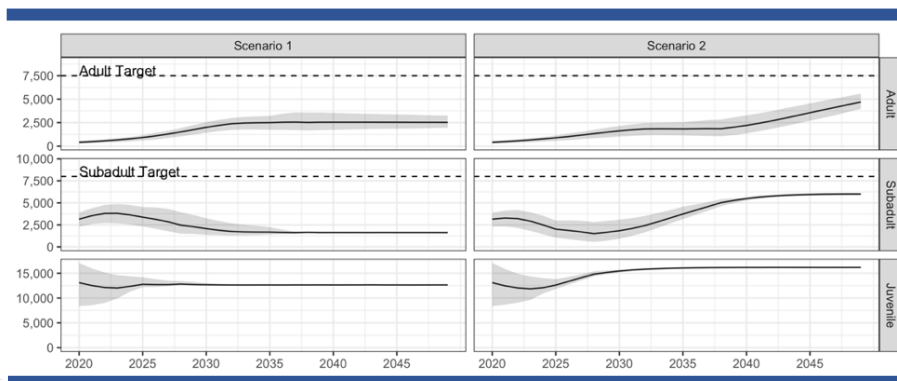


Upper Columbia Sturgeon Simulation Model

FINAL REPORT



Prepared for:

Confederated Tribes of the Colville Reservation, Nespalem, WA
and
FortisBC, Kelowna, BC

Prepared by:

Wendell Challenger¹, Yury Bychkov¹, and David Robichaud

Blue Leaf Environmental, Inc.

2060 Vantage Hwy, Suite 37
Ellensburg, WA



4 June 2021

¹ LGL Limited, 9768 Second Street, Sidney, BC, V8L 3Y8

Table of Contents

INTRODUCTION	1
WORKFLOW OVERVIEW	2
STEP 1: RUNNING THE MODEL	3
STEP 2: REVIEW RESULTS	3
STEP 3: COMPARE MODEL RUNS.....	4
MODEL RUNS	4
GENERAL SETTINGS	5
<i>Model Details</i>	5
<i>Simulation Parameters</i>	6
RESULT SUMMARIES.....	6
HATCHERY RELEASES	7
REMOVAL AND HARVEST PROGRAMS.....	8
<i>Defining Harvest/Removal Rules</i>	9
<i>Availability Warnings</i>	9
TARGETS AND TRIGGERS.....	10
MODEL RESULTS	10
WARNINGS.....	11
MANAGEMENT SUMMARIES	11
ABUNDANCE PLOTS.....	12
SIZE DISTRIBUTION PLOTS	12
COMPARING MODEL RUNS	16
EXAMPLE SCENARIO	18
MANAGEMENT PROGRAMS TAB	19
<i>Comparing Hatchery Release Programs</i>	19
<i>Comparing Harvest and Removal Programs</i>	19
<i>Harvest Slot Availability Warnings and Failures</i>	21
<i>Comparing Required Sampling Effort</i>	23
<i>Abundance Targets Tab</i>	24
COMPARING ABUNDANCES BY LIFE STAGE	25
COMPARING COUNTRY SPECIFIC ABUNDANCES	27
COMPARING TOTAL ABUNDANCES	27
HANDLING TAB	28
POPULATION MODEL FORMULATION	30
OVERVIEW OF POPULATION PROCESSES	31
POPULATION INITIALIZATION	32
GROWTH	36
HATCHERY RELEASES	36
HARVEST AND REMOVALS	36
NATURAL MORTALITY.....	37
MOVEMENTS AND ZONES.....	37
REFERENCES	41

List of Tables

Table 1.	List of zones included in the model.....	8
Table 2.	Summary of potential result item contained displayed on the [Results] tab or within the Excel file downloaded at the end of a simulation run.....	11
Table 3.	Movement probabilities: rows indicate release zone, while columns indicate probability of movement to each of the nine modelled zones	40
Table 4.	Movement probabilities estimated from Upper Columbia stock assessment.....	40

List of Figures

Figure 1.	Model operation flow diagram. User interface is generated by a Shiny application and is composed of three main steps.....	1
Figure 2.	Screenshot of the user interface with the three main interface steps indicated by arrows and the main model controls in the main panel.....	2
Figure 3.	Screen capture of the run completion notification window	4
Figure 4.	Screen capture of the General Settings controls	5
Figure 5.	Screen capture of the result summary control box	7
Figure 6.	Screen capture of the hatchery release program interface	7
Figure 7.	Screen capture of the Removal & Harvest Programs control box	9
Figure 8.	Screen capture of the Target & Triggers control box.....	10
Figure 9.	Example zonal size distribution pre- and post-harvest along with the size distribution of the harvest	13
Figure 10.	Example of handling summary plot for handling rates by removal/harvest program on both a yearly basis and cumulatively across simulated years, with abundances provided for reference.....	14
Figure 11.	Example abundance plot indicating life stage abundance.....	14
Figure 12.	Example of the size distribution summary result indicating size frequencies by year and zone for both hatchery and wild type sturgeon.....	15
Figure 13.	Simulation run comparison page	16
Figure 14.	Screen capture of the model comparison page of the UC Sturgeon application with two model run results files uploaded.....	17
Figure 15.	Screen capture of comparison results generated after running the comparison.....	17
Figure 16.	Screen capture of the targets and settings box	18
Figure 17.	Example output observed under the Management Programs results tab	20
Figure 18.	Hatchery comparison figure showing the scenarios under consideration as well an example scenario where the first model run with one country-specific release program and the second run with two country specific release programs in some years.....	20
Figure 19.	Summary of harvest and removal programs across simulation runs.....	21
Figure 20.	Example of availability warnings and availability failures	22

Figure 21. Summary of effort required to achieve a particular harvest or removal program within a given harvest slot 23

Figure 22. Example output observed under the Abundance Targets results tab 24

Figure 23. Life stage specific abundance plots summarize abundances..... 25

Figure 24. Summary of country specific abundances across simulation runs 26

Figure 25. Comparison of total abundance, and abundances broken down by type across the two example scenarios 27

Figure 26. Example output observed under the Handling results tab 28

Figure 27. Cumulative number of times an individual is handled, on average, by size class and by type..... 29

Figure 28. Cumulative number of times an individual is handled as a result of a harvest or removal program, by size class..... 30

Figure 29. Example of state data logged within the application..... 31

Figure 30. Major population processes modelled on each time step..... 32

Figure 31. Size frequencies for hatchery and wild type sturgeon derived from catch data in the Upper Columbia..... 33

Figure 32. Size specific angling selectivity curve for the Lower Fraser River White Sturgeon sport fishery 34

Figure 33. Observed hatchery size distribution, assumed size selectivity curve, and resulting corrected hatchery size distribution used to initialize the hatchery population 35

Figure 34. Length at age and yearly growth derived from the Korman-Crossman growth analysis..... 35

Figure 35. Age-specific survival rates 38

Figure 36. Map indicated modelled zones 39

Introduction

The *Upper Columbia Sturgeon Simulator* is a management tool for determining probable population responses to various recovery and fishery actions. Underlying the tool is a spatial age-structured population model, which simulates the growth, aging, movement and survival of individual sturgeon within the Upper Columbia River. The model uses currently available stock assessment information to set the population starting point (age specific abundances by location), and then projects the population forward in time based on assumed demographic processes and management settings (i.e., hatchery releases, and removal or harvest programs). Stochastic demographic elements within the model allow it to generate a distribution of possible future population abundances, which are summarized as percentiles at the end of a simulation run.

The underlying model is implemented in the R computing environment (R Core Team 2021) through three custom R libraries, while the outward facing user interface (Figure 1) is generated using Shiny (Chang et al. 2021). Users have access to general simulation settings and management actions such as hatchery releases and harvest schedules when running simulations, while the remainder of the population information is loaded from a settings file. A large number of population settings are maintained within the settings file and are based on the best available stock assessment results. Setting files can be changed by application administrators but are not available to the general user.

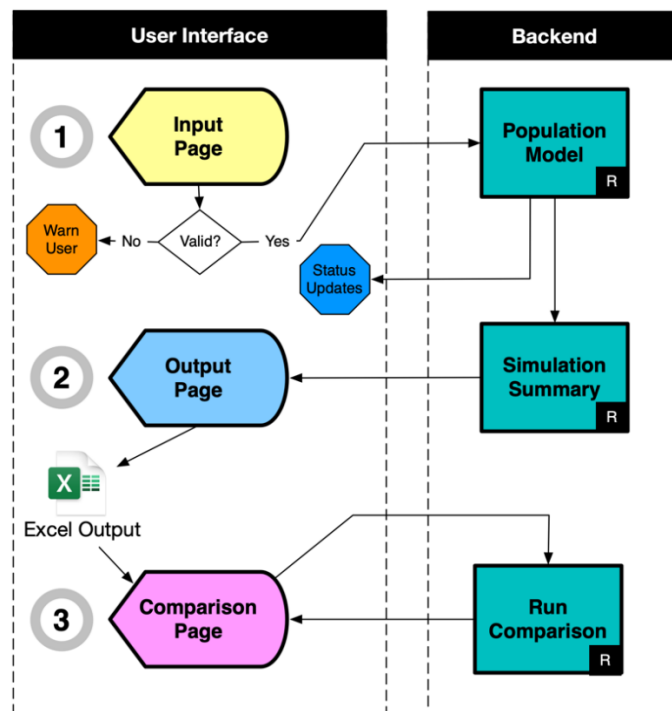


Figure 1. Model operation flow diagram. User interface is generated by a Shiny application and is composed of three main steps. Model computations are done in the backend using three custom R libraries.

Once a simulation has completed, an Excel results file is generated that can be downloaded and saved for future reference. Results from multiple simulation runs can be compared within the application, which generates a series of key summary plots that show population trajectories and management metrics under the different scenarios.

The remainder of this document is broken down into the following sections:

- **Workflow Overview:** General overview on how the model is used to test management questions.
- **Model Runs:** Specific guidance on how to run a population simulation.
- **Model Results:** Overview on the type of results provided and how to interpret them.
- **Comparing Model Runs:** Detailed overview on how to compare results from multiple runs in order to assess different management strategies.
- **Population Model Formulation:** Overview on how the underlying population model was formulated, including data and relationships used to simulate the Upper Columbia population.

Workflow Overview

The *Upper Columbia Sturgeon Simulator* was designed to be used in three main steps:

1. Model Runs;
2. Result Reviewing; and
3. Run Comparisons.

These are reflected by the left-hand side bar of the user interface (Figure 2), which contains links for each of those steps (“Model”, “Results”, and “Compare”). Normally the **[Results]** page

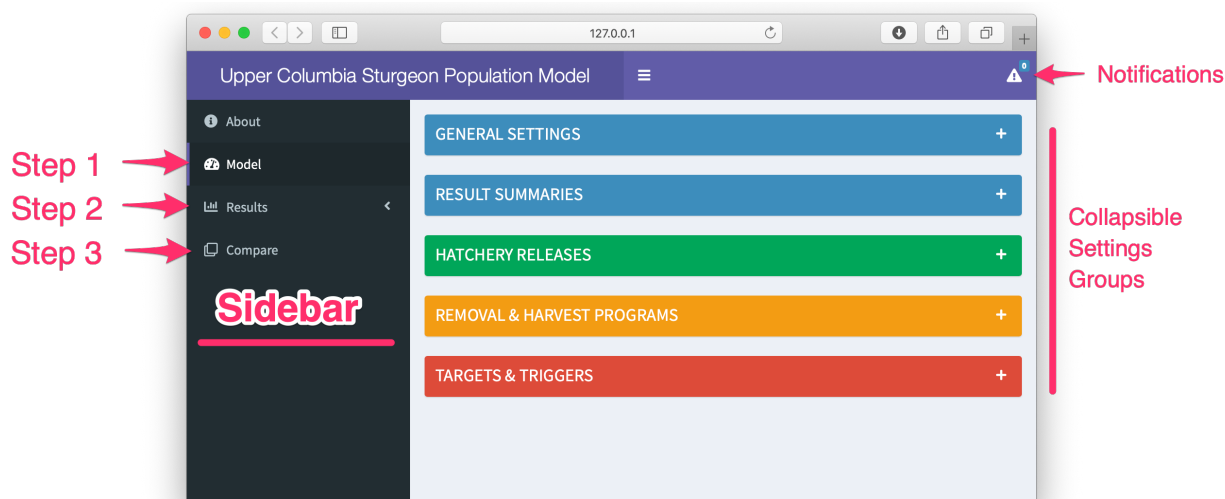


Figure 2. Screenshot of the user interface with the three main interface steps indicated by arrows and the main model controls in the main panel. Notifications dropdown is found in the top right. The interface currently shows the model run page.

remains blank until after a model run has completed. After a run has completed, the results are compiled and loaded in the **[Results]** page, and an Excel file is generated for offline viewing, allowing results to be retained for future reference. After multiple runs have been completed, the retained Excel files can be selected such that the different runs can be directly compared in the Compare page.

Step 1: Running the Model

The first step in using the *Upper Columbia Sturgeon Simulator* is to complete a model run. When the application is first loaded it should by default present the model run page. If this is not the case or you have navigated elsewhere within the application, you may return the model run page by clicking on the **[Model]** link in the left-hand sidebar (Figure 2). This brings up an interface which will contain five main setting boxes:

1. General Settings;
2. Results Summaries,
3. Hatchery Releases;
4. Removal & Harvest Programs; and
5. Targets & Triggers.

Each settings box contains a set of related user controls that allows the user to tweak and initiate a simulation run. Each box can be expanded or collapsed to allow users to quickly navigate throughout. Further details on the settings contained within each control box are summarized in the *Model Runs* chapter.

Step 2: Review Results

Once a simulation has finished running and generating results, the **[Results]** tab will become populated with figures and tables summarizing the model output. These results are also duplicated in the Excel file that can be downloaded from the run completion popup window (Figure 3) or by navigating back to the model run page (i.e., **[Model]** tab) and looking for the results download button which will be located near the “Run Model” button.

When users are satisfied with the settings used for a given model, they are then encouraged to make it more “official” by increasing the number of iterations in order to generate an improved estimate of uncertainty. Users are encouraged to carefully download and file away the Excel results files so they can be used in model run comparisons (i.e., the final workflow step).

A Note About the Excel Results File

The Excel files available for download after each successful model run are a key component of the *Upper Columbia Sturgeon Simulator*. Output files are made available once a simulation has completed and contain all the necessary settings to recreate the results of a simulation, and contain all the summary information required to make comparisons among simulation runs. Users should ensure important simulation runs are downloaded and saved in a safe location for future reference. This is especially true for the files that are created after long simulation runs, which can take considerable time to execute and may be tedious to have to recreate.

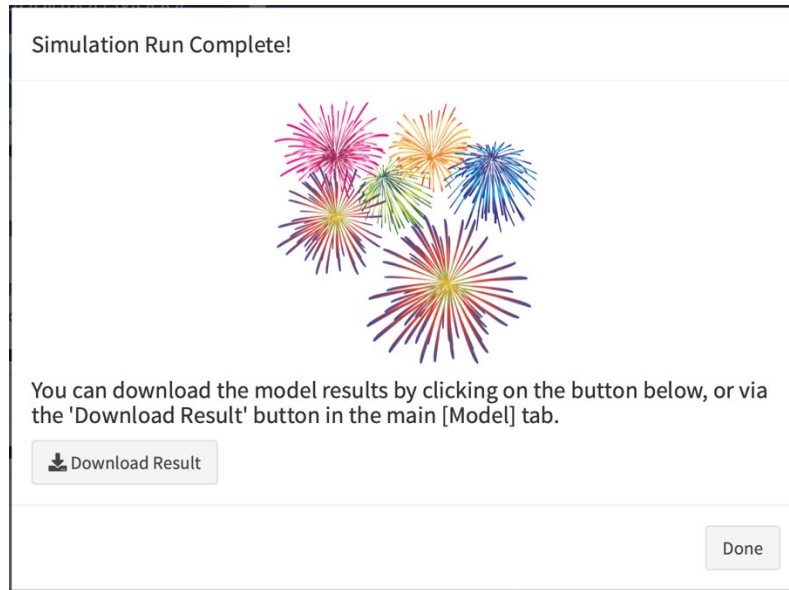


Figure 3. Screen capture of the run completion notification window.

Step 3: Compare Model Runs

The final step involves comparing the results from multiple model runs, which is done within the comparison application accessed under the **[Compare]** tab in the left-hand side bar. Here users are asked to upload the Excel results files from multiple runs. Users should ensure model runs have sensible 'run names' (see *Model Runs > General Settings*) when specifying a model run to ensure the correct files are being uploaded for comparison (but note that run names can be edited after the fact in the 'Settings' worksheet of an Excel output file).

Model Runs

In the main model run page (see Figure 2) there are five main groups of settings found in collapsible control boxes. These include:

1. General Settings;
2. Result Summaries;
3. Hatchery Releases;
4. Removal and Harvest Programs; and
5. Targets and Triggers.

In this interface, the user controls the number of years to simulate as well as management actions such as hatchery release schedules and harvesting. To speed up the execution of a simulation, users can reduce the number of simulation iterations (used to estimate uncertainty) as well as reduce the number of report summaries generated at the end of a simulation.

General Settings

The general settings control box (Figure 4) provides broad control over the simulation, such as the name and description, the number of years to simulate into the future and the number of times to repeat the simulation (i.e., iterations). The button to start the simulation itself is also found here along with the button to download the final results when ready.

Settings are broken down into two main sections:

1. Model Details; and
2. Simulation Parameters

Model Details

Model Details provides an avenue for naming of the simulation run (i.e., *run name*) as well as providing a short description of the purpose or settings used for the run (i.e., *run description*).

[Run Name] - is a short name describing the run that will be used to set subtitles in the result plots, as well as setting the panel titles in plots when comparing multiple runs. After a simulation run has completed, if you wish to change the run name before including it in the comparison application, this can be done by directly editing the 'Setting' worksheet in downloaded Excel results file.

[Run Description] - is a short description of the simulation run, which is a helpful reminder of goals or settings used in the run. The description is used to set plot captions in the main results plots.

The screenshot shows a software interface titled "GENERAL SETTINGS". It is divided into two main sections: "Model Details" and "Simulation Parameters".

Model Details:

- Instructions icon and a plus sign.
- Section title: "Model Details".
- Text: "Provide a name and description to be referenced in summary and comparison plots."
- Field: "Run Name" (text input).
- Field: "Description" (text area with placeholder: "Short description of goals and setting used in the trial.").

Simulation Parameters:

- Text: "Specify when the simulation should start and end. Random number seeds allow a simulation to be repeatable for a given set of conditions. The number of simulations (i.e., iterations) allow uncertainty to be estimated."
- Field: "Start year" (spin box, value: 2020).
- Field: "Random Seed" (spin box, value: 4069).
- Field: "Number of years to simulate" (spin box, value: 10).
- Field: "Number of simulations" (radio buttons: 1 (selected), 10, 50, 100, 250).
- Button: "Run Model".

Figure 4. Screen capture of the General Settings controls.

Simulation Parameters

Simulation parameters control the start of the simulation (i.e., *Start year*), the length of the simulation (i.e., *Number of years to simulate*), the number of simulation iterations to run (i.e., *Number of simulations*), and the repeatability of the simulation (i.e., *Random seed*).

[Start year] - the population is initialized based on a stock assessment that was performed at a particular point in time. The simulation is then run forward to the start year before applying the specified hatchery and harvest rules. To get the most accurate simulation possible, harvest and hatchery releases that occurred after the assessment year should be included. This may require setting the simulation start year close to the assessment year.

[Number of years to simulate] - indicates how many years to project the population forward in time. Longer time horizons require more computations and will take more time to execute.

[Number of simulations] - also known as simulation iterations, are the number of times a simulation should be repeated. Because the simulation includes stochastic components each iteration will produce slightly different results, the distribution of results are used to determine error bounds on projections. When testing out new settings it is recommended that a single simulation iteration is selected (default) in order to speed up execution. Once you are happy with your settings, run the simulation using more iterations in order to determine the error bounds.

[Random Seed] - the random number seed allows simulations to be repeatable for a given set of conditions (i.e., parameter settings). This can be useful when training new people to ensure they can reproduce results exactly.

Result Summaries

One of the most time-consuming steps in a simulation run is the result summary generation step, as such each result summary type can be turned on or off to speed up simulation execution (Figure 5). This can be useful when trialing settings as it can be more time efficient to only select the results that reflect main management goals, then re-run the simulations selecting the full suite once initial testing has been completed.

The most time-consuming result summaries are as follows:

- 1) Management Summaries;
- 2) Size Summaries; and
- 3) Abundance Plots.

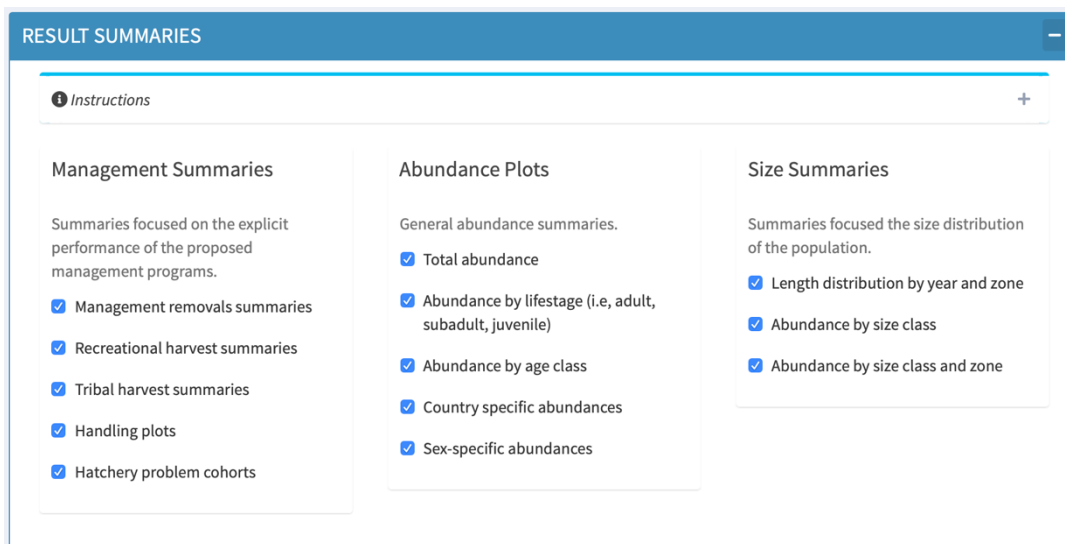


Figure 5. Screen capture of the result summary control box. All results summaries are selected by default when the application first loads.

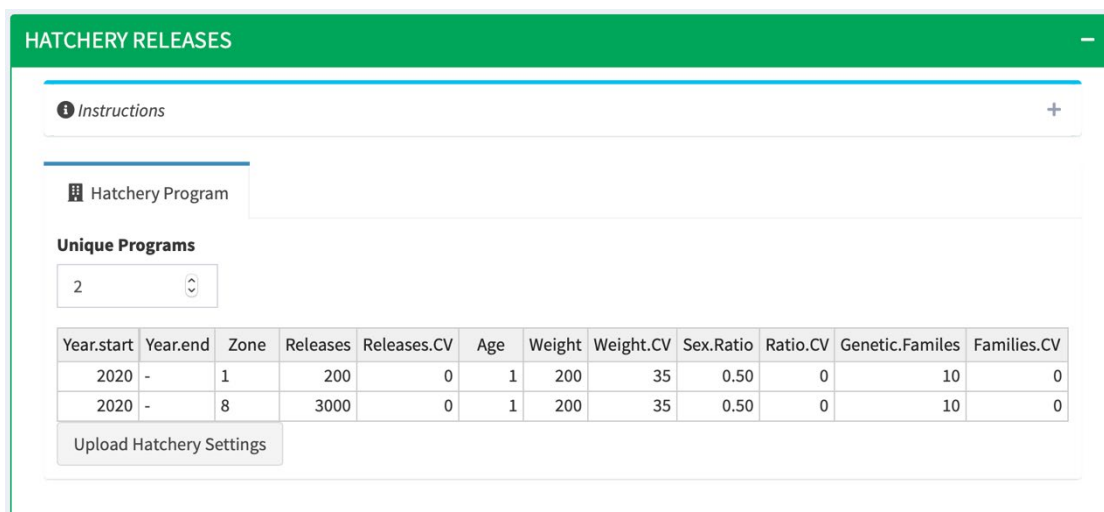


Figure 6. Screen capture of the hatchery release program interface.

Hatchery Releases

Hatchery releases are specified by defining one or more hatchery release programs in a table where each row indicates a unique program with start and end year over which the program applies (Figure 6). Hatchery releases are specified for a set of years defined by the start and end years (i.e., **[Year.start]** and **[Year.end]** respectively). For rules that are required to run until the end of a simulation simply leave the end year blank or use a '-' to indicate an open-end year. The application assumes the program will run to the end of the simulation unless a valid end year is specified.

The **[Zone]** column indicates which zones (Table 1) hatchery fish are released into. Zones can be indicated as a single (e.g., 1), as a range (e.g., 1-3), as a series (e.g., 1,3,6), or as a combination

Table 1. List of zones included in the model.

Zone	Country	Location	RKM	Lat	Long
1	Canada	Zone 1	1248.3	49.333009	-117.699169
2	Canada	Zone 2	1238.2	49.263141	-117.643794
3	Canada	Zone 3	1228.7	49.184784	-117.712475
4	Canada	Zone 4	1215	49.094062	-117.70104
5	Canada	Zone 5	1208	49.03988	-117.614636
6	US	Zone 6 (Border - Little Dalles)	1178.9	48.872421	-117.871112
7	US	Zone 7 (Little Dalles - Evans)	1149.4	48.69929	-118.019763
8	US	Zone 8 (Evans - Rickey Point)	1126.2	48.545245	-118.140024
9	US	Zone 9 (Rickey Point - Gifford Ferry)	1091.6	48.278095	-118.147637

of these approaches (e.g., 1,3-6,9). Zones 1-5 correspond to Canada, and zones 6-9 are in the United States.

The **[Releases]** column indicates the number of hatchery fish to release with **[Releases.CV]** indicating coefficient of variation (CV) in the release number. The CV should be specified as a percentage value (i.e., 0-100) where CV of '0' would indicate no variability in the number released and a CV of '50' would indicate that the standard deviation in release number is 50% of the specified the mean release number.

The **[Age]** and **[Weight]** columns indicate the target age and weight of released hatchery sturgeon. Age is specified in years and should be a whole number, while weights are specified in grams (g). The **[Weight.CV]** column indicates the variation in release weights, indicated as a percentage value (i.e., 0-100). The target weight is assumed to be a threshold weight thereby fish under this weight are not released.

Finally, the **[Sex.Ratio]** and **[Genetic.Families]** columns indicate the sex ratio of releases (0 = all female, 1 = all males) and the number of genetic families. The **[Ratio.CV]** and **[Families.CV]** columns indicate the corresponding coefficients of variation.

Removal and Harvest Programs

Removal or harvest programs are specified in the Removals & Harvest Program control box (Figure 7). Separate programs can be defined for management removals, recreational harvest, and tribal harvest, with the harvest or removal programs kept under a separate tab for each of the three types. Under each tab there will be a check box to enable or disable the program, a slider to set the threshold on the availability warnings, and a table to define the unique harvest program rules.

Year.start	Year.end	Zone	Length.min	Length.max	Type	Removals
2020	2025	6-9	96.00	180.00	hatchery	800
2021	2025	1-5	96.00	160.00	both	400

Figure 7. Screen capture of the Removal & Harvest Programs control box.

Defining Harvest/Removal Rules

Harvest rules are specified for a set of years defined by the start and end years (**[Year.start]** and **[Year.end]** respectively). For rules that are required to run until the end of a simulation simply leave the end year blank or by using a '-' to indicate an open-end year.

The **[Zone]** column indicates which zones (Table 1) the harvest is restricted to. Zones can be indicated as a single (e.g., 1), as a range (e.g., 1-3), as a series (e.g., 1,3,6), or as a combination (e.g., 1,3-6,9). Zones 1-5 correspond to Canada, and zones 6-9 are in the United States.

The harvest slot limit is specified by the **[Length.min]** and **[Length.max]** columns which indicates the minimum and maximum body lengths in centimeters (cm) that may be retained.

The **[Type]** column indicates whether wild and/or hatchery fish may be retained (allowable values: 'wild', 'hatchery', or 'both'). A single type may be specified as either 'wild' or 'hatchery'. When both wild and hatchery fish are to be retained use the term 'both'.

Finally, **[Removals]** indicates the total number of removals that may be allowed if available. The total number of required captures to achieve this goal is estimated and returned as part of the simulation output.

Availability Warnings

The availability warning provides a threshold applied to each unique slot limit, where the total abundance available in the slot limit is compared to harvest or removal goal. If the availability is less than the threshold a warning is issued. For example, an availability warning of 50% means that the harvest goal should be 50% or less of the availability in that slot limit otherwise a warning should be issued. Availability warnings are issued on a per year basis for the slot limit for years where it applies.

Targets and Triggers

Simulations may be run to evaluate the potential effectiveness of various management options for reaching endpoints, which are referred to as “targets” in the applications. Targets and triggers provide quick feedback about the effectiveness of a given management strategy. Targets are displayed on applicable summary plots where the target can be visualized. Targets are available for life stage, country, and problem cohort abundances (Figure 8). Targets can be deactivated by setting the target to zero.

A trigger can be added to any target by selecting the corresponding trigger check box below each target. Triggers provide user notifications at the end of a run on the number of years where the target was met or surpassed. Trigger notifications are also added to the summary tables that accompany summary figures, so that years where the threshold has been met can be quickly identified.

Model Results

Once a simulation has finished running and generating results, the **[Results]** tab will be populated with figures and tables summarizing the model outputs. These results are also duplicated in the Excel file that can be downloaded and saved for future reference or used in the comparison application (see *Comparing Model Runs*). Note that Table 2 summarizes all potential result summaries that can be generated, but a subset can be selected at the time of running. It is suggested that when completing a final model run, that you wish to archive for future reference, that all summary results are selected (see *Result Summaries*).

TARGETS & TRIGGERS

Instructions

Abundance Targets

Set abundance targets of interest. Targets can be turned off by setting abundance to zero. Enabling a target as a trigger will create a notification if the target threshold has been surpassed.

Life Stage	Country	Problem Cohorts
Total Adults 7500 <input type="checkbox"/> Use value as trigger	Canada Adults 2500 <input type="checkbox"/> Use value as trigger	Cohort Abundance 1000 <input type="checkbox"/> Use value as trigger
Subadults 0 <input type="checkbox"/> Use value as trigger	United States Adults 5000 <input type="checkbox"/> Use value as trigger	
Juveniles 0 <input type="checkbox"/> Use value as trigger		

Figure 8. Screen capture of the Target & Triggers control box.

Table 2. Summary of potential result item contained displayed on the [Results] tab or within the Excel file downloaded at the end of a simulation run. All results include summaries for wild and hatchery sub-categories, except 'Warnings' (pooled) and 'Problem Cohorts' (hatchery only).

Result/ Worksheet	Category	Description
Warnings	Warnings	Availability and harvest failure summaries
Management Removals		Size distributions before/after removals
Recreational Harvest		Size distributions before/after harvests
Tribal Harvest	Management Summaries	Size distributions before/after tribal harvests
Handling by Size		Handling rates by size class
Handling by Program		Handling rates by harvest/removal program
Problem Cohorts		Abundance of hatchery problem cohorts
Total		Abundance summary of all age classes combined
Life State		Abundance summarized by life stage (i.e., adult, subadult, juvenile)
Age Classes	Abundance Plots	Abundance by age class
Country		Total and adult abundance by country (i.e., United States and Canada)
Sex Specific		Total abundance across all ages by sex
Size Distribution		Population length distribution by year, zone, and type (i.e., hatchery and wild)
Size Classes	Size Distribution	Total abundance by size class
Size Classes by Zone		Total abundance by size class and zone

Warnings

The warnings worksheet/result tab currently summarizes all harvest warnings and failures. Warnings are issued if take from a harvest or removal program exceed a safety threshold designated by the availability setting (see *Model Runs > Availability Warnings*). Failures are issued if a removal or harvest program specifies more takes that are available in the population. In both cases a probability is presented indicating the percentage of simulation iterations where the warning or failure occurred. Failures and warnings are specific to a particular unique harvest or removal rule and are broken down by harvest or removal program (i.e., management removals, recreational harvest, and tribal harvest).

Management Summaries

Management summaries (Table 2) provide a quick overview of the performance and impact of a removal or harvest program. Each program type (i.e., management removals, recreational

harvest, and tribal harvest) will have a corresponding worksheet/result tab indicating the yearly size distributions by zone, both before and after harvest, with the corresponding slot limits overlaid so that users can judge the efficacy of a particular removal or harvest program (Figure 9). For example, if there are very few individuals expected to exist in a size range corresponding to a slot limit, users may wish to revise the slot limit setting in future simulation runs. Hatchery and wild type size distributions are also indicated allowing users to fine tune harvest programs to better target either population.

Handling rates are summarized by both size class and by harvest or removal program, indicating both year-specific handling and cumulative handling (Figure 10). Currently mortality related to handling is not included in the simulation but could be added in future versions. In all handling figures, the 95 percentiles values across the set of simulation iterations are indicated by shading, with lines indicate the mean value.

Problem cohort abundance was summarized as an abundance plot for Canadian hatchery cohorts (i.e., 2001) and United States hatchery cohorts (i.e., 2003-2010) that were viewed as problematic. Results figures indicate the mean and 95 percentiles from the simulation iterations by year, along with any indicated targets.

Abundance Plots

Abundance plots provide population abundance summaries across different population dimensions (see Table 2). All abundance summary plots indicate yearly means and 95 percentiles, along with any applicable indicated targets, with abundances summarized for wild and hatchery type fish, as well as for both types combined (e.g., Figure 11).

Size Distribution Plots

Size distribution plots (see Table 2) provide an indication of the frequency of sizes in the population by zone and year (Figure 12) as well as abundances by size class. The size frequency overview figure (i.e., Figure 12) is similar to the harvest/removal figures (i.e., Figure 9), but provides an overview of all zones and years at the same time. This can be a useful way to review the behavior and performance of the simulation model, and can be used as another way to assess or confirm the impact of various management strategies. For example, the effect of fishing behavior on the size distribution can be tracked by comparing zone size frequencies over the simulation period. The impact of hatchery release programs can be viewed in a similar manner. Relative abundance by zone can also be compared to later stock assessment data to determine whether the simulation is moving individuals throughout the study area in a manner that is consistent with best available information.

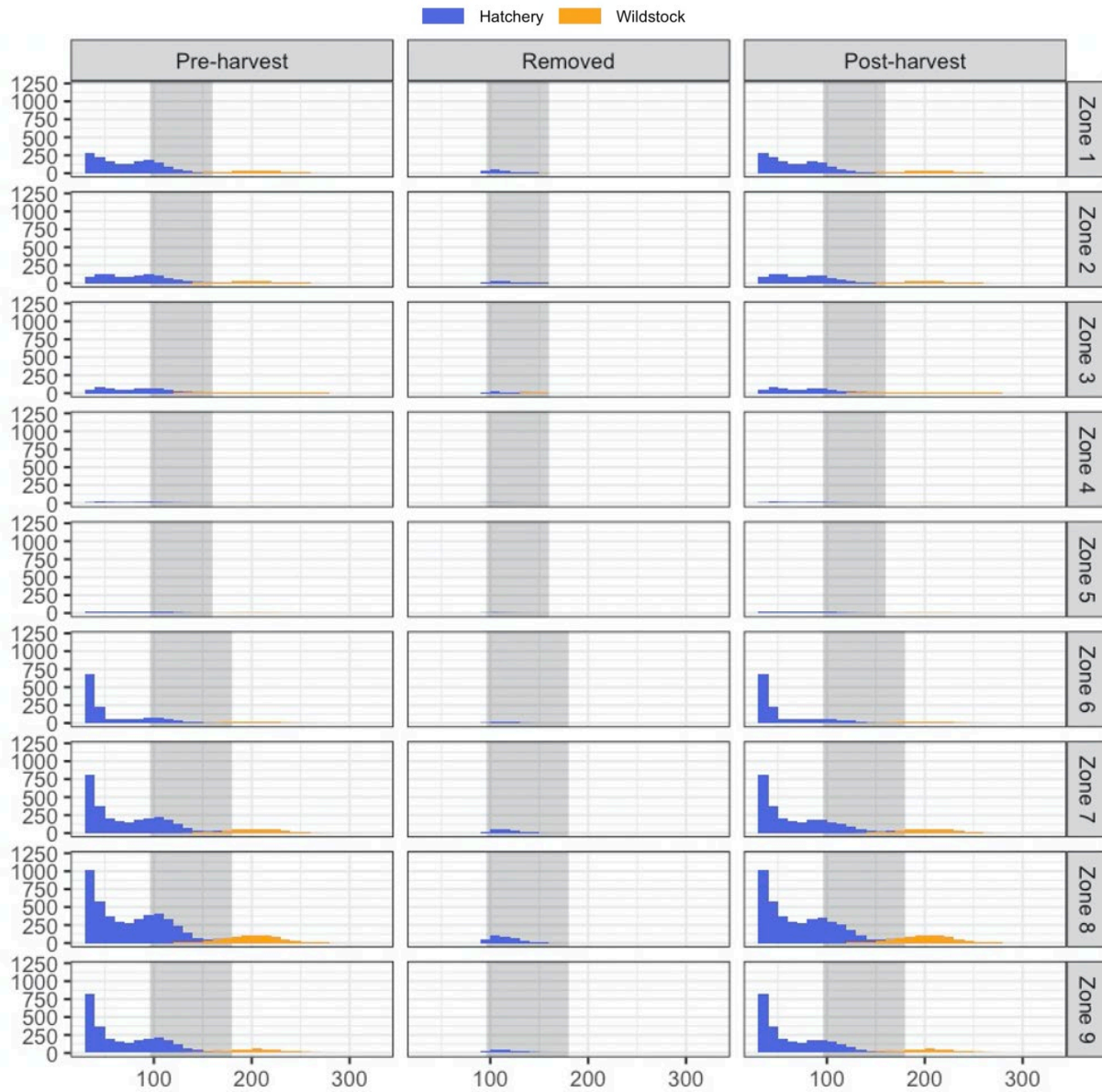


Figure 9. Example zonal size distribution pre- and post-harvest along with the size distribution of the harvest. Shading indicates zonal slot limit, whereas bar color indicates hatchery or wild type fish.

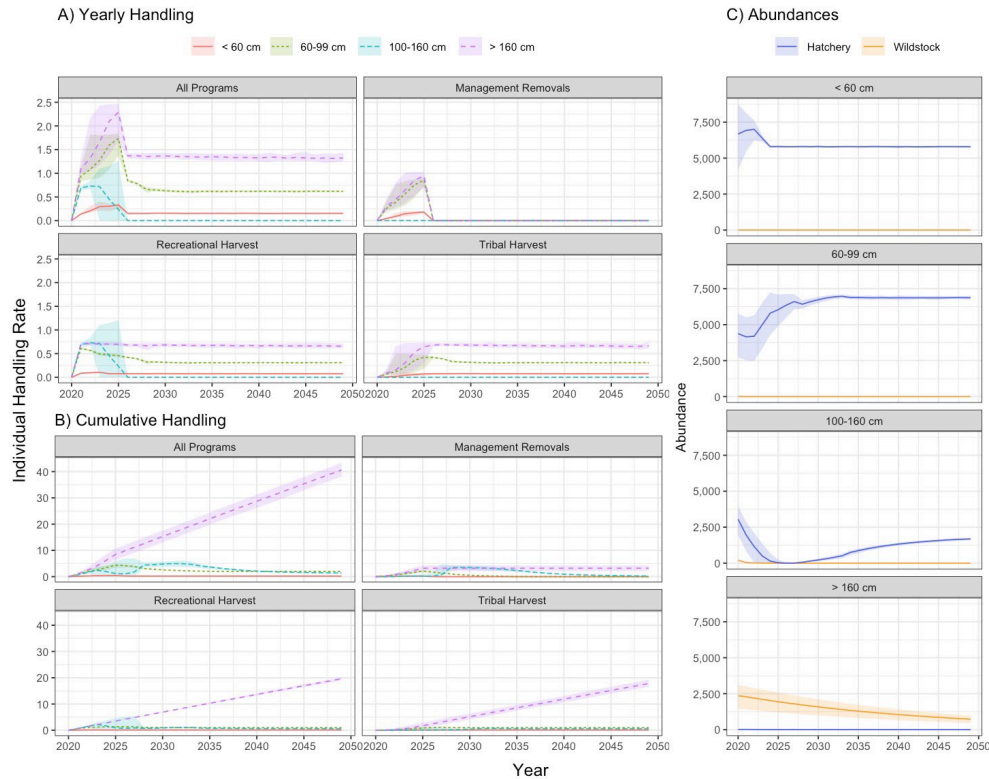


Figure 10. Example of handling summary plot for handling rates by removal/harvest program on both a yearly basis (A) and cumulatively across simulated years (B), with abundances (C) provided for reference. Lines indicate means, while shading indicates the 95 percentiles.

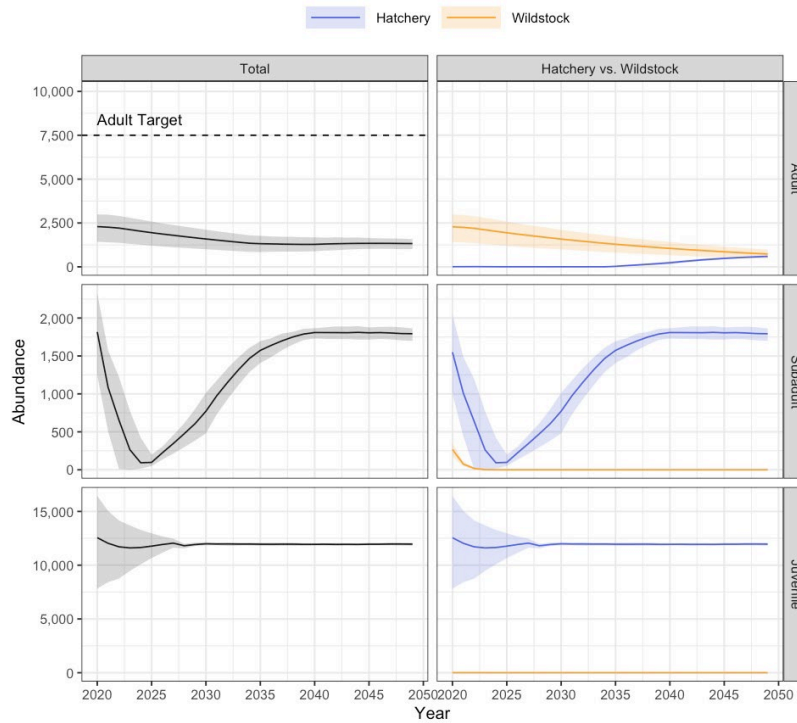


Figure 11. Example abundance plot indicating life stage abundance (i.e., juveniles, age 1-10; subadults, ages 11-20, and adults, ages 21+). Lines indicate means, while shading indicates the 95 percentiles.

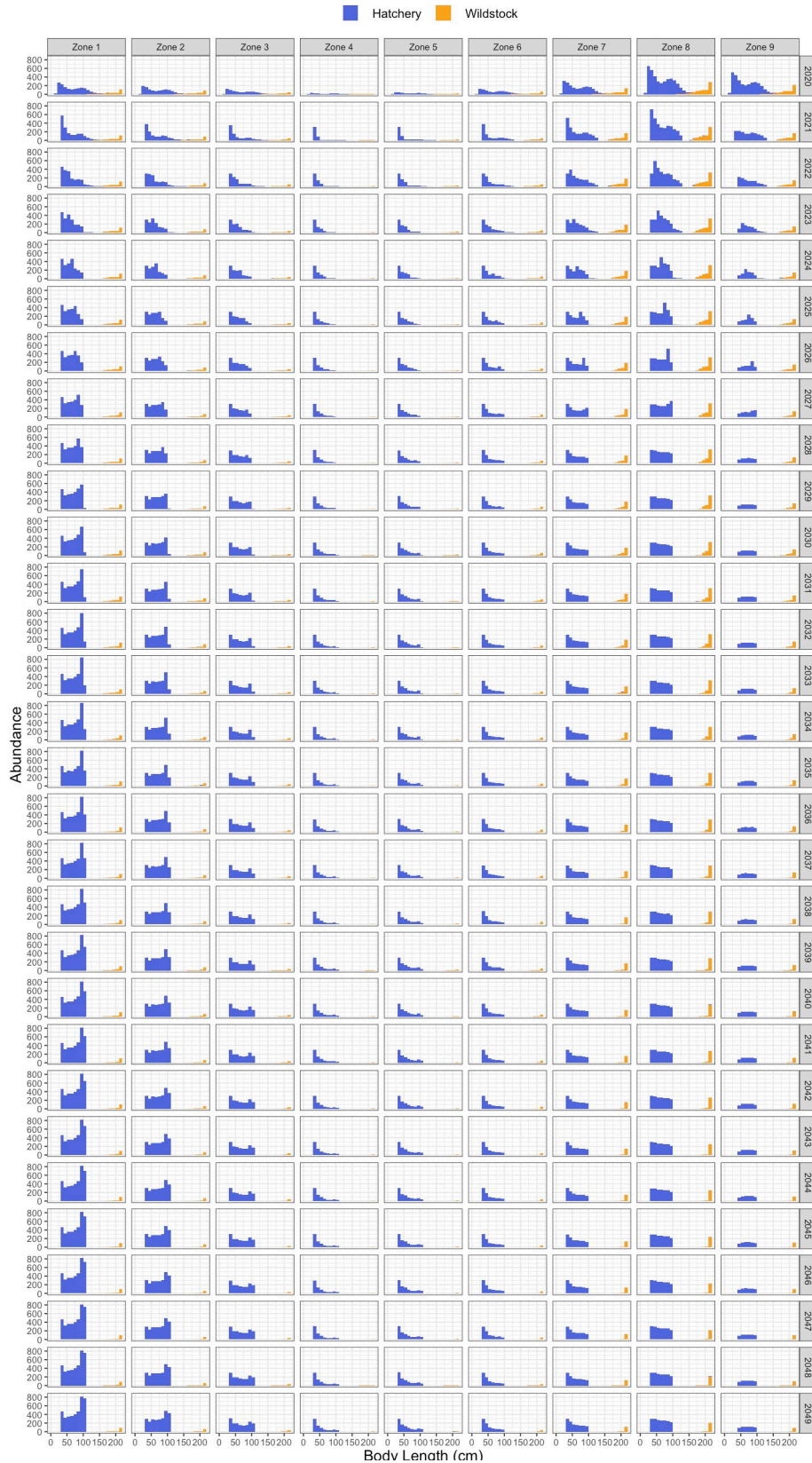


Figure 12. Example of the size distribution summary result indicating size frequencies by year and zone for both hatchery and wild type sturgeon.

Comparing Model Runs

The final step in the *Upper Columbia Sturgeon Simulator* workflow is comparing results between model runs (see *Workflow Overview*). Prior to running comparisons, users need to ensure the Excel results files (generated after a successful model run) were downloaded and saved to their computer (see *Workflow Overview > A Note About the Excel Results File*). Also, users should ensure that all results summary options were selected (see *Model Runs > Result Summaries*) and that multiple simulation iterations were selected (see *Model Runs > General Settings > Simulation Parameters*).

Comparisons are performed by selecting the **[Compare]** link in the left-hand sidebar (Figure 2). This will navigate the user to comparison page which has three main sections that can be expanded or collapsed by the user (Figure 13):

1. Model Runs;
2. Targets and Settings; and
3. Comparison Results.

Comparisons are run by first uploading two to five Excel files from the individual runs that are to be compared (Figure 14). Once the upload has completed then hit the “Compare Runs”

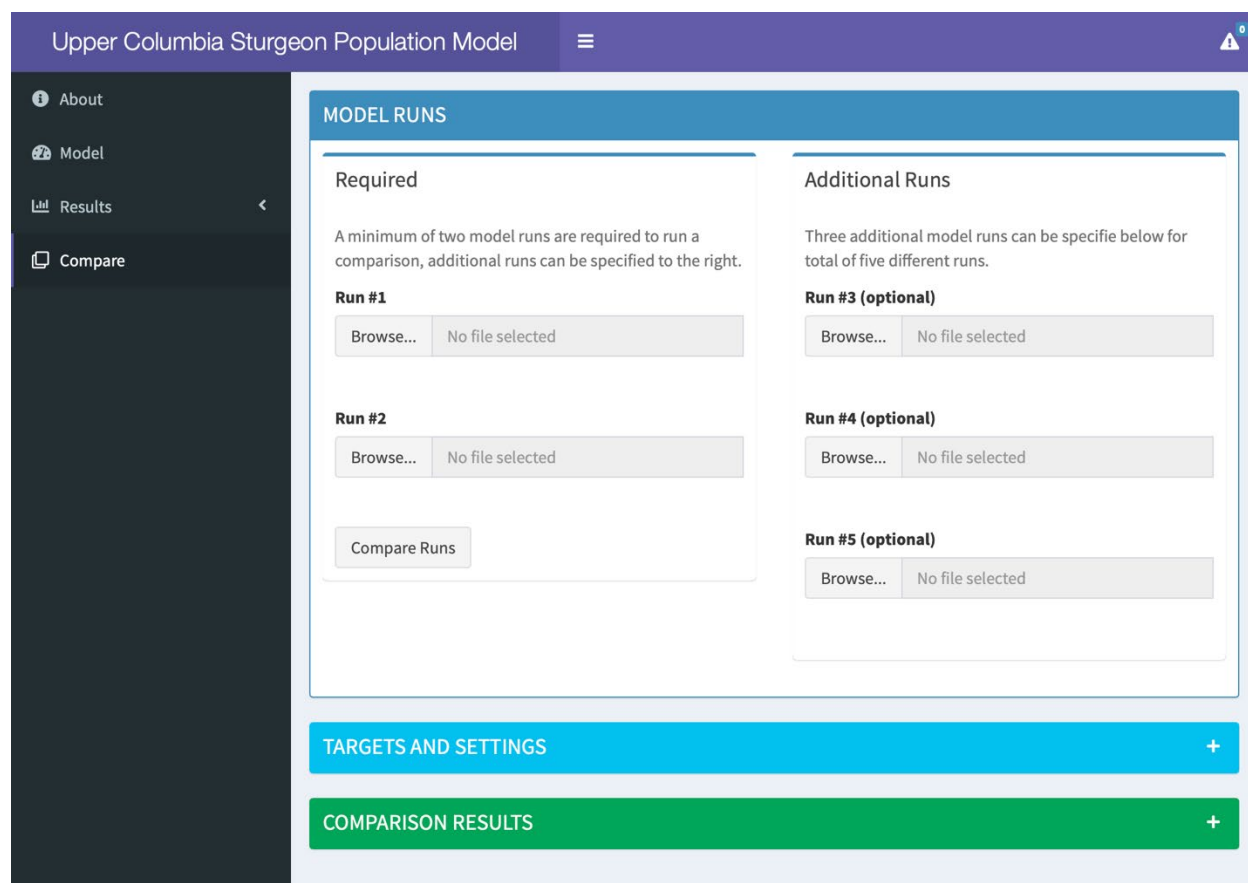


Figure 13. Simulation run comparison page.



Figure 14. Screen capture of the model comparison page of the UC Sturgeon application with two model run results files uploaded.

button to initiate the comparison procedure. Comparison results will be displayed in the “Comparison Results” box (Figure 15) as they become available, and are organized under three broad categories:

1. Harvest Programs;
2. Abundance Targets; and
3. Handling

In each plot, runs are distinguished from each other by the ‘run name’ specified at the start of the run (and saved in the settings tab of the results Excel file). The targets displayed on each selected plots can be revised at any time using the “Targets and Settings” control box (Figure 16).

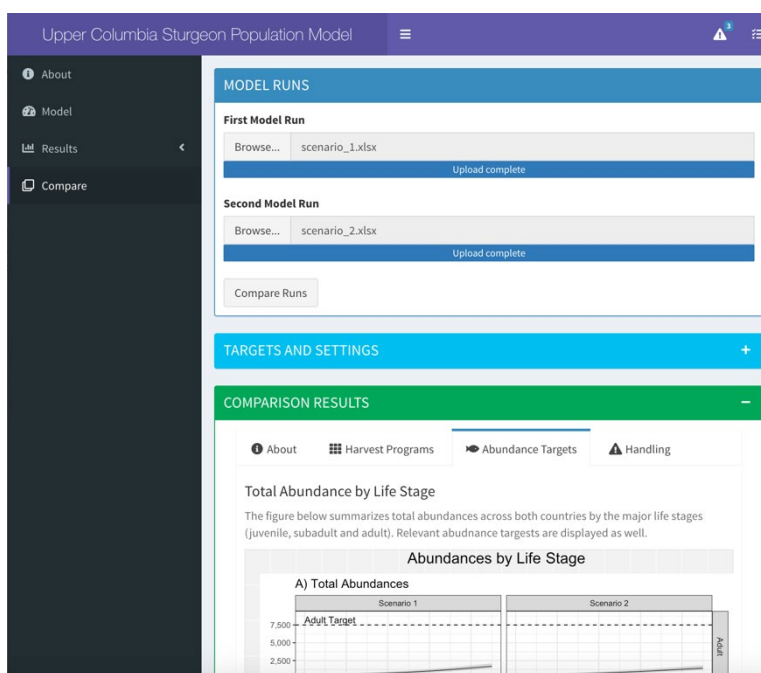


Figure 15. Screen capture of comparison results generated after running the comparison.

Figure 16. Screen capture of the targets and settings box.

Example Scenario

To demonstrate the figures generated by the comparison page, two example scenarios were run and compared. Both were simulated over 30-year time horizons using the following settings for each simulation:

Scenario 1

- Adult abundance target (sum of all zones) = 7,000 adults by 2050
- Release number (annual) = 3,200 (3,000 in US, 200 Canada)
- Size at release = 200 g
- Harvest target – US recreational = 1,000 fish per year
- Harvest target – US Tribes = 1,000 fish per year
- Management removal target – US = 15 fish per year
- 1st Recreational harvest slot limit range – US = 127-160 cm FL (2020-2025)
- 2nd Recreational harvest slot limit range – US = 96-160 cm FL (2026 and beyond)
- Tribal harvest slot limit range – US = 96-160 cm FL (all years)
- Management removal slot limit range – US = 160-180 cm FL only hatchery fish (2020-2025)

Scenario 2

- Adult abundance target (sum of all zones) = 7,000 adults by 2050
- Release number (annual) = 3,200 (3,000 in US, 200 Canada)
- Size at release = 200 g
- Harvest target – US recreational = 1,000 fish per year

- Harvest target – US Tribes = 200 fish per year
- Management removal target – US = 800 fish per year
- Management removal target – Canada = 400 fish per year
- 1st Recreational harvest slot limit range – US = 127-160 cm FL (2020-2025)
- 2nd Recreational harvest slot limit range – US = 96-160 cm FL (2026 and beyond)
- Tribal harvest slot limit range – US = 96-160 cm FL (all years)
- Management removal slot limit range – US = 96-180 cm FL only hatchery fish (2020-2025)
- Management removal slot limit range – Canada = 96-160 cm FL (2021-2025)

The resulting Excel output downloaded from the **[Model]** page in the shiny application was saved to a hard drive, then inputted into the comparison page and run to generate the results discussed below, by the three main organization tabs.

Management Programs Tab

The “Management Programs” tab provides summaries and diagnostics to compare the removal and harvest programs implemented in each run (Figure 17), including:

1. Compare the differences in the hatchery programs between model runs;
2. Summary of availability warnings and failures during the simulations;
3. Compare the difference between the removal/harvest programs between model runs; and
4. Summary of the effort required to meet removal/harvest goals.

Comparing Hatchery Release Programs

The first result under this tab is a summary of the hatchery programs are compared visually by comparing the total number of yearly releases by country (Figure 18). In the two scenarios under consideration the same release programs are considered (Figure 18a). In scenarios where multiple release programs occur within a country, stacked colored bars are used to differentiate among release programs (see Run 2 panel, Figure 18b).

Comparing Harvest and Removal Programs

The among-run differences in the harvest and removal programs are visualized based on unique harvest slots (i.e., indicate unique harvest slots [unique slots are the combination of country, slot limit, and target type {i.e., wild, hatchery or both}], Figure 19). This allows a quick way to reference the total harvest or removals within a harvest slot (i.e., the total stacked bar height), as well as the individual contribution from each harvest or removal programs (i.e., the stacked bar color) for each year of the simulation. Model runs that feature no removals or harvest from a given harvest slot are clearly indicated with the label “No Programs Available.”

In the example, the first model run has significantly more US Tribal harvest in the 96-160 cm size slot, while the second model run has management removals in the 96-160 cm size slot in Canada and the 96-180 cm size slot in the US that are not in the first run (Figure 19). The first

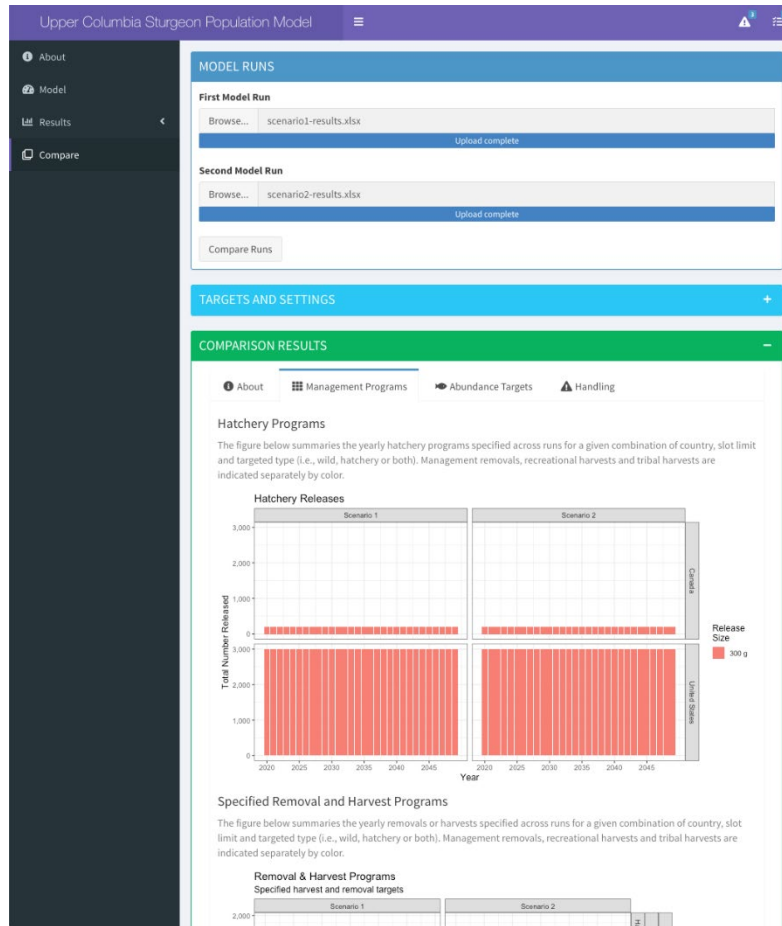


Figure 17. Example output observed under the **Management Programs** results tab.

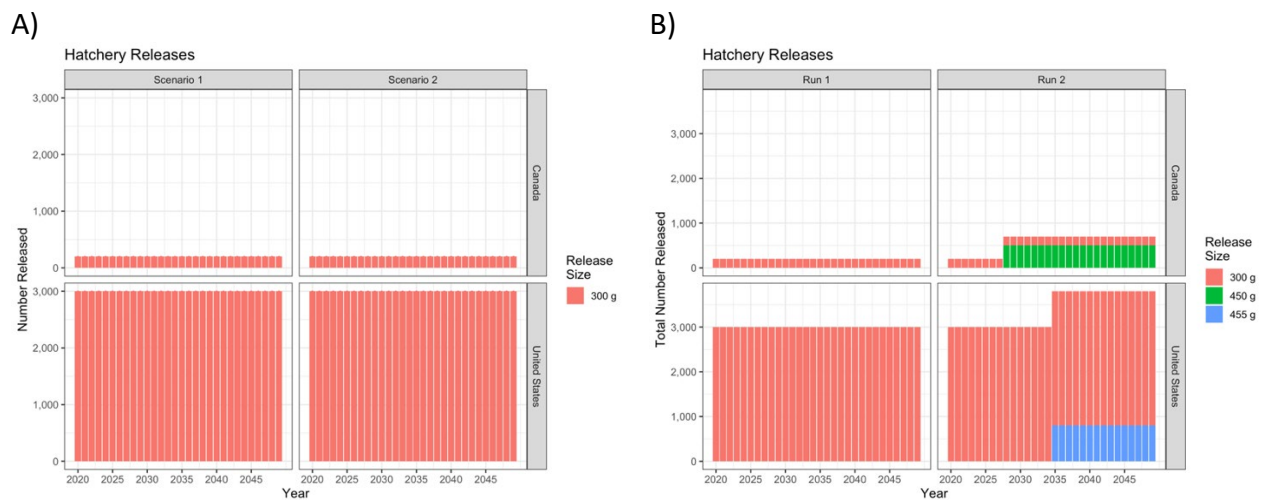


Figure 18. Hatchery comparison figure showing the scenarios under consideration (A) as well an example scenario (B) where the first model run with one country-specific release program (left hand panels in figure B) and the second run with two country specific release programs in some years (right hand panels in figure B).

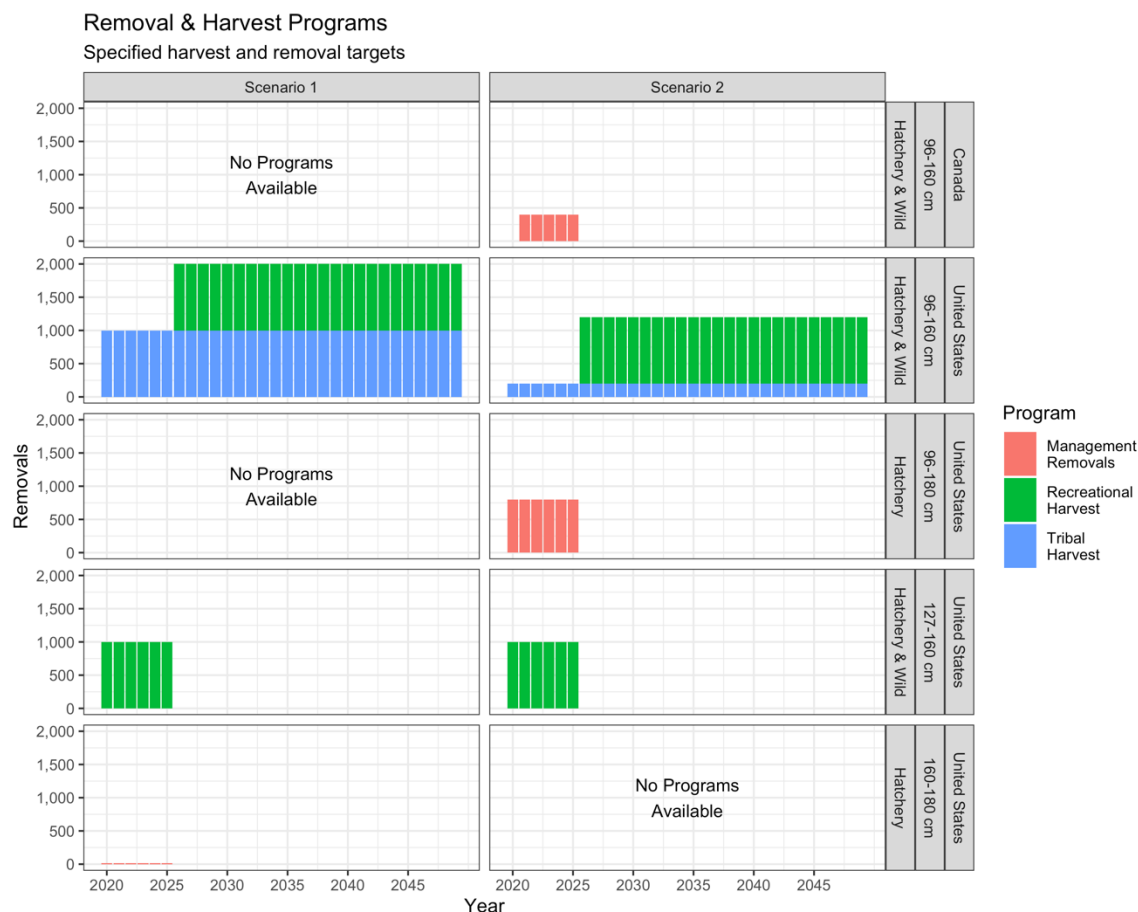


Figure 19. Summary of harvest and removal programs across simulation runs. Rows indicate unique harvest slots (i.e., the combination of country, slot limit, and target type [i.e., wild, hatchery or both]). Harvest slots that were not used in a simulation run are indicated by “No Programs Available.”

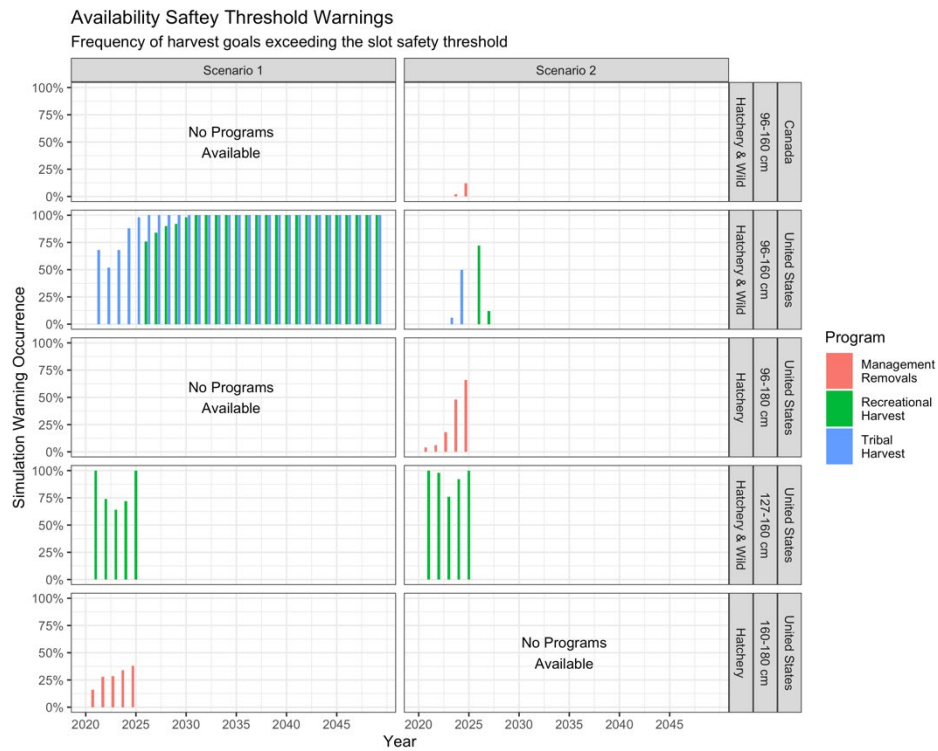
run also has a small number of management removals in the 160-180 cm size slot in the US that is not present in the second run.

Harvest Slot Availability Warnings and Failures

When managers are designing a harvest or removal program, they may wish to ensure that the abundance within that harvest slot does not exceed availability, or that a particular safety threshold remains intact. As part of the simulation model, the availability within a harvest slot is also monitored (see *Model Runs > Removal and Harvest Programs > Availability Warnings*). A warning is issued when harvest goals exceed the availability with a harvest slot by the specified safety margin. A failure error is issued when the harvest goal exceeds total availability within the harvest slot. The frequency of warnings and failures in harvest slot availabilities are summarized using the same harvest slots as the harvest programs summary figures, and indicate the number of simulation iterations where the warning or failure occurred (Figure 20).

In the example comparison, the harvest slot featuring a 96-160 cm slot limit within the US appeared to be problematic, surpassing the safety threshold in most runs (a safety threshold of

A) Availability Warnings



B) Availability Failures

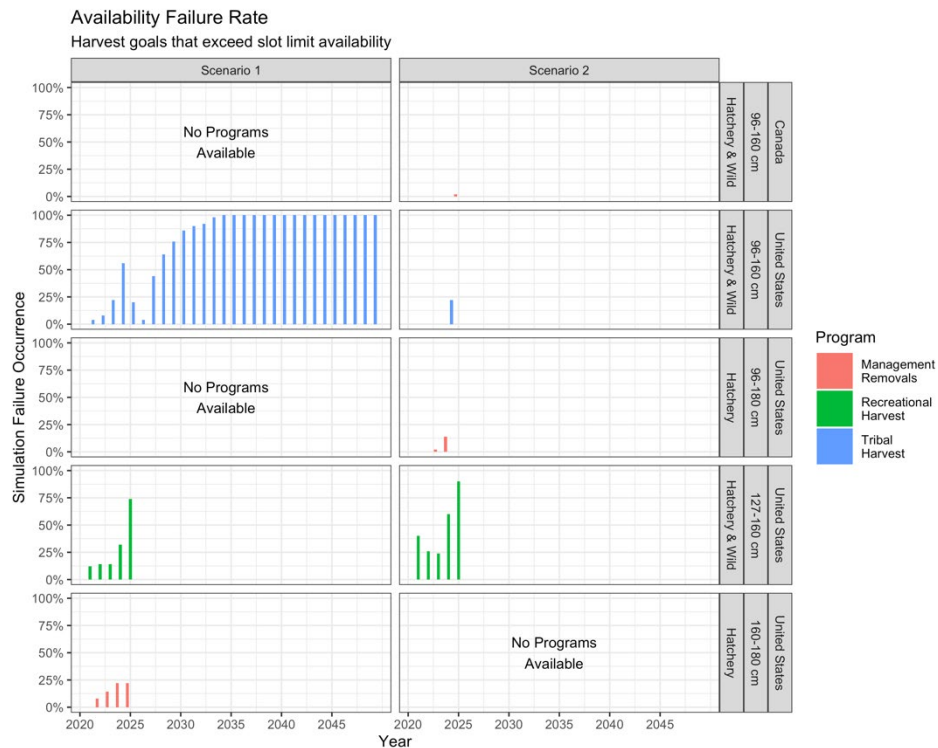


Figure 20. Example of availability warnings and availability failures. Both figures indicate the frequency of warnings or failure across simulation iterations.

50% - harvest goals had to be 50% of availability or less; Figure 20a). In most runs the harvest goal within this harvest slot also exceeded availability, indicating that few individuals can be expected to age into older age categories since nearly all were being harvested (Figure 20b). This presented an obvious recruitment issue for this harvest quota. Note that the figure only indicates a tribal harvest failure, because the simulation draws harvest and removals in a particular order, starting with management removals, followed by recreational harvest, and then tribal harvest (see *Population Model Formulation > Harvest & Removals*). The order can be changed, or concurrent harvesting could be programmed in future versions of the application.

The potential overharvesting of the 96-160 cm harvest slots resulted in differing abundance trajectories, which are explored further in the *Abundance Targets Tab* section.

Comparing Required Sampling Effort

The final comparison result under the Management Program tab is the effort requirement figure. The simulator works by determining the total number of captures required to achieve the designated harvest goals within a harvest slot in order to meet a harvest goal or to get as close as possible if availability is less than the harvest goal (see *Population Model Formulation > Harvest & Removals*). In this case, the average number of captures required to achieve a harvest or removal goal, along with the 95 percentiles (shading), are presented for each harvest or removal program (Figure 21).

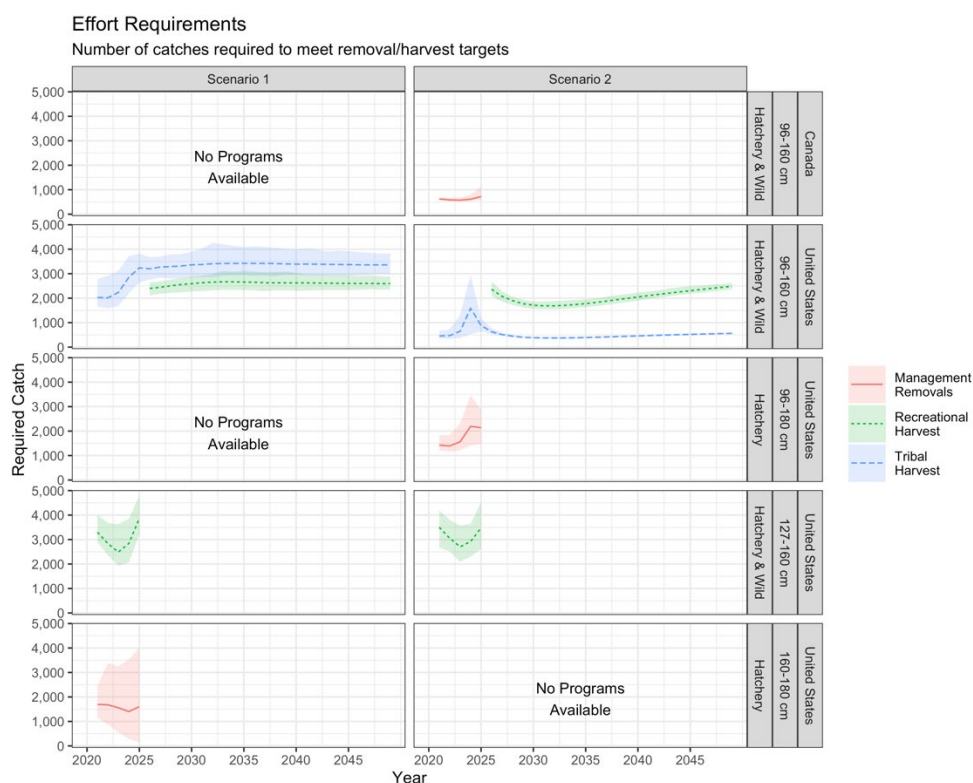


Figure 21. Summary of effort required to achieve a particular harvest or removal program within a given harvest slot. Lines indicate the mean and shading indicates the 95 percentiles across available simulation iterations.

When assessing the efficacy of a harvest or removal program the required effort should always be reviewed to ensure the program is feasible. In the example, the first scenario indicates that a large amount of effort would be required to meet the relatively small harvest goal in the United States 160-180 cm slot limit focusing on hatchery fish. This large effort requirement is due to non-targeted individuals being caught as bycatch during the effort to capture targeted individuals. Given how few individuals are targeted in this harvest slot (i.e., Figure 19), managers may wish to reconsider either the slot limit or the number of takes for this program.

Abundance Targets Tab

Abundance comparisons among model runs are contained in the “Adult Targets” tab on the Comparison page (Figure 22). If targets have been specified, these will be displayed on applicable plots. Targets and colors can be updated at any time (see Figure 16).

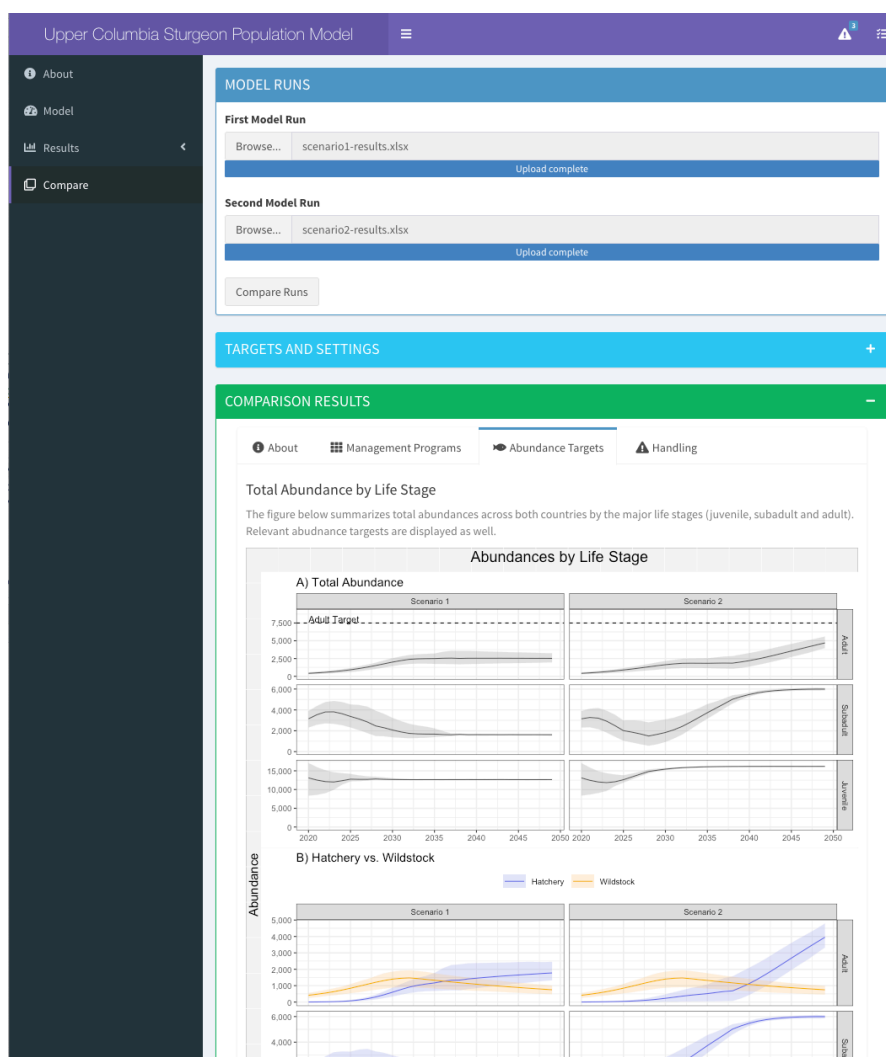


Figure 22. Example output observed under the **Abundance Targets** results tab.

Currently, abundance comparisons are made among model runs for:

1. Life Stage specific total abundances;
2. Country specific abundances;
3. Total abundances across all categories; and
4. Problem hatchery cohorts.

Additional abundance comparison plots can be added in future versions of the application required; output is based on the simulation results output file which has far more summary types than currently presented under the Abundance Target tab.

Comparing Abundances by Life Stage

Life stages were defined as juvenile (age 1-10), subadult (age 11-20), and adult (21+). The abundance trajectories were compared for total abundance as well as abundance by type (i.e., hatchery or wild type) across the two runs (Figure 23). The adult target was set at 7,500 and a subadult target was included as an example of additional targets being specified. **NOTE: this simulation uses an older growth model; the current model uses the Korman-Crossman growth model.**

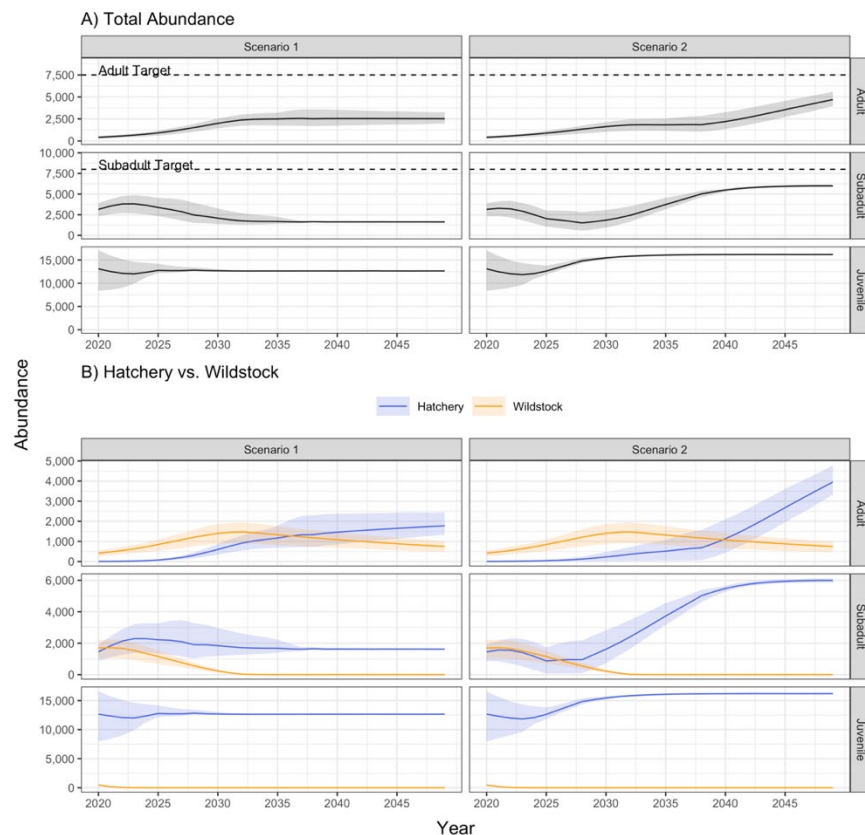


Figure 23. Life stage specific abundance plots summarize abundances for juvenile (age 1-10), subadult (age 11-20), and adult (21+) age categories. Summaries are also broken down by hatchery and wild types.

Comparing the two example scenarios, total adult abundance stabilizes at around 2,500 individuals under the first scenario, but is on an upward trajectory towards the adult target goal of 7,500 (falling just shy of the target by the end of the 30-year simulation period) under the second scenario. Furthermore, juvenile and subadult abundances stabilized at a lower level in Scenario 1, while juveniles and subadults were increasing or stabilizing at higher levels in Scenario 2 (Figure 23). Given that the removals in Scenario 1 in the 96-160 cm size limit were higher in Scenario 1 (Figure 19), the removal rates in this scenario appear to be preventing recruitment into older age classes at a sufficient rate to ensure population growth. The growth in Scenario 2 is driven by hatchery fish.

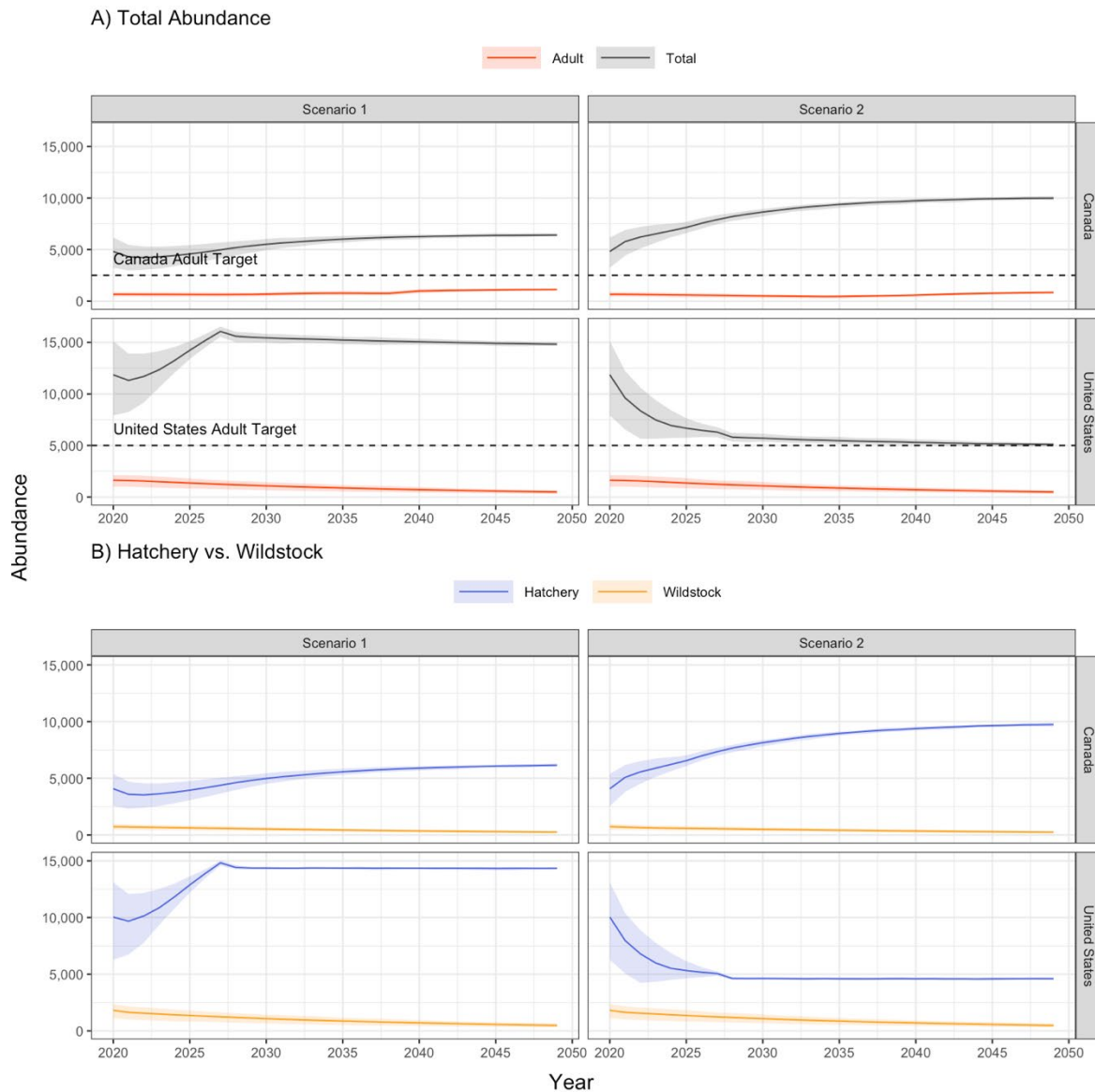


Figure 24. Summary of country specific abundances across simulation runs. Summaries include A) adult and total abundances; and B) total abundances summarized by hatchery and wild types.

Comparing Country Specific Abundances

Country-specific total abundance and country-specific abundance by type (i.e., hatchery and wild type) are also compared along with any applicable targets (Figure 24). Summaries include total (i.e., age 1 and older) and adult (i.e., age 21 and older) abundances. As noted in Figure 23, Scenario 1 features stable abundances while Scenario 2 results in abundance increases, but neither meet the adult abundance targets. Both countries have similar trajectories as movement rates are assumed to be in equilibrium at the start of the simulation. Changes in movement rates could be modelled in future model iterations if the information existed. The comparison also makes it clear that the observed increases under Scenario 2 are the outcome of increased hatchery abundances.

Comparing Total Abundances

Finally, the total abundances (age 1 and older) in the total Upper Columbia River are also compared (Figure 25). Similarly, this comparison shows stable abundances in Scenario 1 and an increase in Scenario 2. As discussed previously, this is likely due to overharvest in the juvenile and subadult age categories.

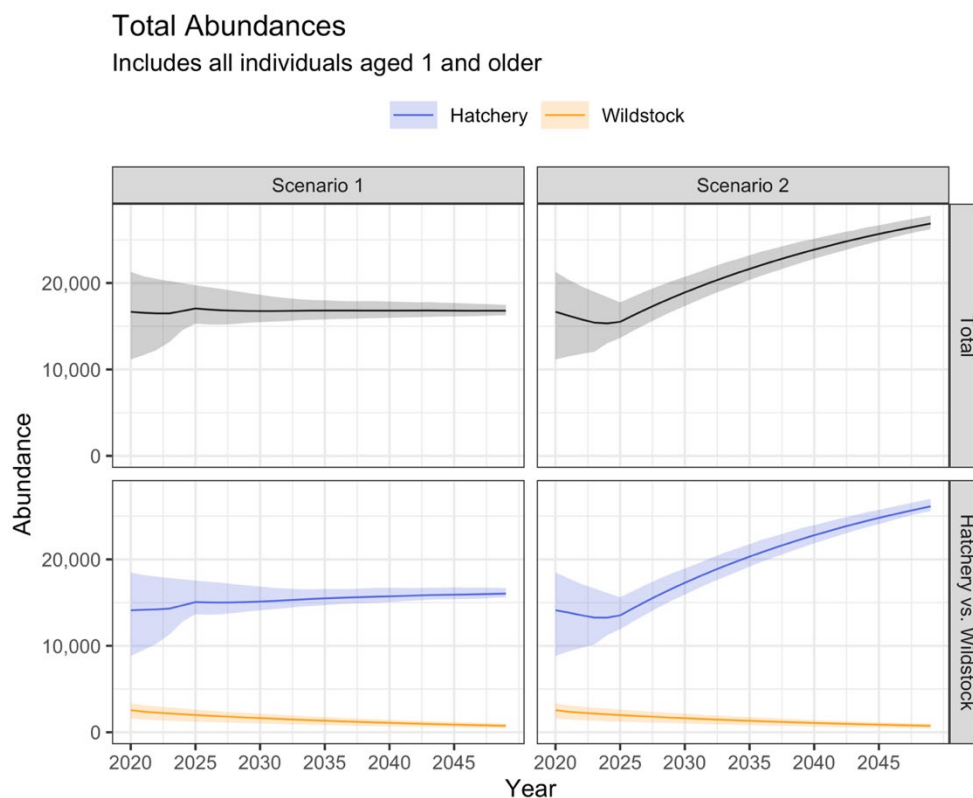


Figure 25. Comparison of total abundance, and abundances broken down by type (i.e., hatchery or wild type) across the two example scenarios.

Handling Tab

The Handling tab (Figure 26) provides summaries of the average number of times an individual is handled by size class (Figure 27) and by harvest/removal program (Figure 28). Most handling is attributed to the largest size class due to the selectivity curve and the cumulative time spent in the larger size class. Wild type fish were handled more than hatchery fish because wild type fish make up a large component of this class size class, especially given the requirement to release wild fish in most removal/harvest programs. Interestingly, not only does Scenario 2 come closer to the management abundance targets, but overall handling levels are noticeably lower.

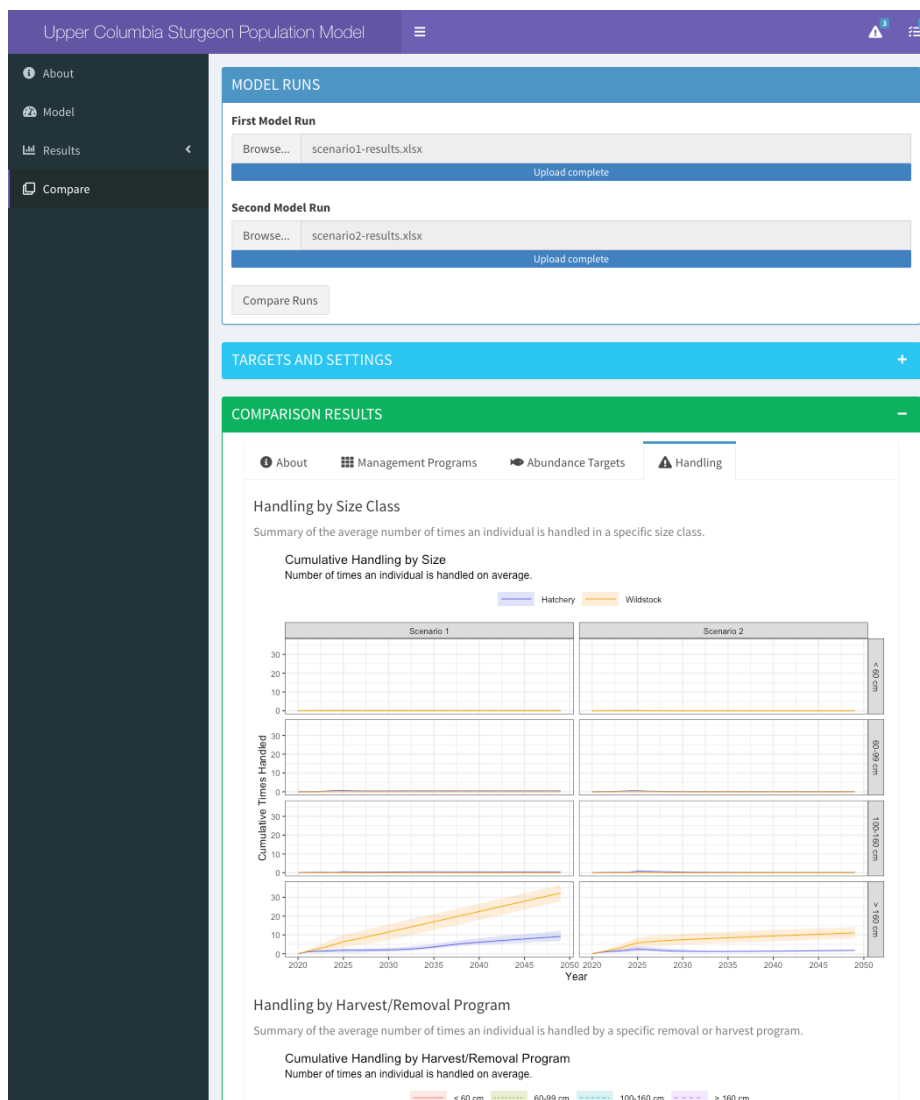


Figure 26. Example output observed under the **Handling** results tab.

Cumulative Handling by Size

Number of times an individual is handled on average.

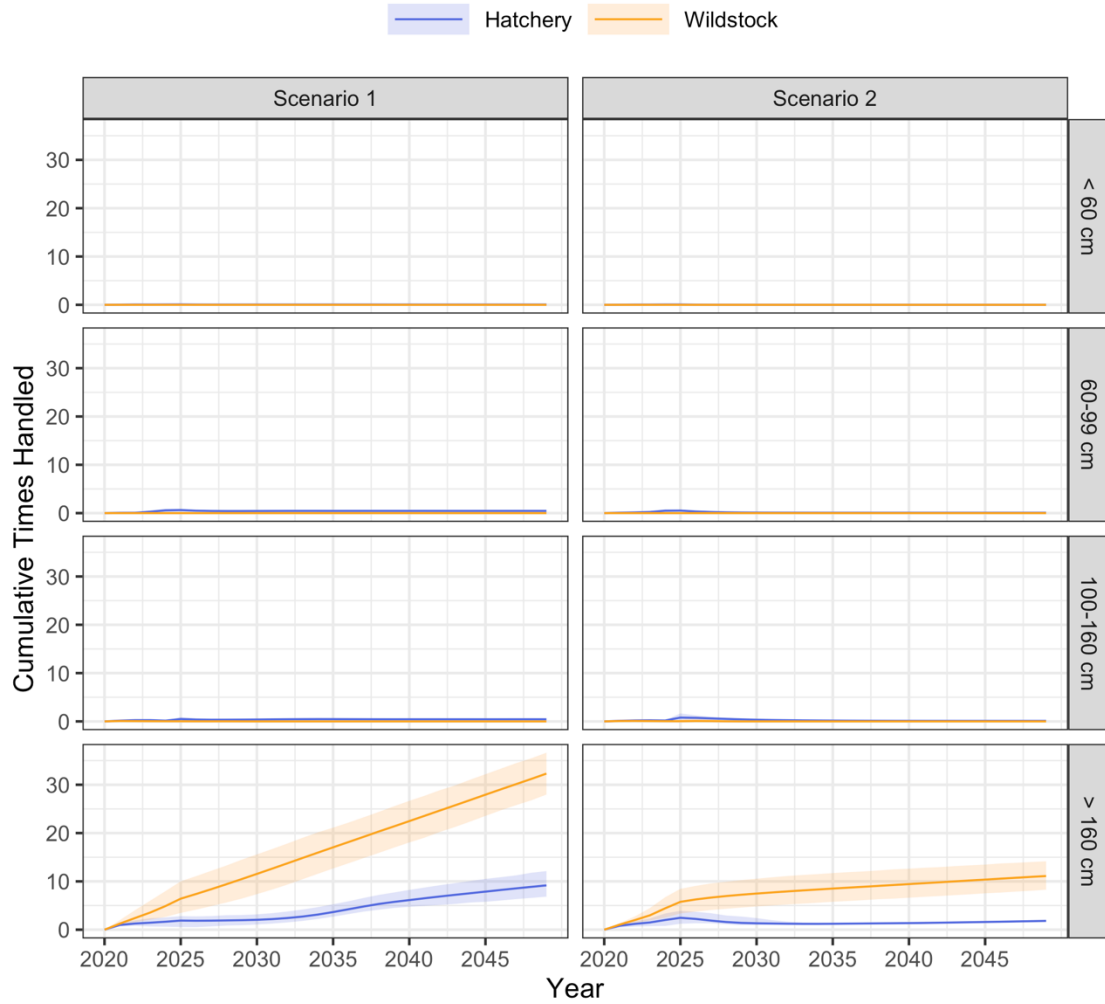


Figure 27. Cumulative number of times an individual is handled, on average, by size class and by type (i.e., hatchery or wild types).

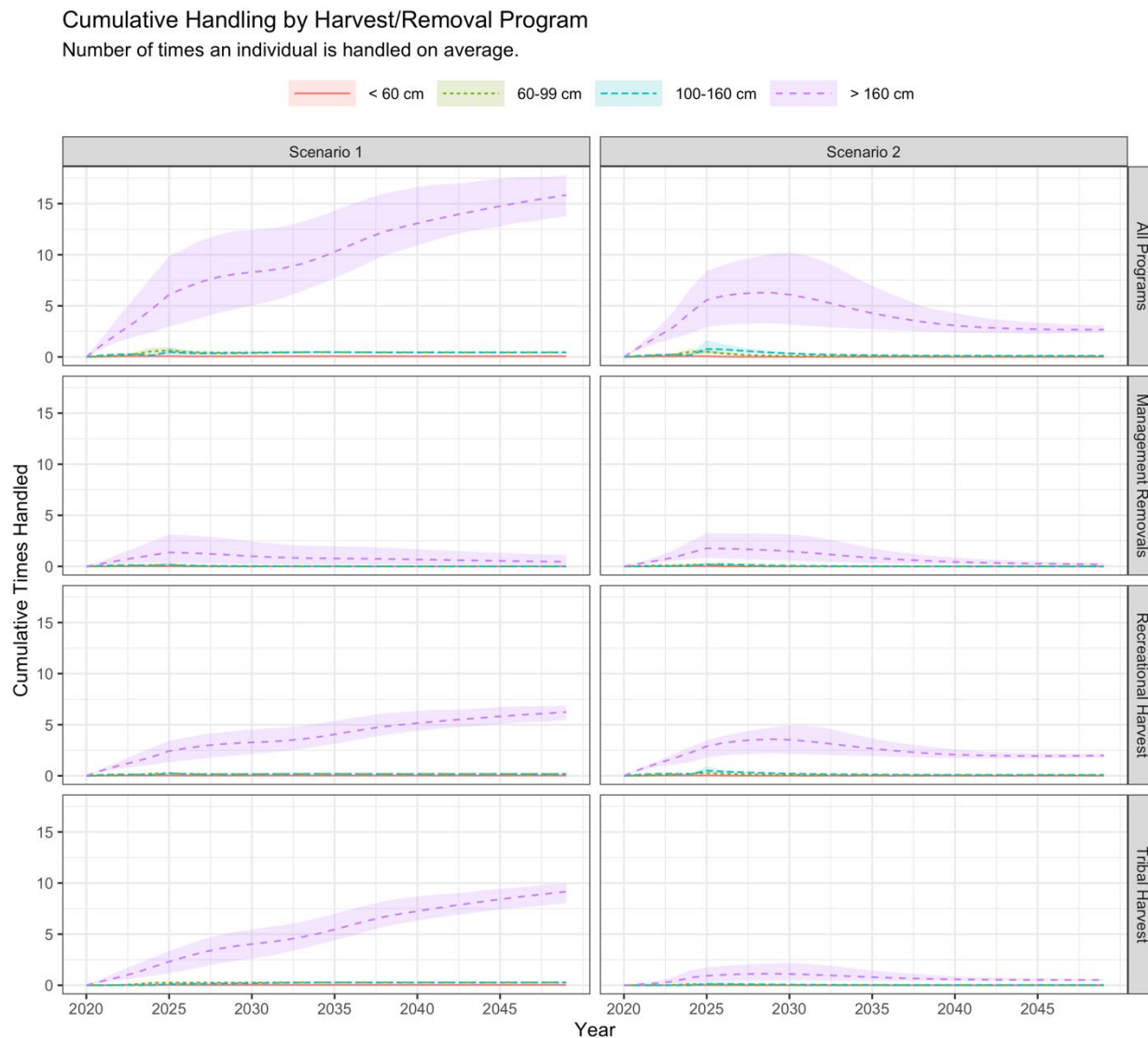


Figure 28. Cumulative number of times an individual is handled as a result of a harvest or removal program, by size class.

Population Model Formulation

The population model is an individual-based simulator where a population of individuals is stepped through aging, movements, growth, and mortality (i.e., fishery and natural) based on a combination of stock assessment data (used to initialize the population) and user input (which defines hatchery releases and fishery takes and handling pressure). While handling is currently recorded, mortality as a result of handling load is not currently modelled (although the application was designed so that such features could be easily added). Data are stored as a flat list (Figure 29), with each row representing an individual, and multiple simulation iterations are kept together. Each column represents an attribute such as sex, age, length, weight, location, and handling counts; thereby allowing individuals to grow and move at different rates depending on their age and location. The architecture also makes it simple to keep track of

sim	id	yr	year	sex	origin	cohort	family	type	age	length	growth	weight	handled.manage	handled.sport	handled.tribal	handled	zone	country	alive
1	1	2	2021	1	1	1979	NA	1	40	210.1000	0.0000000	74.68940	0	0	0	0	2	1	TRUE
1	2	2	2021	1	2	1984	NA	1	35	203.0255	1.8254542	67.11008	0	1	0	1	9	2	TRUE
1	3	2	2021	1	1	1947	NA	1	72	231.2000	0.0000000	100.71589	1	0	0	1	2	1	TRUE
1	4	2	2021	2	1	1987	NA	1	32	194.7000	0.0000000	58.88155	0	0	0	0	2	1	TRUE
1	5	2	2021	2	1	1993	NA	1	26	179.5000	0.0000000	45.67698	0	0	0	0	1	1	TRUE
1	6	2	2021	2	2	1991	NA	1	28	187.8694	2.6694468	52.66555	0	0	0	0	8	2	TRUE
1	7	2	2021	2	2	1972	NA	1	47	218.6551	0.9550867	84.60752	0	2	0	2	7	2	TRUE
1	8	2	2021	2	2	1981	NA	1	38	208.7090	1.5089569	73.15539	0	0	0	0	9	2	TRUE
1	9	2	2021	2	1	1994	NA	1	25	178.0000	0.0000000	44.49509	0	0	0	0	1	1	TRUE
1	10	2	2021	2	1	1994	NA	1	25	178.4917	3.1916672	44.88017	1	0	0	1	8	2	TRUE
1	11	2	2021	1	2	1992	NA	1	27	186.7327	2.7327462	51.67646	0	2	0	2	8	2	TRUE
1	12	2	2021	2	2	1942	NA	1	77	232.4849	0.1849434	102.47489	0	0	0	0	9	2	TRUE
1	13	2	2021	1	2	1868	NA	1	151	250.7000	0.0000000	129.70542	0	0	0	0	8	2	TRUE
1	14	2	2021	2	2	1996	NA	1	23	172.7134	3.5134394	40.49551	0	1	0	1	8	2	TRUE
1	15	2	2021	2	2	1985	NA	1	34	201.6046	1.9045785	65.65370	0	1	0	1	8	2	TRUE
1	16	2	2021	1	2	1988	NA	1	31	194.8791	2.2791002	59.05092	1	3	0	4	8	2	TRUE
1	17	2	2021	1	2	1976	NA	1	43	213.6000	0.0000000	78.64558	1	0	0	1	1	1	TRUE
1	18	2	2021	2	1	1982	NA	1	37	205.5000	0.0000000	69.69861	0	0	0	0	2	1	TRUE
1	19	2	2021	1	2	1963	NA	1	56	225.2858	0.5858400	92.88395	0	2	1	3	8	2	TRUE
1	20	2	2021	2	2	1958	NA	1	61	227.6540	0.4539661	95.96830	0	1	0	1	9	2	TRUE

Figure 29. Example of state data logged within the application.

additional attributes by simply adding new columns. Using the tidyverse suite of data manipulation packages in R (Wickham et al. 2019), computational speeds were comparable to using arrays, yet the memory footprint was drastically reduced in comparison.

Overview of Population Processes

When a model run is started, an age structured population is first initialized, then a yearly time step loop is carried out, whereby all simulation iterations are advanced by one year at a time, until the user-defined end of the simulation time period (Figure 30). Within a given year, a number of population processes are carried out in succession. At the start of each year individuals are first grown based on the Korman and Crossman growth curve (see *Population Model Formulation > Growth section*), which assigns a growth value based on the individual's current location (i.e., US or Canada) and their current length. Next, contributions to the population from natural recruitment would have been added, but currently this step has been disabled due to lack of evidence for natural recruitment in the Upper Columbia River. Next, hatchery releases are added to the population, based on the user-defined hatchery schedule, with initial movement rates dependent on the and the release location (i.e., US or Canada). Next, removal and harvest programs are carried out in succession, with management removals first, followed by recreational and tribal fisheries. This is the most time-consuming step because handling rates and handling summary statistics need to be computed in order to generate harvest summary plots (displayed as part of the simulation output). After harvest, natural mortality is accounted for, based on a mortality at age curve that was built from Lower Fraser River White Sturgeon population data. Finally, individuals that are still alive at the end of the annual time step are then moved across the nine zones, based on an array of among-zone movement probabilities.

The time loop process is continued until the specified number simulation years are reached. For long simulations, due to the memory restrictions, results must be written out to file every couple of years and reread. Shorter simulations are able to retain all results in memory and therefore will run proportionately quicker. Where possible, the application attempts to keep results in memory to speed up simulation execution.

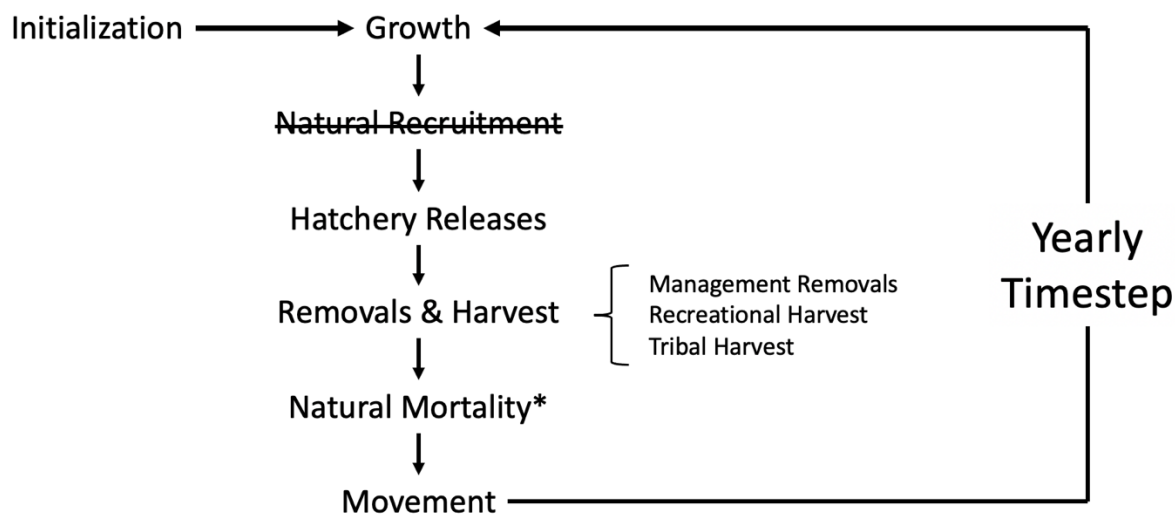


Figure 30. Major population processes modelled on each time step.

Population Initialization

At the start of the simulation, an age-structured population is created then distributed across the nine zones according to movement probabilities. The starting values for total abundance of hatchery and wild stock populations were based on the abundance estimate of wild type (1,500; CV 12%) and hatchery-derived fish (11,000; CV 10%). Each simulation iteration started with a slightly different number of hatchery and wild type fish, based on the respective estimate and coefficient of variation. Individuals in each initial population were then assigned sizes based on catch size frequencies, adjusted for gear selectivity, and an age was assigned based on growth curves. Afterwards, individuals were distributed spatially based on the stationary distribution of the movement probability matrix. As such, the initial population represents an equilibrium state, based on best available stock assessment data, prior to the initiation of the forward simulation.

Sizes were assigned to the initialized population based on observed size frequency catch data, after including adjustments for size-based catchability differences. Age-specific catch estimates of the population were available, and could have been used, but the estimates were derived from data with a small sample size and with large gaps between observed age categories, and which was not consistent with the size frequency data (which showed a much smoother distribution; Figure 31). Given the importance of the size structure when simulating the effects of slot limit fisheries on the population, the size frequency data were prioritized. The only drawback with size frequency catch data was the potential bias of size selective fishing gear, where gear typically used to catch White Sturgeon can preferentially capture larger fish over smaller fish. As such, size frequency data typically underrepresents smaller individuals and therefore is a biased sample of the true size distribution. Biases at larger sizes are also possible, if larger individuals are selected out of the gear, but this was viewed as unlikely for the Upper

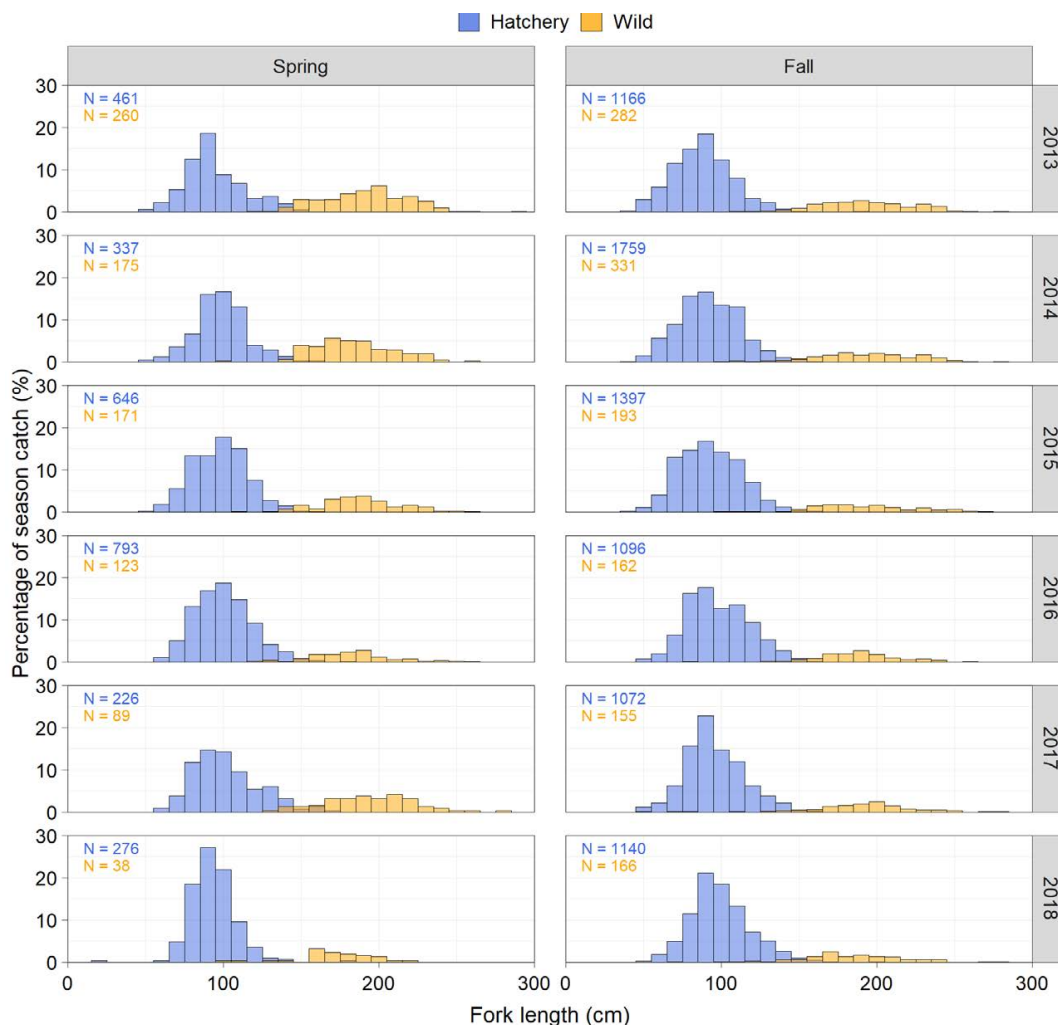


Figure 31. Size frequencies for hatchery and wild type sturgeon derived from catch data in the Upper Columbia.

Columbia population given that the majority of fish were smaller hatchery releases, and the wild adult population were still of a moderate size.

Correcting size biases in catch data can be done if the gear selectivity is known for a particular fishery. The size-selectivity of the Upper Columbia fishery has not been currently estimated so an angling size-selectivity curve estimated in the Lower Fraser River White Sturgeon sport fishery was used as a proxy (Figure 32; Challenger et al 2020). This size-selectivity curve was estimated as part of an age-structured spatial mark-recapture stock assessment model which was used to monitor the Lower Fraser River White Sturgeon population, targeting sturgeon of similar size as the Upper Columbia test fishery. The original curve was estimated based on ages, but a size-specific version was derived based on growth curves estimated for that population (RL&L 2000). The s-shaped selectivity curve estimated for that fishery suggested that sturgeon ≥ 100 cm tend to be fully selected into a sport angling fishery, indicating that size frequency catch for hatchery fish was likely impacted by size selectivity, but that the wild population was likely fully selected into the fishery (few if any wild fish fell below this size threshold). Natural

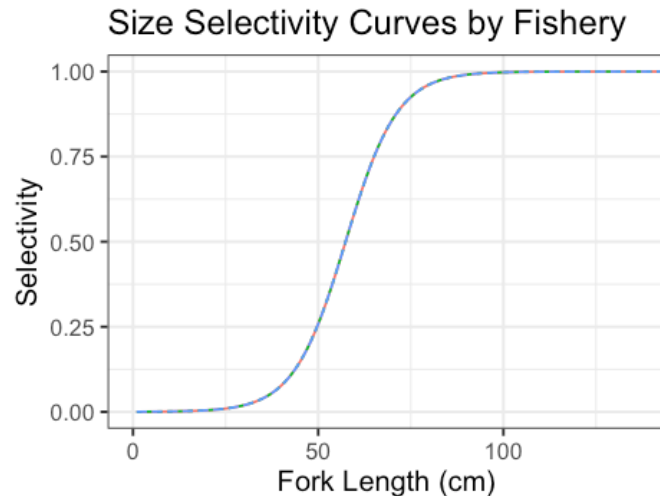


Figure 32. Size specific angling selectivity curve for the Lower Fraser River White Sturgeon sport fishery. Adapted from Challenger et al. 2020.

recruitment in the upper Columbia River has not been observed for many years, thus it is highly unlikely there were younger, smaller cohorts of wild fish that were missed.

Applying the Lower Fraser River White Sturgeon angling selectivity curve to the hatchery size frequency data allowed a corrected hatchery size distribution to be derived (Figure 33). Because this size distribution was computed as a proportion of catch (rather than as a frequency), it could be multiplied against the hatchery population size in order to derive the final hatchery size distribution that was used to initialize the population. This resulted in abundances in a series of size bins, which were normalized by randomly distributing individuals within a size bin. The size frequency of the wild population did not require the same correction as the vast majority of catch was in the asymptotic portion of the selectivity curve and therefore size-selectivity adjustments would have a minimal effect. Similar to the hatchery population, wild type size bin proportions were determined from observed size-frequency data, so that differing starting population sizes could be assigned to each size bin, with individuals randomly distributed within a size bin.

After the initial population was assigned sizes, the Korman-Crossman growth model was used to assign ages based on length-at-age curves derived from the growth model (Figure 34). The Korman-Crossman growth model is a country-specific two-season growth model. Given that the model operates on a yearly time step, growth across the two seasons were combined. Then length at age was determined by starting sizes at Age 1 (i.e., 20 cm and 25 cm for Canada and US fish, respectively), then adding yearly growth until the asymptotic size was reached. Because individuals in the wild population often exceeded the asymptotic size of the Canadian growth curve (Figure 34), the US growth curve was used to assign ages when initializing the population. Ages were generally not used in the simulation beyond incrementally aging the population and determining age class and life stage abundances (juveniles: Ages 1-10; subadult: Ages 11-20; adult: Ages 21+).

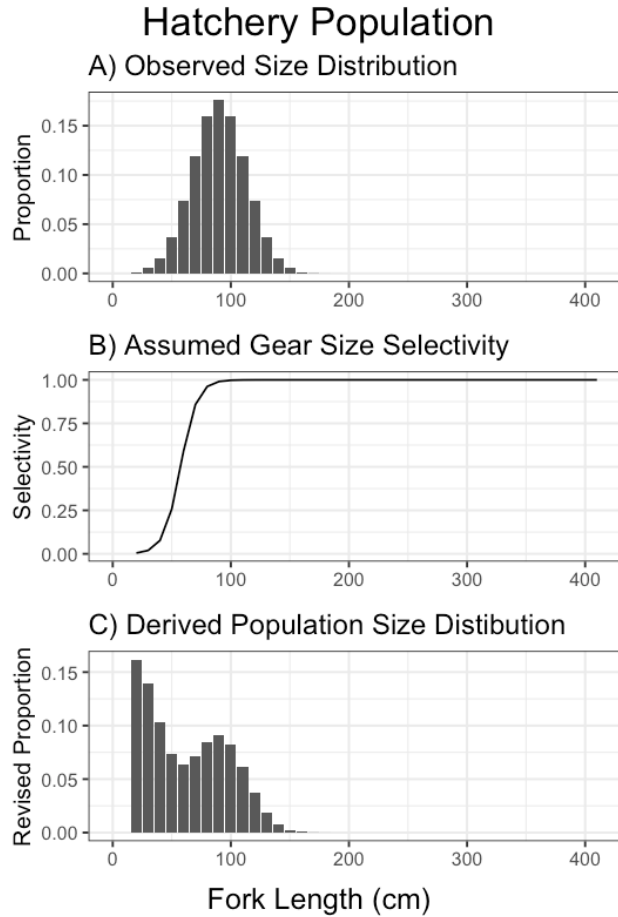


Figure 33. Observed hatchery size distribution (A), assumed size selectivity curve (B) and resulting corrected hatchery size distribution (C) used to initialize the hatchery population.

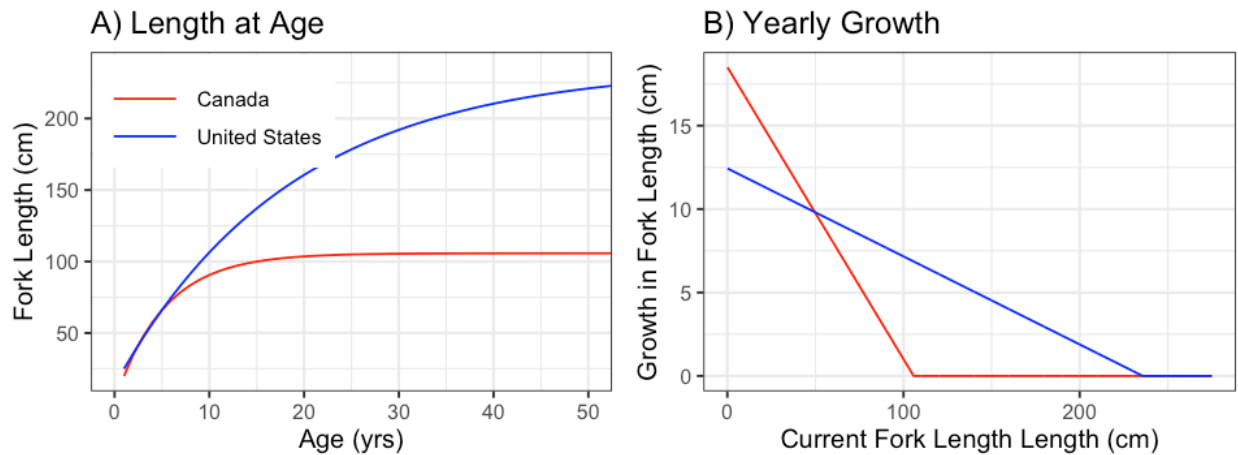


Figure 34. Length at age and yearly growth derived from the Korman-Crossman growth analysis.

Growth

Yearly growth was modelled as occurring at the start of each time step (Figure 30) based on an individual's current size, and location (i.e., United States or Canada; Figure 34b). The projected growth was added to the current individual length. Variation in growth rates was not currently considered. To speed up the simulation execution, a growth table was 'pre-computed' at the start of the simulation based on 1 mm size intervals.

Hatchery Releases

Depending on the user-defined hatchery release schedule (see *Model Runs > Hatchery Releases*), after growth, any hatchery releases were added to the population on a per year basis. A hatchery release schedule includes year, size, age, location, and abundance information. If the hatchery release schedule included a non-zero CV setting, then the corresponding attribute was varied in each simulation iteration. If a CV setting was included for the release number, then a truncated normal distribution was assumed, where the release number would be equivalent or lower than the indicated release number in order to simulate the potential effects of hatchery shortages.

Harvest and Removals

In each simulated 'year', harvest was assumed to occur after growth and hatchery releases, but prior to natural mortalities (Figure 30). Similar to hatchery releases, this was based on user settings and consisted of three potential fisheries (i.e., management, recreational, and tribal) which could be run concurrently or separately. Within the year, simulation fisheries were run sequentially, with management removals occurring first, followed by recreational fisheries, and then tribal fisheries. Depending on the specified slot limit and harvest amount, the total number of captures required to achieve a harvest goal was determined based on a gear selectivity curve (Figure 32) and abundances in the current zone (assuming equal fishing pressure across all zones for which harvest was specified as being non-zero; Figure 9). This was done by first computing the effective number of individuals after accounting for selectivity (e.g., 50% selectivity for a particular size would imply two individuals were the same as one individual that was 100% selected into the fishery), and then calculating the total number of captures required to reach the slot limits, based on random sampling of the effective individuals.

Once the total number of captures was determined to meet the goal, targeted individuals were removed, the remaining number of captures distributed among non-targeted individuals based on their size and the size-selectivity curve (assuming sampling with replacement; i.e., catch and release). As such, removal rules specifying a large number of individuals relative to the available abundances could produce unrealistically high capture and handling rates. Thus, summaries of simulated fishing effort and handling summaries should be reviewed as part of the output to ensure whether a harvest goal was feasible.

As part of the harvest removal routine, summaries of the zone-specific size distributions were determined (both before and after harvest), along with specified slot limits, to help users assess the efficacy of a removal or harvest program (Figure 9).

Natural Mortality

Age-specific mortality curves were used to simulate mortality in each simulated year. The survival-at-age data were based on estimates from the Lower Fraser White Sturgeon population, but adapted for different growth rates observed in the Upper Columbia (Figure 35a). The Lower Fraser White Sturgeon assessment model uses a length-based regression within the integrated population model (Challenger et al. 2020). Adult survival rates were assumed to reach a maximum annual survival rate of 96%, which were consistent rates estimated within the Canadian portion of the Upper Columbia (Figure 35b). Age specific survival rates were lower than what were used in a previous life cycle model used to analyze of the Upper Columbia population (Figure 35a). The primary motivation for adapting Lower Fraser River White Sturgeon estimates was that it allowed differential survival to be assigned to younger smaller fish. Once size- or age-specific survival estimates become available for the Upper Columbia fishery, the survival-at-age curve can be updated. The simulation does not currently include variation in the age-specific mortality curves that may occur within populations or between years.

Movements and Zones

The Upper Columbia simulation considered nine distinct zones across Canada and the United States (Table 1 and Figure 36). At the end of each simulated year, individuals are moved among zones based on a common movement probability matrix (Table 3). Values were adjusted slightly from estimated movement rates (Table 4) to allow movements among all zones, and to ensure the stationary distribution (i.e., the zonal proportions after a movement rates among zones reaches an equilibrium) resulted in zonal abundances that reflect catch data (see Figure 36). Without this adjustment, currently estimated movement rates (i.e., those in Table 4) resulted in a disproportionately large Canadian population.

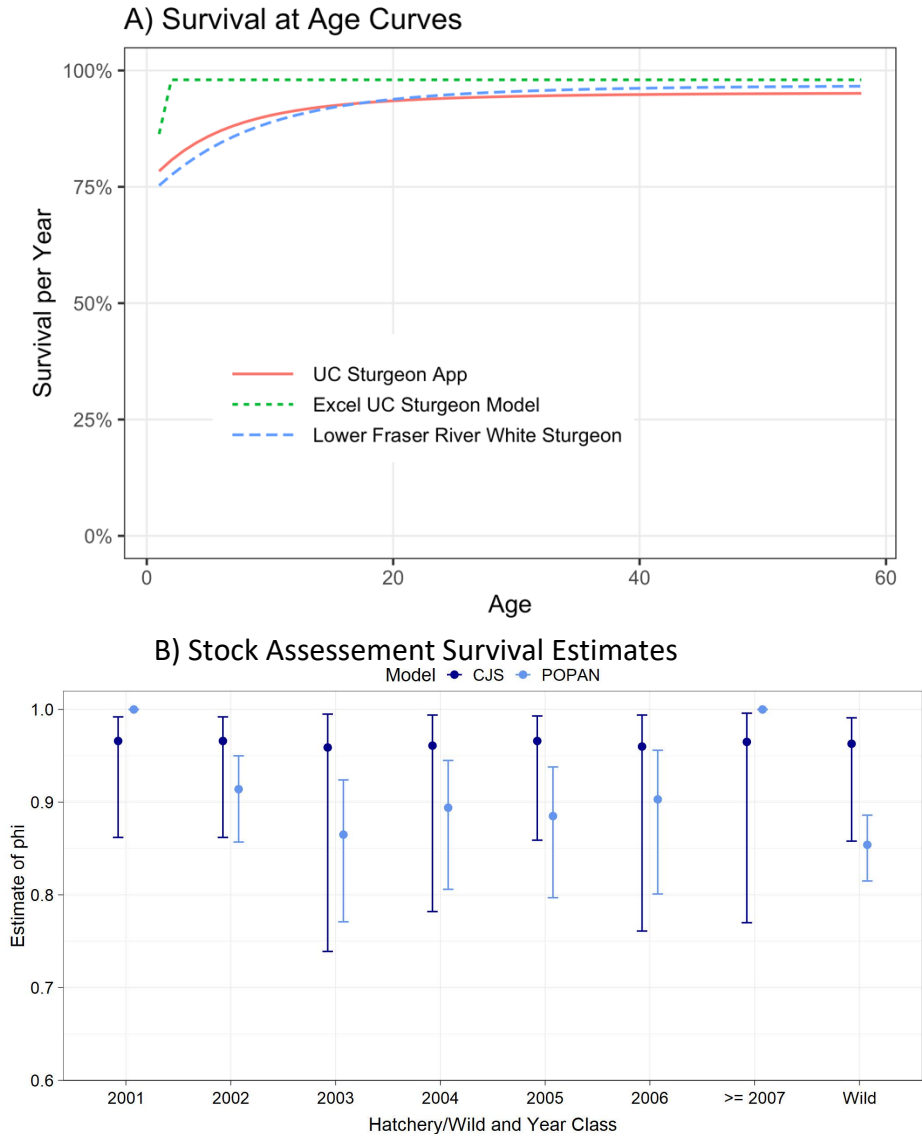


Figure 35. A) Age-specific survival rates used in the current and past versions of the model and B) Upper Columbia stock assessment Canadian survival estimates. Lower Fraser River White Sturgeon estimates adapted from Challenger et al. 2020.

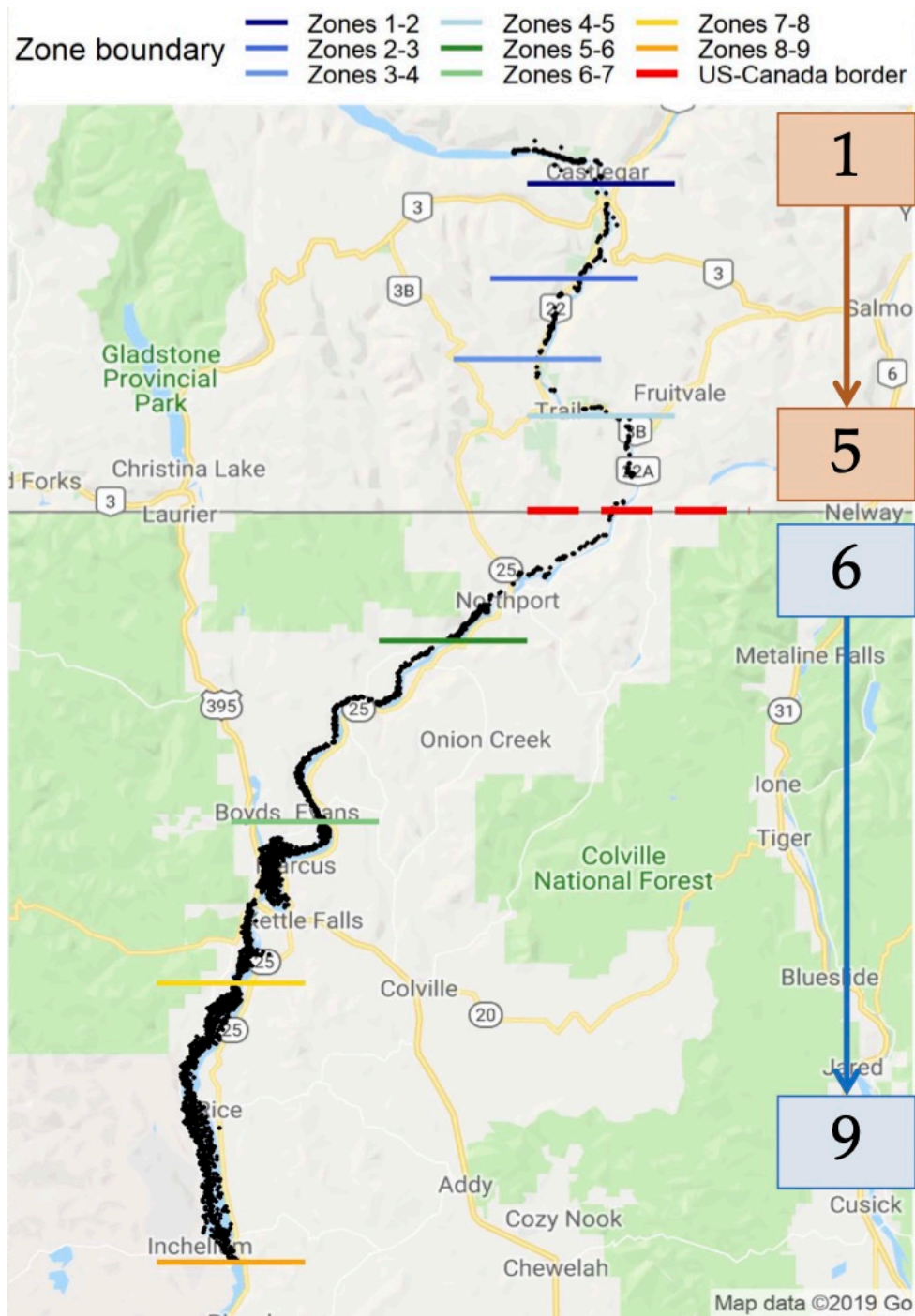


Figure 36. Map indicated modelled zones (see Table 1). Dots indicate capture events.

Table 3. Movement probabilities: rows indicate release zone, while columns indicate probability of movement to each of the nine modelled zones. Darker orange shading indicates movement within Canadian zones, while darker blue shading indicates movements within United States zones. Lighter shading indicates movements into the respective countries. Underline values indicate adjustments to allow movements to all zones.

		To Zone								
		1	2	3	4	5	6	7	8	9
From Zone	1	78.00%	8.00%	4.70%	2.00%	<u>2.00%</u>	3.00%	<u>1.00%</u>	1.10%	0.20%
	2	15.00%	66.00%	10.00%	1.30%	<u>0.45%</u>	4.50%	<u>0.03%</u>	<u>0.03%</u>	2.70%
	3	10.40%	18.00%	58.10%	2.70%	1.40%	8.00%	<u>0.05%</u>	<u>0.05%</u>	<u>1.30%</u>
	4	<u>0.05%</u>	12.50%	12.50%	37.50%	25.00%	12.30%	<u>0.05%</u>	<u>0.05%</u>	<u>0.05%</u>
	5	8.00%	10.90%	6.00%	8.00%	50.00%	15.00%	<u>0.05%</u>	<u>0.05%</u>	2.00%
	6	1.90%	2.90%	1.90%	1.00%	3.80%	32.70%	16.30%	25.00%	14.50%
	7	1.70%	0.90%	1.70%	<u>0.10%</u>	0.90%	6.70%	32.10%	33.20%	22.70%
	8	0.60%	1.00%	0.40%	<u>0.10%</u>	0.20%	3.20%	18.70%	47.20%	28.60%
	9	0.40%	<u>0.05%</u>	0.30%	<u>0.03%</u>	<u>0.03%</u>	1.90%	13.60%	39.70%	44.00%

Table 4. Movement probabilities estimated from Upper Columbia stock assessment. Darker orange shading indicates movement within Canadian zones, while darker blue shading indicates movements within United States zones. Lighter shading indicates movements into the respective countries.

		To Zone								
		1	2	3	4	5	6	7	8	9
From Zone	1	89.90%	3.70%	3.90%	0.70%		0.40%		1.10%	0.20%
	2	17.30%	68.00%	9.30%	1.30%		1.30%			2.70%
	3	10.80%	24.30%	58.10%	2.70%	1.40%	1.40%			1.40%
	4		12.50%	12.50%	37.50%	25.00%	12.50%			
	5	8.00%	12.00%	6.00%	8.00%	60.00%	4.00%			2.00%
	6	1.90%	2.90%	1.90%	1.00%	3.80%	32.70%	16.30%	25.00%	14.50%
	7	1.70%	0.90%	1.70%		0.90%	6.70%	32.10%	33.20%	22.70%
	8	0.60%	1.00%	0.40%		0.20%	3.20%	18.70%	47.20%	28.60%
	9	0.40%		0.30%			1.90%	13.60%	39.70%	44.00%

References

- Challenger, W., K.K. English, and T. Carruthers. 2017. Integrated spatial and age mark recapture (ISAMR) model (v2.0) for Lower Fraser River White Sturgeon. Report for the Habitat Conservation Trust Foundation, Victoria, BC.
- Challenger, W., K.K. English, D. Robichaud, and T.C. Nelson. 2020. Status of White Sturgeon in the lower Fraser River in 2019 derived using an integrated spatial and age mark recapture (ISAMR) model. Report for the Fraser River Sturgeon Conservation Society, Vancouver, BC, and BC Ministry of Forest, Lands, Natural Resource Operations and Rural Development, Surrey, BC.
- Chang, C., J. Cheng, J.J. Allaire, C. Sievert, B. Schloerke, Y. Xie, J. Allen, J. McPherson, A. Dipert, and B. Borges. 2021. shiny: Web Application Framework for R. <https://CRAN.R-project.org/package=shiny>
- Wickham and many others. 2019. Welcome to the tidyverse. *Journal of Open Source Software*, 4(43), 1686, <https://doi.org/10.21105/joss.01686>
- R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>
- RL&L (RL&L Environmental Services Limited) 2000. Fraser River White Sturgeon monitoring program-comprehensive report (1995– 1999). Final report to British Columbia Fisheries, Victoria.