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Harvest, Catch-effort, and Biological Data of Dolly Varden (*Salvelinus malma*) from the Rat River Collected by Community-based Monitoring Programs: 2015–2022

Colin P. Gallagher¹, Robert Bajno¹, Harry Carmichael², Florence Carmichael²,
Archie Jerome³, Ellen V. Lea¹, Joseph Neyando³, Johnnie Storr⁴, Billy Wilson³,
and Kimberly L. Howland¹

¹Fisheries and Oceans Canada
Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6

²Ehdiitat Renewable Resources Council
P.O. Box 229
Aklavik, NT X0E 0A0

³Tetlit Renewable Resources Council
P.O. Box 30
Fort McPherson, NT X0E 0J0

⁴Aklavik Hunters and Trappers Committee
P.O. Box 133
Aklavik, NT X0E 0A0

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Long-term fisheries-dependent programs, used to monitor and assess the population of anadromous Dolly Varden from the Rat River, collect information annually using standardized approaches to: estimate total harvest from coastal and inland subsistence fisheries, acquire relative abundance indices (catch-per-unit-effort; CPUE), and characterize biological properties including demographic attributes. The programs are: 1) monitoring of summer coastal fisheries (Herschel Island and Shingle Point) to collect harvest data and tissue samples for genetic mixed-stock analyses, 2) the Rat River Harvest Monitoring program to collect harvest, catch-effort, and biological data from three traditional camps during the upstream migration, and 3) community harvest surveys performed in Aklavik and Fort McPherson, NT to obtain harvest data from inland subsistence fisheries. These programs are managed by Fisheries and Oceans Canada and implemented by Gwich'in and Inuvialuit from Aklavik and Fort McPherson. This document reports on the data collected between 2015 and 2022 and compares these to the longer available time-series to describe longer-term variability and indications of changes in the population. Along the coast, the Rat River stock was almost exclusively captured at Shingle Point, where its contribution to the mixed-stock fishery varied 12–52% among years. The majority (90%) of the harvest experienced by the population occurred in inland fisheries during the upstream migration. The annual total harvest experienced by the population ranged between 270 and 879 fish (mean = 497) between 2015 and 2022 and became considerably lower (< 400 fish) between 2018 and 2022. Harvest was typically within the 5% rate used by co-management decision-makers as a guide for the annual harvest recommendations. Catch-effort data indicates population abundance was improved from 2015–2018 and declined thereafter with an exception of a higher mean value in 2021. Among years, mean fork length and round weight ranged 497–557 mm and 1,497–2,198 g, respectively, while mean condition factor ranged 1.11–1.25. Mean annual age ranged 6.0–7.2 years (minimum age of 3 years and maximum age of 15 years) with the majority of captured fish between 5 and 8 years. Annual mortality varied without trend although males experienced higher mortality relative to females (0.62 vs. 0.52). The mean gonado-somatic index of current-year non-spawning and spawning females was 0.82% and 10.5%, respectively, while those of males were 0.13 and 6.4%, respectively. Fecundity was an average of 5,676 eggs and was positively correlated with length. In some years, fish sampled earlier in the upstream migration tended to be larger individuals (> 550 mm) while those captured later were typically smaller ones (< 450 mm), while current-year spawners were consistently more prevalent earlier during the upstream migration. The recent decline in harvest and catch-effort suggests the stock has experienced a decline in status.

INTRODUCTION

Monitoring of fish populations using standardized annual fisheries-dependent approaches are important to developing a time-series of data used to evaluate changes in indicators of stock productivity, including harvest, relative abundance, and demographic properties. Furthermore, these data can be used in fisheries stock assessment models to estimate current population status and inform management decisions. Fisheries-dependent data collected for the Rat River stock of anadromous Dolly Varden (*Salvelinus malma*) (dhik'ii; Gwich'in) (iqalukpik; Inuvialuktun) has provided a valuable source of information for co-management decision-making to ensure the sustainable harvest and conservation of this culturally important population for both Gwich'in and Inuvialuit people from communities in the Mackenzie Delta area of the Northwest Territories (DFO et al. 2019).

The Rat River stock of Dolly Varden is natal to Fish Creek, a headwater tributary (transboundary between Yukon Territory and Northwest Territories) to the Rat River situated in the Richardson Mountains southwest of the hamlet of Aklavik (Figure 1). Dolly Varden from this stock are highly philopatric, genetically distinct from other populations, and demonstrate a complex life cycle (Figure A1) (Harris et al. 2015, Gallagher et al. 2018). Dolly Varden are relatively short-lived (few attain ages ≥ 10 years) and exhibit partial migration where one component of the population remains in freshwater for their entire life (stream-resident; almost exclusively males) while the other undertakes seasonal feeding migrations (anadromous; both females and males but predominantly females) between Fish Creek and the Beaufort Sea (Gallagher et al. 2019, Morrison et al. 2019). Anadromous Dolly Varden from the Rat River can spawn in consecutive or alternate years and can skip ocean migration (i.e., remain in the Fish Creek watershed during summer) once or multiple times during their lifetime (Gallagher et al. 2018). While spawning occurs primarily in the fall, there is strong evidence that a component of the adult population will spawn during summer (Gallagher et al. 2018). Although both have a similar silver colouration during migration, males and females display vivid and contrasting colouration and morphology when in spawning condition. Anadromous males display secondary spawning characteristics (e.g., kype, enlarged teeth) to defend territory from other males that are looking to access females staging at redds, whereas the stream-resident males will attempt to spawn with anadromous females using a sneaker strategy to reduce the chance of negative encounters with anadromous males.

The anadromous stock is harvested for subsistence using single mesh gill nets either during summer when feeding along the Yukon coast (i.e., a mixed-stock fishery) or between late summer and fall when migrating (returning upstream) in the Mackenzie Delta or lower Rat River. There has been a long history of work dating back to the 1980s among Gwich'in communities, co-management bodies, and Fisheries and Oceans Canada (DFO) to collect information to monitor the stock given that important declines in population abundance were identified by harvesters. The desire to conserve the stock and advance sustainable harvesting measures to ensure fishing for future generations prompted establishing programs to collect fisheries data and a co-management working group (Rat River Working Group established in 1995) that use the results from programs, along with Indigenous knowledge, to help guide decision-making. The Working Group provides recommendations on annual harvest level (i.e., voluntary), gear type, best practices for handling fish, and research of stocks in the Gwich'in Settlement Area (see Lea et al. 2021 for more details).

Currently, fisheries-dependent data for the Rat River stock are collected annually from: 1) monitoring of summer coastal fisheries to collect harvest data and tissue samples for mixed-stock genetic analyses, 2) the Rat River Harvest Monitoring program, established in its current form in 1995, which uses expert Gwich'in harvesters trained to collect harvest, catch-effort, and

biological data during the upstream migration (see Harwood 2001), and 3) community harvest surveys performed in Aklavik and Fort McPherson, NT to obtain harvest data from inland subsistence fisheries (see Lea et al. 2021).

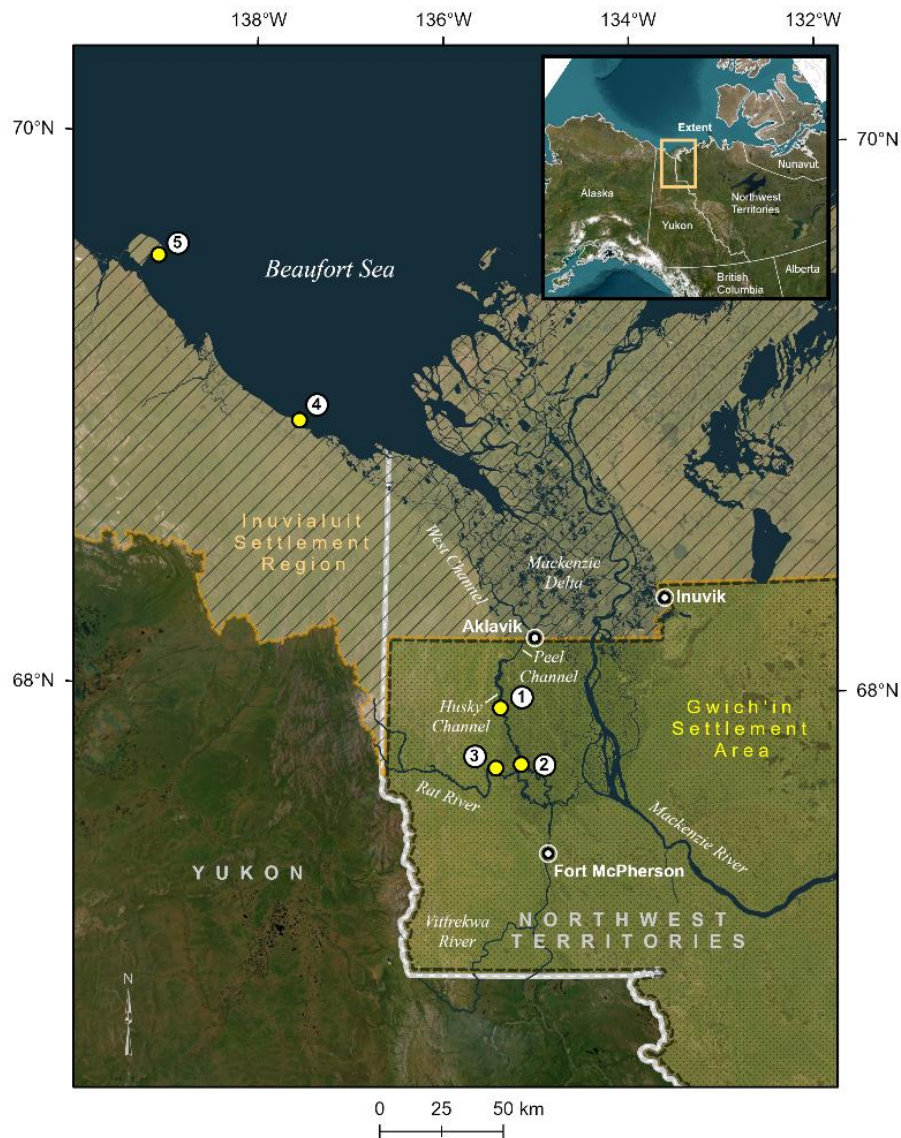


Figure 1. Locations in the Inuvialuit Settlement Region and Gwich'in Settlement Area where monitors annually collect information for anadromous Dolly Varden relevant for population assessment of the Rat River stock. Comprehensive fisheries data were collected during the upstream migration of the stock in the Mackenzie Delta (Husky Channel) at (1) Big Eddy, and in the Rat River at (2) the mouth and (3) Destruction City. Genetic samples and harvest data used to investigate the mixed-stock fishery were collected at (4) Shingle Point and (5) Herschel Island. Community harvest surveys for Dolly Varden were performed in Aklavik and Fort McPherson.

This research document presents reported stock data from the subsistence harvests and the results of the Rat River Harvest Monitoring Program between 2015 and 2022 (note, data from previous years are summarized by Harwood 2001, Harwood et al. 2009, Roux et al. 2012, DFO et al. 2019, Gallagher et al. 2020, Lea et al. 2021). Specifically, the research document:

-
- Determines the contribution of Dolly Varden from the Rat River to the mixed-stock-fishery along the Beaufort Sea coast (i.e., Herschel Island and Shingle Point) using genetic mixed-stock analyses;
 - Tabulates the estimated reported harvest from coastal and inland fisheries;
 - Estimates the annual harvest rate of the stock;
 - Summarizes catch-per-unit-effort (CPUE) and biological data (length, weight, age, survival/mortality, growth) collected from the Rat River Harvest Monitoring Program; and
 - Characterizes reproductive properties pertaining to maturity, fecundity, and gonado-somatic index.

Data from 2015–2022 were examined for trends over time and compared to results from previous years to characterize longer-term variability and indicators of change in the population. The trends and patterns in harvest, relative abundance, population demographics, and vital rates were used to inform the current stock status of anadromous Dolly Varden from the Rat River. The outcomes will provide information to characterize the fishery and biological properties of the population, and will help inform co-management decision-makers that implement the Integrated Fisheries Management Plan (IFMP; DFO et al. 2019) for Dolly Varden.

METHODS

COASTAL HARVEST AND GENETIC MIXED-STOCK ANALYSES

Dolly Varden subsistence fisheries, along the Yukon coast (Beaufort Sea), generally take place from early spring (mid-June) until late summer (late-August) and primarily occur at Herschel Island (Qikiqtaruk) Territorial Park and Shingle Point (Tapqaa) (Figure 1). The coastal fisheries target mixed-stocks originating from river systems in the Yukon, Northwest Territories, and Alaska. Inuvialuit fisheries monitors from Aklavik stationed at Shingle Point collected annual harvest and biological data along with tissue samples including adipose fin clips (stored in 95% ethanol). A similar harvest data collection and fisheries-dependent monitoring program was performed by Yukon Territorial Parks Rangers at Herschel Island. The Rangers were Inuvialuit beneficiaries who collected data from their own catches or from harvesters visiting or transiting between Aklavik and Kaktovik, Alaska (not very common). The monitoring at Shingle Point occurred mainly between mid-July until end of the first week of August, while monitoring at Herschel Island occurred mid-June to late-August (Table 1).

MIXED-STOCK ANALYSES OF COASTAL SAMPLES

Genetic stock identification estimates stock proportions through comparisons of genetic information in individuals of unknown origin to genetically characterized reference stocks. The accuracy and precision of genetic stock identification relies on a combination of factors such as quality of genetic data, representativeness of samples, and discernable genetic structure amongst the stocks contributing to the mixed fishery (Utter and Ryman 1993). The success of mixed-stock analyses (MSA) relies on the reasonable characterization of all stocks that may contribute to the fishery (i.e., the baseline). Stocks that contribute to the mixed-fishery, but have not been sampled and incorporated into the reference genetic baseline, may impact the accuracy of MSA.

Table 1. Fisheries-dependent programs, their location, and timing used to collect data relevant for the population assessment of Dolly Varden from the Rat River.

Program	Location	Latitude (N)	Longitude (W)	Timing*
Coastal harvest monitoring	Herschel Island	69.56887°	138.91848°	1
	Shingle Point	68.99407°	137.39262°	2
Rat River harvest monitoring	Big Eddy ⁺	67.96425°	135.34080°	3
	Mouth of Rat R.	67.75958°	135.13894°	3
	Destruction City (Rat R.)	67.74563°	135.38124°	3
Community harvest surveys	Aklavik	68.22000°	135.00878°	4
	Fort McPherson	67.43745°	134.88316°	4

*1: mid to late June – mid to late August; 2: mid-July – early August; 3: late July – early September; 4: late July – early/ late September.

⁺Husky Channel of Mackenzie Delta

For genetic stock identification of Dolly Varden coastal fishery harvests at Shingle Point and Herschel Island, a reference genetic baseline was developed. The baseline included all Dolly Varden stocks that could contribute to fisheries along the Beaufort Sea coast. The stock structure of Canadian northern-form Dolly Varden was described by Harris et al. (2015). Using fifteen microsatellite DNA markers, Harris et al. (2015) characterized five distinct genetic stocks supported anadromous Dolly Varden (Firth River drainage, Babbage River, Big Fish River, Rat River, and the Vittrekwa River). Anadromous and resident Dolly Varden from these systems were included in the baseline. Additionally, Krueger et al. (1999) reported that Dolly Varden from rivers on the North Slope of Alaska have contributed to Canadian coastal fishing sites. Therefore a subset of Dolly Varden from the North Slope of Alaska were also included in the baseline. These included the Kongakut River, Hulahula River, Canning River (Main Fork and Marsh Fork), Kavik River, Ribdon River, Saviukviayak River, Ivishak River, Echooka River (Sagavanirktok River system), and Anaktuvuk River (Colville River system).

Using twelve microsatellite DNA markers (see Harris et al. 2015; markers Sa72zim, Sa15UG and Sco19 were removed from these analyses), genetic variation was assessed and genetic stock structure characterized across all Dolly Varden stocks (data not shown). Based on the genetic differentiation observed, a genetic baseline consisting of eight distinct stocks (2670 individuals in total) was established. The stock structure of Canadian Dolly Varden was preserved as described in Harris et al. (2015). However, samples from the Firth River drainage and Kongakut River were genetically undistinguishable and thus were combined to represent a single genetic stock. The remaining Alaskan Dolly Varden stocks were assigned to four Alaskan regional reporting groups (categorized based on genetic data and geography; DFO unpublished, Crane et al. 2005): 1) Hulahula River and Canning River; 2) Kavik River; 3) Ribdon, Saviukviayak, Ivishak, and Echooka rivers, and 4) Anaktuvuk River.

Evaluating the discriminatory power of the genetic baseline for genetic stock identification followed similar methods outlined in Gallagher et al. (2020). To assess efficacy, simulated mixture and individual assignment analyses were employed using the 100% simulation and leave-one-out tests using the program ONCOR (Kalinowski et al. 2007). The 100% simulation evaluated the accuracy of the genetic baseline by simulating, using the method of Anderson et al. (2008), a mixed fishery sample from which all individual genotypes are from the same

baseline stock. One thousand simulations were done on mixtures containing 500 individuals generated using baseline sample sizes. Assignment estimates report the success of simulated mixtures assigning back to their respective baseline stocks. In the leave-one-out test, the genetic baseline was evaluated for how well individual fish are removed from the baseline, how well fish are assigned back to their stock of origin, and to which stock individuals were most often incorrectly assigned.

Additionally, performance of the genetic baseline was tested by estimating proportions of simulated fishery mixtures constructed of known-origin fish removed from the baseline without replacement and examining the resolving power of the baseline by performing MSA against the remaining baseline individuals. Ten mixtures for MSA were constructed by randomly removing 10% of individuals from each baseline stock. Estimates of mixture proportions were carried out in ONCOR.

Two methods were used for mixture-stock analysis. A conditional maximum likelihood method, implemented in ONCOR, was used to estimate mixture proportions and assign individuals captured in the mixed fishery to a baseline stock. For the mixture analysis, 95% confidence index (CI) were reported by bootstrapping 1,000 times. The second approach used a Bayesian mixture model, as implemented in the program cBAYES (Neaves et al. 2005). In this analysis, stock composition estimates were generated using nine 10,000 iteration Markov Chain Monte Carlo (MCMC) chains. For eight of the nine MCMC chains, the initial proportion values were set to 0.86 for a particular stock, with that stock changing for each chain. For the remaining seven stocks, proportion values of 0.14 were equally distributed. For the remaining MCMC chain, initial proportion values were equally distributed across all eight baseline Dolly Varden stocks. Convergence of chains was assessed with the Gelman and Rubin shrink factor (< 1.2). Calculation of stock composition was accomplished by combining the last 1,000 iterations of each chain.

The proportion of the contribution by the Rat River stock to a coastal fishing site was multiplied by the total reported harvest for the site to determine the number of Dolly Varden from the Rat River that were harvested from coastal fisheries in a given year.

INLAND HARVEST

The catches reported from the Rat River Harvest Monitoring Program and the annual community harvest surveys, consistent with Lea et al. (2021), that were undertaken in the communities of Aklavik and Fort McPherson (Table 1; Figure 1), were used to tabulate the total harvest by inland fisheries for Dolly Varden collected between 2015 and 2022. Briefly, a community monitor was hired by each of the Aklavik Hunters and Trappers Committee, Ehdiiat Renewable Resources Council (Aklavik), and Tetlit Gwich'in Renewable Resources Council (Fort McPherson) to interview subsistence harvesters fishing in the Aklavik and Fort McPherson areas. These community monitors were responsible for contacting harvesters twice a week, either in person or remotely (i.e., by phone, radio, or message) to record the number and location of Dolly Varden harvested along the Rat River Dolly Varden migration route (i.e., in Peel Channel, Husky Channel, and the Rat River areas). Interviews occurred around the peak Dolly Varden fishing season for each community, generally between late-July and mid-September. Genetic mixed-stock results reported by Gallagher et al. (2020) indicated that the large majority (~ 98%) of fish sampled in the Rat River Harvest Monitoring Program between 2012 and 2014 were from the Rat River stock. Therefore, it was assumed that all Dolly Varden captured in Mackenzie Delta fisheries (i.e., harvest reported near Aklavik and further south up to and including the Rat River, based on community harvest surveys and monitoring programs) were from the Rat River. An exception was Dolly Varden reported harvested near Fort McPherson, typically from a site locally known as Eight Mile, which were assumed to belong to

the Vittrekwa River stock. It should be noted that although harvest data from the Rat River Harvest Monitoring Program were reported separately from the community harvest surveys, these subsistence fishing activities generally overlapped in both time and space (Table 1). The harvest rate was calculated by dividing the estimated total harvest from the Rat River by the estimated population abundance values, based on mark-recapture studies, from the same year (Gallagher et al. 2026). No abundance estimates were available for 2020 and 2021, therefore, the 2019 estimates were used. In a single year, two population abundance estimates were generated given recaptures were obtained either from fisheries-dependent or -independent programs (Gallagher et al. 2026), which made it possible to calculate two separate rates of harvest. An average of the two was calculated in order to generate an estimated annual harvest rate.

RAT RIVER HARVEST MONITORING

The Rat River Harvest Monitoring Program is an annual fisheries-dependent data collection program for anadromous Dolly Varden, that is implemented by Gwich'in harvesters (termed 'harvest monitors' or 'char monitors') at their traditional fishing camps during the upstream migration period of the Rat River stock (Harwood 2001, Harwood et al. 2009, Roux et al. 2012, Gallagher et al. 2020). There are three sites along the freshwater migration corridor that are used for sampling: 1) Husky Channel of the western Mackenzie Delta at a location called Big Eddy, 2) mouth of the Rat River, and 3) a location in the Rat River called Destruction City (Table 1; Figure 1, Figure A2). The monitors had life-long experience on the land and with fisheries in the Mackenzie Delta or Rat River. When a monitor first became involved in the program, training was provided to measure and record biological data on standardized data sheets and collect samples (e.g., otoliths). Monitors would undertake their subsistence fishing activities and perform their monitoring duties by not only collecting data from their own catches but sometimes from other harvesters who were nearby. The intention was to have the monitor's use their experience and knowledge to determine when to start data-collection activities, where to set nets, what gill net mesh size to use, and when to sample fish. Often the monitors communicated with each other on the status of the upstream migration to help guide when to begin monitoring efforts.

The harvest monitors were tasked with recording the number of Dolly Varden and other species harvested from their gill net(s) on a daily basis. If other harvesters were in close vicinity and actively fishing, the monitor could request they voluntarily share harvest information (note, this only occurred at the mouth of Rat River site between 2015 and 2022). Monitors recorded the soak time of each net set and also noted the mesh size and total length of the net in order to calculate catch-effort. Biological sampling of Dolly Varden entailed selecting a sub-sample of the total catch (typically 75 fish per location) throughout the monitoring period and recording fork length (± 1 mm), weight (± 50 g), sex (male or female), maturity ('immature', a sexually immature juvenile or resting adult and described as a 'non-spawner'; or 'mature', an adult expected to spawn in the fall of the current year and described as a 'spawner'), and gonad weight (± 0.5 g) on standardized data sheets. Maturity was visually assessed based on the size and colour of testes and ovaries. Otoliths were removed and placed in a labelled envelope for age estimation. Muscle (only from Big Eddy), mature ovaries (fecundity and egg diameter; only from mouth of the Rat River), and adipose fin (DNA sample; all locations) were also collected. There were instances when monitors would release Dolly Varden that were alive and in good physical shape from their gill nets when they were aware they were approaching the voluntary harvest level assigned to the program prior to the fishing season. Whenever possible, the monitors recorded the lengths of Dolly Varden that were released alive from a net. Monitors also reported the recapture of any tagged fish and recorded the tag number and colour on the data sheet.

On a daily basis, the monitors recorded qualitative data pertaining to the water conditions where the net(s) was set to help inform interpretation of catch-effort data given their reported influence on capture efficiency for Dolly Varden. Both the height of the water (i.e., a proxy for discharge) and the amount of debris in the water (e.g., woody, aquatic vegetation), were recorded using a categorical scale ('high', 'normal', 'low') at each of the three sites. Additionally, water clarity (i.e., a proxy for turbidity; 'clear' or 'dirty') was also recorded.

The duration of monitoring efforts was generally intended for 35 days with a start date typically occurring at the end of July (determined by the monitors) and mainly coincided with the period when Dolly Varden began migrating past their camp. Supplementary funding for the program extended the duration of the monitoring period to 40 days in 2019, 2020, 2021, and 2022, and also provided mentoring opportunities by the experienced monitors to others who were interested in learning. Although monitoring activities did not encompass the entire upstream migration period, it was assumed that the duration covered the majority of the upstream run of fish and would yield a representative sample of the population and catch-effort data would be indicative of the relative abundance of the population. There was change in the composition of the monitors at Big Eddy as John Carmichael (senior monitor; started in 1995) and Tyler Carmichael performed the work from 2015-2018, followed by Tyler Carmichael in 2019, and then Harry and Florence Carmichael from 2020-2022. Additionally, monitoring at Destruction City transitioned from Selwyn Kay (senior monitor; started in 1989) to Joseph Neyando and Archie Jerome starting in 2021.

The monitoring program received approval from the Rat River Working Group annually, to comprehensively sample a specified number of Dolly Varden per year (between 210 and 300 for 2015-2022 time period), which was divided equally among the three locations.

AGE ESTIMATION

Otoliths were prepared and read in the age estimation laboratory of Fisheries and Oceans Canada's Freshwater Institute following the methods outlined in Gallagher et al. (2016). Whole otoliths were immersed in water in a glass petri dish and observed with a black background using a Leica or Nikon dissecting microscope (10–40x magnification) and reflected light. A confidence index rating was assigned for each age estimated: 'good', 'fairly good', 'fair', 'fairly poor', or 'poor' (ICES 2006). Estimates that received a rating of fair, fairly poor, or poor, or that were ≥ 9 years were embedded in epoxy, thin sectioned (0.35 mm thick), and re-read. Whenever there was disagreement in age between the whole and section method for a single sample, the reader re-examined the sample (the section and the second whole otolith, when available) to estimate the best final age.

CATCH-EFFORT AND BIOLOGICAL INFORMATION

The catch-per-unit-effort (CPUE) was calculated as the number of Dolly Varden captured per 25 m of gill net, per 24 hours among mesh sizes (102 mm, 114 mm, and 127 mm) and with all sizes combined. The mean, standard deviation (SD), and range of CPUE values were calculated for each sampling year among monitoring locations.

The biological data were tabulated among years and mesh sizes with sample size, mean, mode (age), and range of fork length and age for females, males, and the total sample. The same tabulation was performed for females and males identified as 'mature' (i.e., expected to spawn in the current year). Length and age frequency distributions among years were created using the total sample and for each sex and mesh size. Boxplots were used to help visualize changes in trends 2015–2022 from the entire time-series of data. A locally weighted smoothing (loess) regression analysis was used to identify patterns in the length and weight data. Growth data

(i.e., length- and weight-at-age) were plotted and the mean length of predominant age classes (5–8 years) (i.e., $n \geq 5$ per age class per year) was calculated and plotted against year to infer changes in growth among years.

Logarithmically transformed fork length was assessed for parametric or non-parametric distribution and a t-test or Mann-Whitney test, respectively was used to statistically compare size of fish between pairs of mesh sizes in a given year. The same approach was used to assess whether male and female size differed within a mesh size in a given year. Age was statistically evaluated using a Mann-Whitney test to determine if there were differences in age between pairs of mesh sizes among years and whether there was a difference between males and females (regardless of mesh size) within a year.

Fulton's condition factor (K) for each fish was calculated using fork length and mass data:

$$K = \frac{W \times 10^5}{L^3}$$

where W is round weight and L is fork length. The annual distribution and interannual variation of K was examined using boxplots.

The survival rate (S) was calculated using the age data from the total sample for each sampling year and the combined total among years according to Robson and Chapman (1961):

$$S = \left(\frac{T}{\sum N + T - 1} \right)$$

$$T = \sum_{x=0}^k x(N_x)$$

where N is the total number of fish fully recruited to the gear (modal age +1), and x is the sequential coded age (first age coded as 0, second as 1, third as 2, etc.) of those fully recruited. T is derived from the vulnerable ages in the samples. The survival of the combined total of females and males was calculated to evaluate differences between the sexes.

The standard error of S (SE_S):

$$SE_S = \sqrt{S \left(S - \frac{T - 1}{\sum N + T - 2} \right)}$$

and 95% confidence intervals were also calculated. Annual mortality was calculated as $1-S$. Survival and confidence intervals were calculated using the FSA (Simple Fisheries Stock Assessment Methods) package in R (Ogle et al. 2023).

The reproductive characteristics were examined by determining the proportion of 'immature' (i.e., non-spawner) and 'mature' (i.e., spawner) individuals among age and size classes. For samples with gonad weight, the gonado-somatic index (GSI %) was calculated as:

$$GSI = \frac{\text{gonad weight (g)}}{\text{round weight (g)}} \times 100$$

and plotted against age and length for 'immature' and 'mature' females and males to infer ontogenetic changes in reproductive investment. The frozen whole ovaries of mature females intending to spawn in the fall that were collected by the monitor at the mouth of the Rat River were later thawed in a 10% formalin solution, neutralized with Formalex, and all oocytes were counted to determine total fecundity and egg diameter ($n = 119$). Egg diameter was estimated

from the mean of three measurements of 10 randomly selected eggs, which did not vary greatly in size, aligned on a ruler. Fecundity was plotted against length and weight and a linear regression (i.e., best fit) was used to characterize the relationship. The relationship between fork length and egg diameter was examined using a Pearson correlation.

All tabulation and statistical analyses of the biological data were performed in R (version 4.2.2) using base R and specialty packages while the graphics were created using R's ggplot package (R Core Team 2022).

RESULTS AND DISCUSSION

GENETIC MIXED-STOCK ANALYSES

The genetic baseline was robust for mixed-stock analyses (MSA) to determine contribution estimates of Rat River Dolly Varden to the coastal fisheries at Herschel Island and Shingle Point. Results of the 100% simulations in ONCOR suggested that precision of the genetic baseline was high and ranged from 88.7% (Alaska reporting group: Hulahula and Canning rivers) to > 99% for each of the Canadian Dolly Varden stocks (mean = 99.8, SD = 0.002, $\sigma^2 = 4.09^{-6}$). Across all baseline stocks, mean estimate was 97.9% (SD = 0.034, $\sigma^2 = 1.17^{-3}$).

Accuracy of the individual assignments based on the leave-one-out test, in ONCOR, indicated that 99% of Rat River individuals in the genetic baseline were correctly assigned back to the Rat River stock. The largest misidentification of Rat River individuals was to the Vittrekwa stock (0.5%) followed by 0.25% misassigned (1 individual) to each of the Big Fish River and an Alaskan reporting group (Ribdon, Saviukviayak, Ivishak, and Echooka rivers) stock. For the remaining Canadian stocks, Big Fish River, Vittrekwa River, and Babbage River each had correct assignment of 99%, 99% and 95% respectively. The Firth River drainage and Kongakut baseline stock correctly assigned 84.6% of individuals with the largest misidentification assigned to the Hulahula and Canning rivers (correctly assigned 68.9% of fish) reporting group at 7.1%. The Hulahula and Canning rivers are the most easterly systems, in Alaska, incorporated into the genetic baseline. The remaining Alaskan reporting groups reported 82.1% to 92.2% correct assignment.

The genetic baseline was shown to be effective for the purpose of estimating proportions of Rat River individuals to a mixed fishery during MSA of simulated mixtures of known-origin fish. Across the MSA assessments, 98.9% (SD = 0.008, $\sigma^2 = 6.40^{-5}$) of Rat River individuals were correctly identified as belonging to the Rat River Dolly Varden stock.

For MSA of the coastal fisheries at Herschel Island and Shingle Point, both conditional maximum likelihood and Bayesian mixture methods produced similar results (Table 2). Dolly Varden samples collected from coastal fisheries between 2015 and 2022 revealed no significant contribution of the Rat River stock to the Herschel Island fishery because the 95% CI of the estimated contribution included 0 (Table 2). The only exception was in 2016 when 1.5% (95% CI = 0.2–4.0%) of the genotyped coastal samples were categorized as belonging to the Rat River stock (n = 3 fish). Higher contributions of Rat River Dolly Varden were detected at Shingle Point, which averaged approximately 27.5% and ranged between 12% (in 2021) and 52% (in 2015) among years (Table 2).

The higher contribution of the Rat River stock at Shingle Point compared to Herschel Island subsistence fisheries is consistent with results from 2011–2014 (Gallagher et al. 2020). In the 12 years of available information, the Rat River stock was only ever detected in one year at Herschel Island, which underscores how infrequently the population is found in coastal fisheries west of Shingle Point. Although Herschel is a far distance for Rat River Dolly Varden to travel

from their spawning and overwintering area, satellite tagging data from a small number of fish indicates a tagged individual from the stock made its way nearly as far west and in the vicinity of the island, albeit offshore (152 km) (Gallagher et al. 2021). Further study is needed to better understand the marine movements of the stock and its implications for fisheries. While it appears the Rat River population rarely occupies nearshore locations in the Herschel Island area, it does not exclude the possibility that the stock may be inclined to occupy more offshore areas as fish travel further west and away from the mouth of the Mackenzie River.

Table 2. Estimates of contribution rates (%) and 95% confidence intervals, in brackets, of the Rat River Dolly Varden stock to samples harvested at Herschel Island and Shingle Point between 2015-2022. Results are based on stock mixture analyses using Bayesian and conditional maximum likelihood approaches with BAYES and ONCOR software, respectively. n is the sample size of fin clips that were genotyped.

Year	Herschel Island			Shingle Point		
	BAYES	ONCOR	n	BAYES	ONCOR	n
2022	0.06 (0–0.5)	0	247	12.64 (0.4–40.8)	12.5 (0–37.5)	8
2021	0.04 (0–0.2)	0	336	12.41 (6.0–20.8)	12.33 (5.5–20.5)	73
2020	0.14 (0–1.2)	0	96	0.79 (0–7.4)	0	12
2019	0.32 (0–1.1)	0.3 (0–0.9)	337	34.6 (27.7–42.3)	34.71 (27.1–43.0)	144
2018	0.01 (0–0.4)	0	267	26.22 (12.0–44.9)	26.92 (11.5–46.2)	26
2017	0.64 (0–2.3)	0.58 (0–1.7)	172	15.0 (10.0–20.8)	15.1 (10.1–20.8)	159
2016	1.50 (0.2–4.0)	1.45 (0–3.6)	138	37.76 (31.5–43.9)	38.1 (32.3–44.3)	246
2015	0.12 (0–1.0)	0	113	52.37 (46.6–58.8)	52.5 (46.7–57.8)	270

Caution is warranted in the interpretation that no Rat River Dolly Varden were harvested at Shingle Point in 2020. Because the number of adipose fin clip samples that were genotyped ($n = 12$) was low relative to the total reported harvest of Dolly Varden at Shingle Point ($n = 40$; Gallagher et al. unpublished) (i.e., majority of harvest was not sampled for genetic analysis), it is possible that individuals from the Rat River stock were harvested but their genotypes were not present in the genotyped samples. Similarly, the stock was detected at Shingle Point in 2022, but a low number of genetic samples ($n = 8$) relative to the reported harvest ($n = 30$; Gallagher et al. unpublished) were analyzed. An alternative approach for estimation purposes could be to apply a 23.4% contribution rate, which is the average from 2011–2021 (excluding 2020), to the reported harvest in 2020 and 2022, which yields an estimated harvest of 9 and 7 Rat River Dolly Varden, respectively. Regardless, because the reported harvest at Shingle Point was considerably low in both years, the accuracy of removals from the Rat River from the site becomes less of an issue for precise harvest data for co-management purposes.

HARVEST INFORMATION

On average, the proportion of the total reported harvest of the Rat River stock in coastal and inland fisheries accounted for 10% and 90%, respectively among years. In most years, < 5% of the harvest occurred on the coast, however, notable exceptions were observed in 2015 and 2019 when approximately 25% of the annual harvest occurred along the coast. The estimated number of Rat River Dolly Varden harvested from coastal fisheries varied considerably among years with high values (> 100) in 2015 ($n = 196$), 2016 ($n = 121$), and 2019 ($n = 109$), and

relatively low values (≤ 12) in 2018 and 2020–2022 (Table 3). Community surveys of inland fisheries during the upstream migration ranged between reports of 358 (in 2017) and 14 (in 2018) (Table 3). Most of the inland harvest of Dolly Varden were reported from the Rat River Harvest Monitoring Program (range = 223–491) while reports from the community surveys typically accounted for $< 20\%$ of the total harvest. The total harvest for Dolly Varden from the Rat River ranged between 879 (in 2017) and 273 (in 2022), and demonstrated a decreasing trend between 2015 and 2022 (Pearson $r = -0.83$) (Table 3). In most years, the total harvest was lower than the voluntary harvest level suggested by the co-management partners from the Rat River Working Group (Lea et al. 2021) (Table 3). The average harvest rate among years was $\leq 5\%$ apart from 2019 when the rate was slightly higher (7.3%) (Table 3).

Table 3. Number of Dolly Varden from the Rat River stock harvested from coastal and inland locations, voluntary harvest level, and annual harvest rates between 2015–2022. Harvest rate 1 = population abundance based on recaptures from the Rat River Harvest Monitoring Program (Gallagher et al. 2026) divided by the total harvest. Harvest rate 2 = population abundance based on recaptures from seining program (Gallagher et al. 2026) divided by the total harvest.

Year	Beaufort Sea Coast¹	Inland: Community Harvest Surveys²	Inland: Rat River Harvest Monitors	Total Harvest	Voluntary Harvest Level	Harvest Rate 1 (%)	Harvest Rate 2 (%)	Average Harvest Rate (%)³
2022	4	43	223	270	450	4.3	5.2	4.7
2021	11	48	262	321	450	6.1 ^B	4.3 ^B	5.2 ^B
2020	0	15	272	287	750	5.4 ^B	3.8 ^B	4.6 ^B
2019	109	89	256	454	750	8.6	6.1	7.3
2018	12	14	309	335	600	1.9	1.6	1.8
2017	30	358	491	879	600	3.0	3.3	3.2
2016	121 ^A	172	369	662	450	2.8	4.6	3.7
2015	196	148	425	769	450	4.9	2.5	3.7

¹Based on estimates of genetic mixed-stock analyses.

²Mackenzie Delta and Rat River only.

³Average between Harvest rate 1 and Harvest rate 2.

^A 118 fish from Shingle Pt. and 3 fish from Herschel Island

^B Based on the 2019 population estimate given 2020 and 2021 estimates were unavailable.

In the years following the voluntary closure (2006-2008), harvest remained relatively low given that a more conservative approach towards harvest decision-making was implemented (Figure 2). From 1997–2005, in addition to the harvester’s and monitor’s knowledge on stock status, the voluntary harvest guideline was based on 10–15% of the most recent available population estimate while in 2009 it was between 5 and 10%, which subsequently changed to 5% starting in 2010. In recent years when harvest guidelines were surpassed (2015–2017), they were associated with a period of increased abundance estimates for the stock (Gallagher et al. 2026). In most years when total harvest surpassed the guideline, the tallies from the inland fisheries, which are possible to track in-season compared to the mixed-stock (whose contributions cannot be determined until after the fishing season), were close to the guideline. A subsequent decline (starting in 2018; Gallagher et al. 2026) in abundance was concomitant with lower reported harvest (Figure 2). The estimated inland harvest data underscores how harvesters have been compliant with the conservative recommendations made by the Rat River Working Group. It is also important to consider that factors other than stock abundance, such as environmental and socioeconomic conditions, would also have influenced annual harvest patterns.

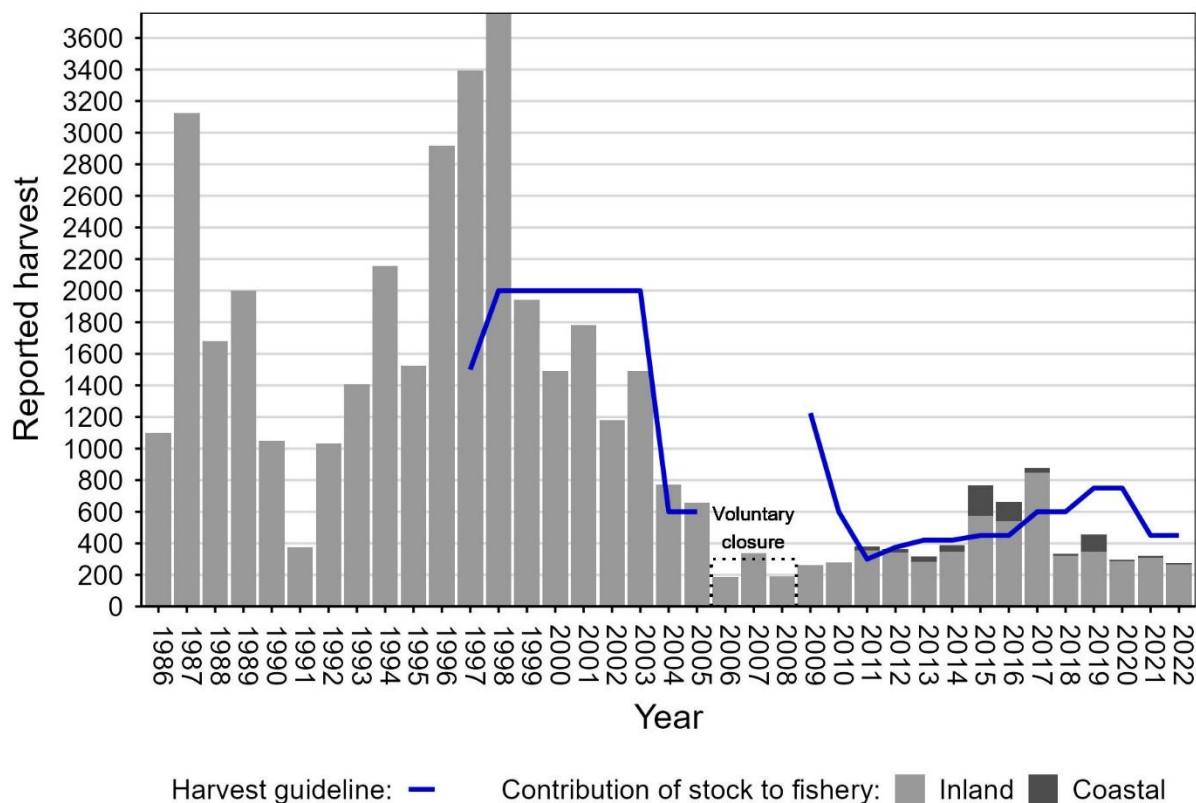


Figure 2. Total harvest of Dolly Varden from the Rat River, 1986–2022. Coastal harvest data available starting in 2011 based on results from genetic mixed-stock analyses.

RAT RIVER HARVEST MONITORING DETAILS

The monitors stationed at the three sites had slight (± 2 days) to moderate (> 7 days) differences in start dates and program duration among locations and years (Table 4). The monitors at Big Eddy tended to start earlier while those at Destruction City would typically monitor for the longest amount of time compared to other sites (Table 4). In most years, the monitors achieved their allocated amount to comprehensively sample their harvest (Table 5). Supplemental length information from fish captured in nets that were measured and released

back to the water were obtained in 2016, 2017, and 2021, mainly from the site at the mouth of the Rat River (Table 5).

Since 2014, the timing of the start of monitoring activities at the mouth of Rat River and Destruction City appears to be occurring approximately one week earlier compared to other years (Figure 3). At Big Eddy, the start time has varied sinusoidally over time with relatively early start dates (i.e., ~ July 22) occurring in 1998 and 2013, and later start dates (i.e., ~ August 9) in 2002 and 2018 with incremental annual changes between peaks and troughs (Figure 3). Altogether, these temporal patterns among monitoring locations may be indicative of change in the upstream migration timing of Dolly Varden. Earlier migration timing associated with climate change has been observed in other salmonids (Kovach et al. 2013, Dempson et al. 2017).

Table 4. Start and end dates, and total number of days at three sampling locations (Big Eddy, mouth of Rat River, and Destruction City) for the Rat River Harvest Monitoring Program (2015-2022). Note: in 2021 data were collected until September 9 but no fish were captured after September 5 and data after that date were not used in catch-per-unit-effort calculation.

Year	Big Eddy			Mouth of Rat River			Destruction City		
	Start date	End date	Total days	Start date	End date	Total days	Start date	End date	Total days
2022	Jul. 30	Sept. 12	44	Jul. 30	Sept. 7	38	Aug. 1	Sept. 8	38
2021	Jul. 21	Sept. 7	41	Jul. 31	Sept. 9	40	Aug. 6	Sept. 9	34
2020	Jul. 24	Sept. 8	46	Jul. 26	Sept. 11	47	Jul. 26	Sept. 10	51
2019	Jul. 31	Sept. 3	34	Aug. 3	Sept. 10	38	Aug. 3	Sept. 10	41
2018	Aug. 6	Aug. 28	22	Aug. 5	Sep. 4	30	Aug. 5	Sep. 10	37
2017	Aug. 5	Sep. 2	28	Aug. 1	Sep. 4	34	Aug. 1	Sep. 4	34
2016	Jul. 31	Sep. 2	33	Aug. 2	Sep. 3	32	Aug. 2	Sep. 6	39
2015	Aug. 1	Aug. 26	25	Jul. 20	Aug. 20	31	Jul. 20	Aug. 21	33

Table 5. Sampling characteristics among the three locations (Big Eddy, mouth of Rat River, and Destruction City) of the Rat River Harvest Monitoring Program (2015–2022).

Year	Big Eddy			Mouth of Rat River			Destruction City		
	Dead-sampling allocation	Dead-sampled	Live-released*	Dead-sampling allocation	Dead-sampled	Live-released*	Dead-sampling allocation	Dead-sampled	Live-released*
2022	75	73	0	75	75	0	75	75	0
2021	75	75	102	75	61	64	75	60	0
2020	100	92	0	100	100	5	100	72	0
2019	100	67	0	100	100	0	100	74	0
2018	75	74	0	75	75	0	75	75	0
2017	75	75	0	75	76	52	75	75	0
2016	70	70	17	70	70	37	70	70	0
2015	70	70	0	70	70	88	70	70	0

*measured for fork length only

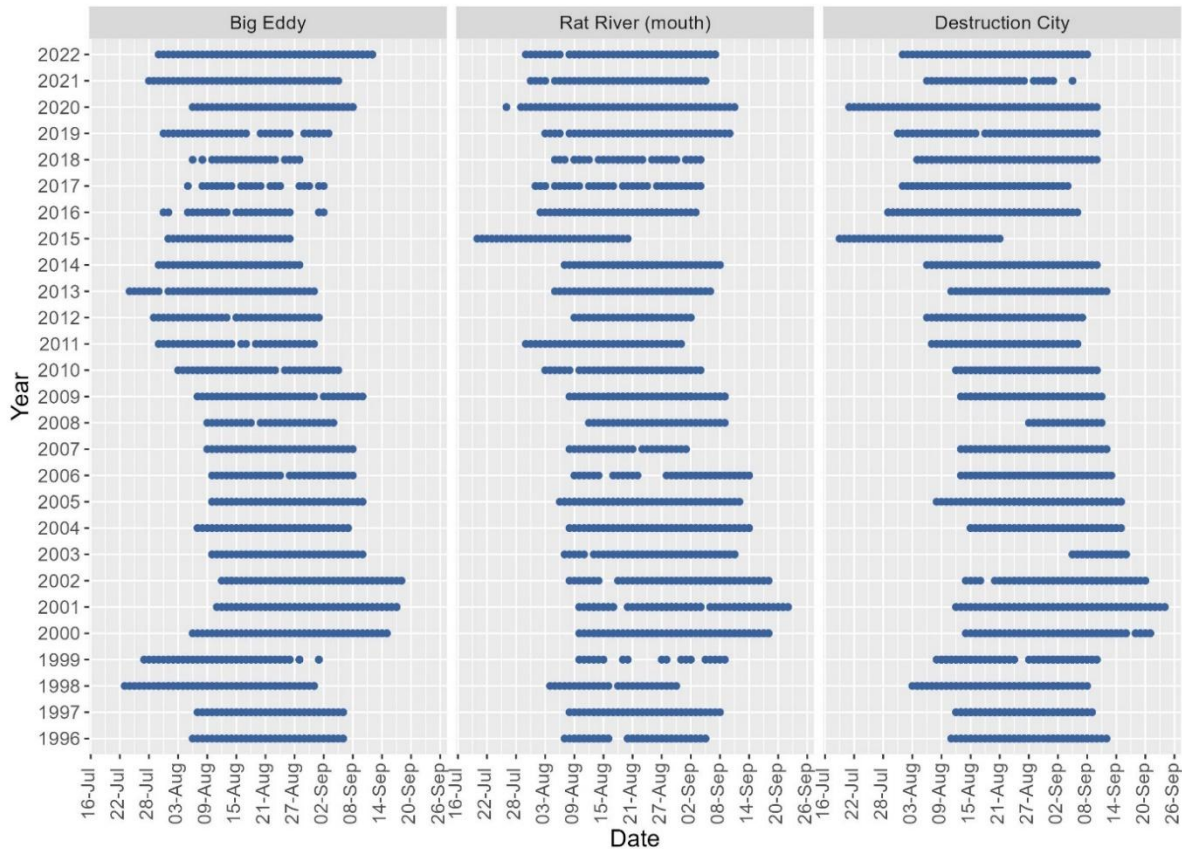


Figure 3. Dates when catch-per-unit-effort data were collected among the three sites (Big Eddy, mouth of Rat River, and Destruction City) of the Rat River Harvest Monitoring Program, 1996–2022. The start-date tends to coincide when Dolly Varden arrived at the sites.

CATCH-EFFORT

The dominant gill net mesh size used between 2015 and 2022 was 114 mm (64.8%) followed by 102 mm (29.1%) and 127 mm (6.1%; only used at Big Eddy in 2021 and Destruction City in 2020). The monitors seldom used different mesh sizes within a year with exceptions that include Destruction City in 2020 when they started the program mainly using a 127 mm mesh net for approximately two weeks and then alternated blocks of days with 114 and 102 mm mesh nets (Figure 4). In 2021, monitors at Big Eddy started with a mix of 114 and 127 mm mesh, and after peak catches of fish in late August, the 127 mm mesh net was solely used (Figure 4). Monitors tended to consistently use nets with the same mesh sizes among years (i.e., 114 mm); however, in some instances they would change to a different mesh size within a given year.

The most common gill net length was 22.9 m (32.1%), other gill net length used ranged between 12.8 m and 22.9 m. There were high instances of zero-catches ($n = 430$; 31.8% of CPUE records) in the monitoring program across years (Figure 5). The monitors' daily catches of Dolly Varden tended to start low and slowly increase to a peak typically observed in the third week of August; although, some years also demonstrated a separate yet much smaller bump in catches in the first week of August (e.g., mouth of Rat River and Big Eddy in 2019, mouth of Rat River in 2018 and 2016, and Destruction City in 2018 and 2017) (Figure 4). Patterns in catches, in some years, were consistent among sites (e.g., daily catches ≤ 10 fish 2018–2020) or considerably different (e.g., higher catches at Big Eddy and mouth of Rat River compared to Destruction City in 2015) (Figure 4).

Within a given year, the start of a monitoring season had many occurrences of zero catches (Figure 5). In many instances, CPUE would gradually increase and the greatest proportion of relatively higher values (i.e., ≥ 10 fish/25 m/24 hrs) occurring by approximately the second or third week of August before subsequently decreasing (although 2016 and 2017 were exceptions) (Figure 5). In other years (e.g., all sites in 2020), there was no clear temporal pattern.

Catch-effort between 2015 and 2022 was assessed using a total of 1,353 records (includes zero-catches). CPUE was relatively high (i.e., predominantly > 10 fish/25 m/24 hrs) among sites between 2015 and 2017 (along with Destruction City in 2018) with mean values from combined mesh sizes among sites as high as > 20 fish/25 m/24 hrs (Table 6; Figure 6). A subsequent decline in CPUE was evident where mean annual values were < 5 fish/25 m/24 hrs that was followed by an increase in 2021 at the mouth of Rat River and Destruction City sites but not for Big Eddy, based on the 140 mm stretch mesh gill nets (Table 6; Figure 6). In the following year (2022), the mean/median CPUE decreased, particularly for Big Eddy (Figure 6). The CPUE values in 2015–2018 indicated higher relative abundance that were comparable to values from the middle (~ 2008 –2012) and start (late 1990s) of the time-series (Figure 6, Figure 7) suggesting a cyclical pattern.

Although CPUE data from the Rat River Harvest Monitoring Program can be highly variable within a season and among sites, the temporal pattern of the annual grand mean CPUE generally follows patterns of abundance estimates. Specifically, the available time-series of mean CPUE and abundance from the same year are positively correlated (Spearman $r = 0.59$) (Figure A3), which underscores the utility of the CPUE data to track the abundance of the stock.

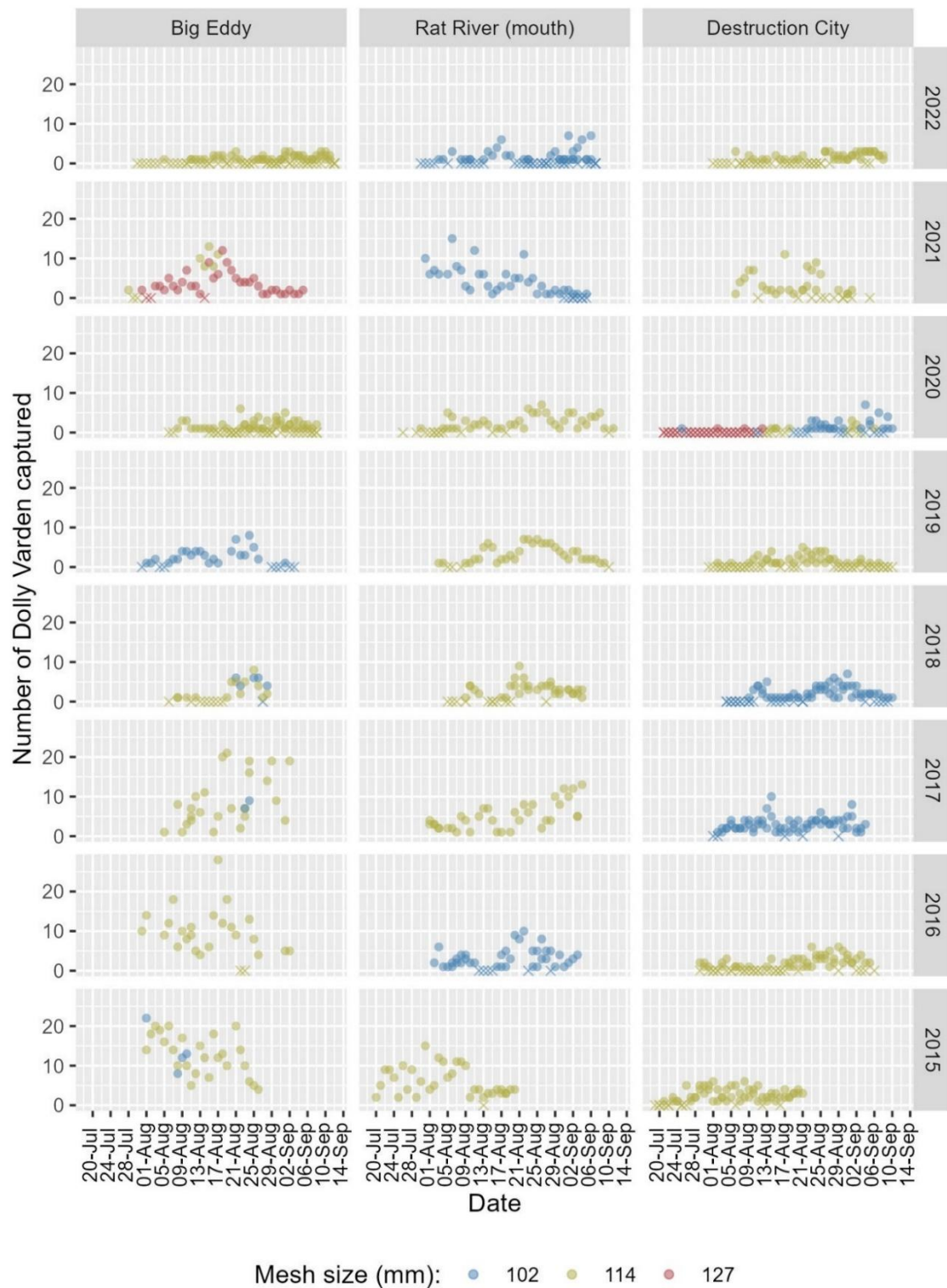


Figure 4. Daily number of Dolly Varden captured among gill net mesh sizes from the three sampling locations (Big Eddy, mouth of Rat River, and Destruction City) of the Rat River Harvest Monitoring Program (2015–2022). Instances of zero catch are illustrated with an x. Note: a catch of 38 fish on August 20, 2015 at Big Eddy is not shown to better visualize the graphic. Gill net mesh are 102 mm (blue), 114 mm (yellow) and 127 mm (red).

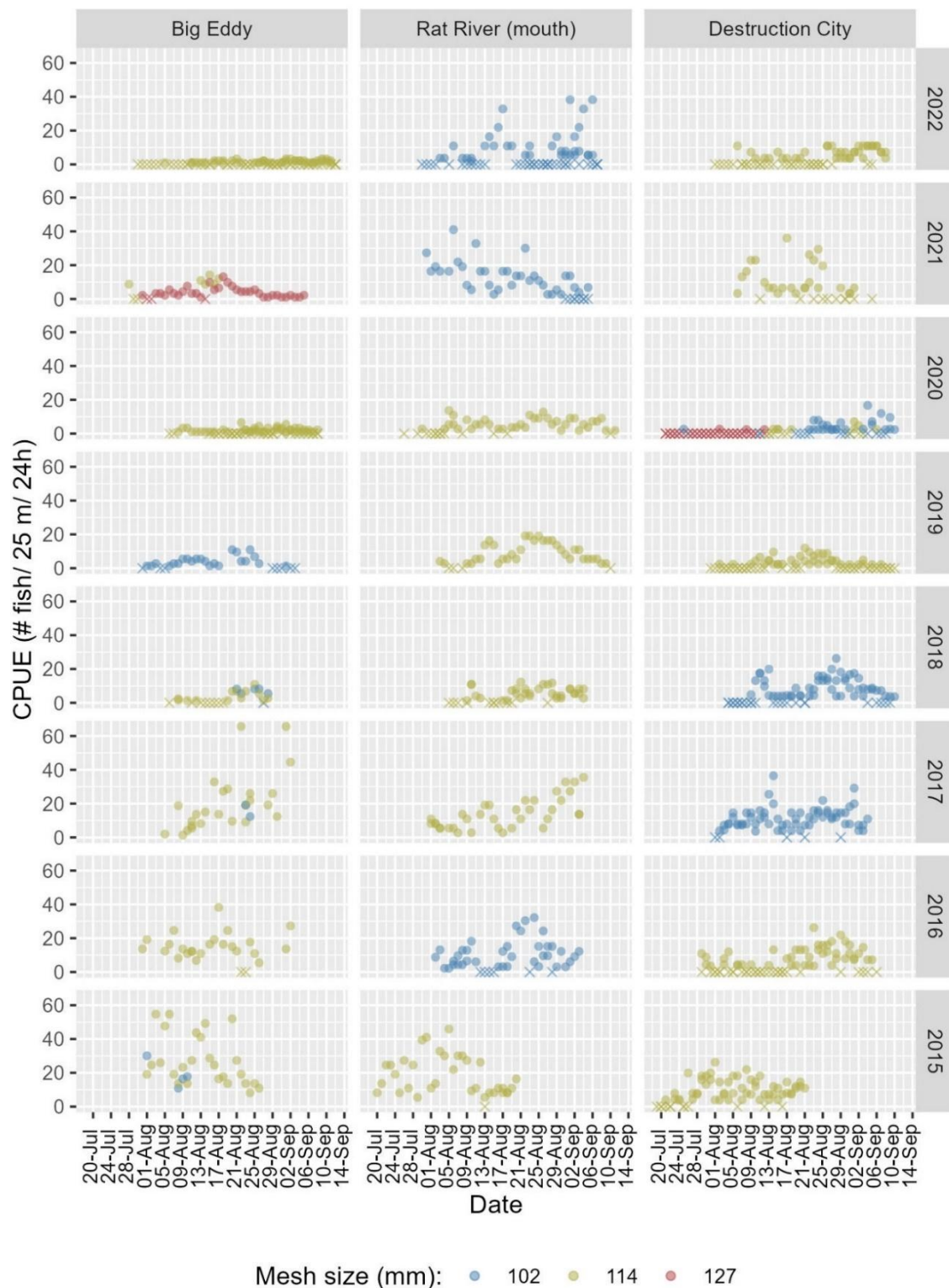


Figure 5. Daily catch-per-unit-effort (CPUE; # fish/25 m/24 hours) among gill net mesh sizes from the three sampling locations (Big Eddy, mouth of Rat River, and Destruction City) of the Rat River Harvest Monitoring Program (2015–2022). Instances of zero catch are illustrated with an x. Gill net mesh are 102 mm (blue), 114 mm (yellow) and 127 mm (red).

Table 6. Number of gill net sets (*n*), mean (standard deviation in brackets) and range of catch-per-unit-effort (CPUE, number per 25 m per 24 hours) of Dolly Varden from the Rat River Harvest Monitoring Program among 102, 114, 127 mm and combined gill net mesh size (2015–2022) at three locations: Big Eddy, mouth of Rat River, and Destruction City.

Location	Year	102 mm			114 mm			127 mm			Combined		
		<i>n</i>	Mean	Range	<i>n</i>	Mean	Range	<i>n</i>	Mean	Range	<i>n</i>	Mean	Range
Big Eddy	2022	-	-	-	96	0.8 (1.0)	0–3.3	-	-	-	96	0.8 (1.0)	0–3.3
	2021	-	-	-	8	7.9 (5.3)	0–14.2	37	3.7 (3)	0–13.1	45	4.4 (3.8)	0–14.2
	2020	-	-	-	106	1 (1.3)	0–6.6	-	-	-	106	1 (1.3)	0–6.6
	2019	31	3.2 (3.2)	0–10.9	-	-	-	-	-	-	31	3.2 (3.2)	0–10.9
	2018	6	5.9 (3.2)	0–8.2	21	2.5 (3.1)	0–10.9	-	-	-	27	3.2 (3.4)	0–10.9
	2017	2	15.7 (4.8)	12.3–19.1	25	20.3 (17.2)	1.4–65.6	-	-	-	27	19.9 (16.6)	1.4–65.6
	2016	-	-	-	26	14.6 (8.1)	0–38.3	-	-	-	26	14.6 (8.1)	0–38.3
	2015	4	18.8 (8.1)	10.9–30.1	26	27.1 (14.8)	8.2–54.7	-	-	-	30	26 (14.3)	8.2–54.7
Mouth of Rat River	2022	71	5.8 (9.2)	0–38.3	-	-	-	-	-	-	71	5.8 (9.2)	0–38.3
	2021	46	10.3 (9.8)	0–41	-	-	-	-	-	-	46	10.3 (9.8)	0–41
	2020	-	-	-	51	4.5 (3.8)	0–13.7	-	-	-	51	4.5 (3.8)	0–13.7
	2019	-	-	-	38	8.3 (6.1)	0–19.1	-	-	-	38	8.3 (6.1)	0–19.1
	2018	-	-	-	44	4.7 (3.9)	0–12.3	-	-	-	44	4.7 (3.9)	0–12.3
	2017	-	-	-	35	14 (9.1)	2.7–35.5	-	-	-	35	14 (9.1)	2.7–35.5
	2016	44	9.5 (8.3)	0–32.2	-	-	-	-	-	-	44	9.5 (8.3)	0–32.2
	2015	-	-	-	35	18.1 (11.6)	0–45.9	-	-	-	35	18.1 (11.6)	0–45.9
Destruction City	2022	-	-	-	72	3.7 (4.2)	0–10.9	-	-	-	72	3.7 (4.2)	0–10.9
	2021	-	-	-	35	8.7 (9.8)	0–36	-	-	-	35	8.7 (9.8)	0–36
	2020	39	3.1 (3.7)	0–16.7	16	1.7 (2.1)	0–7.2	42	0.2 (0.6)	0–2.6	97	1.6 (2.9)	0–16.7
	2019	-	-	-	79	2.1 (2.9)	0–11.9	-	-	-	79	2.1 (2.9)	0–11.9
	2018	76	6.7 (6.5)	0–26.2	-	-	-	-	-	-	76	6.7 (6.5)	0–26.2
	2017	68	10.7 (6.7)	0–36.5	-	-	-	-	-	-	68	10.7 (6.7)	0–36.5
	2016	-	-	-	77	5.9 (6.4)	0–26.2	-	-	-	77	5.9 (6.4)	0–26.2
	2015	-	-	-	66	8.7 (6.5)	0–26.2	-	-	-	66	8.7 (6.5)	0–26.2

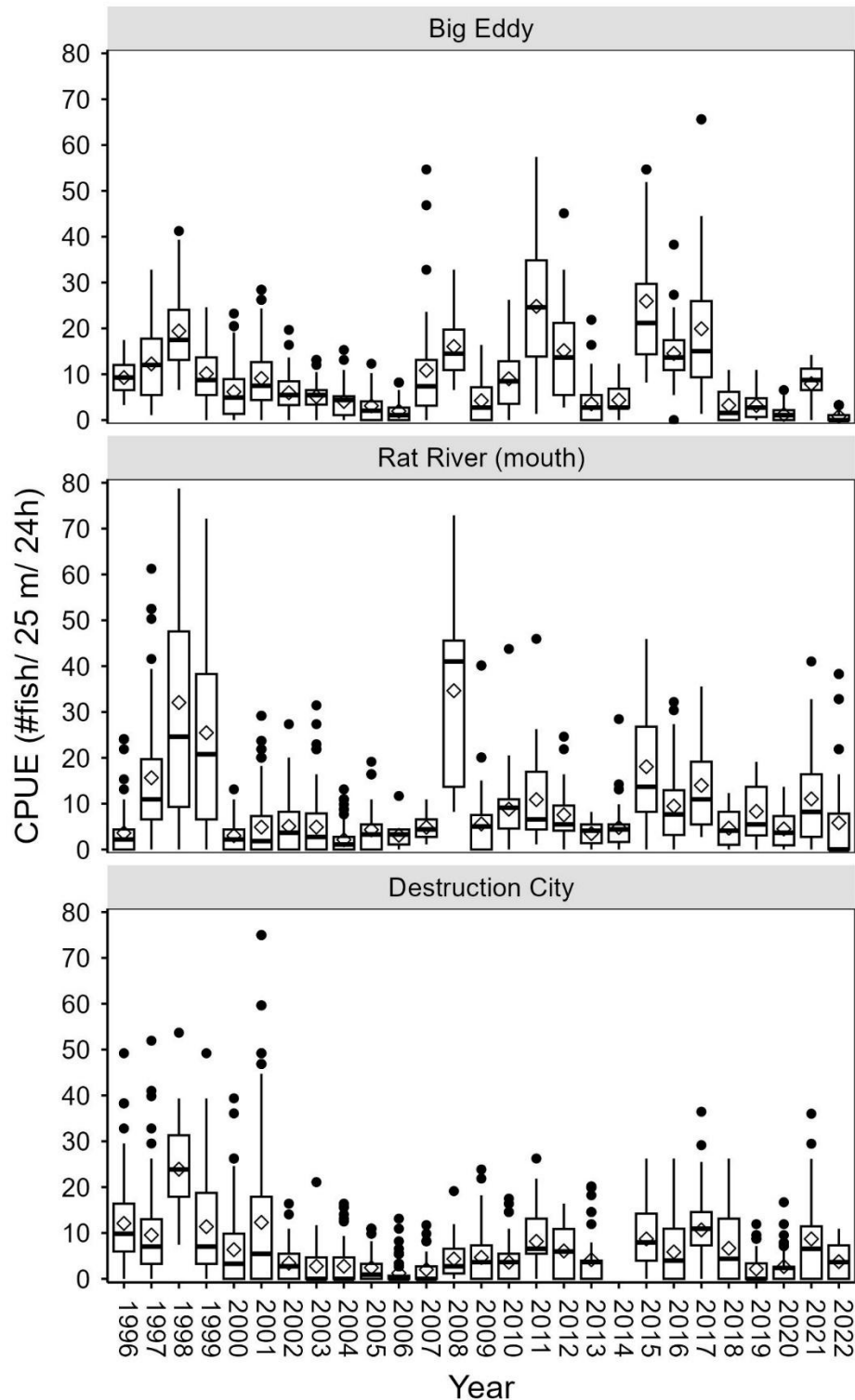


Figure 6. Boxplot of catch-per-unit-effort (CPUE; 102 and 114 mm stretch mesh) median (—), mean (◊), quartiles, and outliers (●) of Dolly Varden captured among the three sites of the Rat River Harvest Monitoring Program (Big Eddy, mouth of the Rat River, Destruction City). Note: one outlier in 2011 at mouth of Rat River had a CPUE equal to 132 (not shown for graphical visualization purposes) and Destruction City used 127 mm mesh gill nets in 2014.

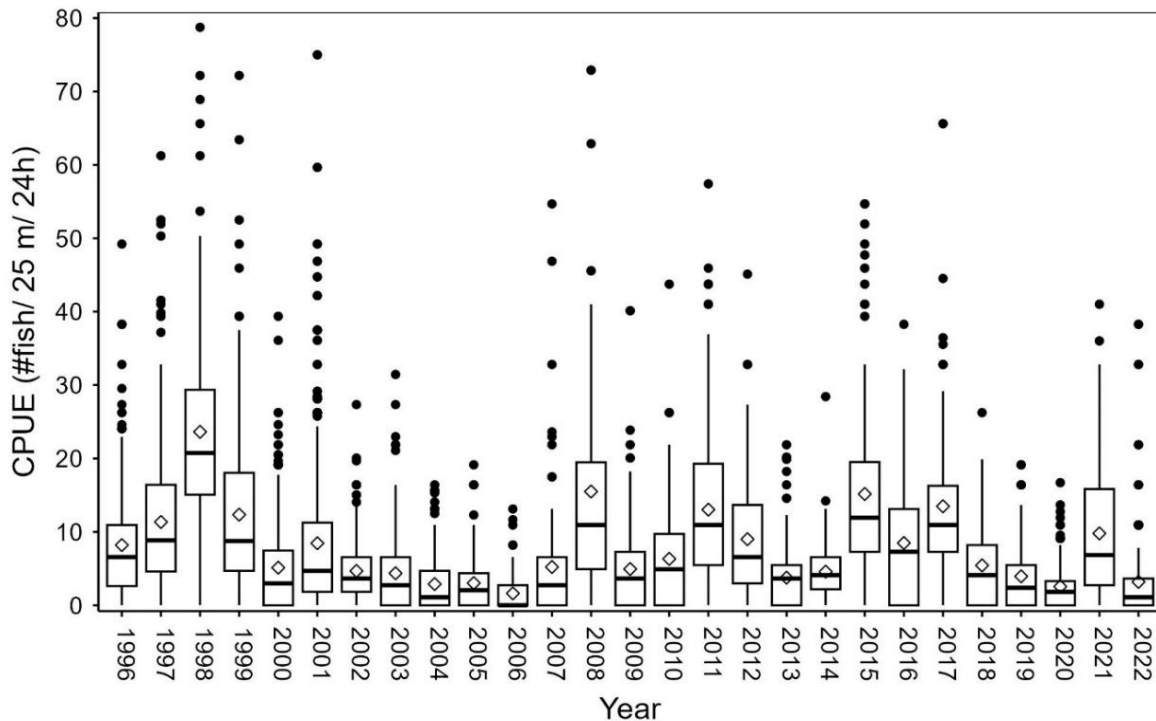


Figure 7. Boxplot of catch-per-unit-effort (CPUE; 102 and 114 mm stretch mesh) median (—), mean (◊), quartiles, and outliers (●) of Dolly Varden captured in the Rat River Harvest Monitoring Program (sites combined). Note: one outlier in 2011 at mouth of Rat River had a CPUE equal to 132 (not shown for graphical visualization purposes).

BIOLOGICAL INFORMATION

Between 2015 and 2022, the monitors comprehensively sampled 1,794 harvested Dolly Varden while an additional 365 fish were measured for length prior to release.

Length and Weight

The monitors collected an average of 276 length and 222 weight measurements per year. Between 2015 and 2022, Dolly Varden measured for length were mainly collected from gill nets with 114 mm stretched mesh ($n = 1,380$; 64.1%) followed by 102 mm ($n = 615$) and 127 mm ($n = 131$), while $n = 28$ length measurements did not have an associated mesh size recorded. In most years, the majority of samples were from the 114 mm mesh size with the exception of 2021 when length measurements were nearly equally distributed among various mesh sizes (102 mm, $n = 125$; 114 mm, $n = 112$; 127 mm, $n = 125$).

Overall Sample

Mean fork length of Dolly Varden among years and across all mesh sizes ranged from 497 mm to 557 mm while mean weight was between 1,497 g and 2,198 g (Table 7; Figure 8). Statistically significant differences in the length of fish were detected between 102 and 114 mm mesh with the exception of 2015 and 2019 (Table 7, Table A1). Mean fork length was significantly greater in the 102 mm mesh compared to the 114 mm mesh size in 2016 (567 mm vs. 485 mm), 2021 (530 mm vs. 509 mm) and 2022 (518 mm vs. 486 mm) while the opposite was observed in 2017, 2018 and 2020 (Table 7, Table A1). Length frequency distributions illustrate the considerably higher proportion of fish > 550 mm captured in gill nets with 114 mm mesh in the latter years (Figure 9). Only one year (2020) had an adequate sample size to

assess the 127 mm mesh, which captured significantly larger sizes (mean = 552 mm) of fish than 102 mm (mean = 464 mm) and 114 mm (mean = 531 mm) mesh (Table 7, Table A1; Figure 9). Length was evaluated separately among gill net mesh sizes given the high prevalence of differences observed.

The mean length and weight of fish increased gradually between 2015 and 2021 from 511 mm/1,680 g to 531 mm/2,156 g, followed by a decline (497 mm/1,497 g) in 2022 (Figure 10, Figure 11). In 2019, the heaviest (5,600 g) and second longest (748 mm) Dolly Varden was sampled in the program to date. In most years the distribution of sizes appeared unimodal with the majority of samples between the ~ 450 and 600 mm size classes (Figure 8). In 2016, 2019 and 2020 the size distributions were bimodal with one peak occurring among ~ 400–450 mm (predominantly juveniles) and another at 525–600 mm (adults) (Figure 8). Interestingly, in 2022, the distribution of sizes was relatively uniform apart from a high (23.3%) proportion of smaller sizes (425–450 mm). (Figure 8).

The mean sizes of Dolly Varden observed among the more recent years (2016–2021) were the highest observed in the entire time-series of data (average = 534 mm/1,944 g vs. 457 mm/1,462 g prior to 2016) (Figure 10, Figure 11). Sizes have been trending upward since approximately 2006 as the prevalence of large fish (> 600 mm) in the sample has been increasing. The time-series of size and weight data demonstrates a sinusoidal pattern with an increase and decline between 1995 and 2006 followed by increasing trend ever since, apart from lower means in 2012 and 2022 (Figure 10, Figure 11). The apparent decrease in length and weight in 2022 appears similar to the event in 2012 yet requires additional years of data to inform whether this is the beginning of a declining trend (i.e., years 2000–2006) (Figure 10, Figure 11).

The cause of the increase in size between 2006 and 2021 requires further investigation given the interrelationships among responses of density dependent factors (population abundance) in freshwater overwintering habitats, fish growth, and duration in and productivity/quality of marine feeding areas. Courtney et al. (2019) noted that increased maximum sizes of anadromous Dolly Varden from the Chukchi and Beaufort seas since the 1960s may be linked with increased primary production in both regions.

Male and Female: Total Sample and Current Year Spawners

On average, females were 524 mm long and weighed 1,809 g. Males were slightly larger, with an average length and weight of 532 mm and 1,942 g. Among years, the length frequency distributions between female and male sizes consistently demonstrated that males tended to be more predominant among size classes > 550–600 mm with almost no females attaining sizes > 650 mm (Figure 12). However, mean size of females and males within a given mesh size did not differ in most years, apart from 2019 when males were larger than females in 102 mm (mean of 582 [male] vs. 539 [female] mm) and 114 mm mesh (mean of 577 [male] vs. 548 [female] mm) and 2022 when females were larger than males in the 102 mm mesh (mean of 532 [female] vs. 486 [male] mm) (Table 7, Appendix Table A2).

Consistent with the length and weight results using the overall samples (all stages and sexes combined), females and males have increased in size and mass from 2015 to 2021 (Figure 13) with sizes in recent years among the highest throughout the entire time-series (since 1995), however sizes of fish (especially males) were noticeably lower in 2022 (Table 7; Figure 13). Between 2015 and 2022, the overall average size of mature female and male fish that were going to spawn in the fall was 560 mm (range = 393–690 mm) and 558 mm (range = 383–740 mm), respectively, while the average weight was 2,033 g (range = 600–3,350 g) and 2,059 g (range = 650–4,700 g), respectively (Table 8; Figure 14). In most years, males tended to have greater mean and distribution of sizes regardless of mesh size (Table 8; Figure 15, Figure 16).

Table 7. Sample size (n), mean, mode (age only), and range of fork length and age for male and female, and the total sample of Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022) captured using 102 mm, 114 mm, 127 mm mesh gill nets, and the combined total sample. Note that the Total includes samples where sex or mesh size was not recorded.

Year	Gill Net Mesh Size (mm)	Male								Female								Total				
		Fork length (mm)			Age (years)				Fork length (mm)			Age (years)				Fork length (mm)			Age (years)			
		n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range
2022	102	24	486	423–583	22	5.5	6	3–7	51	532	400–690	48	7.4	7	4–11	75	518	400–690	70	6.8	5,7	3–11
2021	102	15	560	427–709	14	7.5	5	5–10	46	546	424–650	42	7.8	8	4–12	125	530	417–709	56	7.7	8	4–12
2020	102	17	458	366–618	15	5.5	5	4–7	49	466	304–617	44	5.9	5	3–10	66	464	304–618	59	5.8	5	3–10
2019	102	19	582	500–700	17	7.1	6, 7	5–9	48	539	355–640	43	7.2	7	5–12	67	551	355–700	60	7.2	7	5–12
2018	102	27	507	391–709	26	6.6	6, 7	4–15	58	480	317–616	53	6.4	6	4–10	90	492	317–709	82	6.5	6	4–15
2017	102	23	494	414–568	23	6.2	6	5–8	49	482	347–584	49	6.5	6	5–10	75	485	347–584	76	6.4	6	5–10
2016	102	45	577	437–709	42	6.3	6	5–8	25	573	458–669	23	6.7	7	5–8	107	567	437–709	65	6.4	6	5–8
2015	102	6	526	480–595	6	6.5	6	6–8	4	506	450–551	3	6.3	6	6–7	10	518	450–595	9	6.4	6	6–8
2022	114	56	471	304–650	56	5.1	5	3–12	92	495	350–650	90	6.5	5	3–11	148	486	304–650	146	6.0	5	3–12
2021	114	24	511	403–740	22	5.9	5	4–9	48	540	415–688	46	7.1	8	4–10	112	509	403–740	68	6.7	5	4–10
2020	114	54	523	420–675	51	6.4	6	4–9	138	536	423–657	128	7.3	7	4–11	197	531	408–675	179	7	7	4–11
2019	114	71	577	397–748	69	7.3	7	4–10	102	548	326–665	95	7.2	7	5–12	174	559	326–748	165	7.2	7	4–12

Year	Gill Net Mesh Size (mm)	Male								Female								Total				
		Fork length (mm)			Age (years)				Fork length (mm)			Age (years)				Fork length (mm)			Age (years)			
		n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range
2018	114	45	555	425–653	45	6.6	7	5–8	67	539	405–637	63	7	7	5–11	112	545	405–653	108	6.8	7	5–11
2017	114	77	572	350–710	74	6.7	6	4–9	67	560	315–690	65	7.1	7	4–13	194	564	315–710	139	6.9	7	4–13
2016	114	72	502	337–705	66	5.8	5	4–9	64	484	343–638	63	5.8	5	4–11	156	485	337–705	132	5.8	5	4–11
2015	114	78	516	313–710	76	6	6	4–9	117	505	344–655	113	6.5	6	4–11	287	511	313–710	194	6.3	6	4–11
2021	127	22	543	354–682	20	7	8	4–10	41	585	455–670	40	7.6	8	5–11	125	552	354–682	60	7.4	8	4–11
2020	127	2	651	634–668	2	9	9	9–9	4	599	552–638	4	10.5	8,9,10,15	8–15	6	616	552–668	6	10	9	8–15
2022	Total combined sample	80	476	304–650	78	5.2	5	3–12	143	508	350–690	138	6.8	5	3–11	223	497	304–690	216	6.2	5	3–12
2021	Total combined sample	61	535	354–740	56	6.7	5	4–10	135	556	415–688	128	7.5	8	4–12	362	531	354–740	184	7.2	8	4–12
2020	Total combined sample	73	511	366–675	68	6.2	6	4–9	191	519	304–657	176	7	7	3–15	269	516	304–675	244	6.8	6,7	3–15
2019	Total combined sample	90	578	397–748	86	7.2	7	4–10	150	545	326–665	138	7.2	7	5–12	241	557	326–748	225	7.2	7	4–12
2018	Total combined sample	72	537	391–709	81	6.6	7	4–15	125	512	317–637	128	6.8	7	4–13	224	524	317–723	212	6.7	7	4–15
2017	Total combined sample	100	554	350–710	101	6.6	6	4–9	116	527	315–690	115	6.8	6	4–13	275	541	315–710	221	6.7	6	4–13

Year	Gill Net Mesh Size (mm)	Male								Female								Total				
		Fork length (mm)			Age (years)				Fork length (mm)			Age (years)				Fork length (mm)			Age (years)			
		n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range
2016	Total combined sample	117	531	337–709	108	6	6	4–9	89	509	343–669	86	6.1	5	4–11	263	519	337–709	197	6	5	4–11
2015	Total combined sample	84	517	313–710	82	6	6	4–9	121	505	344–655	116	6.5	6	4–11	297	511	313–710	203	6.3	6	4–11

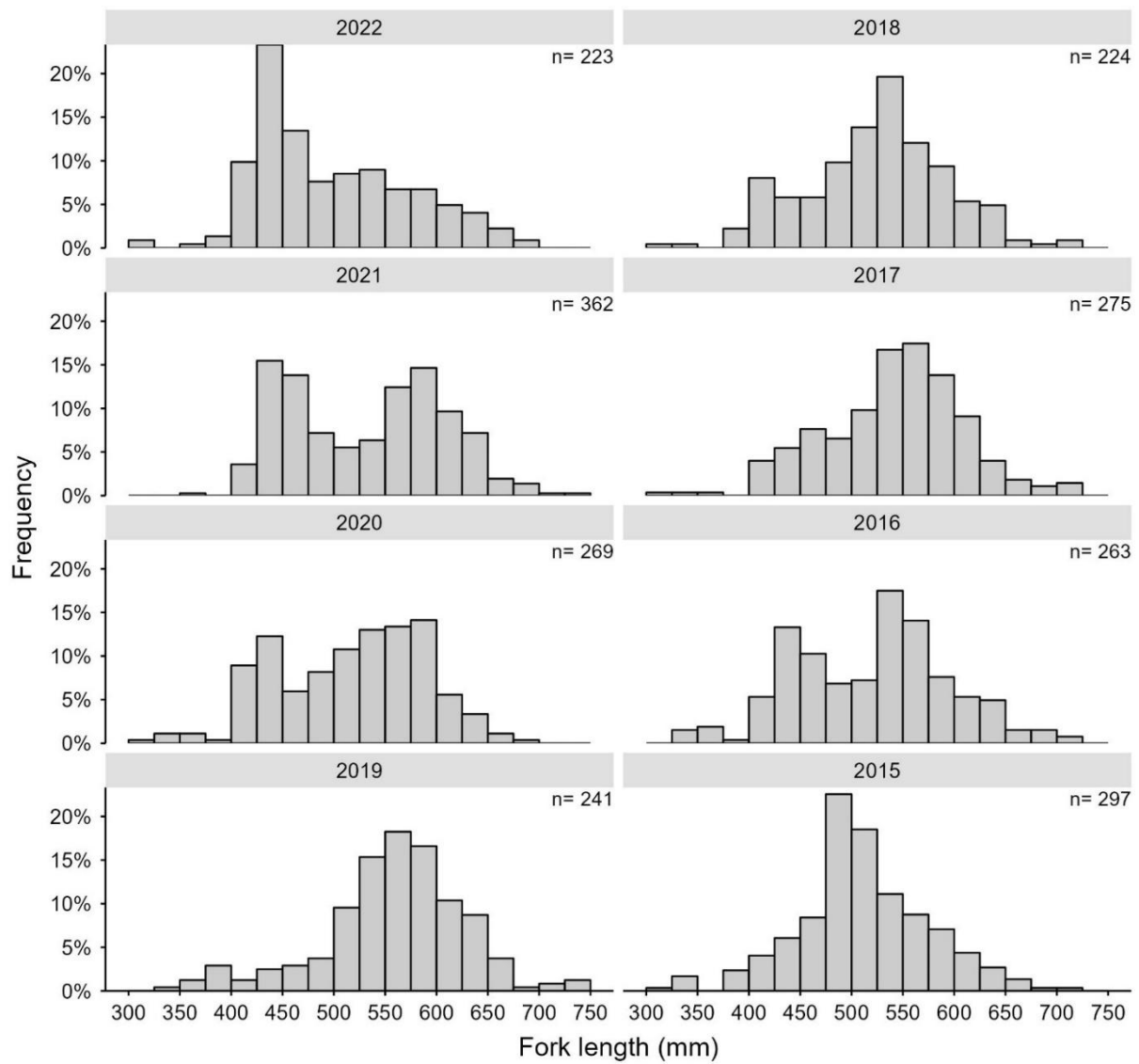


Figure 8. Fork length frequency of the total sample of Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022). *n* is the sample size.

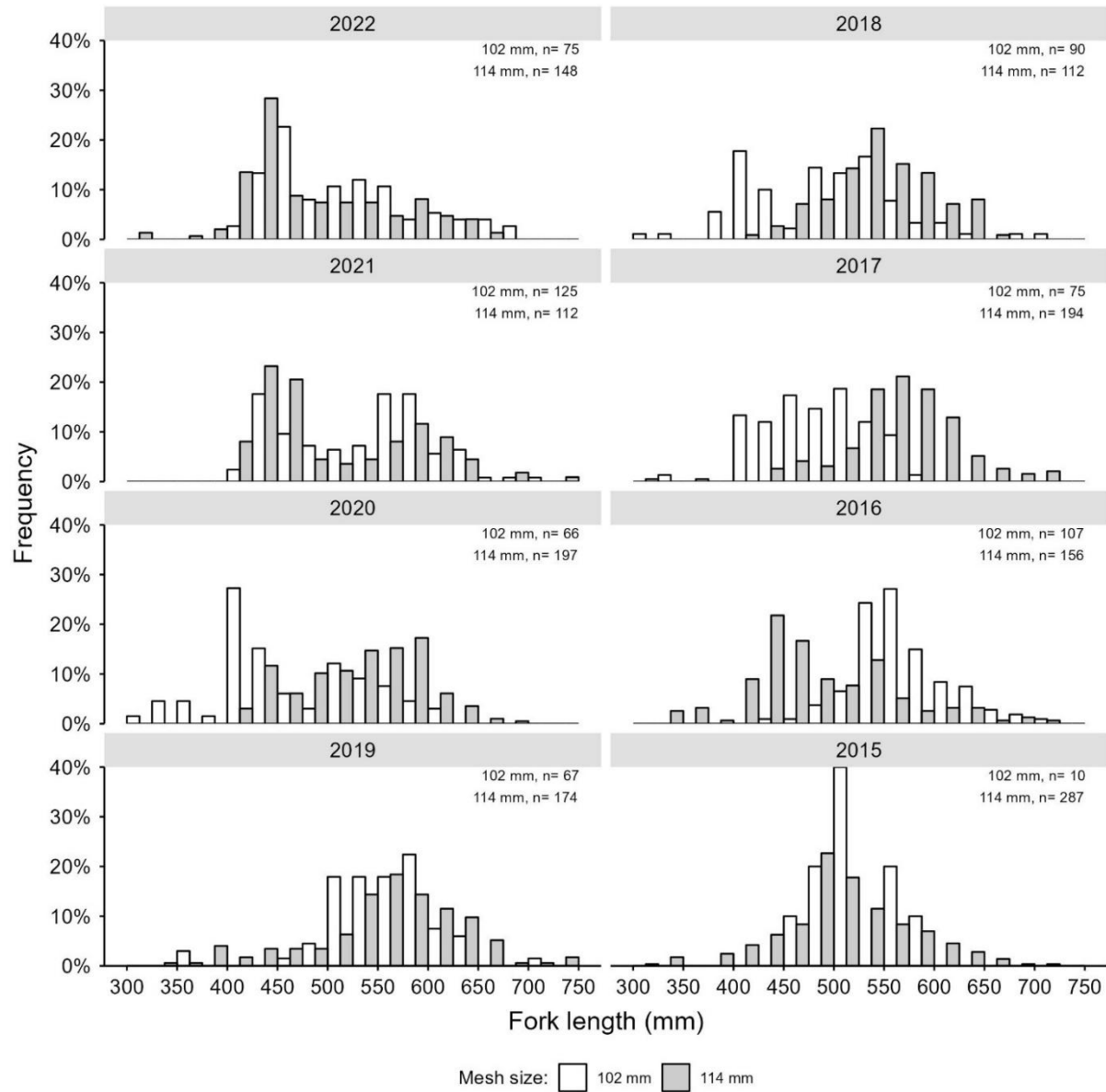


Figure 9. Fork length frequency of the total sample of Dolly Varden from the Rat River Harvest Monitoring Program captured using 102 mm and 114 mm mesh gill nets (2015–2022). *n* is the sample size.

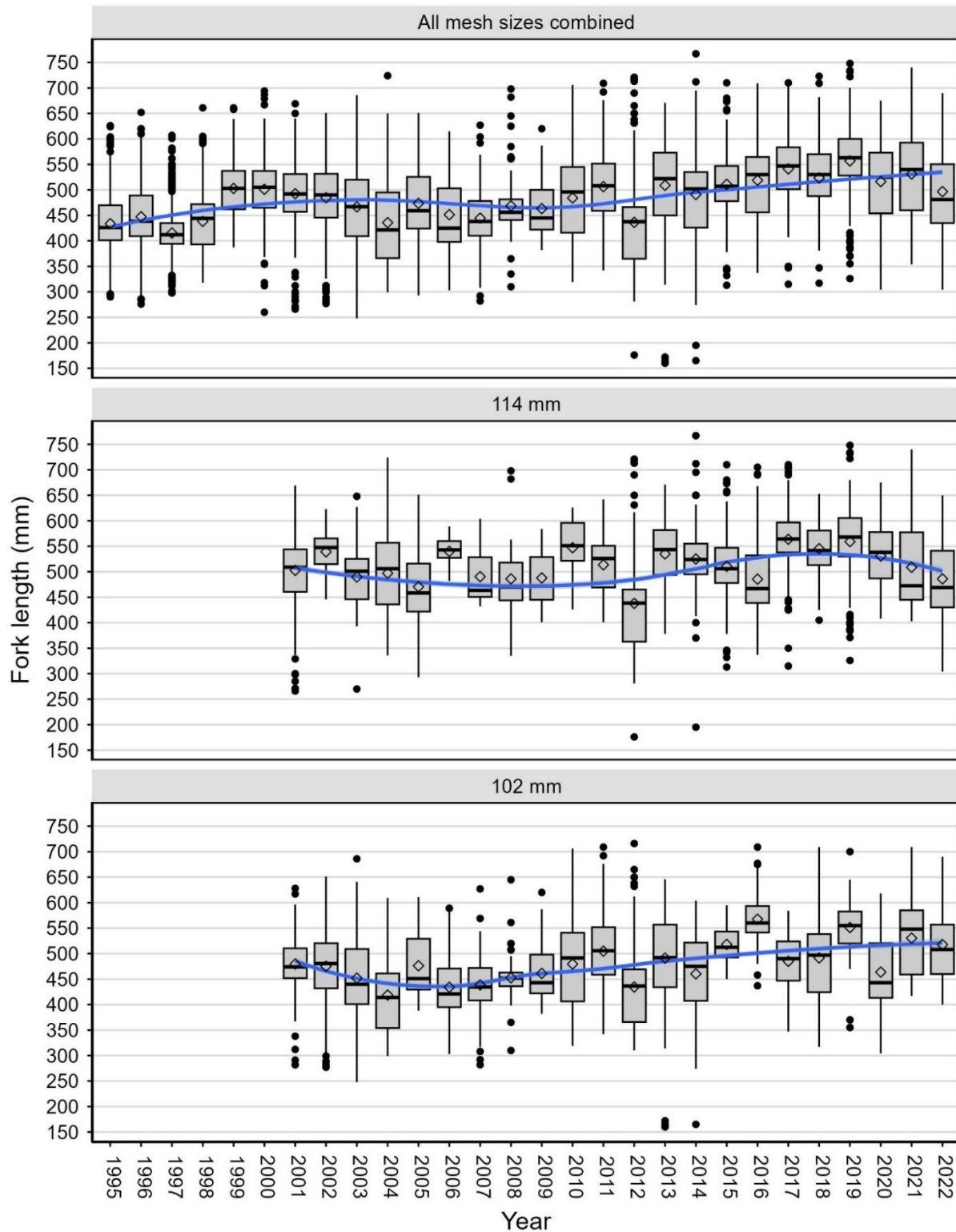


Figure 10. Box plots of fork length (median [—], mean [◇], quartiles, and outliers [•]) of all Dolly Varden sampled among gill net mesh sizes from the Rat River Harvest Monitoring Program. Blue line is a LOESS regression. Note, recording mesh size started in 2001.

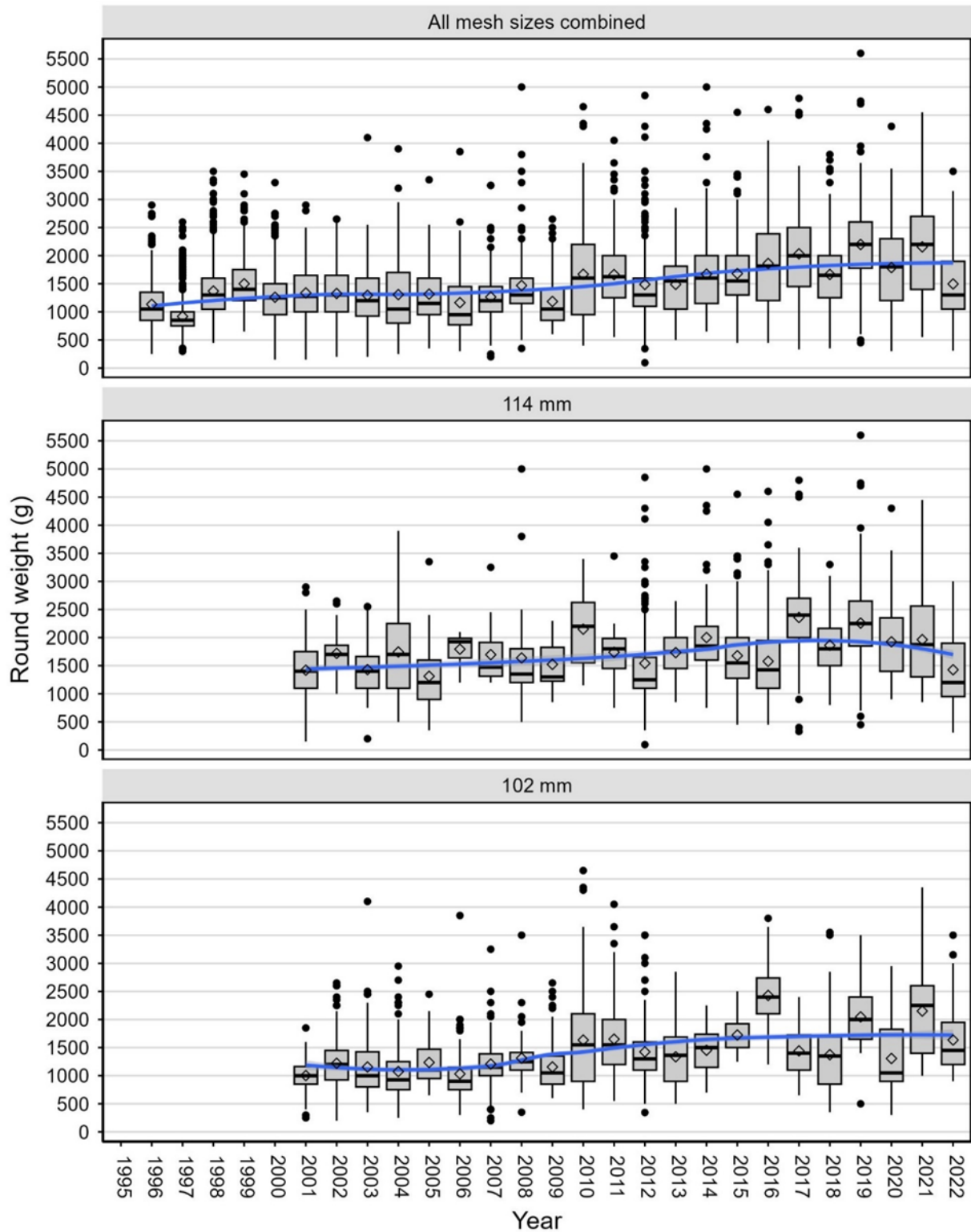


Figure 11. Box plots of round weight (median [—], mean [◊], quartiles, and outliers [●]) of all Dolly Varden sampled among gill net mesh sizes from the Rat River Harvest Monitoring Program with. Blue line is a LOESS regression. Note, recording mesh size started in 2001.

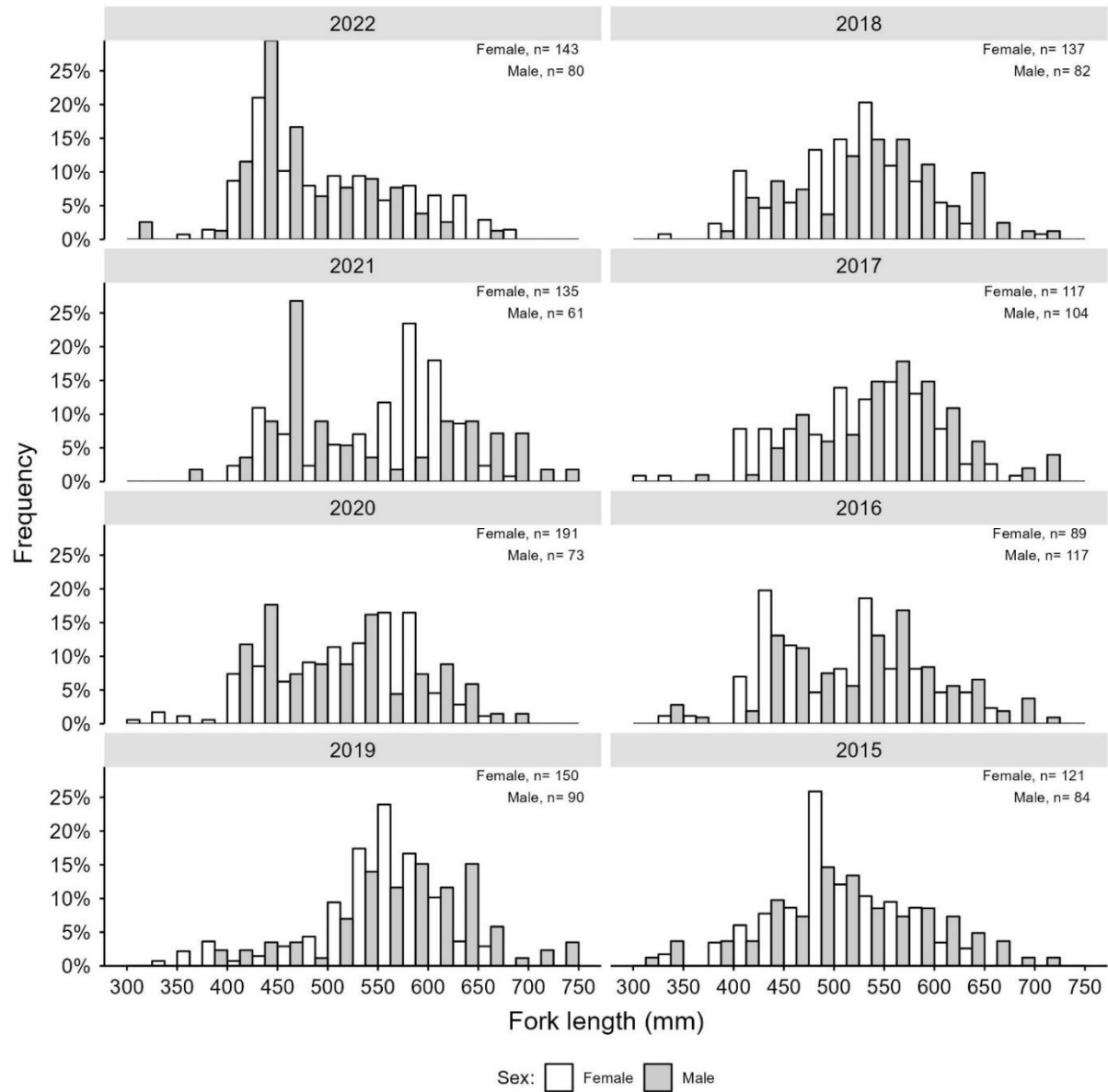


Figure 12. Fork length frequency distribution of female and male Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022). *n* is the sample size.

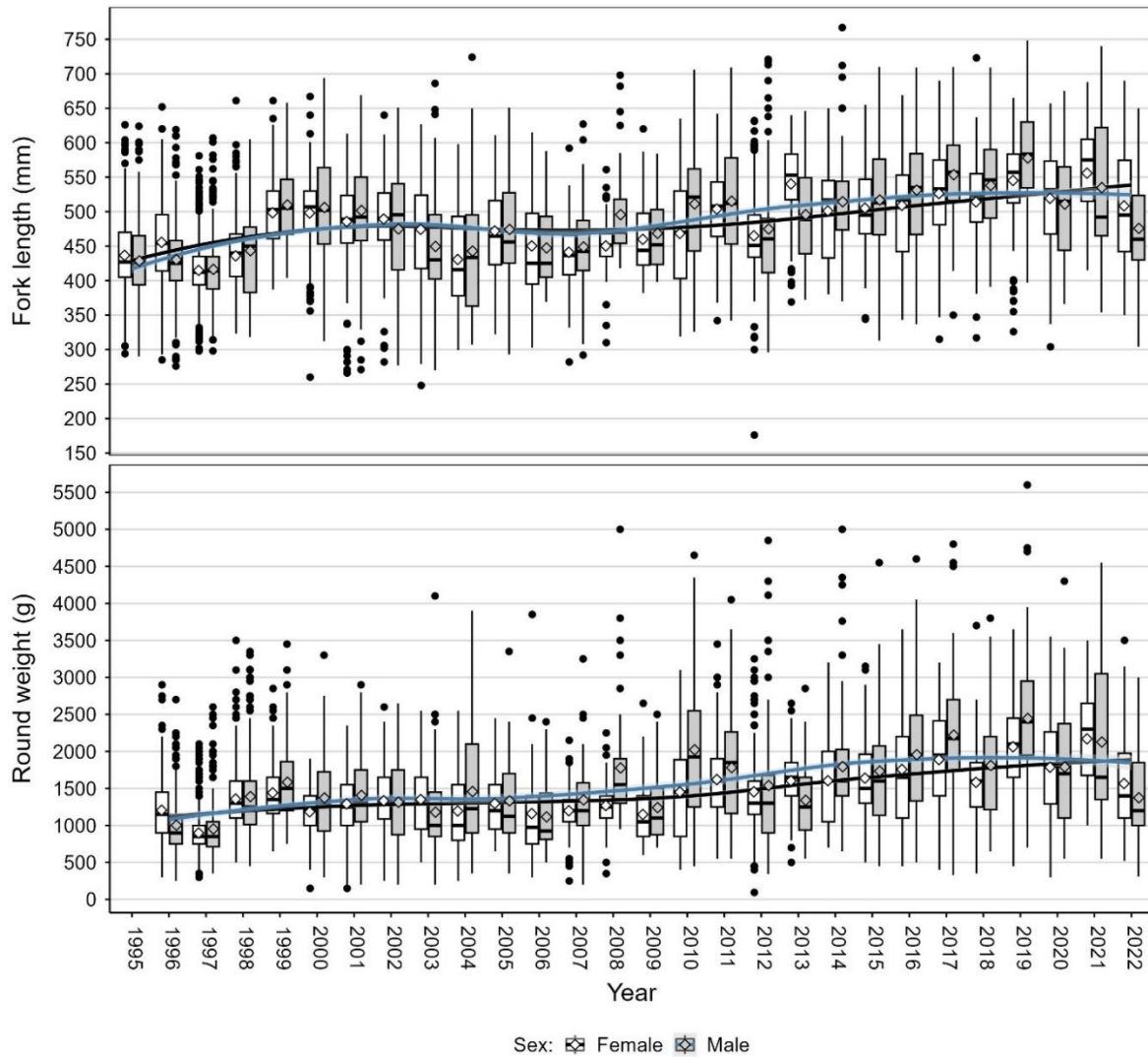


Figure 13. Box plots of fork length and round weight (median [–], mean [◇], quartiles and outliers [●]) of female and male Dolly Varden from the Rat River Harvest Monitoring Program (all gill net mesh sizes combined). Blue (males) and black (females) lines are a LOESS regression. Note, weights not recorded in 1995.

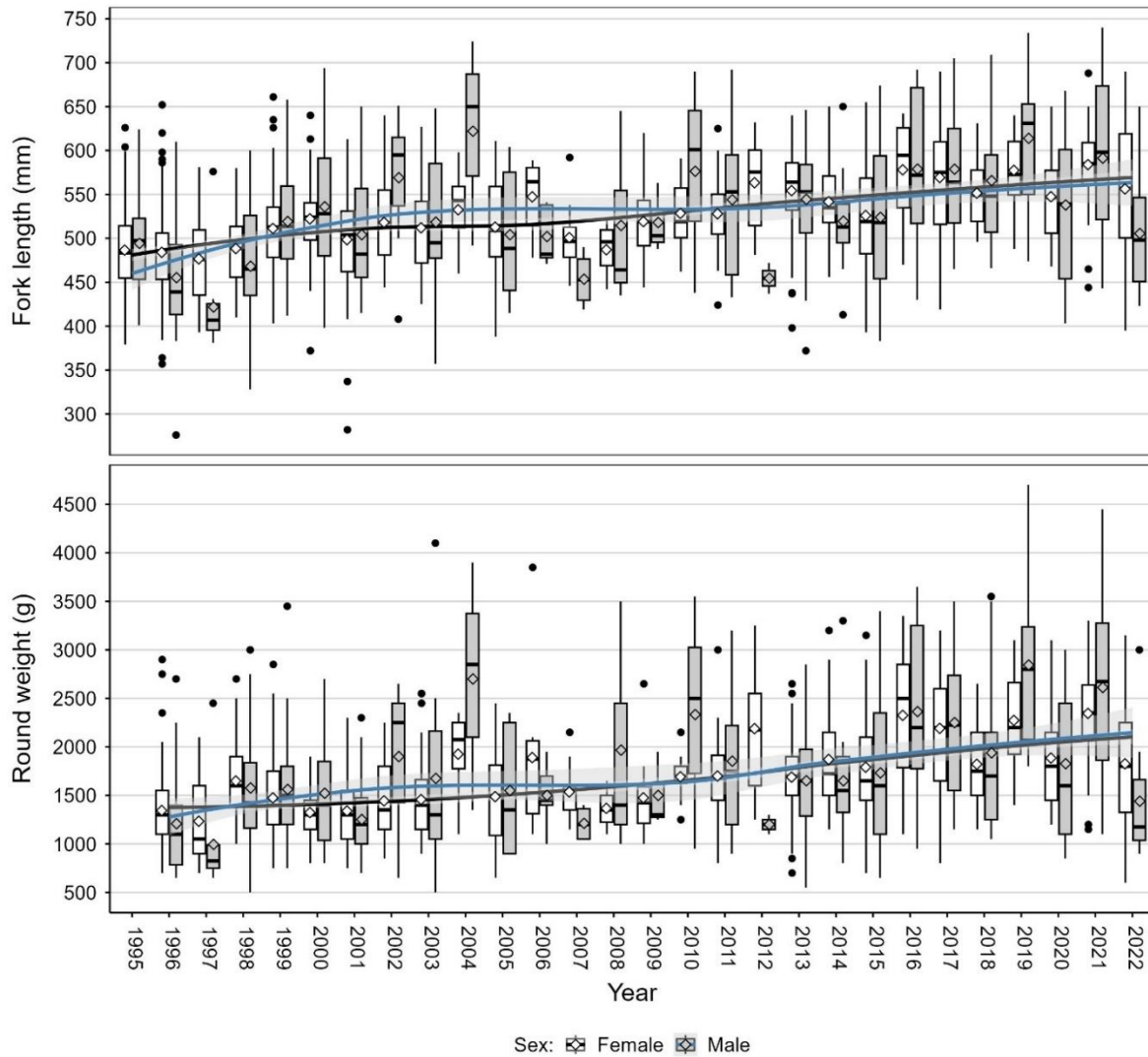


Figure 14. Box plots of fork length and round weight (median [–], mean [◇], quartiles and outliers [●]) of female and male Dolly Varden from the Rat River Harvest Monitoring Program identified as current-year spawners (all gill net mesh sizes combined). Blue (males) and black (females) lines are a LOESS regression. Note, weight not recorded in 1995.

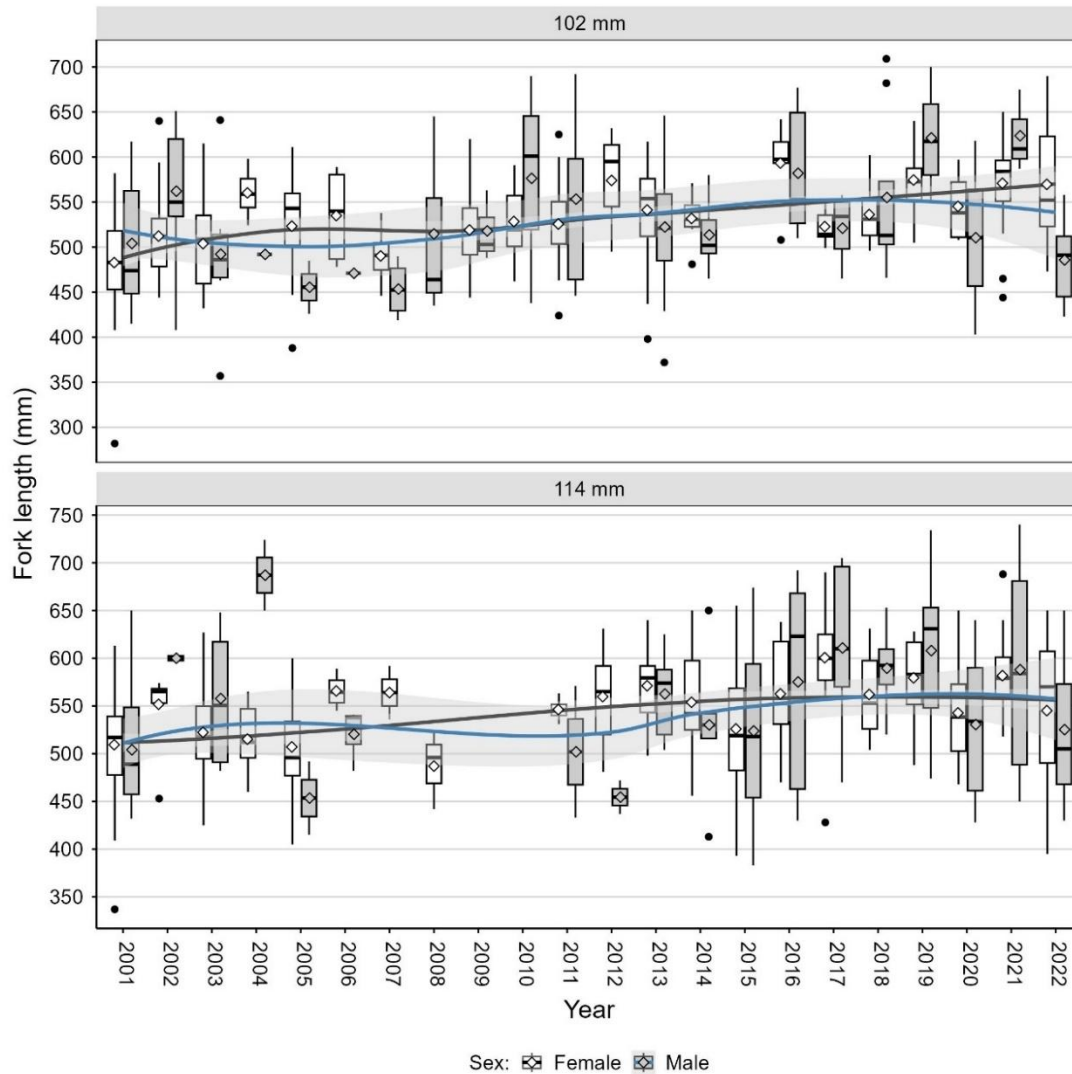


Figure 15. Box plots of fork lengths (median [—], mean [◊], quartiles, and outliers [●]) of female and male Dolly Varden from the Rat River Harvest Monitoring Program identified as current-year spawners captured using 102 mm and 114 mm stretch mesh gill nets (2001–2022). Blue (blue) and black (females) lines are a LOESS regression. Note: recording mesh size started in 2001.

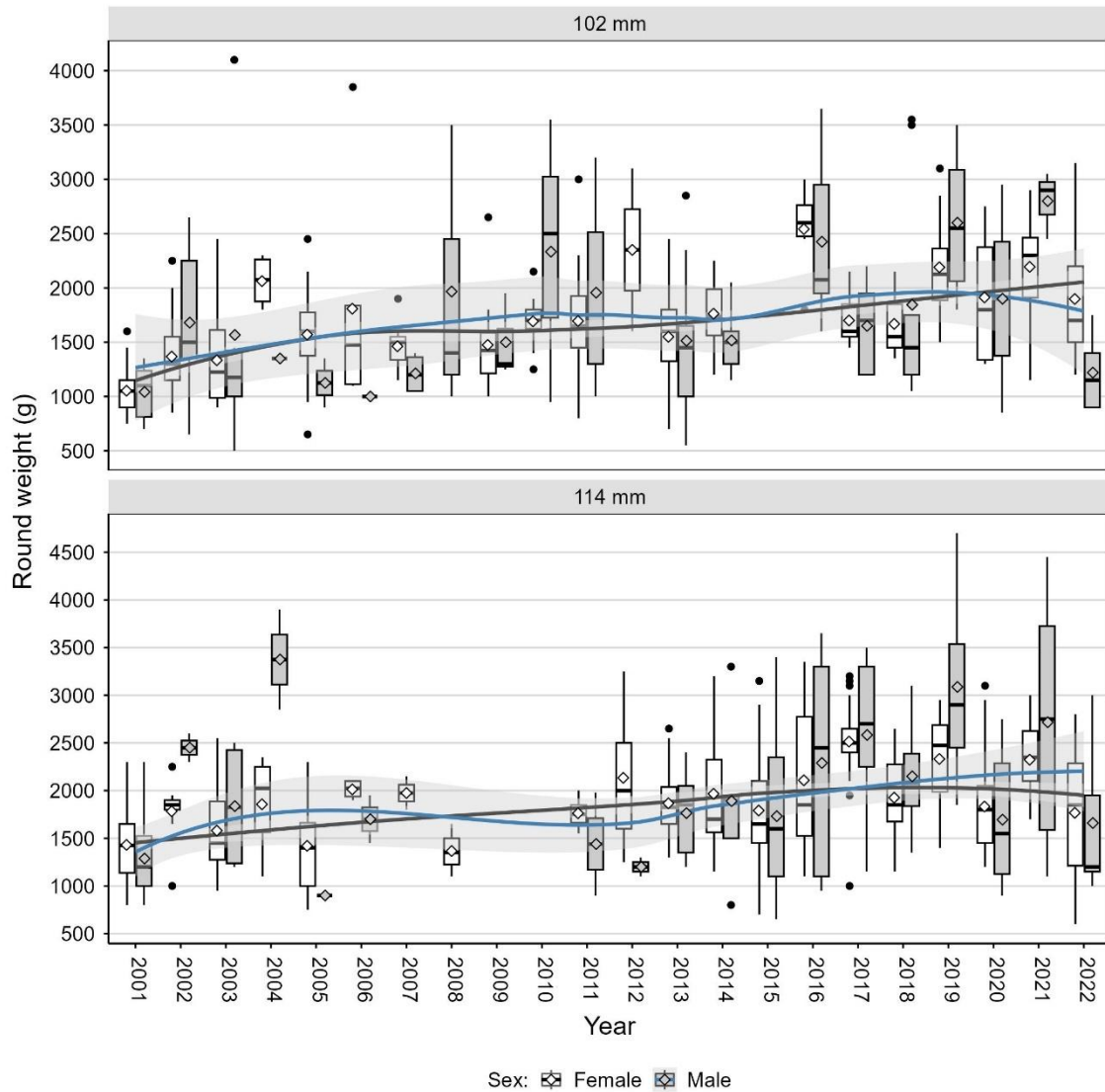


Figure 16. Box plots of round weight (median [–], mean [◇], quartiles, and outliers [●]) of female and male Dolly Varden from the Rat River Harvest Monitoring Program identified as current-year spawners captured using 102 mm and 114 mm stretch mesh gill nets (2001–2022). Blue (blue) and black (females) lines are a LOESS regression. Note: recording mesh size started in 2001.

Table 8. Sample size (n), mean, mode (age only), and range of fork length and age for male and female Dolly Varden, from the Rat River Harvest Monitoring Program, identified as current-year spawners (2015–2022). Fish caught using 102 mm, 114 mm, and 127 mm mesh gill nets, and the combined total sample.

Year	Gill Net Mesh Size (mm)	Male							Female						
		Fork length (mm)			Age (years)				Fork length (mm)			Age (years)			
		n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range
2022	102	5	486	423-558	5	6.2	6, 7	5-7	25	570	473-690	24	8.5	9	6-11
2021	102	3	624	587-675	3	8.3	7, 8, 10	7-10	24	571	444-650	23	8.3	7-9	6-12
2020	102	2	510	403-618	2	5.5	5, 6	5-6	4	545	508-597	4	8	7, 9	7-9
2019	102	4	621	550-700	3	7	5, 7, 9	5-9	10	574	505-640	8	7.9	7	7-12
2018	102	9	555	466-709	8	7	7	6-8	13	536	496-602	11	7.1	6, 7	6-10
2017	102	5	521	465-558	5	7.4	8	6-8	11	523	499-554	11	7.1	6, 7	6-10
2016	102	6	582	510-677	6	6.7	6	6-8	6	593	508-642	6	6.8	7	6-7
2015	102	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2022	114	5	525	430-650	5	7.0	6	5-12	30	545	395-650	30	7.9	9	5-11
2021	114	6	588	450-740	5	6.8	7	5-9	27	582	518-688	25	8	8	6-10
2020	114	10	530	428-640	9	6.9	6	5-9	42	543	468-650	38	8.1	9	6-11
2019	114	5	608	474-734	5	8.6	8	8-10	14	580	488-628	13	8.1	7	6-12
2018	114	4	590	520-653	4	7	7	7-7	19	562	504-631	18	7.7	8	6-11
2017	114	9	611	470-705	9	7.6	7	6-9	21	601	428-690	21	8.3	8	6-13
2016	114	5	575	430-692	5	7	5-9	5-9	6	563	470-638	6	7.8	7	6-11
2015	114	25	524	383-674	23	6.3	6	5-8	51	526	393-655	48	7.1	6	5-11
2021	127	3	565	443-673	3	7.7	5, 8, 10	5-10	23	600	548-645	22	8	8	6-11
2020	127	1	668	668	1	9	9	9	4	599	552-638	4	10.5	8-10, 15	8-15
2022	Total combined sample	10	506	423-650	10	6.6	6	5-12	55	556	395-690	54	8.2	9	5-11

Year	Gill Net Mesh Size (mm)	Male							Female						
		Fork length (mm)			Age (years)				Fork length (mm)			Age (years)			
		n	Mean	Range	n	Mean	Mode	Range	n	Mean	Range	n	Mean	Mode	Range
2021	Total combined sample	12	591	443-740	11	7.5	7	5-10	74	584	444-688	70	8.1	8	6-12
2020	Total combined sample	13	538	403-668	12	6.8	6	5-9	50	547	468-650	46	8.3	9	6-15
2019	Total combined sample	9	614	474-734	8	8	8	5-10	24	577	488-640	21	8	7	6-12
2018	Total combined sample	13	566	466-709	12	7	7	6-8	32	552	496-631	29	7.5	7	6-11
2017	Total combined sample	14	579	465-705	14	7.5	7, 8	6-9	33	569	419-690	33	7.8	8	6-13
2016	Total combined sample	11	579	430-692	11	6.8	6	5-9	12	578	470-642	12	7.3	7	6-11
2015	Total combined sample	25	524	383-674	23	6.3	6	5-8	51	526	393-655	48	7.1	6	5-11

Condition Factor

The average annual condition factor of Rat River Dolly Varden from 2015–2022 was between 1.11 and 1.25 (Figure 17). Although distributions among years were highly overlapping, it was apparent that fish condition was notably lower in 2018. Over the time-series, condition has varied considerably as a higher prevalence of relative lower values (< 1.2) were apparent in the late 1990s and early 2000 with relatively high (> 1.3) average values observed in most years between 2007 and 2012 (Figure 17).

Age and Survival/Mortality

From 2015–2022, the mean annual age of the total Dolly Varden sampled by the Rat River monitors ranged between 6.0 and 7.2 years, with ages ranging from a minimum of 3 to a maximum of 15 years (Table 7) and the majority of captured fish between 5 and 8 years (Figure 18). Significant differences in ages were observed between the 102 and 114 mm mesh nets in all years except 2019 (Table A3). Distributions of ages among mesh sizes overlapped in most years; however, sampling year 2020, which demonstrated the largest difference between mean ages captured in the 102 and 114 mm mesh (1.2 years), had age distributions that were noticeably skewed towards younger and older ages, for these two respective mesh sizes (Figure 19). The age data from different mesh sizes were combined given the small differences (generally < 1 year) in age. Statistically significant differences in age between males and females were only observed in 2015 and 2020–2022 where the mean ages of females were slightly ($\sim < 1$ year) older than males (Table 7, Table A4; Figure 20).

Confidently assessing age trends using the time-series of data from the monitoring program is complicated by differences in age estimation protocols. Otoliths collected from 1995–2006 were aged whole by the same reader while in all subsequent years a new protocol was implemented that employed a combination of methods (whole and thin-section through the transverse plane) that tended to yield older ages (Gallagher et al. 2016). Between 1995 and 2006 mean age was similar among years (~ 5.5 years) (Figure 21). From 2007 to 2021 mean age appears to have gradually increased (from ~ 5.5 to ~ 7 years), which was accompanied by the observation of the oldest ages recorded for the stock (age-15) in 2018 and 2021 (Figure 21).

Survival estimates using the Robson-Chapman method varied without trend between 2015 and 2022, with values typically between 0.4 and 0.5 (Table 9). Survival based on the combined years was 0.54 with the lowest and highest survival value observed in 2018 (0.38) and 2022 (0.63), respectively. Females had a higher mean survival than males (0.48 vs. 0.38) (Table 9).

Although no temporal trend in survival was detected from 2015–2022 during a period when population abundance was high and subsequently declined (Gallagher et al. 2026), assessment of 2009–2014 data indicated that increasing Robson-Chapman survival estimates was associated with increasing abundance for the stock (Gallagher et al. 2020).

Growth

Length-at-age plots demonstrated that anadromous Dolly Varden from the Rat River grew quickly between age-3 (mean length = 352 mm) and 6 (mean length = 510 mm) (Figure 22). The rate of growth became slower for fish $\geq$ age-7, when a relatively high proportion of the stock attain sexual maturity (see 'Reproductive characteristics' section below). Males and females demonstrated distinct growth patterns starting at age-5 as males grew to larger sizes compared to females (Figure 22). Growth expressed at weight-at-age demonstrated patterns consistent with length-at-age (Figure 23). Mean length among individual age classes of females and males

was not considerably different between 2015 and 2022, although size was noticeably smaller for ages 6 and 7 by 2022 (Figure 24).

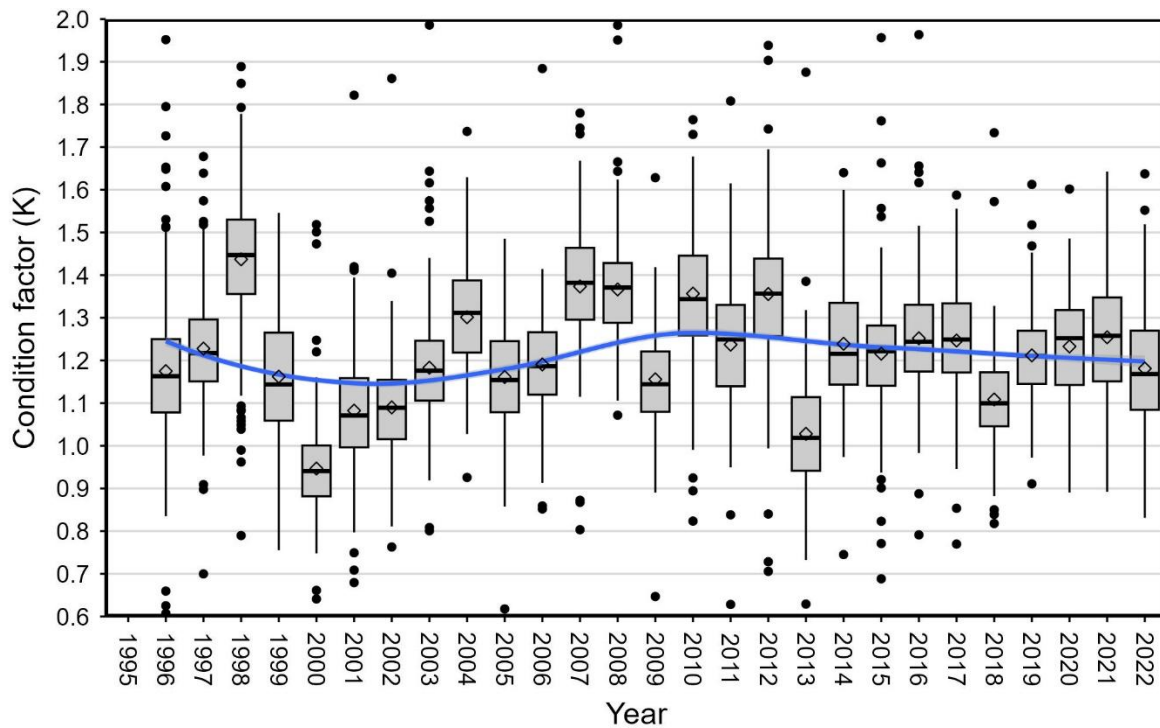


Figure 17. Box plot of Fulton's condition factor (median (—), mean (◇), quartiles and outliers (●)) of Dolly Varden from the Rat River Harvest Monitoring Program (1995–2022). Blue line is a LOESS regression. Note, outliers < 0.6 and > 2 were not illustrated in the figure.

Table 9. Robson-Chapman estimates of annual survival (S), 95% confidence intervals (CI), mortality (A), and range of age for Dolly Varden from the Rat River Harvest Monitoring Program among sampling years (2015–2022) and years combined.

Year	S	95% CI	A	Age range
2022	0.63	0.59–0.68	0.37	5–12
2021	0.41	0.33–0.49	0.59	8–12
2020	0.51	0.45–0.57	0.49	7–15
2019	0.42	0.37–0.48	0.58	7–12
2018	0.36	0.29–0.43	0.64	7–15
2017	0.47	0.42–0.52	0.53	6–13
2016	0.52	0.47–0.57	0.48	5–11
2015	0.41	0.35–0.47	0.59	6–11
Total sample	0.54	0.52–0.56	0.46	6–15
Total female	0.48	0.45–0.51	0.52	7–15
Total male	0.38	0.34–0.43	0.62	6–10

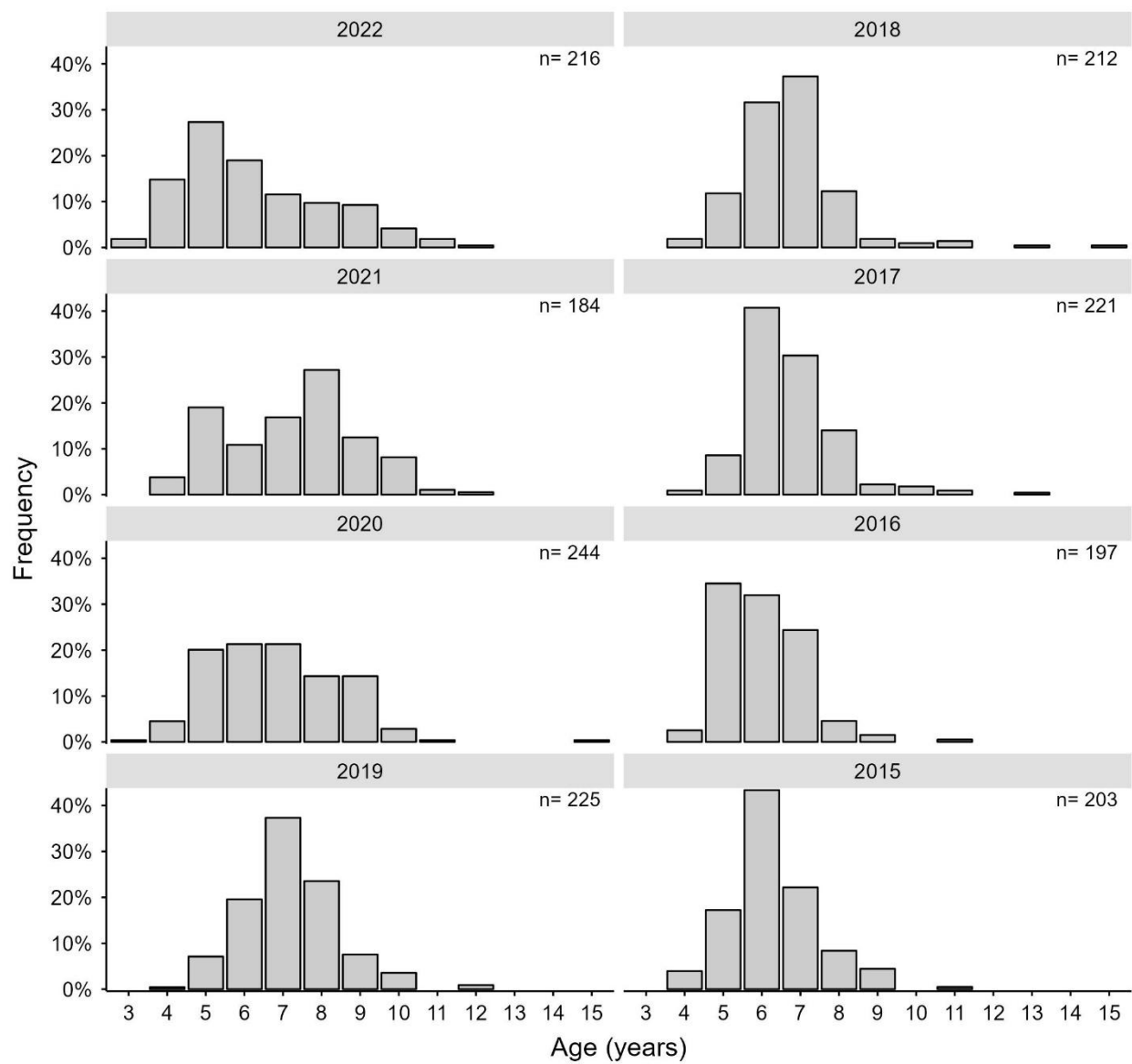


Figure 18. Age frequency of Dolly Varden from the Rat River Harvest Monitoring Program 2015–2022 (all samples combined). *n* is the sample size.

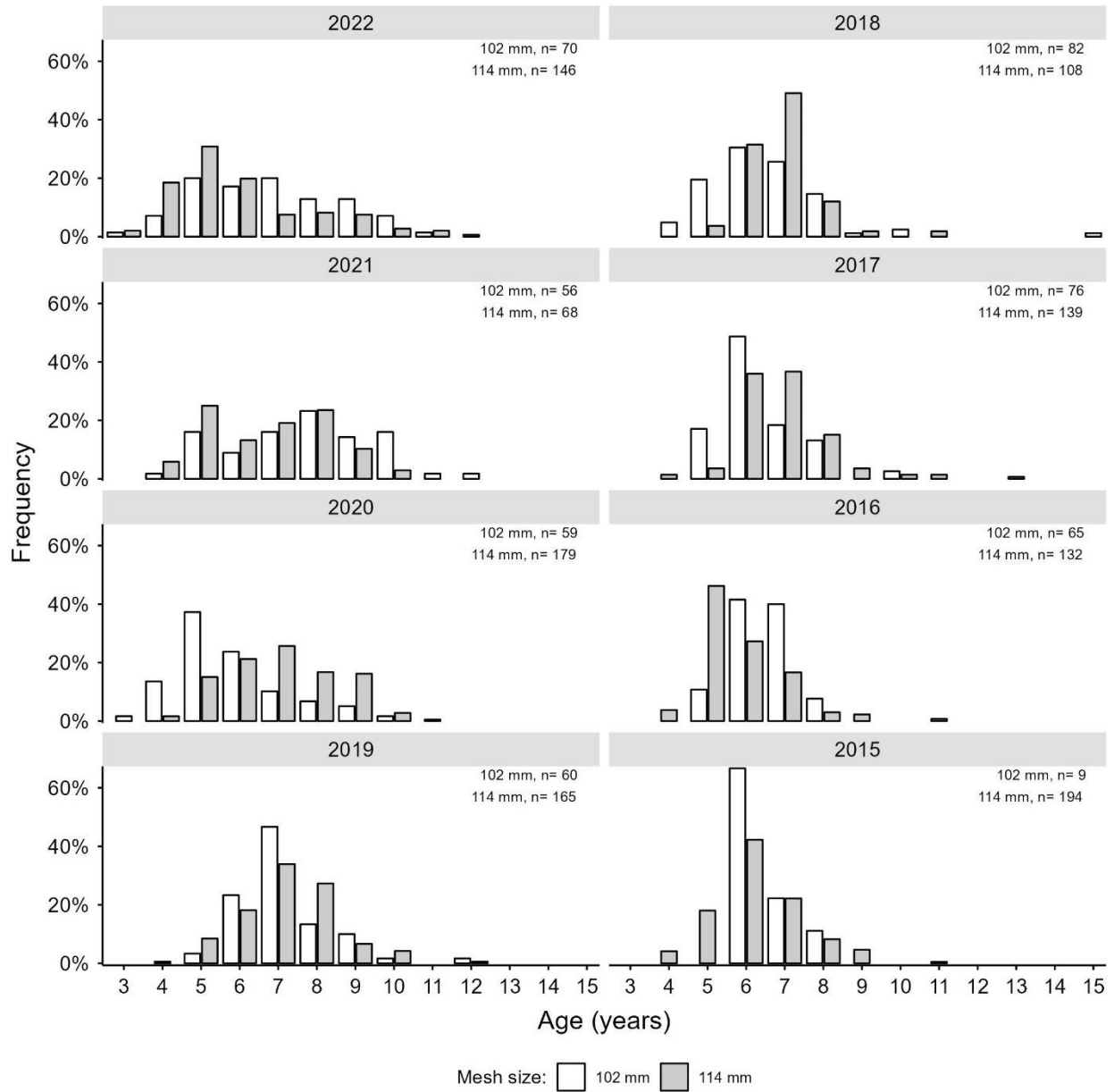


Figure 19. Age frequency of Dolly Varden from the Rat River Harvest Monitoring Program captured using 102 mm (open bars) and 114 mm (shaded bars) mesh gill nets (2015–2022). *n* is the sample size.

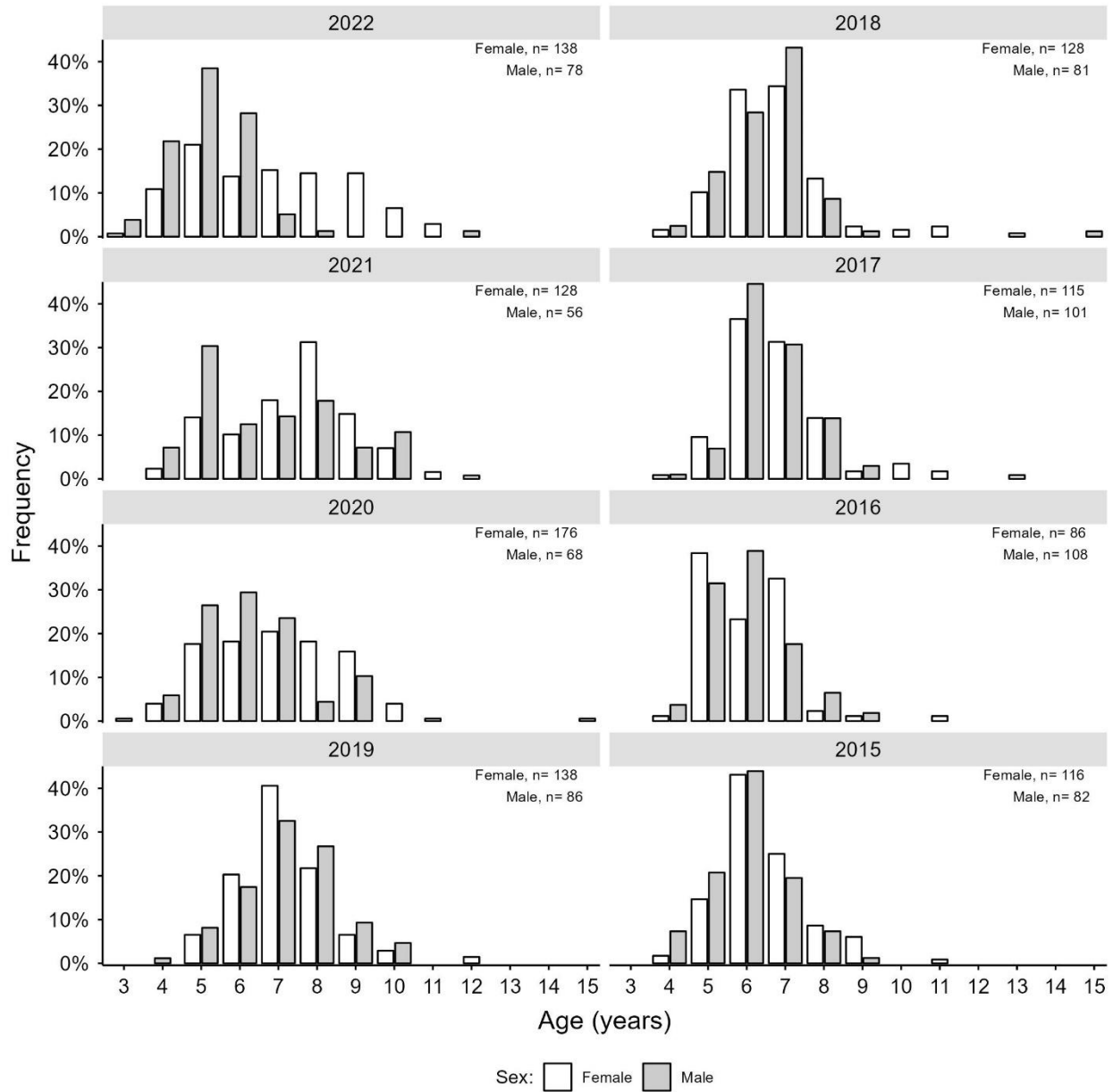


Figure 20. Age frequency of female (open bars) and male (shaded bars) Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022). n is the sample size.

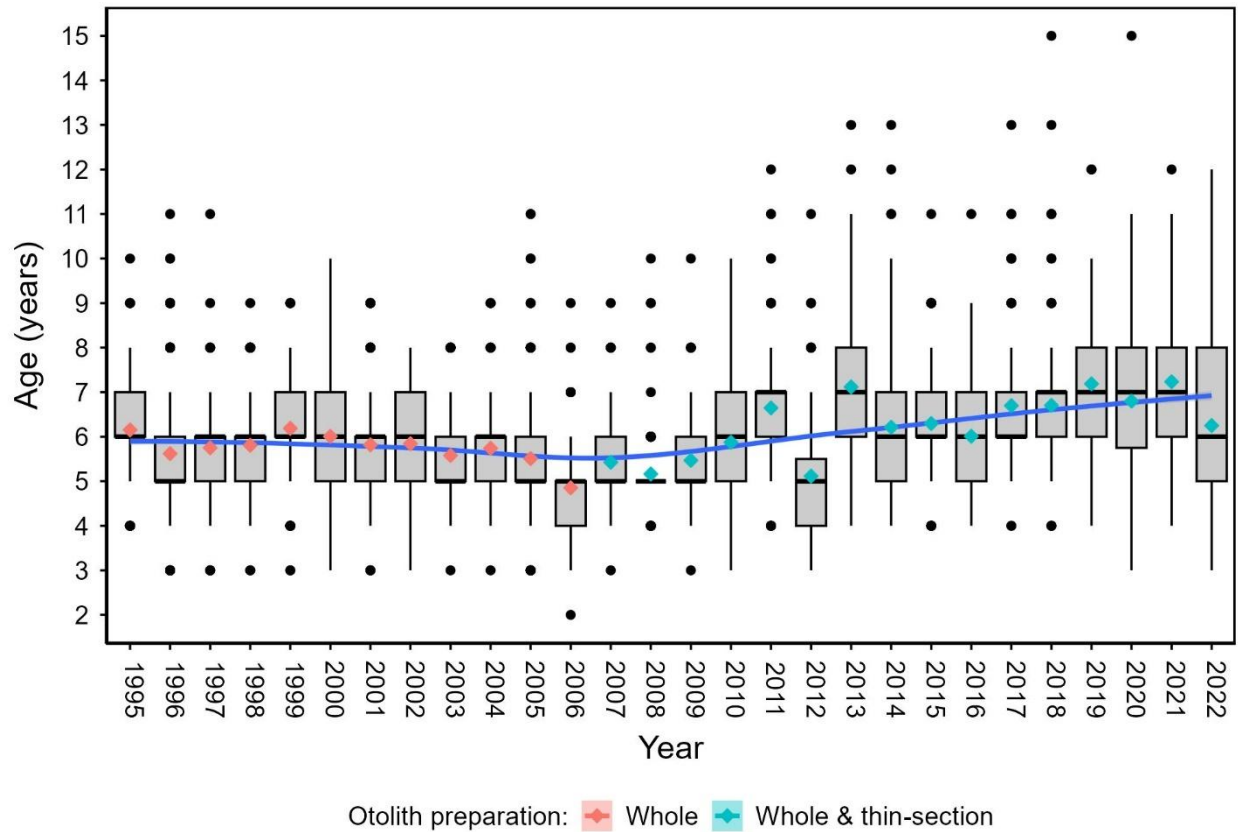


Figure 21. Box plot of age (median [—], mean [◇], quartiles, and outliers [●]) of all Dolly Varden sampled from the Rat River Harvest Monitoring Program (1995–2022). Annuli were counted from otoliths either prepared whole (red diamond; 1995–2006) or a combination of whole and thin-sectioned (blue diamond) methods (2007–2022). Blue line is a LOESS regression.

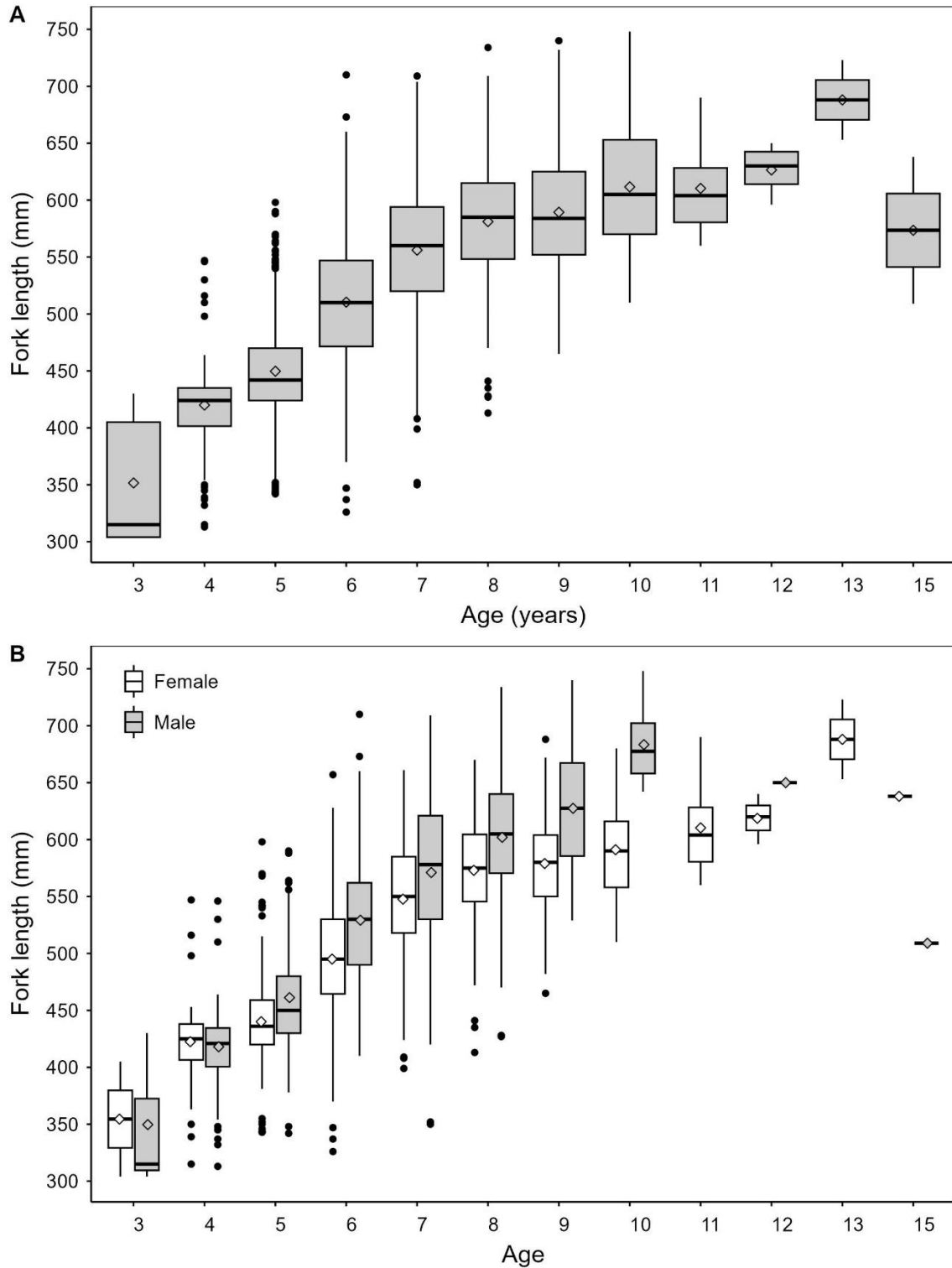


Figure 22. Box plot of length-at-age (median [—], mean [◇], quartiles and outliers [•]) for: A) the total sample and B) female (open bars) and male (shaded bars) Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022).

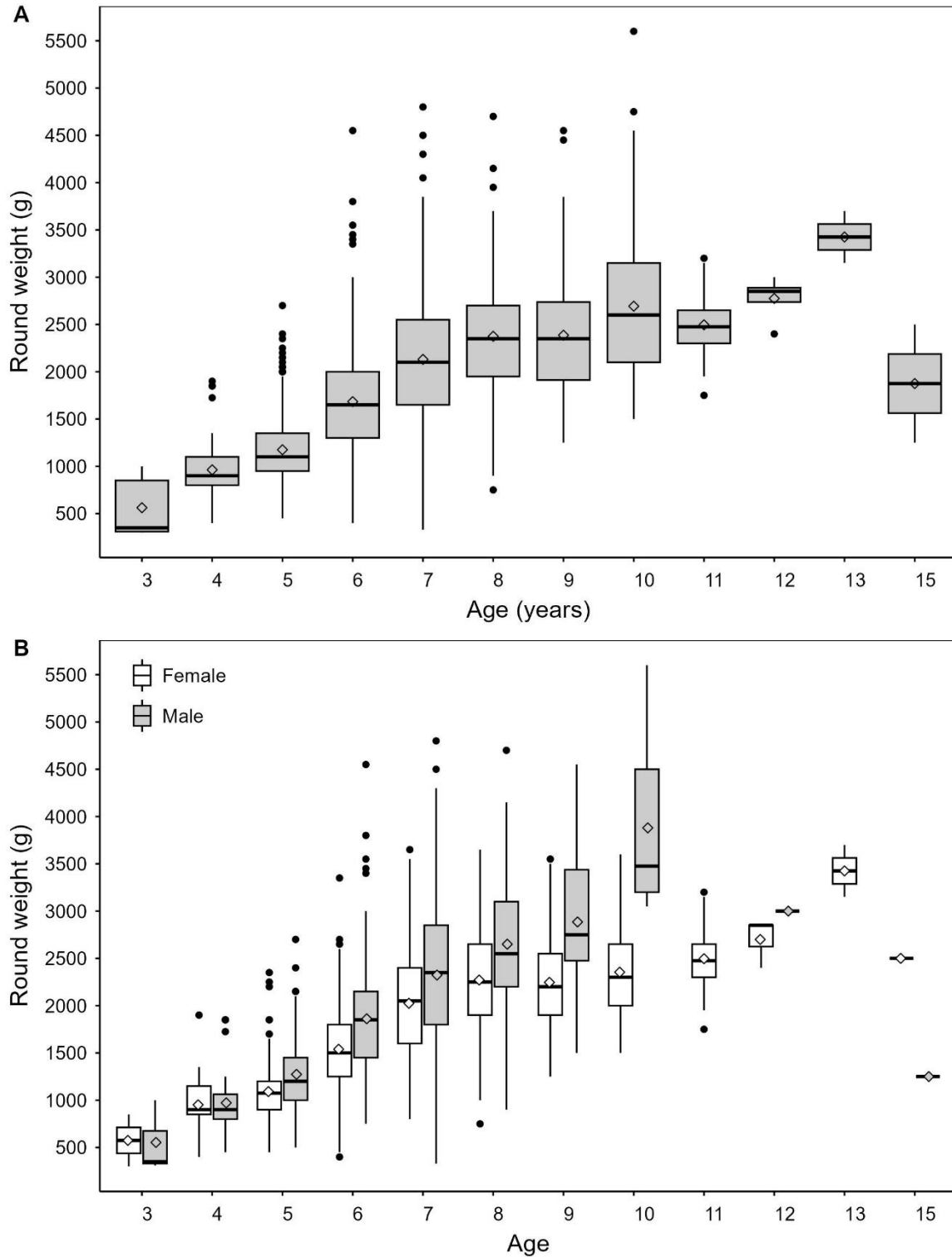


Figure 23. Box plot of weight-at-age (median [—], mean [◊], quartiles, and outliers [•]) for: A) the total sample and B) female (open bars) and male (shaded bars) Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022).

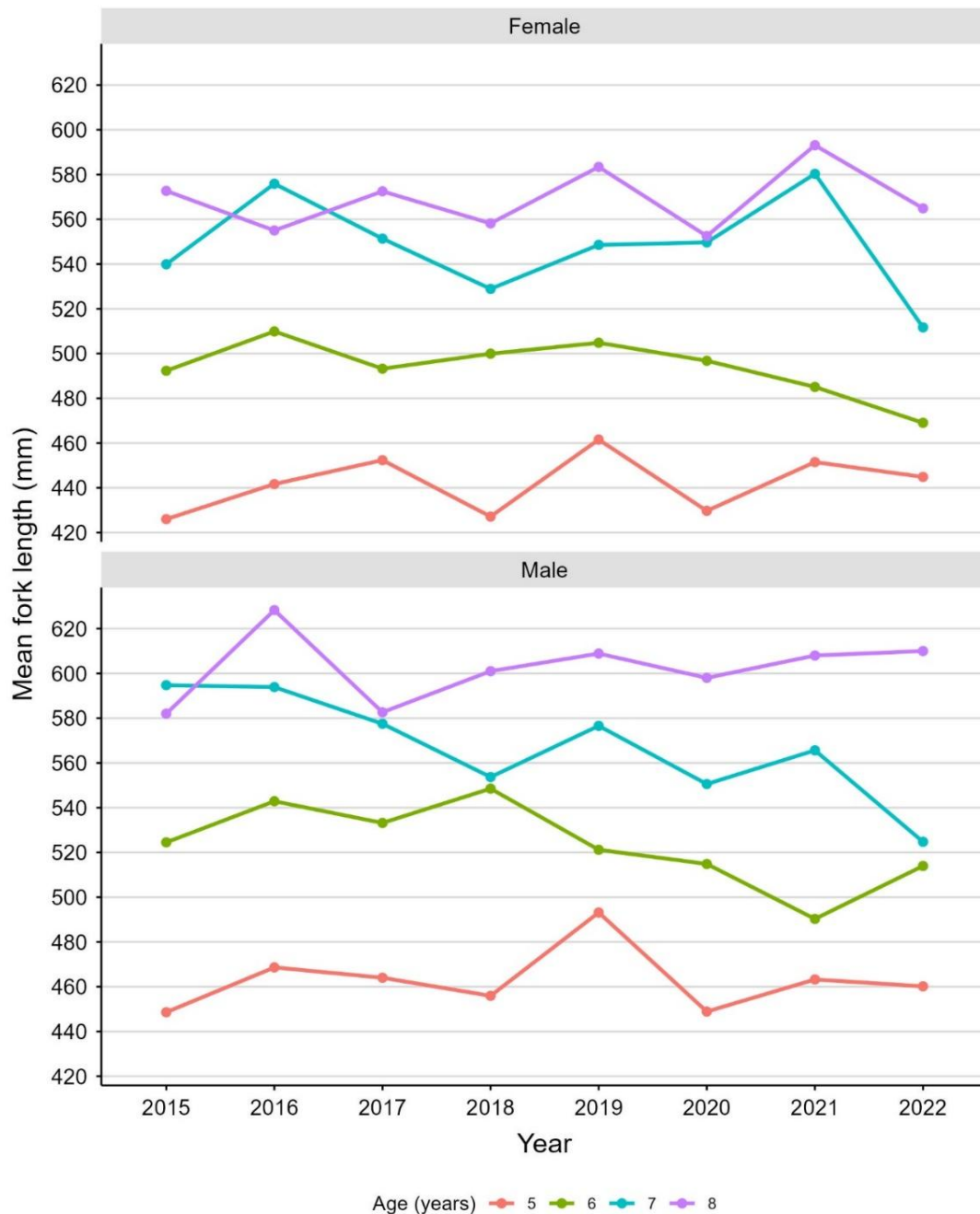


Figure 24. Mean fork length among relatively abundant age classes of female and male Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022). Age class 5 is red, age class 6 is green, age class 7 is blue, and age class 8 is purple.

Proportion of Non-spawners and Spawners

The composition of male and female current-year non-spawners and spawners sampled from the subsistence fishery between 2015 and 2022 was variable (Table 10; Figure 25). In most years there tended to be between 1.5 to 2.5 times more females than males harvested by the monitors. Female and male non-spawners accounted for approximately 30–50% and 25–35% of the total annual sample, respectively. Females not spawning in the current year were typically

slightly more abundant in the sample compared to males except in 2016 and 2017. Female current-year spawners were considerably more abundant than current-year spawning males (~ 2 times), particularly in 2021–2022 (5.5–6.1 times) with the exception of 2016 when they were observed in equal proportions (Table 10). The contribution of female spawners varied considerably among years with values as low as 10% (in 2019) and as high as 37.8% (in 2021). The annual proportion of male spawners was ~ 6% apart from a relatively high value of 11.9% observed in 2015 (Table 10). Ultimately, current-year spawners, regardless of sex, accounted for ~ 25% of harvested fish among years (Figure 25).

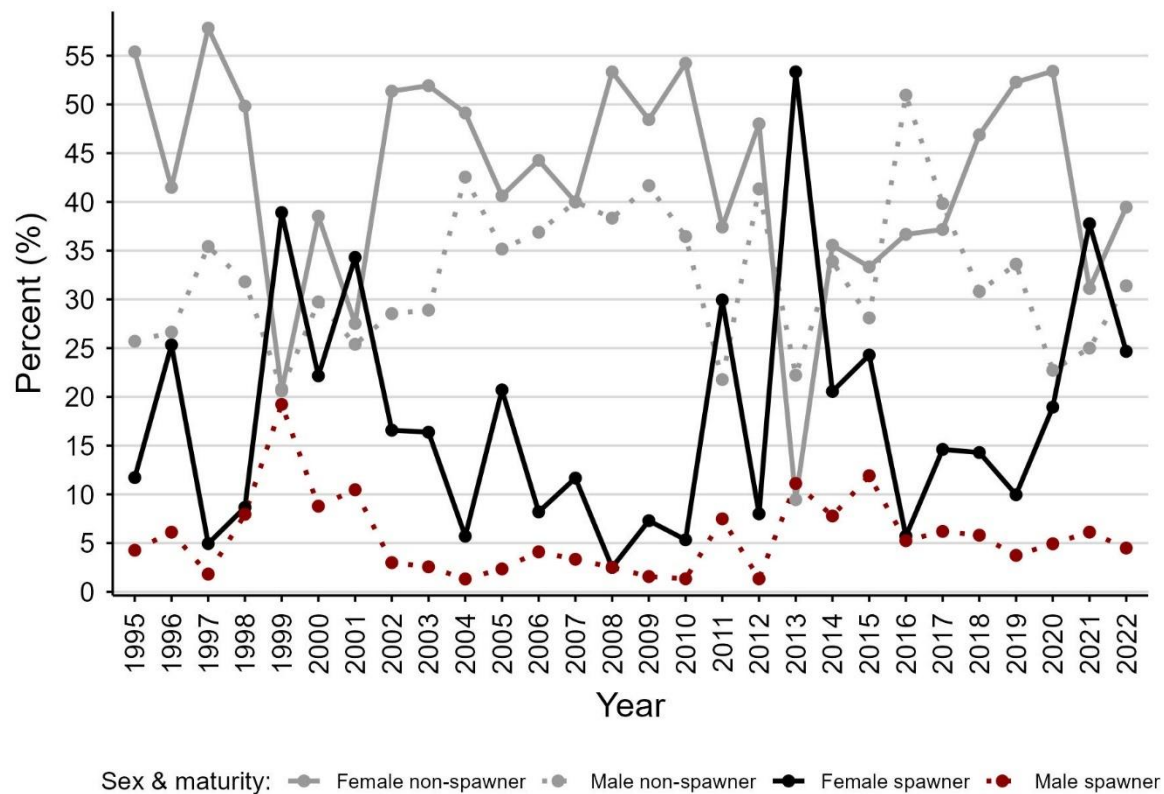


Figure 25. Frequency (%) of anadromous Dolly Varden captured from the Rat River Harvest Monitoring Program identified as female (solid line) and male (dashed line) current-year non-spawners (grey) and spawners (female [black] and male [red]) (1995–2022).

The relatively smaller proportion of male spawners observed on an annual basis is a result of the combination of the natural bias towards females in the anadromous component of the population and because nearly all males spawn in alternating years (~ 85–93%) (Gallagher et al. 2018, Gallagher et al. 2026). Additionally, it has been suggested that males may forgo ocean migration (i.e., remain in the Fish Creek watershed during summer) more often during their lifetime compared to females in order to reduce their probability of mortality (Gallagher et al. 2018), which might further explain their lower prevalence in the Rat River Harvest Monitoring Program. Females spawn in both consecutive and alternate years in almost equal amounts (Gallagher et al. 2026), which helps explain the greater prevalence of females identified as spawners in the sample.

Table 10. Percentage and number (in brackets) of dead-sampled anadromous Dolly Varden from the Rat River Harvest Monitoring Program identified as female (F) and male (M) current-year non-spawners and spawners (2015-2022). Female to male ratios (F:M) are also provided. Note: the number of fish that had undetermined sex/maturity among sampling years varied between 0 and 2.4%.

Year	Female non-spawner	Male non-spawner	Female spawner	Male spawner	Total (n)	F:M non-spawner	F:M spawner	F:M total	% non-spawner	% spawner
2022	39.5 (88)	31.4 (70)	24.7 (55)	4.5 (10)	223	1.2:1	5.5:1	1.7:1	70.9	29.2
2021	31.1 (61)	25 (49)	37.8 (74)	6.1 (12)	196	1.2:1	6.1:1	2.2:1	56.1	43.9
2020	53.4 (141)	22.7 (60)	18.9 (50)	4.9 (13)	264	2.3:1	3.8:1	2.6:1	76.1	23.8
2019	52.3 (126)	33.6 (81)	10 (24)	3.7 (9)	241	1.5:1	2.6:1	1.6:1	85.9	13.7
2018	46.9 (105)	30.8 (69)	14.3 (32)	5.8 (13)	224	1.5:1	2.4:1	1.6:1	77.7	20.1
2017	37.2 (84)	39.8 (90)	14.6 (33)	6.2 (14)	226	0.9:1	2.3:1	1.1:1	77	20.8
2016	36.7 (77)	51 (107)	5.7 (12)	5.2 (11)	210	0.7:1	1:1	0.7:1	87.7	10.9
2015	33.3 (70)	28.1 (59)	24.3 (51)	11.9 (25)	210	1.1:1	2:1	1.4:1	61.4	36.2

Reproductive Characteristics

The proportion of current-year spawners among age and size classes was considerably different between females and males (Figure 26). The presence of mature individuals increased gradually for females starting at age-5 (3.1%) up to age-9 (61%) where the prevalence of mature individuals remained fairly consistent. Males also began spawning at age-5 (7.7%) and the prevalence of mature fish gradually increased up to age-9 (30%), although at a substantially lower extent compared to females. Mature Dolly Varden made up a small proportion (< 15%) among the smaller (< 450 mm) size classes, with the smallest recorded mature female and male Dolly Varden equal to 393 mm and 383 mm, respectively. The proportion of mature females gradually increased among size classes (i.e., > 50% mature for fish ≥ 600 mm) whereas males remained relatively consistent (~ 15%), up to size class ≥ 650 mm where values increased to between 35 and 50% (Figure 26).

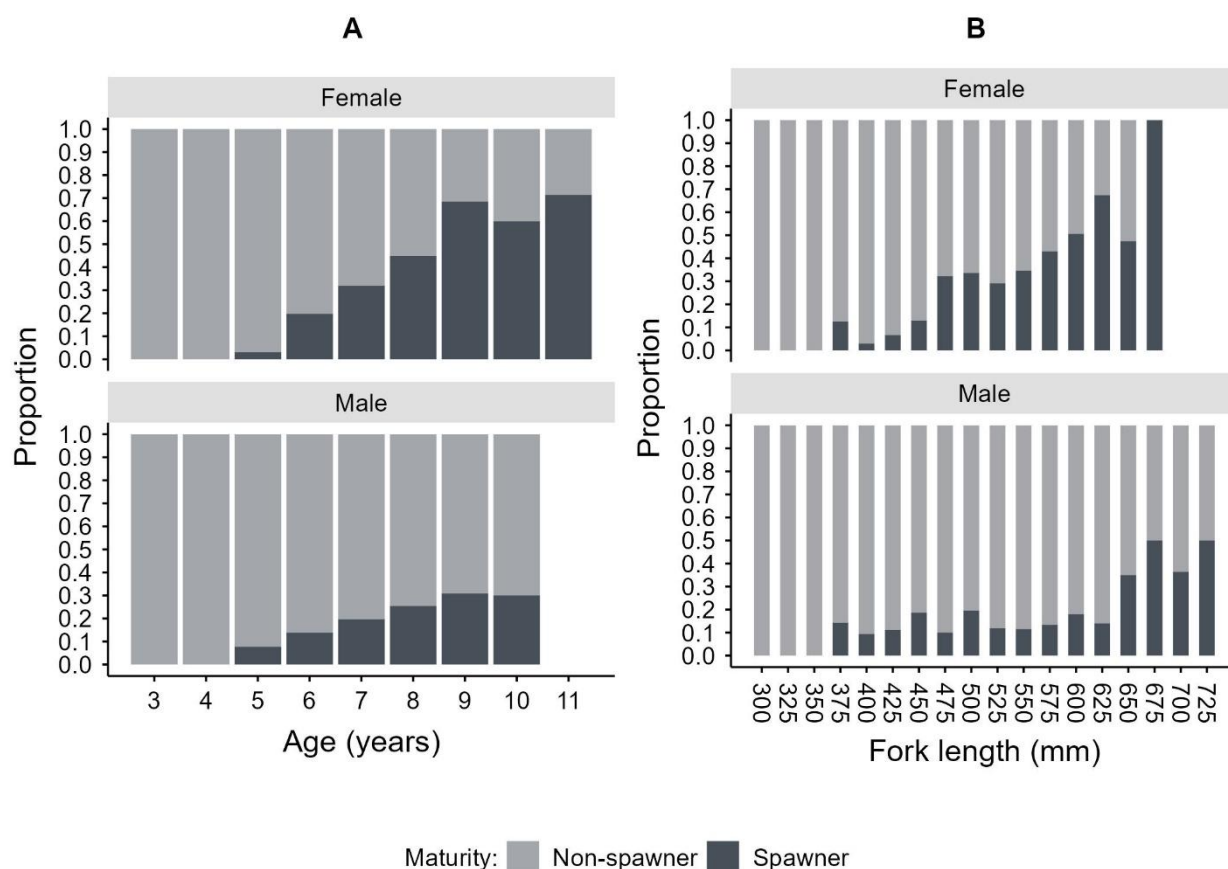


Figure 26. Proportion of female and male anadromous Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022) identified as current-year non-spawning (i.e., either sexually immature juvenile or resting adults) and spawning among A) age and B) fork length size classes.

The gonado-somatic index of non-spawning and mature Dolly Varden from the Rat River were distinctly different across the various age and size classes (Figure 27). Likewise there were differences between sexes; the mean GSI of current-year non-spawning and spawning females was 0.82% (range = 0.01–4.08%) and 10.5% (range = 5.17–24.9%), respectively, while those of males was 0.13 (range = 0.004–2.3%) and 6.4% (range = 3.95–11.0%), respectively (Figure 27). GSI values were similar and tightly clustered among each of the age and size classes for both sexes in the case of non-spawners, while those of fish that were likely to spawn in the

current year were considerably more variable (Figure 27). There were no discernable differences between sexually immature and resting adult GSI values given these overlapped between fish that would be confidently considered to be all sexually immature (e.g., age-3–4, < 350 mm) or adult (e.g., age-9–10, > 600 mm).

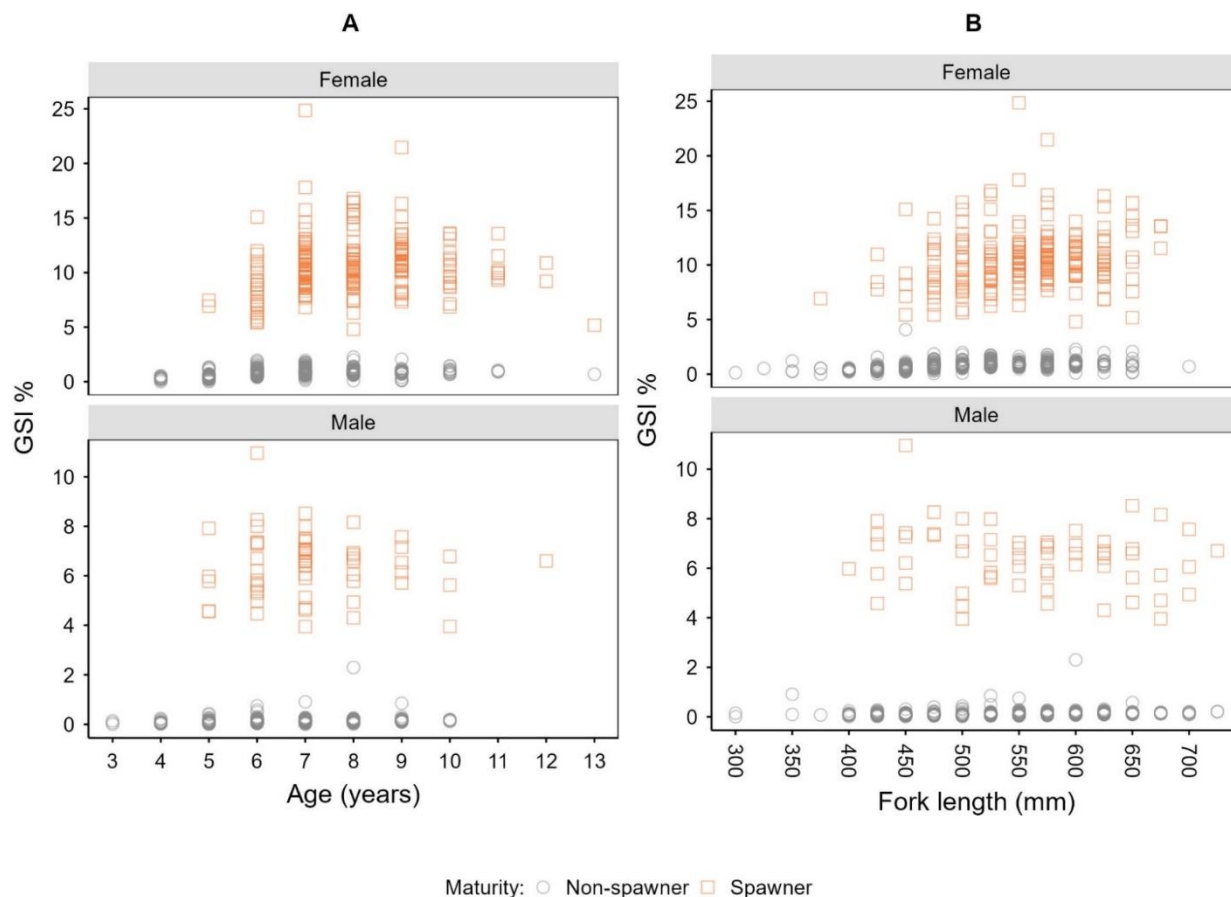


Figure 27. Gonado-somatic index (GSI) of female and male anadromous Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022) collected from Big Eddy and mouth of Rat River sites) identified as current-year non-spawning (i.e., either sexually immature juvenile or resting adults) and spawning among A) age and B) size classes. Non-spawners are light grey circle and spawners a light orange square.

Mean fecundity was 5,676 and ranged between 2,419 and 10,315 eggs. A linear relationship best explained fecundity as a function of fork length or weight (Figure 28). Fecundity generally increased with length ($r^2 = 0.58$) and weight ($r^2 = 0.62$) but with a high level of variability in egg numbers at a given size, particularly in fish > 550 mm/2,000 g (Figure 28). Egg diameter had a grand mean of 3.7 mm (range of means = 2.5–5.1 mm) and demonstrated a weak positive correlation with fork length (Pearson $r = 0.22$).

Mean fecundity using mature ovaries from 2015–2022 was 30% higher compared to those from 1983 (i.e., 5,676 vs. 4,221 eggs) (Gillman and Sparling 1985). Although the mean size of mature females sampled in Gillman and Sparling (1985) was smaller (442 mm vs. 567 mm), which helps explain the lower fecundity given its positive correlation with length, it is not known what sizes of fish were used. Therefore, it is difficult to elucidate if there has been a change in fecundity (proportional to fish size) in the population.

Precisely determining the age and size class where the majority of males and females attain sexual maturity using the biological data collected in the Rat River Harvest Monitoring Program is limited as the need to account for the proportion of fish that spawn in alternate years, which appears to become less prevalent as fish get older (> 550 mm/ $\sim$ age-7) (see Gallagher et al. 2026). The high prevalence of mature individuals among older ages and larger sizes ($\geq$ age-9, > 650 mm; Figure 26) supports the interpretation that Dolly Varden approaching senescence will adopt a higher rate of annual spawning versus alternate year spawning. It is likely that the majority of fish in the population will spawn for the first time at age-6 (~ 500 mm fork length) assuming they began ocean migration at age-4, migrated the following year, and spawned for the first time after their second annual migration at age-6 (Gallagher et al. 2018).

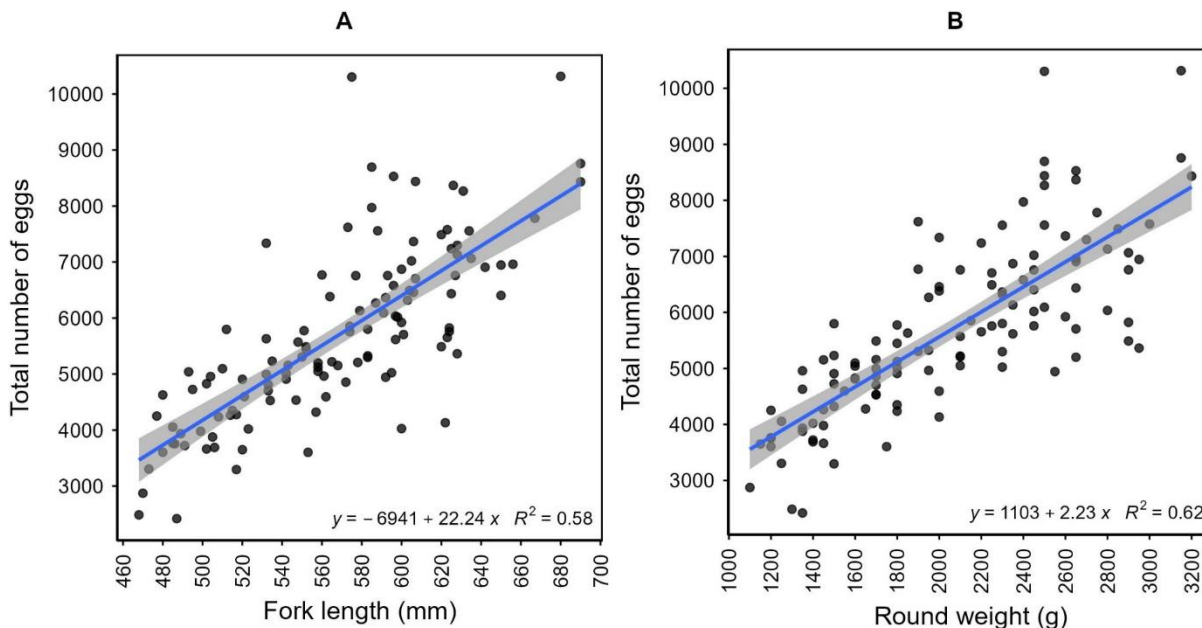


Figure 28. Fecundity of current-year spawning individuals plotted against A) fork length and B) round weight of Dolly Varden from the Rat River Harvest Monitoring Program (2015–2022). Blue line is the linear regression fitted to the data and the grey shaded area is the 95% confidence interval.

Timing of Size-classes and Spawning Fish during Upstream Migration

In some years there appeared to be structure in the size-class composition of migrating Dolly Varden over the duration of the monitoring program. Specifically, the size composition of fish sampled at the start of monitoring (i.e., earlier during the migration) tended to consist of larger individuals (> 550 mm) while those captured later ($\sim$ third week of August) were typically smaller (< 450 mm) (e.g., Big Eddy 2021, mouth of Rat River 2017, and Destruction City 2022) (Figure 29, 30, 31). This pattern was not evident in all years as there were multiple instances of a wide range of sizes (i.e., large and small) sampled throughout the duration of the monitoring program (e.g., Big Eddy 2016, mouth of Rat River 2015, Destruction City 2017). Additionally, the observed size structure did not appear consistent among sites within a year (e.g., 2020 was structured at Destruction City but not the other sites; although, note that various gill net mesh sizes were used during the fishery at Destruction City, which likely influenced sizes of harvested fish). However, exceptions were observed in 2021 when all three sites demonstrated size structure over time and in 2019 when no structure was evident among the three locations. Interestingly, Destruction City appeared to have the most years when a temporal size structure

was observed (all years except 2019 and 2017) (Figure 31) while only a few years were apparent for the other sites.

Female and male Dolly Varden expected to spawn in the fall were predominantly captured at the start of the monitoring program and common in most years until ~ August 10 (Figure 32, 33, 34). Non-spawners (juveniles and resting adults) subsequently followed and were the most prevalent in the later part of the upstream migration. Current-year spawners were rarely observed in late August/early September.

Earlier studies have demonstrated Dolly Varden that are larger-sized and/or current-year spawners leave the ocean and return to their natal stream before smaller-sized juvenile fish (McCart 1980). In the Firth River, spawning individuals are reported to arrive at the spawning area one month earlier than juvenile non-spawners (Glova and McCart 1974). Given the Rat River monitors were instructed to randomly sample fish, the observed size structure or lack of it was likely not an artefact of biased sampling. The higher prevalence of years with apparent size structure at Destruction City, the monitoring site furthest upstream in the Rat River, compared to the other locations might indicate that the smaller fish that have entered the Rat River after traversing the Mackenzie Delta might be slower to move upstream (e.g., take some time to stage within the river before moving up to the spawning area). Further study is necessary to better understand the timing of upstream migration among size-classes of Rat River Dolly Varden and why it appears that a temporal size structure is seemingly apparent in some years and sampling locations over others in the upstream migration corridor. A stronger contrast in temporal size structure may have been more apparent had sampling continued well into September when presumably more smaller-sized fish would have been captured.

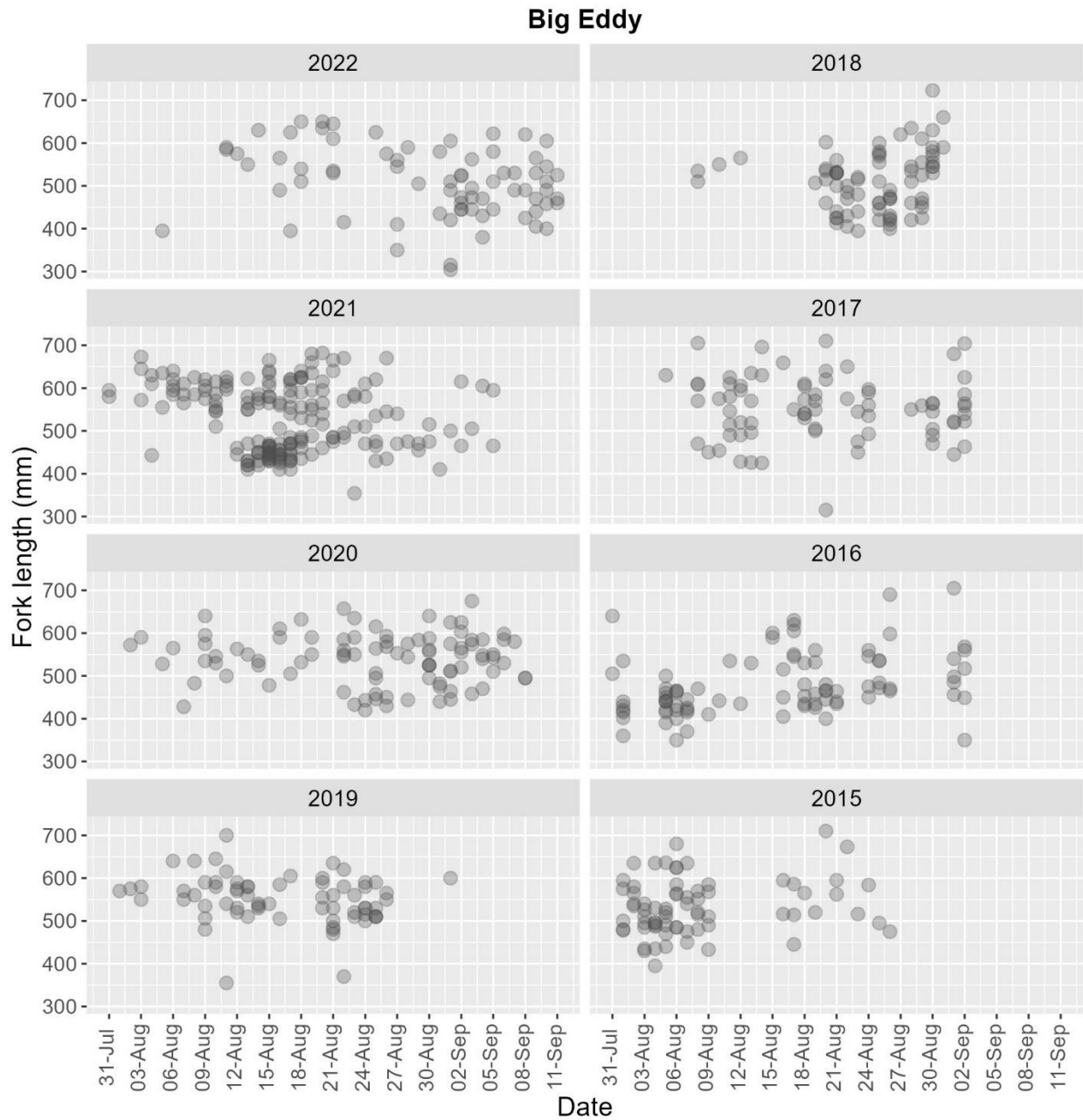


Figure 29. Daily occurrence of fork length size classes of Dolly Varden captured at the Big Eddy location of the Rat River Harvest Monitoring Program (2015–2022).

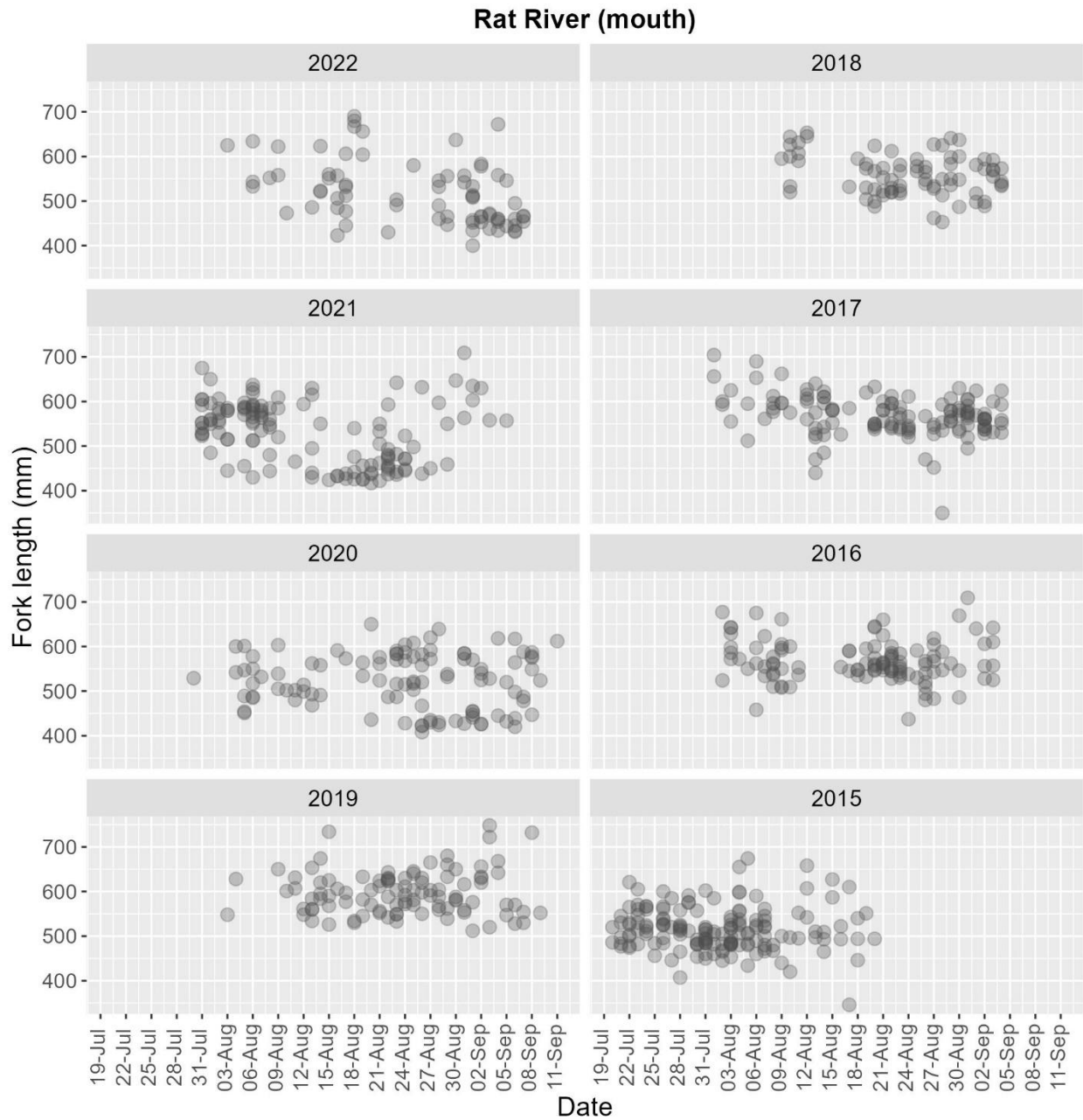


Figure 30. Daily occurrence of fork length size classes of Dolly Varden captured at the mouth of Rat River location of the Rat River Harvest Monitoring Program (2015–2022).

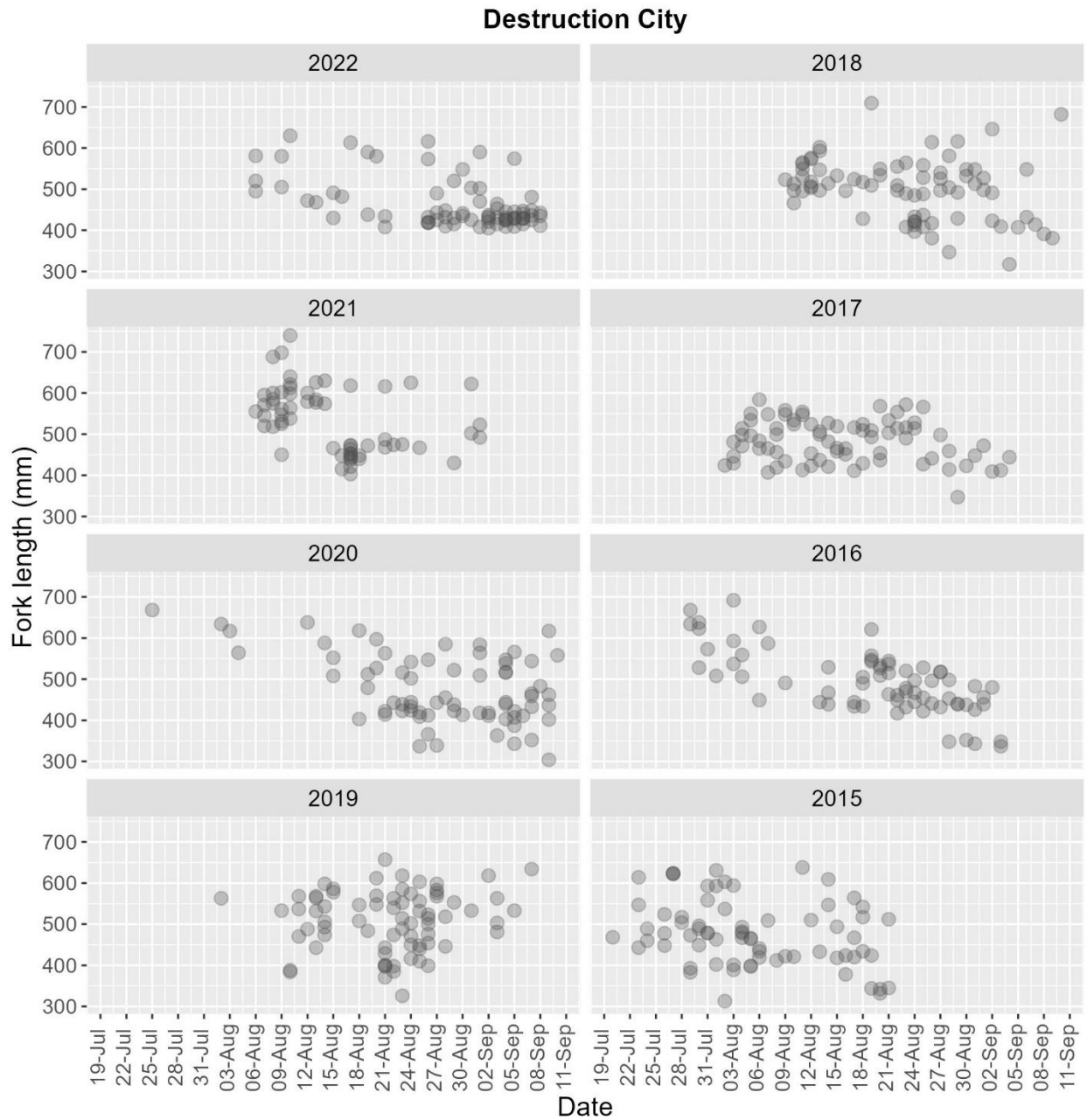


Figure 31. Daily occurrence of fork length size classes of Dolly Varden captured at the Destruction City location of the Rat River Harvest Monitoring Program (2015–2022).

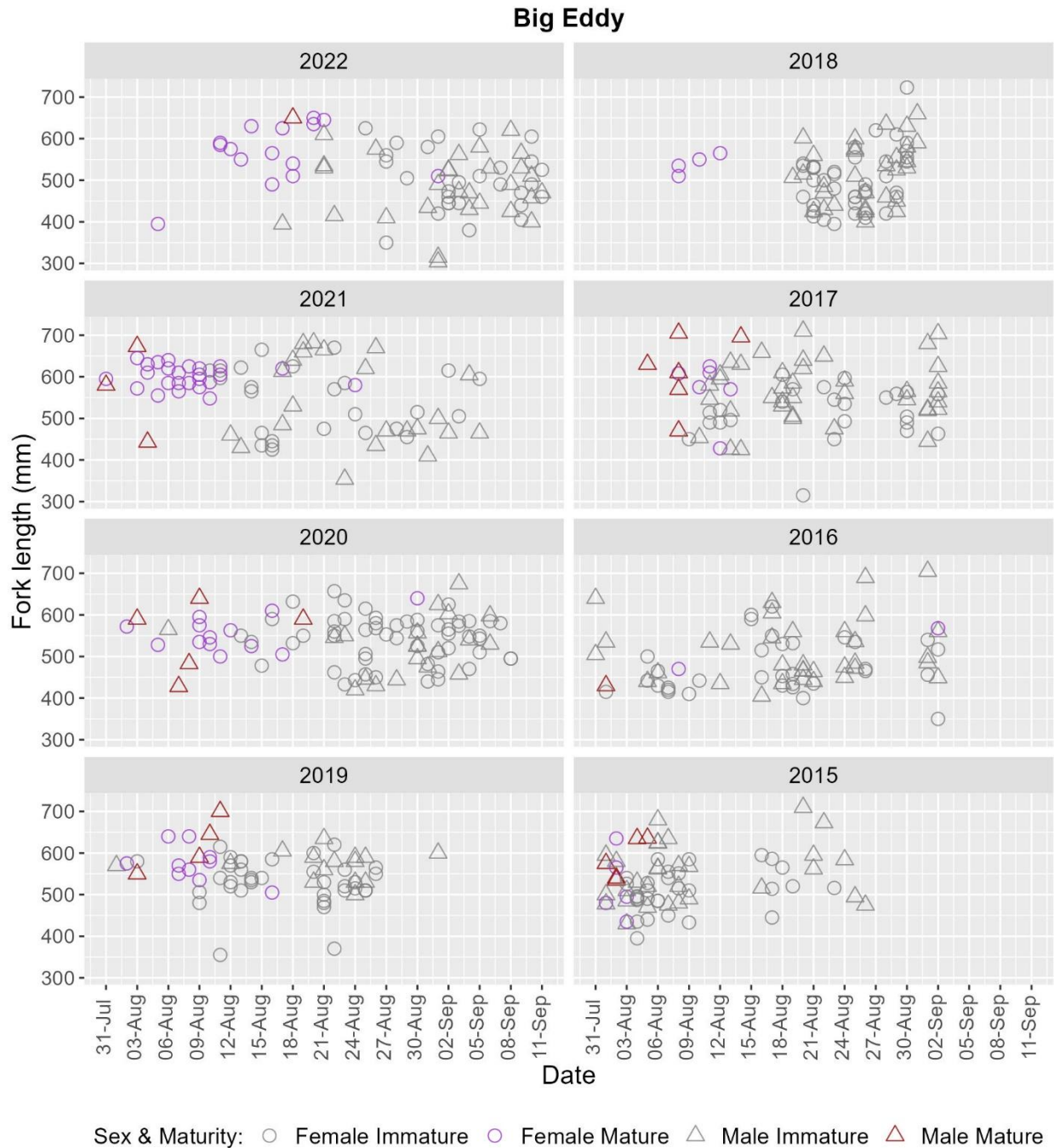


Figure 32. Daily occurrence of female and male Dolly Varden identified as mature and immature captured at the Big Eddy location of the Rat River Harvest Monitoring Program (2015–2022). Immature females are grey circles, mature females are purple circles, immature males are grey triangles, and mature males are red triangles.

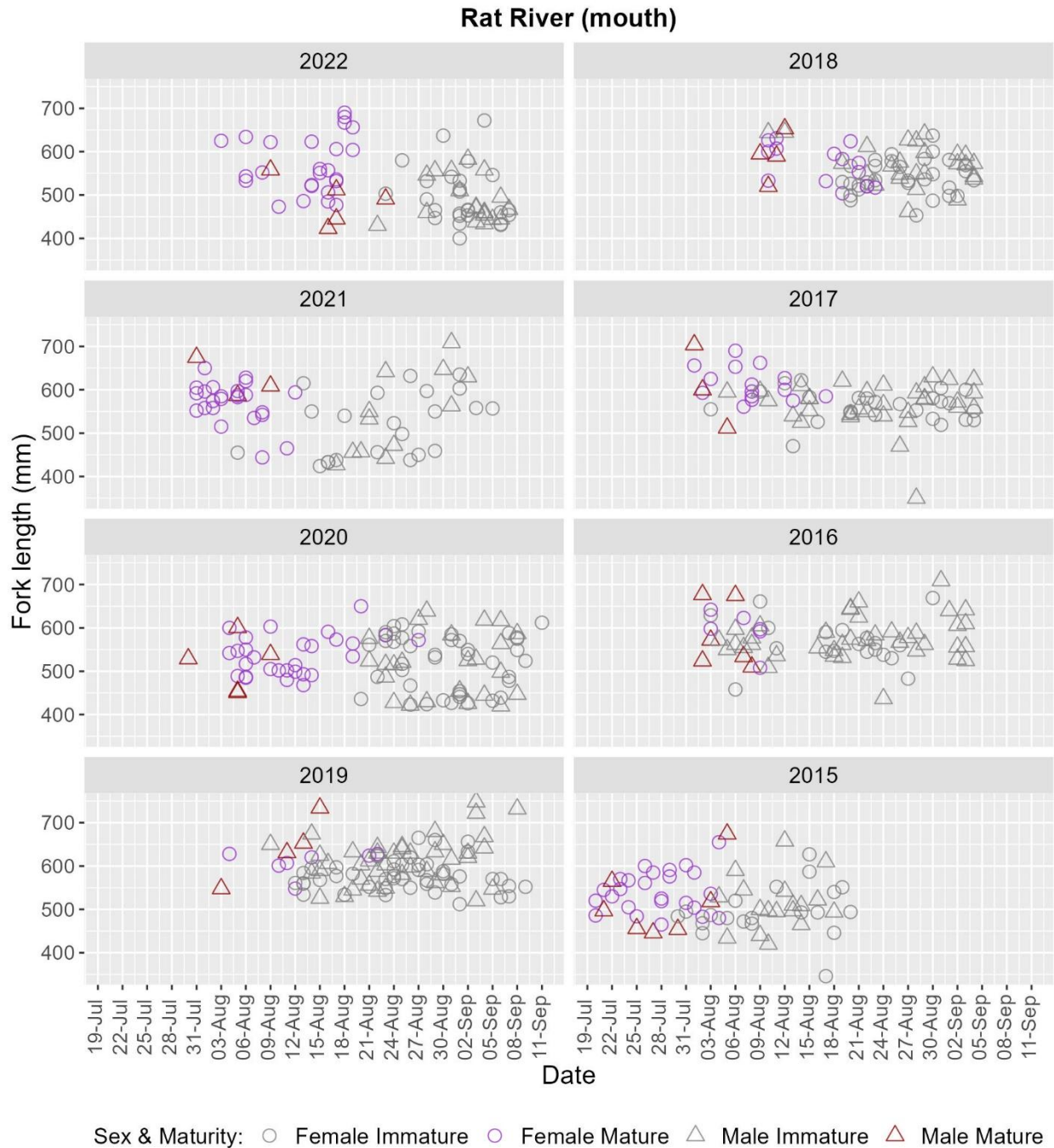


Figure 33. Daily occurrence of female and male Dolly Varden identified as mature and immature captured at the mouth of Rat River location of the Rat River Harvest Monitoring Program (2015–2022). Immature females are grey circles, mature females are purple circles, immature males are grey triangles, and mature males are red triangles.

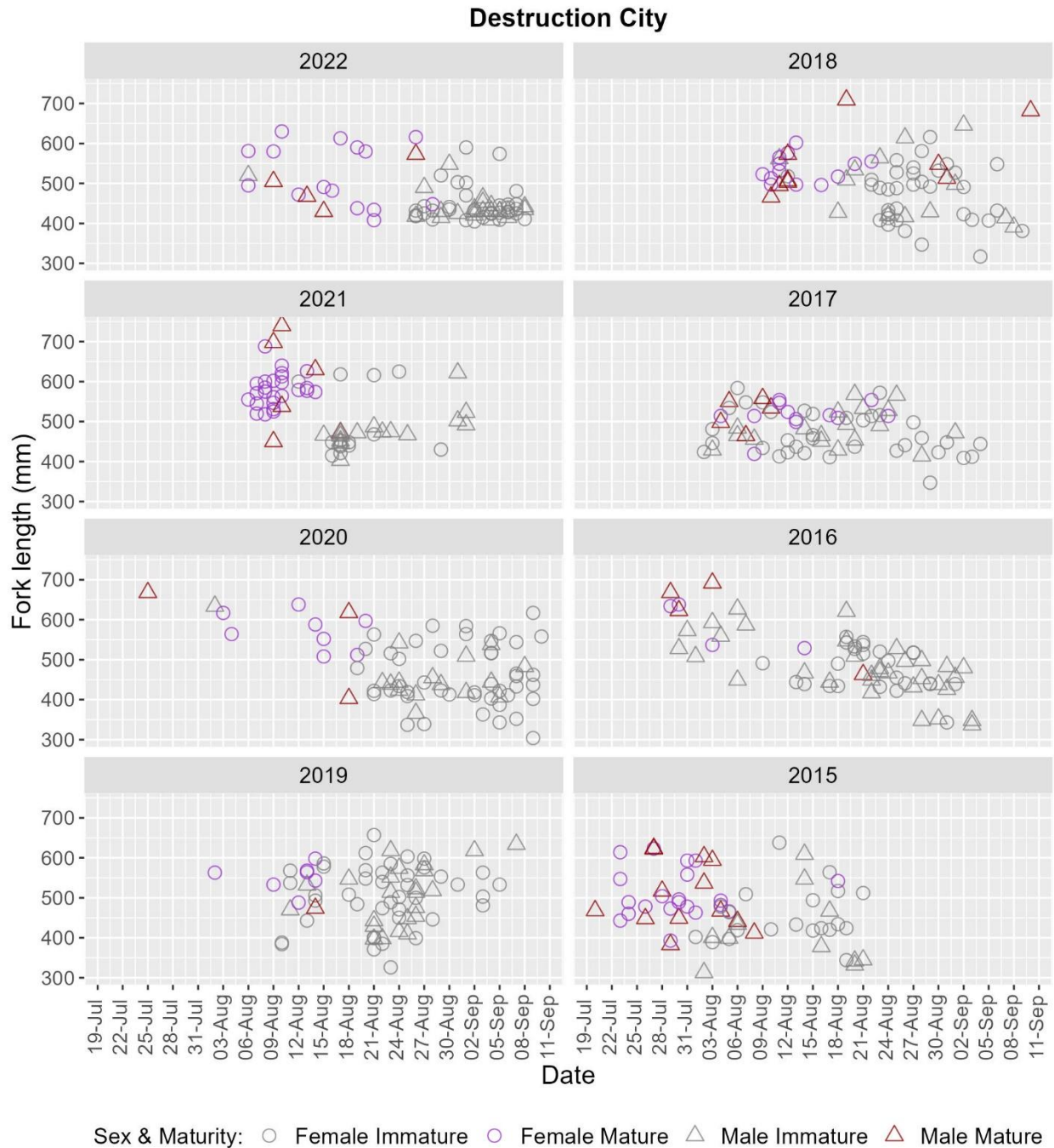


Figure 34. Daily occurrence of female and male Dolly Varden identified as mature and immature captured at the Destruction City location of the Rat River Harvest Monitoring Program (2015–2022). Immature females are grey circles, mature females are purple circles, immature males are grey triangles, and mature males are red triangles.

SUMMARY

The trends in harvest, relative abundance, and biological indicators for Dolly Varden from the Rat River obtained through harvest surveys and fisheries-dependent monitoring programs performed between 2015 and 2022 revealed:

- In the summer coastal fisheries, where genetic samples are collected regularly, the Rat River stock is almost exclusively captured at Shingle Point.
- Percent contributions to the overall harvest at Shingle Point averaged 27.5% per year and were highly variable among years (12–52%).
- The majority (90%) of the harvest experienced by the population occurs in the inland fisheries when fish are migrating upstream towards spawning and overwintering habitats.
- The number of fish harvested has decreased following relatively high values reported between 2015 and 2017. Recommended harvest levels have been more conservative since 2006 and in recent years the annual harvest has typically been < 400 fish.
- Annual harvest rate was typically < 5% of the most recent estimated population abundance size.
- Catch-effort data indicates population abundance was improved from 2015–2017/18 (2018 based on Destruction City only) and declined thereafter with an exception of the increased mean value in 2021.
- The temporal pattern in catch-effort data appeared to complement the general trends observed in population abundance (based on mark-recapture results) and reported total harvest (i.e., relatively higher values in 2015–2017 followed by a decline).
- Fish are attaining larger sizes compared to the 1990s and early 2000s. The increase in size applies to both males and females, and to current-year spawners.
- Mean age has increased from ~ 7.5 (2015–2018) to ~ 8.1 (2019–2022) years.
- Condition factor was relatively stable apart from a lower value observed in 2018.
- Annual mortality varied without trend. Males experienced higher annual mortality compared to females (0.62 vs. 0.52).
- Length and age frequency distributions among years indicate variable recruitment of juvenile fish into the fishery (particularly in 2021 and 2022).
- Growth of fish is variable within an age-class yet the average size among the more abundant age classes did not appear to change substantially among years.
- Females were between 1.5 and 2.5 times more prevalent than males in the anadromous component of the population sampled at the monitoring sites. The annual proportion of spawning females varied between 10% and 37.8% while males intending to spawn in the current year were consistently lower (~ 6%) given their greater propensity to spawn in alternate years.
- Sexual maturity was observed in fish as young as age-5 and the proportion of mature individuals increased gradually among age and size classes.
- The mean gonado-somatic index (GSI) of current-year non-spawning and spawning females was 0.82% and 10.5%, respectively while those of males was 0.13% and 6.4%, respectively.

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- Fecundity was an average of 5,676 eggs and was positively correlated with length.
 - In some years, fish sampled earlier during the upstream migration tended to be larger individuals (> 550 mm) while those captured later were typically smaller ones (< 450 mm).
 - Female and male current-year spawners were more prevalent earlier during the upstream migration among the three monitoring locations.

CONCLUSION

As of 2022, anadromous Dolly Varden from the Rat River appear to be in a state of low abundance after experiencing a period of relatively higher population productivity between approximately 2013 and 2017. Based on the results from the fisheries-dependent Rat River Harvest Monitoring Program and the fisheries-independent tagging program, this appears to be the second important decline since 1995 (first was in 2004), when fisheries-dependent and -independent programs coincided. However, it is important to underscore that “decline” is relative given that in the greater context of time the stock has experienced a more substantial decrease in abundance decades ago (Benson 2010). Interestingly, the recent decline in relative abundance and estimated abundance was not accompanied by higher rates of annual mortality. It is unclear whether the smaller mean size observed in 2022 was a result of a pulse of juveniles into the population, an absence (i.e., due to mortality) of older adults, or both. This most recent decline suggests the population can experience important fluctuations in abundance over short periods of time. The decline in 2004 was preceded by harvest rates that were considerably higher (up to 36%), which may have contributed to reductions in population abundance (Howland et al. 2012). It is unlikely that the recent decline is a product of harvest given the low rate of removal experienced by the stock (i.e., typically < 5%). The role of freshwater and marine environmental factors on recruitment, growth, mortality, and migration tactics and timing of Dolly Varden and its implications for subsistence fisheries requires additional research. For example, although speculative, the trend of a sustained increase in sizes of anadromous fish may indicate enhanced feeding in marine habitats (e.g., Courtney et al. 2019).

Maintaining the time-series of the various fisheries-dependent programs, in addition to the fisheries-dependent program undertaken for the stock (see Gallagher et al. 2026), is important to evaluate environmental-related hypotheses pertaining to changes in population productivity. Equally important is the knowledge held by experienced Gwich'in and Inuvialuit harvesters, particularly elders, that can inform how environmental conditions might be driving changes in the population and fisheries. Co-interpretation of the fisheries data by Knowledge Holders and scientifically trained researchers would be one approach to generate dialogue and information about trends in observed changes for Rat River Dolly Varden. Although there are round-table discussions about harvesters'/monitor's observations and the data results of the monitoring program at the annual Rat River Working Group meeting (see Lea et al. 2021), there is opportunity to improve how information is shared and interpreted in order to gain a more comprehensive understanding of how the population and the fisheries it supports are changing. Given the complex and rapid environmental change occurring in the western Canadian Arctic, utilizing multiple sources of information such as community-based fisheries monitoring data is required to inform population assessment of Dolly Varden from the Rat River to better understand causes of variation in stock abundance.

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APPENDIX. TABLES AND FIGURES

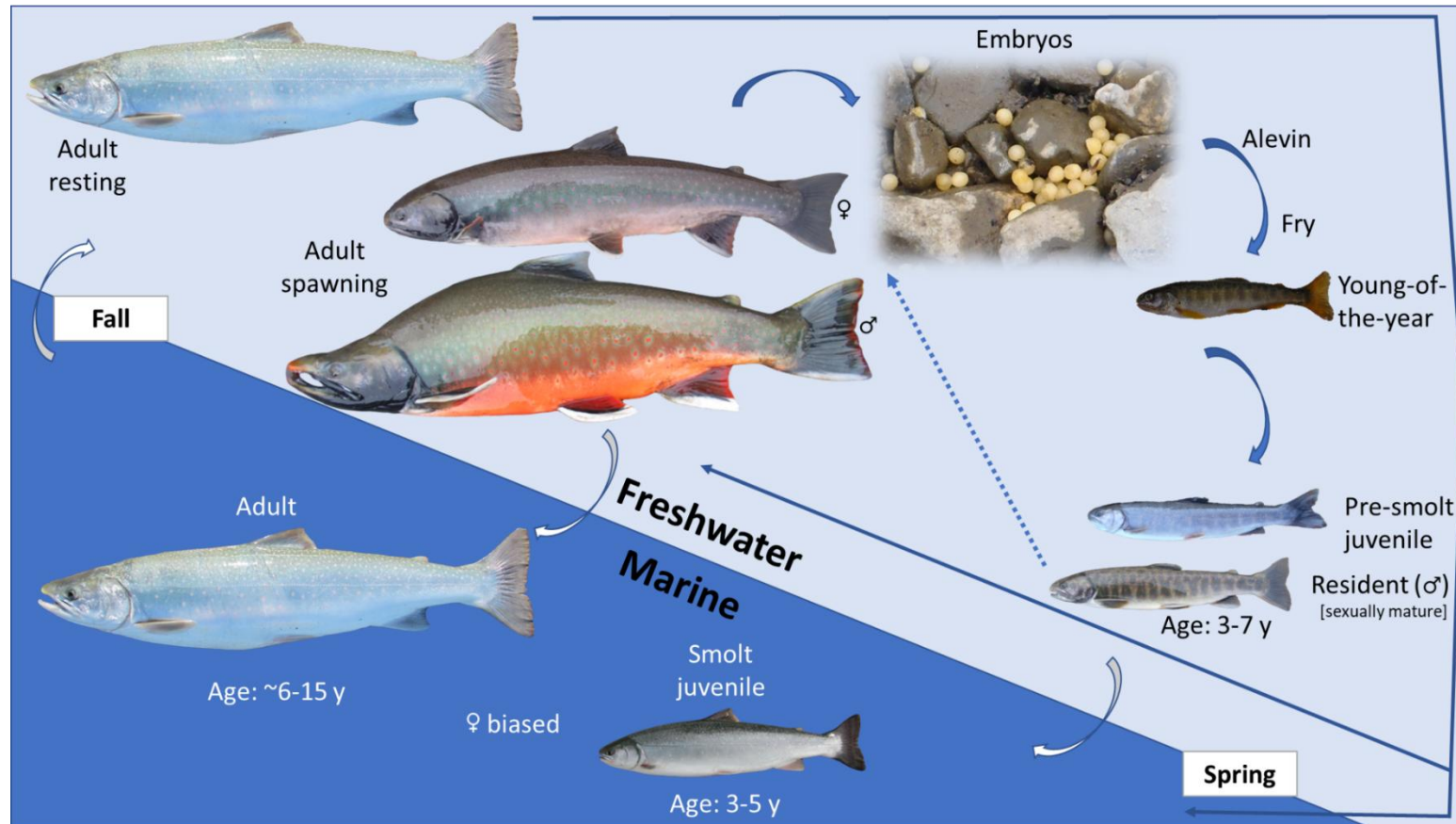


Figure A1. Life cycle of Dolly Varden from the Rat River. Embryos develop in gravel-cobble substrates with groundwater springs in Fish Creek and juvenile stages reared in the watershed. A component of males will adopt a resident life history tactic and remain and attain sexual maturity in freshwater, and will spawn with anadromous individuals. The anadromous component of the population begin seasonal migrations as juveniles to the Beaufort Sea starting between ages 3 and 5. After approximately two annual migrations anadromous fishes attain sexual maturity. Mature (i.e., intending to spawn in the current year), resting (i.e., sexually mature but does not spawn in the current year), and juvenile anadromous fish return to freshwater to reproduce and/ or overwinter in Fish Creek. Some anadromous fish (female and male) can skip ocean migration and remain in the Fish Creek watershed during summer and spawn in the following year, and conduct an ocean migration in the following spring. Photos by Colin Gallagher.



Figure A2. Images taken by Rat River Harvest monitors (2015–2022). A) Mouth of Rat River (2017), B) Camp at Destruction City (2017), C) Selwyn Kay, monitor at Destruction City (2017), D) John Carmichael, monitor at Big Eddy (2017), E) John Carmichael, monitor at Big Eddy (2017), F) Camp at mouth of Rat River (2017), G) Camp at Destruction City (2018), H) Sampling fish at Destruction City (2018), I) Big Eddy (2018), J) Sampling fish at Big Eddy (2018), K) Sampling fish at Destruction City (2019), L) Tyler Carmichael, monitor at Big Eddy (2019), M) Weighing a Dolly Varden at Big Eddy (2019), N) Harry Carmichael, monitor at Big Eddy (2021), O) Sampling fish at Mouth of Rat River (2022).

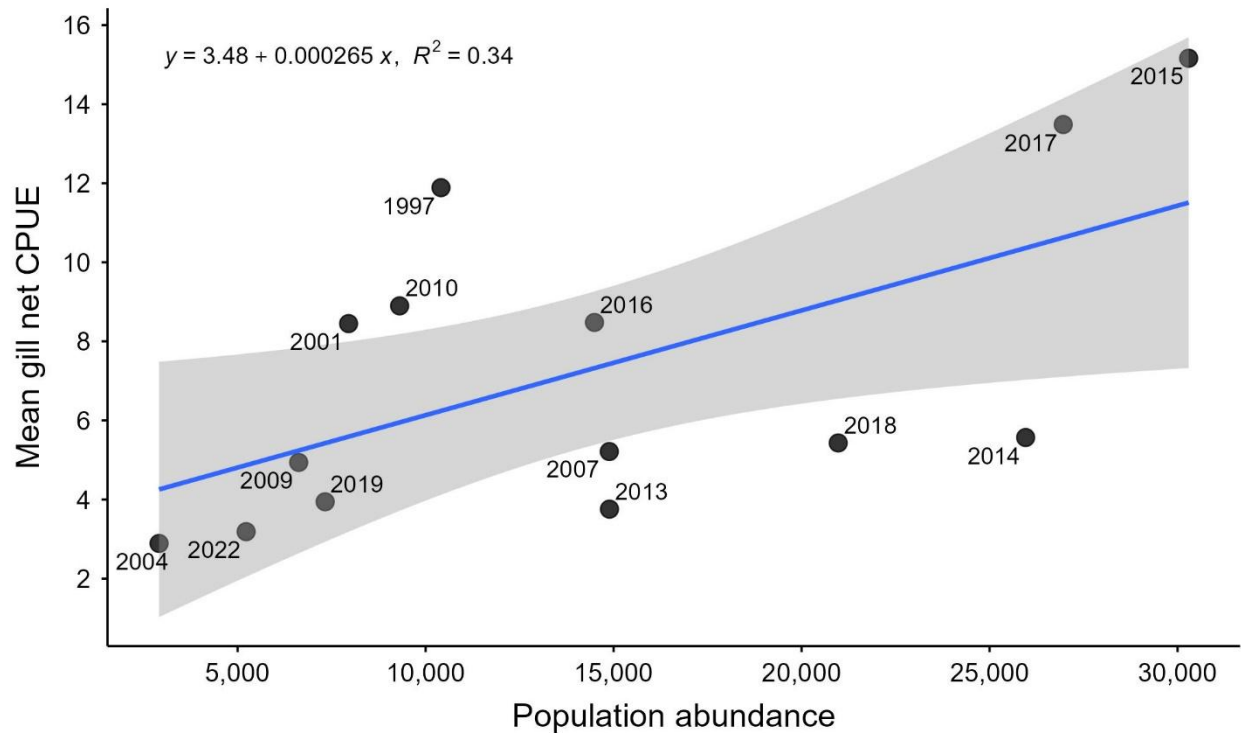


Figure A3. Relationship between annual grand mean of catch-per-unit-effort (CPUE; # fish/25 m/24 h) (i.e., all mesh sizes and locations combined) and population abundance estimates. A linear regression is fitted to the data (blue line) with 95% confidence intervals (grey area).

Table A1. Fork length (log10 transformed) characterized as follows: parametric (P) or non-parametric (NP) distributions and the results of Mann-Whitney test (U) or two-sample t-test (t) to examine for differences in length of Dolly Varden between gill net mesh sizes as part of the Rat River Harvest Monitoring Program (2015-2022). Statistically significant results ($p \leq 0.05$) are in bold and df is the degrees of freedom.

Year	102 mm	114 mm	127 mm	102 vs. 114 mm	114 vs. 127 mm	102 vs. 127 mm
2022	NP	NP	-	U = 7,090, $p < 0.001$	-	-
2021	NP	NP	NP	U = 8,281, $p = 0.021$	U = 4,571, $p < 0.001$	U = 6,306, $p = 0.017$
2020	P	NP	P*	U = 3,140, $p < 0.001$	-	-
2019	NP	NP	-	U = 5,119, $p = 0.14$	-	-
2018	P	P	-	t = -5.96, df = 1,146.7, $p < 0.001$	-	-
2017	P	NP	-	U = 1,997, $p < 0.001$	-	-
2016	P	NP	-	U = 13,926, $p < 0.001$	-	-
2015	P	NP	-	U = 1,560, $p = 0.64$	-	-

*statistical test not performed as 127 mm mesh only had a sample size of $n = 6$.

Table A2. Fork length (log10 transformed) characterized as follows: parametric (P) or non-parametric (NP) distributions and the results of Mann-Whitney (U) or two-sample t-test (t) to examine for differences in length between male (M) and female (F) Dolly Varden (all maturity stages combined) within gill net mesh size captured in the Rat River Harvest Monitoring Program (2015-2022). Sample sizes were too low ($n \leq 10$) in some years to perform tests while the 127 mm mesh was only used in 2020 and 2021. Statistically significant results ($p \leq 0.05$) are in bold. df is the degrees of freedom.

Year	102 mm		114 mm		127 mm		102 mm	114 mm	127 mm
	M	F	M	F	M	F			
2022	NP	P	NP	NP	-	-	U = 829, p = 0.014	U = 2,996, p = 0.098	-
2021	P	NP	NP	NP	NP	NP	U = 303, p = 0.487	U = 677, p = 0.23	U = 534, p = 0.234
2020	P	P	NP	NP	*	*	U = 434, p = 0.803	U = 4,202, p = 0.17	-
2019	P	NP	NP	NP	-	-	U = 248, p = 0.004	U = 2,784, p = 0.01	-
2018	P	NP	NP	P	-	-	U = 658, p = 0.242	U = 1,216, p = 0.084	-
2017	P	NP	NP	NP	-	-	U = 488, p = 0.362	U = 2,348, p = 0.356	-
2016	P	P	P	P	-	-	T = -0.36; df = 1,48; p = 0.72	t = -1.29; df = 1,133; p = 0.2	-
2015	*	*	P	P	-	-	-	U = 4,167, p = 0.306	-

*statistical test not performed due to small sample size or one mesh sized used so no comparison could be made

Table A3. Results of Mann-Whitney test (U) to examine for difference in ages of Dolly Varden between gill net mesh size captured among years in the Rat River Harvest Monitoring Program (2015–2022). Sample sizes were too low ($n \leq 10$) in some years to test. Statistically significant results ($p \leq 0.05$) are in bold.

Year	102 mm vs. 114 mm	102 mm vs. 127 mm	114 mm vs. 127 mm
2022	U = 6,551, p < 0.001	-	-
2021	U = 2,472, p = 0.004	U = 1,838, p = 0.34	U = 1,575, p = 0.02
2020	U = 2,774, p < 0.001	*	*
2019	U = 4,702, p = 0.55	-	-
2018	U = 3,506, p < 0.01	-	-
2017	U = 3,852, p < 0.001	-	-
2016	U = 6,084, p < 0.001	-	-
2015	*	-	-

*statistical test not performed due to small sample size

Table A4. Results of Mann-Whitney test (U) to examine for difference in ages between male (M) and female (F) Dolly Varden captured among years in the Rat River Harvest Monitoring Program (2015–2022). Statistically significant results ($p \leq 0.05$) are in bold.

Year	M vs. F
2022	U = 7,973, $p < 0.001$
2021	U = 4,482, $p = 0.006$
2020	U = 7,563, $p = 0.001$
2019	U = 5,632, $p = 0.506$
2018	U = 5,602, $p = 0.304$
2017	U = 6,159, $p = 0.42$
2016	U = 4,801, $p = 0.673$
2015	U = 5,678, $p = 0.015$
