Status of White Sturgeon in the Lower Fraser River in 2019 Derived Using an Integrated Spatial and Age Mark Recapture (ISAMR) Model

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KEY POINTS AND FINDINGS

1. The Lower Fraser White Sturgeon Monitoring and Assessment Program uses two separate models to generate abundance estimates: 1) an Integrated Spatial and Age-structured Mark-Recapture (ISAMR) model (described herein); and 2) a Bayesian mark-recapture model (BMR24), reported separately (Nelson et al. 2020).

2. Both the BMR24 and ISAMR models indicated that the abundance of 60-279 cm fork length (FL) (age 7-55) White Sturgeon in the lower Fraser River has been in a continual state of decline since 2004.

3. The ISAMR and BMR24 models were found to produce similar abundance estimates and trends for both 60-99 cm FL (age 7-12 "juvenile") and 100-159 cm FL (age 13-22 "subadult") sturgeon, but were found to diverge significantly in the last three years for 160-279 cm FL (age 23-55 "adult") sturgeon. The ISAMR model showed an increasing abundance trend for 160-279 cm FL sturgeon (with a 2019 abundance estimate of 21,687), whereas the BMR24 estimate for this size group showed a decline (from 16,073 in 2015 to 12,512 in 2019).

4. The 2019 ISAMR abundance estimate for 60-279 cm FL (age 7-55) Lower Fraser White Sturgeon was 44,809 (95% CIs ± 4.2% of the estimate), which is 24.7% lower than the program's highest annual abundance estimate in 2006 and 3.9% lower than the 2018 ISAMR estimate.

5. The decline in the total abundance of 60-279 cm FL (age 7-55) Lower Fraser White Sturgeon from 2004 to 2011 was driven by declines in age-7 recruitment since 2001, which led to substantial decline in the abundance of 60-99 cm FL (age 7-12) juvenile sturgeon and subsequently of 100-159 cm (age 13-22) subadult sturgeon.

6. If low levels of recruitment persist, ISAMR abundance forecasts suggest the population would continue to decline, with a possible leveling in approximately 40 years (i.e., early 2060s) at approximately 27,000 sturgeon (60-279 cm FL). An increase in future recruitment (e.g., 1.6 times current levels) could stabilize abundances to approximately current levels by the mid 2040s, but would not reach a proposed recovery target of 60,000 individuals in the 60-279 cm size class (age 7-55), an abundance level estimated to have occurred from 2003-2006. This recovery target has not been formally ratified and was considered as part of an exploratory exercise.

EXECUTIVE SUMMARY

An Integrated Spatial and Age-structured Mark-Recapture (ISAMR) model was developed from 2015-17 for the analysis of PIT tag mark-recapture data available for Lower Fraser River White Sturgeon. Challenger et al. (2017) provided a detailed description of Version 2.0 of the ISAMR model and compared the abundance estimates derived from the ISAMR model with those derived from the Bayesian 24-month mark-recapture (BMR24) model, which has been historically used within the Monitoring and Assessment Program (Nelson et al. 2017).

Both the ISAMR and BMR24 models use Bayesian estimation to provide point estimates and credible intervals, however the two models have very different population modelling structures. The ISAMR model uses a demographic model where cohorts are tracked and contains age classes, while the BMR24 model employs size groups, but does not consider cohorts. The demographic model within the ISAMR model transitions fish through the available age classes over the course of the assessment period, explicitly modelling the process of births and deaths. In contrast, the BMR24 model assigns individual fish to a size-class for a series of 24-month analysis periods and assumes demographic closure within each 24-month assessment period; yearly abundance time series are then constructed from the independent 24-month assessment periods. The two models also differ in how gear selectivity is handled. The ISAMR model incorporates a selectivity-at-age relationship that is estimated from the data, while the BMR24 model does not include differential selectivity by age and thus assumes that individuals within each size group are equally recruited into the sampled population. The ISAMR model also incorporates a sampling effort relationship based on the total number of boat trips within a region and considers all captures within the assessment period in a single analysis framework. The BMR24 model does not directly consider sampling effort and because yearly abundance estimates are derived in each independent 24-month period, sampling information is not shared across the entire sampling time series. Despite these differences, annual abundance estimates for each of the three main size/age classes have been shown to display good agreement for 2000-2016 (see Challenger et al. 2017).

Subsequent analyses incorporating the 2017 to 2019 mark-recapture data into both the ISAMR and BMR24 models continue to produce similar abundance estimates and trends for both 60-99 cm FL (age 7-12 "juvenile") and 100-159 cm FL (age 13-22 "subadult") size groups. However, estimates and trends for 160-279 cm FL (age 23-55 "adult") sturgeon have diverged significantly in the last three years. The ISAMR model results showed a continuing increasing abundance trend for 160-279 cm FL sturgeon (with a 2019 abundance estimate of 21,687), whereas the BMR24 estimate for this size group showed a decline (from 16,000 in 2015 to 12,500 in 2019). This divergence in the abundance estimates for 160-279 cm FL adult sturgeon accounted for 67% of the difference between the total yearly abundance estimates from the two models since 2015. An analysis review of the 2000-2018 data indicated that the BMR24 model was more sensitive to recent changes in the distribution of tagging and sampling effort than the ISAMR model (Nelson et al 2019) and concluded that the best estimates of abundance for 60-279 cm Lower Fraser White Sturgeon are those derived using the ISAMR model.

The 2019 abundance estimate for 60-279 cm FL (age 7-55) Lower Fraser White Sturgeon derived from the ISAMR model was 44,809 (95% CIs ± 4.2% of the estimate). This abundance

estimate was 24.7% lower than the program's highest annual abundance estimate in 2006 and 3.9% lower than the 2018 estimate.

The estimated decline in 60-279 cm FL (age 7-55) White Sturgeon abundance in the lower Fraser River from 2004 to 2011 was driven primarily by the sustained decline in estimated age-7 recruitment since 2001. This lack of replenishment resulted first in the decline of 60-99 cm FL (age 7-12) juvenile sturgeon starting in 2003, and then subsequently of 100-159 cm (age 13-22) subadult sturgeon since 2011. Recent moderate improvements in age-7 recruitment into the sampled population have begun to stabilize 60-99 cm FL (age 7-12) juvenile sturgeon abundances at levels approximately 32% that of 2001, but the 100-159 cm (age 13-22) subadult sturgeon continue to decline. Currently, estimates of 160-279 cm FL (age 23-55) mature sturgeon have been increasing, but are anticipated to show a decline in coming years as the lack of sustained replenishment begins to impact older demographic groups.

Given the current age-7 recruitment rates, the overall abundance of 60-279 cm FL (age 7-55) sturgeon is forecasted to decline into the foreseeable future, possibly leveling off after approximately 40 years (i.e., early 2060s). Specifically, the 100-159 cm FL size group (age 13-22) of subadult sturgeon is expected to continue to decline until the 2030s, with adult sturgeon (age 23-55; 160-279 cm FL) predicted to begin declining in the mid 2020s, with a continued decline until approximately 2060. Forecast modelling also indicated that an immediate and sustained 60% increase in age-7 recruitment into the sampled population (i.e., 1.6 times current levels) was expected to stabilize the 60-279 cm FL (age 7-55) sturgeon total abundance at levels similar to 2019, while a sustained increase of 140% (i.e., 2.4 times current levels) would be required to achieve a level of adult abundance estimated in 2005.

Given the estimated declining trend in abundance, interim recovery goals will be important for managing Lower Fraser White Sturgeon. For example, Challenger et al. (2017) suggested a potential population target of 60,000 60-279 cm FL (age 7-55) Lower Fraser River White Sturgeon, based on levels of abundance estimated to have occurred from 2003 through to 2005. Similarly, 20,000 mature sturgeon (160-279 cm; age 22-55) could be another potential target (Challenger et al. 2017, Nelson et al. 2018) as it is the abundance level expected within the decade. Only the projection scenario that had more than a doubling of recruitment into age-7 was able to sustain either of these targets, suggesting that substantial increases in recruitment will be required to meet either of these potential abundance targets. Given the long-lived nature of White Sturgeon, it will take a considerable amount of time to achieve and sustain either of these targets. Neither target have been formally ratified, but should be reviewed as useful threshold endpoints in a more formal assessment process. The targets herein were only considered as an exploratory exercise.

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INTRODUCTION

The Integrated Spatial and Age Mark Recapture (ISAMR) model was developed for the PIT tag mark-recapture data available for Lower Fraser River White Sturgeon (Challenger et al. 2017). The model is a class of an age-structured mark-recapture model (e.g., see Coggins et al. 2006) that tracks cohort abundances for 58 age classes over four spatial areas on a yearly time step. A subset of age classes are typically reported. Challenger et al. (2017) provided a detailed description of the ISAMR model (Version 2.0), including mathematical formulation and data assembly procedures, as well as comparisons of abundance estimates with those derived from the Bayesian 24 month mark-recapture (referred to as BMR24) model (i.e., Gazey and Staley 1986), which uses a 24-month rolling data window and has historically been used since 2000 as the primary abundance model for this sturgeon population (e.g., Nelson et al. 2017).

Both the ISAMR and BMR24 models are spatial mark-recapture models employing Bayesian estimation to provide abundance estimates of Lower Fraser River White Sturgeon across four sampling regions within a core assessment area (Figure 1), but differ in their specifications. The BMR24 model employs three primary size groups, but does not have a mechanism for modelling transitions between group sizes. As a result, the model assumes demographic closure (i.e., no births, deaths, immigration or emigration) during a series of 24-month assessment periods used to reconstruct the full abundance time series. In contrast, the ISAMR model is an open demographic model which reports on 52 age classes (i.e., age 7 to 55) and transitions fish within a cohort through available age classes on each yearly time step by explicitly modelling birth and
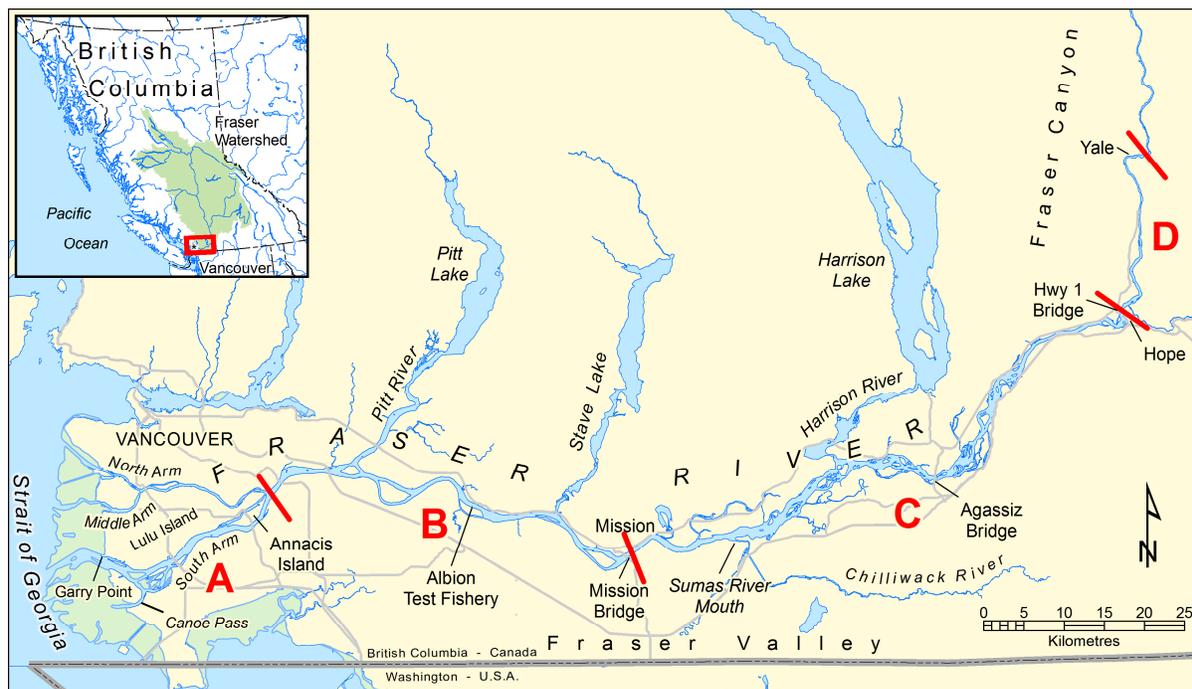
Figure 1. **Boundaries of the four sampling regions (A, B, C, and D) that comprise the core assessment area.**

death. New recruits are modelled as entering the first age class (i.e., age 1), with mortality based on extrapolating the mortality-at-age curve estimated for captured age classes. The ISAMR model therefore considers all data from the assessment period at one time, rather than parceling the data into smaller contiguous periods. A subset of abundances are reported on (i.e., age 7-55) due to the reduced catch rates under age-7 as a result of size selectivity of sport anglers, and to match the upper size limit used by the BMR24 size classes. Comparisons between the two models are made by mapping the ISAMR age classes to the corresponding BMR24 size classes, based on a documented growth curve for Lower Fraser River White Sturgeon (RL&L 2000, English and Bychkov 2012, Whitlock and McAllister 2012).

Sampling methods (e.g., sport angling) are expected to produce size selectivity differences in catch due to sport fishers targeting larger-sized sturgeon. The ISAMR model directly handles this issue by estimating a selectivity-at-age relationship from the data, while the BMR24 model restricts size groups to sizes that are assumed to be fully recruited by the employed fishing gear; it does this by ignoring catch below 60 cm FL in size. Due to the different approaches in potential gear selectivity, some comparisons between the ISAMR and BMR24 models use "adjusted" ISAMR abundances, where the effects of selectivity-at-age corrections on abundance estimates are removed.

The two models also differ in how yearly sampling effort is handled. The ISAMR model directly models the effect of yearly sampling effort (i.e., boat days) on catch rates and therefore the predicted yearly catch in each age category. The BMR24 model, because of the rolling 24-month analysis windows, does not include sampling effort, but instead assumes a consistent or random sampling effort within each 24-month analysis window.

The objective of this report is to update the Challenger et al. (2017) results with two additional years of sampling effort and to compare these results to the updated estimates from the BMR24 model (Nelson et al. 2020).

METHODS OVERVIEW

Sport angling captures were included if they occurred in one of the four lower Fraser River sampling regions that make up the core assessment area of this study (Figure 1) with a known number of angling boat trips made each year (Table 1). Because age of captured sturgeon is a requirement for the model, age of fish were estimated via a von Bertalanffy growth model developed for lower Fraser River White Sturgeon (i.e., $L_a = 370.1 \times (1 - \exp(-0.025a))$; RL&L 2000, English and Bychkov 2012, Whitlock and McAllister 2012). For recaptures of previously marked individuals, aging was determined based on the age determined at first capture and the elapsed time between captures. The ISAMR model considers untagged and tagged captures separately, thus the model includes both untagged captures released with a tag, and untagged captures released without a tag.

In total there were 160,232 capture events available from sport angling captures and the Albion Test Fishery (a Pacific Salmon test fishery that occasionally captures sturgeon as incidental catch) in Region 2 from 1999-2019. Of these capture events, 78,392 were untagged captures (74,167 tagged and the remainder not tagged) and 81,840 were recaptures of previously tagged

Table 1.   **Angling boat trips to each sampling region by year.**

| Year	A	B	C	D	Total
2000	65	220	555	19	859
2001	101	261	597	33	992
2002	79	174	479	30	762
2003	67	264	659	17	1,007
2004	61	330	996	48	1,435
2005	99	344	1,390	34	1,867
2006	55	353	1,309	66	1,783
2007	53	294	1,599	37	1,983
2008	34	448	1,206	66	1,754
2009	50	483	884	74	1,491
2010	44	474	888	113	1,519
2011	42	471	896	68	1,477
2012	41	597	1,027	88	1,753
2013	46	565	1,243	141	1,995
2014	51	446	1,208	116	1,821
2015	33	477	1,416	183	2,109
2016	32	379	1,145	218	1,774
2017	36	257	987	129	1,409
2018	42	222	851	156	1,271
2019	49	305	1,057	202	1,613

individuals. The dataset was filtered to produce a subset of data for analysis that only included samples from 2000-2019 which met the compatibility criteria for the model. Of the 160,232 total captures, 17,595 were found to be incompatible with the analysis (e.g., outside assessment years [2000-2019], outside the modelled age classes, or repeat captures within a year) leaving 142,637 captures retained in the analysis. Of the original 78,392 untagged captures, 1,750 were removed (458 occurred outside the assessment period, 343 could not be aged, 149 had ages greater than the oldest age class, and 800 were captured outside the assessment area). Of the original 81,840 recaptures, 15,845 did not meet analysis criteria and were removed (881 occurred outside the assessment period, 427 were outside the assessment area, 81 could not be aged, 87 had ages greater than the oldest age class, 13,957 were removed for occurring within the same calendar year, and 412 recaptures were orphaned due to the previous filtering steps and treated as untagged captures for the purpose of the analysis).

The 142,637 captures that were retained where then analyzed using the same model formulation described in Challenger et al. (2017). A single S-shaped selectivity-at-age curve was estimated and shared across all assessment years. The curve represents how catchability of sturgeon falls to zero as we move from older individuals, which are targeted by anglers, to younger, smaller individuals, which are not targeted by the fishing gear to the same degree. The ISAMR does support multiple selectivity curves, which can be used to model changes in fisher behavior over time, however this application was not found to be necessary (see Challenger et al. 2017). Instantaneous sampling rates for each region were modelled as a linear function of the number of angling boat trips to each region in each year (see Table 1), with separate coefficients estimated for each region. This formulation was the same as Challenger et al. (2017), except with updated boat trip data.

Markov Chain Monte Carlo (MCMC) was used to sample from the posterior distribution using the Metropolis-Hastings algorithm to generate and accept parameter proposals. Trace plots were used to assess convergence of MCMC chain. A total of 10 million posterior samples were taken after a burn-in of 50,000. The complexity of the model necessitated thinning the MCMC chain to every 900th proposal to remove autocorrelation in the derived abundance metrics. This resulted in 10,000 retained posterior samples.

RESULTS AND DISCUSSION

Estimates of select ISAMR output include mortality, recruitment (historical and assessment period), yearly regional sampling rates, selectivity-at-age, and movement probabilities (Figure 2). Results are broadly similar to previous analyses by Challenger et al. (2017) with lower mortality rates for older age classes, close-to-complete gear selectivity for sturgeon of age 12 and older, and substantial declines in recruitment to the sampled population within the assessment period. As indicated in prior analyses, sturgeon also showed a tendency to remain within a given sampling region, with higher fidelity for sampling regions further away from the river mouth (Figure 2d).
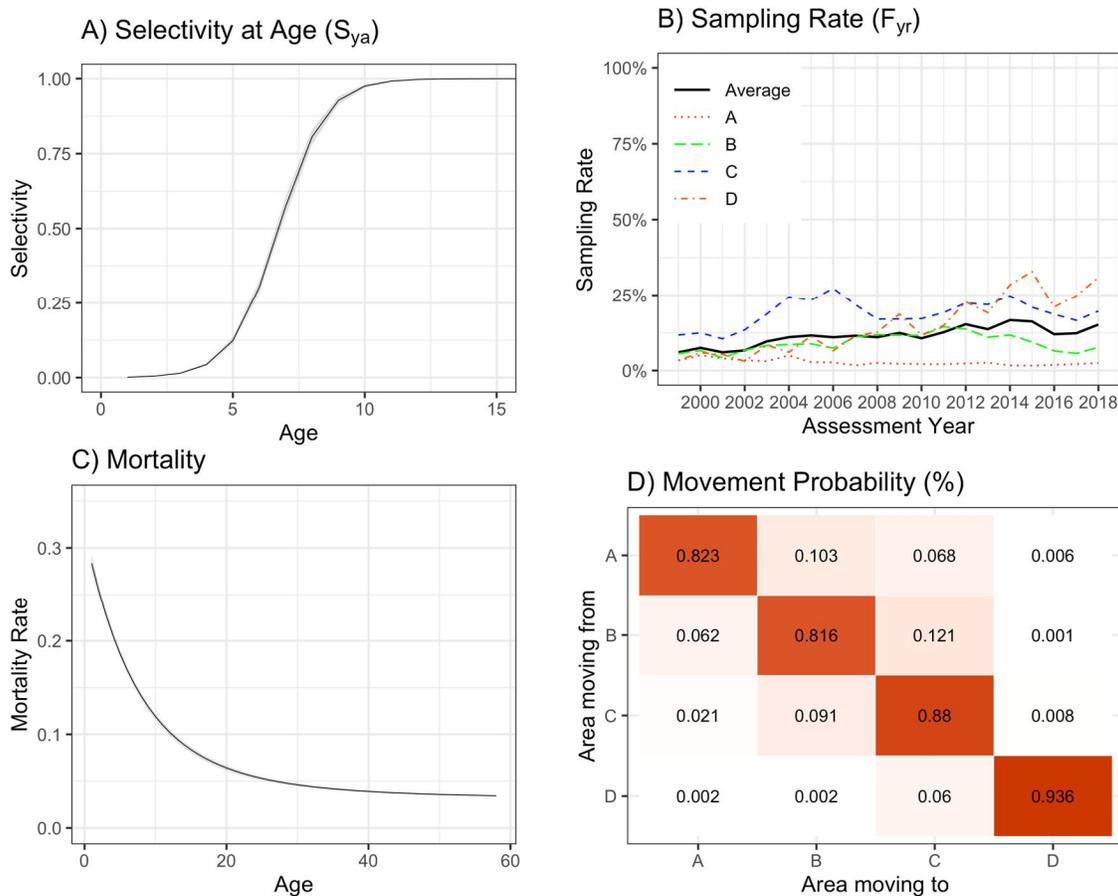

Figure 2. **Select ISAMR model output including: A) selectivity-at-age; B) regional sampling rates; C) estimated mortality rate; and D) regional movement probabilities.** Shading indicates 95% credible intervals.

Abundance estimates for the population exposed to sampling were broken down into recruitment into age-7 (Figure 3), as well as for subsequent age class groupings (Figure 4). Age-7 was used as an indicator for juvenile recruitment due to this age class being roughly 50% selected into the fishery (Figure 2a), and thus estimates are well supported by observed catch data. Historical age-7 recruitment showed a steady increase from 1980 up to an estimated peak of 8,499 individuals (95% CI: 7,311, 9,829) that occurred at the start of the assessment period in 2001 (Figure 3). After the 2001 peak, age-7 abundances began a steady and precipitous decline until leveling-off at an estimated abundance of under 2,000 individuals from 2012-2015, the lowest level of estimated age-7 abundances within the study period. Following this low point, there have been some modest signs of improvement over the last four years (i.e., 2016-2019) although uncertainty is higher than estimates earlier in the time series, with a mean abundance estimate for 2019 of 2,727 (95% CI: 1,943, 3,711).

Estimates of younger age classes are possible, but less observed catch occurs in these younger age categories, requiring a stronger reliance on the mortality curve extrapolation (Figure 2c), a parametric curve estimated based on catch and mark-recapture histories from older age classes (i.e., age 7-55) where the majority of catch occurs (i.e., higher selectivity; Figure 2a). As such, only age-7 and older abundances were reported, as this was the first age class to be at least 50%
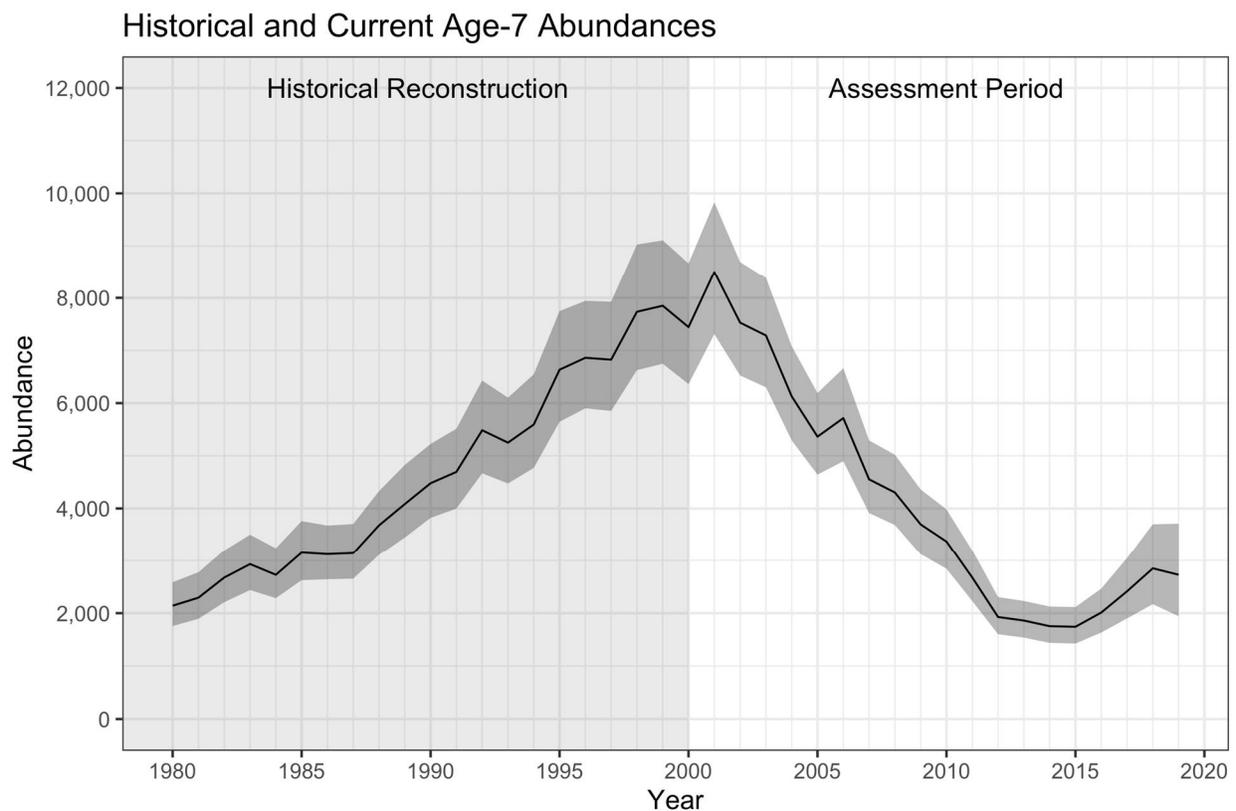
Figure 3.   Estimated age-7 abundances prior to and during the assessment period with 95% credible intervals (dark grey shading). Light grey shaded region indicates historical estimates.
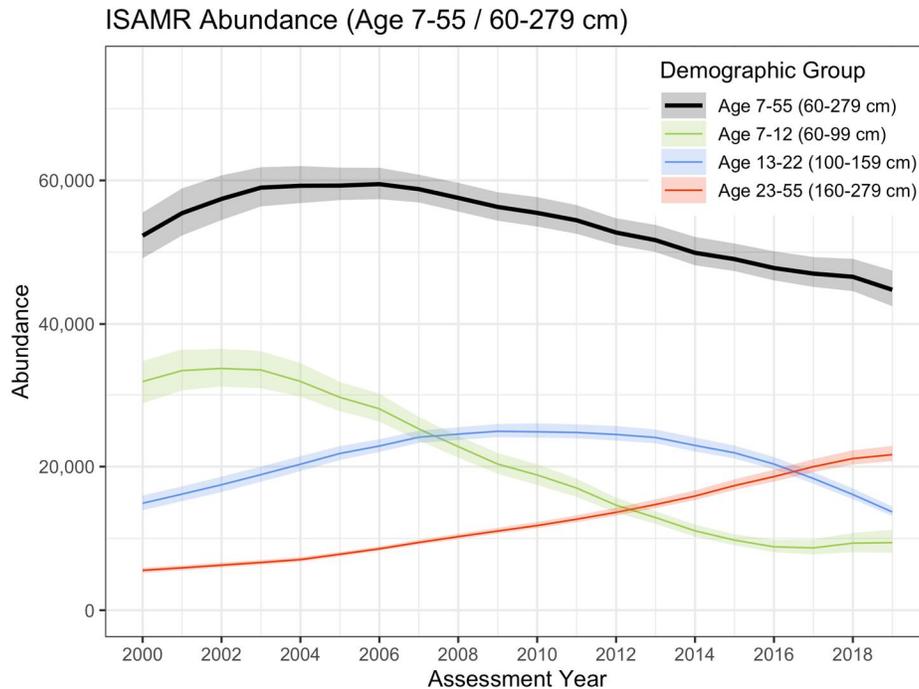
Figure 4. **Abundance estimates of age 7-55 (60-279 cm FL) Lower Fraser River White Sturgeon from 2000 to 2019.** Shading indicates 95% credible intervals.

selected into the fishery (Figure 2a). Thus, age-7 represents an evidence-based measure of effective juvenile recruitment, that may, or may not, be a reliable indicator of the temporal pattern of recruitment into younger age classes. The reduction in estimated recruitment levels could be the result of reductions of any component from egg production through to hatching and emergence as well as survival from of free swimming larvae through to exogenous feeding and subsequent survival into older age classes prior to age-7. As such, care should be taken when interpreting temporal patterns in age-7 abundance as a direct indicator of temporal patterns in egg production or abundance levels in younger age categories.

While these estimates are not exact reconstructions, they should reflect general trends in age-specific abundances. Estimates of abundance for age 7-55 (60-279 cm FL) were presented for 2000-2019 (Table 2), with an illustration of these estimates shown in Figure 4. These are estimates of all sturgeon age 7-55 (60-279 cm FL) that used the core assessment area during the study period. That said, within a given year, individual sturgeon may have temporarily been outside the core assessment area due to emigration which is typically short lived (Robichaud et al. 2017). As such, abundance estimates represent the population of sturgeon using the lower Fraser River at some point during the sport angling season, which covers the majority of the calendar year.

Table 2.   Abundance estimates of age 7-55 (60-279 cm FL) Lower Fraser River White Sturgeon from 2000 to 2019.

Year	Abundance Estimate	95% CI[1]		Bounds as % of Abundance Estimate	CV (%)[2]	Annual % Change
		Low	High			
2000	52,292	49,884	54,841	4.7%	2.5%	
2001	55,426	53,058	57,926	4.4%	2.2%	6.0%
2002	57,440	55,159	59,860	4.1%	2.1%	3.6%
2003	59,023	56,856	61,276	3.7%	1.9%	2.8%
2004	59,296	57,342	61,392	3.4%	1.7%	0.5%
2005	59,312	57,583	61,146	3.0%	1.5%	0.0%
2006	59,518	57,878	61,208	2.8%	1.4%	0.3%
2007	58,822	57,320	60,405	2.6%	1.4%	-1.2%
2008	57,607	56,136	59,230	2.7%	1.4%	-2.1%
2009	56,350	54,893	57,981	2.7%	1.4%	-2.2%
2010	55,513	54,050	57,142	2.8%	1.4%	-1.5%
2011	54,477	53,034	56,099	2.8%	1.5%	-1.9%
2012	52,764	51,383	54,365	2.8%	1.5%	-3.1%
2013	51,714	50,349	53,346	2.9%	1.5%	-2.0%
2014	49,961	48,597	51,617	3.0%	1.5%	-3.4%
2015	49,079	47,718	50,752	3.1%	1.6%	-1.8%
2016	47,845	46,439	49,530	3.2%	1.6%	-2.5%
2017	47,071	45,566	48,801	3.4%	1.8%	-1.6%
2018	46,625	45,002	48,493	3.7%	1.9%	-0.9%
2019	44,809	43,065	46,832	4.2%	2.2%	-3.9%

[1] CI – Credible Interval
[2] CV – Coefficient of Variation

Overall, abundance trends include:
1. the increase in adult abundances (age 22-55, 160-279 cm FL) since 2000;
2. the decrease in subadults (age 13-22, 100-159 cm FL) since 2012 (including a 43.1% decline over the six years since 2013); and
3. a steady decline in age 7-12 juveniles (60-99 cm FL) from 2002 to 2016 (Figure 4; including a 70.5% decline over the 15 years since 2004).

These three patterns are indicative of a strong historical recruitment pulse (e.g., the peak in age-7 abundance; Figure 3), followed by a reduction of recruitment into the juvenile age category. This reduced replenishment of juvenile sturgeon resulted in the estimated decline of age 7-12 (60-99 cm FL) juvenile sturgeon starting in 2003, which subsequently resulted in a decline of age 13-22 (100-159 cm FL) subadult sturgeon that commenced later in 2011 (Figure 4). Both demographic groups showed the same general temporal pattern as age-7 recruitment, but were right-shifted and slightly more spread-out (Figure 4).

Recently, estimated age-7 recruitment has shown signs of stabilizing with possible improvements since 2012 although uncertainty is higher in this portion of the time series (i.e., Figure 3). Depending on the duration the potential stabilization in age-7 recruitment, it should first stabilize estimated abundances in the age 7-12 demographic, followed by the subadult age 13-22 demographic (i.e., age 13-22; 100-159 cm FL). Currently, the juvenile category is showing signs of stabilization, while the subadult category is estimated to be in a state of decline as the majority of the abundance in this demographic are from the 2002-2012 age-7 cohorts, which exhibited a steady year-over-year decline (Figure 3). The mature adult size class (i.e., age 22-55; 160-279 cm FL) has increased in abundance over the last 2 decades, due to the earlier age-7 recruitment pulse, however this trend is expected to reverse once cohorts with lower estimated abundances start to take over this category, and individuals currently in this category either age out (i.e., older than age 55) or die. This peak is expected to occur soon, as most cohorts from the earlier age-7 recruitment pulse (Figure 3) should enter this category in the coming years. We explore the implications of this further in the forecast section below.

Finally, abundance estimates showed a high level of precision, which is due largely in part to the large sample size as well as the high percentage of the adult population that is estimated to have already been marked (Figure 5). Older age classes (i.e., age 13 and older) show the highest level of marking, with marking rates progressively dropping for younger age groups. This is not unexpected, as larger individuals are typically targeted by sport fishers, furthermore older individuals have also been exposed to the marking program for a longer period of time than younger individuals. Interestingly, the group with intermediate selectivity (i.e., ages 7-12) showed a decline in the percent marked in the last two years of the assessment period, while older groups showed a general increase with some signs of leveling-off. This may be partly the result of recent moderate increases in age-7 recruitment (Figure 3), but may also be indicative of a shift in size classes targeted by fishers and implies that future analyses may need to fit a separate selectivity- at-age curve for more-recent assessment years. Finally, the youngest age class group (age 2-6) shows constant low selectivity levels associated with the low catch rates, illustrating the limited information available for these younger ages. Sampling programs using angling techniques targeting these smaller sturgeon could be included in the ISAMR model by fitting a separate selectivity curve for differing catch methodologies. Expansion of the Monitoring and Assessment Program to include a juvenile sampling program would allow for the reliable estimation of recruitment to age classes prior to age-7, and could provide a quicker turn-around for assessing changes in recruitment.

The inclusion of age structuring in the ISMAR model also makes forward abundance projections possible by combining age-specific abundance estimates with estimated age-specific mortality rates and future recruitment (i.e., age-7 recruitment) scenarios. Population abundances were forecast from 2020 through to 2070 under a scenario where the average age-7 recruitment levels (i.e., 2014-2019) were maintained (Figure 6). This scenario was then compared to scenarios where recruitment was increased by 1.6 times and 2.4 times that of current recruitment, in order to determine the effect of improved recruitment on the population size (Figure 7). No evaluations were made under the scenarios of further recruitment decline.
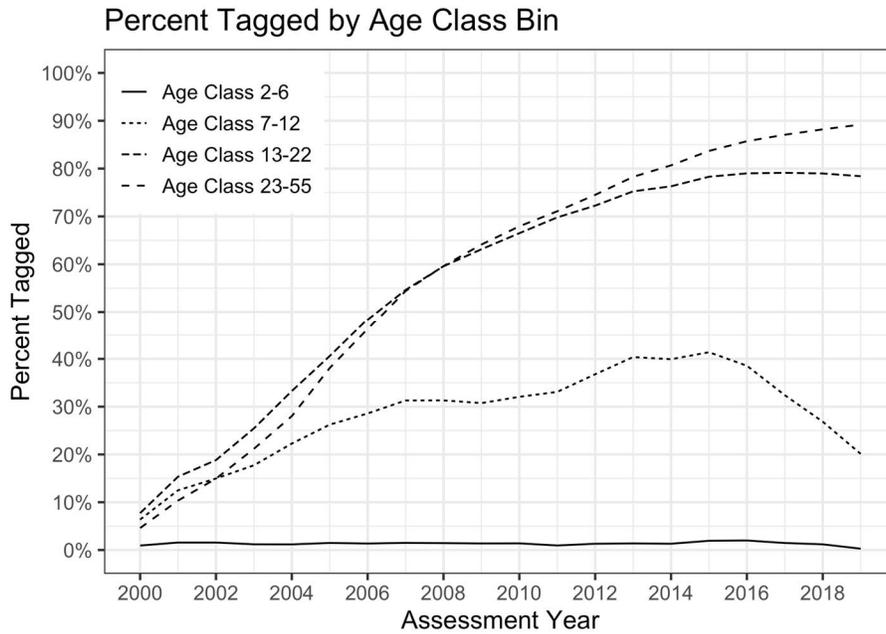
Percent Tagged by Age Class Bin

Figure 5. **Estimated percent of the population tagged, by age class bin and assessment year.**
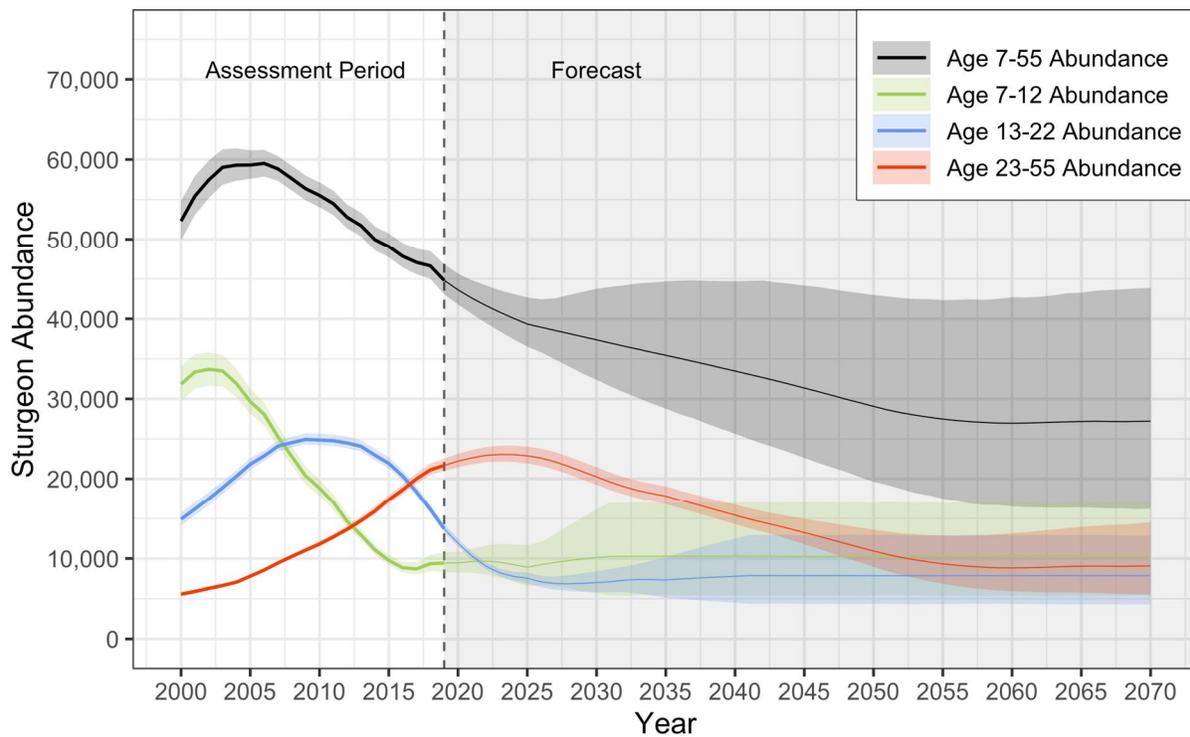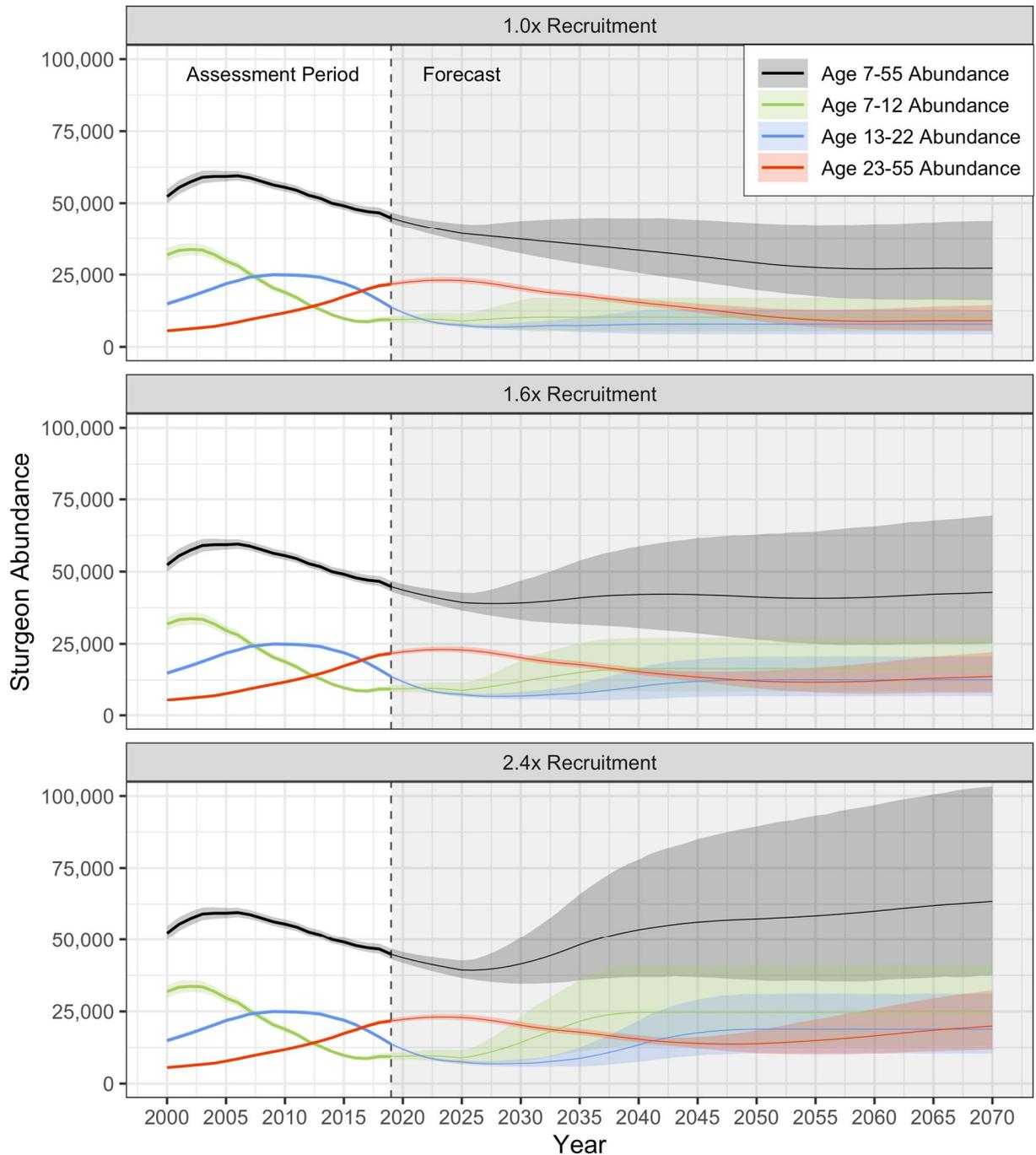

Figure 6. **Abundance estimates for Lower Fraser River White Sturgeon for 2000-2019, and abundance projections for 2020-2070 (assuming that annual age-7 recruitment remains the same as recent estimates, e.g., 2012-2019 recruitment).** Background grey shading indicates projected years.

Figure 7.   Abundance projections for Lower Fraser River White Sturgeon for 2020-2070 assuming that annual age-7 recruitment under three recruitment scenarios. The "1.0x Recruitment" scenario (top panel) assumes a recruitment state the same as recent (i.e., 2014-2019) recruitment estimates [the top panel is the same as Figure 6, but with Y axis scaled to match other two panels]. The "1.6x Recruitment" (middle panel) and "2.4x Recruitment" (bottom panel) scenarios assume future age-7 recruitment will be 1.6 times and 2.4 times as high as recent recruitment, respectively. Background grey shading indicates projected years.

Forecasts were generated based on the posterior distribution of age-specific abundances and mortality rates, along with the recruitment scenario under consideration. Each posterior sample contained a unique set of age-specific abundances and age-specific mortalities, which were projected forward based on a sample-specific average recruitment value with a year-to-year variation drawn from a normal distribution. The unique average recruitment value assigned to each posterior sample was drawn from the posterior distribution of age-7 recruitment over the last 10 years (mean: 8,889, sd: 2,541). Year-to-year variation in the forecasted recruitment was based on the year-to-year variability in the posterior average of age-7 recruitment over the last 10 years (i.e., an estimate of process error; sd: 2,364). In all scenarios a period of 10 years was used to transition recruitment from current levels (i.e., the sample specific average recruitment value) to the recruitment scenario level (e.g., 1.6 times). This procedure created a posterior predictive distribution of age-specific abundances up to 2070 for each recruitment scenario.

Under the maintained scenario (i.e., "1.0x Recruitment"), total abundance for age 7-55 (60-279 cm FL) sturgeon would be expected to continue to decline over the next 40 years (i.e., until the 2060s), before leveling off at approximately half the abundance level (i.e., approximately 27,000 [95% CI: 16,000, 43,500]) estimated at the start of the assessment period (i.e., early 2000s; Figure 6). Within the forecasted period, juvenile sturgeon (age 7-12; 60-99 cm FL) would continue to remain stable at the current levels of approximately 10,300 individuals (95% CI: 5,400, 17,000) per year. This would result in a continued decline of subadults (age 13-22; 100-159 cm FL) until 2025, followed by a stabilization at approximately one third of the 2010 abundance (i.e., approximately 7,900 [95% CI: 4,300, 12,900]). Abundances of adult sturgeon (age 23-55; 160-279 cm FL) would peak by the early 2020s (i.e., approximately 23,000 [95% CI: 22,100, 24,100]), followed by a gradual decline through 2060, after which it would be expected to stabilize at less than half of the anticipated peak (i.e., approximately 9,000 [95% CI: 5,700, 14,200]). The rate of decline for this group is slower than other groups due to the higher number of age classes (33 ages) included in this grouping (as compared to six ages for juveniles and 10 ages for subadults).

Under the "1.6x Recruitment" scenario, total abundance of age 7-55 (60-279 cm FL) would decline for several years and stabilize by the mid-2040s at an abundance close to current population levels (i.e., approximately 41,000 [95% CI: 26,200, 63,100]), which is approximately 70% of the peak abundance estimated in the early 2000s (Figure 7, middle panel). Under this scenario, juvenile sturgeon (age 7-12; 60-99 cm FL) would, by definition, stabilize at abundance levels 1.6 times higher than current levels (approximately 16,400 [95% CI: 8,600, 27,100]). Age 13-22 (100-159 cm FL) sturgeon were also forecasted to decline until the late 2020s, but with abundances stabilizing twenty years later (i.e., late 2040s) at approximately 1.6 times higher than under the "1.0x Recruitment" scenario (i.e., approximately 12,500 [95% CI: 6,900, 20,600]). Similar to the "1.0x Recruitment" scenario, adult sturgeon (age 23-55; 160-279 cm FL) would achieve peak abundance by mid 2020s, followed by a decline, but abundances would stabilize a little later, by the mid-to-late 2060s, at approximately 1.6 times the current abundance for adult sturgeon.

Under the "2.4x Recruitment" scenario, total abundance of age 7-55 (60-279 cm FL) sturgeon would still continue to decline for several years, until the mid 2020s, before the cohorts from the improved recruitment years reach age-7 (Figure 7, bottom panel), and the age 7-55 population begins to increase through to 2070, when abundances are predicted to reach the 2003 peak (i.e.,

approximately 63,400 [95% CI: 37,400, 103,300]). Juvenile sturgeon (age 7-12; 60-99 cm FL), and subadult sturgeon (age 13-22; 100-159 cm FL) would be expected to stabilize by the early 2040s and 2050s respectively at abundance levels approximately 2.4 times those under the "1.0x Recruitment" scenario. Adult sturgeon (age 23-55; 160-279 cm FL) would still be expected to peak by the mid 2020s, decline, then start to increase by the mid 2040s and continue to increase through 2070 to an abundance level approximately 86% of the 2020s peak. It should be noted that in these projections, the window required for stabilization for most demographic groupings were protracted due to the long-lived nature of sturgeon.

Challenger et al. (2017) suggested that a potential recovery target of 60,000 individuals in the 60-279 cm size class (age 7-55), which represents the population size estimated from 2003 to 2006. An additional target of 20,000 adult sturgeon (age 22-55) has also been suggested (Challenger et al. 2017, Nelson et al. 2018), which represents the anticipated peak abundances forecasted for the mid 2020s. None of these targets have been ratified by a formal assessment process, but are considered herein as an exploratory exercise. Under the status quo scenario (i.e., "1.0x Recruitment") and the "1.6x Recruitment" scenario, neither interim recovery targets are sustained. Only under the "2.4x Recruitment" scenario can either of these targets be achieved and sustained, suggesting that substantial increases in juvenile recruitment would be required to approach or meet these proposed targets. Given the long-lived nature of White Sturgeon, it will take a considerable amount of time to achieve these targets. Furthermore, these forecasts only considered general improvements in recruitment; they did not explicitly consider the relative effectiveness of potential mechanisms, such as improving early survival (e.g., decreased bycatch), or improving reproductive success (e.g., spawning habitat restoration, increased fecundity). Rather, the purpose for these forecasts was to show the magnitude of improvement in recruitment required to reach a proposed target.

As in previous reports, we emphasize the importance of taking immediate actions to improve both recruitment and survival rates of juvenile fish. Forecasts assumed a lag of only 10 years before recruitment improvements would be observed in the monitored component of the population. Delays to action will push recovery timelines out even farther than was modelled. Moving forward, the ISAMR model should continue to be used to evaluate efficacy of various strategies toward achieving approved goals and should also continue to be used within the Monitoring and Assessment Program in general.

The ISAMR model represents a fairly recent addition to the Lower Fraser River White Sturgeon Monitoring and Assessment Program, and as such estimates were also compared to those derived from the BMR24 model, the historical assessment model used within the program. Abundance estimates can be sensitive to capture probability estimates, which can be affected by gear selectivity. For example, smaller fish are often less targeted by sports anglers relative to larger fish. If allowances are not made, this can bias abundance estimates. While the BMR24 does not explicitly model gear selectivity, it does restrict the analysis to size groups that are readily caught by the primary sampling method (sports angling). By contrast, the ISAMR model directly estimates gear selectivity, which could alter abundance estimates for smaller fish not fully selected into the fishery, relative to the BMR24 model. As such, the ISAMR abundance estimates were presented in two forms: 1) the "adjusted" estimate back-adjusts abundance for gear selectivity in order to better match BMR24 assumptions (Figure 8a; see Challenger et al. 2017 for a full description); and 2) the "unadjusted" estimates (Figure 8b). The unadjusted

ISAMR abundances are expected to be higher for younger ages and smaller size groups where catch is more likely to be affected by gear selectivity.

As reported previously, both models showed similar abundance estimates and trends in abundance across size/age groups (Figure 8) and four sampling regions (Figure 9; note that only adjusted ISAMR abundances are presented). Both models showed the same general trends in
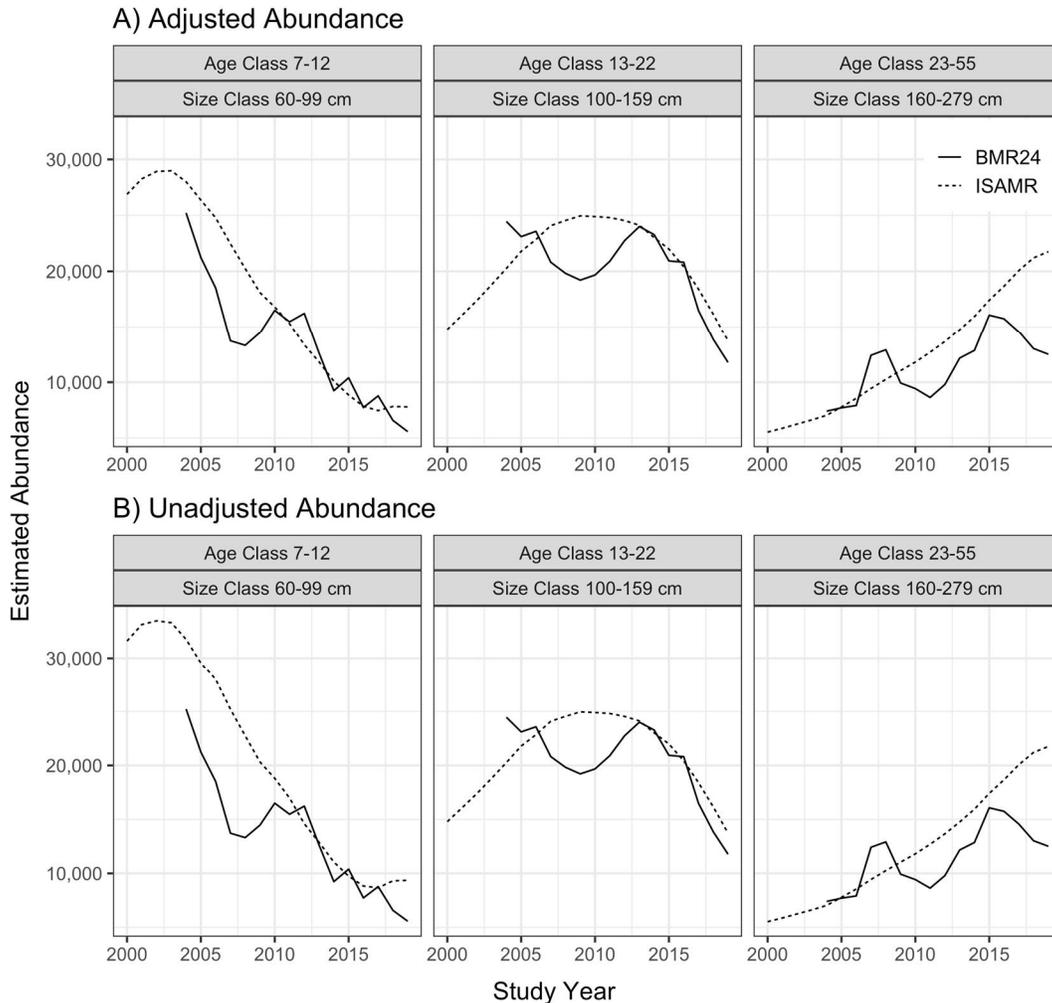
Figure 8. **Comparison of assessment area BMR24 and ISAMR abundances for size groups with gear selectivity differences for A) adjusted ISAMR abundances and B) unadjusted ISAMR abundances.** Size groups (see Nelson et al. 2020) affected by gear selectivity differences are located in the left-side panels, while groups largely unaffected by gear selectivity differences are located in the middle and right-side panels. Adjusted ISAMR abundance modelling removes the effect of age-specific selectivity for comparison with the BMR24 estimates. Unadjusted ISAMR abundance modelling includes gear selectivity differences, and thus results are larger than the adjusted ISAMR estimates for age 7-12 sturgeon which are not fully recruited into the fishery.
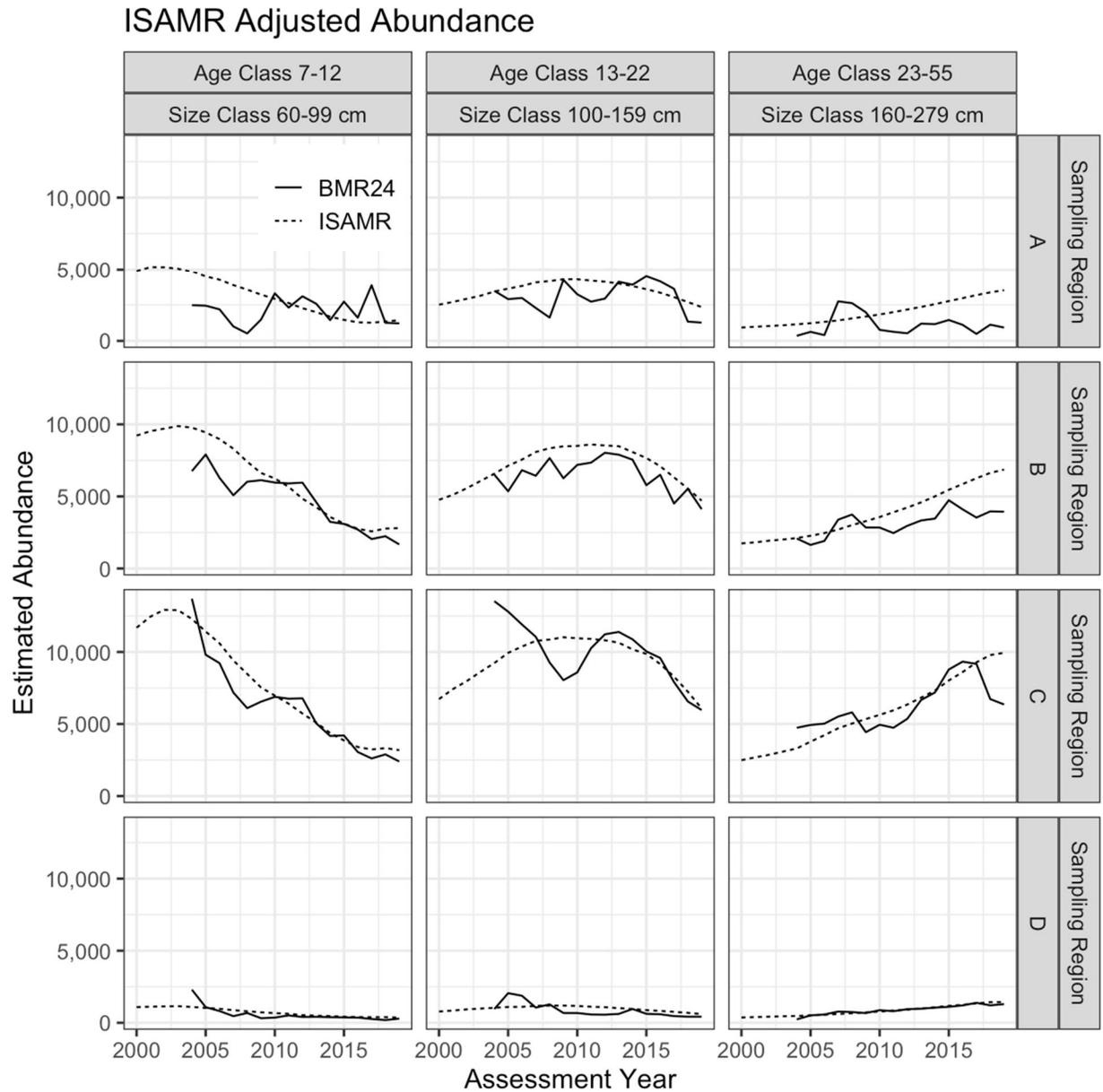
Figure 9. **Comparison of assessment area BMR24 and adjusted ISAMR abundances across the four sampling regions.** Size groups (see Nelson et al. 2020) were matched to age classes based on the length-at-age equation (see English and Bychkov 2002). Adjusted ISAMR abundance modelling removes the effect of age-specific selectivity for comparison with the BMR24 estimates.

abundances for juveniles (i.e., 60-99cm FL; age 7-12), subadults (i.e., 100-159 cm FL; age 13-22) throughout the assessment period and for most of the assessment period for adults (i.e., 100-159 cm FL; age 23-55).

Absolute abundance estimates for juveniles (i.e., 60-99cm FL; age 7-12) differed depending whether ISAMR estimates were adjusted to remove the effect of the selectivity corrections (Figure 8a versus Figure 8b, leftmost panels). Back-adjusting estimates resulted in lower ISAMR abundance estimates, and a closer match between the BMR24 estimates in this age group and the unadjusted ISAMR estimates (inclusion of the selectivity curve inflates abundance estimates in the younger age classes for the relatively lower catchability experienced by these individuals; Figure 2a). While selectivity did affect absolute scaling of the abundance estimates, both models showed a similar precipitous decline in estimated juvenile abundances throughout the assessment period.

Abundance estimates for the subadults (i.e., 100-159 cm FL; age 13-22) showed no difference between the adjusted and unadjusted ISAMR abundance estimates, which was consistent with the high selectivity estimated for these ages. Estimates from both models were also very similar in both trends and absolute abundances since 2013 (middle panels, Figure 8), with both estimating a sharp abundance decline in recent years (i.e., 2013-2019). That said, subadult estimates did show substantive differences from 2006-2011. The precise reason for these differences is unknown, but there is interest in determining whether 10-20% of Lower Fraser sturgeon in this size/age category could have left the lower Fraser River core assessment area during these years. In recent years, there appears to have been a higher number of 150-180 cm sturgeon recaptures that have not been detected for more than 10 years after their initial release as subadult fish, which could lend some support to this temporary emigration hypothesis.

Mature adults (i.e., 160-279 cm FL; age 23-55 adults) also showed a general agreement between the two models from 2002-2015. There is no difference between adjusted and unadjusted ISAMR abundance estimates, indicating that this size class is fully recruited into the sampling gear. While there was general agreement prior to 2016, estimates in recent years have featured a prominent deviation. The BMR24 abundance estimates suggest a notable decline, while ISAMR abundance estimates show an increase (rightmost panels, Figure 8). This divergence is prominent enough that it accounts for approximately 67% of the total difference in the 60-279 cm FL (age 7-55) abundance estimates between the two models since 2015. The differences in abundance estimates generated by the two models prompted additional data reviews and analysis of the 2000-2018 data by Nelson et al (2019), where it was determined that the BMR24 model was also more sensitive to recent changes in the distribution of tagging and sampling effort than the ISAMR model, and concluded that the best estimates of abundance for 60-279 cm Lower Fraser White Sturgeon are those derived using the ISAMR model.

While this prominent deviation accounts for most of the difference between the two models, the BMR24 abundance estimates also showed higher year-to-year variability for the adult size group than the ISAMR abundance estimates. Demographically, large year-to-year changes in mature sturgeon are unlikely, especially as the same pattern is not observed in younger demographic groupings. As such, the divergence may also be the result of other forms of sampling error, in which case estimates may come back into closer agreement at a later point in time (e.g., subadults from 2007-2013 showed a similar deviation, middle panels, Figure 8). Strictly speaking, a large year-to-year variability in mature adults could only be demographically feasible if there were sequential periods where there was a consistent bout of either immigration or emigration from the core assessment area (e.g., tributaries outside the mainstem). While telemetry studies do not generally provide support for this possibility (e.g., Robichaud et al.

2017), this consideration does highlight one of the largest differences between the two modelling approaches: the BMR24 model only considers 24 months of tagging data at any one point in time, while the ISAMR model considers the entire history of tagging data. If temporary emigration events in the population occur over a period greater than 24 months, then the BMR24 estimates could show more year-to-year variation than the ISAMR model, which uses the full time series and a cohort based demographic model to produce more stable age-specific estimates. As a result, each model has a different biological population of interest; the BMR24 model considers sturgeon that have used the lower Fraser River in the last 24 months, while the ISAMR model considers sturgeon that have used the lower Fraser River at any point during the entire assessment period.

When broken down by sampling region, most of differences between the two model estimates appear to occur in sampling regions A and B, which are the two sampling regions in closest proximity to the river mouth (Figure 9). In contrast, estimates in region D showed the strongest agreement and is the sampling region farthest from the river mouth. This again may reflect differences in sensitivity to temporary emigration between the two models. Given the general agreement between the models in regard to most abundance categories, and abundance trajectories, it is also possible that the deviation in mature sturgeon abundance estimates may be resolved in future analyses as additional years of data are collected.

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APPENDIX A
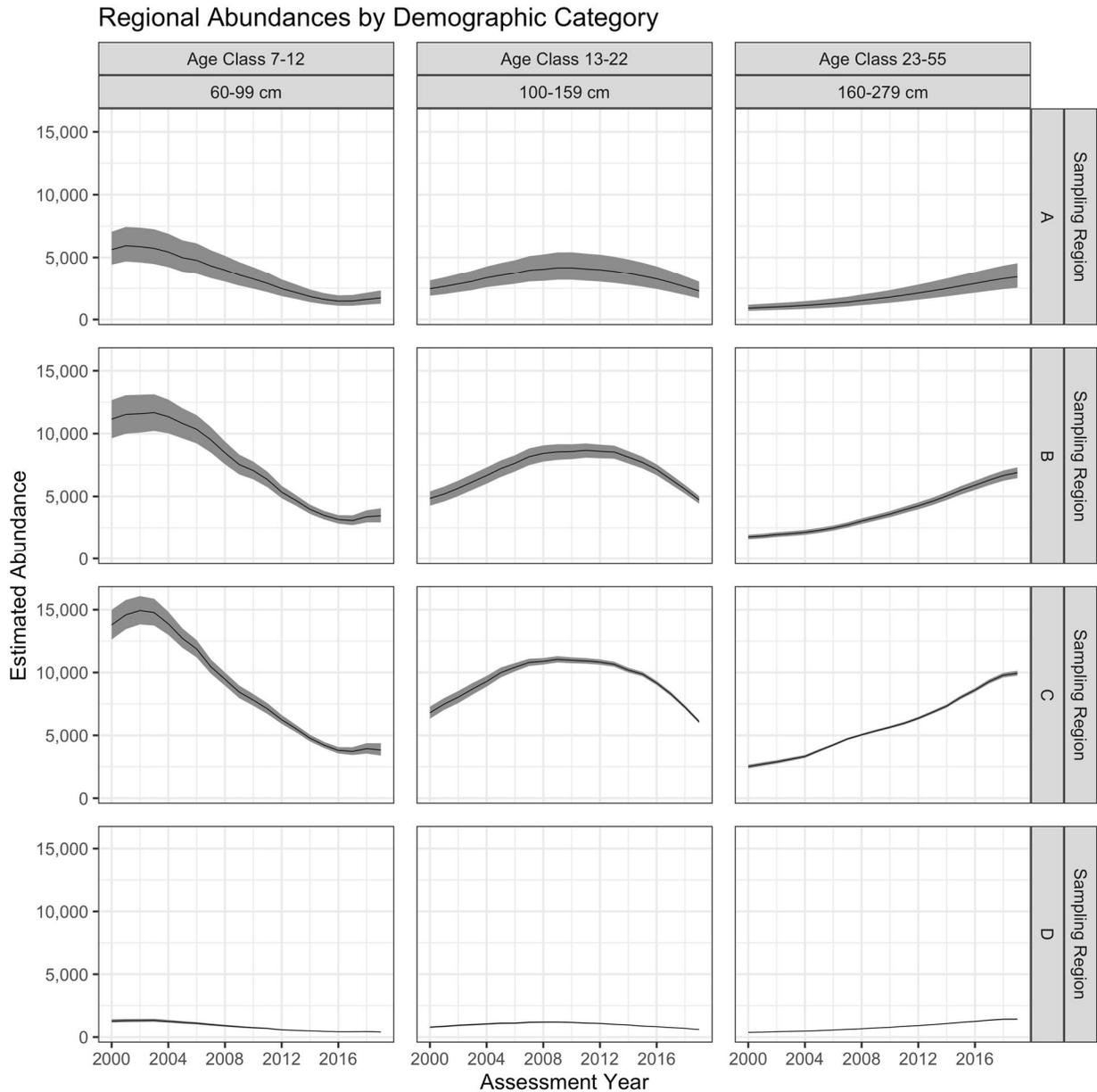
Figure A1. Estimates of region-specific abundances (sampling regions A, B, C, and D), broken down by age class for ages that are fully recruited into the fishery. Panel rows indicate sampling regions, while panel columns indicate size/age groups. Size groups are based predicted length-at-age growth model (RL&L 2000). Shaded region indicates 95% credible intervals.