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A Population Model for the Atlantic Sturgeon (*Acipenser oxyrinchus*) Spawning Population of the Saint John River, New Brunswick

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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

An assessment of Atlantic Sturgeon in the Saint John River (SJR), New Brunswick is presented. A two-sex age-structured model was developed using stock synthesis (SS3) software with data from the commercial landings from the SJR and Bay of Fundy (BoF). Sensitivity analyses explored various assumptions in the population model, including historical depletion in the early SJR fishery (late 19th century), selectivity of the SJR fishery, the magnitude of catches in the Bay of Fundy, sex ratio of catches, and steepness of the Beverton-Holt stock-recruit relationship. In most scenarios, the female Spawning Stock Biomass (SSB) was estimated to be above SSB_{MSY} (the SSB at maximum sustainable yield) in 2020. Short-term (10-year) projections indicated that with the current Total Allowable Catch (TAC; 175 males and 175 females), the biomass would decline but remain above SSB_{MSY}. Historical depletion since 1891 (three generations) are also presented for the purposes of Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessment (COSEWIC 2011). A separate analysis for the tagging data estimated fishing mortality since 2009 to be similar in trend and magnitude to those from the SS3 models.

INTRODUCTION

Advice on the status of the spawning population of Atlantic Sturgeon (herein referred to as Sturgeon) in the Saint John River (SJR) was requested by Fisheries and Oceans Canada (DFO) resource managers to improve management of the commercial fishery. Specifically, they asked DFO Science to:

- provide an estimate of the current spawning stock biomass, as well as advice on appropriate reference points;

- provide advice as to whether the current 350 fish commercial quota (175 males and 175 females) is appropriate relative to the estimate of spawning stock biomass.

This advice is expected to guide decisions in the management of food, social, and ceremonial allocations, commercial quota allocations, and access for recreational fishers. It is also expected to support decisions related to the current terminal licence policy in the commercial fishery.

Previous assessments of the SJR Sturgeon have used a variety of methods for mortality and abundance estimates, often requiring equilibrium assumptions (Bradford et al. 2016, Dadswell et al. 2017). Data collection in the modern fishery (since 2007) along with biological studies and the extensive historical catch series have provided an opportunity to explore use of more complex models for assessment. A statistical catch-at-age (SCA) model estimates historical abundance and biomass from multiple data types. To do so, the SCA generates a reconstruction of the population that best explains the data, i.e., catch, catch per unit effort (CPUE), and length/age compositions, provided to the model. Such a model can provide a framework for calculating reference points suitable for management purposes.

Stock synthesis (SS3) is an age-structured assessment model designed for flexibility in data inputs and model complexity (Methot and Wetzel 2013). Initially designed for U.S. West coast groundfish and sardine assessments, its flexibility has allowed for use in stock assessments of diverse species around the world (Dichmont et al. 2016). Ease of access to software packages such as SS3 has allowed for extensive testing, simulation, and peer review of the model code in a variety of configurations. The companion r4ss R package provides standardized reporting of model diagnostics and presentation of model output.

For SJR Sturgeon, SS3 provided a convenient platform for a 2-sex model and multiple fleet structure accompanied by different data formats (catches in both weight and numbers, and composition data in both lengths and ages). The approach to the SS3 assessment was to develop a reference model, from which further modifications could be explored in sensitivity tests and scenarios. The major areas of uncertainty associated with fitting an SCA model are explored and the implications on reference points and the appropriateness of the current total allowable catch (TAC) is discussed. However, no preference is given to the reference model, i.e., it is not a "preferred" model. Rather, alternative model configurations are explored by adjusting the reference model accordingly.

METHODS

CATCH AND COMPOSITION DATA

Historical commercial Sturgeon landings were taken from Bradford et al. (2016) (Figure 1). Composition data from the SJR fishery were taken from Dadswell et al. 2016 (Figures 2 and 3). In this assessment, only harvested animals were considered in the composition data. This assumes that there is negligible mortality of animals that were released following capture. Age

and size structure data presented in Dadswell et al. (2016) were used in the model to estimate selectivity of the Bay of Fundy (BoF) catches (Figures 4 and 5).

CPUE STANDARDIZATION

Standardization of fishery CPUE (numbers of fish caught per net per day) was utilized to derive an index of abundance for the Sturgeon population. Catch rates can change over time due to factors other than abundance, and the standardization process identifies such factors and accounts for their impacts (Maunder and Punt 2004).

Here, a Generalized Linear Model (GLM) was fitted to catch rates using year, month, and river flow as covariates. The full model is of the form

$$C_\mathrm{d} = g^{-1}(Y_d \times M_d + W_d + \mathrm{offset}[\log(E_d)]),$$

where C_d is the catch, Y is the year, M is the month, W is the river flow (standardized), E is the effort (number of nets) offset variable (with a fixed coefficient of 1) on day d, and $g^{-1}()$ is the inverse of the link function of the GLM. Year and month were categorical variables with interaction effects.

River flow data was characterized by the water discharge (reported hourly) from the Mactaquac Generating Station (Figure 6). For each logbook day, the daily mean water discharge was calculated from the hourly values (Figure 7). For the GLM, the logarithm of the daily mean was then transformed to a Z-score (standard normal transformation). The CPUE series was only analyzed from 2009–2020 since the water discharge data was only available back to 2009. September records were excluded from the analysis since there were very few fishing events in that month.

Simpler models were fitted by removing covariates and/or interaction effects from the full model. All models used either the Poisson or negative binomial distribution, with the latter to account for overdispersion, with a log link function in the GLM. Then, AIC (Aikaike Information Criterion) was used to select the best model. The analyses were performed using the glm() and glm.nb() functions in the stats and MASS R packages, respectively.

TAGGING DATA

Sturgeon captured during the commercial fishery are retained for harvest or sampled (fork length, total length, sex) and released. Fish not selected for harvest are tagged with an external T-bar tag (Floy) inserted near the dorsal fin. Since 2012, Sturgeon have been double tagged with both a Floy tag and a Passive Integrated Transponder (PIT) tag inserted under the skin between the dorsal and lateral scute rows. All captured fish are checked for PIT tags with a hand-held examining unit (Biomark 601 PIT tag reader).

Tagging records and the analysis of the tagging data with the Brownie model are described in Appendix A.

BIOLOGICAL PARAMETERS

Growth, natural mortality, and maturity parameters were fixed in the SS3 model. Sex-specific length-at-age for SJR Sturgeon has been modelled with a von Bertalanffy growth function. Bradford et al. (2016) reported growth parameters with the t_0 parameter fixed to zero since only older animals (greater than 15 years) were included in the analysis. Stewart et al. (2015) estimated parameters, including t_0, using juveniles and subadult samples collected from Minas Basin. This assessment considered BoF catches, and thus, the parameters from Stewart et al. (2015) were the preferred values to characterize growth at immature ages (Table 1).

Parameters for the length-weight relationship were taken from Dadswell et al. (2017) using total length and round weight conversion factors. The coefficient of variation in length-at-age was fixed to 0.1 in the SS3 model.

Natural mortality (M) was estimated from indirect estimators developed through meta-analysis. These estimators are used to predict M from maximum age and von Bertalanffy growth parameters. Sex-specific values of M were estimated, with growth parameters or maximum ages of 51 and 43 for females and males, respectively (Stewart et al. 2015). M values from several estimators were calculated (Table 2). The parameters from Then et al. (2015) estimator that used growth parameters were the preferred values (Table 1). While Then et al. (2015) indicated that the estimator using maximum age is the preferred method, these estimates were high relative to those from the older estimators and previous estimates of M for the SJR stock (Dadswell et al. 2017), and considered less plausible when considering the life history of the stock.

While growth and natural mortality were sex-specific, SS3 only considers female maturity in the calculation of Spawning Stock Biomass (SSB). Currently, no maturity schedule has been estimated for the SJR stock. However, the size composition of SJR commercial fishery of could provide some insight. The length of first maturity in females has been reported to be 160 cm (Stewart et al. 2015), and this was used as the length of 5% maturity. Visual inspection of the ascending limb of the length frequency of catches as a proxy for the maturity schedule would suggest 175 cm as the length of 50% maturity (Dadswell et al. 2017). Maturity-at-length was modeled as a logistic function and converted into maturity-at-age internally in the model and reported in the output (Figure 8). For males, an additional SS3 run was used to report maturity-at-age using 140 cm and 160 cm as the length of 5% and 50%, respectively.

Steepness is a parameter (with a range of 0.2–1.0) of the Beverton-Holt stock recruit relationship describing the resilience of the population and the rate of recovery when the stock is at very low levels. Steepness is typically difficult to estimate and no meta-analysis is currently available for developing a prior value for *Acipenseridae*. Whitlock and McAllister (2012) used three different values of steepness in their assessment of Fraser River White Sturgeon, which would be equivalent to a uniform prior. For the reference model, a value of 0.6 was chosen in consideration of the late maturity and periodicity in spawning of Atlantic Sturgeon. Annual recruitment (age 0) was calculated using the stock-recruit relationship internal to the model. No recruitment deviates were estimated in the assessment. The sex ratio of recruits was set at 50% female.

MODEL STRUCTURE

In the reference model, separate fishing fleets for the SJR and BoF catches were modeled in SS3. To accommodate the historical catches in weight pre-2007 and the modern catches (in numbers) post-2007, the SJR fishery was further split into two fleets with selectivity parameters shared between them. The estimated parameters in the model included unfished recruitment (R_0, in logspace) and those controlling selectivity for the fleets.

Sex-specific length composition of the removals in the SJR fishery were used, as well as unsexed length and age composition reported in Dadswell et al. (2016) for the BoF fishery. Accordingly, sex-specific selectivity for the SJR fleet and a unisex selectivity for the BoF fleet. The SJR fishery selectivity was modeled as a Gaussian function for the ascending limb only (typically referred to as logistic selectivity), while the BoF fishery was modelled as a Gaussian function with independent ascending and descending limbs ("dome"-shaped). Since the composition comprised of only harvested animals, selectivity is therefore the product of

availability spatially, contact selectivity between the animals and the gear, and fishery retention. The multinomial distribution was used in the likelihood for the composition data.

The SJR fishery CPUE was specified to be an index of female spawning stock numbers.

Fishing mortality (F) was estimated in SS3 using the hybrid method option, which calculates F such that the predicted catches match the observed values. A constraint was placed on F such that it could not exceed 3, corresponding to a maximum annual harvest rate of approximately 0.94. The model was run using the full time series of catches to 1880, when the stock was assumed to be in an unfished state. The stock likely experienced high F with the rapid depletion in the initial years of the SJR fishery, likely fishing out the exploitable portion of the stock (Bradford et al. 2016, Dadswell et al. 2017). Thus, sensitivity runs with alternative values of maximum F of 1 and 6, corresponding to harvest rates of 0.62 and 0.99, respectively, to evaluate the importance of this constraint.

The SS3 model consists of two major components, with the first component being the estimation component (using maximum likelihood) for the historical reconstruction of the stock, and the second component being the forecast component intended to generate short-term projections of the stock from a schedule of catches or fishing mortality for the near future. The forecast was configured with the intention to test the current TAC of 175 females and 175 males for the next decade, i.e., from 2021–2030. However, the structure of the reference model, in which a single SJR fishery fishes both sexes, only allows for setting a combined-sex TAC. Thus, the forecast was run with a catch forecast of 300 animals, which from initial tuning resulted in removals of approximately 175 females (and fewer males).

A separate configuration of SS3 was generated to explicitly allow testing of the 175–175 TAC. This configuration required separation of SJR removals for females and males into separate fleets. As a result, historical catches also needed to be split by sex. While harvested catches in the modern SJR fishery are reported by sex, an assumption about the sex ratio of historical catches prior to 2007 is needed. A value of 60% female catches by weight was used based on the modern data (Figure 9). This configuration (termed "SSF" for separate sex fleet) is notably different from the reference model in the assumptions regarding sex ratio in the catches and the relative F between sex. In the SSF, the sex ratio is fixed and the estimated F are independent between sex, while in the reference model, the sex ratio varies with the ratio of F constant over time. This modification potentially generates a different reconstruction of the stock history compared to the reference model.

An additional sensitivity run modeled dome selectivity for the SJR gillnet fishery. Compared to the reference model, an additional parameter for the descending limb of the selectivity function was estimated.

In the reference model, 60% of the historical BoF catches were considered to originate from the SJR stock, following the stock composition analysis of Wirgin et al. (2012). Sensitivity analysis explored additional scenarios with 30% and 90% BoF catches of SJR origin.

To evaluate uncertainty with respect to steepness values, a likelihood profile was generated comparing biomass and F from values of 0.45 to 0.85. Several other diagnostics were utilized, including a likelihood profile for the unfished recruitment parameter and a retrospective analysis to evaluate the consistency of model estimates as recent data were removed.

Stock synthesis version 3.30.15 was used for this paper.

REFERENCE POINTS

Estimates of F and SSB relative to reference points can be used to make stock status determination. In a multiple-fleet model where fishing fleets have disparate selectivity patterns and apical F, it can be difficult to define a single value for F to describe the fishing pressure that the stock experiences in an individual year. For SJR Sturgeon, the summary F was defined to be the F calculated at the apical value for the SJR fishery in the model. For models with SJR logistic selectivity, this corresponded to the maximum age of 60 years. For the model run with SJR dome selectivity, the F at the age of 40 years was used as the summary F.

With no information on steepness, reference points that use the stock-recruit relationship, such as maximum sustainable yield (MSY), may not be appropriate. In such a situation, alternative proxies for the fishing mortality at MSY (F_{MSY}) that use per-recruit calculations are frequently used. Here, $F_{0.1}$, the mortality at which the change in yield-per-recruit is 10% of that at F = 0, and $F_{X\%}$, the mortality that reduces spawning potential ratio (SPR, the ratio of the spawning biomass per recruit relative to that at F = 0) to X% were reported as potential reference points for fishing mortality. A range of SPR values from X = 20, 30, 40, 50, and 60% was calculated, where a higher SPR threshold reflects higher precaution in terms of conservation. These reference points are relative to the summary F.

In contrast, it is difficult to calculate a biomass reference point that is agnostic about the stock-recruit relationship. The spawning stock biomass at MSY (SSB_{MSY}), or potentially some scalar thereof, is provisionally presented as a biomass reference point. Values of SSB_{MSY} vary among models depending on the value of unfished recruitment and steepness, but the ratio SSB/SSB_{MSY} in 2020 could be used as a status determinant and can be robust across models.

Reference points were calculated internally in SS3 during the forecast phase. The mean fishing mortality rate during 2018–2020 was used as the F benchmark for stock status (relative to F reference points), while the SSB in 2020 was used as the biomass benchmark.

COSEWIC CONSIDERATIONS

Depletion calculations for the purposes of COSEWIC assessment are presented in Appendix B.

RESULTS

CPUE STANDARDIZATION

From the null model (intercept-term only), additional covariates decreased the AIC, often by several hundred units (Table 3). Using AIC, the full model that used the negative binomial GLM was selected as the best model. In estimating the overdispersion parameter, the negative binomial GLM provided a better fit in terms of AIC relative to the corresponding Poisson GLM. The treatment effects for the year, month, year-month, and water flow groups were each statistically significant at α = 0.05 in the full model. Model residuals were fairly well-behaved overall (Figure 10). Residuals appeared to be normally distributed with no apparent trends with respect to year and month, although they remained somewhat heteroscedastic with respect to predicted values.

The observed CPUE series, calculated as annual geometric means, shows a notable decline from 2009 to 2012 (Figure 11). During the middle of the series (2011–2018), observed values were relatively stable, if not slightly increasing, followed by a slight decrease since 2018. The recent decrease appears to correspond with the lower flow more frequently observed in the summer and autumn months (Figure 7). The standardized series flattened the decreasing trend at the beginning of the time series such that the decline was not as pronounced as the observed

values (Table 4). The stability in the middle of the time series remained, while the drop from 2019 to 2020 was less pronounced compared to observed values.

STOCK SYNTHESIS MODEL FIT AND DIAGNOSTICS

The reference model estimated that the unfished female Spawning Stock Biomass (SSB_0) was 347 t in 1879 (Table 5; Figure 12). Rapid depletion of the stock occurred with early catches in the 1880s, with the fishing mortality for the SJR fishery reaching the maximum of 3 in 1883 (Figure 12), and the fishery closed soon afterwards. The stock was not fished into extinction because the fishery selectivity was restricted to a subset of the spawning component (see selectivity estimates in the next paragraph). The juvenile and young spawner components of the stock that were invulnerable or only partially vulnerable to the fishery remained and contributed to the stock recovery. The stock recovery continued into the 1910s, but then stabilized in the 1920s, as the SJR fishery continued and catches from the BoF began. From the 1920s until 1980, the stock continued to increase, but at slower rate than in the late 19th and early 20th century. Another period of higher F occurred in the 1980s coinciding with notable removals in the BoF. Since 2007, at the start of the modern fishery, the stock size has been decreasing, although at a slower rate than estimated in the past. The stock has remained above SSB_{MSY} since the late 19th century.

Full selectivity of the SJR fishery was estimated to be 200 cm and 180 cm for females and males, respectively (Figure 13). These values correspond to approximately 35 and 25 years, respectively, using mean length-at-age. The selectivity curve was larger than the maturity-at-length. The BoF fishery caught smaller, immature fish with the dome selectivity peak at 150 cm (18 years).

The model generally generated good fits to the SJR female length composition, although the model predicts higher abundance of large animals that are only occasionally seen in the data (e.g., 2015 and 2016; Figure 14). The fit to the SJR male composition, on the other hand, was poorer. The mode of the predicted distribution often matches the observed, although the mode frequently changed over time (Figure 15). Due to the larger sample size of the BoF length composition relative to the age data, the model fitted the lengths much better (Figures 16 and 17).

The predicted index was flat relative to the standardized series (Figure 18). The change in the estimated spawning stock numbers over 2009–2020 time period was relatively smaller relative to the standardized CPUE (Figure 19). In particular, the decreasing trend of the standardized values during 2009–2011 was not captured in the predicted index.

The estimated apical F of 3 in 1883, that hit the specified boundary, is a potential structural constraint in the model. The apical F in 1883 also reached the respective upper boundary in alternative runs with max. F = 1 or 6. This implies there is no information in the data to inform the model of the depletion in the early years of the fishery, and these must be specified in the model indirectly through the maximum F constraint. As maximum F increases, the unfished stock size and current spawning biomass (both in absolute magnitude and relative to SSB_{MSY}) decrease, with the rate of decrease diminishing with increasing maximum F (Figure 19).

The SSF configuration with fixed sex ratio in historical catches was more optimistic, i.e., larger stock and higher current biomass, compared to the reference model (Figure 20). To maintain the 60:40% female:male ratio in the 1880s catches, the apical F for males reached the maximum F value in 1883, but the female F was lower, generating higher SSB compared to the reference model. In contrast, the sex ratio in the reference model changes over time, but often exceeds 60% (Figure 21). The SSF configuration for the stock synthesis model functionally behaved similar to the maximum F = 1 scenario.

When dome selectivity was estimated for the SJR fishery, the estimated SSB and SSB/SSB$_{MSY}$ was higher compared to the reference model for much of the time series (Figure 22). The mode of the selectivity curve indicated that the highest fishing pressure is at age 40 and 26 for females and males, respectively (Figure 23). Based on the ratio of females and males in the length composition, the model estimated that the apical fishing mortality experienced by males was approximately 80% of that for females. The fit to the length composition, particularly for the upper tail of the distribution, was improved compared to the reference model (Figures 24 and 25).

The assumption regarding the percent stock origin of BoF catches only affects the current depletion, with lower SSB and slightly higher F in 2020 if the percent SJR origin is high (Figure 26). Biological reference points, e.g., unfished spawning biomass, are unaffected, because of the maximum F constraint for 1883.

On the surface, the profile likelihood for steepness (h) indicated that lower values were preferred, with the minimum at h = 0.30 (Figure 27). However, such low values imply that there is little to no density dependence in the population and there is no fishing mortality can be sustainable. In other words, SSB$_{MSY}$ approaches SSB$_0$ as steepness approach 0.2 (Figure 28). Such a value also implies that the recent SSB is similar to that in the 1880s despite markedly lower catches (Figure 28). Recent fishing mortality is also markedly high with very low steepness (Figure 29). For comparison with the reference model and other sensitivity fits, a range of more plausible values between 0.45–0.85 was used. As the steepness value used in the model increased, the current biomass became more optimistic (Figure 28). The unfished biomass remained unchanged, since it is dependent on the maximum F value, although the biomass at MSY decreases with increased steepness.

The likelihood profile for R$_0$ (unfished recruitment parameter) shows a minimum at the estimate, with a steep profile on the left-hand side while the change in likelihood is flatter on the right hand side (Figure 30). This suggests that R$_0$ was well-estimated, while noting the potential interaction with the maximum F constraint on the estimate of this parameter.

The retrospective analysis did not reveal major pathological problems. As data were removed (from 2014–2019), historical SSB and F do not substantially change (Figure 31). The Mohn's rho for the estimated SSB was less than 0.01.

Alternative model configurations were considered with the intention of improving the fit of the index and composition data. Recruitment deviates were estimated (as penalized parameters), and the length composition data was down-weighted relative to the index by reducing the annual sample sizes for the multinomial distribution in the likelihood. In either case, the estimates did not change. In the case of estimating recruitment deviates, the standard errors of the deviates were not more precise relative to the standard deviation specified in the penalty function.

Additional fit with the inclusion of tagging data in the stock synthesis model was also considered. Partial mixing is not modeled in SS3, and several fits explored different assumptions regarding the time lag (two or four years) until full mixing occurred, with the chronic tag loss rate as an estimated parameter. Again, model estimates were not particularly different compared to the reference model. This could arise for several reasons: (1) the tagging data were in general agreement with the catch, index, and composition data regarding recent mortality; (2) by default, the likelihood for the tagging data was down-weighted relative to the composition and index and further methodological work is needed to find the appropriate weighting; or (3) the tagging data were not informative in the model; for example, the mixing lag resulted in a truncated data set that did not significantly influence the assessment. These fits were not further considered.

A shorter model was considered to remove the influence of the early catch series and the assumptions needed to incorporate those data in the assessment. A truncated model that used data since 1990 was initially developed with recruitment as estimated deviates from mean recruitment. However, the deviates were not estimated well and resulted in a population with constant recruitment modeled. Furthermore, the model estimated a small population that was heavily exploited with fishing mortality often exceeding 1. This magnitude of F was not considered to be plausible in comparison to estimates from other methods (e.g., Dadswell et al. 2017, Tsitrin et al. 2021). The truncated model was also removed from further consideration.

A summary of the sensitivity scenarios and their effects on model output relative to the reference model is provided in Table 6.

REFERENCE POINTS

Provisional fishing mortality reference points are presented in Table 7. Spawning potential ratio (SPR) does not vary among models that have very similar selectivity estimates. All models used the same female biological parameter values and the calculations are not dependent on steepness. Thus, SPR calculations differed in the SJR Dome model relative to all others. On the other hand, $F_{0.1}$ for the SSF was estimated higher (0.13) compared to the other models (0.10). The calculation of $F_{0.1}$ uses the ratio of F between females and males in 2020. In the SSF, the F was approximately 0.015 and 0.031 for females and males, respectively (Table 7). In the SJR Dome model, $F_{0.1}$ = 0.15 as a result of selectivity and apical F ratio between sexes. The F ratio is one in all other models. Potential stock status for removal rate is presented as the estimated F in 2020 relative to $F_{0.1}$ and $F_{50\%}$ (Table 8).

On the other hand, the provisional biomass reference point SSB_{MSY} increased as the unfished stock size increased and decreases when the steepness value used in the model increased (Table 8).

From the suite of the models evaluated here, all scenarios showed that the $F_{benchmark}/F_{50\%}$ less than one and $F_{benchmark}/F_{0.1}$ less than one (Table 8). Similarly, SSB/SSB_{MSY} greater than one in 2020 in all scenarios except when steepness equals 0.45. Comparisons of the F benchmark relative to alternative reference points are shown in Table 9.

The projection component implemented an approximation of the current 175–175 TAC for 2021–2030. Compared to the 2020 benchmark, the fishing mortality and spawning biomass increases and decreases, respectively, in all models with the ratio of the change larger as the unfished stock size is smaller and steepness is lower. In 2030, the forecasted $F/F_{0.1}$ less than one in 2030 in all cases, but $F/F_{50\%}$ greater than one in the low steepness (h < 0.6) and Maximum F = 6 scenarios (Table 8). For biomass, SSB/SSB_{MSY} remains greater than one except in the low steepness (h = 0.45 and presumably lower values) scenario.

DISCUSSION

The stock synthesis (SS3) model represents the first attempt to develop a population model for SJR Sturgeon. The assessment model utilizes the extensive historical catch data, growth parameters estimated from biological sampling, and length composition from the modern fishery. There are notable uncertainties in the assessment that were revealed during the model fitting process.

Among the different data types, the most impactful changes to the model results arose from alternative assumptions of the catch history (over those for the index, composition, and tagging data). Catch data alone also could not inform stock depletion in the early years of the fishery in the late 19th century. The fishing mortality, and thereby depletion, was constrained by the

maximum F value, which necessitated the sensitivity analysis. It is also possible that the selectivity of the early fishery, before gillnet size restrictions were implemented, was different compared to the modern fishery. No data were available for this assessment to inform early selectivity.

Second, the stock-recruit parameters are influential in calculating biomass reference points as well as current depletion. While the unfished recruitment parameter is typically estimated, steepness is typically difficult to estimate in an age-structured model, and no prior information was available to inform this assessment. A value of 0.6 was initially chosen in the reference model using a relatively low value that reflects the late maturity and potentially lower resilience of Sturgeon relative to taxa with early maturity and higher resilience.

The utility of the sensitivity analyses is to evaluate if there are any conclusions that are robust to such uncertainties. Almost all models explored here showed that the stock was above SSB_{MSY} in 2020 and would remain above SSB_{MSY} with the current TAC. Only in low steepness scenarios (h = 0.45 and lower values) would the stock be below SSB_{MSY}. The alternative historical catch scenarios did not alter the current stock status relative to SSB_{MSY}. In essence, the stock is above SSB_{MSY} since catches today are lower compared to the early years of the fishery.

To navigate uncertainty in steepness, the assessment was evaluated by whether the management advice was impacted by the value of steepness. For the range of steepness values evaluated in the profile, and in the full set of alternative models here, the stock was estimated to be above SSB_{MSY} in 2020, except for the lowest extreme value (h = 0.45). Furthermore, the fishing mortality reference points proposed here are invariant to the value of steepness.

Estimates of abundance and biomass are of the closed population, which includes the residents and active spawners in the SJR, as well as migrating individuals and inactive spawners outside the river. With the assessment model, abundance estimates of active spawners in the SJR would require assumptions regarding movement or spawning frequency. The stock-recruit relationship is invariant to spawning frequency and movement so long as these processes are time invariant.

The fishery CPUE was modeled as an index of total spawning abundance, including mature, but not actively spawning individuals. An index of active spawners would remain proportional to the modeled index to the extent that the proportion actively spawning is independent of mortality and total abundance. There is contrast in the observed and standardized CPUE which was not captured in the predicted index in the assessment. With the longevity of Sturgeon and estimated F, such a reduction was not possible during 2009–2011. This suggests that abundance and other factors, i.e., availability and/or targeting, remain conflated in the standardized series. Alternative data sets, e.g., water levels in the lower SJR (Oak Point), and temperature measurements, spanning the historical CPUE series, can be incorporated in future work with CPUE standardization.

The tagging data provided an opportunity for a complementary assessment of the stock and subsequent comparison of models that used different data. Compared to the SS3 model, the Brownie model does not need additional assumptions regarding historical depletion. Both models agree on the trend and magnitude in F, which gradually increased from 2009–2019 followed by a drop in 2020 due to lower catches in SS3 and fewer recaptures in the tag data. While there are notable uncertainties in the SS3 model, results from different models can provide insight on the plausibility of trends and magnitude of fishing mortality.

While there are no maturity schedules estimated for the SJR stock, no sensitivity analysis was done since the specified maturity was already near the selectivity estimates of the SJR fishery.

Maturity should not be greater than the SJR selectivity, which provides an upper bound for the former. Lower maturity estimates would create a more optimistic scenario with respect to SSB estimates.

FUTURE WORK

For this assessment, stock synthesis was chosen as the platform for its flexibility of features and extensive peer review. Along with extensive simulation testing and prior use, this limits the need for debugging code and reliability issues. However, generalized packages may often lack features needed to fully model all the biological and management processes for the stock at hand.

Development of an age-structured model that more explicitly accounts for Sturgeon biology, fishing behavior, and management would incorporate the following features:

- Sub-groups that divide a cohort into mature and immature components which explicitly account for spawning behavior in their vulnerability to the SJR fishery (Gibson and Myers 2003). Such sub-groups will also have probability of movement into the SJR to account for periodicity in spawning.

- An in-river component of the stock which more explicitly accounts for escapement from the fishery. While estimates of stock size comprises of individuals in the river, estuary, and marine environments, the productivity of the stock is determined by the in-river component. A simple single-area model that may be a suitable simplification in some cases, but is more likely to fail in extreme cases (e.g., low escapement), would result in little to no recruitment, but a simple model allows for all mature individuals to contribute to spawning. Simulation studies are needed to explore the impact of such approximations.

- A more robust tag component to the age-structured model that incorporates incomplete mixing relative to the time at liberty due to skip spawning. Likelihood weighting between tag data and other components also needs to be further explored.

- An explicit sex-specific TAC and F projections without the need to separate fleets for historical reconstruction. This allows more flexibility in the forecast module without altering the estimation component; i.e., the model should ideally fit to total catches instead of requiring an additional assumption on historical sex ratio.

- Predicted length composition matches the values observed in the modern fishery since all harvested fish are now recorded. An approach similar to a virtual population analysis (VPA) or length-based stock reduction analysis (SRA) (Wor et al. 2018) is more appropriate compared to a parametric selectivity function. Selectivity varies with time to reflect year-specific retention behavior by the fishery, as inferred from the length composition.

Simulation testing would be needed for novel models to ensure it performs reliably and is capable of recovering simulated parameters (Deroba et al. 2015).

Finally, a prior for steepness could be developed in the future from biological parameters (see Cortés 2020 as an example). Additional information on female fecundity, spawning frequency, and survival at the egg and larval stages in the absence of density dependence could also be used to develop a prior (Mangel et al. 2010, Brodziak et al. 2015).

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TABLES

Table 1. Biological parameters for SJR Atlantic Sturgeon. Length parameters are in terms of total length (cm) and weight parameters are in terms of round weight (kg).

Parameter	Female	Male	Source
Von Bertalanffy Linf (cm)	264	230	Stewart et al. (2015)
Von Bertalanffy K (yr^{-1})	0.04	0.06	Stewart et al. (2015)
Von Bertalanffy t_0 (yr)	-0.94	-0.60	Stewart et al. (2015)
Length-weight a (coefficient)	2e-5	2e-5	Dadswell et al. (2017)
Length-weight b (exponent)	2.72	2.72	Dadswell et al. (2017)
Length of 50% maturity (cm)	175	160	Visual comparison of length composition
Length of 5% maturity (cm)	160	140	Stewart et al. (2015)
Natural mortality (yr^{-1})	0.06	0.09	Then et al. (2015) using growth parameters

Table 2. Natural mortality values from indirect estimators that use growth parameters or maximum observed age (t_{max}).

Method	Equation	Female	Male
Then et al. (2015) – maximum age	$4.899\, t_{max}^{-0.916}$	0.13	0.16
Then et al. (2015) – growth	$4.118\, K^{0.73} Linf^{-0.33}$	0.06	0.09
Hoenig (1983)	$3\, /\, t_{max}$	0.06	0.07
Hewitt and Hoenig (2005)	$4.22\, /\, t_{max}$	0.08	0.10

Table 3. AIC comparison of GLM models for CPUE standardization. Theta is the overdispersion parameter of the Negative Binomial (NB) GLM. The negative binomial distribution approaches the Poisson distribution as theta approaches infinity. Dash (-) = Not applicable.

Model Covariates	Distribution	Degrees of Freedom	ΔAIC	θ
Intercept	Poisson	1	1,669	-
Y	Poisson	12	846	-
Y + M	Poisson	14	604	-
Y × M	Poisson	34	358	-
Y + M + W	Poisson	15	567	-
Y × M + W	Poisson	35	287	-
Intercept	NB	2	470	2.5
Y	NB	13	235	4.2
Y + M	NB	15	137	5.2
Y × M	NB	35	27	7.1
Y + M + W	NB	16	129	5.4
Y × M + W	NB	36	0	7.8

Table 4. Time series of observed and standardized CPUE, along with the lognormal standard error of the standardized series. Values are re-scaled such that the mean of each series is 1.

Year	Observed	Standardized	Std. Error
2009	2.81	2.10	0.16
2010	1.54	1.59	0.11
2011	0.72	0.63	0.19
2012	0.45	0.75	0.13
2013	0.99	1.11	0.14
2014	0.52	0.66	0.18
2015	1.10	0.88	0.16
2016	0.78	0.82	0.12
2017	1.20	1.30	0.19
2018	0.75	0.88	0.13
2019	0.69	0.68	0.13
2020	0.46	0.61	0.14

Table 5. Time series of spawning stock biomass (tonnes; females only), spawning stock numbers (including females, males, and both), and fleet fishing mortality in the reference model. In 1879, the population numbers reflect unfished conditions.

Year	SSB (F)	Summary F	SSN (F)	SSN (M)	SSN (B)	SJR F	BoF F
1879	347	0	7,856	4,525	12,380	0	0
1880	252	0.83	5,670	3,187	8,857	0.84	0
1881	118	1.39	2,866	1,582	4,448	1.42	0
1882	44	2.69	1,206	655	1,861	2.73	0
1883	23	2.95	681	379	1,060	3	0
1884	19	2.04	569	334	903	2.07	0
1885	20	0.77	606	378	984	0.78	0
1886	24	0.38	719	474	1,193	0.39	0
1887	29	0	886	613	1,499	0	0
1888	37	0	1,096	790	1,887	0	0
1889	44	0	1,324	982	2,306	0	0
1890	53	0	1,565	1,182	2,747	0	0
1891	62	0	1,815	1,385	3,200	0	0
1892	71	0	2,070	1,586	3,657	0	0
1893	80	0	2,327	1,782	4,109	0	0
1894	90	0	2,582	1,966	4,549	0	0
1895	100	0	2,834	2,136	4,969	0	0
1896	110	0	3,079	2,284	5,363	0	0
1897	117	0.08	3,258	2,349	5,607	0.08	0
1898	122	0.06	3,380	2,342	5,722	0.06	0
1899	129	0.03	3,521	2,334	5,855	0.03	0
1900	135	0.03	3,673	2,320	5,993	0.03	0
1901	143	0.01	3,836	2,304	6,140	0.01	0
1902	150	0	4,002	2,290	6,292	0	0
1903	157	0.01	4,134	2,256	6,390	0.01	0
1904	162	0.01	4,224	2,209	6,434	0.01	0
1905	165	0.02	4,275	2,158	6,432	0.02	0
1906	167	0.02	4,281	2,105	6,386	0.02	0
1907	169	0.02	4,261	2,065	6,325	0.02	0
1908	170	0.01	4,236	2,046	6,282	0.01	0
1909	170	0.03	4,184	2,036	6,219	0.03	0
1910	168	0.04	4,081	2,015	6,096	0.04	0.01
1911	166	0.01	3,995	2,017	6,012	0.01	0
1912	165	0.02	3,930	2,038	5,968	0.02	0.01
1913	163	0.02	3,854	2,053	5,907	0.02	0.02
1914	162	0.02	3,776	2,068	5,845	0.02	0.01
1915	160	0.02	3,713	2,096	5,809	0.02	0
1916	159	0.01	3,682	2,142	5,824	0.01	0
1917	160	0.01	3,679	2,199	5,878	0.01	0

Year	SSB (F)	Summary F	SSN (F)	SSN (M)	SSN (B)	SJR F	BoF F
1918	161	0.01	3,688	2,260	5,948	0.01	0
1919	161	0.02	3,696	2,315	6,010	0.02	0
1920	162	0.02	3,706	2,366	6,071	0.02	0
1921	162	0.02	3,717	2,412	6,129	0.02	0
1922	162	0.02	3,729	2,452	6,182	0.02	0
1923	163	0.02	3,752	2,494	6,246	0.02	0
1924	164	0.01	3,794	2,544	6,338	0.01	0
1925	166	0.01	3,857	2,601	6,458	0.01	0
1926	169	0.01	3,926	2,657	6,583	0.01	0
1927	172	0	4,004	2,715	6,718	0	0
1928	175	0.01	4,082	2,767	6,849	0.01	0
1929	178	0.01	4,161	2,817	6,977	0.01	0
1930	181	0	4,235	2,851	7,086	0	0.03
1931	184	0	4,309	2,881	7,190	0	0
1932	188	0	4,402	2,930	7,332	0	0
1933	191	0	4,495	2,978	7,473	0	0
1934	195	0.01	4,571	3,013	7,584	0.01	0
1935	197	0.01	4,624	3,031	7,654	0.01	0
1936	199	0.01	4,673	3,046	7,719	0.01	0
1937	201	0.01	4,727	3,066	7,794	0.01	0
1938	204	0.01	4,787	3,091	7,878	0.01	0
1939	207	0	4,851	3,119	7,970	0	0
1940	210	0	4,918	3,150	8,068	0	0
1941	213	0	4,986	3,183	8,170	0	0
1942	216	0	5,049	3,213	8,262	0	0
1943	219	0	5,108	3,240	8,348	0	0
1944	221	0	5,163	3,264	8,428	0	0
1945	224	0.01	5,210	3,283	8,493	0.01	0
1946	225	0.01	5,242	3,293	8,535	0.01	0
1947	227	0.01	5,272	3,303	8,574	0.01	0
1948	229	0	5,309	3,318	8,627	0	0
1949	231	0.01	5,343	3,332	8,675	0.01	0
1950	233	0.01	5,376	3,347	8,723	0.01	0
1951	235	0	5,412	3,365	8,777	0	0
1952	236	0.01	5,446	3,381	8,827	0.01	0
1953	238	0.01	5,466	3,389	8,855	0.01	0
1954	238	0.01	5,474	3,388	8,862	0.01	0
1955	238	0.01	5,477	3,384	8,861	0.01	0
1956	239	0.01	5,491	3,389	8,880	0.01	0
1957	240	0.01	5,509	3,395	8,904	0.01	0.01
1958	240	0.02	5,499	3,381	8,880	0.02	0.01
1959	240	0.01	5,487	3,368	8,855	0.01	0

Year	SSB (F)	Summary F	SSN (F)	SSN (M)	SSN (B)	SJR F	BoF F
1960	240	0.02	5,482	3,360	8,842	0.02	0.01
1961	240	0.01	5,487	3,358	8,844	0.01	0.01
1962	241	0.01	5,512	3,370	8,881	0.01	0
1963	243	0.01	5,542	3,388	8,929	0.01	0
1964	244	0	5,574	3,408	8,982	0	0
1965	245	0.01	5,601	3,422	9,023	0.01	0.01
1966	246	0.01	5,620	3,433	9,053	0.01	0
1967	248	0.01	5,647	3,451	9,098	0.01	0
1968	249	0	5,675	3,465	9,140	0	0.01
1969	248	0.02	5,663	3,454	9,117	0.03	0
1970	247	0.02	5,638	3,438	9,076	0.02	0
1971	247	0.01	5,642	3,440	9,082	0.01	0
1972	247	0.02	5,634	3,435	9,069	0.02	0
1973	246	0.01	5,624	3,428	9,052	0.01	0
1974	247	0.01	5,640	3,435	9,075	0.01	0
1975	248	0.01	5660	3,445	9,105	0.01	0
1976	247	0.03	5,643	3,432	9,075	0.03	0
1977	247	0	5,644	3,430	9,074	0	0
1978	247	0.02	5,655	3,436	9,091	0.02	0
1979	243	0.05	5,578	3,381	8,959	0.05	0.01
1980	235	0.08	5,396	3,256	8,652	0.08	0.02
1981	227	0.04	5,235	3,145	8,380	0.04	0.02
1982	223	0.04	5,153	3,088	8,241	0.04	0.01
1983	219	0.05	5,068	3,036	8,104	0.05	0.01
1984	213	0.06	4,951	2,965	7,917	0.06	0.01
1985	206	0.06	4797	2,861	7,658	0.06	0.05
1986	200	0.06	4,652	2,763	7,415	0.06	0.02
1987	196	0.03	4,580	2,719	7,299	0.03	0.02
1988	184	0.17	4,324	2,557	6,881	0.18	0.03
1989	164	0.19	3,885	2,289	6,175	0.2	0.02
1990	152	0.09	3,632	2,146	5,,778	0.09	0.01
1991	149	0.05	3,564	2,120	5,684	0.05	0.03
1992	147	0.05	3,534	2,117	5,651	0.05	0.02
1993	147	0.03	3,533	2,132	5,666	0.03	0.03
1994	146	0.06	3,527	2,144	5,671	0.06	0.02
1995	145	0.06	3,502	2,148	5,650	0.06	0.01
1996	143	0.08	3,468	2,150	5,618	0.08	0
1997	141	0.06	3,440	2,155	5,595	0.06	0
1998	141	0.03	3,456	2,185	5,641	0.04	0.01
1999	144	0.02	3,521	2,245	5,766	0.02	0
2000	148	0.01	3,617	2,326	5,943	0.01	0
2001	150	0.05	3,672	2,376	6,048	0.05	0

Year	SSB (F)	Summary F	SSN (F)	SSN (M)	SSN (B)	SJR F	BoF F
2002	151	0.03	3,717	2,415	6,132	0.03	0
2003	155	0	3,822	2,492	6,314	0	0
2004	161	0	3,955	2,584	6,539	0	0
2005	167	0	4,088	2,670	6,757	0	0
2006	172	0	4,218	2,750	6,969	0	0
2007	176	0.03	4,305	2,794	7,099	0.03	0
2008	179	0.02	4,364	2,815	7,179	0.02	0
2009	180	0.04	4,398	2,816	7,214	0.05	0
2010	181	0.03	4,417	2,806	7,223	0.03	0
2011	182	0.04	4,433	2,794	7,227	0.04	0
2012	182	0.03	4,441	2,778	7,219	0.03	0
2013	182	0.06	4,426	2,748	7,174	0.06	0
2014	180	0.06	4,374	2,698	7,072	0.06	0
2015	178	0.06	4,321	2,650	6,971	0.06	0
2016	176	0.05	4,281	2,614	6,895	0.05	0
2017	174	0.06	4,239	2,582	6,821	0.06	0
2018	172	0.06	4,183	2,544	6,726	0.06	0
2019	170	0.06	4,129	2,510	6,639	0.06	0
2020	169	0.03	4,113	2,506	6,619	0.03	0

Table 6. Description of the various SS3 model configurations evaluated and their effects on the historical reconstruction and SSB_{MSY} relative to the reference model.

Name	Description	Effect relative to reference model
Reference model	Maximum F = 3, steepness = 0.6, 60% of Bay of Fundy (BoF) catches are SJR origin, identical apical F between sexes	-
Max. F = x	Set maximum F to either 1 or 6	Unfished stock size, SSB_{MSY}, and current stock size decrease as maximum F increases
SSF (Separate-Sex Fleet)	Set historical sex ratio of catch (pre-2007) to be 60% female, apical F is independent by sex	Unfished stock size, SSB_{MSY}, and current stock size increase
SJR Dome	Estimate dome selectivity for the SJR fishery	Unfished stock size, SSB_{MSY}, and current stock size increase
X% BoF	Assume X% of BoF catches are SJR origin	Unfished stock size and SSB_{MSY} unchanged, but current stock size decreases as X% increases
Profile h = x	Use alternative values of steepness, where h = 0.45, 0.50, …, 0.85 (increments of 0.05)	Unfished stock size unchanged, but SSB_{MSY} decreases and current stock size increases as steepness increases

Table 7. Values of fishing mortality biological reference points.

Reference point	Value
$F_{0.1}$ (SSF)	0.13
$F_{0.1}$ (dome)	0.15
$F_{0.1}$ (otherwise)	0.10
$F_{20\%}$ (dome)	0.23
$F_{30\%}$ (dome)	0.12
$F_{40\%}$ (dome)	0.08
$F_{50\%}$ (dome)	0.05
$F_{60\%}$ (dome)	0.03
$F_{20\%}$ (otherwise)	0.27
$F_{30\%}$ (otherwise)	0.15
$F_{40\%}$ (otherwise)	0.09
$F_{50\%}$ (otherwise)	0.06
$F_{60\%}$ (otherwise)	0.04

Table 8. Spawning biomass estimate in 2020 and benchmark fishing mortality estimates (average during 2018–2020), along with forecasted values in 2030 using the current TAC, from the suite of stock synthesis 3 models.

Model	SSB_0	SSB_{MSY}	SSB_{2020}	SSB_{2020} / SSB_{MSY}	$F_{benchmark}$	F_{bench} / $F_{50\%}$	F_{bench} / $F_{0.1}$	SSB_{2030}	SSB_{2030} / SSB_{MSY}	F_{2030}	F_{2030} / $F_{50\%}$	F_{2030} / $F_{0.1}$
Reference model	347	99	169	1.72	0.051	0.86	0.51	159	1.61	0.056	0.93	0.56
Max. F = 1	415	118	242	2.05	0.036	0.59	0.36	233	1.97	0.038	0.63	0.38
Max. F = 6	327	93	148	1.58	0.059	0.98	0.59	137	1.47	0.065	1.08	0.65
SSF	430	132	276	2.10	0.027	0.44	0.27	263	1.99	0.035	0.58	0.35
SJR Dome	398	106	209	2.09	0.037	0.61	0.37	200	1.89	0.039	0.65	0.39
30% BoF	349	99	186	1.88	0.047	0.78	0.47	174	1.75	0.051	0.85	0.51
90% BoF	347	99	154	1.56	0.057	0.94	0.57	146	1.48	0.061	1.02	0.61
Profile h = 0.45	347	122	117	0.96	0.075	1.24	0.75	99	0.81	0.089	1.48	0.89
Profile h = 0.5	347	114	140	1.23	0.062	1.03	0.62	126	1.10	0.071	1.18	0.71
Profile h = 0.55	347	106	157	1.48	0.056	0.93	0.56	145	1.36	0.061	1.01	0.61
Profile h = 0.6	347	99	169	1.72	0.051	0.86	0.51	159	1.61	0.056	0.93	0.56
Profile h = 0.65	347	91	178	1.96	0.049	0.81	0.49	170	1.87	0.053	0.88	0.53
Profile h = 0.7	347	83	185	2.23	0.047	0.78	0.47	178	2.15	0.050	0.83	0.50
Profile h = 0.75	347	75	191	2.55	0.046	0.76	0.46	185	2.47	0.049	0.82	0.49
Profile h = 0.8	347	66	195	2.97	0.044	0.74	0.44	190	2.89	0.047	0.78	0.47
Profile h = 0.85	347	56	198	3.53	0.043	0.73	0.44	194	3.47	0.046	0.77	0.46

Table 9. Benchmark fishing mortality estimates relative to three spawning potential ratio reference points.

Model	$F_{benchmark}$	$F_{benchmark}$ / $F_{40\%}$	$F_{benchmark}$ / $F_{50\%}$	$F_{benchmark}$ / $F_{60\%}$
Reference model	0.051	0.53	0.86	1.25
Max. F = 1	0.036	0.37	0.59	0.87
Max. F = 6	0.059	0.61	0.98	1.44
SSF	0.027	0.27	0.44	0.65
SJR Dome	0.037	0.38	0.61	0.89
30% BoF	0.047	0.48	0.78	1.14
90% BoF	0.057	0.58	0.94	1.38
Profile h = 0.45	0.075	0.77	1.24	1.82
Profile h = 0.5	0.062	0.64	1.03	1.51
Profile h = 0.55	0.056	0.57	0.93	1.36
Profile h = 0.6	0.051	0.53	0.86	1.25
Profile h = 0.65	0.049	0.50	0.81	1.19
Profile h = 0.7	0.047	0.48	0.78	1.15
Profile h = 0.75	0.046	0.47	0.76	1.11
Profile h = 0.8	0.044	0.46	0.74	1.08
Profile h = 0.85	0.043	0.45	0.73	1.07
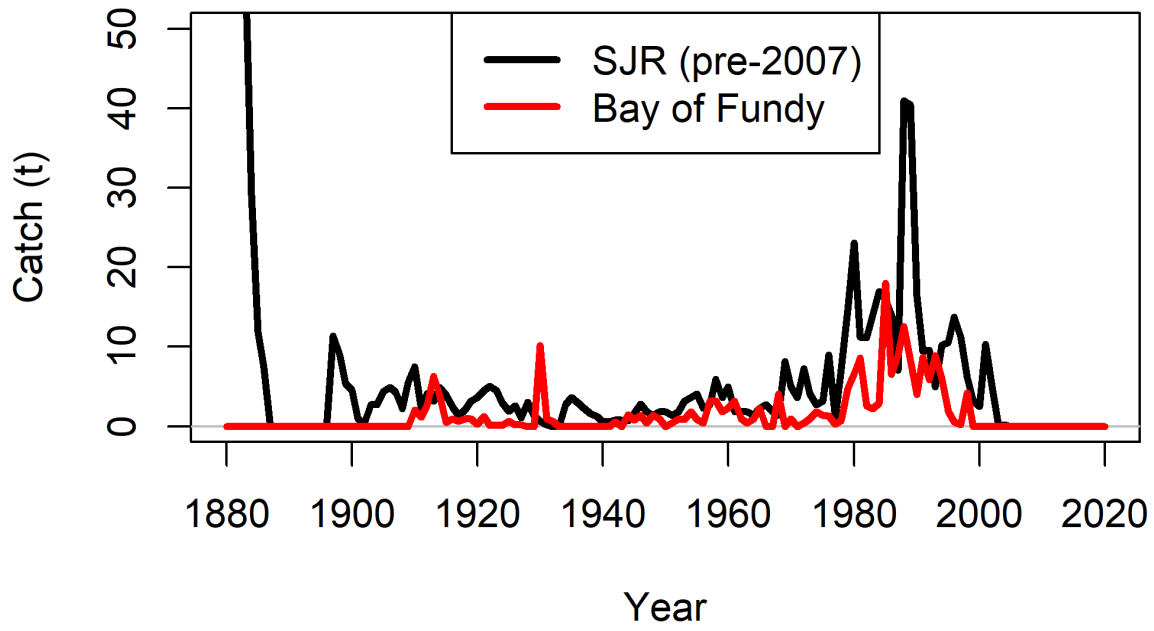
Figure 1. Historical Sturgeon landings (pre-2007, in tonnes) for the assessment. All landings prior to 1890 were greater than 50 t. Values are reported in Table 4 of Bradford et al. (2016).
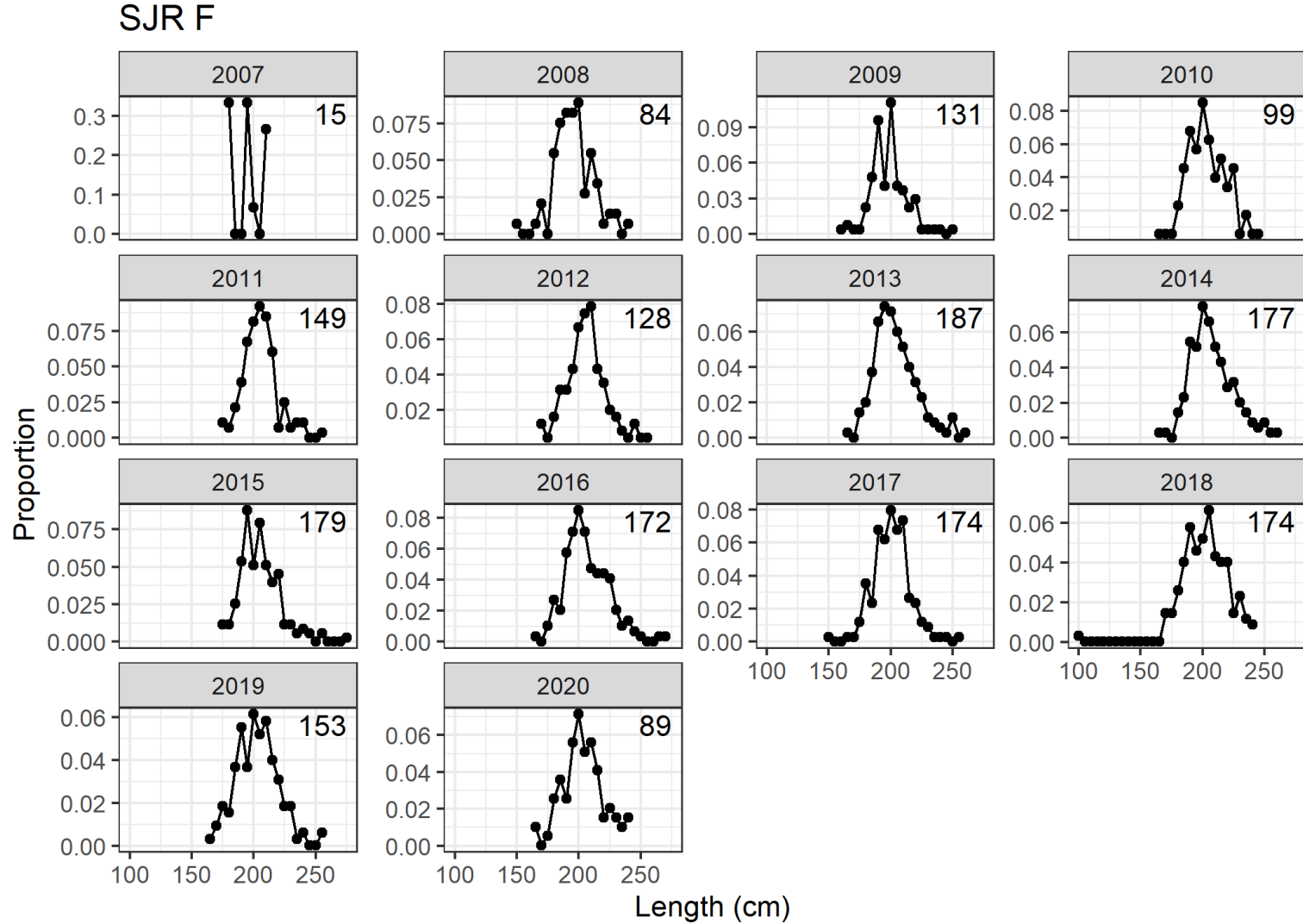
Figure 2. Length composition of harvested females (F) from the Saint John River (SJR) fishery (Dadswell et al. 2016). Numbers on the top right of each panel indicate the sample size.
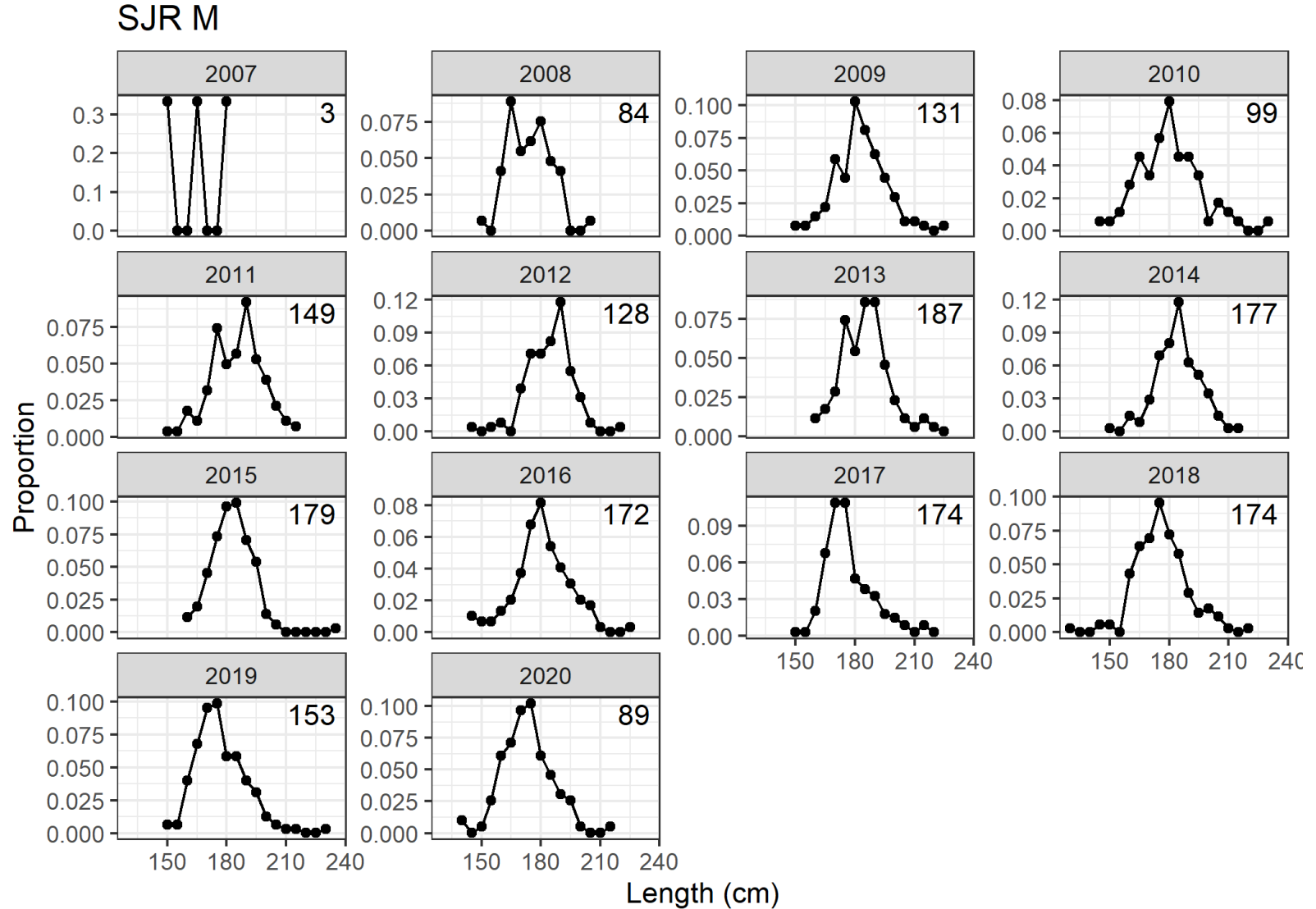
Figure 3. Length composition of harvested males (M) from the Saint John River (SJR) fishery (Dadswell et al. 2016). Numbers on the top right of each panel indicate the sample size.

BOF
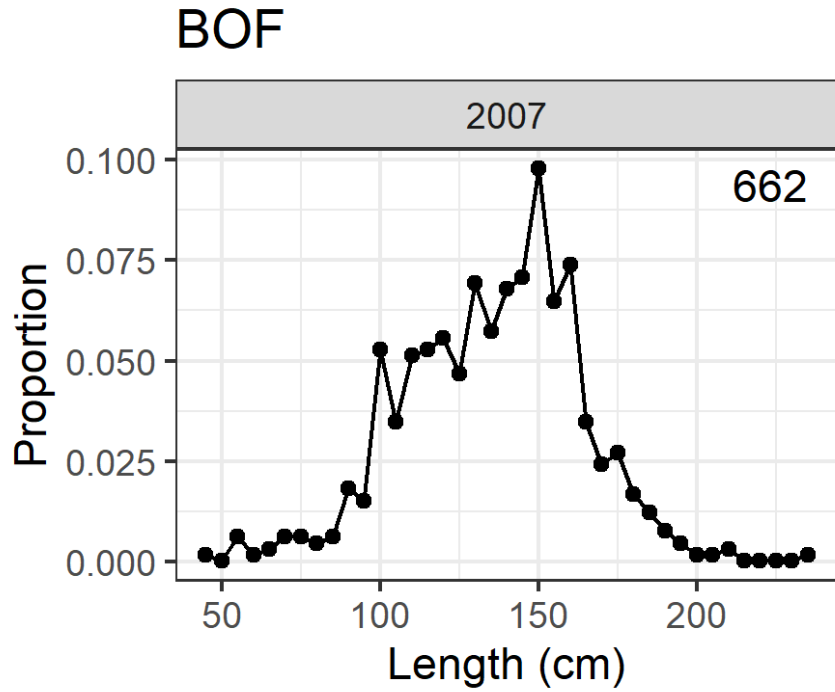
Figure 4. Length composition used for the Bay of Fundy (BoF) fishery, with the sample size in the top right of the panel. Values were digitized from Figure 4 of Dadswell et al. (2016).

BOF
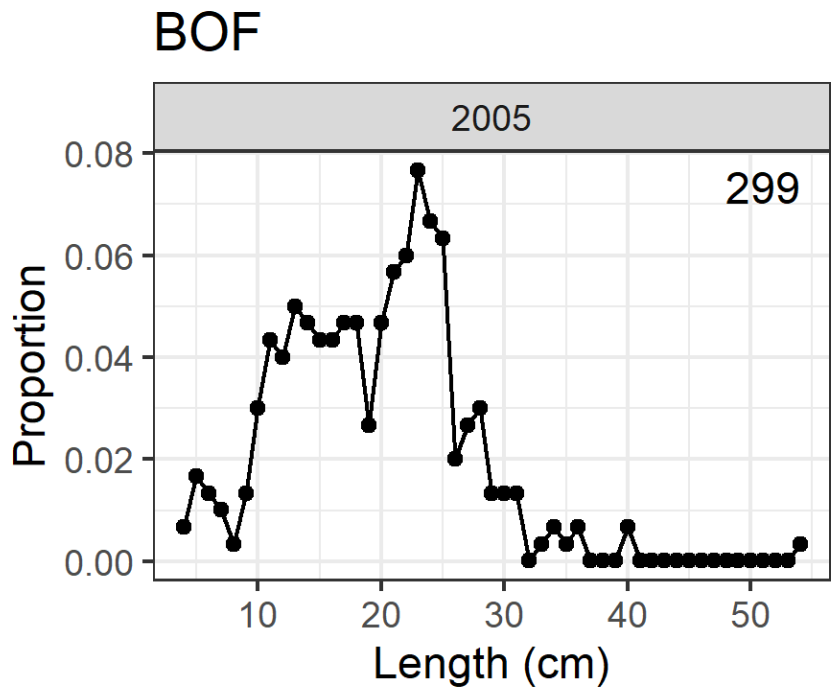
Figure 5. Age composition used for the Bay of Fundy (BoF) fishery, with the sample size in the top right of the panel. Values were digitized from Figure 7 of Dadswell et al. (2016).

Figure 6. Hourly Mactaquac Dam water discharge (cubic feet per second; cfs).
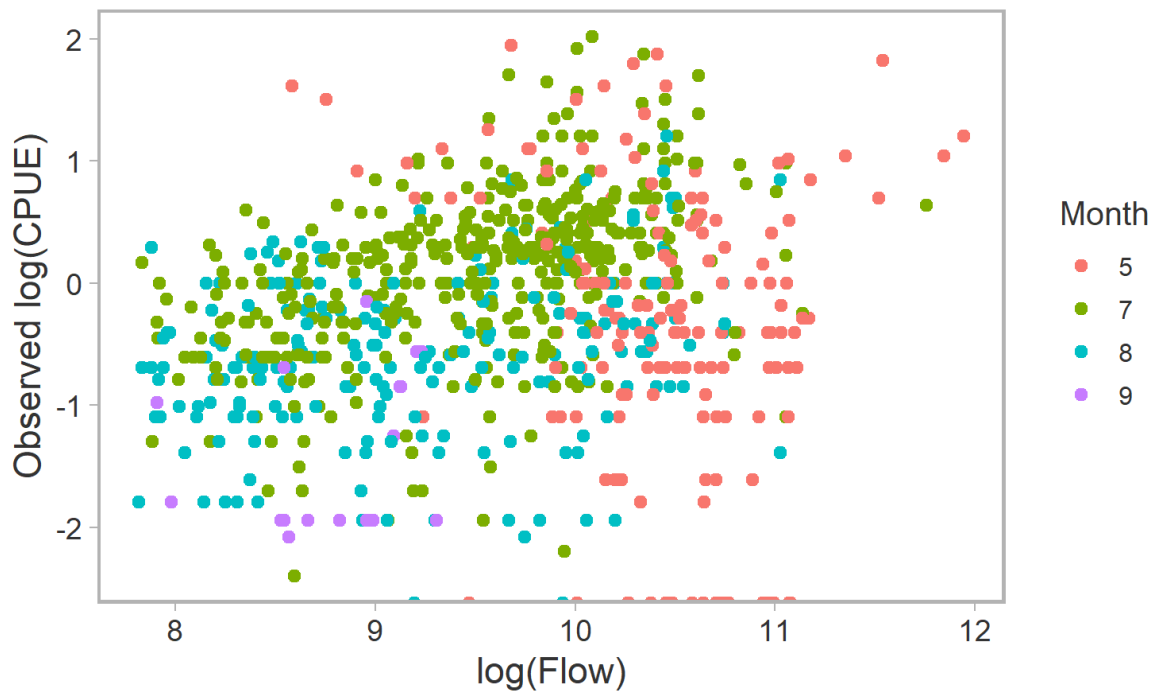
Figure 7. Scatterplot of the log(CPUE) with the logarithm of mean daily discharge from the Mactaquac Dam (x-axis). Colors categorize the month of the fishing event. Month 5 is May, Month 7 is July, Month 8 is August and Month 9 is September.
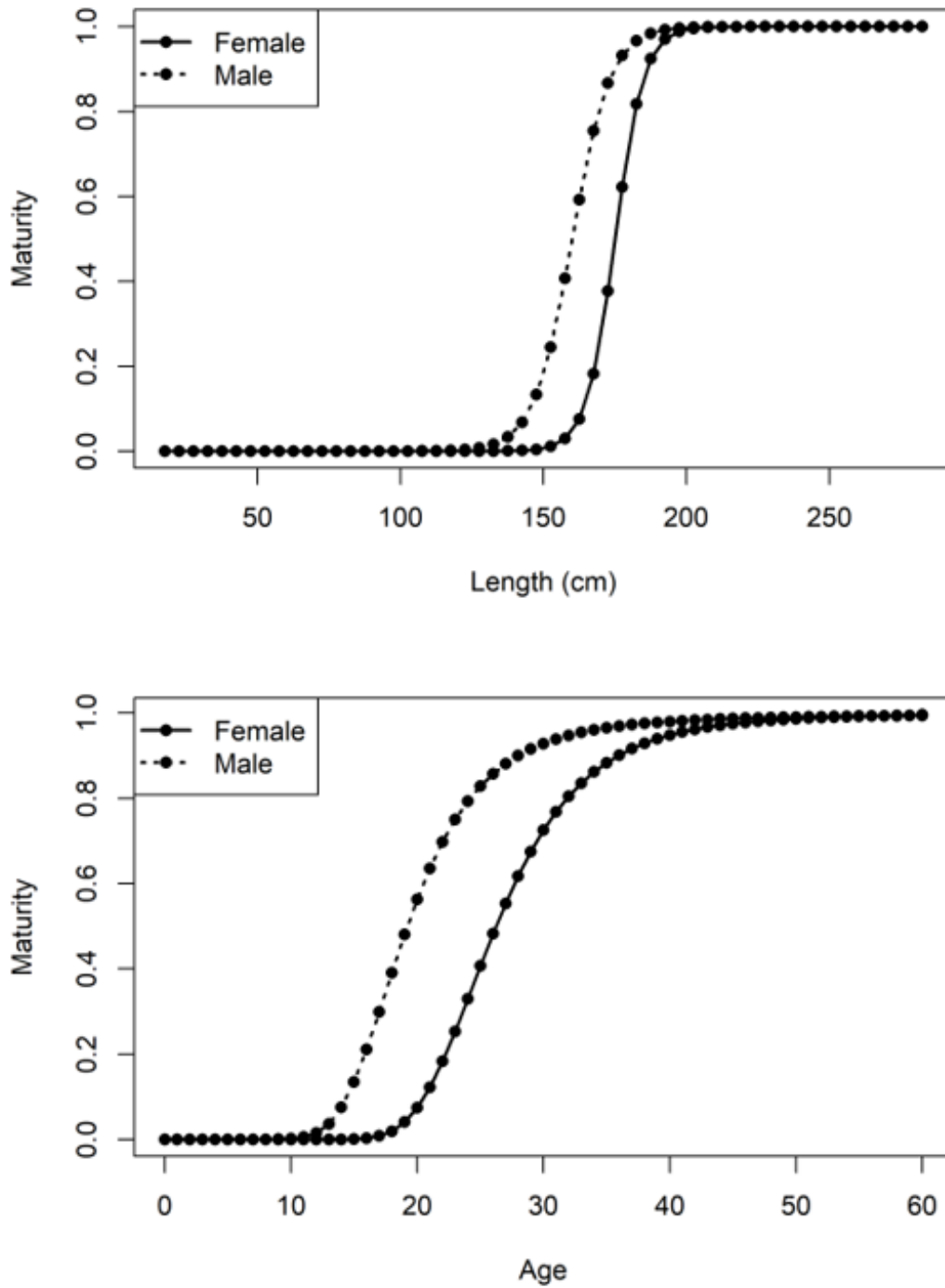
Figure 8. Maturity ogives used in the stock synthesis model. Maturity-at-length was input into the model and the resulting maturity-at-age schedule was calculated in the model.
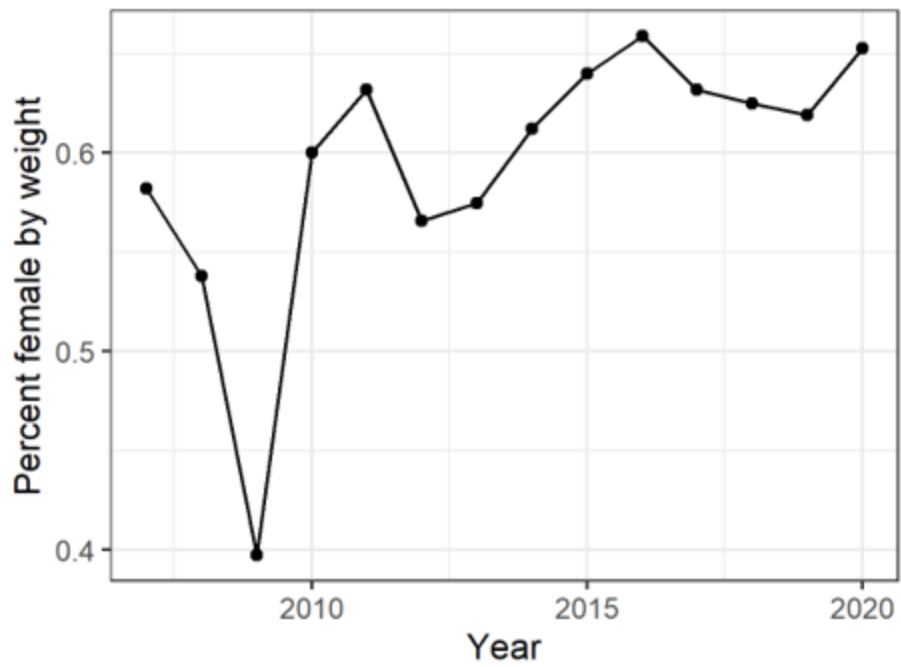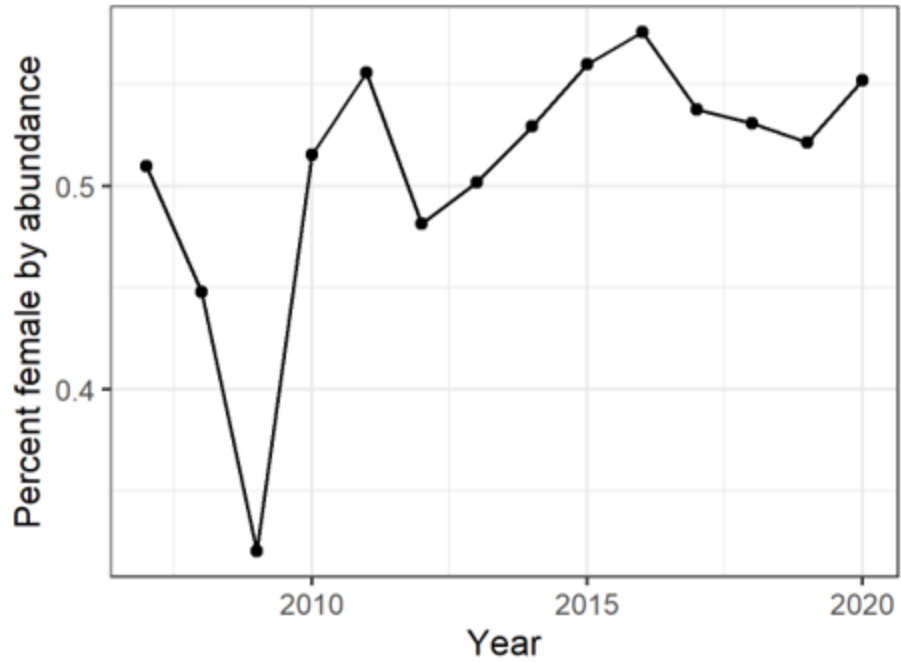
Figure 9. Proportion female by abundance (top) and weight (bottom) in the length composition of the Saint John River (SJR) fishery.
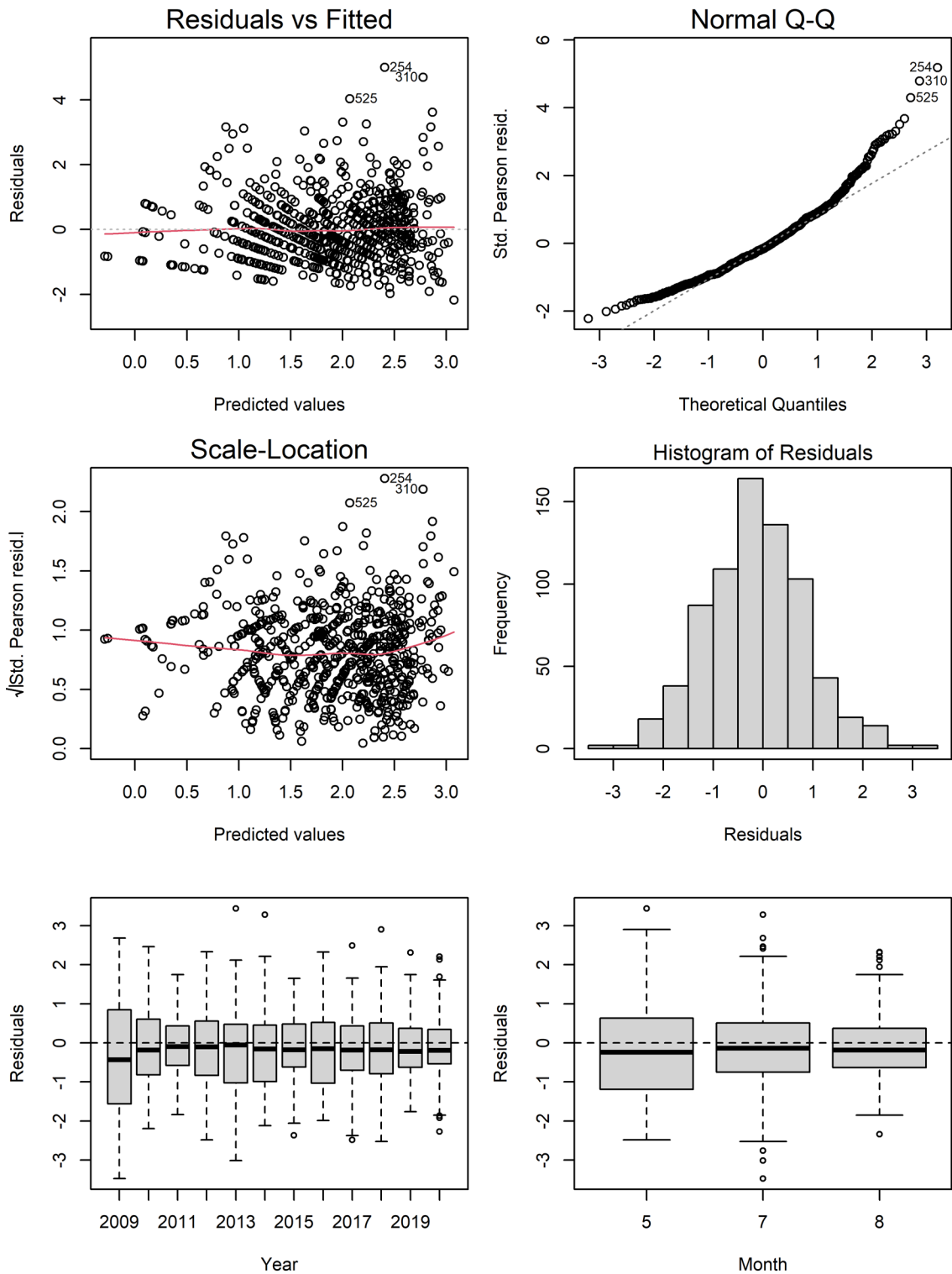
Figure 10. Diagnostics of the full model for CPUE standardization using the negative binomial GLM.
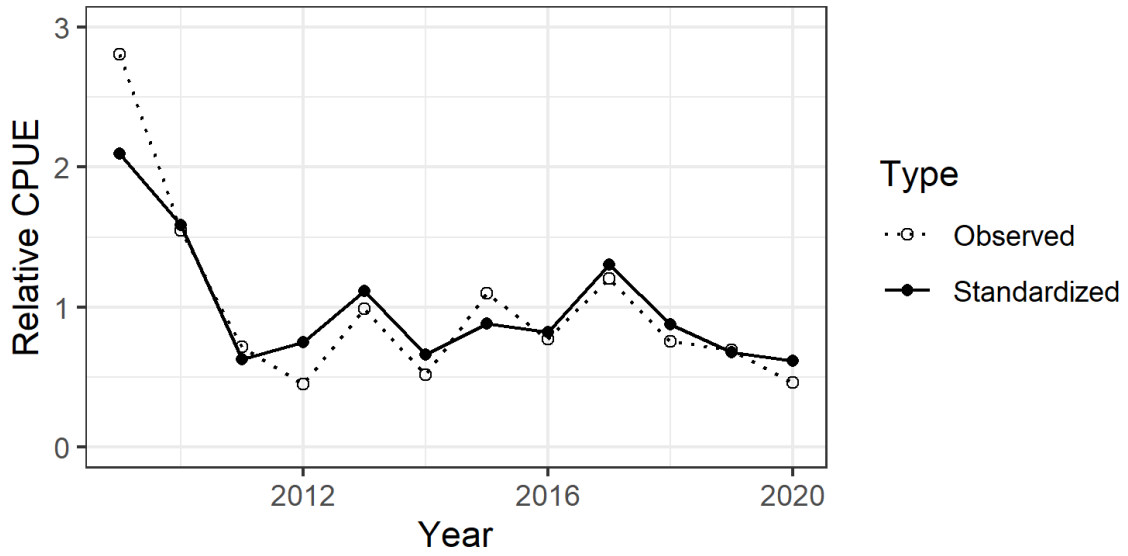
Figure 11. Comparison of the observed and standardized CPUE. To allow for comparison, each series was calculated as annual geometric means, and then rescaled to have a mean of one.
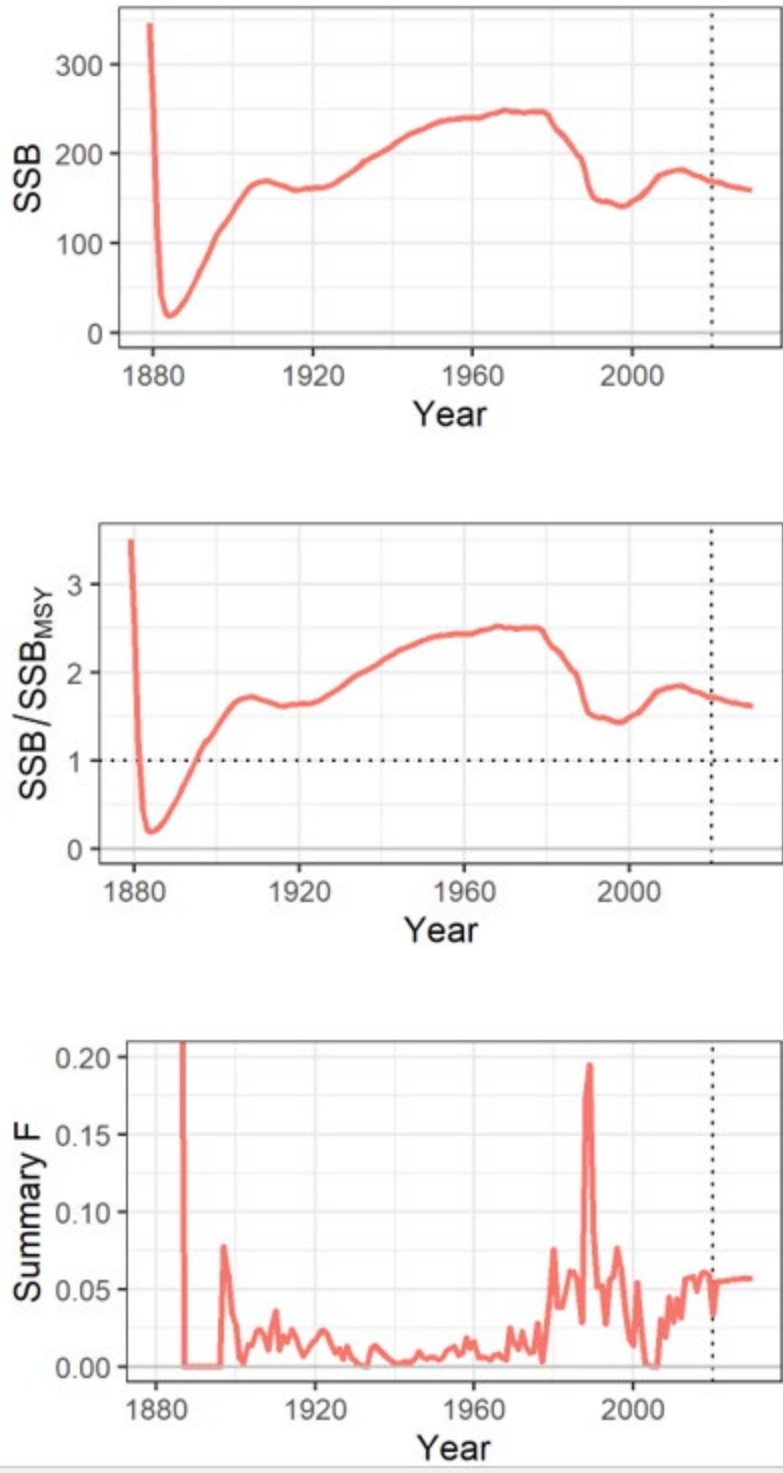
Figure 12. Estimates of SSB (top), SSB/SSB$_{MSY}$ (middle), and F (bottom) from the reference model. Values are reported in Table 5. All fishing mortality (F) rates in years prior to 1886 exceed 0.20. Dotted vertical line indicates year 2020. Values after 2020 are forecasted values from implementing the current TAC.
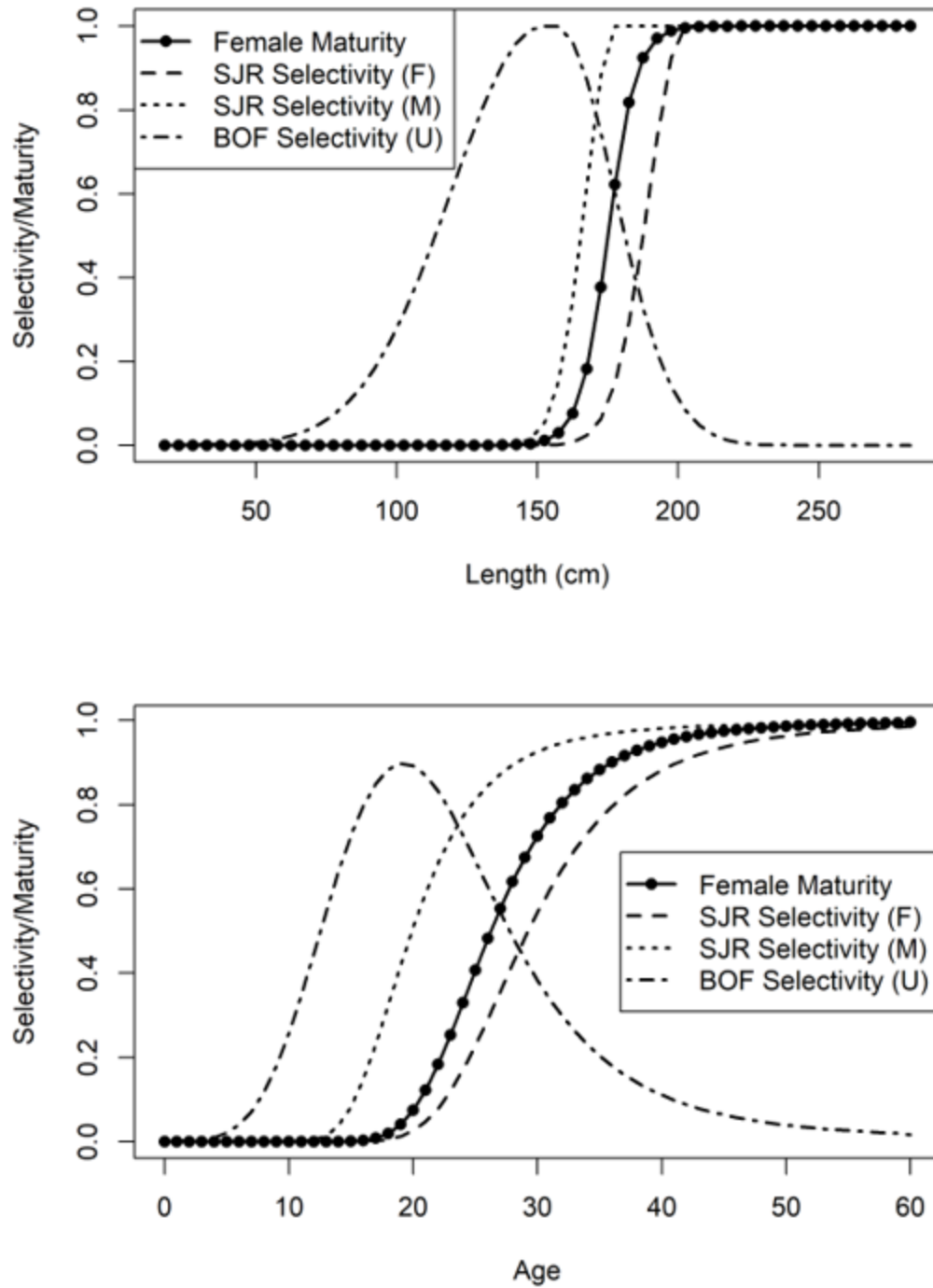
Figure 13. Selectivity estimates from the reference model (shown alongside female maturity for comparison). Selectivity was modeled primarily as a function of length (top) with the corresponding age-based schedule (bottom).
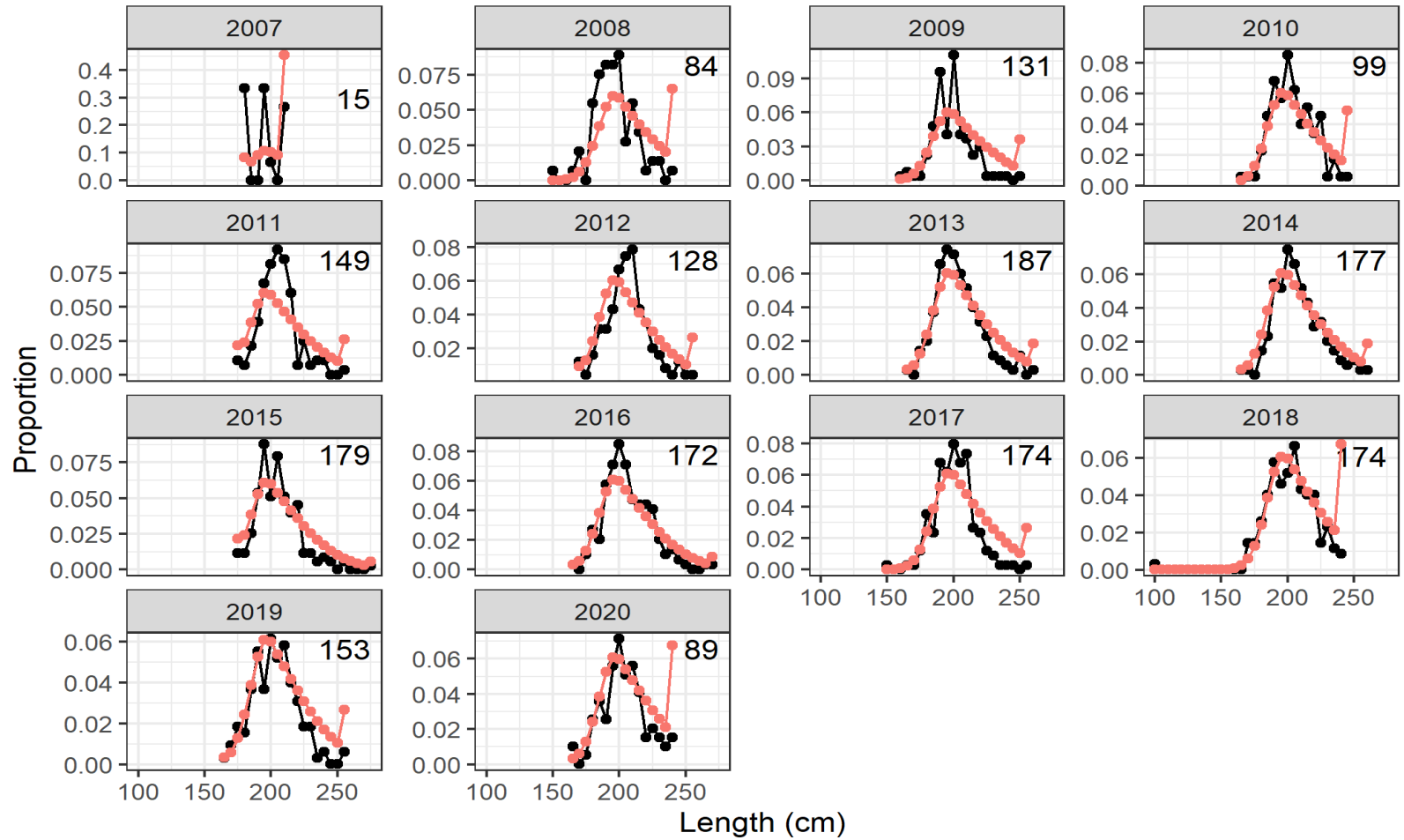
Figure 14. Observed (black) and predicted (orange) length composition of harvested females (F) in the Saint John River (SJR) fishery in the reference model. Numbers in top right of each panel indicate the sample size.
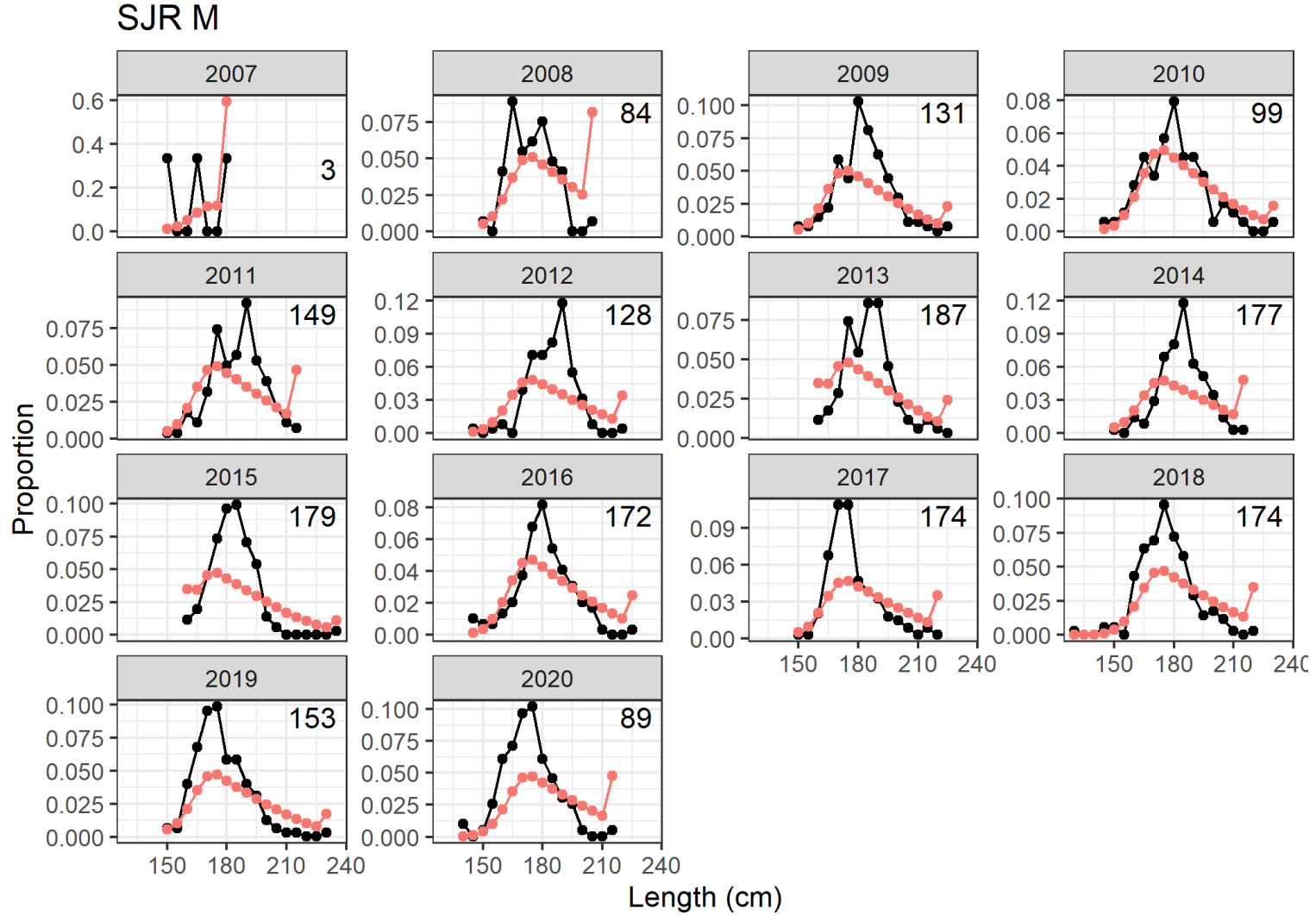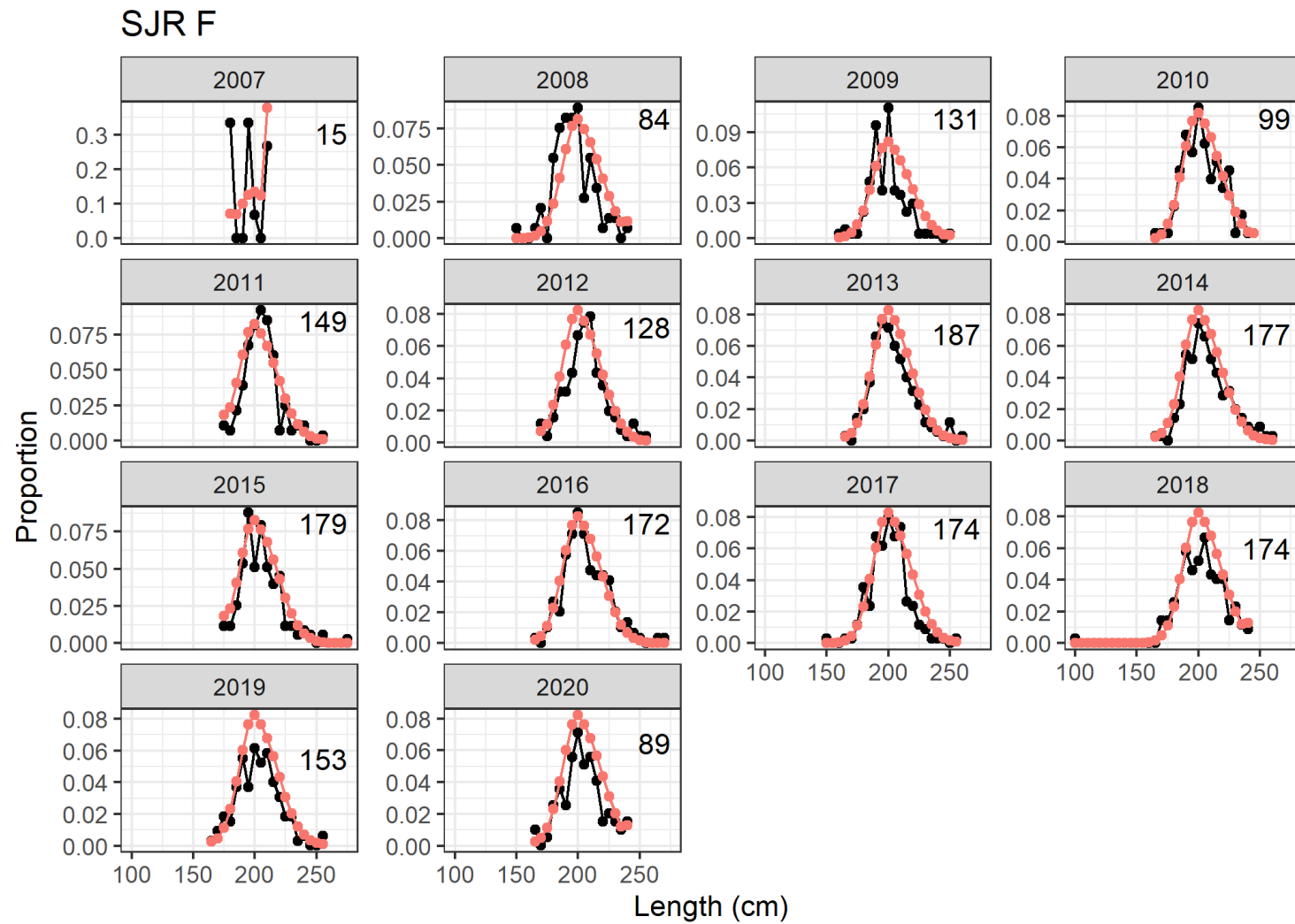
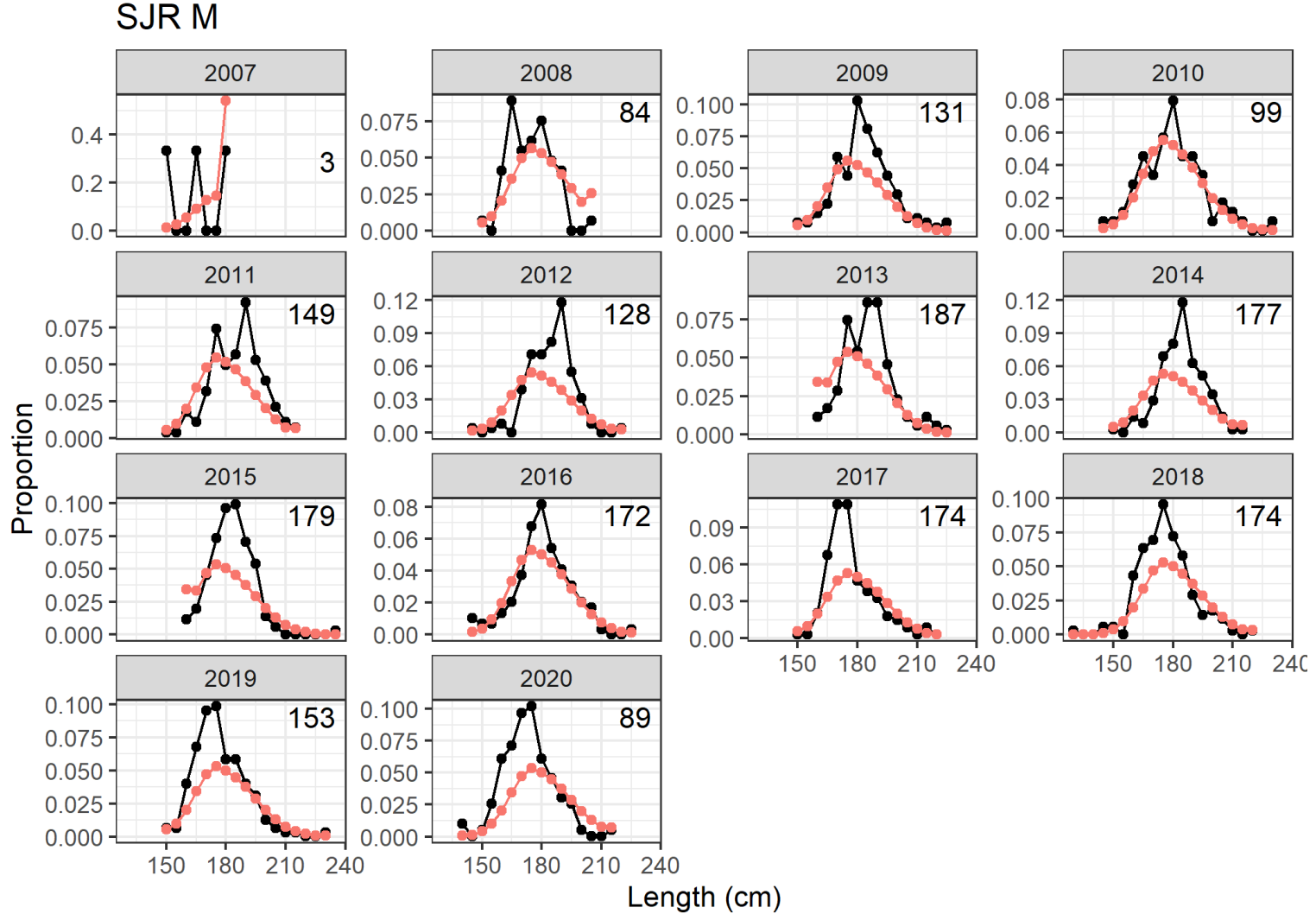*Figure 15. Observed (black) and predicted (orange) length composition of harvested males (M) in the Saint John River (SJR) fishery in the reference model. Numbers in top right of each panel indicate the sample size.*
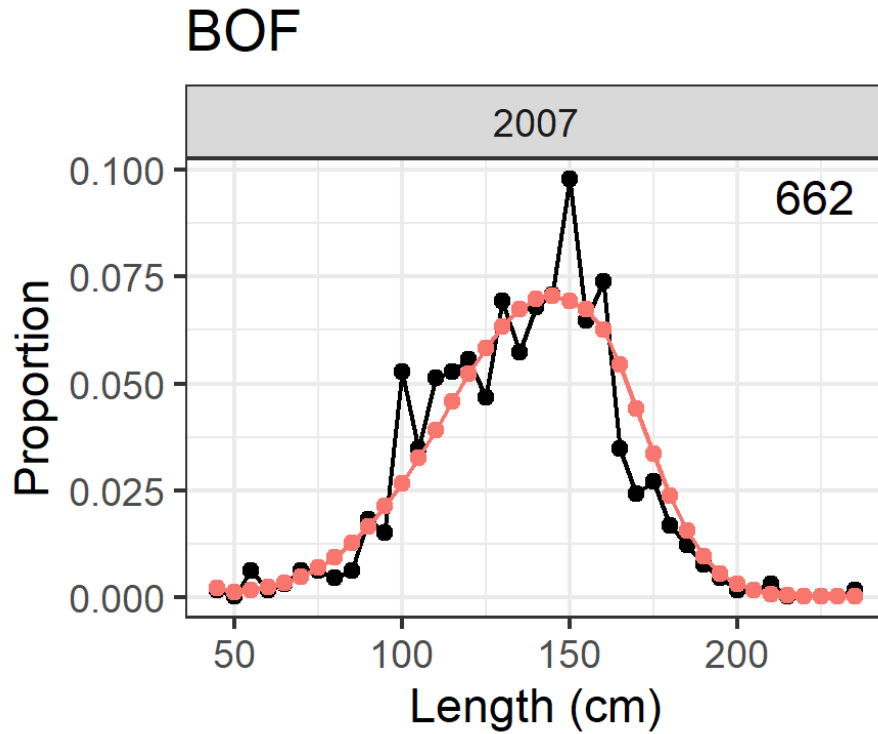
Figure 16. Observed (black) and predicted (orange) length composition of the Bay of Fundy (BoF) fishery. The number in top right of the panel indicates the sample size.
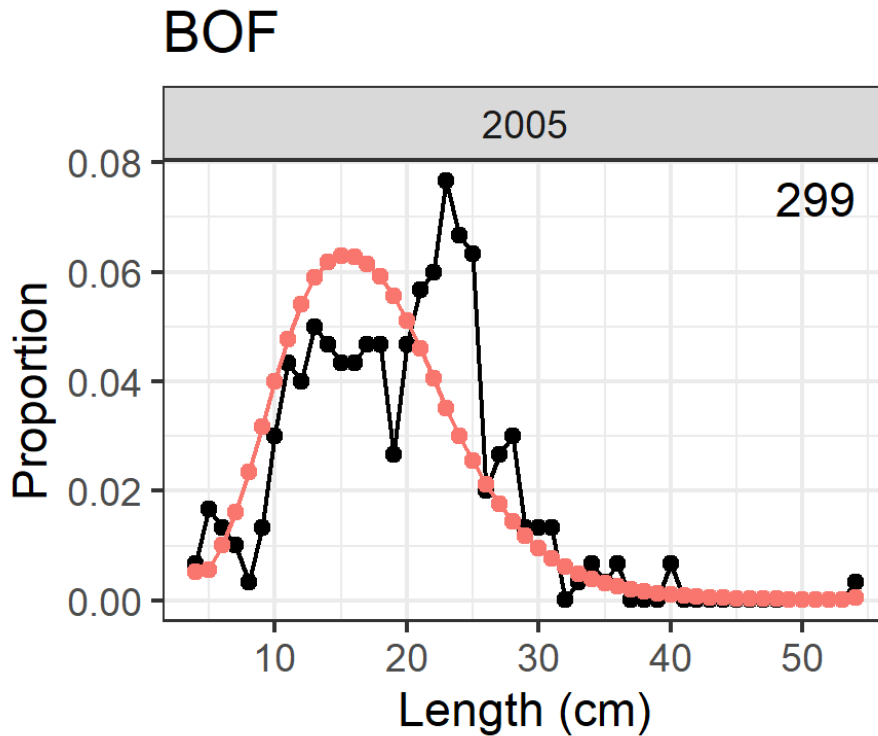
Figure 17. Observed (black) and predicted (orange) age composition of the Bay of Fundy (BoF) fishery. The number in top right of the panel indicates the sample size.
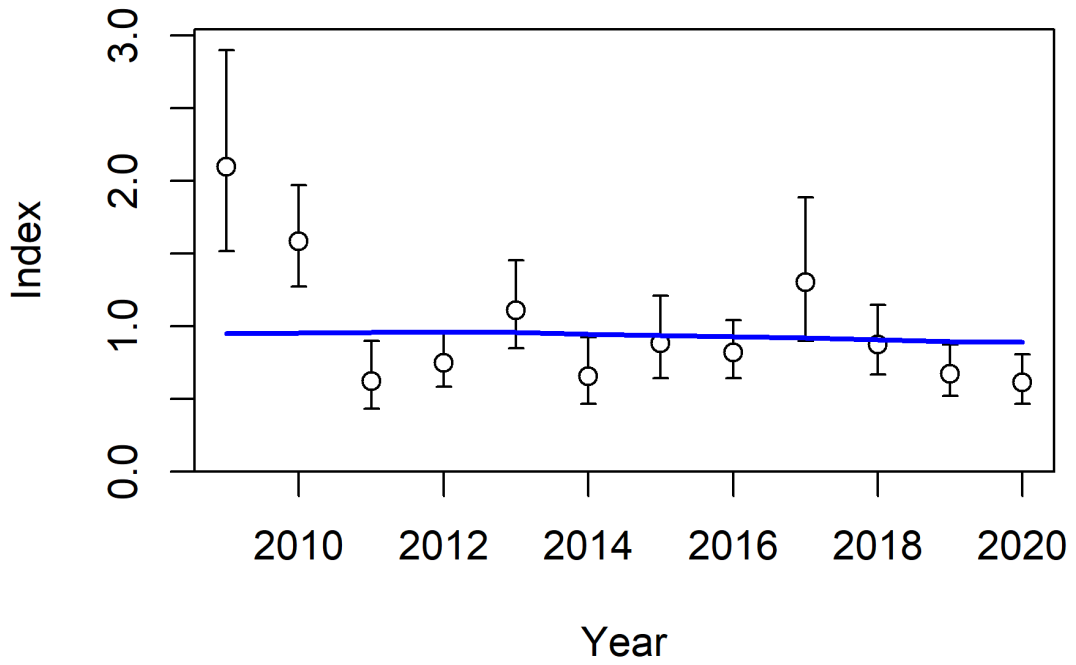
Figure 18. The predicted index (blue) compared to the standardized CPUE (white points with error bars) in the reference model.
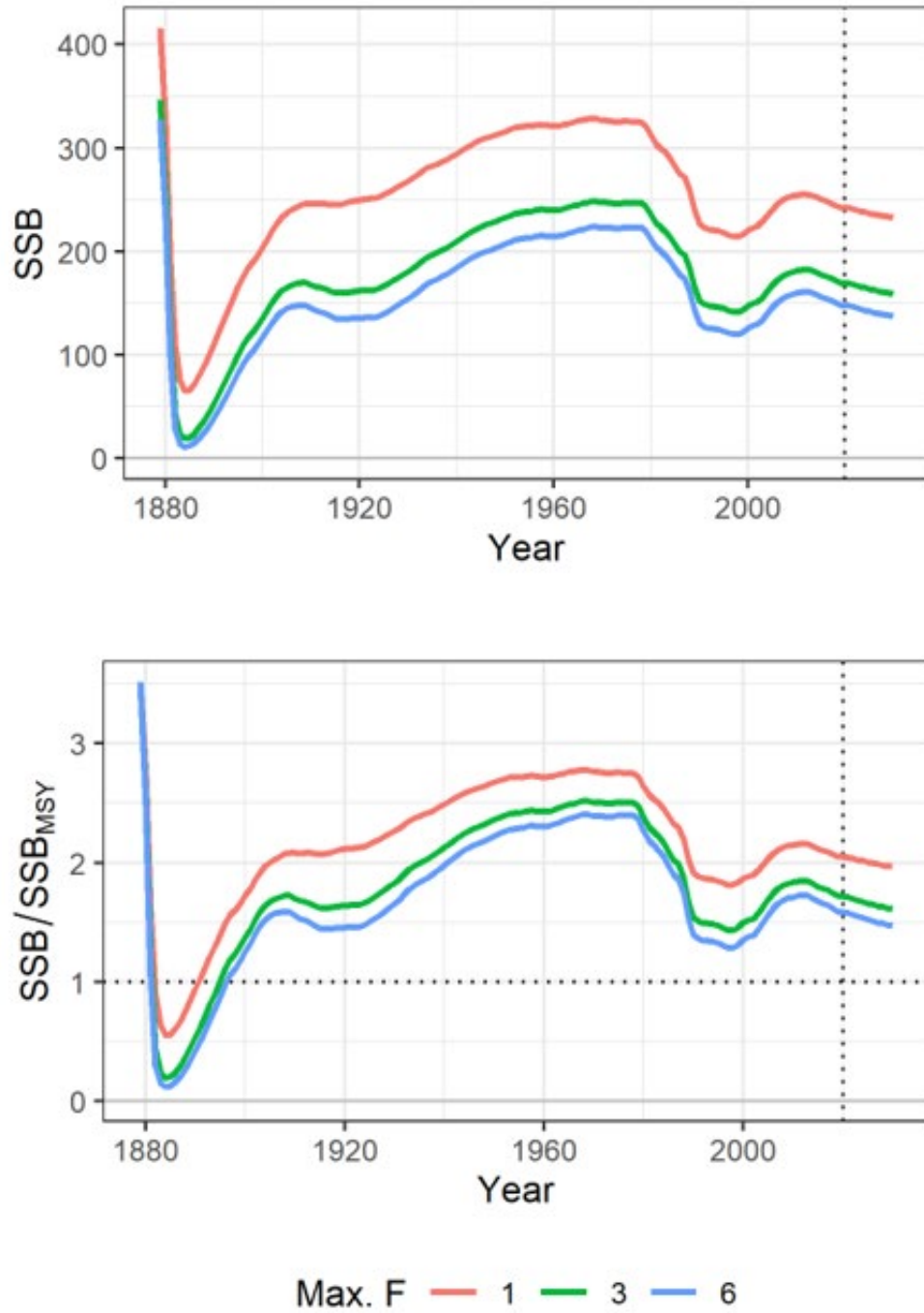
Figure 19. Estimates of SSB and SSB/SSB$_{MSY}$ with alternative assumptions of the maximum F. The reference model is represented by max. F = 3.
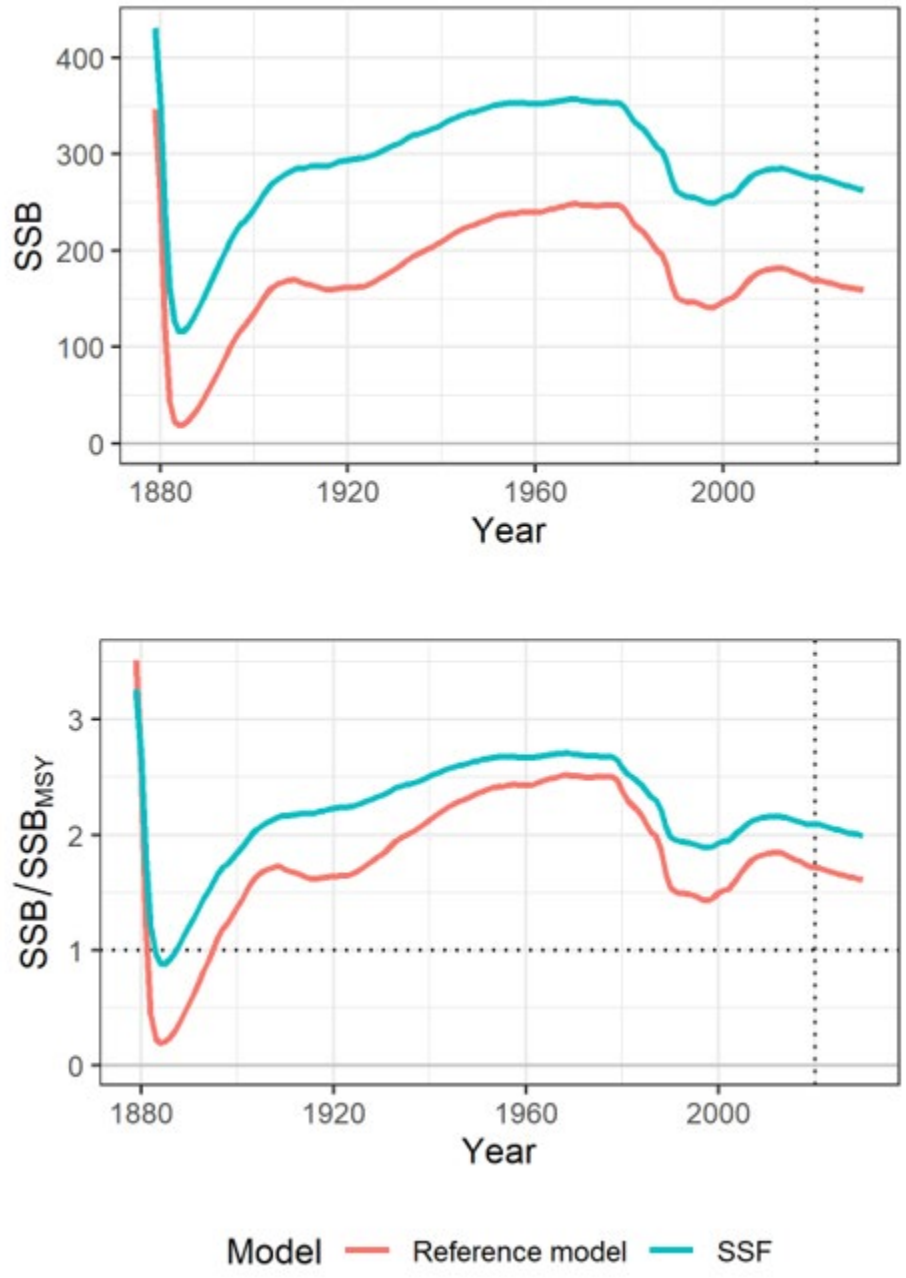
Figure 20. Comparison of SSB estimates between the reference model and the SSF model.
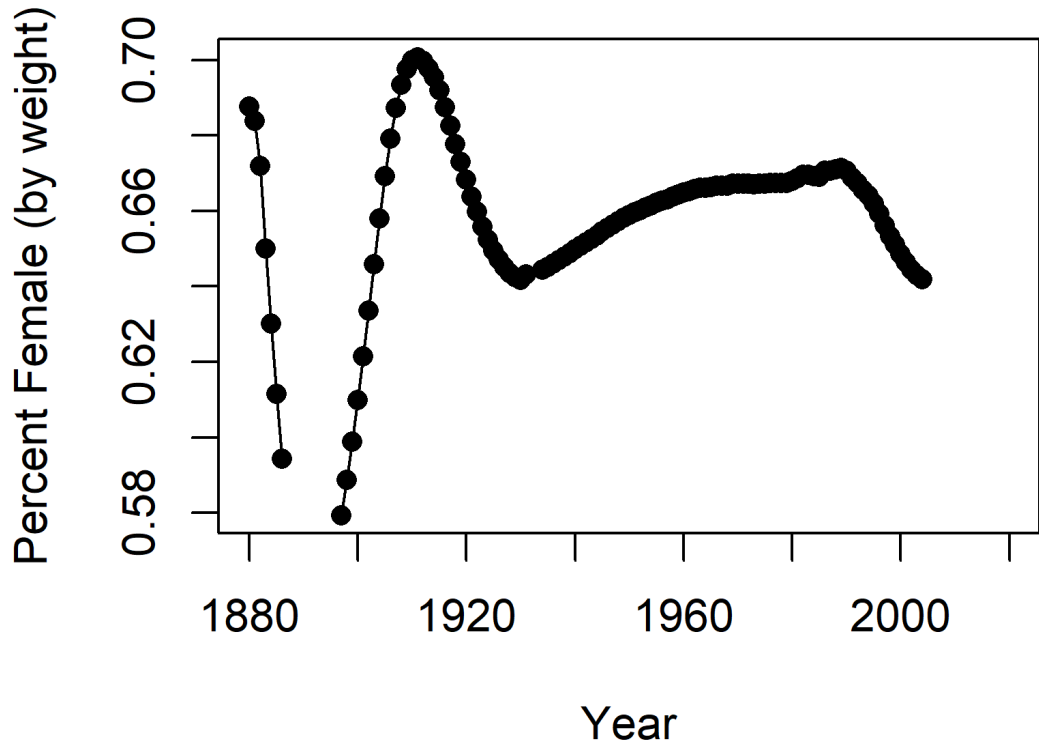
Figure 21. The sex ratio of historical Saint John River (SJR) catches (1880–2005) predicted by the reference model.
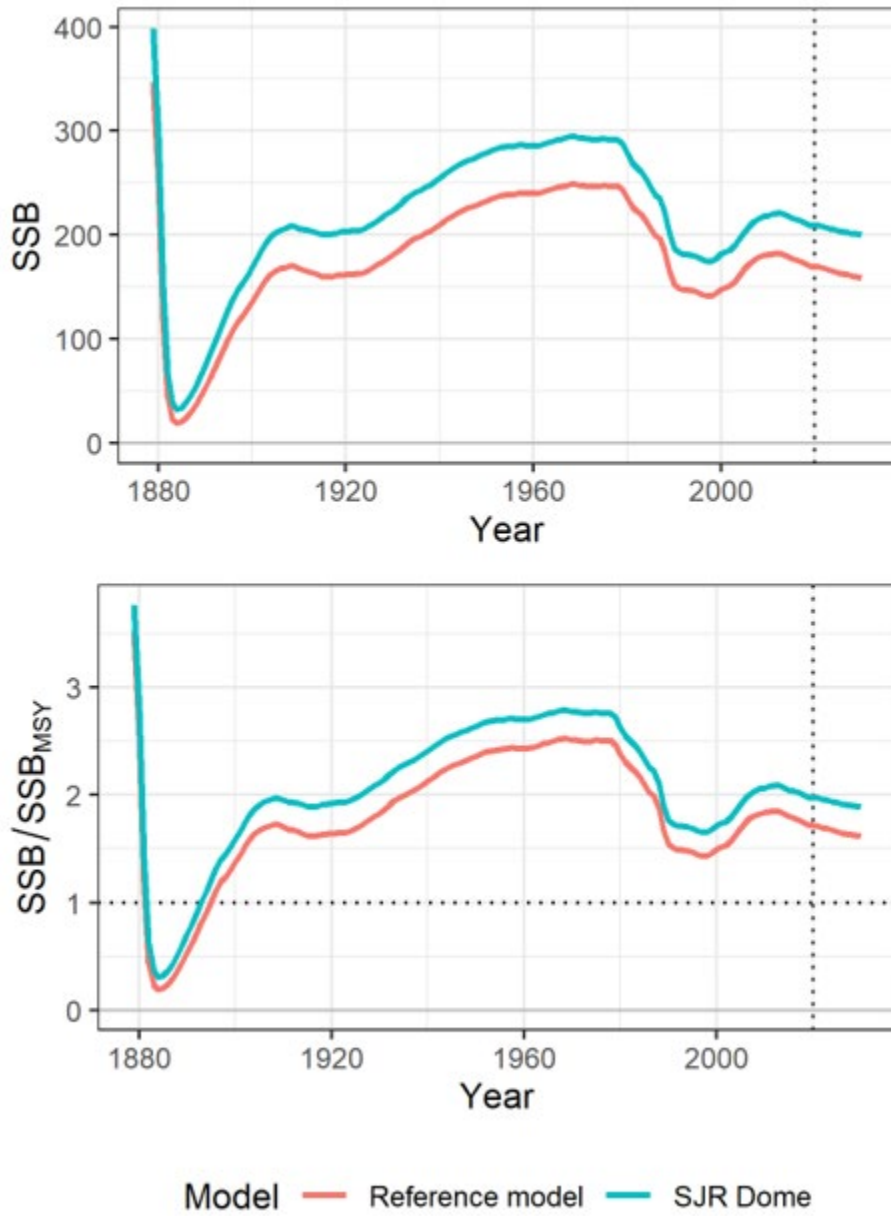
Figure 22. Estimates of SSB and SSB/SSB$_{MSY}$ between the reference model (logistic selectivity in the Saint John River (SJR) fishery) and the model with dome selectivity in the SJR fishery.
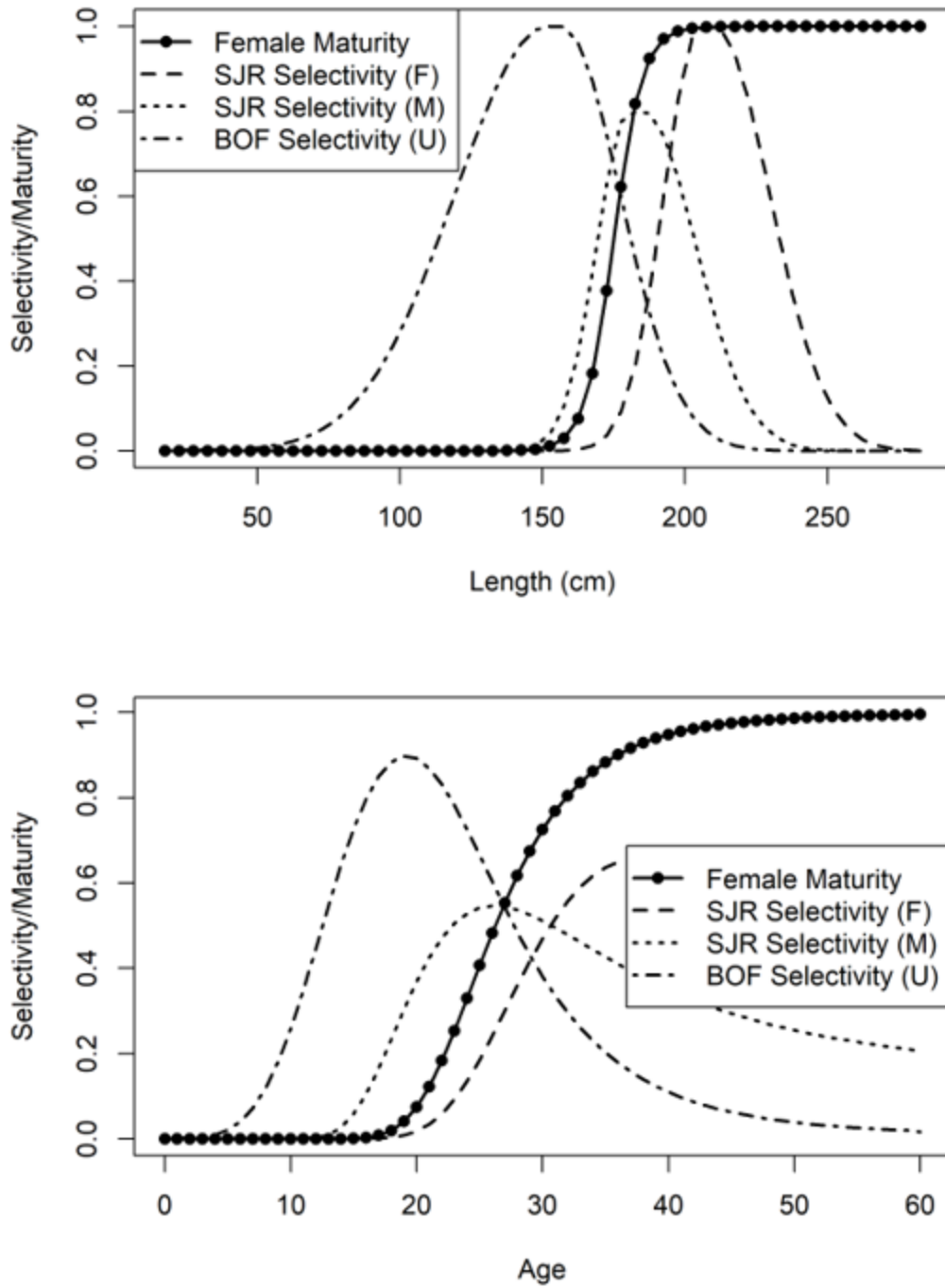
Figure 23. Dome selectivity estimates for the Saint John River (SJR) fishery.

Figure 24. Observed (black) and predicted (orange) length composition of harvested females (F) in the Saint John River (SJR) fishery with dome selectivity. Numbers in top right of each panel indicate the sample size.

Figure 25. Observed (black) and predicted (orange) length composition of harvested males (M) in the Saint John River (SJR) fishery with estimated dome selectivity. Numbers in top right of each panel indicate the sample size
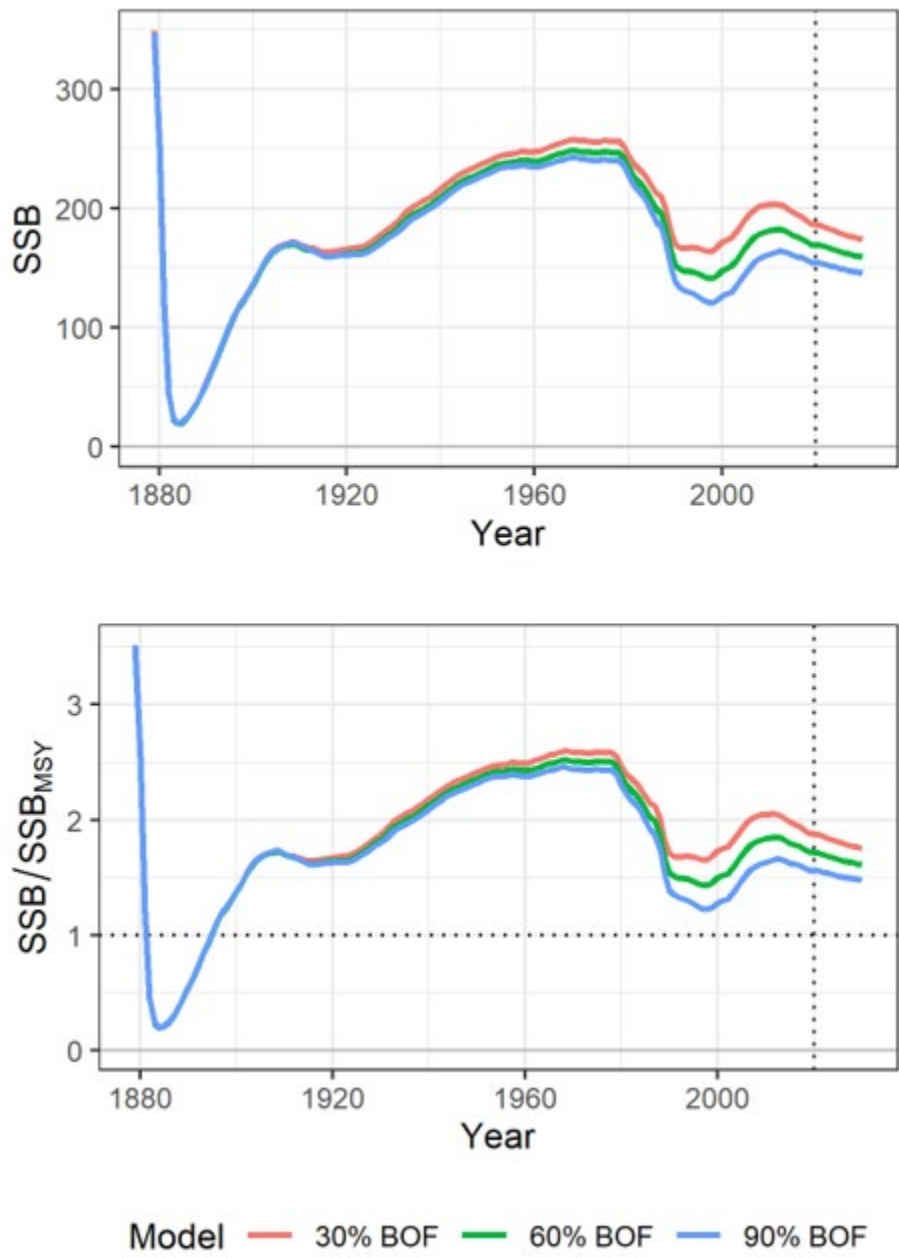
Figure 26. Estimates of SSB and SSB/SSB$_{MSY}$ with alternative assumptions of the percent Saint John River (SJR) fish (30, 60, or 90%) in the Bay of Fundy (BoF) catch. The reference model is represented by the 60% BoF model.
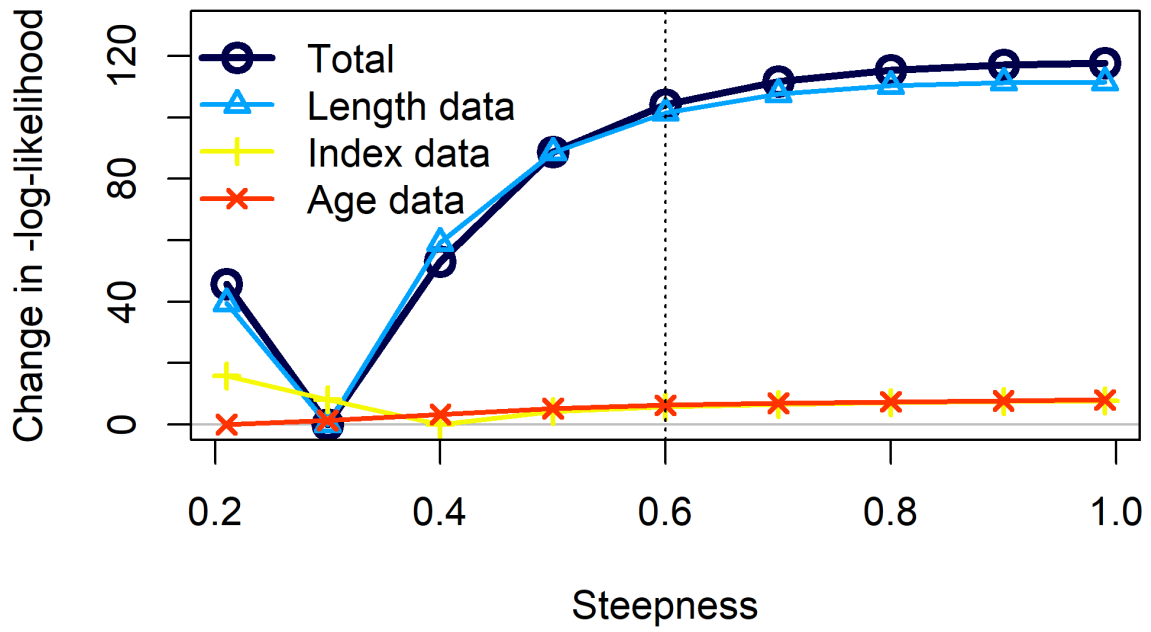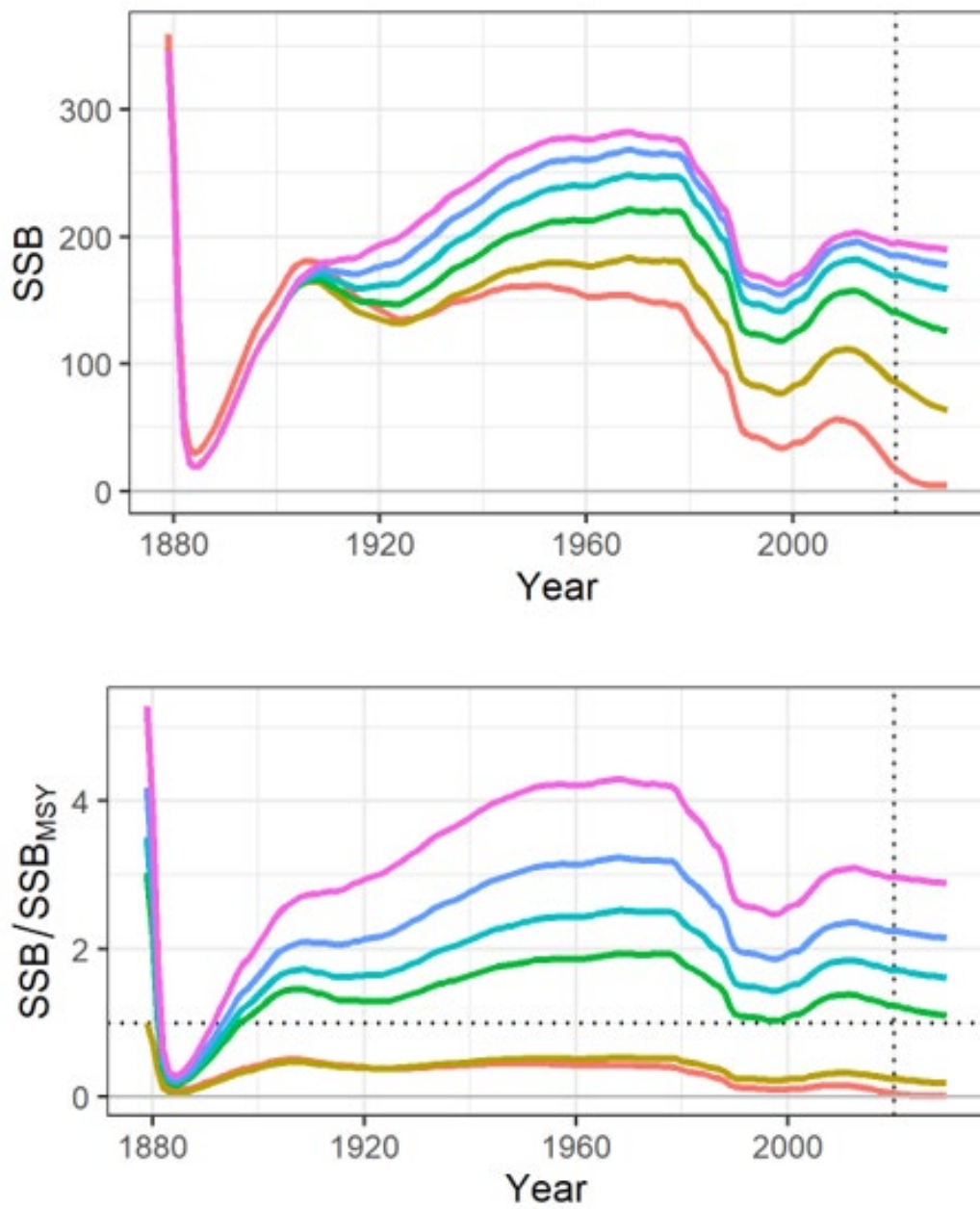
Figure 27. Likelihood profile of steepness in the reference model.

Figure 28. Estimates of SSB and SSB/SSB$_{MSY}$ across the steepness profile. The reference model is the h = 0.6 model.
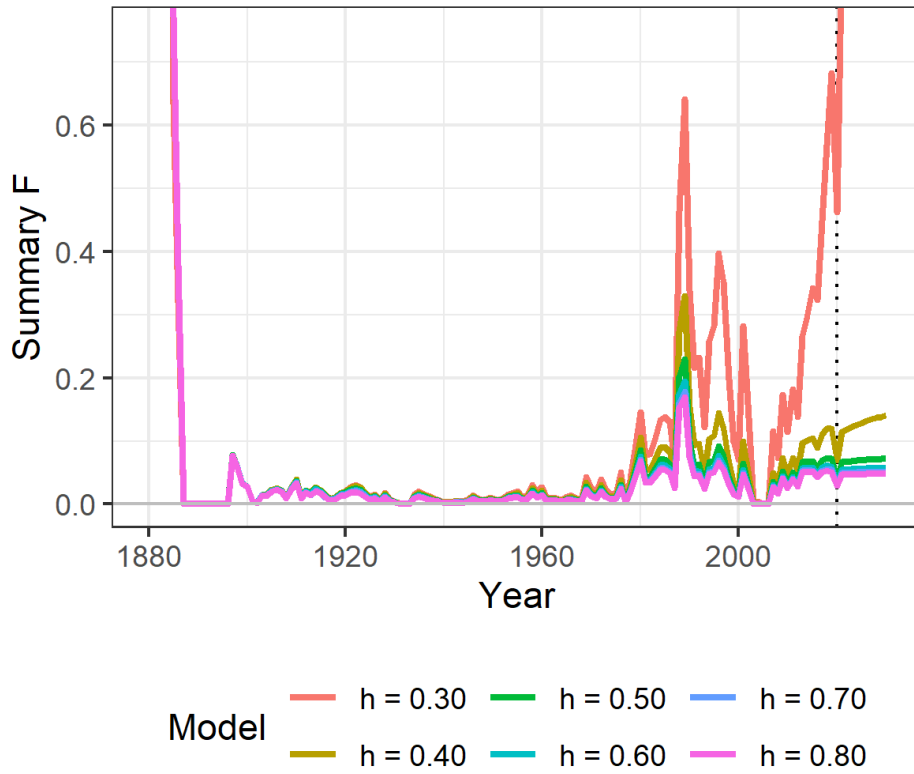
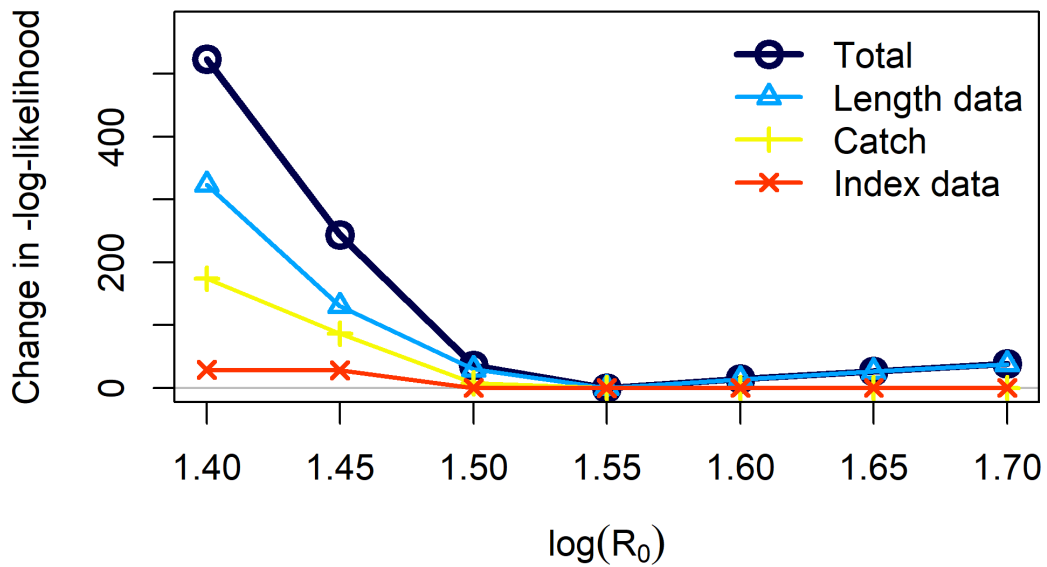*Figure 29. Estimates of F across the steepness profile. The reference model is the h = 0.6 model.*

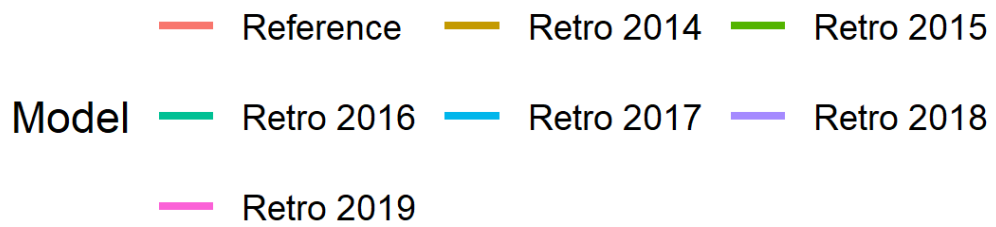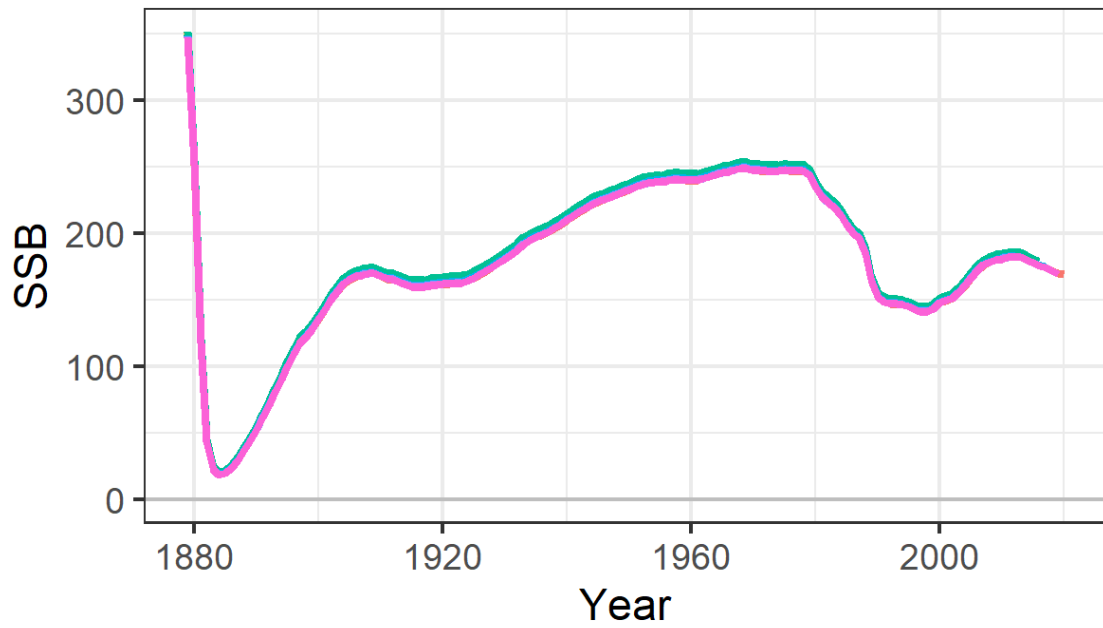*Figure 30. Likelihood profile of the unfished recruitment parameter.*

Figure 31. Retrospective analysis of the reference model with additional years of data are removed from the model (from 2020 back to 2014).

APPENDIX A: BROWNIE TAGGING MODEL

The Brownie model (Brownie 1978, 1985; as cited in Hoenig et al. 1998) is an approach for estimating annual survival in a population from multiple years of tagged releases of animals and subsequent recaptures over time. The model has proven to be flexible framework and allows for modifications to relax and account for strict assumptions, such as immediate, complete mixing of the tags into the population and complete tag retention (see Hoenig et al. 1998, and Waterhouse and Hoenig 2011, as examples), typically associated with tagging models. Methodological improvements have re-parameterized survival into fishing mortality and natural mortality components, increasing its utility for fisheries assessment (Hoenig et al. 1998).

The Saint John River (SJR) Atlantic Sturgeon tagging dataset was processed into a set of releases and recaptures for analysis. Tagging records from the commercial fishery from 2009–2020 were processed into release-recapture events. Each release-recapture event was identified as an independent event for tabulation of total releases and recaptures by year (Table A.1). In this way, the number of release "events" is larger than the number of unique tags released in the population if tags were released and recaptured multiple times following initial release into the population. Most fish are double marked with a PIT and Floy tag, in which case, the tag events were sorted by PIT number, with remaining tag records sorted by Floy number (Figures A.1.). Most tags are recaptured in the same year as release (Figure A.2), after which the mode number of recaptures occurs 2–3 calendar years after release (Figure A.3).

MODEL DESCRIPTION

In a simple Brownie model, we first have the number of tags released in year i (N_i^{rel}). The abundance of tags $N_{i,j}$ of that cohort in the population in year j is

$$N_{i,j} = \begin{cases} N_i^{\text{rel}} & i = j \\ N_{i,j-1}\exp\left(-[F_{j-1} + M]\right) & i < j \end{cases}$$

where F_j is the fishing mortality in year j, and M is natural mortality.

For SJR Atlantic Sturgeon, two additional modifications were made in the dynamics equation, where

$$N_{i,j} = \begin{cases} N_i^{\text{rel}} & i = j \\ N_{i,j-1}\exp\left(-[\ell_{j-i-1}F_{j-1} + M]\right)\phi & i < j \end{cases}.$$

First, chronic tag shedding is believed to occur, and an additional scalar, ϕ, the proportion of tags retained from one year to the next was included in the model.

Second, the mixing of tags, and therefore the availability of tags to recapture, in the SJR fishery varies relative to the year of release. The catchability of within-year recaptures is expected to be higher as fish remain in the river. In years immediately after tagging, catchability is lower as animals are less likely to return due to the periodic spawning behavior. These latent effects on catchability ℓ_k, where $k = j - i$ is the time lag between release and recapture in calendar years, alters fishing mortality of tags following release and is modeled as separable effects on F_j. After 4 years, the average period between spawning, tags could be considered to be fully mixed into the population, i.e., $\ell_k = 1$ for $k = 4, 5, \ldots$

For years $i \leq j$, the recaptures $R_{i,j}$ is predicted by the Baranov equation,

$$R_{i,j} = \frac{\ell_{j-i}F_j}{\ell_{j-i}F_j + M}\left(1 - \exp\{-[\ell_{j-i}F_j + M]\}\right)N_{i,j}\lambda$$

where λ is the tag reporting rate. Here, a 100% reporting rate was assumed ($\lambda = 1$).

The log-likelihood L of the model uses a multinomial distribution for the fates of tag cohort i over years $i \le j$,

$$L = \sum_i \left(\sum_{i \le j} \left[r_{i,j} \log (\hat{p}_{i,j}) \right] + (N_i^{\text{rel}} - \Sigma_i r_{i,j}) \log (1 - \Sigma_i \hat{p}_{i,j}) \right)$$

where $r_{i,j}$ is the observed number of recaptures, $\hat{p}_{i,j} = \hat{R}_{i,j}/N_i^{\text{rel}}$ is the predicted proportion of tags recaptured, with the hat operator (^) denoting an estimate, and the last term in the equation is the likelihood component of tags that have not been seen since release. The estimated parameters were F_j, ϕ, and ℓ_k for $k = 0, 1, 2, 3$.

Since ϕ and M are not uniquely identifiable parameters (both describe chronic tag loss from causes other than fishing), ϕ was estimated with M = 0.06 and a joint likelihood profile was used to describe the correlation in the parameters. The Brownie model was implemented in Template Model Builder (TMB), an R package for implementing rapid, complex models (Kristensen et al. 2016).

RESULTS

With M = 0.06, the Brownie model estimated fishing mortality rates between 0.04–0.09 during 2009–2020 (Table A.2). The trend in F is steadily increasing over time (Figure A.4) from F = 0.04 to 0.07 between 2009 and 2019. In 2020, the F was lower due to the decreased number of recaptures relative to previous years. In 2016, the F peaked at 0.09, arising from a high number of recaptures of the 2016 tag cohort.

The model fit is predominated by the within-year recaptures (Figures A.5–7), and the estimated latent effect for the within-year recaptures indicated much higher (6.41x) probability of capture. Between 1–3 years after release, the relative catchability is lower (< 1) and gradually increases.

With fixed M = 0.06, the estimated tag retention rate was 0.81. The joint likelihood profile of M and tag retention indicated very high correlation between the two parameters (Figure A.8), indicating that both parameters cannot be simultaneously estimated.

The estimated F in the Brownie model closely matched those in SS3 in terms of trend, despite utilizing different data. In both, F has increased since 2009, although very slowly, followed by a pronounced more drop in the terminal year (Table A.2). The Brownie F estimates are also similar in magnitude for most SS3 configurations.

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Kristensen, K., Nielsen, A., Berg, C.W., Skaug, H., and Bell, B.M. 2016. TMB: Automatic Differentiation and Laplace Approximation. J. Stat. Soft. 70. doi:10.18637/jss.v070.i05.

Waterhouse, L. and Hoenig, J.M. 2011. Instantaneous-Rates Tagging Models Allowing for Delayed Mixing of Newly Tagged Cohorts: Partial Year Tabulation of Recaptures. N. Am. J. Fish. Manage. 31: 995-1004.

TABLES

Table A.1. Tag releases and recapture events tabulated for the Brownie model.

Release Year	Releases	Recaptures 2009	Recaptures 2010	Recaptures 2011	Recaptures 2012	Recaptures 2013	Recaptures 2014	Recaptures 2015	Recaptures 2016	Recaptures 2017	Recaptures 2018	Recaptures 2019	Recaptures 2020
2009	339	68	18	5	2	1	4	3	2	2	1	2	3
2010	283	.	71	2	3	4	4	6	0	2	3	1	0
2011	231	.	.	57	0	3	2	1	1	2	0	3	0
2012	158	.	.	.	48	0	7	4	11	4	3	3	0
2013	209	.	.	.	.	58	1	5	4	8	5	5	1
2014	218	.	.	.	.	.	67	1	9	5	9	3	3
2015	126	.	.	.	.	.	.	36	3	2	6	4	3
2016	310	.	.	.	.	.	.	.	135	0	10	18	4
2017	90	.	.	.	.	.	.	.	.	17	1	1	0
2018	71	.	.	.	.	.	.	.	.	.	16	0	0
2019	70	.	.	.	.	.	.	.	.	.	.	16	1
2020	57	.	.	.	.	.	.	.	.	.	.	.	12

Table A.2. Brownie model parameter estimates. CV is the coefficient of variation.

Parameter	Estimate	Std. Error	CV
F_2009	0.04	0.01	0.29
F_2010	0.05	0.02	0.28
F_2011	0.04	0.01	0.29
F_2012	0.05	0.02	0.3
F_2013	0.04	0.01	0.28
F_2014	0.06	0.02	0.27
F_2015	0.05	0.01	0.28
F_2016	0.09	0.02	0.27
F_2017	0.04	0.01	0.3
F_2018	0.06	0.02	0.29
F_2019	0.07	0.02	0.3
F_2020	0.04	0.01	0.33
chronic_tag_retain	0.81	0.04	0.05
latent_0	6.41	1.7	0.27
latent_1	0.26	0.08	0.32
latent_2	0.56	0.15	0.26
latent_3	0.76	0.17	0.23
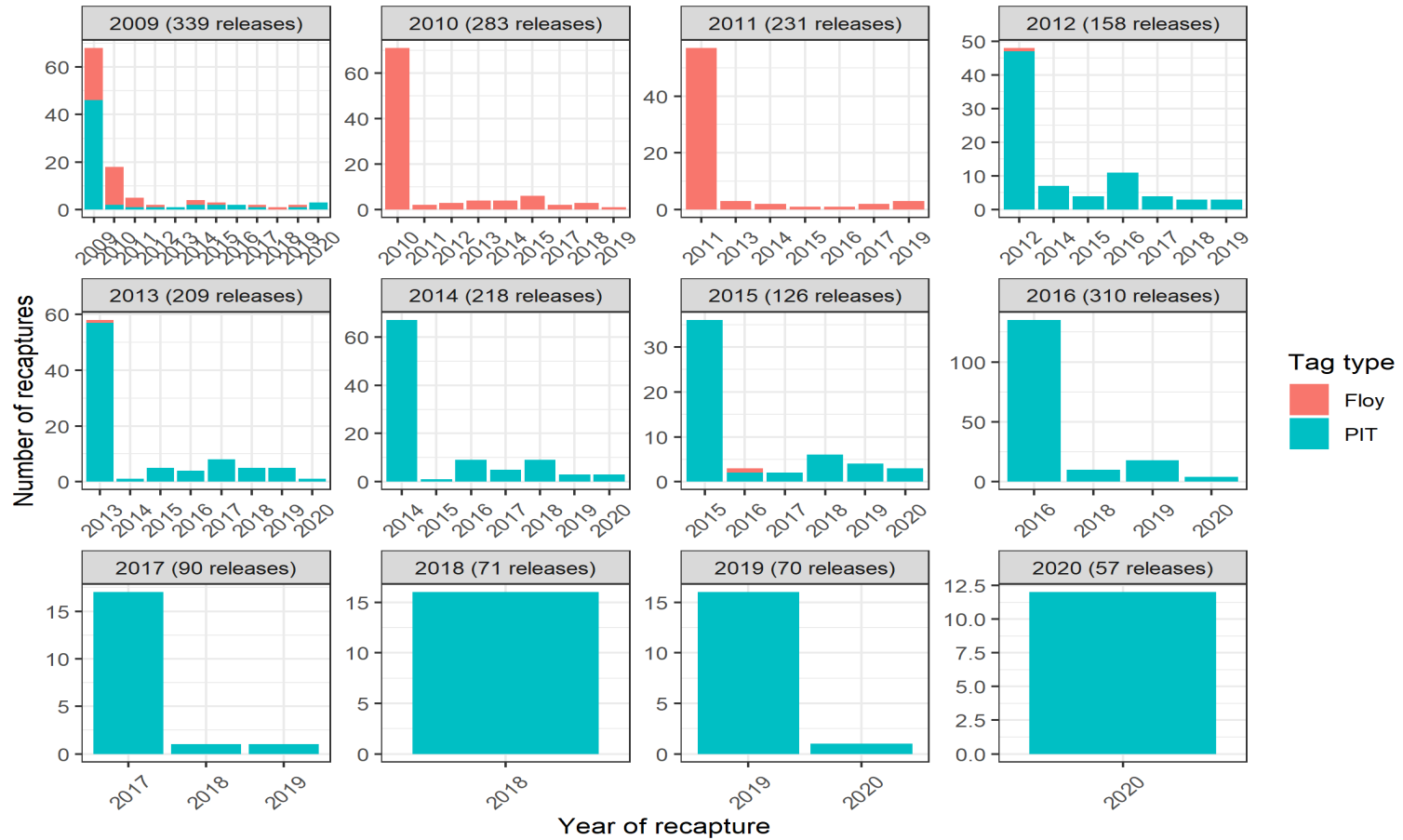
Figure A.1. Annual recaptures of tags by release cohort. Tag type indicates how the tag events were identified in the logbook database. Most animals are double-tagged and were first identified by PIT number. The remaining records were then identified by Floy number.
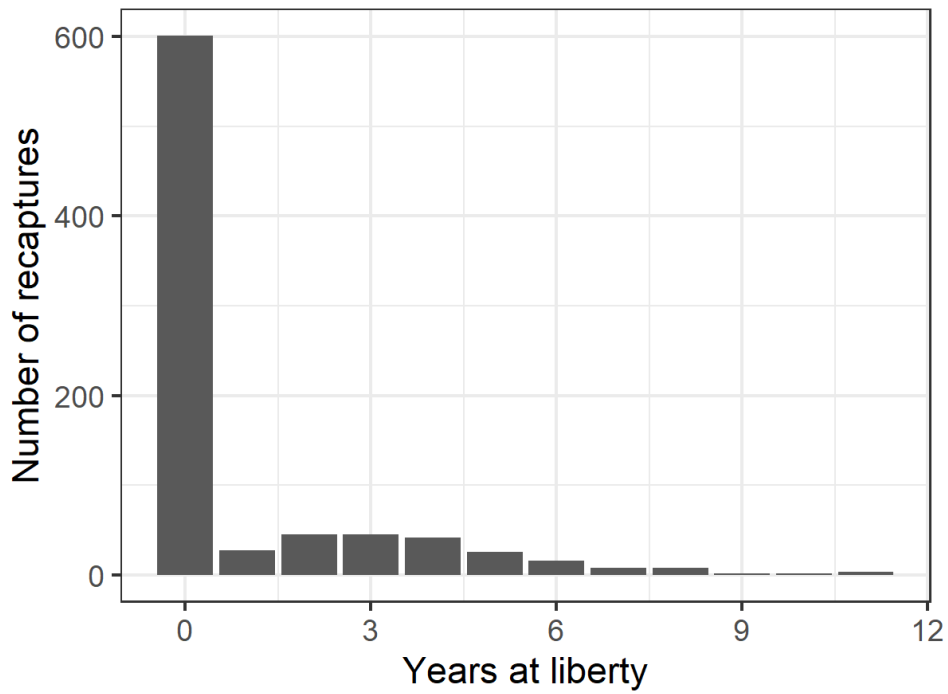
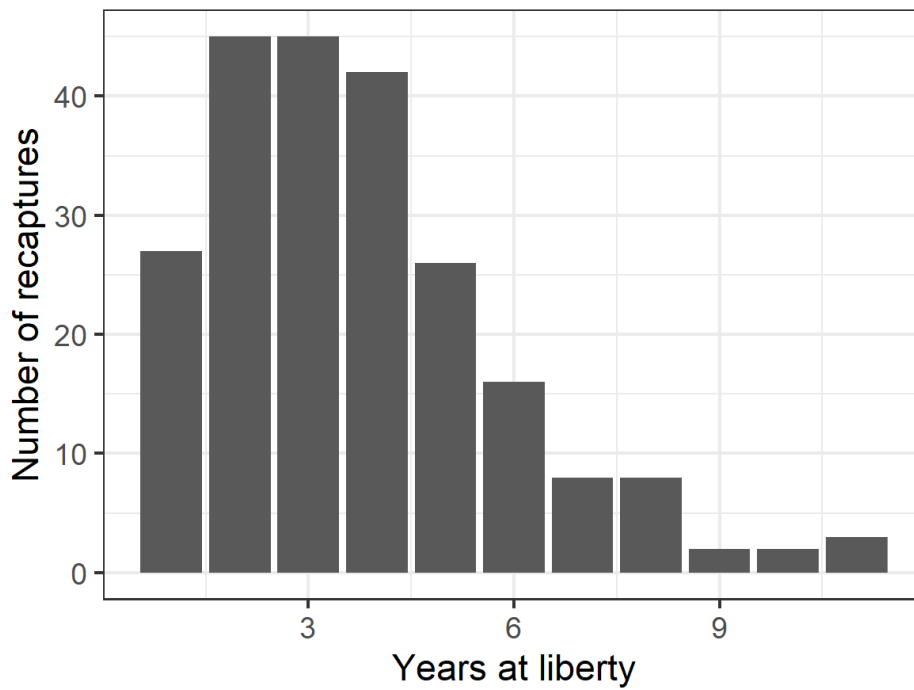*Figure A.2. Tag recaptures vs. time at liberty in whole calendar years.*

Figure A.3. Tag recaptures vs. time at liberty in whole calendar years, excluding recaptures within-year of release.
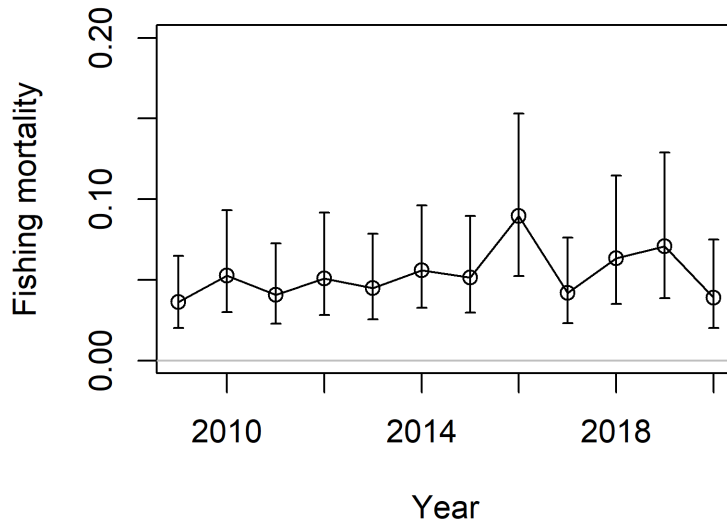
Figure A.4. Time series of F estimates from the Brownie model, with error bars defining the 95% confidence interval of estimates.
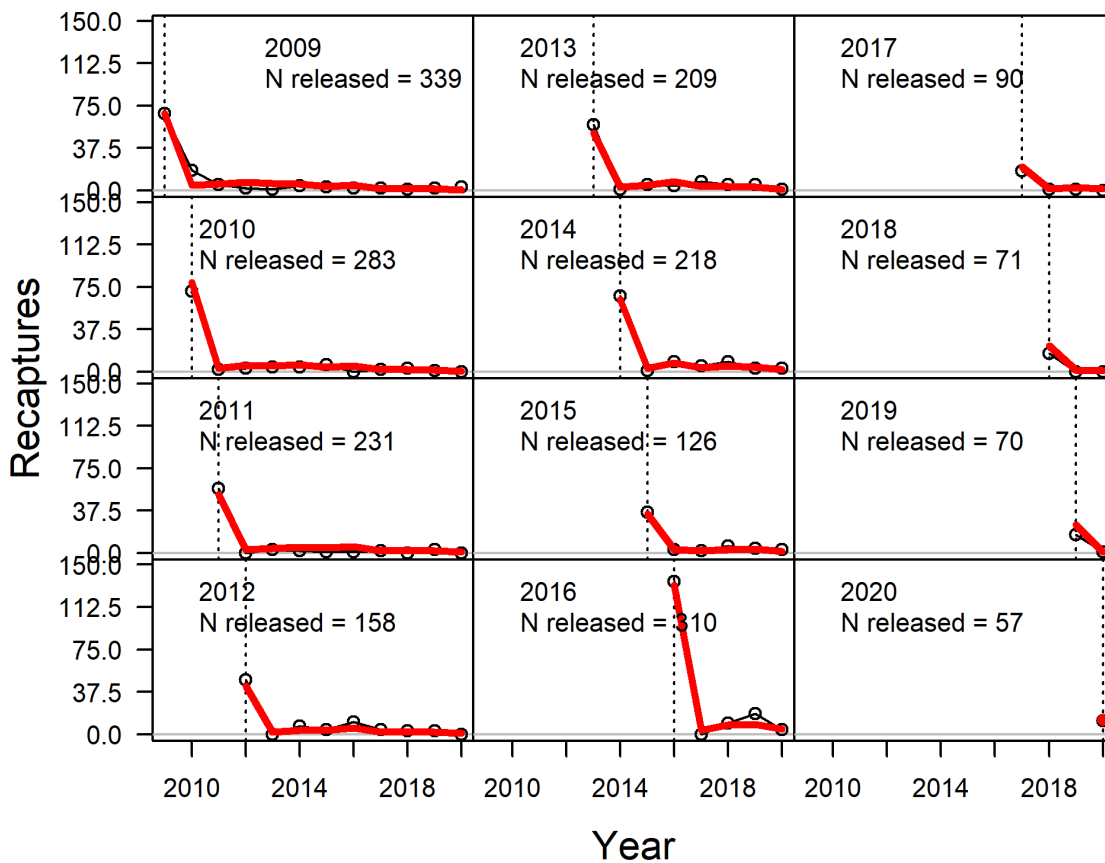

Figure A.5. Observed (black points) and Brownie model predicted (red lines) tag recaptures. Dotted vertical lines indicate the year of release for the tag cohort.
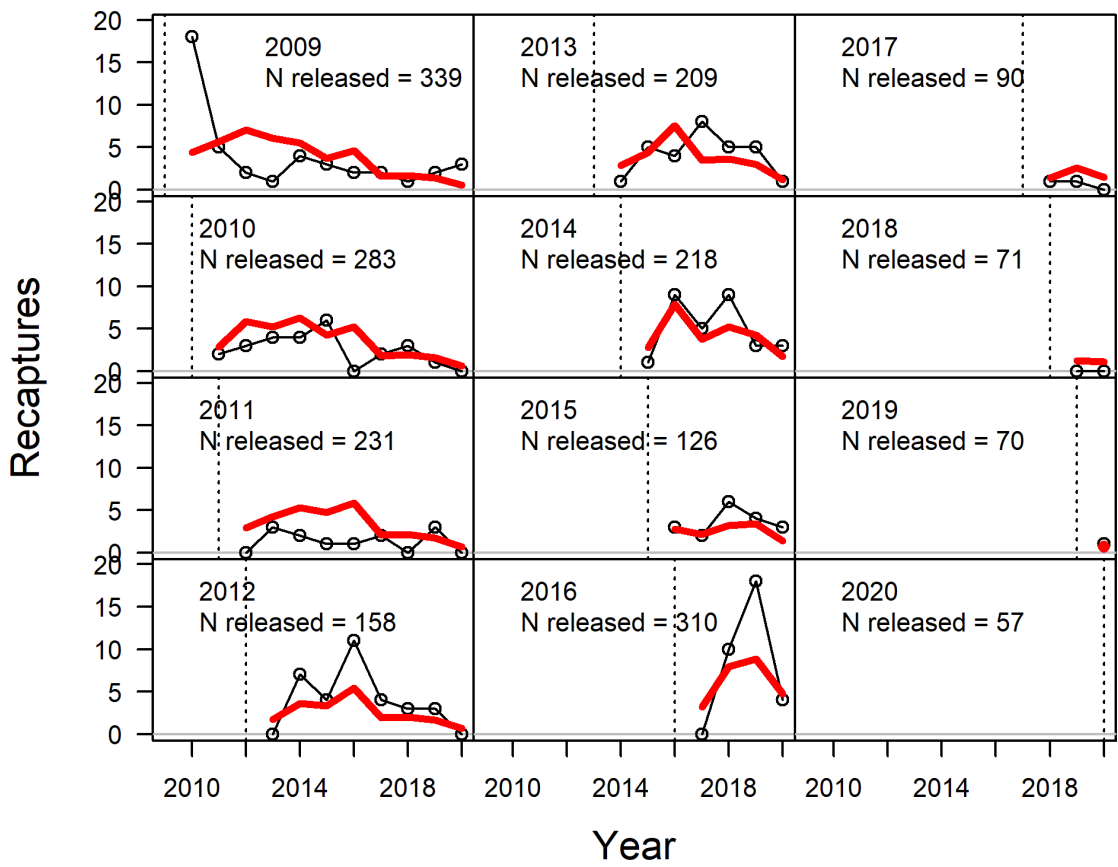
Figure A.6. Observed (black points) and Brownie model predicted (red lines) tag recaptures. Zoomed figure excludes within-year recaptures. Dotted vertical lines indicate the year of release for the tag cohort.
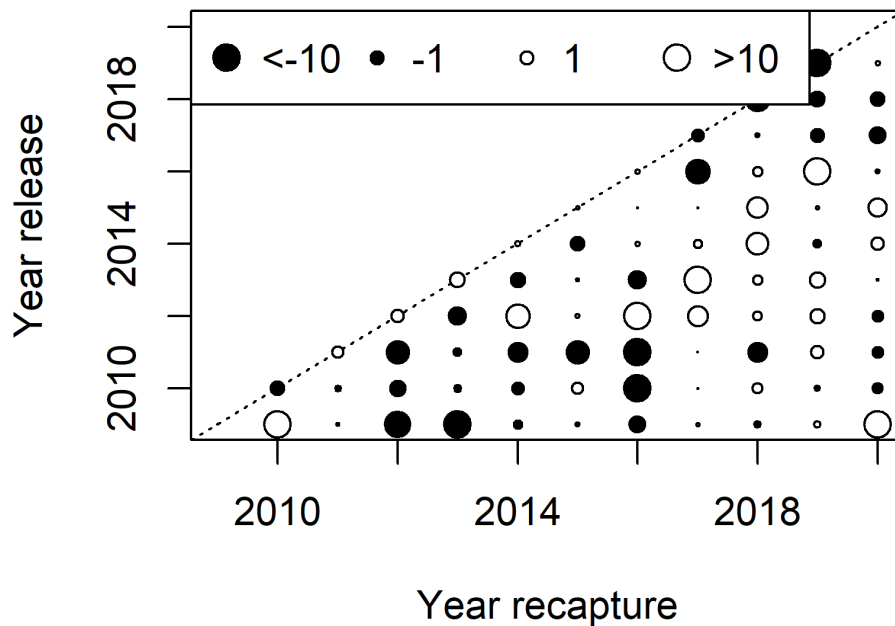
Figure A.7. Pearson residuals of observed and predicted tag recaptures. The dotted diagonal line is the 1-1 line indicates recaptures within-year (recapture year is the release year).
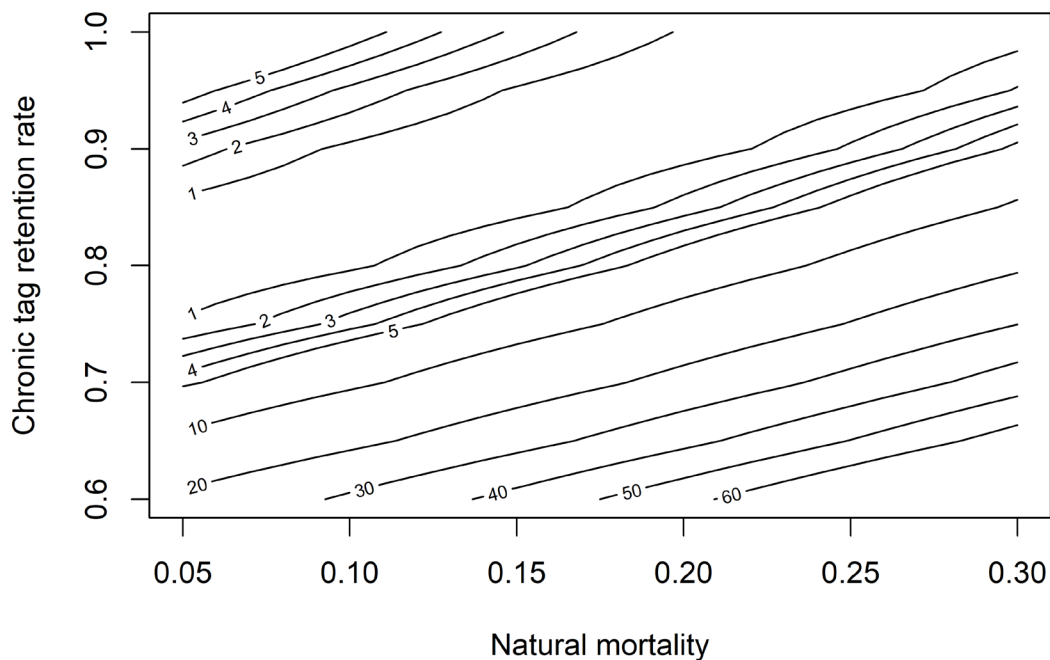

Figure A.8. Likelihood profile of M (natural mortality) and φ (chronic tag retention rate) in the Brownie model. The contour plot maps regions of the likelihood surface and reports the change in the Negative Log-Likelihood (NLL) relative to the minimum observed in the profile. The profile highlights the banded ridge where the difference in the NLL < 2 relative to the minimum, indicating that M and phi that are not uniquely identifiable parameters.

APPENDIX B: COSEWIC CONSIDERATIONS

In anticipation of COSEWIC assessment for SJR Atlantic Sturgeon, stock synthesis (SS3) output that would be relevant to COSEWIC Metric A, which calculates the historical changes in abundance in the past 3 generations, is reported. From maturity-at-age schedule and natural mortality, the Mean Generation Time (MGT) was calculated as

$$\text{MGT} = \frac{1}{M} + a_{50}$$

where the female parameters for natural mortality (M) and the age of 50% maturity (a_{50}) were used. A value of a_{50} = 23 years was used, which was interpolated from maturity-at-age internally calculated in SS3 from maturity-at-length and length-at-age, to obtain a generation time of 43 years.

It is important to reiterate that no maturity schedule has been estimated for the stock, and that maturity parameters for the SS3 model was calculated by visual inspection of the length composition as a proxy for maturity. The MGT used here is also higher than in the 2013 Recovery Potential Assessment (RPA) (DFO 2013) where the age of first maturity was used.

From sex-specific maturity-at-age, Spawning Stock Numbers (SSN) was from the abundance-at-age estimates for females and males. The change in abundance over three generations was calculated as the ratio of SSN in 2020 relative to that in 1891 in each model configuration and sensitivity run. The uncertainties associated with the various SS3 configurations, along with the lack of a formal model-weighting scheme, precluded calculation of a probability associated with these changes in abundance.

The stock in 1891 was near its lowest following the high catches in the 1880s. The stock is more abundant today, resulting in depletion ratios > 1 (Table B.1.). The ratio increases when either the steepness, the max. F, or the percent SJR origin of BoF catch increases.

Table B.1. Estimates of historical (in 1891) and current (in 2020) spawning stock numbers (female, male, and both) from the suite of stock synthesis models.

Model	Female SSN SSN_{2020}	Female SSN_{1891}	Female Ratio	Male SSN_{2020}	Male SSN_{1891}	Male Ratio	Total SSN_{2020}	Total SSN_{1891}	Total Ratio
Reference model	4,113	1,815	2.27	2,506	1,385	1.81	6,619	3,200	2.07
Max. F = 1	5,751	3,370	1.71	3,487	2,353	1.48	9,238	5,724	1.61
Max. F = 6	3,622	1,395	2.60	2,205	1,116	1.98	5,827	2,511	2.32
SSF	6,472	4,434	1.46	3,579	1,785	2.01	10,051	6,219	1.62
SJR Dome	4,997	2,450	2.04	3,205	1,876	1.71	8,202	4,326	1.90
30% BoF	5,751	3,370	1.71	3,487	2,353	1.48	9,238	5,724	1.61
90% BoF	3,622	1,395	2.60	2,205	1,116	1.98	5,827	2,511	2.32
Profile h = 0.45	2,889	1,824	1.58	1,678	1,387	1.21	4,567	3,211	1.42
Profile h = 0.5	3,433	1,819	1.89	2,043	1,385	1.48	5,476	3,204	1.71
Profile h = 0.55	3,826	1,816	2.11	2,309	1,385	1.67	6,135	3,201	1.92
Profile h = 0.65	4,327	1,815	2.38	2,655	1,386	1.92	6,982	3,201	2.18
Profile h = 0.7	4,490	1,815	2.47	2,771	1,386	2.00	7,262	3,201	2.27
Profile h = 0.75	4,618	1,815	2.54	2,864	1,387	2.06	7,482	3,202	2.34
Profile h = 0.8	4,721	1,815	2.60	2,940	1,388	2.12	7,661	3,203	2.39