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Assessing Population Dynamics of Arctic Char, *Salvelinus alpinus*, from the Halokvik and Jayko Rivers, Cambridge Bay, Nunavut, Canada

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Foreword

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

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TABLE OF CONTENTS

ABSTRACT

Arctic Char, *Salvelinus alpinus*, are frequently exploited in the Halokvik and Jayko rivers by Cambridge Bay fishers for subsistence and commercial purposes. Commercial fisheries for anadromous Arctic Char in the Halokvik River date back to 1968 and at the Jayko River the commercial fishery began in 1975; both have been subjected to periodic closures throughout their history. Harvest data are available for both systems and each has a long-time series of fishery-dependent data. Fishery-independent data are limited for both waterbodies. Through collaboration with the Ekaluktutiak Hunters and Trappers Organization (EHTO), Fisheries and Oceans Canada (DFO) developed the Cambridge Bay Arctic Char Integrated Fisheries Management Plan (IFMP) to promote a common understanding of the "basic rule" for the sustainable management of arctic fisheries. To assess the sustainability of these stocks and to further our understanding of commercial harvest on stock persistence, we applied depletion-based stock reduction analysis (DB-SRA) and other data limited models to assess Arctic Char status and formulate sustainable fisheries management options. Our data indicate that commercial fishery harvests in both rivers underwent significant inter-annual variation. Growth in standard length and round weight of anadromous Arctic Char differed with year, river and sex. Male fish had 16% higher L_{∞} and 18% lower k values than females in the Halokvik River while male char had 4% higher L_{∞} and 9% higher k at the Jayko River. In terms of empirical relationships between natural mortality and somatic growth parameters, M was estimated to be 0.1485 ± 0.1272 per year and 0.1758 ± 0.0372 per year at the Halokvik and Jayko rivers, respectively. Using the DB-SRA model, the mean and standard error values of virgin biomass (K) were estimated to be 104.99 ± 0.55 t and 167.15 ± 0.58 t in the Halokvik and Jayko rivers, respectively. Arctic Char in the Halokvik River appeared healthy before 1988 and the population appears to have been overfished since then. Fishing pressure was acceptable until 2004 and the fisheries showed a five-year period of overexploitation during 2005–2010. Currently, the population is still in the overfished state. In the Jayko River, a healthy state was sustained until 1992. Since then, the population has been in an overfished state as F increased. In particular, since 2012, the population has been overfished as the fishery is in a state of moderate overexploitation. Both fisheries have experienced overfishing as determined by the assessment.

INTRODUCTION

The community of Cambridge Bay in the Kitikmeot Region of Nunavut has long sustained commercial, recreational and aboriginal (CRA) fisheries for anadromous Arctic Char (*Salvelinus alpinus*). Since 1972, Fisheries and Oceans Canada (DFO) has been operating a fishery-dependent plant sampling program in the region as a means to collect harvest and biological data (length, weight and age) from commercially harvested Arctic Char fisheries on an annual basis (Kristofferson and Carder 1980, Carder and Low 1985, Day and de March 2004, Day and Harris 2013). In addition, there have been sporadic fishery-independent studies in the region to monitor stock status and enumerate stock size for Arctic Char, the latter involving experimental weirs or counting fences (Carder 1981,1988,1991, McGowan 1990, McGowan and Low 1992). These data have been used in several fisheries stock assessments conducted through the DFO Canadian Science Advisory Secretariat (CSAS) to summarize Arctic Char harvest information and fishery-dependent biological data (Day and Harris 2013, DFO 2013, Harris et al. 2021), to estimate a biomass index in relation to large-scale environmental variables (Zhu et al. 2014a) and to resolve biological reference points by use of hierarchical Bayesian modelling (Zhu et al. 2014b).

Despite this long time series of fishery-dependent information collection, many fundamental knowledge gaps still remain that have hindered the ability to apply the precautionary approach framework for fisheries management. For example, commercial fisheries in the Cambridge Bay region are known to be mixed-stock fisheries (Harris et al. 2016, Moore et al. 2016) but it is still unclear as to precisely which populations are being harvested in commercial fisheries and to what extent each discrete stock is harvested. Moreover, there are limited data available for river-specific abundance indices (i.e., stock enumerations or fishery dependent catch and effort data) for Arctic Char in the region. To date, stock assessments have assumed rivers correspond to discrete Arctic Char populations. A relatively recent stock assessment used a surplus production model approach with gillnet-based abundance indices and surrogate estimates of effort over time based on relationships between large-scale environmental variables and occasional observations of effort (Zhu et al. 2014a). The analyses for the population dynamics, however, reflected the overall area and therefore the results combined the harvest histories for Arctic Char across all waterbodies in the Cambridge Bay region (Zhu et al. 2014b).

In 2014, DFO, in collaboration with the Nunavut Wildlife Management Board (NWMB), the Ekaluktutiak Hunters and Trappers Organization (EHTO), the local fish processing plant (Kitikmeot Foods Ltd.), local commercial fishers, community members and other stakeholders, developed the Cambridge Bay Arctic Char Commercial Fishery Integrated Fisheries Management Plan (IFMP). The IFMP is not a legally binding document/plan, but it incorporates risk assessment into management decisions, and promotes a common understanding of the “basic rules” for the sustainable management of the fishery resource in accordance with the powers granted pursuant to the *Fisheries Act*. To maintain the sustainability of commercially harvested Arctic Char in the Cambridge Bay region, we are required to assess the relationship between standing abundance and total allowable catch for managing Arctic Char from commercially fished individual rivers in the region. In this assessment, we assume that river-specific fisheries are supported by mixed stocks of Arctic Char (Harris et al. 2016, Moore et al. 2016), and that the stock composition does not change annually (Kristofferson and Berkes 2005). The overarching objective of this assessment was to use a variety of data-poor stock assessment methods (e.g., data limited models, depletion based stock reduction analysis [DB SRA]; Dick and MacCall 2011), Data Limited Methods Toolkits (DLMT; Carruthers et al. 2014) to assess stock status and sustainability in the Halokvik and Jayko commercial Arctic Char fisheries. The results are then interpreted within the precautionary approach framework (DFO 2006). First, we used biological data collected from multi-mesh gillnets and weirs at both fisheries to estimate standard growth model parameters and size-dependent natural mortality. Second, we structured a DB-SRA model to assess the population production and sustainable harvest levels. Third, we incorporated results into the precautionary approach fisheries management framework to facilitate resolution of biological reference points (BRPs) and harvest control rules (HCRs). We discuss both information gaps and research plans for long-term monitoring of Jayko and Halokvik river Arctic Char, but also other fisheries in the region, and the implications of our assessment for Arctic Char sustainability in these systems.

MATERIALS AND METHODS

STUDY AREA

Commercial fishing for Arctic Char was operated by gillnets at Freshwater Creek in 1960 near the community of Cambridge Bay. Because of declining fish abundance, the fishery there ended in 1962. The commercial fishery moved to the mouth of the Ekalluk River, after which seven rivers were primarily fished including the Ekalluk, Paliryuak, Halokvik and Lauchlan rivers flowing into Wellington Bay, the Jayko River flowing into Albert Edward Bay (Figure 1). Among these, Arctic Char in the Halokvik and Jayko rivers were exclusively fished by gillnets prior to 1994, but from 1994 to the present, these two fisheries have been conducted with weirs except for the Halokvik in 1995 and 2001 and the Jayko in 1995 when gillnets were used (Day and Harris 2013). The upstream run of returning Arctic Char at both locations begins around mid-August and lasts until the first week in September (Kristofferson and Carder 1980).

DATA COLLECTION

Three different types of datasets are included in this study: commercial quota and harvest data, fishery-dependent biological data from the fish plant sampling program, and short-time series of abundance indices from fishery-independent and fishery-dependent surveys. DFO Resource Management collects and collates quota and harvest information from each commercial waterbody on an annual basis. Biological fishery-dependent data used in this assessment for the Halokvik River were collected from 1968 to 2015 while Jayko River data were collected from 1975 to 2015. Every year, biological sampling includes individual fork length, round weight, sex, and sagittal otoliths for a minimum of 200 anadromous Arctic Char, which were randomly sampled in a stratified manner (e.g., every third fish) throughout the operation of the river-specific fishery (VanGerwen-Toyne and Tallman 2011).

DFO has been monitoring the Arctic Char fishery in Cambridge Bay area since 1971 (Kristofferson and Carder 1980, Carder 1981,1984,1988,1991, Carder and Low 1985, Carder and Stewart 1989). Data collected from fishery-dependent surveys, including harvest information, biological data (fork length ±1 mm, round and dressed weights ±1 g, sex and otoliths), and catch per unit effort (CPUE) or abundance indices, have been used to assess the population status of various exploited Arctic Char stocks in the region. Additionally, there were several sporadic fishery-independent surveys that enumerated the standing abundance of several stocks in the region using conduit pipe weirs (McGowan 1990). To collect a representative sample of the population abundance indices, experimental multi-mesh gill nets were fished consisting of the following stretched mesh sizes: 38.1 mm (1.5”), 63.5 mm (2.5”), 88.9 mm (3.5”), 114.3 mm (4.5”) and 139.7 mm (5.5”) in both the Halokvik (2011-2015) and Jayko (2010-12 and 2014-15) rivers. Each panel of the multi-mesh gill net, made of transparent monofilament, was 30’ in length resulting in research nets that were 150’ in length (Harris et al.

2021). Soak time for experimental nets is typically 24 hours and all catches are summed as an indicator of relative abundance of anadromous Arctic Char.

DATA EXPLORATION AND SUMMARY

In order to ensure the reliability of model outputs, a standard protocol for data exploration was used to determine outliers, heterogeneity and linearity (Zuur et al. 2010). In particular, outliers in the current dataset may influence the outcomes of statistical power and data interpretation while heterogeneity may cause serious trouble in analysis of variance (ANOVA) and linear regression (Fox 2008). Dot plots were used to examine outliers of variables when those overlapped with a defined sequential distribution. Homogeneity of variance was assessed by box plots to show conditional distributions of fork length, round weight and age against sex, year and river system. To reduce measurement biases from limited sample sizes, length or weight-at-age data were truncated to those age classes that were equal to or less than 24 years; this represented greater than 97% of all aged fish in both rivers.

The R-based analysis packages, nlme, mgcv and R2jags were used in R environment (version 3.2.3, R Core Team, 2014) for data summaries including ANOVA and pairwise comparison if significant differences were detected. ANOVA was used to examine differences in the arithmetic mean of length, weight and age of anadromous Arctic Char under varying river and year effects. Bonferroni tests for pairwise comparisons were conducted to look at pairs of differences under specific covariance, given α=0.05 (Zar 2010).

GROWTH AND NATURAL MORTALITY

The standard von Bertalanffy growth model (von Bertalanffy 1938) was used to fit sexual differences in fork length versus age of the Arctic Char in the Halokvik and Jayko rivers. During 2010-2015, a total of 939 char from Halokvik River and 1013 char from Jayko River were included in the analysis of length-at-age growth patterns. Growth model parameters were estimated using JAGS (version 4.3, Just Another Gibbs Sampler; Lunn 2009), a program developed for the statistical analysis of Bayesian hierarchical models using Markov chain Monte Carlo (MCMC) simulation. We used hierarchical models to structure prior log-normal probability function parameters for L_∞ and k, where L_∞ is the asymptotic average length and k is the Brody growth rate coefficient, delineated by McAllister et al. (2000) and Zhu et al. (2014b). Gamma probability functions for the prior structuring process and observation errors were used (Zhu et al. 2014a). We ran three chains of 2,500,000 MCMC iterations and a thinning interval of 250 iterations, resulting in a total chain length of 10,000 MC samples. A total of 50,000 burn-in iterations were discarded for each run. Associated with 9891 effective samples, the autocorrelation function was used to examine if the resulting subset of posterior samples got independent draws (Zhu et al. 2014b).

Given the lack of direct estimates for natural mortality (M) for most species, fisheries scientists often indirectly estimate the parameter by examining the relationships between M and reproductive investment and growth rate (Pauly 1980, Gunderson and Dygert 1988, Chen and Watanabe 1989). Owing to a scarcity of detailed life history information, the empirical relationships implicitly assume that M is a species- or stock-specific constant, which can be applied to all exploited ages and sizes of the species or stocks in question. Several developments in line with the general size-spectrum theory (Gislason et al. 2010) suggest that M should be scaled with individual size in the animal population studied. Lorenzen (1996, 2000) modeled the parameter M by using a power function of weight-mortality for a variety of freshwater and marine species. Lorenzen (1996) compared natural mortality of fishes from freshwater, marine, and aquaculture ponds, and concluded that no significant differences were found in the natural ecosystems. In polar systems, however, he proposed the model parameters, b=-0.292 and M_u=1.69 of a power function be used. All numerical expressions for estimates of model parameters of standard growth models and natural mortality are summarized in Table 1.

DEPLETION-BASED STOCK REDUCTION ANALYSIS

When there is limited information accounting for the demographic parameters of the exploited fish stock, depletion-based stock reduction analysis (DB-SRA) is a potentially useful method that incorporates two data-poor stock assessment models: depletion-corrected average catch (DCAC; MacCall 2009) and stochastic stock reduction analysis (SRA; Walters et al. 2006). DCAC was extended by using the potential-yield formula of Alverson and Pereyra (1969) and Gulland (1970) to estimate fishery production that would likely be sustainable. DCAC incorporates uncertainty in model parameters M, ratios of B_{MSY} to B_o, F_{MSY} to M, and relative changes in biomass (Δ) using Monte Carlo simulations. Stock reduction analysis (SRA) can complement more detailed stock assessment methods by using historical catch data in conjunction with estimates of relative stock reduction due to fishing. This method can reconstruct possible trajectories of recruitment rates, stock sizes and potential stock decline (Kimura et al. 1984, Walters et al. 2006). Deterministic SRA models provide a single stock size trajectory while stochastic SRA models attempt to provide probability distributions for stock size over time under alternative hypotheses about unfished recruitment rates and about variability around assumed stock–recruitment relationships (Walters et al. 2006, Dick and MacCall 2011).

DB-SRA is implemented using a delay-difference Pella-Tomlinson-Fletcher generalized production (PTFGP) model (Pella and Tomlinson 1969, Fletcher 1978). As noted by McAllister et al. (2000), a major drawback of the generalized production model is that modeled productivity near the origin can be unrealistically high, especially when n<1, where n is the shape parameter indicating that the productivity is near infinite rates of surplus production per capita as abundance decreases to low levels (Quinn and Deriso 1999).They recommended that the PTFGP be used at $B > B_{MSY}$, and that a Schaefer model be used for $0 < B < B_{MSY}$ with a join-point at B_{MSY}. Data required in DB-SRA include estimates of annual catch (i.e., the commercial harvest), approximate natural mortality rates and age-at-maturity. The outputs facilitate the estimation of BRPs concerning overfishing level (OFL) and maximum sustainable yield (MSY). Given the limited amounts of data required for the model, the DB-SRA is rather promising for cases of data-limited fisheries. The model notation is summarized in Table 2, and initial values of the model parameters are as follows:

- ***Harvest***: Commercial harvest between 1975 and 2015 from the Jayko and Halokvik rivers were tabulated from multiple harvest information sources (see Harris et al. 2021).
- ***Natural mortality* (*M*)**: the prior distribution function for natural mortality followed a two-parameter lognormal distribution. It consisted of log-transformed mean and log-scale standard deviation (SD). Prior values of natural mortality for Arctic Char were estimated by multiple empirical models. The initial value for SD was assumed to be 0.4 in terms of Hoenig’s analysis (Hoenig 1983) to relate the total mortality rate to maximum age, which is different from the value of 0.5 recommended by MacCall (2013). Following the recommendation of Dick and MacCall (2011), we used an SD of 0.4 in the model.
- ***Maturity-at-age* (t_m)**: maturity-at-age was estimated either by plotting the proportion of age versus maturity or by applying relationships between demographic growth parameters and maturity status (Gulland 1971).
- **F_{MSY}/M**: ratio of fishing mortality at maximum sustainable yield (MSY) to natural mortality, which is a measure of potential BRPs for fisheries management There is no estimate of F_{MSY}/M for Arctic Char. Previous studies have suggested that natural mortality is a proxy for

sustainable fishing mortality, approximated using the optimal estimate of $F_{MSY}=M$ (Gulland 1971). Zhou et al. (2012) examined the relationship between M and life history and BRPs of 245 fish species and suggested $F_{MSY}/M=0.87$ (SD=0.05) for teleost fish. Thus, we applied a normal distribution function to construct a posterior probability distribution function for F_{MSY}/M, using expectations of 0.8 (SD=0.2) (Wetzel and Punt 2011).

- $\boldsymbol{B_{MSY}/B_0}$: ratio of biomass at MSY to the virgin biomass. We structured a normal distribution function for a posterior probability distribution function for B_{MSY}/B_0 of 0.6 and a SD of 0.05. To avoid extremely skewed values of the estimates, we assumed this parameter followed a bounded beta distribution of 0.05 and 0.95.

Exploratory runs were initialized using the following parameter ratios: relative stock status $\Delta=0.6$, $F_{MSY}/M=0.8$ and $B_{MSY}/B_0=0.6$ as starting points. Using these initial values, DB-SRA then estimated four Monte Carlo-drawn parameters: natural mortality (M), the ratio of MSY fishing rate to M (F_{MSY}/M), the relative abundance or biomass at maximum latent productivity (N_{MSY}/N_0 or B_{MSY}/B_0) and the relative depletion level (B_T/B_0) in a specific year T. The timeframe used for calculating DCAC, was 1976-1994 for the Halokvik River and 1991-2005 for the Jayko River, to include an entire variation period of Arctic Char fisheries harvest in commercial fishing systems over years. Also, Δ and OFL were calculated for 2014 and 2015, respectively.

BIOLOGICAL REFERENCE POINTS AND RECOMMENDATION

There are several fishery assessment values of catch and biomass to be designated as BRPs or HCRs for fisheries management and regulation measures. Beyond these, the Precautionary Principle, proposed by FAO in the Conduct Code for Responsible Fisheries (FAO 1995a,b), declares that the limitations, uncertainties or lack of data for the assessment or for the estimation of parameters, cannot be justification for not applying regulation measures, especially when there is information that the stocks are over-exploited. As stated in the DFO precautionary approach (DFO 2006), the recommended boundaries of limit reference point (LRP) and upper stock reference (USR) point are 0.2 K and 0.4 K, respectively, where K is carry capacity of the population productivity.

RESULTS AND DISCUSSION

FISHERIES HARVEST

Commercial fisheries in the Halokvik and Jayko rivers varied among years. Between 1968-2015, annual commercial harvest for anadromous Arctic Char varied from 1.12 to 26.20 t averaging 6.58 ± 0.63 t (mean ± SE) across all years at the Halokvik River. Between 1975-2015, annual commercial harvest at the Jayko River varied between 2.23 to 17.31 t averaging12.24 ± 0.56 t (Figure 2).

SPATIOTEMPORAL VARIATION IN SIZE AND AGE

During fishery-independent surveys from 2010 to 2015 (Figure 3), Halokvik River Arctic Char ranged in fork length from 209 to 905 mm with a mean of 554.72 ± 3.48 mm (n = 954); round weight ranged from 75 to 7650 g with a mean of 2344.45 ± 42.67 g (n = 954); age ranged from 3 to 26 years old with a mean of 9.93 ± 0.10 years (n = 939). In the Jayko River, fork length of anadromous Arctic Char varied from 75 to 838 mm with a mean of 519.26 ± 4.19 mm (n = 1043); round weight ranged from 45 to 7750 g with a mean of 1835.55 ± 38.58 g (n = 1043); age ranged from 3 to 28 years old with a mean of 11.71 ± 0.15 years (n = 1012). Hotelling's T-squared test showed significant differences in fork length ($F_{1,1995}$=41.53, p<0.0001), round weight ($F_{1,1995}$=78.66, p<0.0001) and age ($F_{1,1949}$=90.40, p<0.0001) for anadromous Arctic Char in Halokvik and Jayko rivers.

The fork length of anadromous Arctic Char differed statistically among years ($F_{5,19}$=16.38, p<0.0001), between rivers ($F_{1,19}$=30.18, p<0.0001) and showed a significant year-river interaction ($F_{3,19}$=4.99, p<0.005). There was no strong disagreement in fork length between sexes ($F_{1,19}$=1.73, p=0.19). As indicated in Figure 4, average fork length was 7% greater in the Halokvik River than in the Jayko River. Round weight differed statistically among years ($F_{5,19}$=22.30, p<0.0001), between rivers ($F_{1,19}$=63.26, p<0.0001) and also showed a strong year-river interaction ($F_{3,19}$=8.00, p<0.0001). A marginal difference in round weight was found between the sexes ($F_{1,19}$=3.92, p=0.05). Round weight of overall fish in the Halokvik River was 28% greater than in the Jayko River (Figure 5). Age composition also differed significantly among years ($F_{5,19}$=11.56, p<0.0001), between rivers ($F_{1,19}$=74.04, p<0.0001) and between sexes ($F_{1,19}$=6.14, p<0.05). No significant interactions among all explanatory variables were detected ($F_{3,19}$=1.01, p=0.39). The average age of all fish from the Halokvik River was 21% less than in the Jayko River (Figure 6). In 2012, larger size and older fish were caught in both the Halokvik and Jayko rivers (Figure 4, 5, 6).

GROWTH AND NATURAL MORTALITY

Growth parameters from standard growth models for Halokvik and Jayko river char are summarized in Table 3 and plots of length-at-age and weight-at-age are presented in Figures 7 and 8, respectively. At the Halokvik River, male fish had a 16% higher estimate of L_∞ and an 18% lower estimate of K compared to females. At the Jayko River, male char had a 4% higher estimate of L_∞ and a 9% higher estimate of K (Figure 9). Comparing weight-growth parameters, Halokvik male char had a 39% higher estimate for W_∞, a 6% higher estimate of b and a 13% lower estimate of K compared to females. Male char at Jayko River had a 23% higher estimate of W_∞, an 8% higher estimate of b and a 3% higher estimate of K, compared to females (Figure 10). Male Arctic Char from Halokvik River had a 38% higher estimate of L_∞ and a 41% lower estimate of K compared to male Jayko River char. Halokvik River females had a 24% higher estimate of L_∞ and a 22% lower estimate of K compared to Jayko River females. Overall, statistically similar growth patterns were found in the weight-based growth of fish from both water bodies.

Natural mortality (M) for Arctic Char from both the Halokvik and Jayko rivers is summarized in Tables 4 and 5. M changed from 2.0834 per year at age 1 to 0.1091 per year at age 25 (mean: 0.1877±0.0818 per year) for male fish and from 2.2843 per year at age 1 to 0.1266 per year at age 25 (mean: 0.2026±0.0887 per year) for female Arctic Char in Halokvik River. For Arctic Char in Jayko River, M varied from 1.1221 per year at age 1 to 0.1775 per year at age 25 (mean: 0.2219±0.0444 per year) for male fish and from 0.7759 per year at age 1 to 0.1569 per year at age 25 (mean: 0.2120±0.0301 per year) for female fish. In terms of growth parameters, the age at 50% maturity (t_m) was estimated to be 10.4 years for Halokvik River and 11.02 years for Jayko River char. Associated with sexual maturity and age effects, it is evident that the value of M declined with ages of the anadromous Arctic Char (Figure 11), leading to overall median of 0.1485±0.1298 per year and 0.1758±0.0380 per year for the Halokvik and Jayko rivers, respectively.

ESTIMATES OF POPULATION STATUS USING INITIAL VALUES

Biomass trends for anadromous Arctic Char in both rivers are shown in Figure 12. The Halokvik River was likely overfished between 1968-1973, resulting in a long-term downward trend in biomass until 2006 when the population biomass was at low state. Since 2006, the biomass has remained relatively stable in this fishery. At the Jayko River, the standing biomass was visualized with three step-wise dynamics: 1975-1982, 1992-2004 and 2010-2015. The biomass decreased from 167.14 t in 1975 to 113.63 t in 1982 with an annual reduction rate of 4%. During 1992 and 2004, the annual reduction in biomass appeared as a rate of 2.82%, declining from 117.13 t to 70.43 t. Between 2010 and 2015, the biomass decreased from 86.29 t to 67.35 t with an annual reduction rate of 3.66%. Overall, at both rivers the biomass appears to have decreased since commercial fishing began at each location. At the Halokvik River, biomass varied from 104.99 t in 1975 to 42.36 t in 2015, decreasing at a rate of 1.45% annually. At the Jayko River, biomass varied from 167.25 t in 1975 to 67.35 t in 2015, decreasing at a rate of 1.46% annually.

In terms of model outputs, the results of both the DCAC and DB-SRA depicting population dynamics undergoing different harvest histories in both rivers are shown in Figure 13. At the Halokvik River, the average commercial harvest was 6.14 ± 0.28 t during 1976-1994. During the same time, the mean DCAC was 3.86 ± 1.09 t, which was equivalent to 63% of the average harvest, resulting in an MCMC estimate of MSY as a proxy of spawning potential ratio (SPR) of 4.29 ± 0.01 t.

At the Jayko River, significant changes in commercial harvest appeared during 1991 and 2005, with an average harvest of 11.37 ± 1.31 t. The mean DCAC, 8.53 ± 1.51 t, was equivalent to 75% of the average commercial harvest during the modeled time period (Figure 13). The MCMC estimate of the posterior probability distribution for MSY was 10.23 ± 0.01 t for the fish stock.

MODEL PERFORMANCE FOR FORMULATING MANAGEMENT TARGETS

Incorporated with initial inputs of M, F_{MSY}/M, B_{MSY}/B_0 and Δ, DB-SRA uses MCMC to generate a series of posterior probability functions for a vector of fish population dynamics parameters. For Halokvik River Arctic Char, the critical population parameters are visualized in Figure 14 and detailed below:

a. M follows a lognormal distribution with a median estimate (± SE) of 0.1108 ± 0.0014 per year,

b. F_{MSY}/M, assuming a normal distribution, has a mean estimate (± SE) of 0.7952 ± 0.0016,

c. B_{MSY}/K, assuming a normal distribution, has a mean estimate (± SE) of 0.5989 ± 0.0005, and

d. relative abundance increase rate (Δ), following a normal distribution, has a mean estimate (± SE) of 0.6004 ± 0.0010.

The biomass-oriented DB-SRA model parameters for Jayko River Arctic Char are visualized in Figure 15 and detailed below:

a. M follows a lognormal distribution with a median estimate (± SE) of 0.1598 ± 0.0008 per year,

b. F_{MSY}/M, assuming a normal distribution, has a mean estimate (± SE) of 0.0.7965 ± 0.0016,

c. B_{MSY}/K, assuming a normal distribution, has a mean estimate (± SE) of 0.5992 ± 0.0005, and

d. relative abundance increase rate (∆), following a normal distribution, has a mean estimate (± SE) of 0.6004 ± 0.0010.

The BRPs for Arctic Char estimated by DB-SRA demonstrated that the mean values of K, B_{MSY}, F_{MSY}, E_{MSY}, M and F_{MSY}/M were greater than median values, indicating an asymmetric or positively skewed distribution (Table 6). Conversely, the mean of the model parameters Δ, B_{MSY}/K and MSY were smaller than the median, meaning that these model parameters did not distribute normally or symmetrically. Among the BRPs, virgin biomass (*K*) values were estimated from the DB-SRA model, resulting in 104.99 ± 0.55 t and 167.15 ± 0.58 t at the Halokvik and Jayko rivers, respectively.

For sustainable fisheries management, MSY was estimated to be 4.291 ± 0.009 t and 10.225 ± 0.014 t for the Halokvik and Jayko rivers, respectively. Correspondingly, the fishing mortality, F_{MSY}, and exploitation rate, E_{MSY}, were estimated to be 0.1193 ± 0.0011 and 0.0961 ± 0.0007 per year for the Halokvik River. For Jayko River Arctic Char, F_{MSY} and E_{MSY} were estimated to at 0.1413 ± 0.0007 and 0.1172 ± 0.0005 per year. Johnson (1980) suggested that an exploitation rate ~10% may be detrimental for population persistence in this species. The optimal exploitation rate estimated by DB-SRA was slightly greater than 10% in the Jayko River but lower in the Halokvik River. Even though the exploitation rate is above 10% for Jayko, Arctic Char are considered to be a "plastic" species, meaning there is great variability in the biological characteristics of the species across its range. Therefore, the sustainable rate for these stocks may be higher than Johnson (1980) noted. Additionally, the impacts of varying exploitation rates on population persistence in this species are not fully understood.

Given our values of B/B_{MSY}, and F/F_{MSY}, we identified two distinct exploitation events: overexploitation of fisheries when $F/F_{MSY}>1.0$ and an overfished population state when $B/B_{MSY}<1.0$ (DFO 2006, Zhu et al. 2014b). Arctic Char at the Halokvik River appeared to be in a healthy state before 1988 and the population appears to have been overfished since then. Fishing pressure had been acceptable until 2004 and the fisheries showed a five-year period of overexploitation from 2005-2010 (Figure 16). Currently, the population is still in the overfished state, but remains at the USR. The LRP and USR values were estimated as 21.00 t and 42.00 t for Arctic Char in the Halokvik River, as depicted in Figure 12.

The LRP and USR values for Arctic Char in Jayko River were estimated to be 33.43 t and 66.86 t, as indicated in Figure 12. In terms of the LRP and USR, the status of the Jayko River Arctic Char appeared to be in a healthy state until 1992. Since then, the population has been in an overfished state. *F* has been increasing since 1992. In particular, since 2012, the population has been overfished and remains overexploited (Figure 16).

Under the precautionary approach to fisheries management and operational measures, both fisheries were considered adjacent to the boundaries between the healthy and cautious zones with the most likely position being just below the URP of 0.8 B_{MSY} (Figure 12). For this reason, there appears to be approximately a 50 % chance that both stocks are in the cautious zone of the precautionary framework (DFO 2006), and therefore there is a likelihood that overfishing is occurring if fishing effort is not well managed. However, the mean value is at the USR which, if sustained, may be ideal for achieving current fishery management objectives. It should be noted that the trend over time shows a steady decline in biomass and if these stocks are not assessed for another 10 years, one would not be surprised if they fall below the LRP. However, there is considerable uncertainty at present, and the low bounds of the credible intervals also overlap the LRPs for these fisheries. Due to this possibility, it is recommended that the next assessment of these stocks occur within 3-5 years.

DB-SRA and DCAC are the most common data-limited methods used by many national and international fisheries management organizations such as the Pacific Council (Dick and MacCall 2011, Wetzel and Punt 2011, Newman et al. 2014). The surprising feature of DB-SRA is that useful information on data-limited fish populations can be retrieved from many types of harvest histories and general knowledge of fish biology. A drawback of DB-SRA is that it requires knowledge of the entire history of harvest (Dick and MacCall 2011). For exploited fish populations, especially for Arctic Char in Cambridge Bay, it is important to ensure the quality of total harvest statistics. In addition to commercial fisheries data collected through a fish plant sampling program, harvest studies are needed to evaluate the proportion of harvest used for subsistence food in the vicinity of the community. As cited by Day and de March (2004) and Zhu et al. (2014b), the Nunavut Harvest Study estimated subsistence harvest in the region to be 50% of the total harvest or fishing mortality (Priest and Usher 2004). For harvest in the Halokvik River, the present fishery-dependent study showed the proportion of subsistence removals would represent less than 5% of the total harvest (L. Harris, DFO Winnipeg, Pers. Comm.). Jayko River is further away from Cambridge Bay and the proportion of harvest for subsistence use was suggested to be minimal. Therefore, in this study, we assumed that the commercial harvest information was close to the true amount of total harvest of Arctic Char in both fisheries.

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TABLES AND FIGURES

Table 1. Summary of growth and natural mortality models used for Arctic Char from the Halokvik and Jayko rivers, Cambridge Bay, Nunavut. The growth parameters are asymptotic length (L_∞: mm) and round weight (W_∞: g), population growth rate (K, per year) and age when length=0 (t_0, year). L_t and W_t are fork length (mm) and round weight (g) at age t. The relationship between fork length (L: mm) and round weight (W: g) was modeled by a power function with regression coefficients a and b. The parameters t_m and M_t are maturity-at-age and age specific natural mortality respectively.

Paramter	**Equation**	**Reference**
Growth	$L_t = L_\infty\left[1-e^{-K(t-t_0)}\right]$ $W_t = W_\infty\left[1-e^{-K(t-t_0)}\right]^b$ $W = aL^b$	von Bertalanffy (1938)
Natural mortality	Life history parameter model	
	$M(t)=\begin{cases}\dfrac{K}{1-e^{-K(t-t_0)}}, t \le t_m \\ \dfrac{K}{a_0+a_1(t-t_m)+a_2(t-t_m)^2}, t \ge t_m\end{cases}$ $a_0 = 1-e^{-K(t_m-t_0)}$ $a_1 = Ke^{-K(t_m-t_0)}$ $a_2 = -0.5K^2e^{-K(t_m-t_0)}$ $t_m = -\dfrac{1}{K}\ln\left\|1-e^{Kt_0}\right\|+t_0$	Chen and Watanabe (1989)
	Length growth parameter-based model	
	$\ln(M_t)=0.55-1.61\ln(L_t\text{: cm})+1.44\ln(L_\infty\text{: cm})+\ln(K)$	Gislason et al. (2010)
	Weight-growth parameter-based model	
	$M_t=1.69W_t^{-0.292}$	Lorenzen (1996, 2000)

Table 2. Depletion-based stock reduction analysis (DB-SRA) for estimating stochastic parameters of population dynamics in terms of catch statistics and biological parameters for Halokvik and Jayko river Arctic Char. Here, C_t and n are a catch history in year t, and the length of catch history in years, respectively. Δ and B_0 are the relative stock status and the virgin biomass. B_{MSY} and F_{MSY} are biomass and fishing mortality when the population is at a level of maximum sustainable yield. Parameters M, g and m are instantaneous natural mortality, shape parameter and MSY, respectively. u is exploitation rate.

Model	Equation	Reference
Depletion-corrected average catch (DCAC)	$DCAC = \frac{\sum C_t}{n + \frac{\Delta}{\left(\frac{B_{MSY}}{B_0}\right)\left(\frac{F_{MSY}}{M}\right)M}}$	MacCall 2009
Stock reduction analysis	$B_t = B_{t-1} + P(B_{t-a}) - C_{t-1}$ $P\left(B_{t-a}\right) = gMSY\left(\frac{B_{t-a}}{K}\right) - gMSY\left(\frac{B_{t-a}}{K}\right)^n$ Here, $g = \frac{n^{n/(n-1)}}{n-1}$ (n>0) $P = B_{t-a}\left(P\left(B_{join}\right) / B_{t-a} + s\left(B_{t-a} - B_{join}\right)\right)$ $s = \left(1-n\right) gmB_{join}^{n-2} K^{-n}$ $u = \frac{F}{M+F}\left(1 - e^{-(F+M)}\right)$	Pella and Tomlinson 1969, Fletcher 1978, McAllister et al. 2000, Walters et al. 2006, Dick and McCall 2011

Table 3. Summaries of standard growth parameters of fork length-at-age and weight-at-age using hierarchical state-space models for Arctic Char from the the Halokvik and Jayko rivers, Nunavut. $L_\infty\_\tau^2$, $W_\infty\_\tau^2$, and k_τ^2 are standard deviations when structuring hierarchical growth parameters of asymptotic fork length L_∞, round weight W_∞, and growth rate K. Model parameter t_0 is theory age when fork length or round weight reaches zero, respectively. σ^2 is a measure of standard deviation between the observed and modeled values.

		Halokvik River					Jayko River				
		mean	**SD**	**2.50%**	**50%**	**97.50%**	**mean**	**SD**	**2.50%**	**50%**	**97.50%**
Male	L_∞	984.34	65.43	876.54	977.15	1134.49	713.60	10.90	693.19	713.16	736.01
	$L_\infty\_\tau^2$	0.98	0.71	0.11	0.81	2.77	1.00	0.70	0.13	0.84	2.79
	K	0.0935	0.0152	0.0655	0.0929	0.1246	0.1588	0.0089	0.1418	0.1587	0.1764
	k_τ^2	0.9553	0.6615	0.1329	0.8024	2.6435	0.8420	0.6259	0.1090	0.6757	2.4860
	t_0	0.2442	0.5857	-0.9850	0.2764	1.2960	1.4793	0.1845	1.0972	1.4855	1.8191
	σ^2	60.4511	1.9937	56.6625	60.4097	64.4984	63.93	1.96	60.25	63.88	67.91
Female	L_∞	849.13	28.52	800.10	846.60	911.89	687.09	11.51	666.00	686.57	711.11
	$L_\infty\_\tau^2$	0.98	0.71	0.12	0.81	2.78	1.02	0.70	0.13	0.87	2.80
	K	0.1134	0.0119	0.0903	0.1134	0.1371	0.1461	0.0096	0.1276	0.1461	0.1651
	k_τ^2	0.9126	0.6541	0.1223	0.7517	2.6116	0.8618	0.6389	0.1113	0.6970	2.5243
	t_0	0.2396	0.4560	-0.7290	0.2682	1.0521	0.8397	0.2538	0.3087	0.8510	1.3020
	σ^2	54.67	1.78	51.34	54.63	58.29	54.53	1.78	51.15	54.49	58.17
All	L_∞	871.90	25.17	827.56	869.91	925.82	697.97	7.78	683.30	697.88	713.77
	$L_\infty\_\tau^2$	0.99	0.70	0.12	0.83	2.77	1.02	0.70	0.13	0.86	2.79
	K	0.1138	0.0098	0.0947	0.1137	0.1333	0.1558	0.0066	0.1431	0.1558	0.1689
	k_τ^2	0.9057	0.6471	0.1193	0.7490	2.5820	0.8519	0.6357	0.1094	0.6832	2.5361
	t_0	0.5147	0.3449	-0.2021	0.5299	1.1411	1.2715	0.1486	0.9688	1.2762	1.5488
	σ^2	58.33	1.35	55.74	58.31	61.05	60.81	1.35	58.23	60.80	63.50
Male	W_∞	9743.48	741.81	8482.45	9671.67	11388.70	3754.27	102.19	3569.51	3748.79	3971.27
	$W_\infty\_\tau^2$	1.34	0.59	0.59	1.21	2.84	0.79	0.48	0.27	0.65	2.05
	b	3.2553	0.4953	2.2117	3.3268	3.9642	3.5456	0.3269	2.7925	3.6070	3.9809
	b_τ^2	0.4974	0.4976	0.0115	0.3475	1.8377	0.4937	0.4942	0.0125	0.3413	1.8352
	K	0.1089	0.0114	0.0855	0.1093	0.1304	0.2140	0.0148	0.1848	0.2142	0.2427
	k_τ^2	0.5563	0.5070	0.0152	0.4162	1.8621	0.4690	0.4340	0.0138	0.3539	1.5960
	t_0	0.1644	0.8121	-1.2740	0.0972	1.8498	2.3148	0.3907	1.4724	2.3428	2.9454
	σ^2	443.75	7.42	429.37	443.65	458.51	509.75	7.92	494.46	509.63	525.47
Female	W_∞	6998.49	372.34	6373.57	6961.08	7832.18	3056.00	91.45	2893.28	3050.44	3250.89
	$W_\infty\_\tau^2$	1.17	0.56	0.49	1.03	2.61	0.69	0.48	0.19	0.54	1.99
	b	3.0653	0.5454	2.0868	3.0918	3.9437	3.2754	0.4733	2.2910	3.3371	3.9629
	b_τ^2	0.5015	0.4993	0.0132	0.3494	1.8606	0.5014	0.4981	0.0123	0.3534	1.8293
	K	0.1256	0.0121	0.1010	0.1261	0.1479	0.2074	0.0179	0.1722	0.2072	0.2427
	k_τ^2	0.5410	0.4952	0.0144	0.4041	1.8084	0.4788	0.4426	0.0140	0.3634	1.6169
	t_0	0.5365	0.8274	-0.9586	0.4995	2.1082	1.9055	0.5565	0.7785	1.9177	2.8846
	σ^2	409.68	7.02	396.34	409.57	423.83	406.36	7.06	392.83	406.32	420.50
All	W_∞	7445.19	355.64	6836.58	7412.73	8243.84	3389.53	80.15	3243.00	3386.16	3554.94
	$W_\infty\_\tau^2$	1.20	0.56	0.51	1.07	2.63	0.77	0.50	0.23	0.63	2.10
	b	3.2625	0.4946	2.2127	3.3361	3.9658	3.5004	0.3622	2.6787	3.5718	3.9780
	b_τ^2	0.4997	0.4958	0.0137	0.3472	1.8305	0.5011	0.4974	0.0130	0.3475	1.8387
	K	0.1291	0.0107	0.1058	0.1298	0.1484	0.2159	0.0141	0.1880	0.2157	0.2435
	k_τ^2	0.5358	0.4871	0.0155	0.4050	1.7922	0.4741	0.4393	0.0129	0.3562	1.6238
	t_0	0.4981	0.7077	-0.6935	0.4250	2.0101	2.1472	0.4166	1.3136	2.1501	2.9055
	σ^2	508.89	7.28	494.92	508.85	523.43	553.87	7.59	539.18	553.79	568.95

Table 4. Natural mortality for anadromous Arctic Char from the Halokvik River, Cambridge Bay, Nunavut, estimated using a life history model (Chen & Watanabe 1989), a length-at-age model (Gislason et al. 2010), and a weight-at-age model (Lorenzen 1996).

Age	Life history model			Length-at-age model			Weight-at-age model			Geometric mean		
	Male	Female	All	Male	Female	All	Male	Female	All	Male	Female	All
1	1.3704	1.3726	2.1180	5.5996	5.2201	10.0001	1.1785	1.6636	1.7491	2.0834	2.2843	3.3336
2	0.6176	0.6266	0.7318	1.5518	1.4771	1.8068	0.5866	0.6288	0.6538	0.8253	0.8349	0.9526
3	0.4116	0.4219	0.4619	0.8076	0.7814	0.8615	0.4077	0.4165	0.4265	0.5137	0.5159	0.5537
4	0.3157	0.3266	0.3476	0.5269	0.5175	0.5449	0.3212	0.3237	0.3279	0.3767	0.3796	0.3960
5	0.2605	0.2718	0.2847	0.3866	0.3850	0.3951	0.2703	0.2716	0.2730	0.3008	0.3052	0.3132
6	0.2247	0.2364	0.2451	0.3046	0.3075	0.3105	0.2369	0.2384	0.2383	0.2531	0.2588	0.2627
7	0.1997	0.2118	0.2180	0.2519	0.2576	0.2572	0.2134	0.2154	0.2144	0.2206	0.2274	0.2291
8	0.1813	0.1938	0.1985	0.2157	0.2232	0.2211	0.1960	0.1987	0.1972	0.1972	0.2049	0.2053
9	0.1673	0.1801	0.1838	0.1895	0.1984	0.1953	0.1828	0.1861	0.1842	0.1796	0.1881	0.1877
10	0.1563	0.1694	0.1724	0.1698	0.1798	0.1762	0.1723	0.1763	0.1741	0.1660	0.1751	0.1742
11	0.1474	0.1609	0.1633	0.1546	0.1655	0.1615	0.1640	0.1686	0.1662	0.1552	0.1649	0.1637
12	0.1403	0.1540	0.1561	0.1426	0.1542	0.1501	0.1571	0.1623	0.1598	0.1465	0.1568	0.1553
13	0.1344	0.1485	0.1503	0.1329	0.1451	0.1409	0.1515	0.1571	0.1546	0.1394	0.1502	0.1485
14	0.1296	0.1441	0.1457	0.1250	0.1377	0.1335	0.1468	0.1529	0.1503	0.1335	0.1448	0.1430
15	0.1257	0.1407	0.1421	0.1185	0.1316	0.1274	0.1428	0.1493	0.1467	0.1286	0.1404	0.1385
16	0.1226	0.1381	0.1394	0.1129	0.1266	0.1223	0.1394	0.1463	0.1437	0.1245	0.1368	0.1348
17	0.1202	0.1363	0.1375	0.1083	0.1223	0.1180	0.1365	0.1438	0.1411	0.1211	0.1338	0.1318
18	0.1183	0.1352	0.1363	0.1043	0.1187	0.1144	0.1340	0.1416	0.1390	0.1182	0.1314	0.1294
19	0.1170	0.1347	0.1359	0.1009	0.1156	0.1113	0.1318	0.1398	0.1371	0.1159	0.1296	0.1275
20	0.1162	0.1349	0.1361	0.0979	0.1129	0.1087	0.1299	0.1382	0.1355	0.1139	0.1281	0.1261
21	0.1159	0.1357	0.1370	0.0953	0.1106	0.1064	0.1283	0.1368	0.1342	0.1123	0.1271	0.1251
22	0.1161	0.1372	0.1386	0.0931	0.1087	0.1045	0.1269	0.1356	0.1330	0.1111	0.1265	0.1244
23	0.1168	0.1395	0.1410	0.0911	0.1070	0.1028	0.1256	0.1346	0.1320	0.1102	0.1262	0.1241
24	0.1180	0.1425	0.1442	0.0894	0.1055	0.1013	0.1245	0.1337	0.1311	0.1095	0.1262	0.1242
25	0.1198	0.1465	0.1484	0.0878	0.1042	0.1000	0.1235	0.1329	0.1304	0.1091	0.1266	0.1246
Median	0.1344	0.1485	0.1503	0.1329	0.1451	0.1409	0.1515	0.1571	0.1546	0.1394	0.1502	0.1485
Standard Error	0.0528	0.0521	0.0810	0.2231	0.2072	0.3958	0.0448	0.0626	0.0663	0.0818	0.0887	0.1298

Table 5. Natural mortality or anadromous Arctic Char from the Jayko River, Cambridge Bay, Nunavut, estimated using a life history model (Chen & Watanabe 1989), a length-at-age model (Gislason et al. 2010), and a weight-at-age model (Lorenzen 1996).

Age	Life history model			Length-at-age model			Weight-at-age model			Geometric mean		
	Male	Female	All	Male	Female	All	Male	Female	All	Male	Female	All
3	0.7402	0.5398	0.6599	1.5882	1.1611	1.4108	1.2020	0.7454	0.9738	1.1221	0.7759	0.9679
4	0.4814	0.3951	0.4499	0.7945	0.7025	0.7614	0.5264	0.4401	0.4894	0.5861	0.4962	0.5514
5	0.3708	0.3208	0.3536	0.5219	0.5023	0.5166	0.3600	0.3316	0.3483	0.4114	0.3766	0.3992
6	0.3100	0.2759	0.2989	0.3912	0.3942	0.3941	0.2862	0.2767	0.2823	0.3262	0.3111	0.3216
7	0.2720	0.2462	0.2639	0.3169	0.3281	0.3226	0.2453	0.2441	0.2448	0.2765	0.2702	0.2752
8	0.2462	0.2252	0.2399	0.2700	0.2843	0.2766	0.2198	0.2229	0.2211	0.2445	0.2426	0.2448
9	0.2278	0.2098	0.2226	0.2382	0.2535	0.2452	0.2028	0.2082	0.2050	0.2224	0.2229	0.2237
10	0.2141	0.1980	0.2096	0.2156	0.2311	0.2226	0.1908	0.1977	0.1937	0.2065	0.2084	0.2083
11	0.2038	0.1889	0.1997	0.1990	0.2142	0.2058	0.1821	0.1899	0.1854	0.1947	0.1973	0.1968
12	0.1960	0.1817	0.1919	0.1864	0.2011	0.1931	0.1756	0.1840	0.1792	0.1858	0.1887	0.1880
13	0.1903	0.1759	0.1859	0.1766	0.1909	0.1831	0.1707	0.1795	0.1745	0.1790	0.1820	0.1811
14	0.1863	0.1711	0.1814	0.1689	0.1826	0.1752	0.1670	0.1760	0.1709	0.1738	0.1765	0.1758
15	0.1840	0.1672	0.1781	0.1627	0.1760	0.1689	0.1640	0.1732	0.1681	0.1700	0.1721	0.1717
16	0.1830	0.1640	0.1760	0.1578	0.1706	0.1638	0.1617	0.1711	0.1659	0.1672	0.1685	0.1685
17	0.1836	0.1614	0.1751	0.1537	0.1661	0.1597	0.1599	0.1693	0.1642	0.1653	0.1656	0.1662
18	0.1855	0.1594	0.1751	0.1504	0.1624	0.1562	0.1585	0.1680	0.1629	0.1641	0.1632	0.1646
19	0.1890	0.1579	0.1763	0.1477	0.1593	0.1534	0.1574	0.1669	0.1618	0.1638	0.1613	0.1635
20	0.1941	0.1569	0.1785	0.1454	0.1567	0.1510	0.1565	0.1660	0.1609	0.1641	0.1598	0.1631
21	0.2013	0.1564	0.1819	0.1435	0.1545	0.1490	0.1558	0.1653	0.1602	0.1651	0.1586	0.1631
22	0.2109	0.1563	0.1866	0.1419	0.1526	0.1473	0.1552	0.1647	0.1597	0.1668	0.1578	0.1637
23	0.2235	0.1567	0.1928	0.1406	0.1510	0.1459	0.1547	0.1642	0.1592	0.1694	0.1573	0.1649
24	0.2400	0.1576	0.2008	0.1395	0.1497	0.1448	0.1543	0.1639	0.1589	0.1729	0.1570	0.1665
25	0.2622	0.1590	0.2110	0.1385	0.1486	0.1438	0.1540	0.1636	0.1586	0.1775	0.1569	0.1688
Median	0.2109	0.1711	0.1928	0.1689	0.1826	0.1752	0.1670	0.1760	0.1709	0.1775	0.1765	0.1758
Standard Error	0.0265	0.0196	0.0237	0.0672	0.0490	0.0596	0.0470	0.0273	0.0372	0.0444	0.0301	0.0380

Table 6. Biological reference points for fisheries management, derived from the DB-SRA model for Arctic Char in the Halokvik and Jayko rivers, Cambridge Bay, Nunavut.

	Mean	SD	2.5%	25%	50%	75%	97.5%
Arctic Char in Halokvik River							
M	0.1505	0.1352	0.0245	0.0659	0.1108	0.1902	0.5106
F_{MSY}/M	0.7952	0.1561	0.5314	0.6826	0.7829	0.8915	1.1327
Delta	0.6004	0.0976	0.4027	0.5336	0.6036	0.6696	0.7799
B_{MSY}/K	0.5989	0.0449	0.5096	0.5688	0.5996	0.6298	0.6843
F_{MSY}	0.1193	0.1115	0.0183	0.0510	0.0871	0.1494	0.4092
E_{MSY}	0.0961	0.0667	0.0178	0.0481	0.0791	0.1266	0.2688
K	104.993	54.493	32.516	63.298	93.916	134.495	236.522
B_{MSY}	62.747	32.612	19.287	37.676	56.259	80.784	142.134
MSY	4.291	0.848	2.344	3.796	4.405	4.896	5.660
Arctic Char in Jayko River							
M	0.1775	0.0845	0.0659	0.1177	0.1598	0.2190	0.3892
F_{MSY}/M	0.7965	0.1567	0.5317	0.6834	0.7842	0.8931	1.1358
Delta	0.6004	0.0977	0.4029	0.5336	0.6035	0.6696	0.7807
B_{MSY}/K	0.5992	0.0450	0.5097	0.5690	0.6000	0.6302	0.6847
F_{MSY}	0.1413	0.0737	0.0469	0.0901	0.1250	0.1751	0.3273
E_{MSY}	0.1172	0.0498	0.0443	0.0811	0.1087	0.1447	0.2346
K	167.148	57.739	82.957	125.640	157.721	198.504	306.197
B_{MSY}	99.836	34.308	49.640	74.952	94.236	118.558	184.006
MSY	10.225	1.374	7.363	9.332	10.289	11.183	12.772

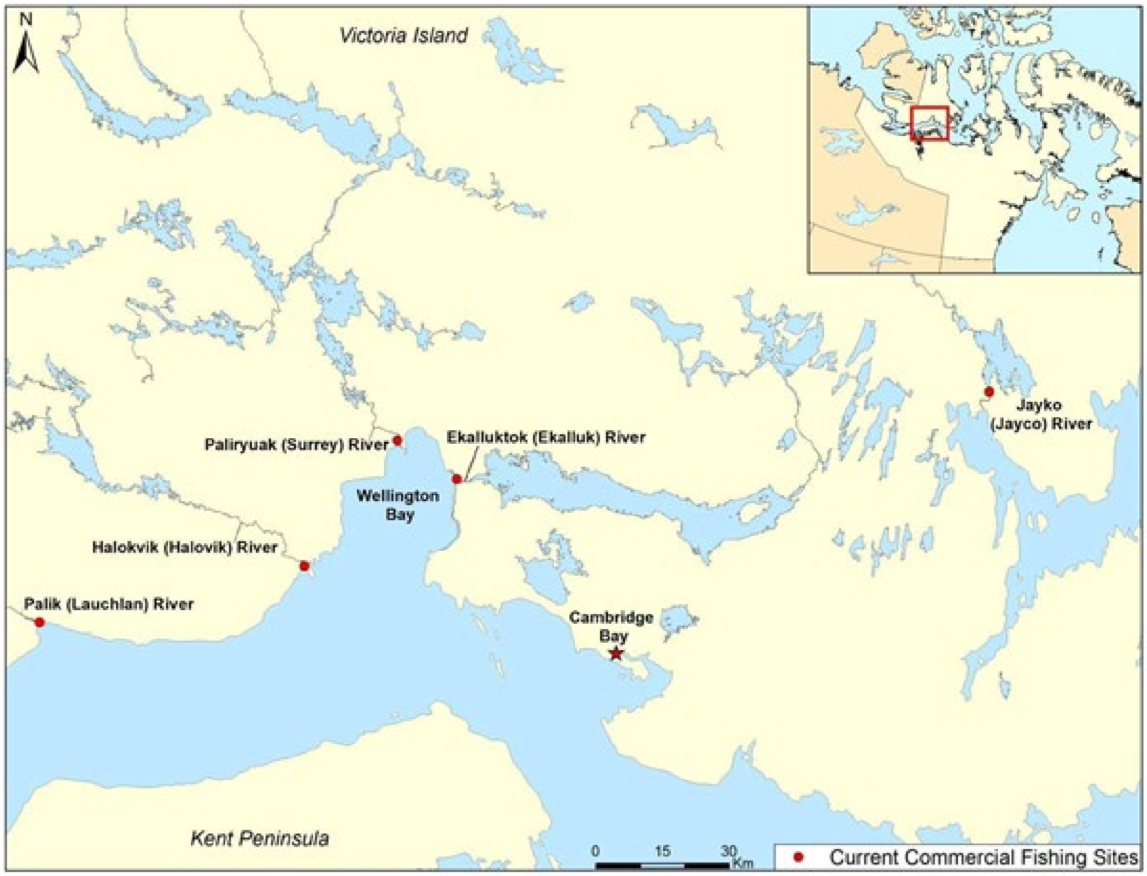

Figure 1. Map of the Cambridge Bay area, Nunavut, showing the current commerical fisheries for Arctic Char in the region. The community of Cambridge Bay is shown with a star.

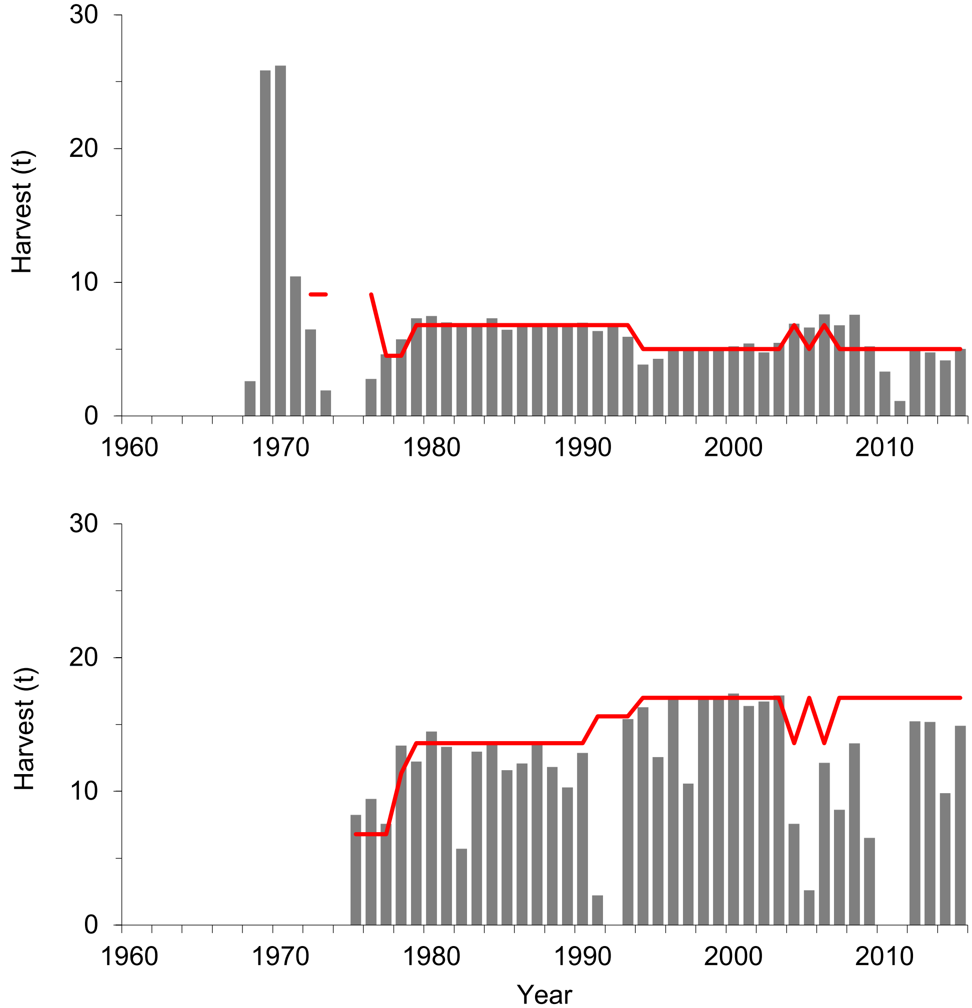

Figure 2. Commercial harvest (grey bar) and quota (red line) for anadromous Arctic Char from the Halokvik (upper panel) and Jayko rivers (lower panel).

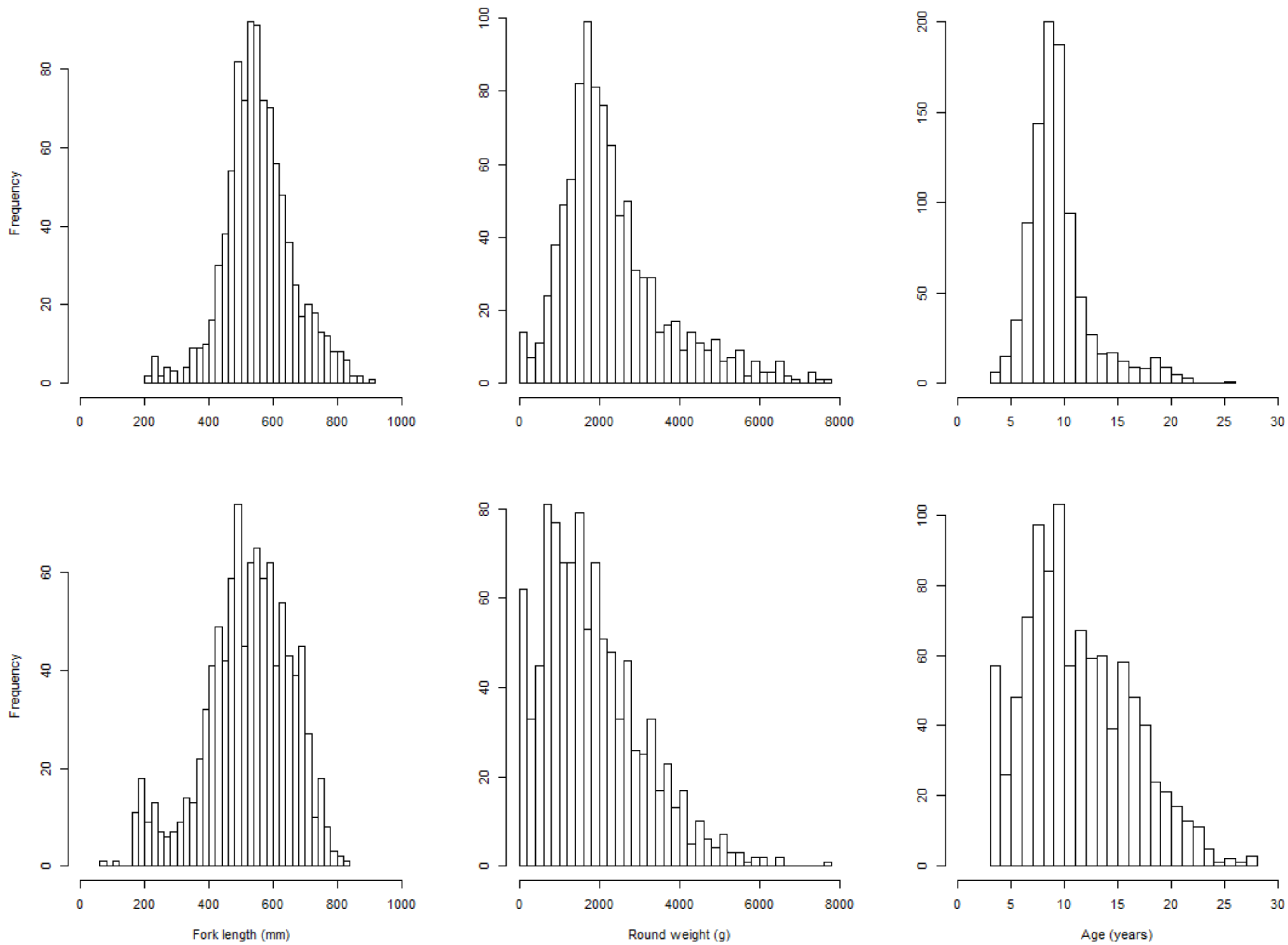

Figure 3. Summaries of biological characteristics of Arctic Char collected from fishery-independent surveys in the Halokvik (upper panels) and Jayko (lower panels) rivers of Cambridge Bay area, Nunavut, 2010-2015.

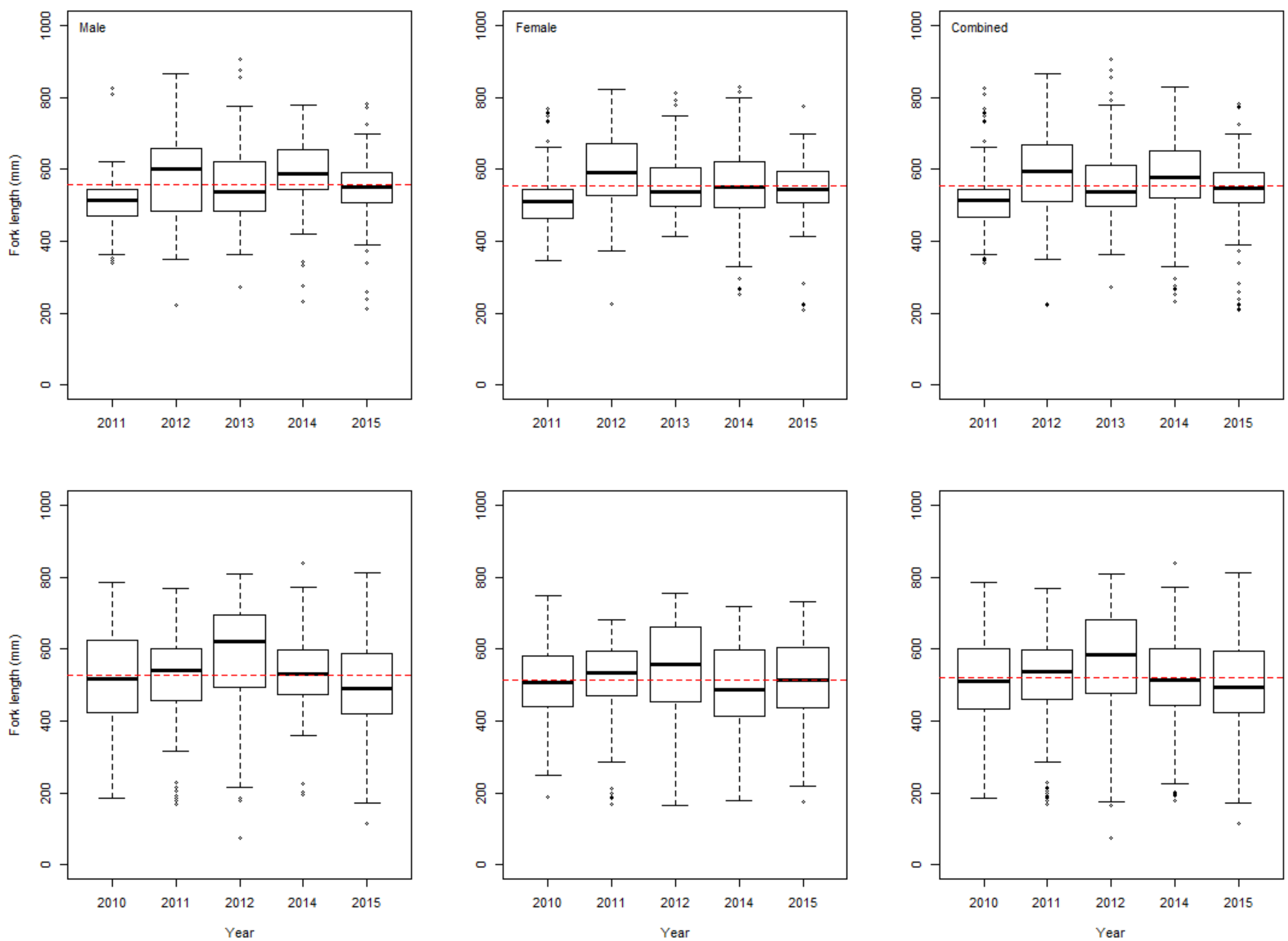

Figure 4. Comparison of inter-annual variation in fork length (mm) collected from fishery-independent sampling of anadromous Arctic Char from the Halokvik (upper panels) and Jayko (lower panels) rivers, Cambridge Bay, Nunavut, by sex (from left to right, males, females and both sexes combined). The average over all years is expressed by a red dashed line.

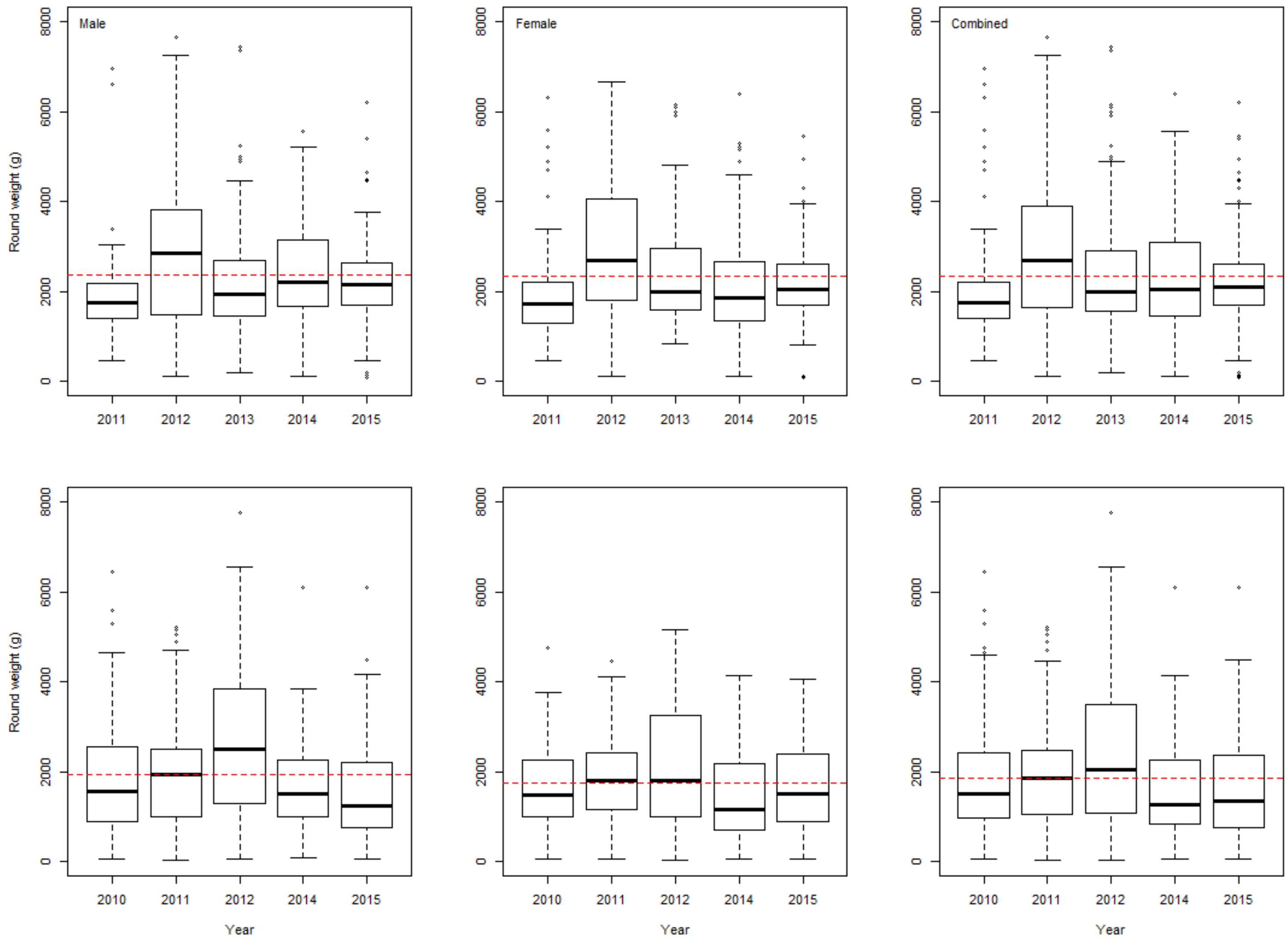

Figure 5. Comparison of inter-annual variation in round weight (g) collected from fishery-independent sampling of anadromous Arctic Char from the Halokvik (upper panels) and Jayko (lower panels) rivers, Cambridge Bay, Nunavut, by sex (from left to right, males, females and both sexes combined). The average over all years is expressed by a red dashed line.

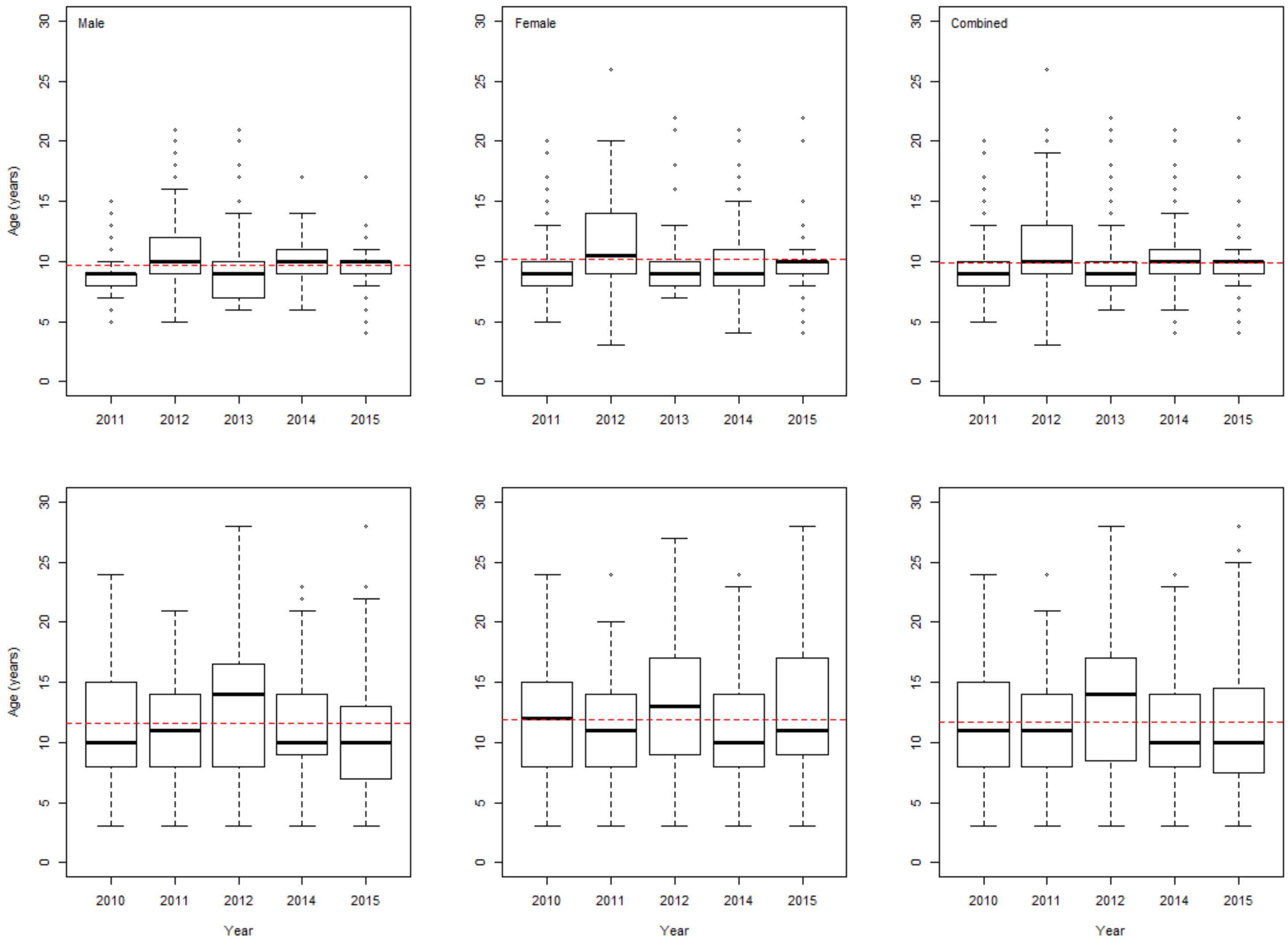

Figure 6. Comparison of inter-annual variation in otolith age (years) collected from fishery-independent sampling of anadromous Arctic Char from the Halokvik (upper panels) and Jayko (lower panels) rivers, Cambridge Bay, Nunavut, by sex (from left to right, males, females and both sexes combined). The average over all years is expressed by a red dashed line.

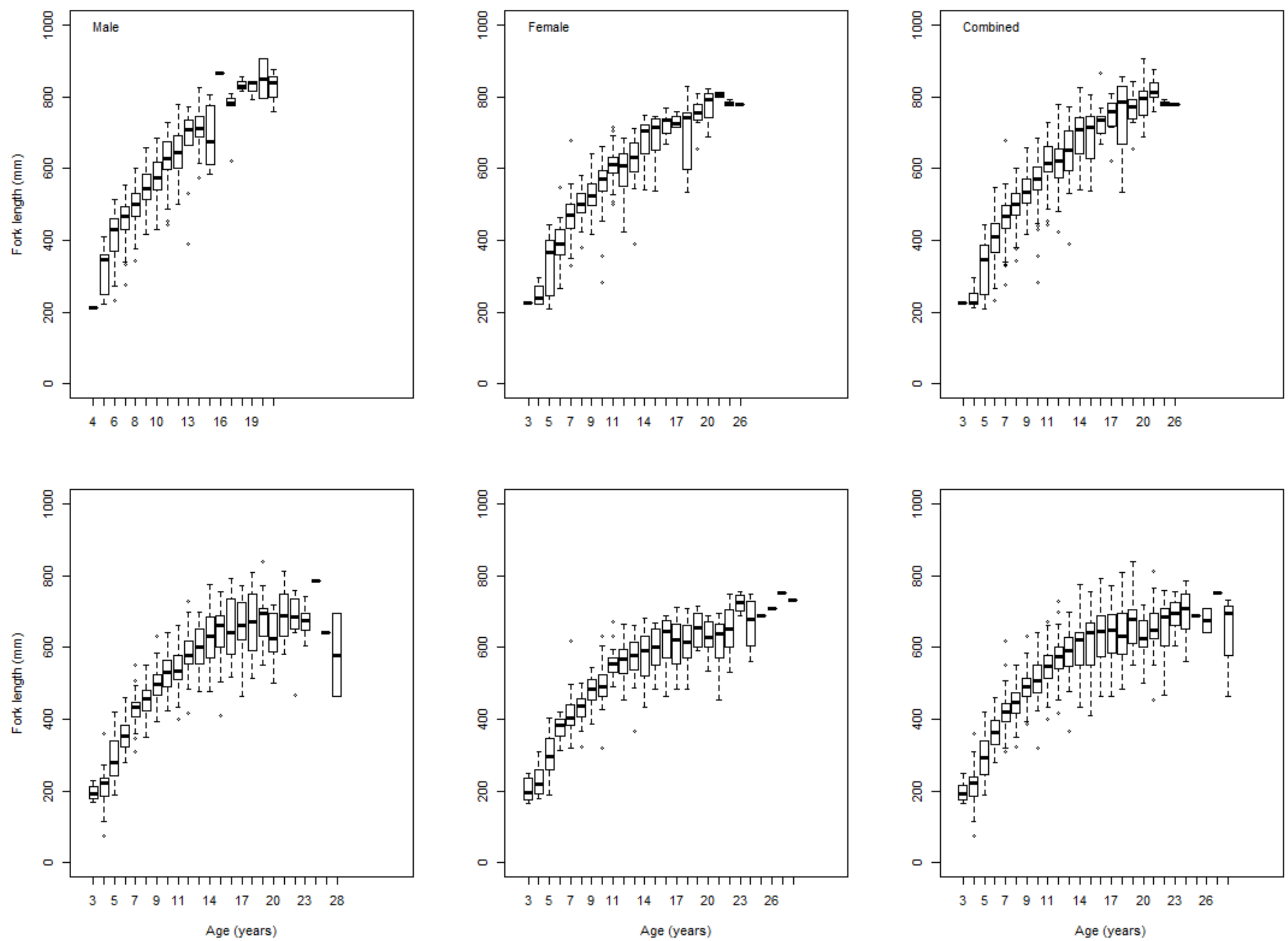

Figure 7. Comparison of length-at-age for male (left), female (middle) and combined (right) anadromous Arctic Char from the Halokvik (upper panels) and Jayko (lower panels) rivers, Cambridge Bay area, Nunavut. Data collected as part of fishery-independent sampling from 2010-2015.

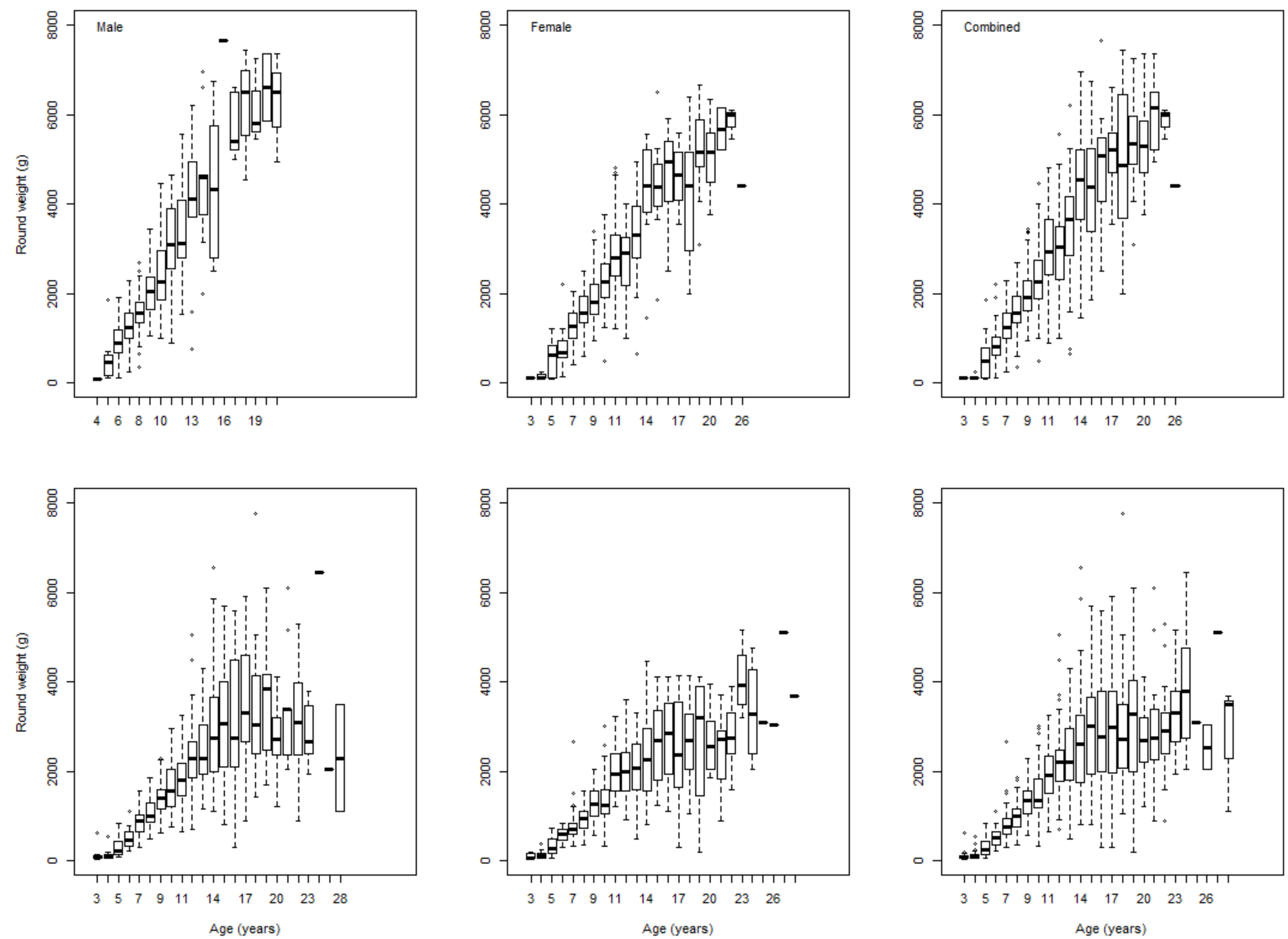

Figure 8. Comparison of round weight-at-age for male (left), female (middle) and combined (right) anadromous Arctic Char from the Halokvik (upper panels) and Jayko (lower panels) rivers, Cambridge Bay area, Nunavut. Data collected as part of fishery-independent sampling from 2010-2015.

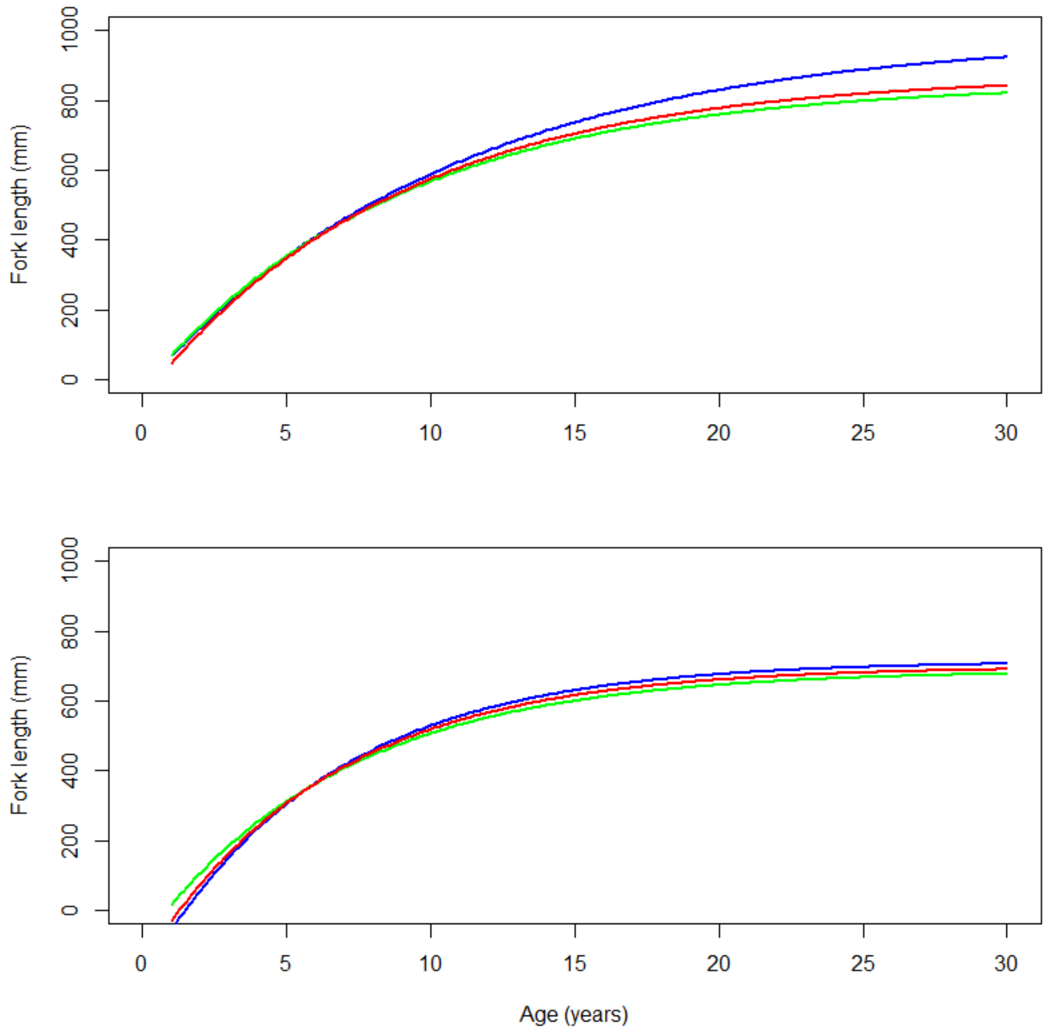

Figure 9. Modeled fork length-at-age growth of female (green), male (blue) and all (red) Arctic Char from the Halokvik (upper panel) and Jayko (lower panel) rivers, Cambridge Bay, Nunavut. Data collected as part of fishery-independent sampling from 2010-2015.

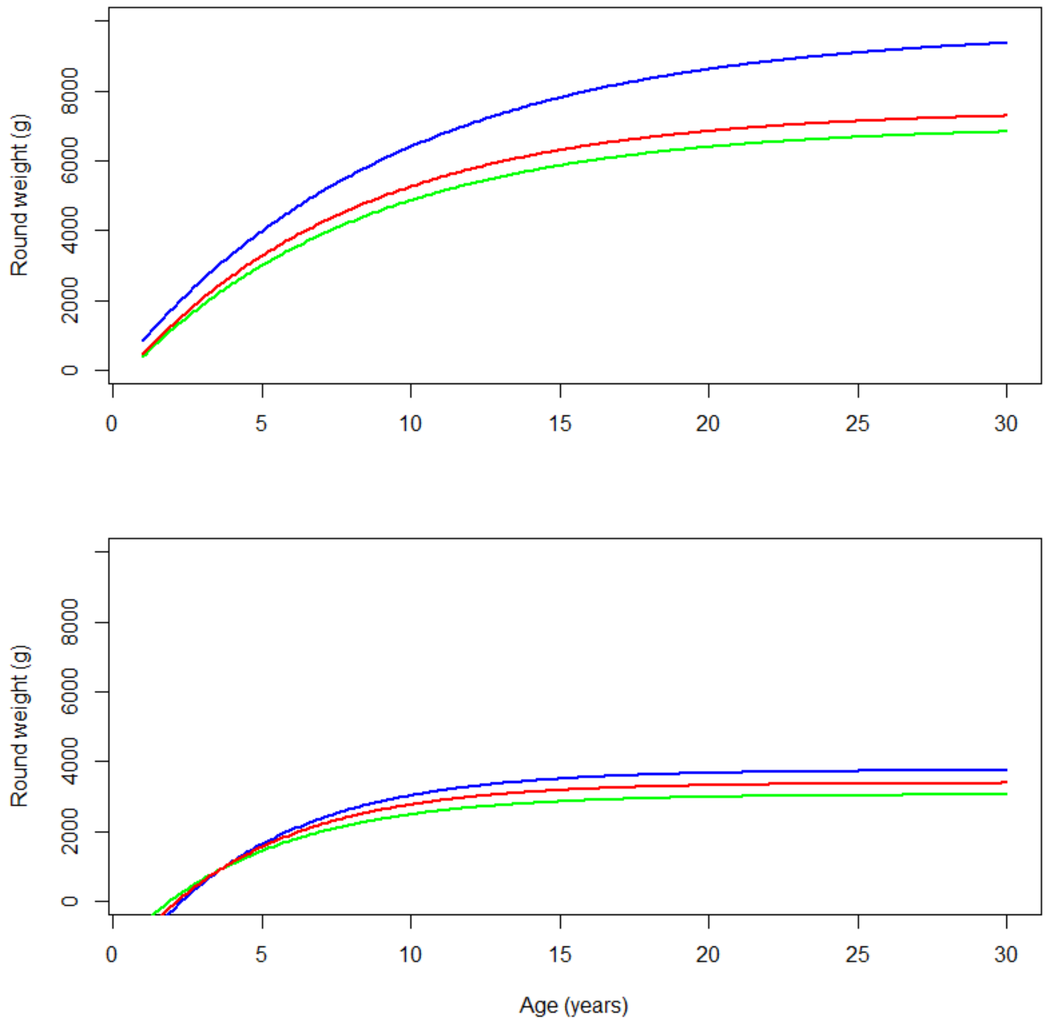

Figure 10. Modeled round weight-at-age growth of female (green), male (blue) and all (red) Arctic Char from the Halokvik (upper panel) and Jayko (lower panel) rivers, Cambridge Bay, Nunavut. Data collected as part of fishery-independent sampling from 2010-2015.

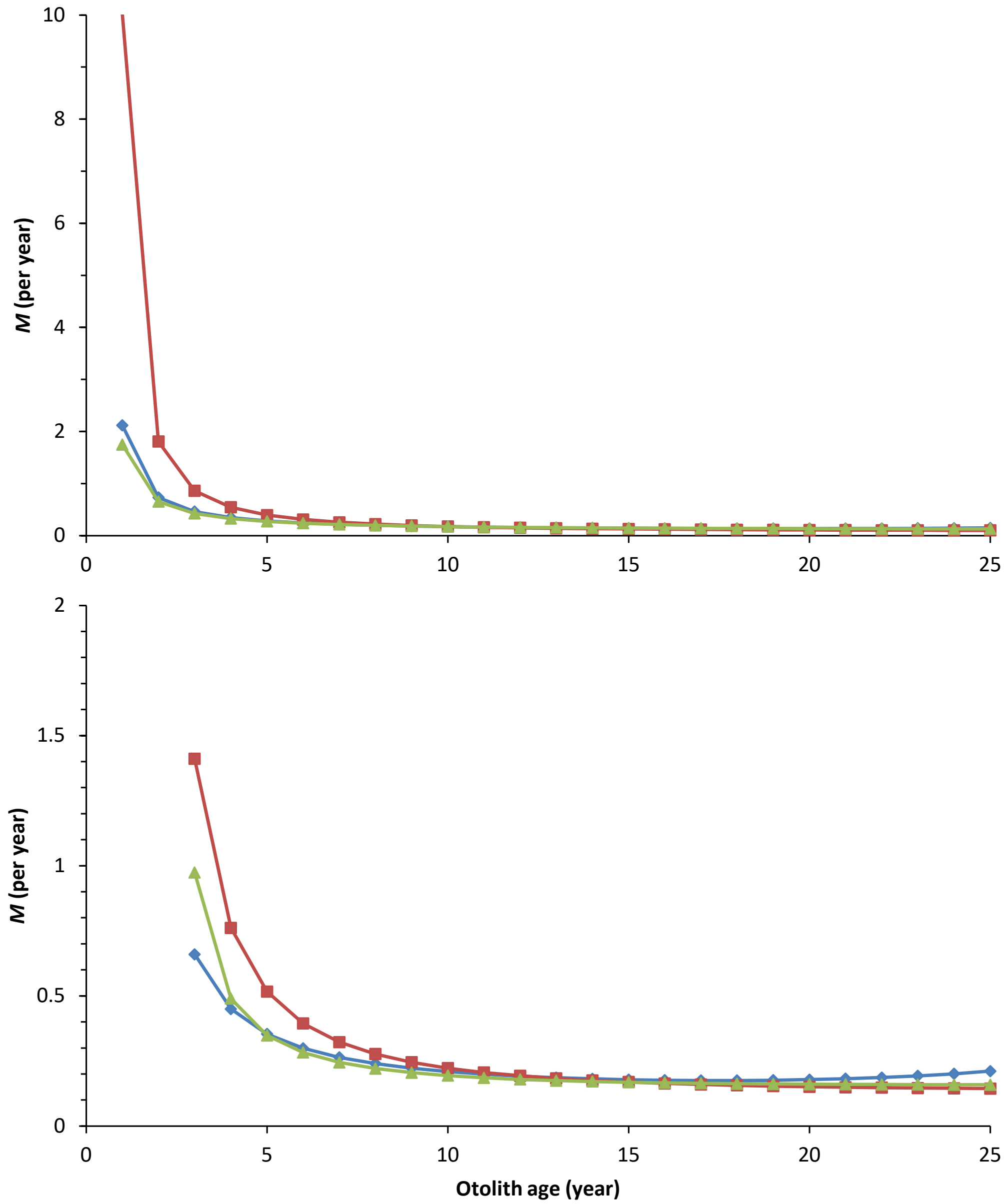

Figure 11. Estimation of age-dependent natural mortality for anadromous Arctic Char from the Halokvik (upper) and Jayko rivers (lower), Cambridge Bay, Nunavut, for estimates derived from the life history model (blue diamonds), length-at-age model (red squares) and weight-at-age model (yellow triangles).

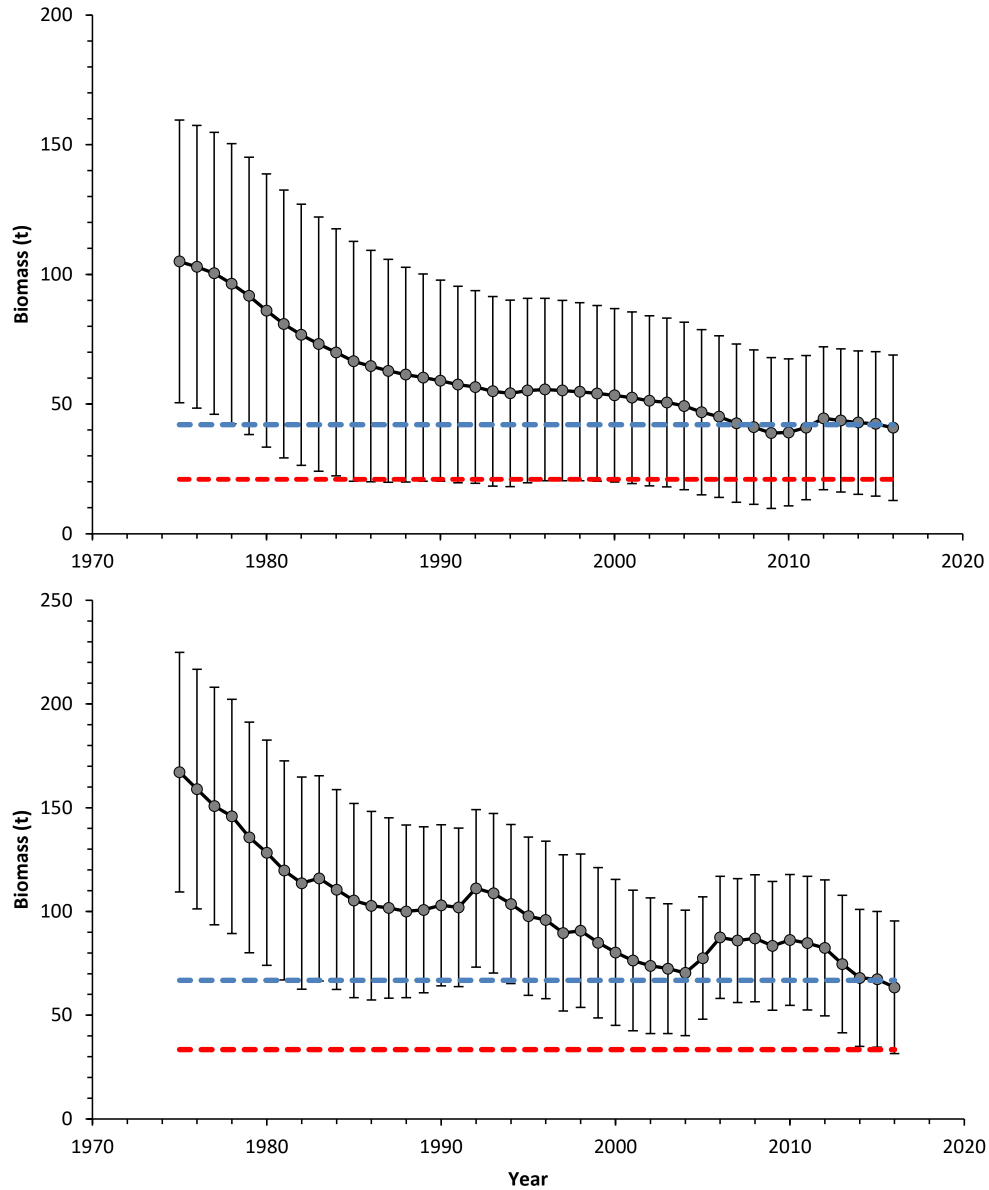

Figure 12. Temporal variation in estimated biomass with one unit of standard deviation from DB-SRA for anadromous Arctic Char in Halokvik (upper panel) and Jayko (lower panel) rivers. Also shown are the limit reference point (LRP, red broken line) and upper stock reference (USR, blue broken line).

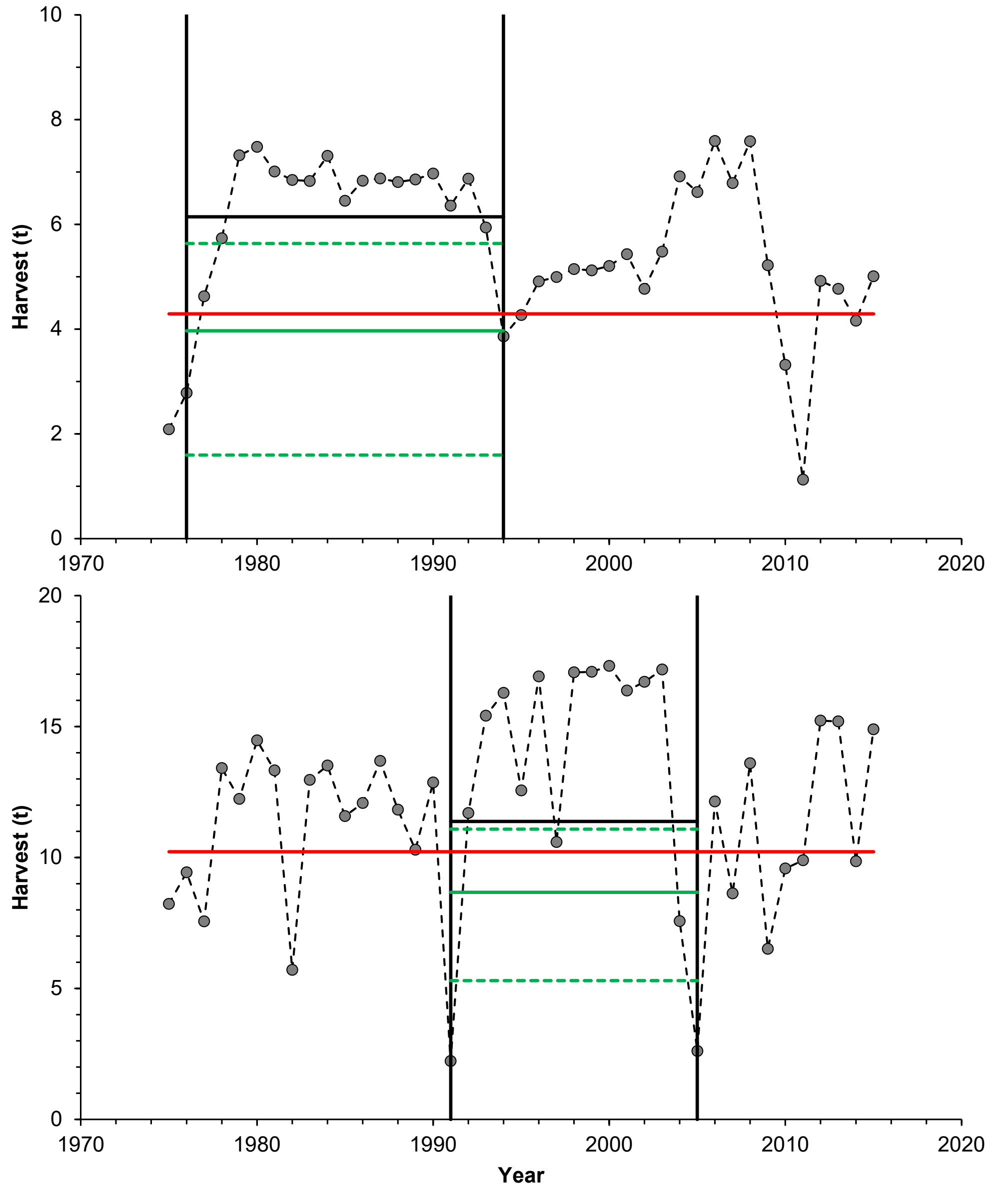

Figure 13. DCAC for anadromous Arctic Char from the Halokvik (upper panel) and Jayko (lower panel) rivers. Black broken lines with grey circles are the time series of commercial harvest used in the assessment. Black vertical lines bracket years over which the commercial harvests are summed and black horizontal lines are geometric means of the commercial harvests over bracketed years. Red horizontal lines are MSY from stock reduction analysis. Green lines are the DCAC median (solid) and 2.5% and 97.5% quantiles (dashed).

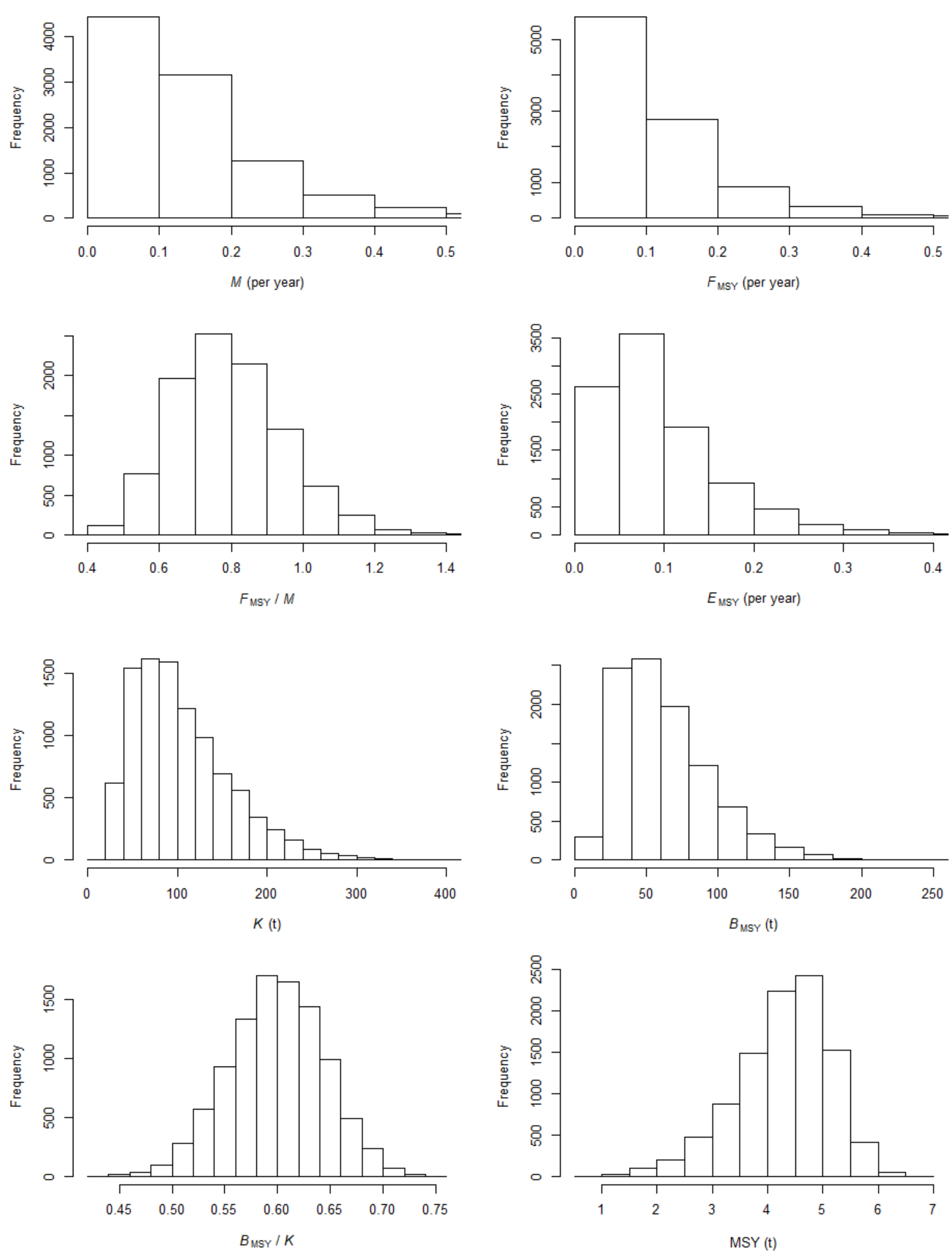

Figure 14. Frequency distributions of parameter values from DB-SRA analysis for Halokvik River Arctic Char.

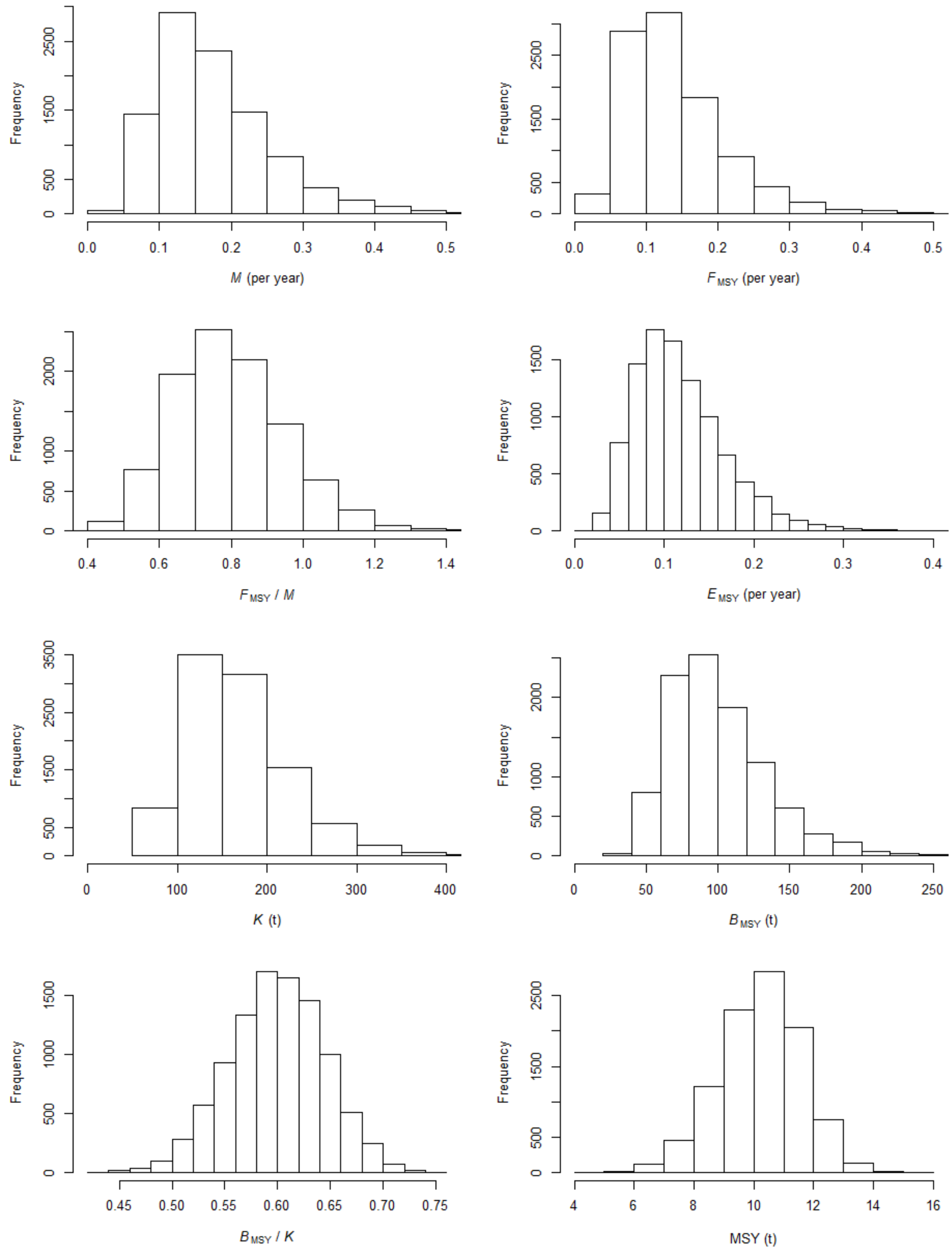

Figure 15. Frequency distributions of parameter values from DB-SRA analysis for in Jayko River Arctic Char.

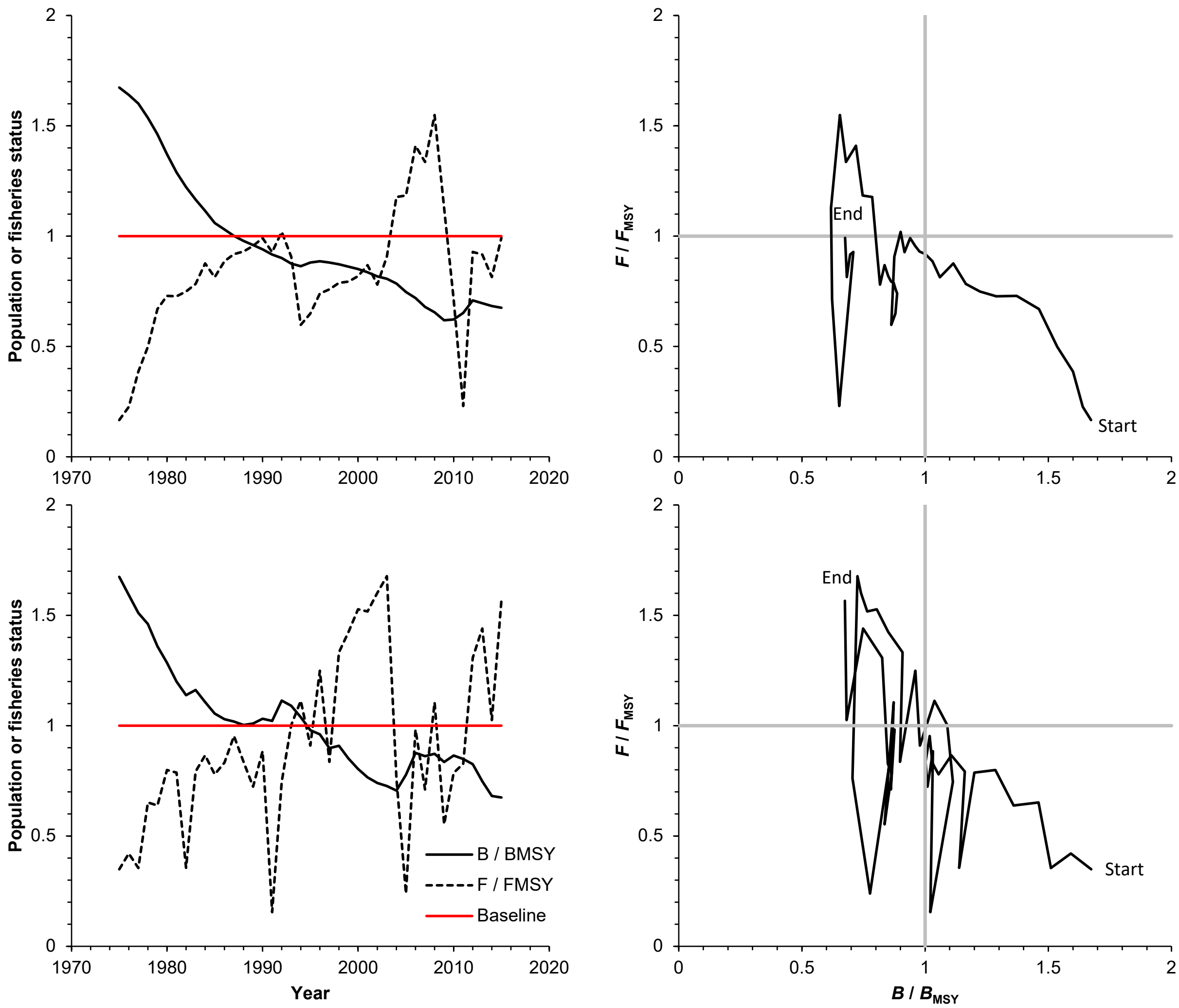

Figure 16. Graphic summary of the Arctic Char stock exploitation history from commercial fisheries in the Halokvik (upper panels) and Jayko (lower panels) rivers , 1975-2015 , demonstrating posterior median trends in stock status (B/B_{MSY}) and fishing status (F/F_{MSY}) calculated using the DB-SRA model. The critical reference to the stock status is delineated by red lines as biomass-specific indicators, as well as historical development of Arctic Char biomass status versus fishing status against reference lines (grey).