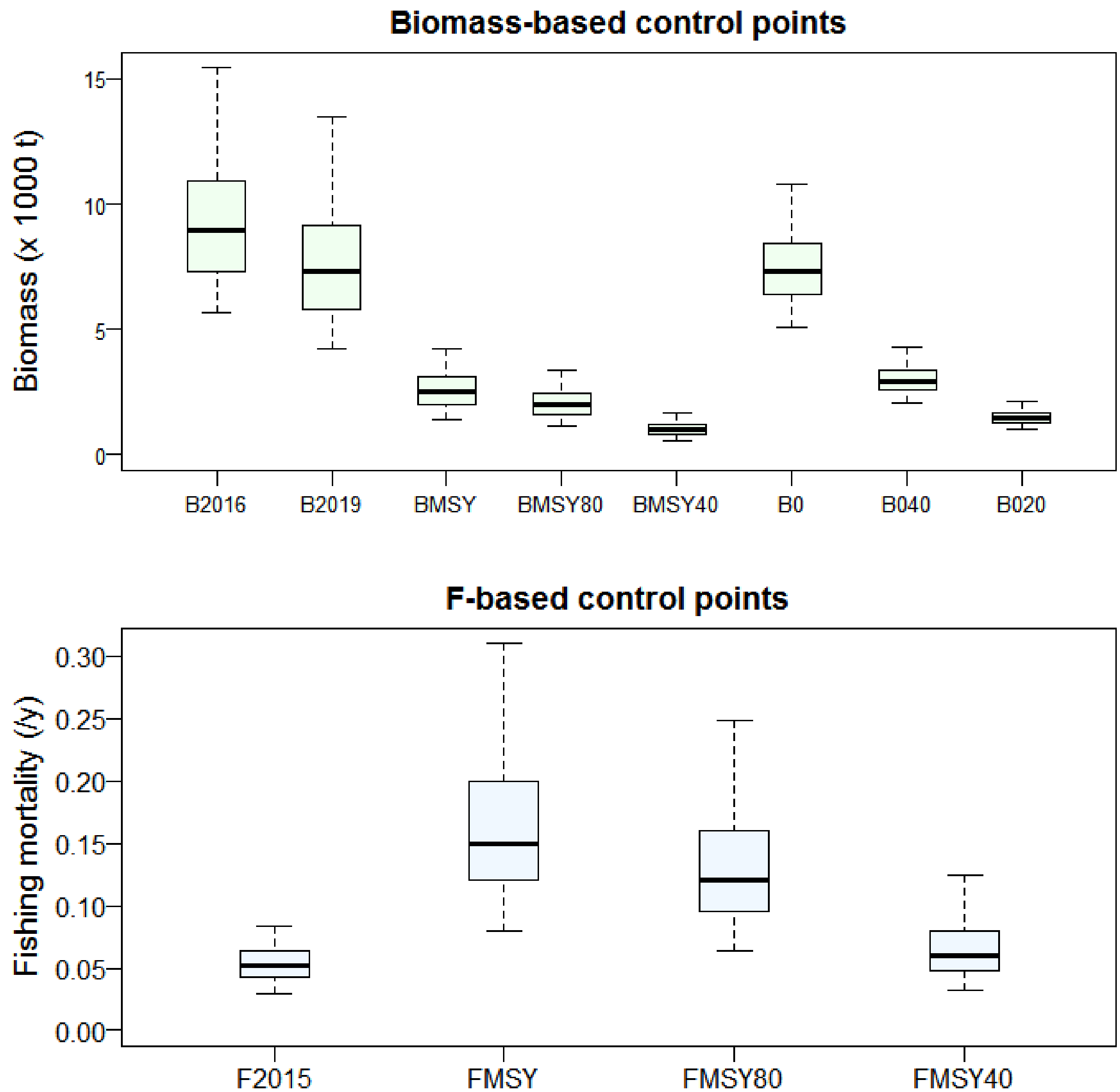


Figure F.11. Example model run: posterior estimates of biomass- and harvest-based reference points for the reference model. ***Top:*** *B2016 = current-year biomass B_{2016}, B2019 = projected-year biomass B_{2019}, BMSY = biomass at maximum sustaible yield B_{MSY}, BMSY80 = biomass at 0.8B_{MSY}, BMSY40 = biomass at 0.4B_{MSY}, B0 = equilibrium biomass B_0 in the absence of harvesting, B040 = biomass at 0.4B_0, and B020 = biomass at 0.2B_0.* ***Bottom:*** *F2015 = current-year harvest rate F_{2015}, FMSY = harvest rate at maximum sustaible yield F_{MSY}, FMSY80 = harvest rate at 0.8F_{MSY}, FMSY40 = harvest rate at 0.4F_{MSY}. Box delimiter and limits represent quantiles at 0.5 (median), 0.25 and 0.75 quantiles, respectively, and the whiskers delimit the 0.05 and 0.95 quantiles. Outliers are not shown.*

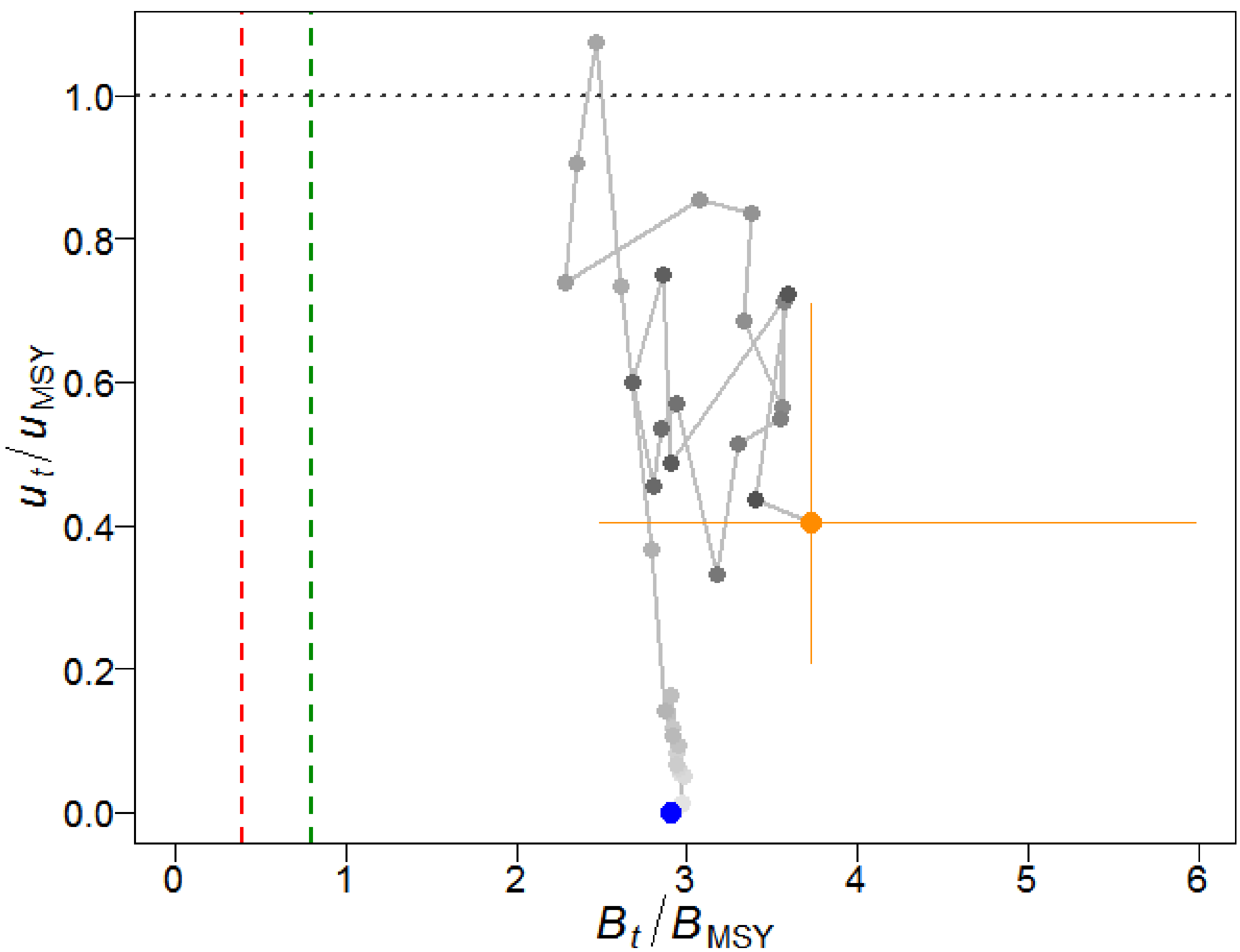


Figure F.12. Example model run: phase plot through time of the medians of the ratios B_t/B_{MSY} (the biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the exploitation rate in year t relative to u_{MSY}). Blue filled circle is the starting year 1980. Years then proceed from light grey through to dark grey with the final year 2016 as a filled orange circle with limit lines represent the 10% and 90% percentiles of the posterior distributions for the final year. Vertical dashed lines indicate the Precautionary Approach provisional limit (red) and upper stock reference (green) points (0.4, 0.8 B_{MSY}), and horizontal dotted line indicates u at MSY.

F.3. ADDITIONAL SENSITIVITY RUNS USING DFO GROWTH MODEL

F.3.1. Introduction

An important component to this stock assessment was testing the sensitivity of the results and the associated advice to key uncertainties in the underlying stock assessment model. Therefore, we ran 25 sensitivity runs (Tables F.2 and F.3) using the DFO growth model (including the example run described above) to test the robustness of the results to uncertainties in:

- natural mortality (M);
- age at knife-edge recruitment (k);
- observation, recruitment and mean weight error (σ_O, σ_R, σ_W);
- model start year; and
- use of CPUE index series.

We tested a relatively wide range of values for M and k because these parameters are key assumptions made by the delay-difference model for which the data available to the model are not very informative. We tested a narrower range of values for the last two sensitivity categories, after discovering that the model results were relatively insensitive to these components.

Selecting the range of M values to test was made difficult by the contradictory nature of the available information. While the literature suggested that M should be low (around 0.04 to 0.06, e.g., Butler et al. 1995; Kastelle et al. 2000) and the DFO GFBio database held a few old females (maximum age = 95, see Table D.4), the majority of the SST ages available in GFBio were young (mean age 19 years, n=1144). In addition, most of these ages were collected in the mid-1990s, near the beginning of the exploitation history when it would be expected that the population would contain the older fish that would be associated with a low M. However, given that the available data held fewer older SST than would be expected from a low M, we considered a number of hypotheses to explain this observation:

a. the ageing was biased low;

b. the older SST were not available to the fishery; or

c. M may be greater than that suggested by the literature.

Although we couldn't rule out hypothesis (a), the availability of a limited test sample of SST otoliths (n=60) prepared using the two methods and read independently by four readers suggested that the age estimates were, on average, not significantly different among preparation methods (see Table D.3 and the associated text in Appendix D). Hypothesis (b) is not easily testable but is potentially true, given that SST are thought to migrate deeper as they get older (Jacobson and Hunter, 1993). The presence of an old (age=95) female specimen from a deep tow in the 2003 Longspine Thornyhead survey off the west coast of Vancouver Island potentially lends some credibility to this hypothesis. Finally, hypothesis (c) cannot be ruled out. We chose to test the model sensitivity to five values of M, ranging from 0.03 to 0.12 (Table F.3).

The delay-difference assumption of knife-edge selectivity at a specific age k is a strong assumption that is difficult to test without age information from the fishery. However, if such information were available, it is likely that another form of model would have been used. The summarised length information presented in Figure D.6 suggests that age 16 might be a good candidate age for knife-edge recruitment. However, these data do not rule out younger and older candidates for k and it was decided to test this assumption using five values for k, ranging in age from 12 to 20 in steps of 2 years. This test was repeated over two values of M, M=0.08 and the other using M=0.10, a plausible value for the observed break & burn age distribution (Table F.3).

The parameterisation of the iSCAM delay-difference model combines observation and process error into a single total variance parameter ϕ^{-2}. This variable is partitioned into observation and process error components through the parameter ρ. These parameters were fixed in the example run described above such that the overall observation error (σ_O) was 0.2 and the recruitment process error (σ_R) was 0.6, the latter being a common value used as a default for teleost finfish. These values were increased to $\sigma_O = 0.3$ and $\sigma_R = 0.8$ and decreased to $\sigma_O = 0.1$ and $\sigma_R = 0.4$ to see how sensitive the model results were to the fixed variance assumptions. These two pairs of error terms were each run at two values of M (0.08 and 0.10) for a total of four sensitivity runs (Table F.3). A further variance component σ_W sets the weight used to fit the mean weight observations, which was fixed at $\sigma_W = 0.15$ for the example run described above. This value was lowered to $\sigma_W = 0.05$ to see the effect of pushing the model to obtain a closer fit to the weight observations. This sensitivity run was repeated for two values of M (0.08 and 0.10) (Table F.3).

Two other types of sensitivity runs were made: one where the assumption of starting the model at an unfished equilibrium was relaxed to starting the model with the population at equilibrium with the fishing mortality in the first year ($F_{t=1}$). This sensitivity run was made for two values of natural mortality (M=0.08 – t_1=[1990, 1996]; M=0.10 – t_1=1991); the starting years 1990 and 1991 differed because of technical requirements for starting the MCMC search while 1996 was used to coincide with the start of the observer trawl program (Table F.3). The other type of sensitivity run – dropping the CPUE index series, using only the CPUE index series, and dropping the NMFS Triennial survey – was only run for M=0.08.

All 25 sensitivity runs were taken to the MCMC level. Each MCMC search was begun with the "best fit" MPD parameter set and run for 50 million iterations after an initial burn-in and scaling period of 150,000 iterations. These iterations were dropped and the remaining iterations were sampled every 5,000 iterations for a total posterior sample of 1,000 draws.

F.3.2. MPD results DFO growth model - sensitivity

An important conclusion arising from this large number of sensitivity runs is that the data available to this model do not allow much discrimination between the range of hypotheses tested. While there are differences in the fits to the available biomass indices and to the mean weight data, these differences tend to be small and probably cannot serve to distinguish between hypotheses except in the most extreme cases. As an example, none of the models were able to fit the initial decrease in the observed mean weights at the end of the 1990s and then fit the gradually increasing trend in these data (Figure F.13). Even when σ_W was dropped to 0.05 (sensitivity runs S11 and S23), there was only a small improvement in the visual fit to this series while these runs showed noticeable deterioration in the fit to the abundance series (particularly to the CPUE series: Figure F.14, but the fit to the QC Sound survey is also poorer: Figure F.15). While the model uses the mean weight data to scale the overall biomass and to obtain recruitment deviation information, it is likely that only an age-structured model would have sufficient flexibility to fit the mean weight series.

In an attempt to make such comparisons more quantitative, the negative log-likelihoods for the fits to each data component of the model have been summarised for the 25 sensitivity runs using the DFO growth model in Table F.4. Only the runs where direct comparisons are valid have been included in this table, thus excluding the sensitivity runs where variances have been changed or the quantity of data vary. There is one immediately obvious conclusion that can be taken from Table F.4: all the models fit the catch data equally well, with every likelihood almost exactly the same. Although the two later start sensitivity runs (S12 and S24) have been omitted from the catch likelihood comparison, the fit to the available catch data is equally good for these runs.

There is a tendency for the fits to the synoptic survey series to improve with increasing k (Table F.4, Figure F.15), an observation that is true for both M=0.08 and M=0.10. However, this improvement in fit is not great and is not likely to be a strong basis for distinguishing between these hypotheses.

Similarly, there is no strong differentiation in the fits to the abundance series and to the mean weight data across the range of investigated values of M (Table F.4, Figure F.15). Low M=0.06 fit better than high M=0.12 in four of the six abundance series, with nearly identical fits to the mean weight series, leading to a similar conclusion as for k.

Apart from the deterioration in the fit to the abundance series resulting from increased weight on the mean weight series, this is little evidence from the fit to the available data to help select between this wide range of alternative model hypotheses. The lack of fit to the abundance data suggests that the mean weight and abundance series are contradictory, a problem that would likely remain even if more complex age-structured models were fitted to these data.

F.3.3. MCMC results DFO growth model - sensitivity

The behaviour of the MCMC traces with respect to this range of sensitivity hypotheses is interesting and possibly informative. Models with age=12 and age=14 at knife-edge recruitment showed more unstable MCMC behaviour than the older ages for k (Figure F.16), which was true for both values of M. Similarly, the M=0.06 and M=0.12 models showed evidence of non-convergence compared to the more intermediate values of M=0.08 and M=0.10. Unsurprisingly, the models with increased variance showed more evidence of MCMC non-convergence than the models with lower variance. While these observations have no theoretical basis for use in distinguishing among hypotheses, they suggest that given these data the range of hypotheses tested in this suite of sensitivity runs likely include a credible set of parameters and that the more extreme values of k and M tested in this suite are less credible than those in the centre of the range.

Median estimates for current biomass lie well above the B_{MSY} and 0.4B_0 target reference points across the full range of sensitivity runs (Table F.5). Only when k=20 is there even a suggestion that median current biomass is dropping to levels that might approach the 0.4B_0 reference level and is in all cases well above B_{MSY}. Table F.6 shows that, while the estimates of current stock status are somewhat independent of the underlying model hypotheses, the estimates of long-term yield are highly dependent on those underlying hypotheses, with median estimates of MSY varying from around 200 t/year for the runs where variance or M are low to greater than 1000 t/year for the models where k is low or M is high.

Quantile plots which compare B_0, B_{2016}/B_0, $u_{2016}/u_{\mathrm{MSY}}$ and MSY across all sensitivity runs grouped by category are presented for M (Figure F.17), for k (Figure F.18), for the variance categories (Figure F.19), for model start year (Figure F.20) and for use of CPUE data (Figure F.21). These plots show that the main determinants for stock status and yield are, unsurprisingly, M and k, with lower values of M giving lower long-term yields and lower stock status while the lower values for k result in very strong stock status and high yields. Other considerations (such as the size of the variance component, the use of CPUE data and the model start year) appear to be much less influential that are the two primary sources of uncertainly.

Three-year projections at the level of recent average catch (600 t/year) are predicted to cause a decline in biomass across all 25 runs in Table F.3 (Table F.5). However, with the exception of the two runs where k=20, the biomass will stay above the 0.4B_0 target reference point (the highest of the reference levels) with high probability (see Table F.7). The two runs where k=20 (S08 and S20) are predicted to go below this threshold (see Table F.7), but this hypothesis is probably the least likely of the sensitivity runs, given the low level of discarding seen for this species (average <10%: delta ratios in Table A.5) and the considerable number of fish below 32 cm (the mean length at age=20: see Table D.8 and length frequency plots in Figure D.6).

Table F.2. Model runs using the DFO growth model evaluated for the Shortspine Thornyhead assessment. Short mnemonic labels are assigned to the various runs, along with sensitivity labels and groups to facilitate the analysis presentation. The column marked 'Reference' indicates the runs that are used in the composite reference scenario to provide advice to managers

Model	Run No.	Label	Sensitivity	Sens. Group	Reference
assess01	1	M.10	S03	1	
assess02	2	M.10+k12	S17	2	
assess03	3	M.10+k14	S18	2	
assess04	4	M.10+k18	S19	2	
assess05	5	M.08	S00	0	R01
assess06	6	M.12	S04	1	
assess07	7	M.10+sig0.3|sigR.8	S21	3	
assess08	8	M.10+syr=1991	S24	4	
assess09	9	M.10+wgtsig.05	S23	3	
assess10	10	M.10+sig0.1|sigR.4	S22	3	
assess11	11	M.10+k20	S20	2	
assess12	12	M.06	S02	1	R02
assess13	13	k12	S05	2	
assess14	14	k14	S06	2	
assess15	15	k18	S07	2	
assess16	16	k20	S08	2	
assess17	17	sig0.3|sigR.8	S09	3	
assess18	18	sig0.1|sigR.4	S10	3	
assess19	19	syr=1990	S12	4	
assess20	20	wgtsig.05	S11	3	
assess21	21	noCPUE	S14	5	
assess22	22	M.03	S01	1	R03
assess23	23	no1998mnW		99	
assess24	24	NMFS-M.03+k21		99	R04
assess25	25	NMFS-M.03+k16		99	R05
assess26	26	NMFS-M.03+k13		99	R06
assess27	27	NMFS-M.06+k21		99	R07
assess28	28	NMFS-M.06+k16		99	R08
assess29	29	NMFS-M.06+k13		99	R09
assess30	30	onlyCPUE	S15	5	
assess31	31	noTriennial	S16	5	
assess32	32	syr=1996	S13	4	
assess33	33	NMFS-M.08+k21		99	R10
assess34	34	NMFS-M.08+k16		99	R11
assess35	35	NMFS-M.08+k13		99	R12

Table F.3. Summary of the analyses performed to test the sensitivity of the delay-difference model to variations in natural mortality M, knife-edge recruitment age k, observation error σ_O and recrutiment error σ_R, mean weight error σ_W, and start year t_1.

Case	Run ID	k	M	σ_O	σ_R	σ_W	t_1
S00	M.08	16	0.08	0.2	0.6	0.15	1980
Sensitivity to *M*							
S01	M.03	16	0.03	0.2	0.6	0.15	1980
S02	M.06	16	0.06	0.2	0.6	0.15	1980
S03	M.10	16	0.1	0.2	0.6	0.15	1980
S04	M.12	16	0.12	0.2	0.6	0.15	1980
Sensitivity to other parameters when *M*=0.08							
Knife-edge recruitment age k							
S05	k12	12	0.08	0.2	0.6	0.15	1980
S06	k14	14	0.08	0.2	0.6	0.15	1980
S07	k18	18	0.08	0.2	0.6	0.15	1980
S08	k20	20	0.08	0.2	0.6	0.15	1980
Observation and recruitment errors (σ_O,σ_R)							
S09	sig0.3|sigR.8	16	0.08	0.3	0.8	0.15	1980
S10	sig0.1|sigR.4	16	0.08	0.1	0.4	0.15	1980
Mean weight error σ_W							
S11	wgtsig.05	16	0.08	0.2	0.6	0.05	1980
Start year t_1							
S12	syr=1990	16	0.08	0.2	0.6	0.15	1990
S13	syr=1996	16	0.08	0.2	0.6	0.15	1996
Index series							
S14	noCPUE	16	0.08	0.2	0.6	0.15	1980
S15	onlyCPUE	16	0.08	0.2	0.6	0.15	1980
S16	noTriennial	16	0.08	0.2	0.6	0.15	1980
***M* 0.10**							
S02	M.06	16	0.06	0.2	0.6	0.15	1980
Sensitivity to other parameters when *M*=0.10							
Knife-edge recruitment age k							
S17	M.10+k12	12	0.1	0.2	0.6	0.15	1980
S18	M.10+k14	14	0.1	0.2	0.6	0.15	1980
S19	M.10+k18	18	0.1	0.2	0.6	0.15	1980
S20	M.10+k20	20	0.1	0.2	0.6	0.15	1980
Observation and recruitment errors (σ_O,σ_R)							
S21	M.10+sig0.3|sigR.8	16	0.1	0.3	0.8	0.15	1980
S22	M.10+sig0.1|sigR.4	16	0.1	0.1	0.4	0.15	1980
Mean weight error σ_W							
S23	M.10+wgtsig.05	16	0.1	0.2	0.6	0.05	1980
Start year t_1							
S24	M.10+syr=1991	16	0.1	0.2	0.6	0.15	1991

Table F.4. MPD negative log likelihoods from the 25 sensitivity runs using the DFO growth model documented in Table F.3 for each data component used in the model. Some likelihoods have been suppressed (see footnotes for reason). The lowest comparable negative log-likelihood for each data component is shaded green while the largest component is shaded pink.

Sens. Run	Run Desc.	Catch	Triennial survey	WCVI Synop.	QCS Synop.	Hecate Synop.	WCHG Synop.	CPUE	Recruit-ment	Mean weight	Total
						Negative log likelihood					
S00	M.08+k16	-74.741	3.053	-0.937	2.651	1.278	-2.061	-3.268	50.917	2.487	102.944
S01	M.03+k16	-74.692	2.901	1.348	4.059	0.665	-2.646	-0.220	60.143	5.532	125.371
S02	M.06+k16	-74.726	3.539	-0.833	2.623	1.259	-2.183	-2.975	53.793	2.657	108.112
S03	M.10+k16	-74.750	2.531	-0.985	2.587	1.283	-2.007	-3.454	49.402	2.538	100.009
S04	M.12+k16	-74.755	2.039	-1.009	2.452	1.281	-1.983	-3.561	48.560	2.695	98.213
S05	M.08+k12	-74.761	1.019	-1.534	8.942	1.943	-1.874	-3.375	49.360	-4.414	98.491
S06	M.08+k14	-74.753	1.692	-1.152	6.211	1.513	-2.179	-3.185	50.023	-0.863	100.572
S07	M.08+k18	-74.730	5.312	-1.012	-0.830	1.288	-1.595	-3.715	51.488	5.377	105.324
S08	M.08+k20	-74.731	7.692	-1.295	-2.843	1.184	-2.203	-3.115	51.927	7.685	108.233
S09[1]	sig0.3|sigR.8	-74.736	–	–	–	–	–	–	–	1.340	–
S10[1]	sig0.1|sigR.4	-74.666	–	–	–	–	–	–	–	5.344	–
S11	wgtsig.05	-74.495	4.300	-1.063	10.954	3.283	-1.329	11.914	54.865	–[5]	–[5]
S12	syr=1990	–[2]	–[3]	-1.107	1.961	1.338	-2.077	-2.922	–[2]	2.130	–[2]
S13	syr=1996	–[2]	–[3]	-1.253	2.650	1.515	-2.001	-2.695	–[2]	1.556	–[2]
S14	noCPUE	-74.749	3.578	-1.147	1.437	1.563	-2.686	–[4]	51.471	-1.807	–[4]
S15	onlyCPUE	-74.736	–[4]	–[4]	–[4]	–[4]	–[4]	-10.601	48.678	1.153	–[4]
S16	noTriennial	-74.729	–[3]	-1.269	1.278	1.424	-2.181	-2.187	50.541	2.309	–[3]
S17	M.10+k12	-74.764	0.756	-1.530	8.535	1.924	-1.979	-3.595	48.576	-3.531	97.452
S18	M.10+k14	-74.760	1.317	-1.179	5.968	1.521	-2.156	-3.355	48.866	-0.649	98.369
S19	M.10+k18	-74.739	4.665	-1.064	-0.799	1.268	-1.579	-3.849	49.816	5.235	101.888
S20	M.10+k20	-74.737	7.044	-1.364	-2.870	1.167	-2.166	-3.333	50.278	7.465	104.597
S21[1]	M.10+sig0.3|sigR.8	-74.749	–	–	–	–	–	–	–	1.306	–
S22[1]	M.10+sig0.1|sigR.4	-74.688	–	–	–	–	–	–	–	5.601	–
S23	M.10+wgtsig.05	-74.585	3.555	-1.061	11.122	3.316	-1.548	11.658	53.509	–[5]	–[5]
S24	M.10+syr=1991	–[2]	–[3]	-1.154	1.931	1.345	-2.016	-3.098	–[2]	2.355	–[2]

[1] likelihoods for abundance indices, recruitment and total suppressed because variances/weights not consistent with other sensitivity runs
[2] likelihood suppressed because the number of model years is not consistent with the other runs
[3] likelihood suppressed because the number of survey indices has been reduced
[4] either no CPUE data or only CPUE data in this sensitivity run
[5] likelihoods suppressed because mean weight variances not consistent with other sensitivity runs

Table F.5. Median values for select MCMC-derived parameters and quantities for the 25 sensitivity runs using the DFO growth model. The value for B_{2019} is that assuming a TAC of 600 t/y. Model run details appear in Table F.2 senstivity details appear in Table F.3.

Run	h	B_0	$\frac{B_{2016}}{B_0}$	$\frac{B_{2019}}{B_0}$	P$\left(\begin{smallmatrix} B_{2019} \\ >B_{2016} \end{smallmatrix}\right)$	$\frac{B_{2016}}{B_{\mathrm{MSY}}}$	u_{MSY}	$\frac{u_{2015}}{u_{\mathrm{MSY}}}$
M.08	0.775	7,338	1.22	0.998	0.00100	3.56	0.139	0.361
M.03	0.784	6,118	0.977	0.746	0	2.56	0.0392	1.78
M.06	0.782	6,761	1.11	0.880	0	3.16	0.0952	0.622
M.10	0.772	8,628	1.37	1.14	0.00700	4.14	0.189	0.203
M.12	0.773	10,676	1.52	1.30	0.0220	4.55	0.252	0.118
k12	0.763	37,029	1.84	1.74	0.0480	5.06	0.113	0.0544
k14	0.771	11,960	1.59	1.43	0.0100	4.54	0.131	0.189
k18	0.783	5,436	0.915	0.633	0	2.84	0.156	0.565
k20	0.784	4,338	0.558	0.235	0	1.73	0.173	1.03
sig0.3|sigR.8	0.787	9,179	0.876	0.725	0.0360	2.54	0.156	0.371
sig0.1|sigR.4	0.776	4,282	1.74	1.32	0	5.63	0.139	0.449
wgtsig.05	0.776	5,371	1.82	1.47	0	5.46	0.139	0.326
syr=1990	0.766	8,644	0.936	0.780	0.00900	2.80	0.139	0.402
syr=1996	0.833	26,143	0.390	0.400	0.512	1.32	0.173	0.276
noCPUE	0.778	6,897	1.75	1.44	0	5.28	0.148	0.265
onlyCPUE	0.765	7,039	0.734	0.540	0.00500	2.98	0.112	0.779
noTriennial	0.781	7,312	1.12	0.902	0.00500	4.68	0.118	0.479
M.10+k12	0.765	95,031	1.89	1.76	0.0580	5.32	0.156	0.0161
M.10+k14	0.774	20,128	1.78	1.61	0.0310	5.11	0.181	0.0721
M.10+k18	0.783	5,568	0.993	0.711	0.00300	3.16	0.213	0.378
M.10+k20	0.774	4,239	0.667	0.328	0	2.09	0.221	0.691
M.10+sig0.3|sigR.8	0.789	10,892	0.978	0.839	0.0780	2.89	0.213	0.212
M.10+sig0.1|sigR.4	0.771	4,521	1.95	1.48	0	6.33	0.181	0.282
M.10+wgtsig.05	0.772	6,108	2.02	1.64	0	6.24	0.189	0.191
M.10+syr=1991	0.773	9,980	1.02	0.882	0.0360	3.11	0.197	0.237

Table F.6. Percentiles of MSY (t) for MCMC samples for the 25 sensitivity runs using the DFO growth model. Model run details appear in Table F.2 senstivity details appear in Table F.3.

Run	5%	50%	95%
M.08	237	356	532
M.03	75.1	97.6	123
M.06	165	232	312
M.10	342	552	1,022
M.12	462	860	2,922
k12	578	1,605	23,028
k14	336	544	12,262
k18	191	279	388
k20	164	229	321
sig0.3|sigR.8	341	484	742
sig0.1|sigR.4	114	182	268
wgtsig.05	185	261	351
syr=1990	306	413	564
syr=1996	1,216	1,350	1,605
noCPUE	215	335	547
onlyCPUE	111	189	299
noTriennial	122	200	302
M.10+k12	1,207	5,439	30,421
M.10+k14	566	1,227	10,827
M.10+k18	255	371	551
M.10+k20	203	294	427
M.10+sig0.3|sigR.8	490	755	1,682
M.10+sig0.1|sigR.4	153	255	402
M.10+wgtsig.05	263	389	552
M.10+syr=1991	450	624	958

Table F.7. Assuming a constant catch policy of 600 t/y, the probability that B_{2019} (or u_{2018}) is greater than reference points used in this assessment for the 25 sensitivity runs using the DFO growth model. Model run details appear in Table F.2 senstivity details appear in Table F.3. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

Run	P$\left(\frac{B_{2019}>}{0.4B_{MSY}}\right)$	P$\left(\frac{B_{2019}>}{0.8B_{MSY}}\right)$	P$\left(\frac{B_{2019}>}{B_{MSY}}\right)$	P$\left(\frac{B_{2019}>}{0.2B_0}\right)$	P$\left(\frac{B_{2019}>}{0.4B_0}\right)$	P$\left(\frac{B_{2019}>}{B_{2016}}\right)$	P$\left(\frac{u_{2018}>}{u_{MSY}}\right)$
M.08	1	1	1	1	0.999	0.00100	0.107
M.03	1	0.995	0.965	1	0.981	0	0.999
M.06	1	1	0.999	1	0.998	0	0.484
M.10	1	1	1	1	1	0.00700	0.0140
M.12	1	1	0.999	1	1	0.0220	0.00200
k12	1	1	1	1	1	0.0480	0
k14	1	1	1	1	1	0.0100	0.00800
k18	1	0.962	0.914	0.994	0.883	0	0.508
k20	0.684	0.450	0.331	0.555	0.204	0	0.916
sig0.3|sigR.8	1	0.990	0.966	1	0.966	0.0360	0.139
sig0.1|sigR.4	1	1	1	1	1	0	0.257
wgtsig.05	1	1	1	1	1	0	0.0540
syr=1990	1	0.991	0.979	1	0.985	0.00900	0.158
syr=1996	0.997	0.913	0.765	0.986	0.499	0.512	0.00100
noCPUE	1	1	1	1	1	0	0.0510
onlyCPUE	0.995	0.963	0.923	0.969	0.735	0.00500	0.672
noTriennial	1	1	1	1	0.996	0.00500	0.294
M.10+k12	1	1	1	1	1	0.0580	0
M.10+k14	1	1	1	1	1	0.0310	0
M.10+k18	0.999	0.983	0.970	0.995	0.945	0.00300	0.223
M.10+k20	0.817	0.622	0.515	0.722	0.378	0	0.763
M.10+sig0.3|sigR.8	1	0.999	0.994	1	0.990	0.0780	0.0200
M.10+sig0.1|sigR.4	1	1	1	1	1	0	0.0560
M.10+wgtsig.05	1	1	1	1	1	0	0.00600
M.10+syr=1991	1	0.995	0.988	1	0.995	0.0360	0.0350

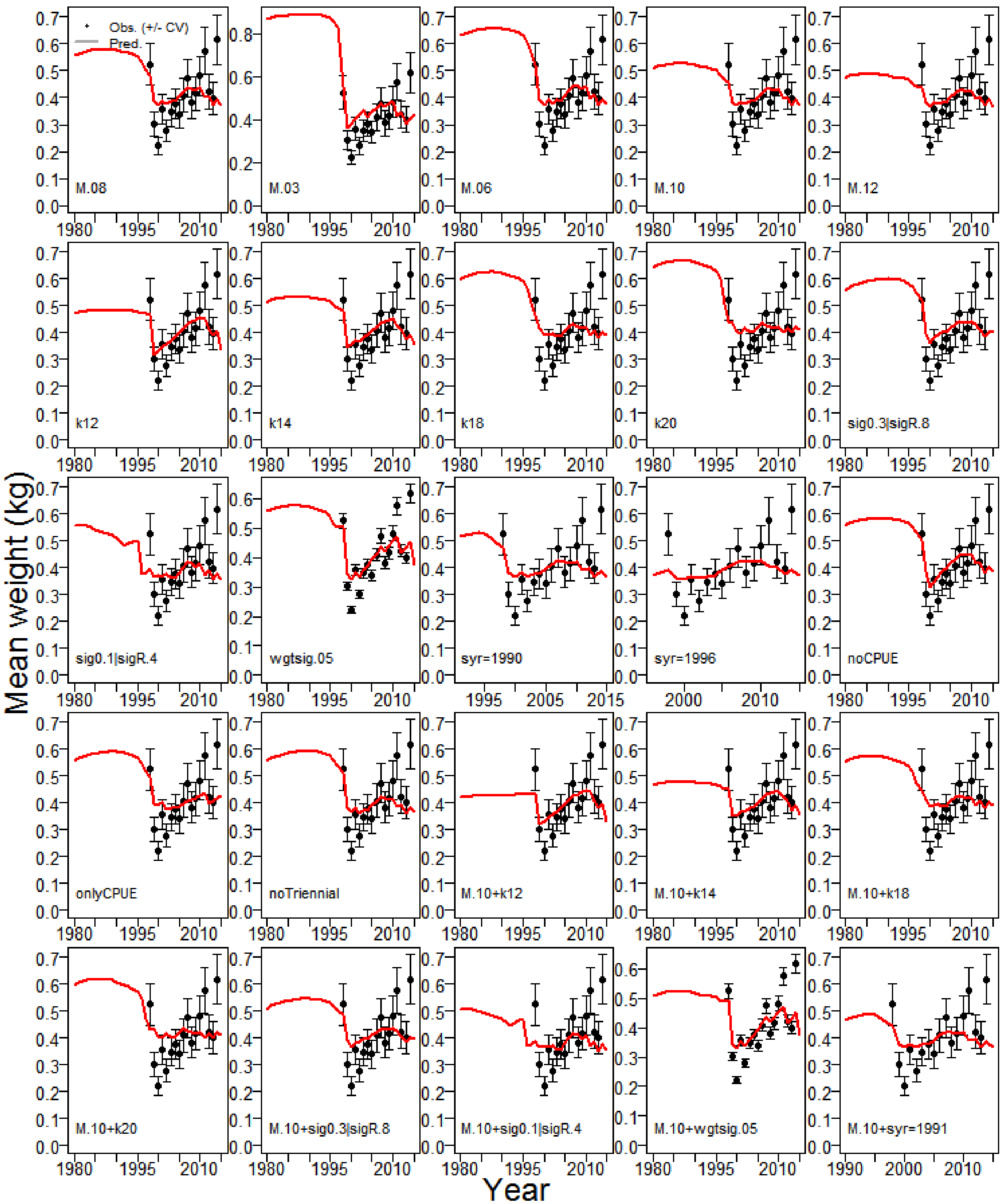


Figure F.13. MPD fit to the mean weight data for the 25 sensitivity runs using the DFO growth model. Predicted mean weights are shown as red lines and observations are shown as points. Error bars on mean weight observations represent a fixed CV using σ_W = 0.15 or 0.05.

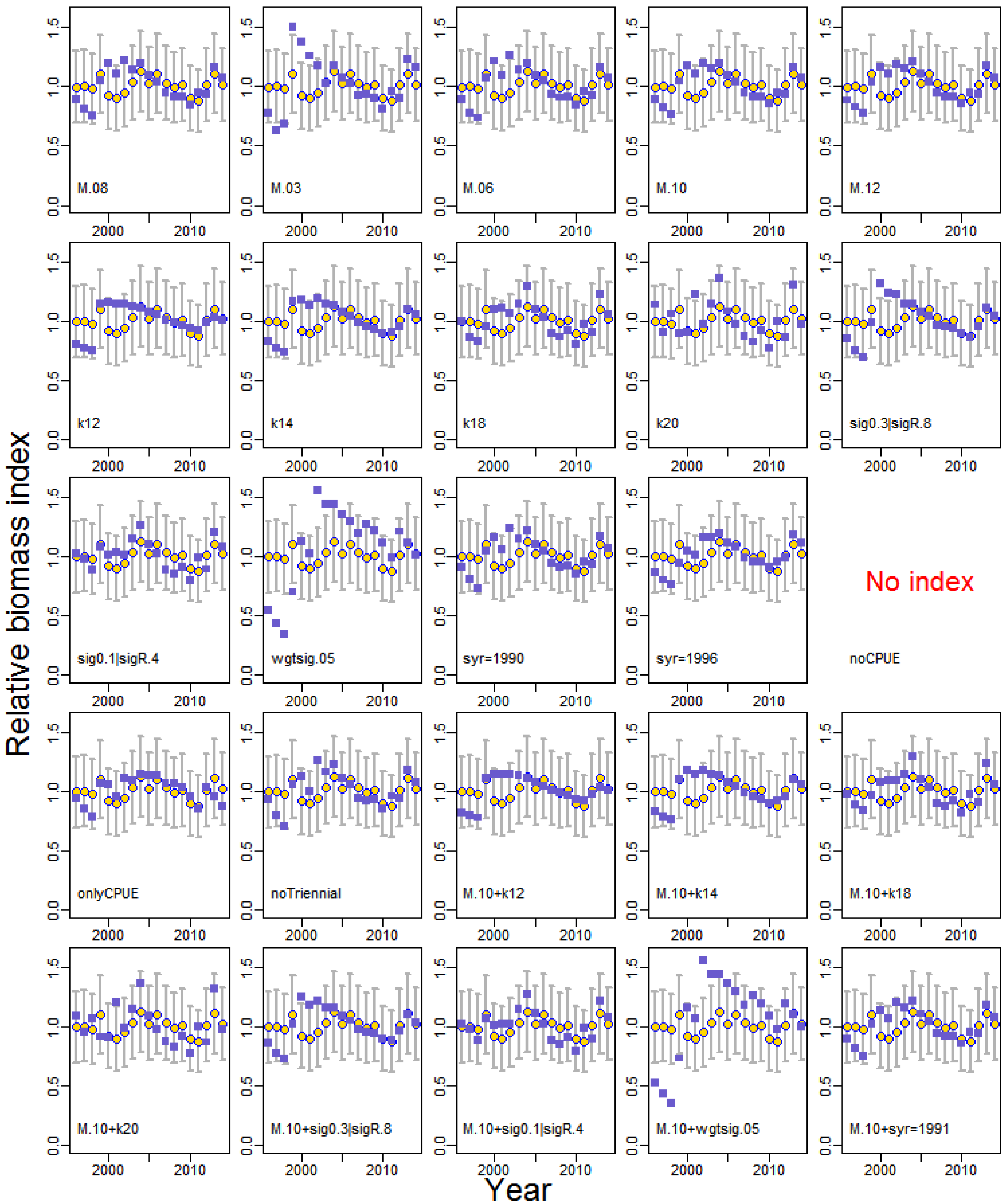


Figure F.14. MPD index fits (25 sensitivity runs using the DFO growth model) for the commercial trawl Shortspine Thornyhead CPUE relative abundance indices. Circles represent observed indices with associated CVs, squares represent the model fit.

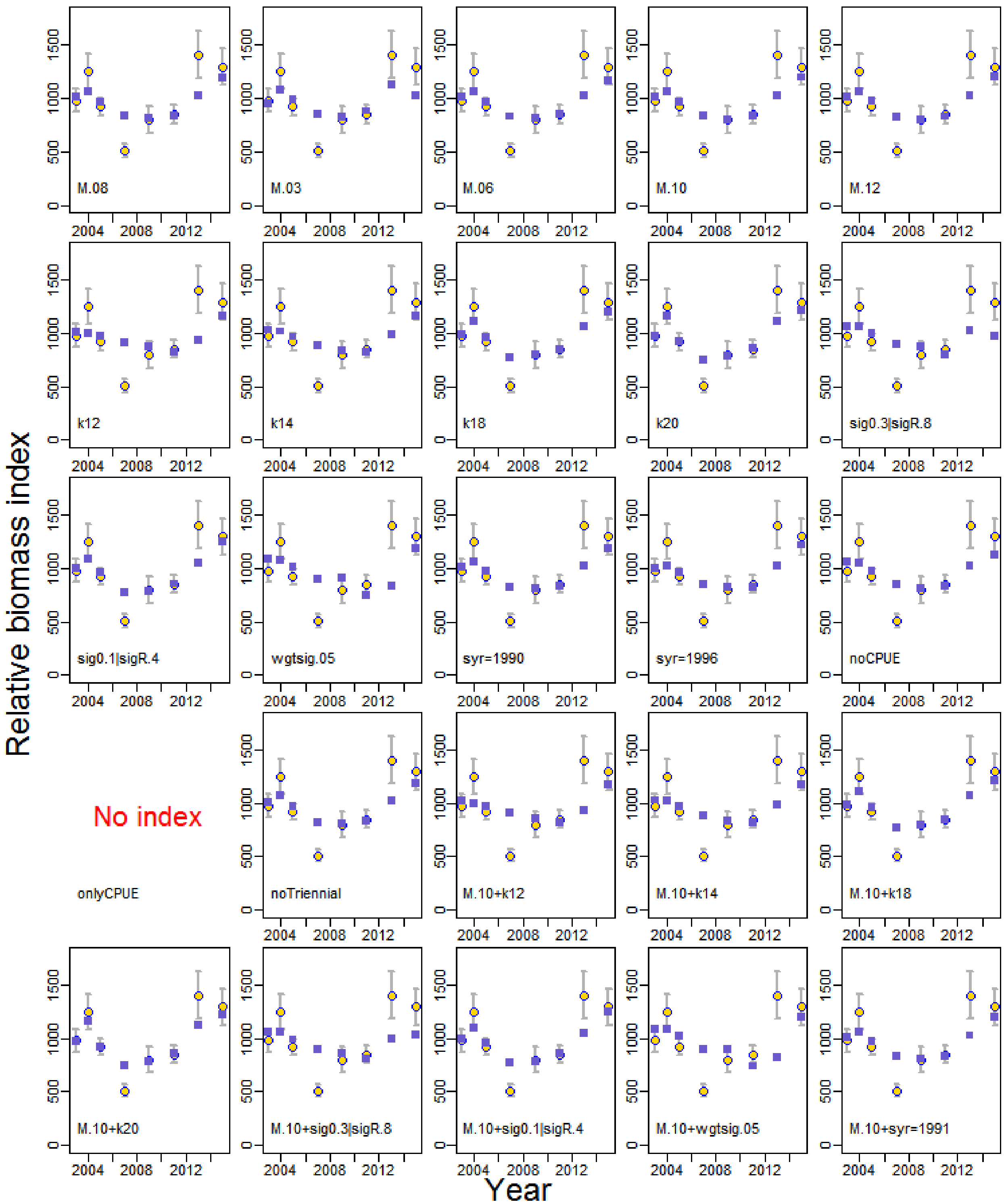


Figure F.15. MPD index fits (25 sensitivity runs using the DFO growth model) for the QCS (Queen Charlotte Sound) synoptic survey relative abundance indices. Circles represent observed indices with associated CVs, squares represent the model fit.

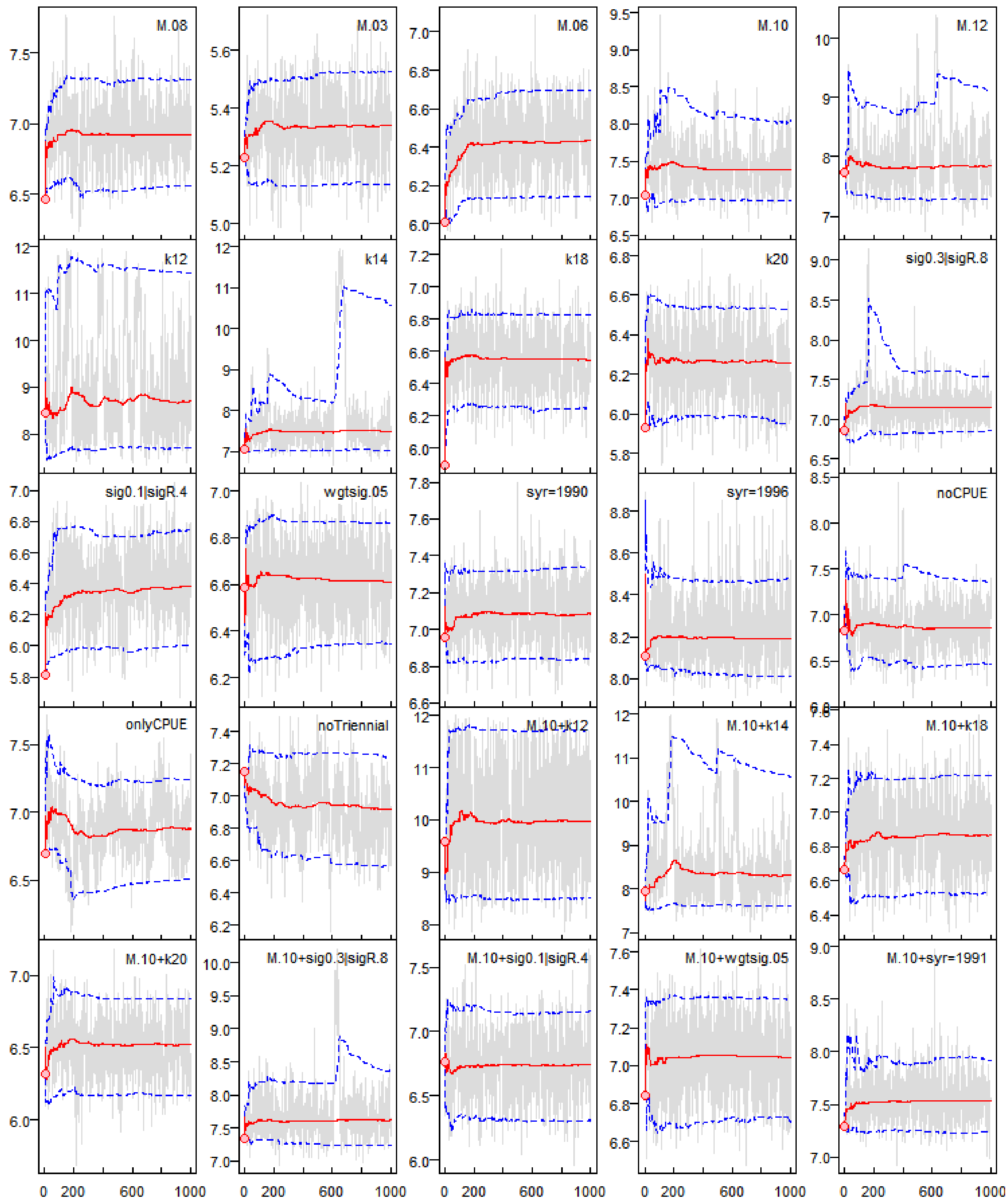


Figure F.16. Trace plots (25 sensitivity runs using the DFO growth model) for MCMC samples of $\log(R_0)$ *(natural log of unfished equilibrium recruitment). The MCMC run had chain length 51.5 million, with a burn-in period of 1.5 million and a sample taken at every 50,000*$^{\text{th}}$ *iterations to yield 1,000 MCMC samples.*

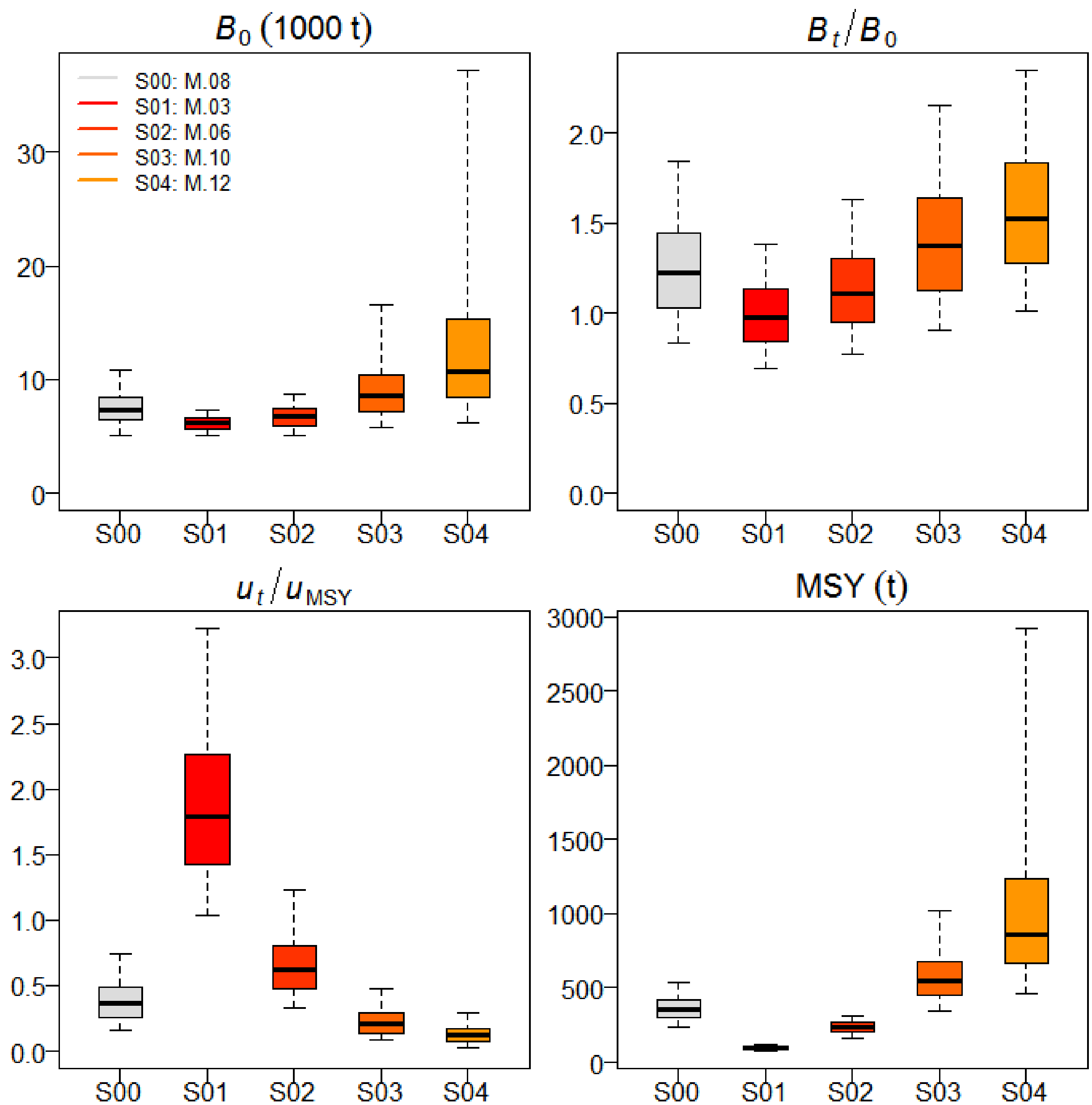


Figure F.17. Quantile plots comparing the example run to other sensitivity runs (all using the DFO growth model) that vary by natural mortality M, where M=0.08 for the example sensitivity (S00), M=0.03 for S01, M=0.06 for S02, M=0.10 for S03, and M=0.12 for S04. Box delimiter and limits represent quantiles at 0.5 (median), 0.25 and 0.75 quantiles, respectively, and the whiskers delimit the 0.05 and 0.95 quantiles. Outliers are not shown.

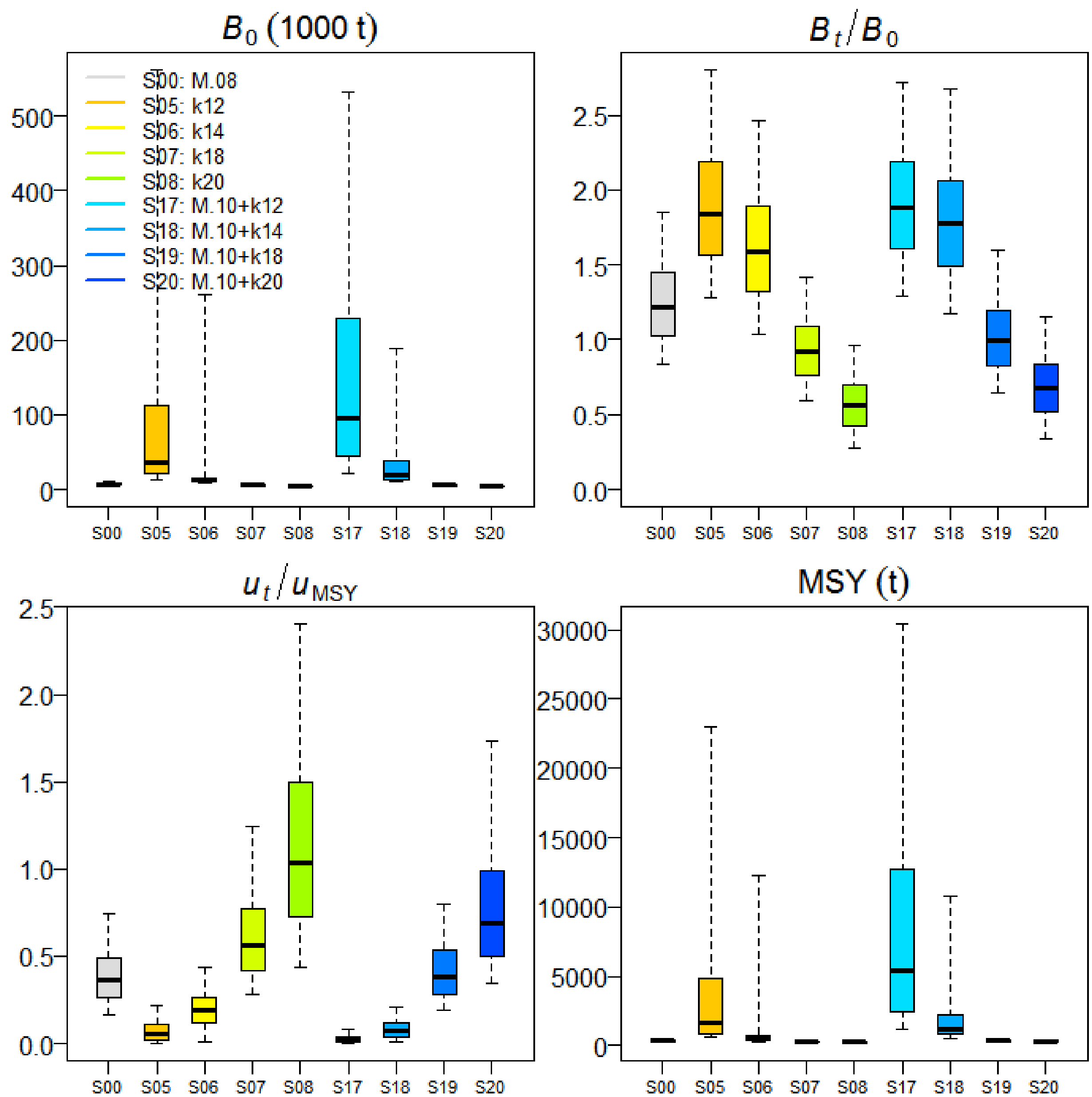


Figure F.18. Quantile plots comparing the example run to sensitivity runs (all using the DFO growth model) that vary by knife-edge recruitment age k, where k=16 for S00, k=12 for S05 and S17, k=14 for S06 and S18, k=18 for S07 and S19, and k=20 for S08 and S20. Quantile box delimiters are detailed in Figure F.17.

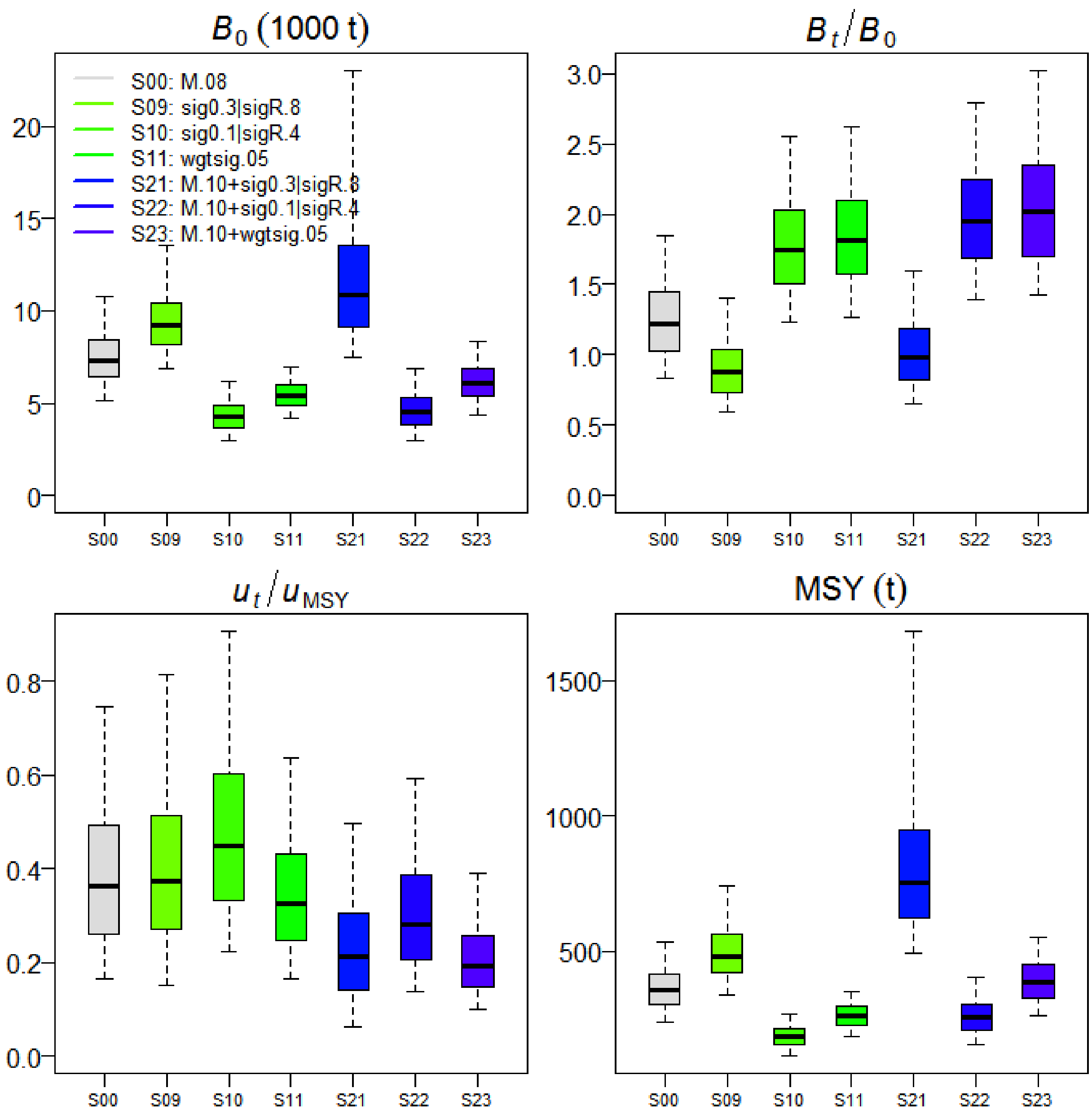


Figure F.19. Quantile plots comparing the example run to sensitivity runs (all using the DFO growth model) that vary by observation error σ_O, recruitment error σ_R, and mean weight error σ_W, where ($\sigma_O, \sigma_R, \sigma_W$) = (0.2, 0.6, 0.15) for S00, (σ_O, σ_R) = (0.3, 0.8) for S09 and S21, (σ_O, σ_R) = (0.1, 0.4) for S10 and S22, and σ_W =0.05 for S11 and S23. Quantile box delimiters are detailed in Figure F.17.

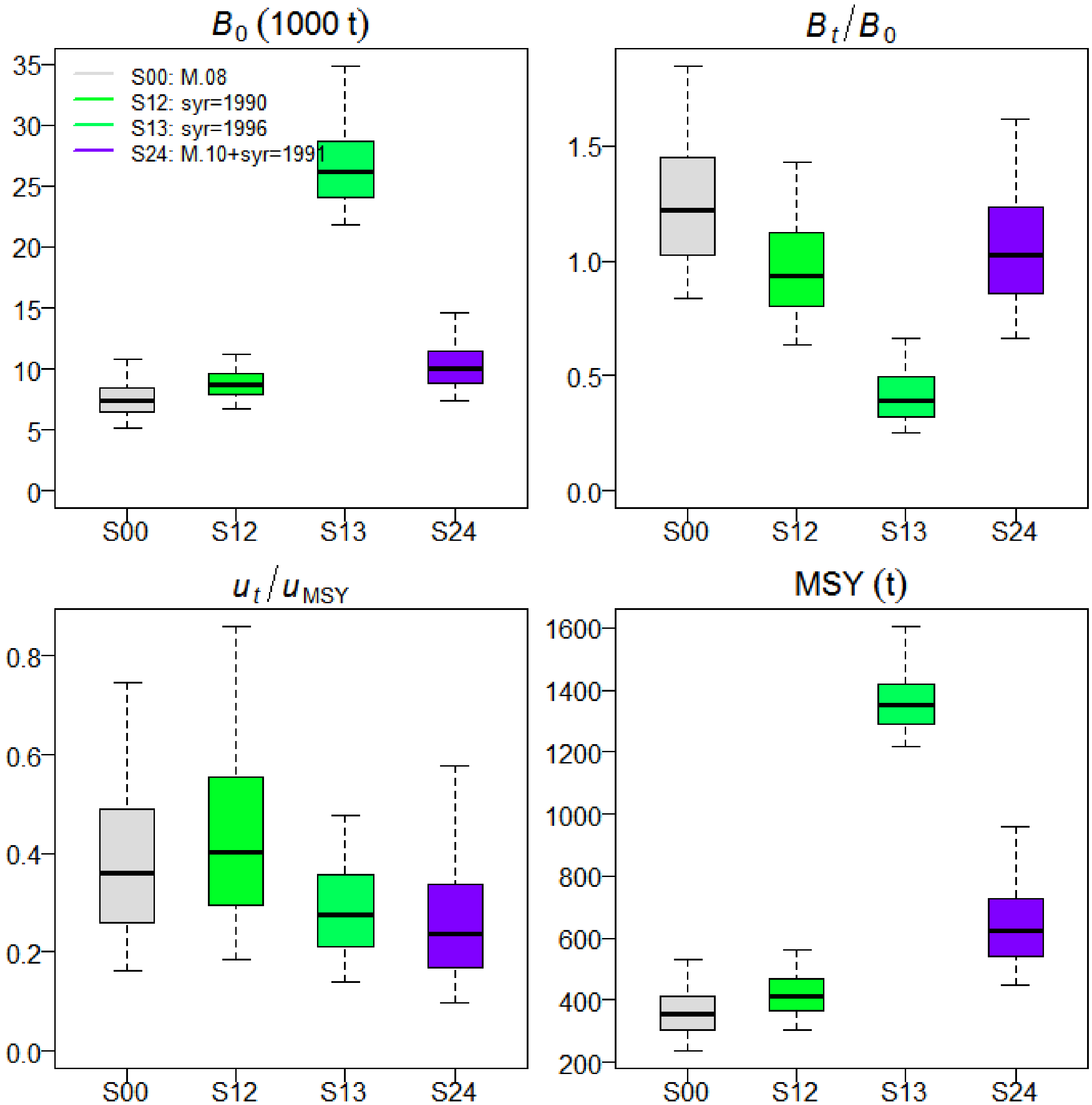


Figure F.20. Quantile plots comparing the example run to sensitivity runs (all using the DFO growth model) that vary by start year t_1, where t_1=1980 for S00, t_1=1990 (M=0.08) for S12, t_1=1996 (M=0.08) for S13, and t_1=1991 (M=0.10) for S24. Quantile box delimiters are detailed in Figure F.17.

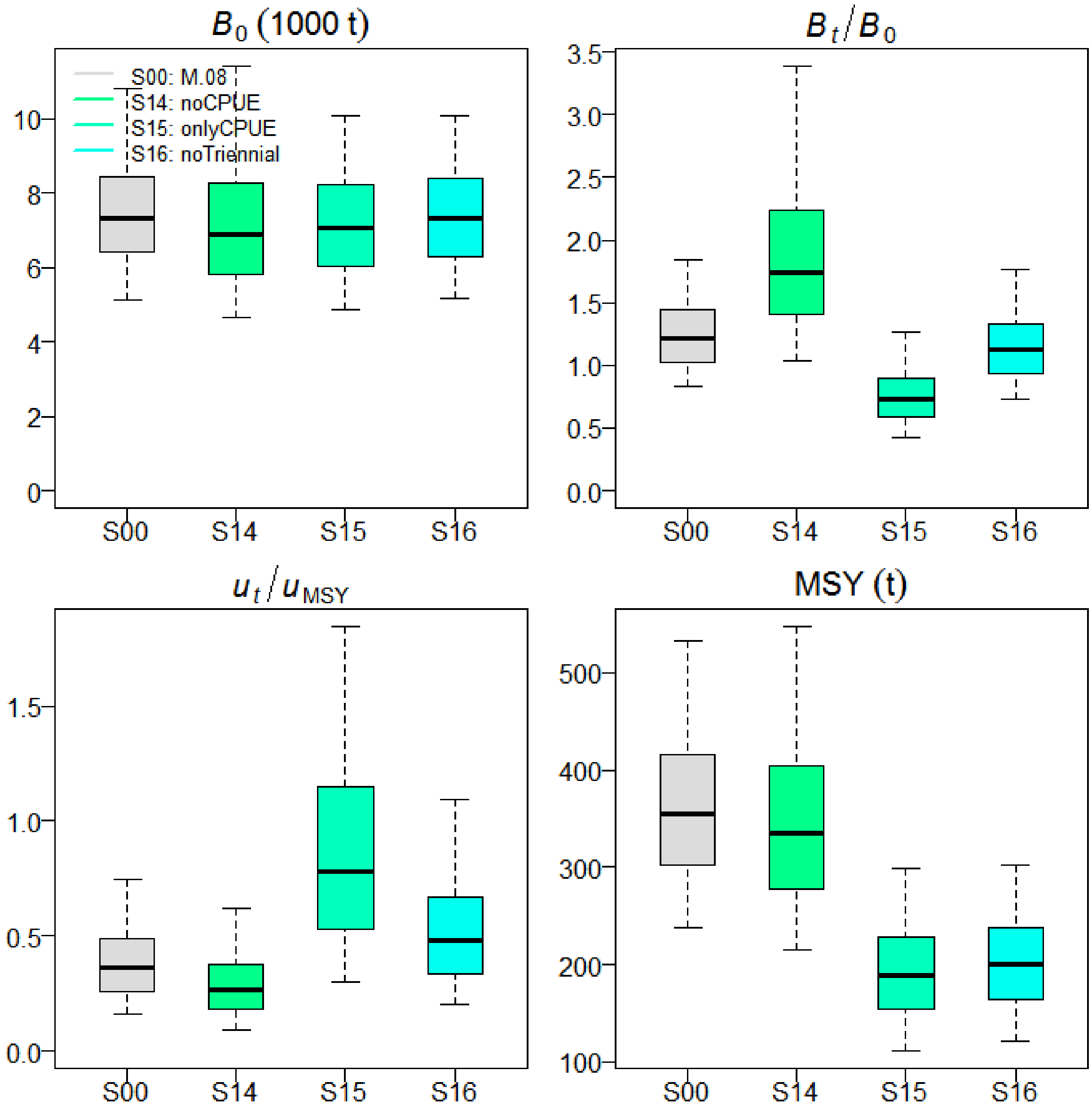


Figure F.21. Quantile plots comparing the example run to sensitivity runs (all using the DFO growth model) that exclude the CPUE index, include only the CPUE index, and exclude the NMFS triennial survey. Quantile box delimiters are detailed in Figure F.17.

F.4. COMPOSITE REFERENCE SCENARIO (MODEL AVERAGE)

A second growth model (called NMFS) was developed for this stock assessment in recognition of the uncertainty associated with ageing this species (see Section 6.1). The ages used in the NMFS growth model were also determined using the "break and burn" methodology, but the available data included older and larger specimens than those observed from BC waters.

Nine model runs were made using the NMFS growth model. These explored three possible fixed values for M (0.03, 0.06, 0.08) across three options for age at knife-edge recruitment: 21 years (corresponding to 29 cm), 16 years (corresponding to 24 cm) and 13 years (corresponding to 21 cm). All runs started at equilibrium in 1980 and used the 5 survey series and the CPUE index series. It was felt that model sensitivities to alternative error assumptions, different starting year assumptions and the effect of removing specific data sets had already been adequately explored using the DFO growth model. MCMC posterior distributions were generated for each run using the procedure described for the example run.

The nine runs using the NMFS growth model were combined with three of the runs which used the DFO growth model (S00 with M=0.08, S01 with M=0.03 and S02 with M=0.06) to comprise a composite reference scenario that spanned a range of key model assumptions that cannot be resolved from the available data.

Uncertainty due to growth, natural mortality, and the age of knife-edged selectivity was included in this composite scenario by selecting 12 model runs from the 34 model runs for inclusion in the final averaged scenario (Table F.8). These 12 model runs spanned hypotheses deemed plausible by the peer review process with respect to growth (options DFO and NMFS), instantaneous natural mortality M (0.03, 0.06, 0.08), and a range of lengths for knife-edge (k) recruitment to the fishery (k = 29, 24, 21 cm). The selection of runs to include in the composite reference scenario included three values for M and one value of k (29 cm) used with the DFO growth model. The remaining nine runs were based on the NMFS growth model and included three values of M and three values for knife-edge recruitment (k =29, 24, 21 cm). The lower values for k in conjunction with the NMFS growth model were selected in recognition that the 29 cm length was probably at the upper end of plausibility, given the slower growth model. An MCMC posterior for the composite reference scenario was constructed by pooling 1000 MCMC samples from each of the selected runs to give a pooled total of 12,000 samples. This pooled posterior was then used to give advice with respect to stock status and projections, with each individual model run contributing equally to the composite reference scenario.

Table F.8. Twelve runs used in the composite reference scenario. DFO growth: L_∞=47.257cm, K=0.0385, t_0=-8.456; NMFS growth: L_∞=84.99cm, K=0.0178, t_0=-2.88; M = natural mortality; (k_L, k_A) = length and age at knife-edge recruitment. Reference ID is that which appears in Table F.2 along with the original model run number. Each run contributed 1000 MCMC samples to the composite reference posterior.

Scenario	Growth	M	k_L(cm)	k_A(y)	Reference	Model Run
1	DFO	0.03	29	16	R03	22
2	DFO	0.06	29	16	R02	12
3	DFO	0.08	29	16	R01	5
4	NMFS	0.03	29	21	R04	24
5	NMFS	0.03	24	16	R05	25
6	NMFS	0.03	21	13	R06	26
7	NMFS	0.06	29	21	R07	27

Scenario	Growth	M	k_L(cm)	k_A(y)	Reference	Model Run
8	NMFS	0.06	24	16	R08	28
9	NMFS	0.06	21	13	R09	29
10	NMFS	0.08	29	21	R10	33
11	NMFS	0.08	24	16	R11	34
12	NMFS	0.08	21	13	R12	35

F.4.1. MPD comparisons

Selected MPD results from the twelve model runs used in the composite reference scenario are presented in Figures F.23 to F.25. Generally, fits through the mean weight data are better for the NMFS growth runs but many of these models predict unrealistically large unfished equilibrium mean weights (Figure F.23), particularly for combinations where M is low and the length at knife-edge recruitment is either 24 or 29 cm. It seems unlikely that the mean weight of Shortspine Thornyhead declined from 2 kg to 0.5 kg in the space of a few years. However, these same model runs fit the increasing trend in mean weight much better than the equivalent runs using DFO growth or the NMFS growth models and higher M values, none of which fit the increasing trend in the mean weight data very well even though the initial estimated equilibrium mean weight seems more sensible.

The fits to the Queen Charlotte Sound Synoptic survey index data are good for the DFO growth model runs but poor for the NMFS growth scenarios that use small k values (Figure F.24). All runs appear to have little trouble fitting the commercial CPUE except for the model based on the DFO growth model using M=0.03 (Figure F.25).

In summary, M=0.03 seems low given the very high calculated equilibrium mean weight and the lack of large Shortspine Thornyhead in the BC fishery, even in samples collected before the mid-1990s (DFO GFBio database). We note that M=0.06 is similar to M=0.05 used by the latest west coast USA Shortspine Thornyhead stock assessment (Taylor and Stephens, 2013). Knife-edge recruitment k=24 cm appears to be more consistent with the distribution of observed lengths in the BC fishery than k=29 cm (Figure F.22), and k=21 cm (or 100 g) is likely too small for characterising full recruitment to the fishery.

F.4.2. MCMC comparisons

Trace plots for the 12 model runs which comprise the composite reference scenario are generally well behaved (Figure F.26). Biomass trajectories for the model runs which use the DFO growth model are largely flat while the model runs which use the NMFS growth model show steep declines as M decreases (Figure F.27). Biomass projections (2016-2019) are downward under all scenarios, with the model runs which assume M=0.03 and the NMFS growth model suggesting unrealistic immediate stock collapse after the biomass has been maintained at high levels for the previous 15 years. Biomass depletion is flat for the model runs which use the DFO growth model while the model runs which use the NMFS growth model show declines increasing as M decreases and as k increases (Figure F.28). Depletion appears to be more heavily influenced by changes in M than changes in k. All model runs other than those which assume M=0.03 and the NMFS growth model show that the stock has remained above the DFO biomass reference points outlined in Section **??** (Figure F.28). The model runs also differ on how biomass and fishing

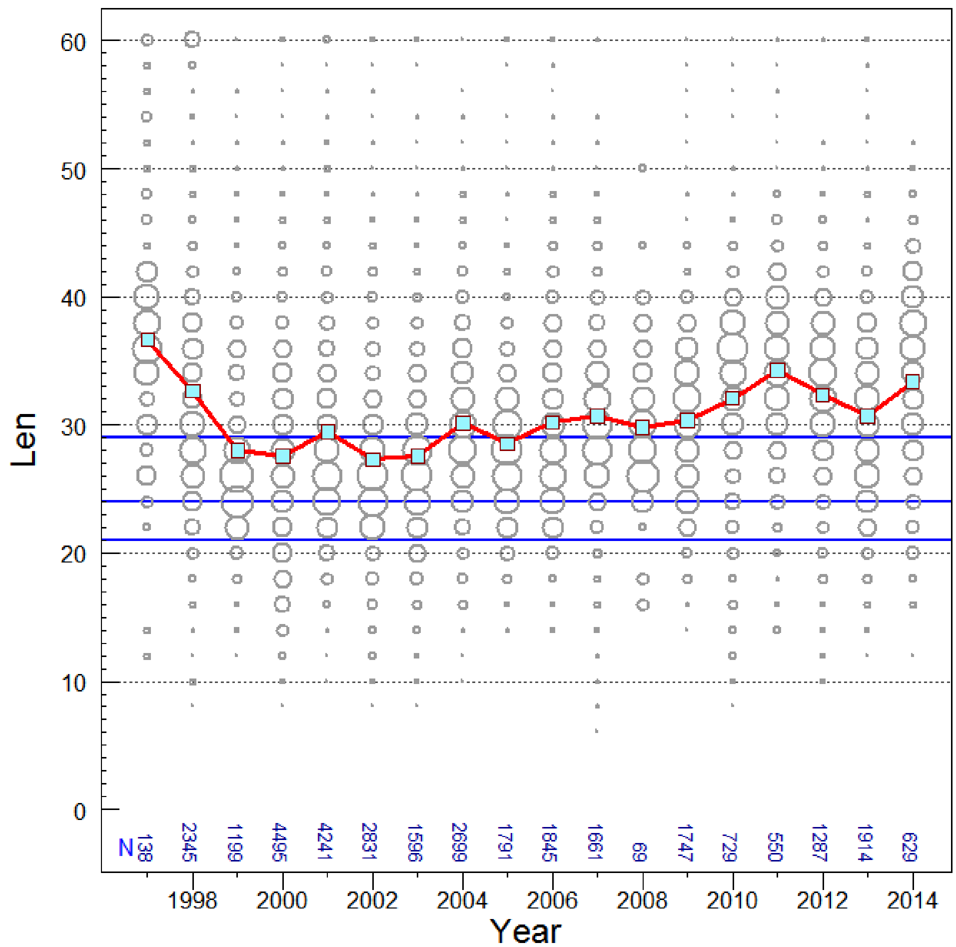


Figure F.22. Commercial length proportions, using 2-cm bins, for Shortspine Thornyhead along the BC coast. Biological data qualification as detailed in Section D.1 (e.g., unsorted random samples). Means of annual length proportions are plotted as squares and connected by a solid line. The lengths at knife-edge recruitment, k = (29, 24, 21) cm, used in the 12 scenarios are indicated by solid horizontal lines.

mortality compare to various candidate reference points, with all runs but one predicting that 2016 biomass and 2015 fishing mortality are above reference levels (Figure F.29). The only exception to this is the model run where M=0.03 and knife-edge selectivity is 29 cm, which seems to be an unlikely combination. Phase plots show how the biomass and harvest rate trajectories have behaved under the different scenarios (Figure F.30). All scenarios largely remain in the DFO Healthy Zone with respect to B_{MSY}; however, the harvest rates have frequently exceeded u_{MSY}.

F.4.3. Composite reference scenario (model average)

The level of biomass depletion (B_t/B_0, Figure F.31) predicted by the composite reference scenario suggests that the stock has remained above the upper stock reference 0.8B_{MSY} since 1980, with a very low probability (0.0078) that it dropped below 0.4B_{MSY} in 1999. However, the stock has since increased to levels well above both reference points, coinciding with a decrease in catches in the early 2000s. Figure F.32 details the trajectory of biomass B_t and harvest rate u_t

in B_{MSY} and u_{MSY} space, respectively, from 1980 to 2016. Median equilibrium biomass before fishing (B_0 or B_{1980}) appears to be roughly 2.5 times the biomass required to generate MSY. Figure F.33 shows the current stock status, represented as B_{2016}/B_{MSY}, for the composite reference scenario as well as each of the 12 contributing scenarios, shown for contrast only. The probability that the stock lies above the USR (in the DFO "healthy zone") is 0.98. The median B_{2016}/B_{MSY} = 2.26 (1.59, 3.48), where values in parentheses represent the 5th and 95th percentiles. Quantities of interest for the composite reference scenario are presented in Table F.9

Table F.9. The 5th, 50th, and 95th percentiles of MCMC-derived quantities from 12,000 MCMC samples comprising the composite reference scenario. Definitions: B_0 – unfished equilibrium biomass, B_{2016} – biomass at the start of 2016, u_{2015} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2015, B_{MSY} – equilibrium biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

	5%	50%	95%
Model-based			
$0.2B_0$	889	1,316	1,963
$0.4B_0$	1,777	2,632	3,926
B_0	4,443	6,580	9,815
B_{2016}	1,965	5,548	10,946
B_{2016}/B_0	0.404	0.793	1.41
u_{2015}	0.0434	0.0828	0.212
MSY-based			
$0.4B_{\text{MSY}}$	641	1,068	1,809
$0.8B_{\text{MSY}}$	1,282	2,137	3,618
B_{MSY}	1,602	2,671	4,522
B_{MSY}/B_0	0.299	0.410	0.538
B/B_{MSY}	0.926	1.85	4.16
MSY	55.9	154	354
u_{MSY}	0.0198	0.0582	0.148
u/u_{MSY}	0.366	1.67	6.69

F.4.4. Harvest Advice

A decision table of probabilities (Table F.10) for the composite reference scenario is the basis of the advice to managers. Note that the probabilities in this table for 2016 cannot change as the 2015 catch has already been taken. The probability that the estimated biomass in 2016, B_{2016}, is greater than the estimated upper stock reference is 0.98, and B_{2016} is always greater than the limit reference point. The estimated harvest rate u_{2015} has a probability of 0.72 of being greater than the estimated harvest rate at maximum sustainable yield.

The average harvest level in the last five years (2010-2014) is estimated to be 572 t coastwide, which is close to the constant catch policy of 600 t listed in Table F.10. Three-year projections indicate that annual catches of 200 t or greater will cause the stock to decline from current levels. At 600 t, the probability that biomass in 2019 is greater than the upper stock reference point, P($B_{2019} > 0.8B_{\text{MSY}}$), is 0.76 and P($B_{2019} > 0.4B_{\text{MSY}}$) is 0.88. At fixed annual catches of 600 t, the probability that the harvest rate will exceed the harvest rate at maximum sustainable yield, u_{MSY}, is 0.84.

Table F.10. Decision table for the composite reference scenario for three reference points – the upper stock reference point 0.8B_{MSY}, the limit reference point 0.4B_{MSY}, and the harvest rate at maximum sustainable yield u_{MSY} – for end-year biomass B_{2016} and mid-year harvest rate u_{2015} and their respective 3-year projections for a range of constant catch strategies (in tonnes). Each value is the probability that current or projected biomass or harvest rate is greater than the indicated reference point. The probabilities are the proportion of MCMC samples from 12 pooled scenarios for which B_t > 0.8B_{MSY}, B_t > 0.4B_{MSY}, u_t > u_{MSY}. For reference, the average catch over the last 5 years (2010-2014) is 572 t.

TAC	P$\left(\frac{B_{2016}>}{0.8B_{\mathrm{MSY}}}\right)$	P$\left(\frac{B_{2019}>}{0.8B_{\mathrm{MSY}}}\right)$	P$\left(\frac{B_{2016}>}{0.4B_{\mathrm{MSY}}}\right)$	P$\left(\frac{B_{2019}>}{0.4B_{\mathrm{MSY}}}\right)$	P$\left(\frac{u_{2015}>}{u_{\mathrm{MSY}}}\right)$	P$\left(\frac{u_{2018}>}{u_{\mathrm{MSY}}}\right)$
0	0.9792	0.9964	1	1	0.72	0
100	0.9792	0.9867	1	1	0.72	0.1412
200	0.9792	0.9604	1	0.9998	0.72	0.4002
300	0.9792	0.9158	1	0.9963	0.72	0.5630
400	0.9792	0.8571	1	0.9799	0.72	0.6884
500	0.9792	0.8043	1	0.9388	0.72	0.7758
600	0.9792	0.7605	1	0.8795	0.72	0.8370
700	0.9792	0.7245	1	0.8259	0.72	0.8816
800	0.9792	0.6874	1	0.7849	0.72	0.9135
900	0.9792	0.6463	1	0.7570	0.72	0.9346
1000	0.9792	0.6025	1	0.7318	0.72	0.9526

F.4.5. Sources of uncertainty

Uncertainty due to growth, natural mortality, and the size of knife-edged selectivity has been evaluated by pooling 12 model runs which span a plausible range of values for these quantities. These included growth (options DFO vs. NMFS growth models), natural mortality – three options (M = 0.03, 0.06, 0.08) for both growth models, and size at knife-edge selectivity – one option for DFO growth (k = 29 cm) and three options for NMFS growth (k = 29, 24, 21 cm). The annual mean weight index increases beginning in the late 1990s/early 2000s, which is in apparent contradiction with the trendless biomass indices. This contradiction, along with the wide range of plausible assumptions regarding the productivity of this stock, combine to indicate that the estimates of 2016 stock status relative to reference points should be taken as a guide rather than as definitive. The composite reference scenario estimates that the stock has maintained its size over the period covered by this stock assessment (Figure F.31), a reflection of the lack of trend in all the available biomass index series. This observation implies that productivity has been adequate to balance removals over the reconstruction period. However, the stock assessment projections indicate that that recent catches will reduce the biomass over the next three years once the information from biomass indices is no longer available. This immediate drop indicates that stock abundance has been maintained in the past through good recruitment generated by the model or that the assumed levels of stock productivity are too low. For these reasons, the three year projections presented in Table F.10 should be considered less reliable than the stock reconstruction presented in Figure F.31.

Available BC Shortspine Thornyhead biological sampling data do not hold many large or old fish. This was notable because the stock assessments for this species both to the north and to the south of BC used growth functions and assumed a natural mortality (M) value that implied that the species lived longer and grew larger than appeared to be the case in BC waters. This difference is reflected in the published data in the most recent stock assessment from the west coast of the United States (Taylor-Stephens 2013). Figure 25 of Taylor and Stephens (2013) shows a much larger proportion of the commercial trawl catch comprising Shortspine Thornyhead greater than 50 cm compared to the equivalent proportion from the BC trawl fishery. The review participants did not agree on the cause of this lack, with some stating that the anomaly was most likely a sampling issue, with the fishery and research surveys operating in regions where the preponderance of large, old Shortspine Thornyhead was small. Others noted that a large proportion of the length observations were from random trawl surveys, several of which went to very deep depths expressly to sample *Sebastolobus*. However, the presence of a sub-population of large and less vulnerable fish implies that there exists a reservoir of spawners which will reduce the risk of over-fishing for the fished population. It is notable that Taylor-Stephens (2013, see Figure 16) allow declining right-hand limb selectivity functions for the trawl fleet and for the trawl surveys to account for the lack of older fish in the fishery and the surveys, which is a by-product of their assumption that M=0.05.

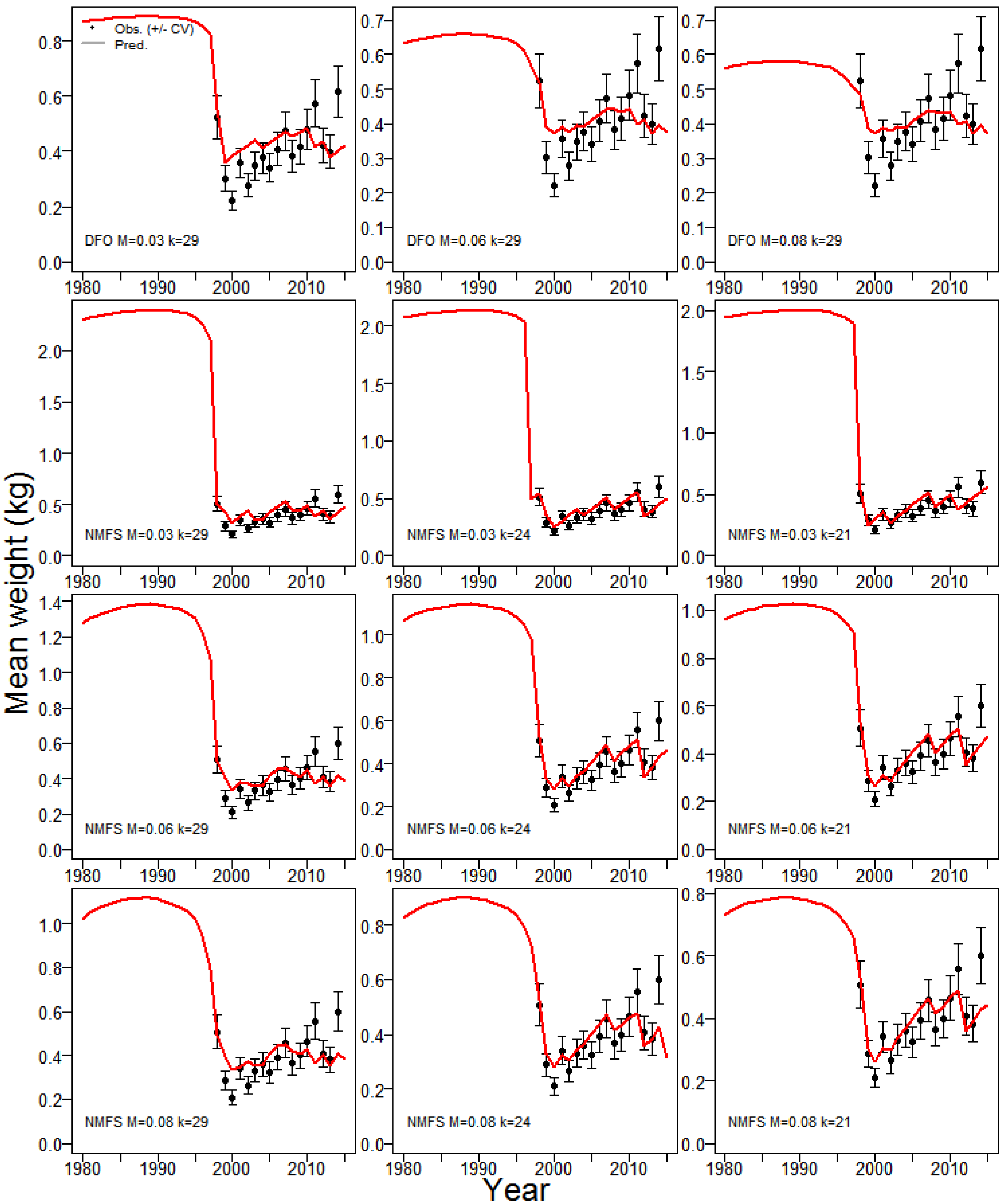


Figure F.23. MPD fits to the mean weight data for the 12 model runs used in the composite reference scenario. Predicted mean weights are shown as red lines and observations are shown as points. Error bars on mean weight observations represent a fixed CV using σ_W = 0.15.

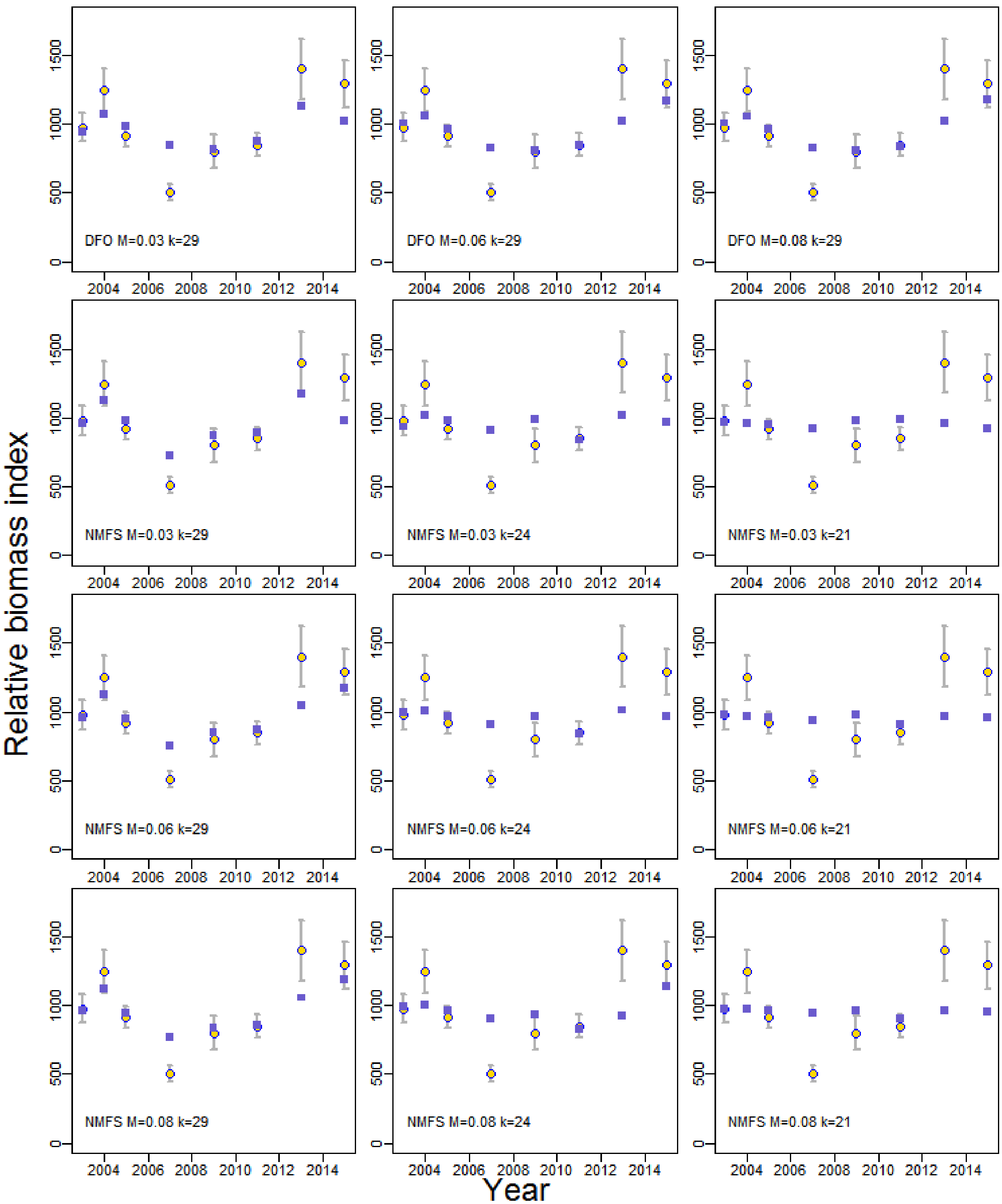


Figure F.24. MPD index fits (12 model runs used in the composite reference scenario) for the QCS (Queen Charlotte Sound) synoptic survey relative abundance indices. Circles represent observed indices with associated CVs, squares represent the model fit.

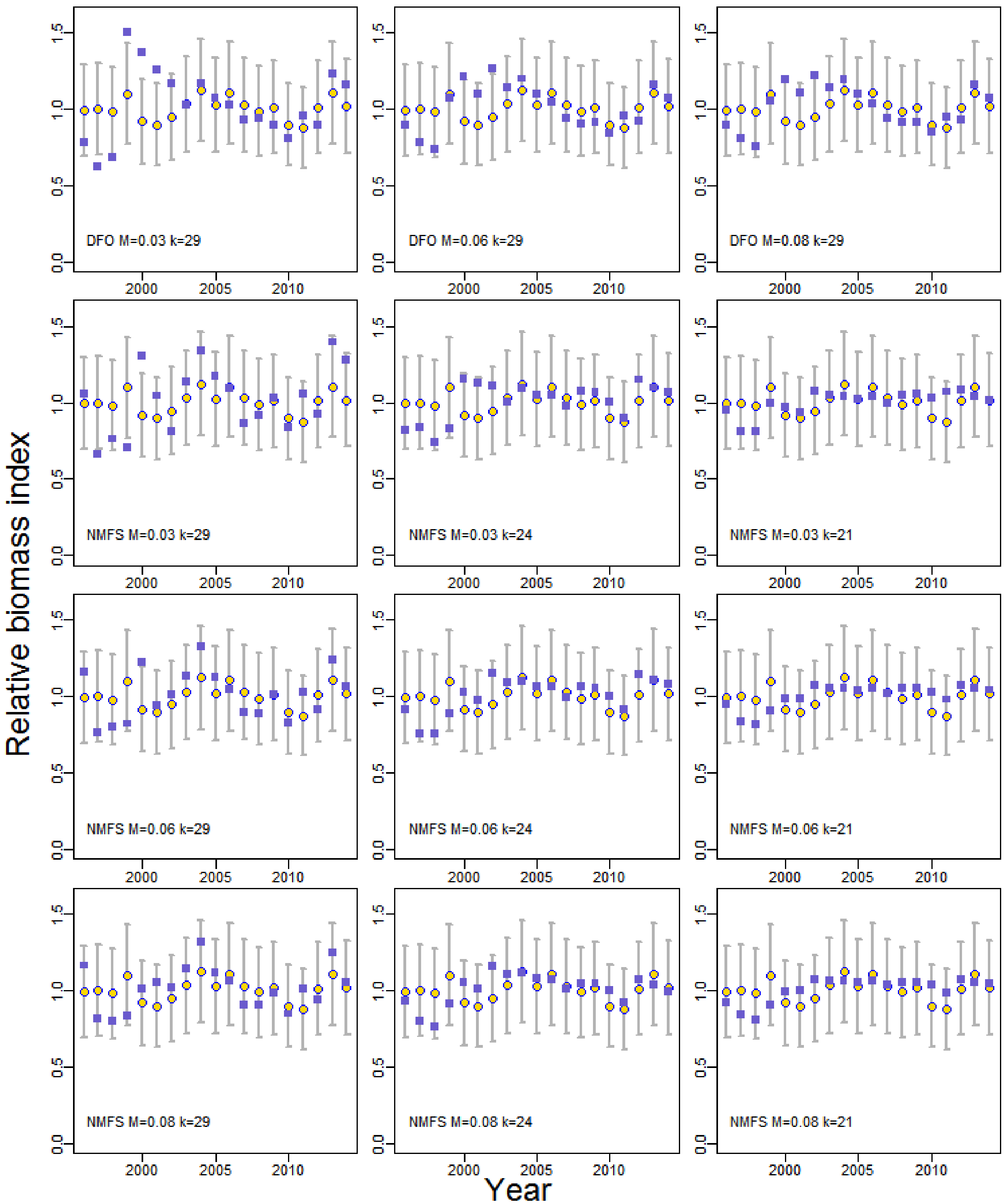


Figure F.25. MPD index fits (12 model runs used in the composite reference scenario) for the commercial trawl Shortspine Thornyhead CPUE relative abundance indices. Circles represent observed indices with associated CVs, squares represent the model fit.

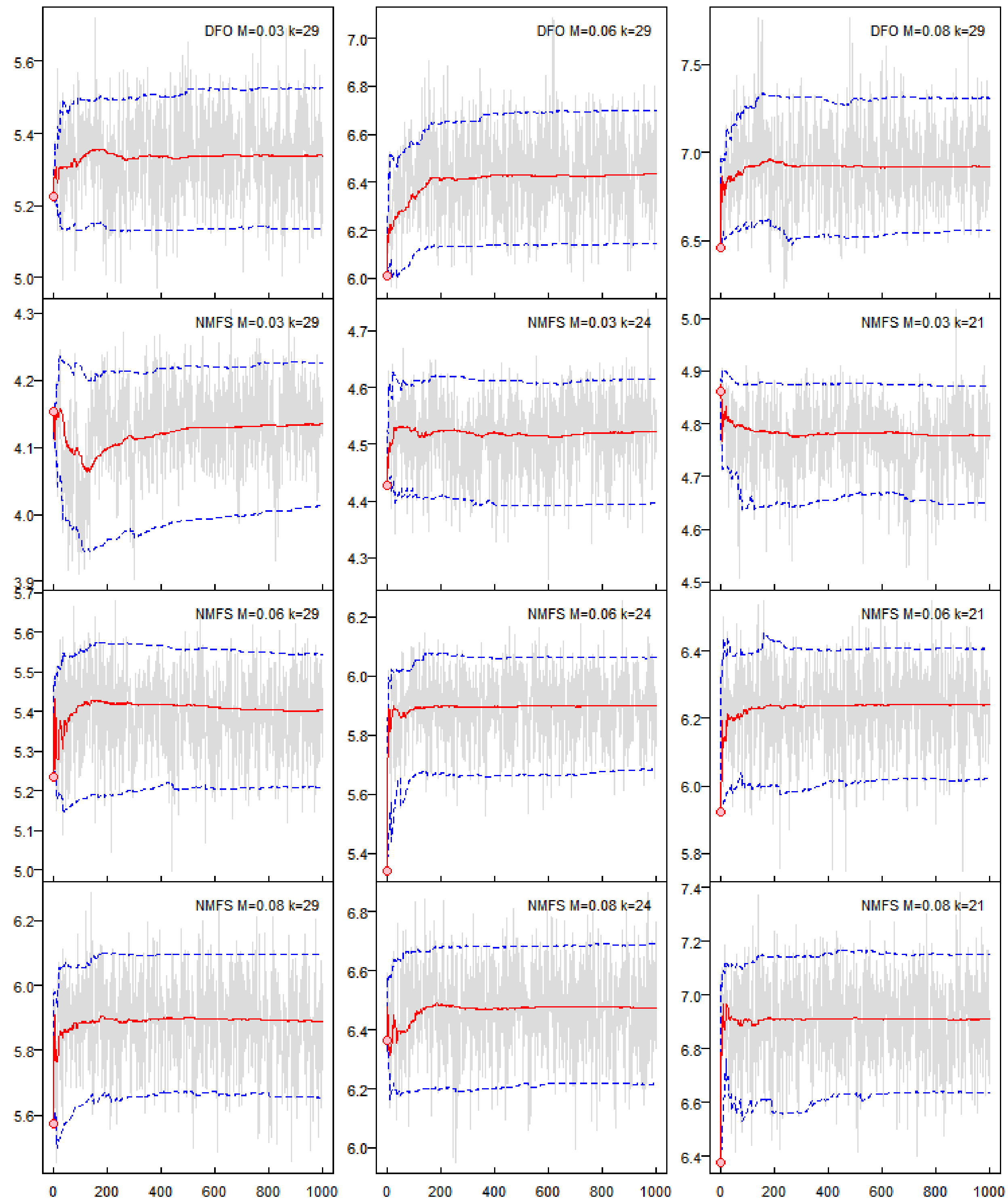


Figure F.26. Trace plots for the 12 model runs used in the composite reference scenario for MCMC samples of $\log(R_0)$ (natural log of unfished equilibrium recruitment). The MCMC runs each had chain length 51.5 million, with a burn-in period of 1.5 million and a sample taken at every 50,000$^{\mathrm{th}}$ iterations to yield 1,000 MCMC samples.

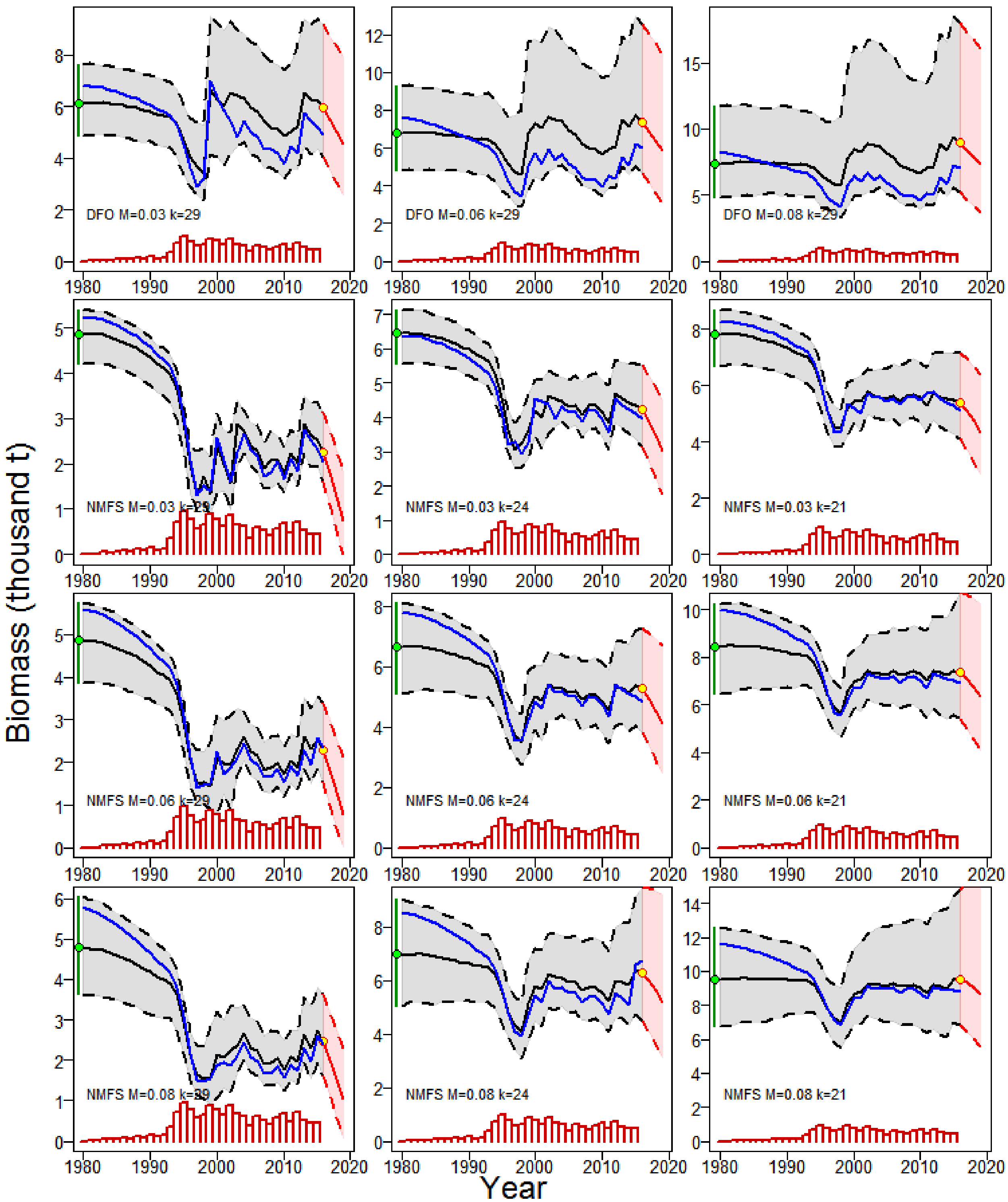


Figure F.27. Posterior estimates of biomass (1000 t) for the 12 model runs used in the composite reference scenario with 95% credibility intervals in grey. The current year biomass (2016, yellow point) and projected biomass (2017-2019, red line), assuming a constant catch policy of 600 t/y, are enclosed by a 95% credibility interval shaded pink. The median posterior estimate of B_0 is shown as a green point (with 95% credibility range) to the left of the time series. The MPD estimate is shown as a blue line. The total catch is shown along the bottom as red bars.

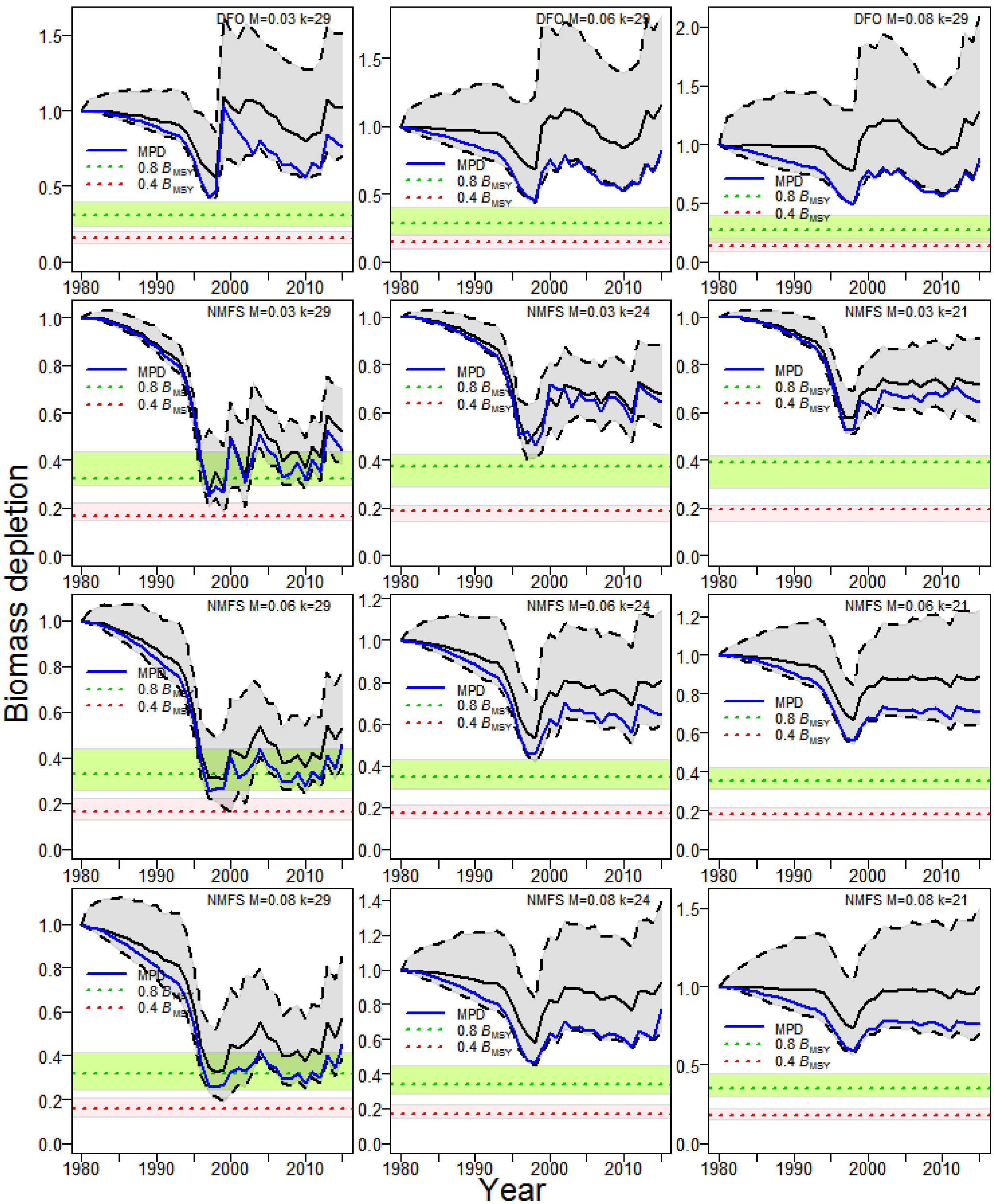


Figure F.28. Posterior estimates of biomass depletion, i.e. B_t/B_0, for the 12 model runs used in the composite reference scenario with 95% credibility intervals. Also displayed on the depletion figure is the MPD estimate (blue line) and the reference points 0.2B_0 (red dashed line) and 0.4B_0 (green dashed line).

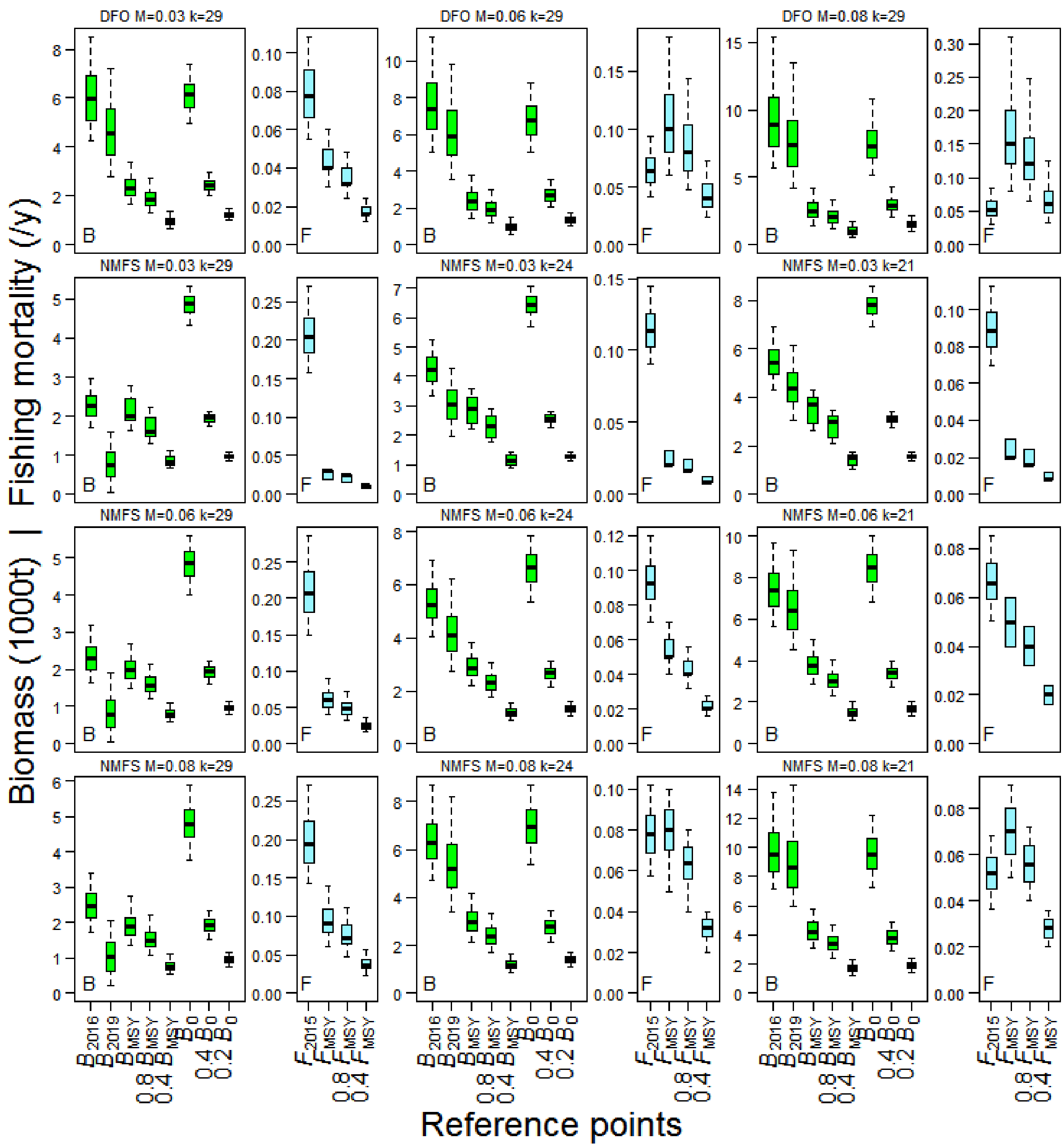


Figure F.29. Posterior estimates of reference points for the 12 model runs used in the composite reference scenario. For each run, green boxplots on the left show biomass-based reference points: B_{2016} = current-year biomass, B_{2019} = protected-year biomass, B_{MSY} = biomass at maximum sustainable yield, 0.8B_{MSY} = biomass at 80% B_{MSY}, 0.4B_{MSY} = biomass at 40%B_{MSY}, B_0 = equilibrium biomass in the absence of fishing, 0.4B_0 = biomass at 40% B_0, and 0.2B_0 = biomass at 20% B_0; blue boxplots on the right show fishing mortality-based reference points: F_{2015} = current-year fishing mortality rate, F_{MSY} = harvest rate at maximum sustaible yield, 0.8F_{MSY} = fishing mortality rate at 80% F_{MSY}, 0.4F_{MSY} = fishing mortality rate at 40% F_{MSY}. Box delimiter and limits represent quantiles at 0.5 (median), 0.25 and 0.75 quantiles, respectively, and the whiskers delimit the 0.05 and 0.95 quantiles. Outliers are not shown.

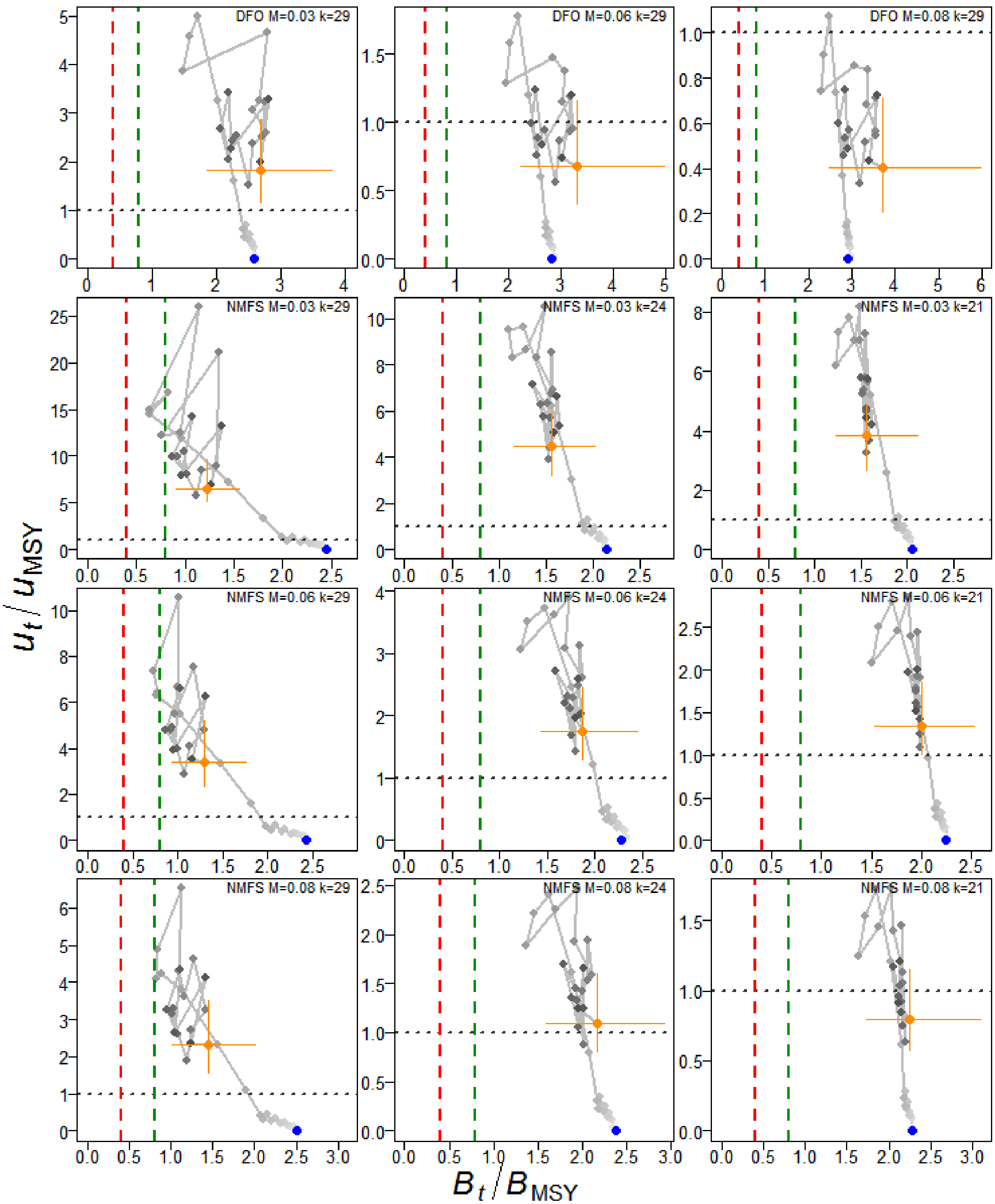


Figure F.30. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the exploitation rate in year t relative to u_{MSY}) for the 12 model runs used in the composite reference scenario. Blue filled circle is the starting year 1980. Years then proceed from light grey through to dark grey with the final year 2016 as a filled orange circle with limit lines represent the 0.1 and 0.9 quantiles of the posterior distributions for the final year. Vertical dashed lines indicate the Precautionary Approach provisional limit (red) and upper stock reference (green) points (0.4, 0.8 B_{MSY}), and horizontal dotted line indicates u at MSY.

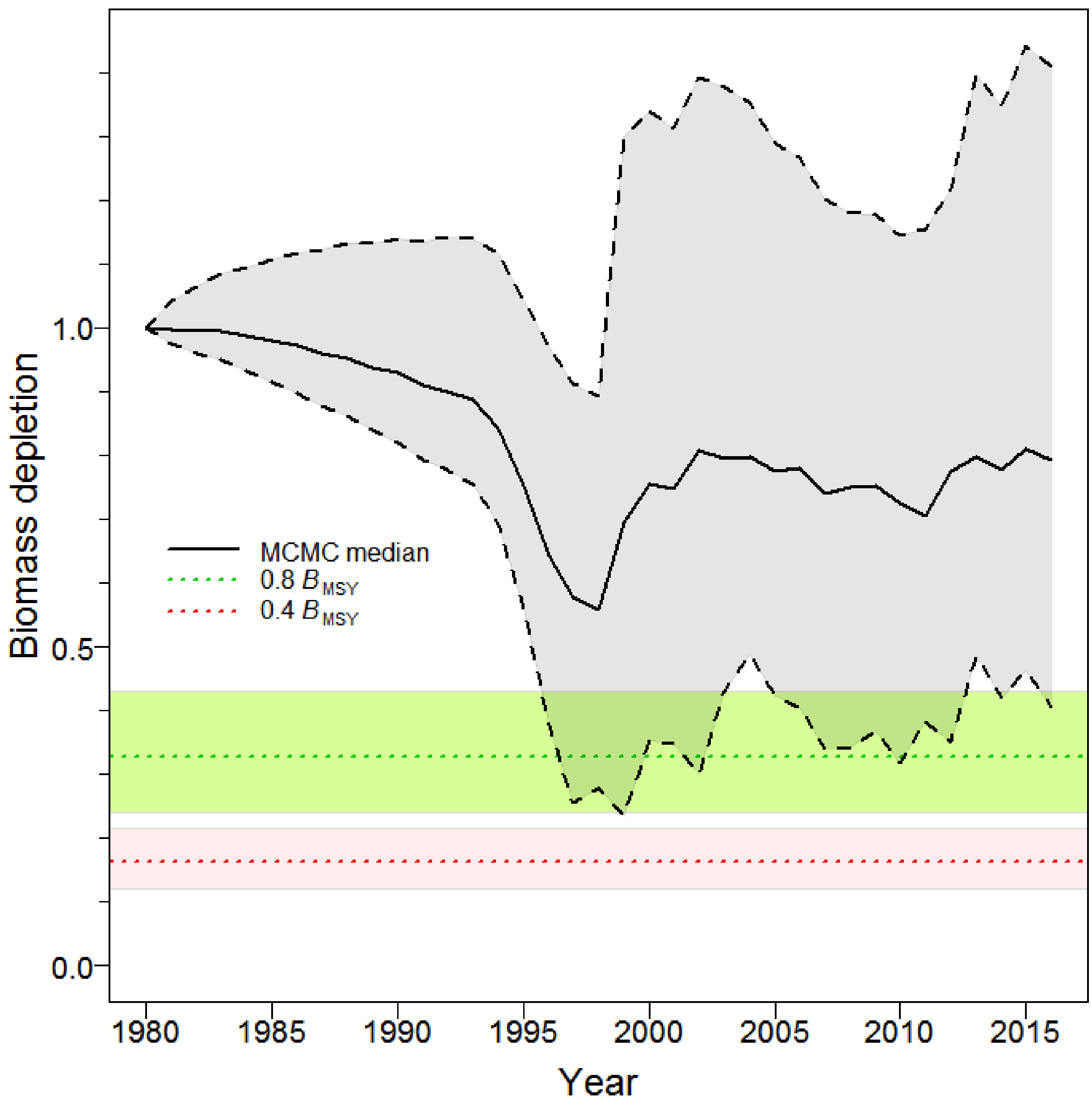


Figure F.31. Median estimates (solid black line) and 90% credibility intervals (black dashed lines, grey fill) for the composite reference scenario B_t/B_0 (biomass in year t relative to that in 1980) for Shortspine Thornyhead. Also shown are the MSY-based reference points (Limit Reference Point, LRP = 0.4B_{MSY} shown as a red band and line; Upper Stock Reference, USR = 0.8B_{MSY} shown as a green band and line) relative to B_0.

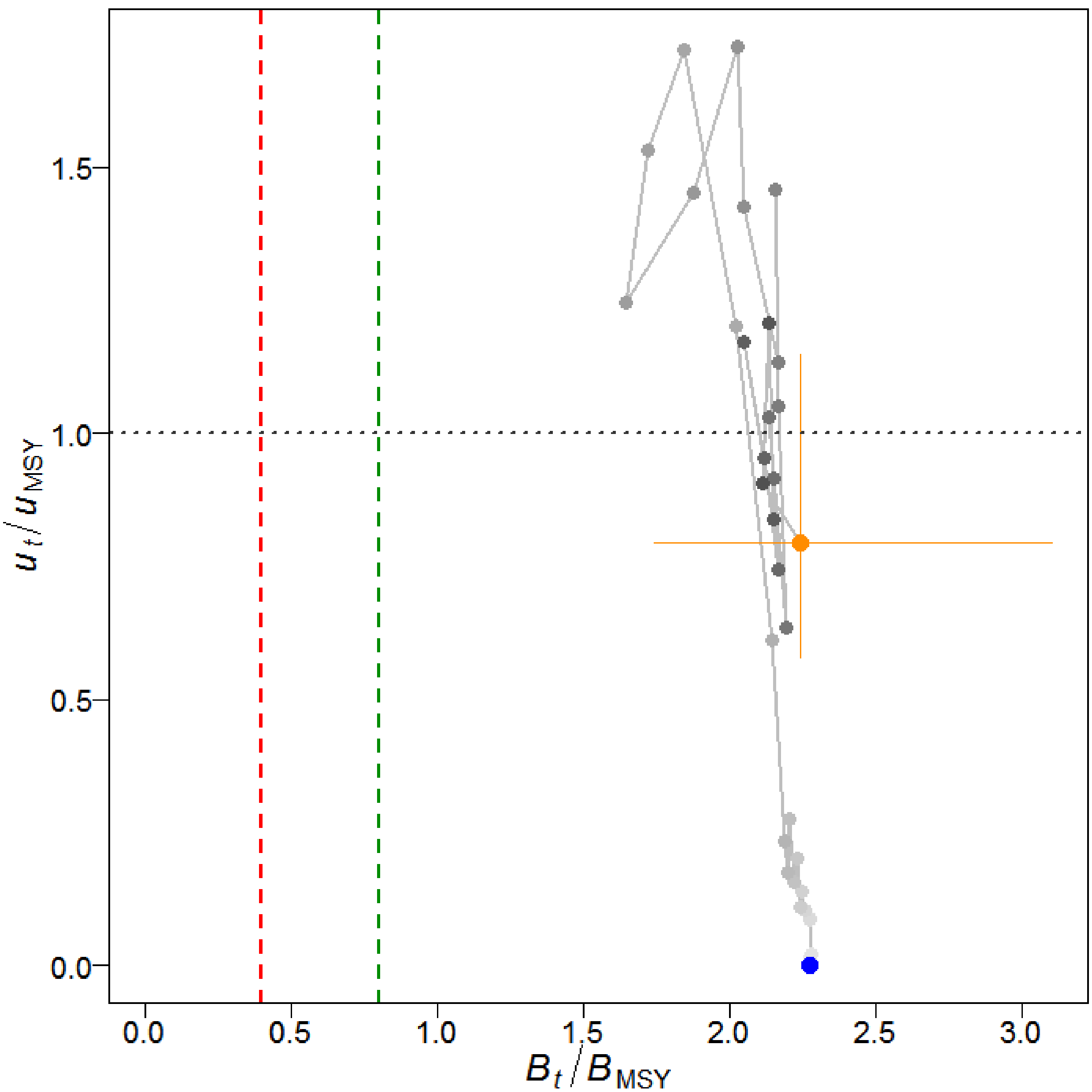


Figure F.32. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the harvest rate in year t relative to u_{MSY}) for the composite reference scenario. Blue filled circle is the starting year 1980. Years then proceed from light grey through to dark grey with the final year 2016 as a filled orange circle with limit lines represent the 0.1 and 0.9 quantiles of the posterior distributions for the final year. Vertical dashed lines indicate the Precautionary Approach provisional limit (red) and upper stock reference (green) points (0.4, 0.8 B_{MSY}), and horizontal dotted line indicates u at MSY.

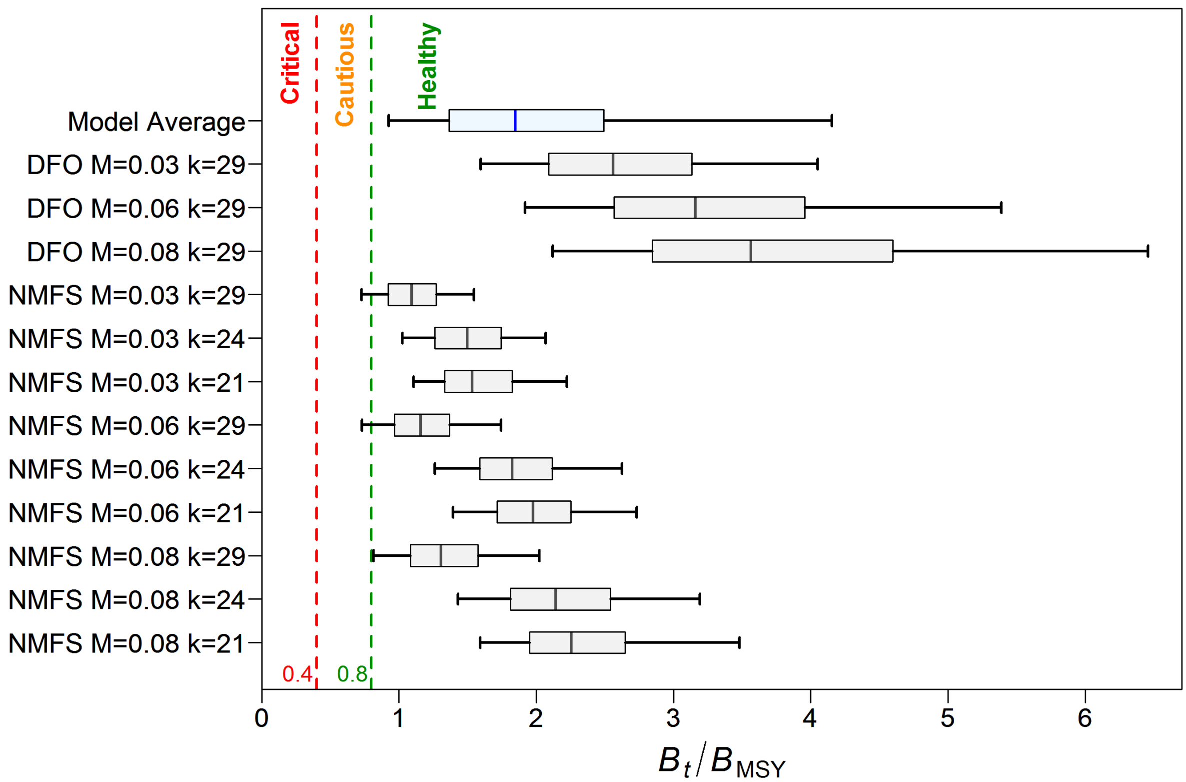


Figure F.33. Current status of the coastwide BC Shortspine Thornyhead stock relative to the DFO Precautionary Approach provisional reference points of 0.4B_{MSY} and 0.8B_{MSY}. The value of B_t/B_{MSY} uses t=2016 for the composite reference scenario and for each of the 12 model runs which comprise the composite reference scenario (see Table F.8 for definitions of these model runs). Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. DFO = Canadian Fisheries and Oceans; NMFS = US National Marine Fisheries Service; M = instantaneous natural mortality (y^{-1}); k = length (cm) at knife-edge recruitment.

F.5. REFERENCES – MODEL RESULTS

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