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Multimodel Assessment of Population Production and Recommendations for Sustainable Harvest Levels of Anadromous Arctic Char, *Salvelinus alpinus* (L.), from the Hornaday River, Northwest Territories

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Foreword

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

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ABSTRACT

Arctic Char from the Hornaday River are an important subsistence resource for residents of Paulatuk, Northwest Territories. A commercial fishery operated concurrently with the subsistence harvest between 1968 and 1986 and was not opened since 1987 due to diminishing catches and reduced size of fish. Data from the Hornaday Char Monitoring Program collected between 1990 and 2013 in addition to data collected from periodic sampling from previous fisheries were used to;

1. characterize population production parameters such as growth and natural mortality;
2. standardize catch-per-unit-effort (CPUE), and;
3. assess the population using three different models in order to determine stock status and determine maximum sustainable yield.

The von Bertalanffy growth model and maximum likelihood estimates demonstrated differences in growth parameters between males (L_∞ = 812 mm, K = 0.18) and females (L_∞ = 748 mm, K = 0.18). Using growth parameters and age-related models, natural mortality was estimated to vary between 1.23 per year at age one and 0.2 per year at age 16. The nominal CPUEs were evaluated by a set of fixed-effect type I-III sum of squares, analysis of variance (ANOVA), generalized linear regression models (Poisson, quasi-Poisson, and negative binomial), and zero-inflated probability (hurdle, zero-inflated Poisson, zero-inflated negative binomial) regression models. The bias-corrected AIC weights were used to assess the relative goodness of the fit of the candidate models to the observed CPUEs in order to select a model.

Three different fisheries assessment models, depletion-based stock reduction analysis (DB-SRA), surplus production model (SPM), and statistical catch-at-age (SCA), were used to estimate the median maximum sustainable yield (MSY) and total abundance (N_{MSY}), biomass (B_{MSY}), fishing mortality (F_{MSY}) and exploitation rate (U_{MSY}) at MSY. The inverse weighted average (± 1SD) among the estimates produced an MSY of 2,496 ± 154 and 5,724 ± 187 in fishable abundance and biomass (kg), respectively. The N_{MSY} was 14,635 ± 1,021 individuals while B_{MSY} was 29,826 ± 1,851 kg. U_{MSY} was estimated to be 0.15. Stock status of Arctic Char from Hornaday River has varied over time with evidence of overfishing observed between approximately 1977 and 1989, and in the mid-1990s. The modelling results indicate stock status is healthy as the stock is not being overfished given the harvest levels are currently below MSY.

Évaluation à multiples modèles de la production de la population, et recommandations à l'égard des niveaux de prises durables de l'omble chevalier anadrome, *Salvelinus alpinus* (L.), dans la rivière Hornaday (Territoires du Nord-Ouest)

RÉSUMÉ

L'omble chevalier de la rivière Hornaday est une importante ressource de subsistance pour les résidents de Paulatuk, dans les Territoires du Nord-Ouest. Une pêche commerciale a eu lieu entre 1968 et 1986, parallèlement avec la pêche de subsistance, mais n'est plus ouverte depuis 1987, en raison de la diminution des prises et de la réduction de la taille des poissons. Les données recueillies par le programme de surveillance de l'omble chevalier de la rivière Hornaday entre 1990 et 2013, ainsi que des données tirées d'échantillonnages périodiques de pêches précédentes ont été utilisées pour :

1. caractériser les paramètres de production de la population, comme la croissance et la mortalité naturelle;
2. normaliser les prises par unité d'effort (CPUE);
3. évaluer la population à l'aide de trois différents modèles, afin de déterminer l'état du stock et son rendement maximal soutenu.

Le modèle de croissance de von Bertalanffy et les estimations du maximum de vraisemblance font état de différences sur le plan des paramètres de croissance des mâles (L_∞ = 812 mm, K = 0,18) et des femelles (L_∞ = 748 mm, K = 0,18). En utilisant les paramètres de croissance et les modèles liés à l'âge, on a estimé que la mortalité naturelle varie entre 1,23 par année à 1 an et 0,2 par année à 16 ans. On a évalué les CPUE nominales au moyen de la somme des carrés d'un ensemble d'effets fixes de type I-III, de l'analyse de la variance (ANOVA), de modèles de régression linéaires généralisés (poisson, quasi-poisson et distribution binomiale négative) et de modèles de régression de probabilité zéro-inflation (poisson zéro-inflation, distribution binomiale négative zéro-inflation). Des poids AIC avec correction de justesse ont été utilisés pour évaluer l'adéquation relative des modèles candidats pour les CPUE observées, afin de sélectionner un modèle.

Trois différents modèles d'évaluation des pêches — un modèle d'analyse de la réduction des stocks fondée sur l'épuisement, un modèle de rendement soutenu et un modèle statistique de prises selon l'âge — ont été utilisés pour estimer le rendement maximal soutenu (RMS) moyen et l'abondance totale (N_{RMS}), la biomasse (B_{RMS}), la mortalité par pêche (F_{RMS}) et le taux d'exploitation (U_{RMS}), dans le contexte d'un rendement maximal soutenu. Le poids moyen inversé (± 1SD) parmi les estimations produisait un RMS de 2 496 ± 154 et de 5 724 ± 187 en abondance et biomasse exploitables (kg), respectivement. La valeur N_{RMS} était de 14 635 ± 1 021 individus, et la valeur B_{RMS} était de 29 826 ± 1 851 kg. On a estimé la valeur U_{RMS} à 0,15. L'état du stock de l'omble chevalier de la rivière Hornaday a varié au fil du temps, et des preuves de surpêche ont été observées entre 1977 et 1989 environ, et au milieu des années 1990. Les résultats de la modélisation indiquent que l'état du stock est sain, puisque celui-ci n'est pas surexploité et que les niveaux de prises sont actuellement inférieurs au rendement maximal soutenu.

INTRODUCTION

Arctic Char, *Salvelinus alpinus* (Linnaeus 1758), symbolize the inter-dependences between fish and their environment as well as between fisheries and Aboriginal societies in the Arctic. The development of commercial, recreational and aboriginal (CRA) fisheries among the northern societies is a reflection of this inter-dependence. Between 1968 and 1986, a commercial Arctic Char fishery occurred on the Hornaday River (Harwood 1999). In addition to the commercial use, Arctic Char is an important target species for recreational and subsistence fisheries especially for northern Canadian societies. As CRA fisheries expand, particularly in the Arctic, their potential capacity is challenged by a number of factors, such as fish production, supporting food-web dynamics, total fishing pressure and habitat suitability (quality and quantity) (Reist et al. 1995, ACIA 2004).

Evaluating the capacity of potential fisheries requires knowledge of fish population dynamics (e.g., growth, natural mortality, spawner and recruitment), fisheries characteristics (e.g., gear-specific catchability, selectivity, and vulnerability) and sampling processes (e.g., sample size, representative gear, and standardization of catch rates). A series of scientific questions associated with resource sustainability, need to be addressed:

- What is the status of the exploited stock and relevant exploitation rates?
- What is the total allowable harvest (TAH) or maximum sustainable yield (MSY)?
- What optional measures are there to approach the sustainability of the exploited stocks?
- What are the associated uncertain sources with the current stock status, adaptive management options, and possible cumulative impacts resulted from changing exploitation histories and Arctic hydroclimatic conditions?

The evaluation of these specific questions also requires time series of investigation-oriented supporting data and knowledge integration. For Arctic Char in the Hornaday River, there is a well-developed community-based Arctic Char monitor program that has been in place since 1989 to collect information on subsistence fisheries in the area (PHTC 1999, Harwood 2009). There has however not been an evaluation undertaken of these monitoring data to examine their accuracy and effectiveness as well as to maximize the information uses and benefits to co-management of the fishery. In particular, the incorporation of this monitoring program into a fisheries decision-making framework requires the evaluation of effectiveness and associated uncertainties with accompanying management strategies (Quinn and Deriso 1999, Walters and Martell 2004). Recently, the Fisheries and Aquaculture Management Branch of Fisheries and Oceans Canada (DFO) has advanced into using integrated fisheries decision-making frameworks incorporating the precautionary approach to ensure resource sustainability and meet the requirements of various eco-certification programs.

In this study, a combination of harvest, biological and catch-effort data from various fisheries and sampling programs of Arctic Char from the Hornaday River were used to assess the sustainability of the stock using three different population models and to evaluate alternative fisheries management strategies. The three assessment models were depletion-based stock reduction analysis (DB-SRA: Walters et al. 2006, MacCall 2009, Dick and MacCall 2011), which requires overall harvests quantities and only limited descriptive information on the fish population biology. The model-based fishery management procedures included surplus production model (SPM: Pella and Tomlinson 1969) and statistical catch-at-age model (SCA: Hilborn and Walters 1992, Quinn and Deriso 1999), which integrate various fishery-related information into baseline models and tend to mimic more elaborate management options in an optimal way if they produce unbiased estimates of the stock sizes. Regardless of their different assumptions and outputs, all candidate models, in general, aimed to:

1. estimate population abundance, biomass, and production;
2. characterize the historical patterns of the variability of the abundance, biomass and production;
3. formulate science advice on the management reference points, and;
4. recommend maximum sustainable yield (MSY).

This is the first multiple model-based exercise using fishery-dependent monitoring information on Arctic Char in the Canadian north. As new evidence becomes available, model-based outcomes and biological reference points from clusters of quantitative models will need to be updated.

MATERIALS AND METHODS

STUDY SITE

The Hornaday River (67°52′10″N 120°13′16″W) is situated within the Arctic Circle on the mainland of northern Canada. It originates approximately 100 km north of Dease Arm of Great Bear Lake, Northwest Territories, and flows northwest for 280 km through the Melville Hills before emptying into Darnley Bay, 14 km (8.7 mi) east of the community of Paulatuk (Figure 1). Approximately 45 km upstream of the Hornaday River delta, a 20 m high waterfall (La Roncière Falls) blocks all further upstream movements of fish (Sutherland and Golke 1978). The river below has several tributaries, (e.g., Aklak and Rummy creeks).

HISTORY OF THE FISHERY AT THE HORNADAY RIVER

Anadromous Arctic Char from the Hornaday River are harvested during their downstream (June-July) and upstream (August-September) migration in the spring and summer, respectively, and in the winter directly in the river at a deep pool in the delta and further upstream from an area called Coalmine (mid-October-November) (Harwood 2009). The residents of Paulatuk have traditionally fished for Arctic Char since settlement in the 1940s. A commerical fishery for Arctic Char occurred between 1968 and 1986 (Figure 2). The quota was originally set to 2,300 kg, then increased to 4,500 kg in 1974 and 1975, and increased again to 6,800 kg in 1976 where it remained unchanged until 1986. Due to community concerns regarding lower catch rates and smaller sized fish, the commercial fishery did not occur in 1987 and has not been opened since. Additonally, there was a small sports fishery with an annual harvest between 100 individuals in 1972 to 200 individuals in 1977. Between 1978 and 1995, the number of char captured by recreational harvesters decreased to the tens or low hundreds (Harwood 1999). The reported subsistence harvest between 1968 and 1997 ranged between 1,000 char (2,300 kg) in 1968 and 1,984 char (4,563 kg) in 1996. Starting in 1998, a voluntary harvest limit of 1,700 fish has been in place. Overall from 1968 - 2013, the various fisheries for char ranged from 479 - 5,456 individuals (mean ± SE = 2,365 ± 174 individuals) and 1,030 - 12,549 kg (5,408 ± 387 kg) annually(Table 1). The majority (about 60%) of the fisheries took place at the estuary of the river during August when the char were on their upstream migration, while an additional 20% of the catch came from the downstream migration in spring and another 20% from the under-ice fishery at the over-wintering holes after freeze-up (Harwood 1999).

COMMUNITY-BASED MONITORING OF ARCTIC CHAR

Along with the rapid increase and sudden decline of char fisheries, the sustianability of this anadromous population has been of increasing interest to Arctic fisheries scientists, decision makers, stakeholders, and resource users. In particular, the decline of the Hornaday River stock of Arctic Char precipitated the establishment of the Hornaday Char Monitoring Program (HCMP) by the Paulatuk Hunters and Trappers Committee (PHTC 1999), Fisheries Joint Management Committee (FJMC), and DFO. The program was initiated to employ harvesters (monitors) to collect harvest, catch-effort and biological information over the course of the fishery at the mouth of the Hornaday River during the upstream migration of char in August. The annual results would be used to monitor trends of population demographics and assess the stock status. Sampling was conducted in 1988 and since 1990 the program, in its current form, has been consistent in collecting biological and catch-effort data annually. During implementation of this program, the monitors are tasked with visiting fishing camps on a daily basis to record the total number of char caught, soak times, the number, length and mesh size of gillnets used, and randomly collect biological data (length, weight, sex/maturity, otolith for ageing) (Harwood 1999, Lea unpubl. rep.). Thus, the program has successfully collected information on the char fisheries between 1990 and 2013.

BIOLOGICAL OBSERVATION

Between 1990 and 2013, a total of 10,986 char were sampled including 6,340 sampled for length-weight measurements and 4,646 fish dead sampled. Over the years, the sample size varied from 58 char in 2007 to 982 fish in 1991 with the average of 458 ± 58 char. In addition to the HCMP, 2,155 char samples were collected from a number of other related research projects in the Hornaday River before 1990, such as commercial fisheries in 1973-1974, 1979, 1981, and 1983, a multimesh experiment in 1981, and a full-span conduit weir in 1986 (MacDonell 1986) and 1987 (MacDonell 1989). These datasets from either multimesh gillnets or weir experiments were pooled to use for estimating e growth and natural mortality parameters given the wide range of ages/sizes (Kristofferson et al. unpubl. rep., MacDonell 1997, DFO 1999). These complemented the truncated size ranges of char sampled from the HCMP. Fork length was measured to the nearest millimetre (mm) and round weigh to the nearest gram (g) for each fish sampled. For dead samples, the biological data also included sex (male or female), gonad maturity and fecundity. Pairs of sagittal otoliths were collected from each dead sampled fish, were cleaned and then placed in a scale envelope to dry, following the ageing determination protocol and criteria from Nordeng (1961). Otoliths were processed at DFO's Freshwater Institute in Winnipeg, Manitoba. Recently, age precision analysis highlighted an emerging issue regarding the ageing difference between readers and methods (Gallagher et al. 2017), and further research on validation and conversion of age readings are needed. In this study, the mixture of ageing results from two readers was used to represent annual variations in the proportion-at-age metrics and cohort strength of the exploited char populations.

CATCH-PER-UNIT-EFFORT (CPUE)

CPUE is an important parameter conventionally used for representing the standing stock status with an assumption of a linear relationship between CPUE and the abundance of the standing stock of interests. In reality, measuring units of fishing effort is imprecise due to varying fishing operations and gear configurations, fisheries, and the possibility of reporting errors. For example, since 1997, there were a total of 2,316 catch-effort records from monitored gillnets at the mouth of the Hornaday River. Fishing efforts were highly diverse, tied with variable fishing behaviours, such as fishing schedule and soak times, as well as mesh size and net length of the gear used (Tables 2, 3 and 4). The fisheries were normally undertaken in August and

September, and day-of-the-year varied from day 197 to 259 with the average of day 224.14 ± 0.19. Over the sampling period, number of gillnet sets for CPUE samples varied from 217 in July (9.37%), 2,059 in August (88.90%), and 40 in September (1.73%). Despite the majority of CPUE samples being taken in August, there were four years when sampling started earlier (mid-July) (1998, 1999, 2009, and 2011) (Table 2). Alternatively, in 2007, the CPUE samples were collected late in the summer, from August 18 to September 16.

Mesh size of gillnets varied from 114 mm to 152 mm with the average (± 1 SD) of 124.4 ± 0.2 mm (Table 3). Most (>98%) of the mesh sizes were either 114 mm, 127 mm, 133 mm, or 140 mm. The net length ranged from 18.29 m to 45.72 m with a mean (± 1 SD) of 43.8 ± 0.1 m. Among these, more than 90% of CPUE records were from nets 45.7 m long (Table 3). Fishing duration ranged from 0.15 h to 26 h with an average (± 1 SD) of 12.2 ± 0.1 h (Table 4) with 74% of the sets having soak time of 12 hours. Catches ranged from 0 to 96 individuals with a mean (± 1 SD) of 5 ± 0.2 fish. Zero catch occurred in 525 or 23% of the net sets. They were either a 'true zero' where fish were not caught because they were absent from the survey area due to unsuitable habitats, severe weather conditions, and mis-matched migration runs or they were a 'false zero' where they were present but not detected due to improper deployment of gear (Martin et al. 2005).

CPUE STANDARDIZATION

Many studies suggested that the observed CPUE must be standardized to ensure relatively accurate comparisons of the changes in abundance over temporal or spatial scales (Maunder and Punt 2004). Without this, any changes or variations in catchability, or changes in CPUE that are attributable to variable catchability may result in incorrect conclusions about changes in fish abundance (Bishop 2006). In the Hornaday River, Arctic Char use the estuary for feeding during the summer and overwinter in the upstream freshwater systems (Harwood 1999). The observed CPUE were largely influenced by several covariates of time, space, soak time, and fishing behaviours. Ignoring these confounding effects, the values of either nominal or simply interpolated CPUE might lead to misrepresenting the temporal tendencies of fish abundance (Maunder and Punt 2004).

CPUE standardization is essential to interpret temporal trends of exploited fish populations. Many methodologies have been established for this type of data analysis. Our standardization methodology was based on the assumptions of the Delury estimator which is mainly applied to a closed or localized population with constant catchability. The assumption of a closed or localized population is somewhat sound for Arctic Char in the Hornaday River, because its spatial distribution is confined to the Darnley Bay area and connecting freshwater systems (Kristofferson et al. unpubl. rep., DFO 1999). Given a set of mesh size used, the catch rate by a set of gillnets is closely related to fishing duration in a nonlinear function (Hansen et al. 1998, Olin et al. 2004). However, catch rate will follow a linear function to soaked hours before the experimental gillnet is saturated. After the saturation, real catchability reduces as the fish accumulate within the limited space (Olin et al. 2004). To minimize these confounding effects and possible violation of the underlying assumptions, we stratified the independent variables by weeks, day-of-the-year (Table 2), mesh size and net length (Table 3), and hour-specific soak time (Table 4).

Applying an unbalanced design, in which factor combinations have unequal numbers of observations (Zar 2010), we explored two Gaussian-based statistical methodologies:

1. a fixed-effect analysis of variance (ANOVA), and
2. count regression modeling to accomplish the CPUE standardization procedure.

For ANOVA, we first assumed the observed CPUE was proportional to the gillnet length for the open water of the Hornaday River estuary. Regardless the effect of net length, the observed CPUE was re-calculated by use of a factor of standard gillnet length of 45.7 m (50 yard). Secondly, we exercised three types of sums of squares ANOVA to select the "best" subset of predictor variables through general linear regressions. This removes redundant or noisy predictors and detects the colinearity from a set of predictors (McCullagh and Nelder 1989). Of the variables included, year and day-of-the-year were chosen as the initial entries into ANOVA because temporal changes in the standardized CPUE were the focus of this study. The variables mesh sizes and soak duration were included to account for the changes of the catchability of gillnets used for the monitoring activities. To increase the normality, the calculated CPUEs were log-transformed (CPUE+1), and categorized by factors of i^{th} week (I = 1,…,9), j^{th} grade of mesh size (j = 1,…,5), k^{th} level of net length in metres (k = 1,…, 6), l^{th} number of soak hours (l = 1,…,26) and y^{th} year (y = 1997,…,2013). The interaction items among the predictors were encompassed in ANOVA to represent the possible combined effects of covariates on the dependent measure (CPUE).

We used three types of sums of squares (SS) for ANOVA. Type one SS analysis adds effects sequentially where the incremental improvement in the error SS can be seen as each effect is added to the ordered model. Normally, the model with different effect orders generates different results. In a type two SS analysis, each effect is adjusted for all other terms except ones that "contain" the effect being tested. Therefore, type two SS analysis does not make use of constraints on the parameters, and alternative model specifications can produce identical results (McCullagh and Nelder 1989). In a type three SS analysis, the SS would be obtained for each variable if it were entered last into the model. The effect of each variable is evaluated after all other factors have been accounted for. Type three SS generally do not test hypotheses about least squares means, but instead test hypotheses that are complex functions of the patterns of missing cells in higher-order interactions and that are typically not meaningful. Nowadays, type I SS analysis is set as default in some types of common statistical software, like R, and S-plus while type III analysis is set by default in SAS, Stata, and Statistica. Type II SS is optional in some common statistical software, but is considered as preferable (Langsrud 2003).

We first examined if the catch-rate data were over-dispersed, where the variance exceeds the mean. Cases of over-dispersion of catch rates were identified in 2003 (mean 1.44 and variance 1.45), and soak hours 5 (mean 0.80, variance 0.97), 7 (mean 0.86, variance 1.15), 10 (mean 1.28, variance 1.29) and 13 (mean 0.85, variance 0.95). Associated with over-dispersion and zero catch issues, we adopted two types of count-based regression models, one belonging to the family of General Linear Models (GLM) and the other zero augmented models. The GLM group of count-based models includes Poisson, negative binomial, and quasi-Poisson regression models. Poisson models assume that the probability of observing individual events is constant in time or space of each sampling unit. In terms of conventional statistical theory, the conditional variance value of a Poisson probability distribution function is equal to the conditional mean, or equi-dispersion (Zar 2010). However, the amount of variation or dispersion for each sampling unit is typically either higher (variance/mean>1, over-dispersion) or lower (variance/mean<1, under-dispersion) than expected. Therefore, over-dispersion or under-dispersion can be modeled in various alternative ways, such as quasi-likelihood Poisson (Wedderburn 1974), negative binomial (Potts and Elith 2006, ver Hoef and Boveng 2007, Lindén and Mäntyniemi 2011, Brodziak and Walsh 2013). In particular, negative binomial regression is used for over-dispersed count data where the conditional variance exceeds the conditional mean. The zero-augmented models, also described as a two-component mixture models, combine a point mass at zero with a proper count distribution, including hurdle regression model (Potts and Elith 2006), zero-inflated Poisson and negative binomial models (Potts and Elith 2006, Zeileis et al. 2008, Brodziak and Walsh 2013). To account for processes causing excess zeros (Lambert 1992), the observed zeros can be modeled simultaneously by zero-inflated Poisson (ZIP) or negative binomial (ZINB) regression (Martin et al. 2005, Zeileis et al. 2008).

To construct a group of zero-inflated count regression models (ZIP, ZINB and hurdle), a canonical link function and logit function (McCullagh and Nelder 1989) were used to model zero and nonzero catches (i.e., true and false negative observations). The probability function of each response distribution in GLM admits a link function to connect the mean with the linear predictor. A logit link function was applied to both ZIP and ZINB, and the starting values were estimated by the expectation maximization algorithm. When applying a negative binomial probability function, we assumed it followed a gamma mixture of Poisson distribution. The variance of these zero-inflated count regression models was expressed as a quadratic function of their respective overall mean so that the resulting mean in ZINB was equivalent to the mean value in ZIP. Hurdle models, developed by Cragg (1971), consists of two parts of mixture models combining a truncated count component for positive count and a hurdle component for zero count, permitting a stochastic process (Martin et al. 2005, Zeileis et al. 2008). Overall, we used six sets of count-based regression models to standardize the observed CPUE with zero catches and characterize the temporal trends of char stock status using the indices of CPUE (Table 5).

GROWTH AND NATURAL MORTALITY

A total of 13,141 length and or weights were integrated from the commercial fishery (n=2,442) and from the HCMP (n=10,699). The collection of 5,159 pairs of otoliths collected from the commercial fishery and the HCMP were used to estimate a set of demographic parameters, such as age and growth as well as total and natural mortality of the fish. The length- and weight-at-age growth parameters were estimated using the von Bertalanffy growth model (VBGM) (Table 6). The length-weight relationships were fit by a power function (Table 11).

Natural mortality (M), a key parameter used to delineate population dynamics, is correlated with changes of life stanzas, body size, growth sequence and metabolic rate, as well as extrinsic factors including predation, disease, prey availability, and abiotic habitat-related environmental conditions (Quinn and Deriso 1999). The estimation of the rate of M used in the stock assessment is an important attribute to estimating yield-per-recruit (Beverton and Holt 1957) and assessing maximum sustainable yield (Hilborn and Walters 1992; Quinn and Deriso 1999). Given that most populations subject to exploitation before scientific information is collected, it is inherently difficult to directly measure or simply separate the natural morality of the exploited fish stock from total mortality due to the confounding effects of recruitment, fishing, and management policy (Quinn and Deriso 1999).

As one of critical parameters for fisheries stock assessment, estimates of M are calculated indirectly from a series of published relationships between M and biological characteristics of the species, such as reproductive investment and growth rate (Pauly 1980, Gunderson and Dygert 1988). Due to the scarcity of life history information, the empirical relationships assumes that M is a species- or stock-specific constant, which can be applied to all exploited ages and sizes of the stock in question. In contrast to this special case of simplification, some developments in line with the general size-spectrum theory (Peterson and Wroblewski 1984, Lorenzen 1996, Gislason et al. 2010) suggest that M should be scaled with individual sizes of fish. Three types of age-specific models were used to estimate M:

1. life history model (Chen and Watanabe 1989),
2. body length scaling model (Gislason et al. 2010), and

3. mass size scaling model (Peterson and Wroblewski 1984, Lorenzen 1996, 2000) (Table 6).

These estimates of natural mortality were age-dependent, incorporating information on age-at-maturity from the VBGM (Chen and Watanabe 1989). Peterson and Wroblewski (1984) used a theoretic size-spectrum model to generate an exponent of -0.25 for *M* to scale the unit of weight. Similarly, Lorenzen (1996, 2000) modelled *M* using a power function of weight-mortality for a variety of fish living in freshwater and marine systems. Lorenzen (1996) compared the estimated natural mortality of fishes from freshwater, marine, and aquaculture ponds, and concluded that no significant differences were found in these ecosystems. In the case of polar systems, however, he proposed the model parameters b=-0.292 and M_u 1.69 of a power function.

DEPLETION-BASED STOCK REDUCTION ANALYSIS (DB-SRA)

Two data-limited stock assessment models, depletion-corrected average catch (DCAC, MacCall 2009) and stochastic stock reduction analysis (SRA, Walters et al. 2006), can be used for the instances where harvest is the only available source of information along with limited data on the population demographics of the exploited fish. DCAC was extended by using the potential-yield formula of Alverson and Pereyra (1969) and Gulland (1970) to estimate fishery production that would be sustainable. DCAC incorporates uncertainty in model parameters *M*, ratios of B_{MSY} to B_{o} (virgin biomass), F_{MSY} to *M*, and relative changes in biomass (Δ) using Monte Carlo simulations. SRA can complement comprehensive stock assessment models by using historical catch data in conjunction with estimates of relative stock reduction due to fishing to reconstruct possible trajectories of recruitment rates, stock sizes, and stock decline (Walters et al. 2006). Deterministic SRA models provide a single stock size trajectory while stochastic SRA attempts 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). Depletion-based stochastic stock reduction analysis (DB-SRA) originates from SRA (Kimura et al. 1984) and incorporates a stochastic framework of simulation (Walters et al. 2006). It is an extension of DCAC by:

1. restoring the link between production and biomass, and;
2. bringing into consideration alternative hypotheses regarding changes in biomass during the historical catch period.

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. 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 conjunction point at B_{MSY} (Schaefer 1957).

To run the DB-SRA (Table 7) model, we structured Arctic Char harvest data from 1974-1996 when the catches exhibited a strong contrast. As suggested by Walters and Martell (2004), we specified ratios F_{MSY}/M = 0.8 and B_{MSY}/K = 0.25 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 ($B_{\mathrm{mnpl}} = B_{\mathrm{MSY}}/K$), and the relative depletion level (B_T/K) in a specific recent year *T*. Associated with the initial values and harvests, we implemented a total of 100,000 Monte Carlo simulations to estimate imprecision in the model parameters delineating the stock productivity and status.

SURPLUS PRODUCTION MODEL (SPM)

Given pairs of abundance or biomass indices and associated harvest series, surplus production model (SPM) may be one of the best and simplest approaches to quantitative fisheries stock assessment (Haddon 2001). Integrating a set of biological parameters such as growth, recruitment, and natural mortality into a comprehensive surplus component, the dynamic behaviour of instantaneous biomass of the exploited stock can be evaluated by differences between the surplus production and harvest removals (Hilborn and Walters 1992, Quinn and Deriso 1999).

To reduce the confounding effects between B_t and K (Meyer and Millar 1999a, b, Millar and Meyer 2000), a discrete form of the SPM was re-parameterized by a relative biomass ($P_t = B_t/K$) to express the annual biomass conditional to K. Based on model outputs, a grid of management-related parameters can be derived, including maximum sustainable production (MSP), fishing mortality at MSP (F_{MSP}), biomass at MSP (B_{MSP}), exploitation (F/F_{MSP}) and biomass statuses (B/B_{MSP}) (Quinn and Deriso 1999). Thus, nonstationarity in the population productivity was integrated into a fisheries management decision framework, primarily addressing:

1. precautionary reference points and stock status zones;
2. harvest strategy and harvest control rules, and;
3. inherent uncertainties and operational risks (Caddy and Mahon 1995, Walters et al. 2008).

A system of symbols (Table 8) is provided for SPM model parameters and modeling procedures.

STATISTICAL CATCH-AT-AGE MODEL (SCA)

Statistical catch-at-age (SCA) model is increasingly favored for population assessments for several reasons. First, changes in age-composition over time may better indicate the temporal trends in fishing mortality and recruitment (Martell et al. 2008). Indeed, this particular capability is one of the main reasons to combine a set of catch-at-age information. Second, contrary to aggregate surplus production models, observed changes in Arctic Char CPUE, collected by the monitoring program at the mouth of the Hornaday River, can realistically reflect the variations both in population status if gillnet selectivity is assumed constant. Thus, the variations in the CPUE can be better related to the changes in cohort strengths of the population abundance from age-structured models, especially when existing information is insufficient to distinguish the exact types of dome-shaped or asymptotic selectivity functions. Finally, a model-based catch-at-age stock assessments provides the ability to use shorter time-series (<20 years) of fishery-independent data, which avoids many of the potential biases associated with fishery-dependent abundance indices.

Several assumptions underpin the applicability of SCA. One of these is that age-specific fishing mortality rate can be modeled as a function of year and age effects (Quinn and Deriso 1999). Under this assumption and after log transformation, fishing mortality can be considered as the sum of a year and age effect. This is imperative in order to combine the time series of catch-at-age data and an index of relative abundance to estimate age-specific absolute stock size. All of these are elaborations of the simple DeLury or depletion model (Leslie and Davis 1939, DeLury 1947). Modern age-structured models approach the same kind of estimates for age-specific abundance, but have taken the effects of natural mortality and age-specific selectivity into calculation of abundance and catchability. In addition, modern SCA also allows statistical estimation of catch-at-age metrics with observation errors and model-related process errors, respectively (Fournier and Archibald 1982, Quinn and Deriso 1999).

For running this first version of Arctic Char SCA models, we hereafter assumed:

1. the growth of char followed the time-invariant VBGM (Hilborn and Walters 1992);
2. time-varying natural mortality changes;
3. that gillnet selectivity and maturity-at-age parameters conformed to an asymptotic or logistic function (Quinn and Deriso 1999, Chuwen et al. 2011, Thorson and Prager 2011);
4. that recruitment and spawner relationship follows a Beverton-Holt model (Beverton and Holt 1957), and;
5. known harvest reports without errors.

Through this exercise of SCA, we ultimately aimed for:

1. integration of the community-based monitoring information on Arctic Char assessment models;
2. reconstruction of the temporal trend of cohort strengths of char abundance that sustained the subsistence harvest, and;
3. evaluation of management options to ensure the sustainability of the Arctic Char populations.

To accomplish these objectives by SCA, we organized the existing biological and fisheries datasets along with a set of auxiliary information about the maturity-at-age, age at 50% selectivity and initial values of model parameters. Because the median day-of-the-year (day 226) was used for fishing char in the estuary of Hornaday River, the fishing timing in the model was set to 0.62 (226/365). Information on the reproductive schedule of Arctic Char in the Hornaday River is limited, current data suggests a minimum age at maturity of 7 or 8 years (Harwood 1999). The initial value of catch-at-age was proposed to age 5 in terms of the observed catch-at-age composition from 113 mm and 127 mm mesh sized gillnets. Applying penalized maximum likelihood estimates (MLE), a set of model parameters were estimated, including $\widehat{N_1}$the initial number-at-age present in the first year, like 1968, $R_{\text{age-1}}$ recruitment from 1968 to 2013, $log\bar{R}$ average age-1 recruits over time period 1968-2013. The notation of the statistical catch-at-age model and the state-space catch-at-age calculations were detailed in Table 9 and Table 10, respectively.

MODEL PLATFORM, MULTI-MODEL INFERENCE AND MULTI-MODEL COMPARISON

The estimations of model parameters of the VBGM, SPM, and integrated statistical catch-at-age model (iSCAM, Martell et al. 2012) were individually executed by automatic differentiation model builder (ADMB). The DB-SRA was conducted by using programmable computer language R. Outputs of these multiple model parameters, such as MSY, B_{MSY}, and F_{MSY}, were generated to inform a set of reference points for managing Arctic Char fisheries in the Hornaday River. To synthesize the resulting model outputs, a meta-analysis, optimal weight for averaging a set of independent inverse variance of each effect size, was explored for a multi-model comparison (Hartung et al. 2008, Marín-Martínez and Sánchez-Meca 2010, Harrison 2011). In conventional statistics, inverse-variance weighting is a method of aggregating two or more random variables to minimize the variance of the weighted average. Each random variable is weighted in inverse proportion to its variance. Applying Monte Carlo simulation, Marín-Martínez and Sánchez-Meca

(2010) assessed the bias and mean squared error of two estimates by weighting relative variance of each effect size. The significance of effect-size index is expressed as a standardized mean difference when the fixed and random effects are associated together. In this study, we followed the recommendation by Marín-Martínez and Sánchez-Meca (2010), and adopted the average ($\hat{\mu}$) of *k* independent standardized mean differences, $\hat{\mu} = \frac{\sum_{i=1}^{k} \widehat{w_i} d_i}{\sum_{i=1}^{k} \widehat{w_i}}$. Here, $\widehat{w_i^2} = 1/(\widehat{\sigma_i^2} + \widehat{\tau^2})$, with random effect within-study variance ($\widehat{\sigma_i^2}$)and between-study variance ($\widehat{\tau^2}$), respectively. Parameter d_i is an unbiased estimator of the standardized mean differences between pairs of model parameters.

Statistical analyses, such as analysis of variance (ANOVA), generalized linear models (GLM) and zero augment models (ZAMs), were conducted by using several statistical packages under R operational environment. Under statistical significance level α=0.05, the analysis of covariate (ANCOVA) was used to test the differences in slopes and intercepts among log-transformed length and weight regressions. The differences in intercepts can be interpreted as ones in magnitude but not the rate of change as slope means. In allometric fish growth studies, differences in the regression slope mean different change in growth rates among groups.

Data were read and graphed using gdata, foreign, ggplot. Statistical analyses were performed by pairwise correlation using Hmisc, Companion to Applied Regression (car) by uses of type I, II, and III SS, leaps for stepwise regression, AER for general regression analysis of count data, and pscl for ZAM. For CPUE standardization, we constructed three GLM models (Poisson, Quasi-Poisson and negative binomial) and three zero-inflated models (hurdle, ZIP and ZINB). Multi-model inference (MMI) makes reliable inferences using results from multiple sets of models rather than the best model picked in terms of the least information-theoretic criterion, such as small-sample-size corrected Akaike information criterion (AICc) (Burnham and Anderson 2002). AICc differences and weight (w_i) can be used to rank the relative importance among the candidate models for a post-hoc analysis. Given w_i, the weight of evidence, a better-supported model is selected with a greater w_i against a less plausible model with the smaller w_i (Burnham and Anderson 2002). Thus, w_i can be indicative of the relative importance of a candidate model for the MMI (Table 5).

RESULTS AND DISCUSSION

LENGTH AND WEIGHT RELATIONSHIP

The average (± 1 SD) fork length and round weight of males (from a range of 198-835 mm and 60-7,150 g, respectively, n = 2,951) was 580 ± 1.6 mm and 2,591 ± 19.3 g, respectively, which was greater than those of females (from a range of 200-785 mm and 75-7,150 g, respectively, n = 2,513) which averaged 561 ± 1.5 mm and 2,256 ± 15.5 g, respectively. The exponential coefficient, b, as a measure of cubic increment of round weight with fork length, was approximately 3, indicating the growth of the fish was isometric (Table 11 and Figure 3). The somatic increases between fork length and round weight (sexes combined) followed a power function with $a = 1.39\times10^{-5}$ and b = 2.98.

An ANCOVA was used to test the differences in slopes and intercepts among log-transformed length-weight linear regression with log-transformed fork length as an independent covariable, log-transformed round weight as a dependent variable, and sex as a categorical factor with two levels (male and female). The results showed a significant effect of fork length ($F_{1,5463} = 5.56\times10^4$, p<0.0001), but no effect of sex ($F_{1,5463}$ = 1.42, p = 0.23) and an interaction between both ($F_{1,5463}$ = 1.81, p = 0.18). The slopes of the regression between log-transformed fork length and round weight were similar for both sexes despite different size ranges (Figure 3). A more parsimonious model was fitted without the interaction to test for differences in slope. The results ($F_{1,5463}$ = 40.76, p<0.0001), showed that sex had a significant effect on the round weight, interpreted as a difference in 'intercepts' between the regression lines of males and females. Biologically, we realized that one set of length-weight regressions can be applied to both sexes of Arctic Char in the Hornaday River, but the size ranges varied.

LENGTH- AND WEIGHT-AT-AGE

To reduce the observation uncertainties due to small age-specific sample sizes (n < 20), growth analyses were constrained to age classes 2-11. Based on the VBGM, male Arctic Char were 8% larger (L_∞ = 812 mm) and had a 3% lower growth rate (K = 0.18 per year) compared to females (L_∞ = 748 mm, K = 0.18 per year (Figure 4) (Table 11). The VBGM parameters for the combined sexes were L_∞ = 771.32 mm and K = 0.1869 per year. The weight-based VBGM parameters differed between sexes, being 20% greater in W_∞ (6342 g) and 9% greater in K (0.19 per year) for males compared to females (W_∞ = 5261 g and K = 0.17 per year) (Figure 5). When sexes were combined, the VBGM growth parameters were W_∞ = 5,828 g and K = 0.19 per year, respectively. So, differences in sex-specific growth were identifiable, indicating greater growth for male fish compared to females.

A two-way ANOVA revealed that the growth in fork length of Arctic Char differed significantly from ages 2 to 13 ($F_{11,5042}$ = 423.50, p < 0.0001) in both sexes ($F_{1,5042}$ = 20.77, p < 0.01) with significant interaction with age and sex ($F_{11,5042}$ = 4.23, p<0.0001). Similarly, age-specific round weight differed by ages ($F_{11,5042}$ = 245.01, p < 0.0001), sexes ($F_{1,5042}$ = 27.96, p < 0.0001) and age-sex interaction ($F_{11,5042}$ = 8.56, p < 0.0001). All tests reflected the clear tendency of fish growth to vary by age and sex.

NATURAL MORTALITY

Table 12 summarized the estimates of M from four age-dependent empirical models (Peterson and Wroblewski 1984, Chen and Watanabe 1989, Lorenzen 1996, Gislason et al. 2010). Incorporating the VBGM parameters, M declines with age and differed with life stanza (Figure 6), and varied in three distinct stanza-related patterns. During recruitment stage at ages 1-3, M decline ranged between 50% and 77% (average = 62%), and from 13% to 39% prior to maturation (ages 4-7). In adulthood, M becomes nearly constant, given that the variation ranged between 0 and 28% (average = 15%).

M differed between sexes and among the empirical models used (Figure 6). On average, females had a higher M than males, and varied with ages from 2.57% in the life history model (Chen and Watanabe 1989) to 14.07% in the length-at-age growth model (Gislason et al. 2010). Significant sexual differences in M appeared in the weight-at-age growth models (Peterson and Wroblewski 1984, Lorenzen 1996). Among the models used, the higher M estimates occurred in ages 1-3 using the Gislason et al. model (2010). After age 3, Peterson and Wroblewski's model yielded the greater M while the lowest estimates were from Lorenzen's model. To avoid the biased estimation of M among models, we combined multiple sets of M values from different models, showing the values varied from 1.23 per year in age 1 to 0.20 per year at age 16 with a geometric mean (± 1 SD) of 0.3 ± 0.07 per year.

AGE COMPOSITION

The age ranged from 2 to 14+ with a majority (≥ 25%) of ages between 5 and 9 years (Figure 7). Over the monitoring period, age 5 was dominant in subsistence harvest in 2008, age 6 in 1997, 1999 - 2001, 2007 and 2009, and age 7 in 1992, 1999, 2003,2005 and 2010 - 2012, while age 9 was dominant in 1989. Among five abundant age classes (5 to 9 years), the age composition varied by years. The average age of Arctic Char was relatively high (~8 years) in 1993-1994, 2003-2006 and 2011 (Figure 8). The Shapiro-Wilk test showed that 76% of the time series of age composition did not conform to a normal distribution (Table 13).

CPUE STANDARDIZATION

Since 1997, there were a total of 2,316 catch-effort records from monitored gillnets at the mouth of the Hornaday River. Fishing efforts were highly diverse, tied with variable fishing behaviours, such as fishing schedule and soak times, as well as mesh size and net length of the gear used (Tables 2, 3 and 4). The fisheries were normally undertaken in August and September, and day-of-the-year varied from day 197 to 259 with the average of day 224.14 ± 0.19. Over the sampling period, number of gillnet sets for CPUE samples varied from 217 in July (9.37%), 2,059 in August (88.90%), and 40 in September (1.73%). Despite the majority of CPUE samples being taken in August, there were four years when sampling started earlier (mid-July) (1998, 1999, 2009, and 2011) (Table 2). Alternatively, in 2007, the CPUE samples were collected late in the summer, from August 18 to September 16.

Mesh size of gillnets varied from 114 mm to 152 mm with the average (± 1 SD) of 124.4 ± 0.2 mm (Table 3). Most (>98%) of the mesh sizes were either 114 mm, 127 mm, 133 mm, or 140 mm. The net length ranged from 18.29 m to 45.72 m with a mean (± 1 SD) of 43.8 ± 0.1 m. Among these, more than 90% of CPUE records were from nets 45.7 m long (Table 3). Fishing duration ranged from 0.15 h to 26 h with an average (± 1 SD) of 12.2 ± 0.1 h (Table 4) with 74% of the sets having soak time of 12 hours. Catches ranged from 0 to 96 individuals with a mean (± 1 SD) of 5 ± 0.2 fish. Zero catch occurred in 525 or 23% of the net sets. They were either a ‘true zero’ where fish were not caught because they were absent from the survey area due to unsuitable habitats, severe weather conditions, and mis-matched migration runs or they were a ‘false zero’ where they were present but not detected due to improper deployment of gear (Martin et al. 2005).

Between 1997 and 2013, a total of 2,289 effective gill net sets were included for CPUE standardization. Pair-wise correlation showed that the un-standardized log-transformed CPUE was positively related to year (r = 0.05, p < 0.05), net length (r = 0.13, p < 0.0001), and fishing duration (r = 0.13, p < 0.0001), yet was negative with mesh size (r = -0.16, p < 0.0001) (Figure 9). There was no significant correlation between the observed CPUE and day-of-the-year (r=-0.01, p > 0.05), but correlation between year and day-of-the-year was significant (r = 0.13, p < 0.0001), indicating the catch rate varied by day-of-the-year. These pair-wise correlations suggested that the observed CPUE of char was significantly reduced as mesh size increased, and that the soak time increased over the duration of the fishing season.

Multiple comparisons using the Scheffe test indicated catch rate is significantly different from zero ($\chi^2_{16} = 101.65$, p<0.0001, Figure 10) and significant different by week ($\chi^2_{8} = 27.43$, p<0.001). Lower catch rates were evident in weeks 3 and 7, mixed with a broad range of outliers and relatively small interquartile ranges in weeks 5 and 6 (Figure 10). Combined with one-way ANOVA and multiple comparisons, we can infer that the catch of anadromous Arctic Char were largely dependent on seasonal migrations and fishing behaviours. Among the multiple variables, year and weeks were included as determinants affecting the seasonal migration of the fish. Fishing behaviours, in this study, are mainly account for mesh size and fishing duration, which were identified as factors affecting the observed CPUE. ANOVA showed log-transformed CPUE varied significantly with mesh sizes ($F_{4,2288}$ = 15.62, p<0.0001). Bonferroni multiple comparison showed that log-transformed CPUE from two common mesh sizes (114 mm and 127 mm), made up 79% of sets in the HCMP, was significantly different from other mesh sizes (p < 0.05). One-way ANOVA revealed that soak hours, ranging from less one hour to 26 hours, significantly influenced the observed CPUE ($\chi^2_{18} = 32.69$, p < 0.05). CPUE versus soak hours was not a linear relationship (Figure 10). CPUE increased between soak hours 1-10 and following which it varied without trend. The highest catch rates were observed in gillnets with the longest soaking hours (26 hours) which was significantly different from nets with the shortest soak time (difference = 9.81 fish, $p < 0.05$).

We conducted a two-way ANOVA in connection with 15 combinations of the four fishing-related factors (year, week, mesh size, and soak hour) (Table 14). Because of missing cells, ANOVA with types I and II SS generated similar results, leading to a fact that all fishing-related factors were significantly interacted with log-transformed catch rate ($F > 4.30$, $p < 0.0001$). In addition, three pairs of interactions were identified significant as year and week ($F > 4.50$, $p < 0.0001$), year and mesh size ($F > 2.00$, $p < 0.001$), and week and mesh sizes ($F > 1.90$, $p < 0.01$).

All three GLMs appeared to fit reasonably well which was evident by the significant goodness-of-fit chi-squared tests ($p<0.0001$) (Table 15). The Poisson regression indicated the parameters were over-dispersed (dispersion index = 6.87 >1; $Z = 12.01$, $p < 0.0001$), which significantly violated the distribution assumptions. The quasi-Poisson and negative binomial models provided similar results for regression coefficients and robust standard errors (Table 15). Of three zero-augmented models (hurdle, ZIP, and ZINB), both non-zero and zero catches were fit separately and the medians of deviance residuals (-0.33 for hurdle, -0.55 for ZIP, -0.33 for ZINB) were considerably greater than those in GLMs (e.g., -0.89 for Poisson). Among the six regression models, the model coefficients varied between -1.33 and 1.43 for year 1998 to 2013, and between -0.37 and 0.40 for the variables mesh size, day-of-the-year and soak hour (Figure 11). The significant differences in model intercepts ranged between -5.15 in the negative binomial model and -2.38 in ZIP. Similarly, standard errors for model intercepts were all >1.0, compared with the values <0.3 for the remaining model variables.

The bias-corrected values of the AICc showed the relative goodness of fit of the candidate models to the observed catch rates (Table 15). The greatest value of AICc was 19,058, indicative that the Poisson model produced the most biased fit to the observed CPUE values. The model with the next highest AIC value was the ZIP (AICc = 16306), followed by the NB, ZINB and hurdle (AICc values 12033, 11984, and 11922), respectively. The hurdle model was identified as the best fitting model with a total of 47 model parameters. Comparing Compared with the hurdle model, the Poisson, negative binomial, ZIP, and ZINB models had virtually no support for the alternatives given the same set of data due to the AICc differences >50 (Table 15). As a result of AIC weight (w_i), it is reasonable to select the unique hurdle model for CPUE standardization of Arctic Char inform the Hornaday River.

When applying the hurdle regression model to standardize CPUE, the time series of estimated CPUE exhibited periods of relatively low (1997-2007) and high (2008-2013) catch rates (Figure 12). Between 2008 and 2013, the average standardized CPUE was 7.53 ± 1.77 individual per gillnet and 18.63 ± 4.39 kg per gillnet, which were 31% (individual-based) and 30% (weigh-based) greater than those between 1997 and 2008 (5.74 ± 0.84 individual per gillnet and 14.34 ± 2.11 kg per gillnet). Despite similar patterns of the standardized CPUE for two different mesh sizes, 114mm versus 127 mm, the average CPUE with the 114 mm mesh (6.85 ± 0.9 individuals per set) was significantly greater than that with the 127 mm mesh (6.16 ± 0.82 individuals per set) ($t = 4.11$, $p < 0.001$; Figure 13a). As a result, we arbitrarily selected 114 mm as a standard mesh size to compute the CPUE values. Although there was a 1% to 60% range in differences in the CPUE values, (e.g., 60% in 2003 and 40% in 2005), there were no statistically significant differences between the best-fitting and nominal CPUE ($t = 0.02$, $p = 0.90 > 0.10$, Figure 13b). The average CPUE for the negative binomial model was about 17% greater while those of the Poisson model were about 10% less than the best-fitting hurdle model in 2000 (Figure 13c). In the same year, the estimated CPUEs from ZINB were 6% greater while the ZIP values were 11% less than the values from hurdle model (Figure 13d). In 2011, the estimated CPUEs from

Poisson and NB were 11% and 13% greater, respectively and those for ZIP and ZINB models were 4% and 6% greater, respectively than the values of hurdle model (Figure 13c-d). Overall, the standardized CPUEs by the best-fitting hurdle model were not significantly different from the Poisson (t = -0.76, p > 0.10), ZIP (t = -0.57, p > 0.10), and ZINB (t = 0.95, p > 0.10), but significantly different from negative binomial estimates (t= -6.57, p < 0.0001).

DEPLETION-BASED STOCK REDUCTION ANALYSIS (DB-SRA)

Of the 10,000 runs, more than 95% of the abundance and 89% of the biomass estimates were considered to be good estimates. DB-SRA abundance and biomass trajectories demonstrated that Arctic Char from the Hornaday River experienced a 58% reduction between 1968 and 1985 and subsequently remained relatively stable (Figure 14). Since 2007, the population size appeared to increase 12% in abundance and 11% in biomass. Combined with Monte Carlo simulations (Figure 15), the abundance dynamics of the char can be characterized by:

a. M follows a normal distribution with arithmetic mean of 0.29 ± 0.0006 per year,

b. a ratio F_{MSY} to M, assuming normal distribution with a model mean of 0.8 ± 0.0016,

c. a ratio N_{MSY} to K that is normally distributed with a model mean of 0.4 ± 0.0005, and

d. parameter delta (Δ) skewed by a lognormal distribution with a median of 0.59 ± 0.0009.

Similarly, the biomass-oriented DB-SRA model parameters (Figure 16) were comparable to the abundance estimates above, parameterized by:

a. a normal distribution for M with a mean of 0.29 ± 0.0006 per year,

b. a ratio of F_{MSY} to M with a normally distributed mean of 0.81 ± 0.0017,

c. a ratio of B_{MSY} to K with a normally distributed mean of 0.4 ± 0.0005, and

d. parameter delta (Δ) by a skewed lognormal distribution with a mean of 0.58 ± 0.0009.

The management reference parameters for the population estimated by DB-SRA demonstrated that the mean values, except DCAC and delta, were greater than median values indicating an asymmetric or positively skewed distribution (Table 16). Conversely, the model parameters DCAC and delta exhibited a mean value that was smaller than the median. Associated with DB-SRA model outputs, the median and standard error values of virgin abundance and biomass were estimated to be 31,302 ± 73 individuals and 68,440 ± 163 kg, respectively. The fishing mortality at MSY, F_{MSY}, was comparable for both abundance (0.22 ± 0.0007 per year) and biomass (0.23 ± 0.0007 per year), which were both smaller than estimates of natural mortality (0.29 ± 0.0006 per year for abundance and 0.29 ± 0.0006 per year for biomass). At MSY, abundance and biomass were estimated to be 12,660 ± 29 individuals and 27,259 ± 64 kg, respectively. The estimate for natural mortality at the optimal exploitation rates (U_{MSY}) was 0.17 ± 0.004 and 0.18 ± 0.0004 per year for abundance and biomass, respectively. The MSY for the char from the Hornaday was estimated to be 2,189 ± 4 individuals and 4,814 ± 10 kg (Figure 17). Combined with the estimated critical values, N/N_{MSY}, B/B_{MSY}, and F/F_{MSY}, two events of overfishing were identified between 1978 and 1995 when F/F_{MSY}>1 and B/B_{MSY}<1 (Figure 18). Overfishing occurred between 1986, and 1995 when B/B_{MSY}<1. Since 2000, B/B_{MSY}>1 and F/FMSY<1, it suggests that the stock has been in a healthy status since (Figure 18).

The overfishing limit (OFL, NMFS 2009), a level of harvest that if exceeded would constitute overfishing, was a threshold of abundance or biomass where the population status was considered to be in an unstable or declining state. Incorporated with the DFO precautionary approach guidelines (DFO 2006), biological reference points for management were formulated (MSY and OFL) (Figure 19). Temporal changes in OFL indicated that fisheries were sustainable since 2005. To maintain the sustainability of the population, we suggest that fisheries management targets should be below MSY (2,189 individuals and 4,814 kg) based on DB-SRA simulations.

SURPLUS PRODUCTION MODEL (SPM)

Given pairs of standardized CPUE and harvest statistics over 1997-2013, the kernel parameters of SPM (K, r, q, σ^2 and τ^2), as well as biological reference parameters for fisheries management (MSY, B_{MSP} and F_{MSP}) were summarized in Table 17. Compared to the CPUE series using two gill net mesh sizes, estimates of K, B_{MSY}, and MSY were higher for the smaller sized mesh (114 mm). The average differences among the estimated parameters were minimal (1.59% in abundance and 1.01% in biomass), suggesting that the effects of gear-specific CPUEs on SPM model parameter estimates can be ignored.

The decline of char population production can be seen from 1975 to 1995, likely due to increasing fishing activity (Figure 20). A recovery of the population was accompanied by subsequent reduction of subsistence harvests. Since 1997, it is estimated that the harvest was maintained at a historically low level while the abundance and biomass of the fish improved steadily. Model parameter sets, $\Phi\{K, r, q, \sigma, \text{and } \tau\}$, were described using log-normal distribution functions (Figure 21 and 22), demonstrating the normal distributions for most abundance-based model parameters and skewed log-normal distributions for most biomass-based model parameters. A critical level $p<0.05$, both pairs of correlations were significantly negatively correlated: K and r (correlation coefficient ρ = -0.74 for abundance and ρ = -0.94 for biomass), and K and q (ρ = -0.82 for abundance and ρ = -0.88 for biomass). Correlations between r and q were positive, although a significant test statistic was found in the SPM model (ρ = 0.86, Figure 22).

Probability distributions of biological reference points for management parameters, F_{MSY}, B_{MSY} and MSY, were interpreted using isograms and bivariate correlations (Figure 23). The values of F_{MSY} were significantly negatively correlated to B_{MSY} of abundance (ρ = -0.74) and biomass (ρ = -0.94). Because a low F_{MSY} resulted in a higher B_{MSY}, given definite MSY, the surplus production model produced values of MSY that were 2,797 ± 3 individuals and 6,104 ± 3 kg. Associated with the estimated natural mortality (M = 0.29 per year), the optimal exploitation rates (U_{MSY}) were estimated to 0.11 ± 0.0002 per year and 0.134 ± 0.0002 per year for abundance and biomass, respectively.

The ratios of F/F_{MSY}, N/N_{MSY}, and B/B_{MSY} were used as biological references. Based on abundance overfishing occurred between 1977 and 1995, when $N/N_{MSY} < 1$ and $F/F_{MSY} > 1$ (Figure 24). Since 1996, the population has been in a healthy state with no indication of overfishing ($N/N_{MSY} > 1$ and $F/F_{MSY}<1$). In regard to trends in biomass, the population from the Hornaday River appears to have been overfished between 1979 and 2006. Beginning in 2006, the fishing pressure was $F/F_{MSY}<1$, suggesting population status was improving. Currently, population status is healthy, characterized by higher abundance and lower fishing mortality (Figure 25).

STATISTICAL CATCH-AT-AGE MODEL (SCA)

The error analyses of a set of 114 SCA model parameters indicated that the model process uncertainty (σ^2 = 0.33) was slightly less than that of observation uncertainty (τ^2 = 0.39). Residual components were minimized of a set of objective log-likelihood functions, which accounted for uncertainties from data inputs, prior distributions for model parameters, and penalty functions. This resulted in a value of 315.61 of overall objective function. Of the negative log-likelihood residuals, harvest and survey-based age composition showed significant residuals (-169.56 and

-158.47) while positive residuals were observed for relative abundance index (23.23) and catch-at-age composition (13.87). Standard error from age composition was $r^2 = 0.43$, suggesting considerable uncertainty of alternative interpretation of the population projection if survey-based proportion-at-age was available alone. In addition to the uncertainty from age composition matrix, the harvest statistics has proven to be another error source impacting the SCA model outcomes as assumed that all harvest reports are accurately.

Three log-transformed residuals were addressed to account for the differences between observed and predicted quantities of model components:

1. relative abundance (CPUE) (Figure 26), and;
2. proportion-at-age (Figure 27 and 28), and harvest (Figure 29).

The mean residual ($\omega = 3.85 \times 10^{-7}$) for CPUE estimates had a strong correspondence with abundance indices, showing large residuals between 1999 and 2007 (Figure 26). Negative residuals between 1983 and 1994 corresponded to the decline in abundance, while positive residuals, from 1995 through 2000 and 2011-2013, corresponded to the recovery of the abundance index. The observed and predicted proportion-at-age series were seen in Figure 27, and residuals were compared in Figure 28. In general, there was good agreement between the observed and predicted proportion-at-age data for char from the Hornaday River, characterized by more age classes and less residuals in ages 7 to 9 years if sample size was >250. In contrast, fewer age classes and evident residuals in modal age classes 7-9 were observed in 2006, 2007 and 2009 when otolith sample size were <55 (Figure 27). Residuals between observed and predicted subsistence harvest were minimal, particularly before 1984 which had an arithmetic mean of 1.58×10^{-5} (Figure 29). Since 1985, major outliers were identified by a positive residual period between 1976 and 1996, and a negative residual period between 1997 and 2006.

Temporal variations in the population abundance and biomass resulted in a profound change since 1995 (Figure 30). Over the examined time period, young-of-the-year (YOY) recruits estimated by SCA model accounted for as much as 42% of the total abundance while the proportions of the SSB averaged 7% of the total biomass. Periodically, absolute YOY recruits were less than 35,000 (40% of the total abundance) until 1995 at which the recruits attained 38,000 individuals (43% of the total abundance). Two periods of strong recruitment were observed in 1995-1996 and 2003-2006 where as many as 50,000 juveniles were estimated which accounted for >46% of total abundance (Figure 30). The SSB consistently remained below 4 tonnes (6% of total biomass) from 1978 to 2011. No significant correlation was observed between SSB and YOY recruitment ($r < 0.01$, $p > 0.05$) (Figure 31). Because of the significantly negative relationship ($r^2 = 0.31$, $p < 0.001$) between abundance of YOY and age 5 (Figure 31), it appeared to violate the assumption of a Beverton-Holt type of covariate relationship between SSB and recruit.

In applying random walk models, two model parameters, natural (M) and fishing mortalities (F), were interpolated to determine the effects of fish mortality on inter-age cohort strengths and inter-annual fishing intensity. For Arctic Char in the Hornaday River, an initial value of M was estimated at 0.29 ± 0.067 per year (Table 12) while time-varying M ranged between 0.31 and 0.43, averaging 0.34 ± 0.007 per year (Figure 32). Over time, M was less than 0.35 until 1991 and increased steadily between 1992 and 2003. Changes in F were less than 0.5 during 1968 - 1975 and 1999 - 2013 yet were greater in 1976 - 1995 when harvest levels were higher. Age-specific F varied significantly with year ($F_{45} = 5.49$, $p < 0.0001$) and age ($F_8 = 9.21$, $p < 0.0001$) for fish > 6 years (Figure 33). For fish < 6 years, no significant difference in F was detected because very of these were captured given the selectivity of gillnet.

Probability distributions for various SCA model structural parameters (constructed by using Metropolis-Hasting algorithm in ADMB), including YOY un-fished recruitment (r_0), average recruitment (r_{bar}), initial values of recruitment (r_{ini}), stock-recruitment relationship parameter (h), ratio of process to total error (ρ), and recruitment compensation ($\boldsymbol{K}$) were summarized in Figure 34. Of the seven model parameters, the standard normal distribution was the most appropriate to describe the probability density of most parameters, except the right skewed (negative distribution) in r_0 and left skewed (positive distribution) for h. At critical level α = 0.05, r_o was significantly negatively related to h, yet positive to the average $^{\gamma}$ ($\bar{\gamma}$), suggesting that the un-fished YOY recruitment can be a strong determinant of the abundance of subsequent pre-mature fish stock. A positive correlation between rho and kappa was also observed reiterating how the model structures can greatly impact the estimations of the recruitment compensation for this species.

Associated with recruitment and spawning relationship (Figure 35), the unfished and fishable spawning was estimated to be 19,922 ± 27 individuals and 7,121 ± 15 kg. MSY of SSB was estimated to be 5,586 ± 6 kg, corresponding to 24,857 ± 39 kg and 0.2217 ± 0.0003 per year for B_{MSY} and F_{MSY}, respectively. Combined with SCA model estimates of natural mortality (average M of 0.2918 ± 0.0001 per year) and F_{MSY}, the optimal exploitation rate (U_{MSY}) at MSY was 0.17 ± 0.0002 per year. Under the same fishing conditions, individual-based MSY and N_{MSY} were estimated to 2,372 ± 5 fish and 10,701 ± 25 fish. Pair-wise correlation between B_0 and B_{MSY} (r = 0.81) and MSY (r = 0.62) were significant, while B_{MSY} was significantly negative to F_{MSY} (r = -0.82). These correlations exhibited that greater total biomass of the stock led to more abundant spawning and lower fishing intensity, given a set of population dynamics parameters.

To evaluate the sustainability of the char population, we examined the ratio of the current adult biomass relative to the adult biomass that would provide the maximum sustainable yield (B_t/B_{MSY}), and the fishing status, the ratio of current fishing mortality relative to the fishing mortality rate that maintains MSY (F/F_{MSY}), over time. Two-dimensional plots were generated in connection with baseline $B_t/B_{MSY} = 1$ and $F_t/F_{MSY} = 1$ (Figure 36) which illustrated that over the time-series, Arctic Char from the Hornaday River were not to be overfished ($B > B_{MSY}$), yet had experienced overfishing ($F > F_{MSY}$) between 1976 and 1998. In regard to spawning biomass, the dynamic changes in SSB relative to SSB_{MSY} showed that the population was overfished ($SSB_t < SSB_{MSY}$) in combination with a fishing mortality that exceeded healthy levels ($SSB_t < SB_{MSY}$ or $F_t > F_{MSY}$) between 1978 and 1986, and 1994 and 1999. Although the current stock and fishing statuses indicate that the population has been in a healthy state since 2007, the majority of Arctic Char have been fully exploited because their assigned exploitation status was around MSY levels. The lower spawning biomass, significantly below the baseline from 1978 to 2009, suggests undergoing state of possible recruitment-overfishing if the overfished spawner biomass status was unchanged. Currently, total population biomass is located in the healthy zone while SSB came across the cautious-healthy area (Figure 37).

TRADE-OFFS OF USING MULTIPLE ASSESSMENTS MODELS AND RECOMMENDATION

We used fisheries data from multiple sources to construct three commonly-used stock assessment models (DB-SRA, SPM, and SCA) to create a set of biological reference points to evaluate the sustainability of Arctic Char in the Hornaday River. The results suggest DB-SRA can more accurately estimate population dynamic parameters, given the existence of harvest information available in the data-poor situation. SPM uses biomass dynamics to fit the time series of CPUE and harvest information assuming the threshold of controllable fishing mortality is less than natural mortality (Hilborn and Walters 1992). Because of its simplicity and less-intensive data requirements, SPM has been generally used to formulate similar sets of model and management parameters to the DB-SRA. SCA is one of the most complicated models with intensive data requirements. Comparisons among model outputs (Table 18) reveal that the estimates of N_{MSY}, B_{MSY}, and MSY were highest and F_{MSY} and U_{MSY} were the lowest in SPM. Alternatively, the SCA model produced the lowest estimates of N_{MSY} and B_{MSY}, but the intermediate estimates of MSY, F_{MSY} and U_{MSY}. Additionally, SCA yielded the lowest MSY and greatest F_{MSY} and U_{MSY}, compared to the other models. Weighting by inverse variance (WIV) was used to determine the average effect sizes for each MSY parameter among the assessment models. The median (± 1 SD) MSY, on the basis of abundance, was 2496±154 individuals, corresponding to 0.18 ± 0.01 per year and 0.15 ± 0.0093 per year for F_{MSY} and U_{MSY}, respectively. For fish biomass, the median (± 1 SD) MSY was 5,724 ± 187 kg, yielding an estimate of F_{MSY} and U_{MSY} equal to 0.1949 ± 0.0133 per year and 0.1553 ± 0.0094 per year, respectively. We recommended that the sustainable harvest levels for Arctic Char in the Hornaday River should be controlled within these management targets.

In order to bring forward the recommended reference targets for the co-management of Arctic Char from the Hornaday River, several concerns in regards to the model outputs should be taken into consideration. First, differences in model assumptions need to be understood. The SCA model has been valued for its complicated structures and detailed year-age interaction. When constructing this SCA model, the model assumptions, included:

1. constant growth and natural morality over age classes;
2. constant logistic function for gear selectivity;
3. a Beverton-Holt model for stock-recruitment relationship, and;
4. known harvest reports without error.

All these assumptions are problematic, such as time-varying growth, mortality, and gear-specific selectivity, as well as density-dependent or independent stock-recruitment relationships (Szalai et al. 2003, Linton and Bence 2011). In addition to these model assumptions, the estimates of fish abundance, biomass, and management reference parameters from SPM were considerably higher compared with the estimates generated by DB-SRA and SCA (Table 18). To account for this level of variation, the WIV was used to integrate multiple model estimates, recommended long-term targets to sustain population production, as the number (± 1 SD) of 2,496 ± 154 and weight (± 1 SD) of 5,724 ± 187 kg for Arctic Char in the Hornaday River.

Second, the accuracy and precision of biological reference points require high quality data of fish biological characteristics, fishery-dependent or -independent CPUE, and harvest statistics. Our analyses indicated that the uncertainties were influential, largely a result of small sample sizes for biological information such as length/weight measurements (Figure 27), ages, and growth (Figure 4-5), variation in fishery-dependent CPUE (Table 2-4, Figure 12, 20, 26), and likely error in harvest statistics (Figure 2, 29). The DB-SRA merged the stochastic stock reduction analysis with depletion-corrected average catch using historical harvest information and estimates of M and maturity-at-age. As mentioned by Dick and MacCall (2011), a number of difficulties arise when comparing DB-SRA outputs with those from other sets of quantitative models. One of the difficulties is the inability to reproduce quantities that were described in data-rich assessments by a simple delay-difference model. Alternatively, estimates of biological reference points such as MSY, B_{MSY} and F_{MSY}, are of high importance to managers, yet the related uncertainties about stock status and the appropriate management approach were inherited from available data inputs and model parameter specification. Evaluated from a set of data-poor or data-limited and data-rich stock assessment models, Wetzel and Punt (2011) commented on the model performance of DB-SRA, particularly robust to the specification of the probability distributions of natural mortality and productivity parameters. Incorporated with some degree of imprecision in parameter estimates, DB-SRA is still well suited to analysis of so-called "one-way trip" which is monotonic declines in abundance (Dick and MacCall 2011). Of our three models, stock status was assessed the most optimistically by SCA as $B/B_{MSY}>2$ (Figure 36) while the most sensitive to fishing pressure was SPM (Figure 24). The char fishery has been assessed as mainly stable by DB-SRA (Figure 18). Through comparisons noted above, we suggest that model specification largely impact the model performance. Our second consideration relating to model performance is the issue of data quality. With regard to overdispersion of variance in age composition and CPUE, effective sample size (ESS, Hulson et al. 2012) should be taken into consideration. In terms of stratified sampling design and biological measurements for char during 1973-2013 (n = 13141), ESS suggests a minimum 358 char be sampled per year, with a size range of 120-835 mm and a criterion of 10 fish per 2 cm length interval (Brouwer and Griffiths 2005). As for CPUE data, several critical variables should be considered, including sampling months when fish stay for feeding (August), mesh sizes (113 mm and 127 mm), mesh length (50 yards), and fishing duration (12 hours). These variables were statistically significant influence of the accuracy and representative of CPUE for the fish (Table 14). There are no studies on multivariate effects of sampling date, mesh size, fishing duration and ESS on the accuracy of CPUE data. To accommodate these unknown processes and possible model misspecification, future research will be required to find the best solution in improving CPUE accuracy either through field experiments or model-based simulation.

Finally, there are a set of bio-physical mechanisms governing the hydroclimate changes and fisheries production dynamics, which are needed to well understand the importance of niche use and resource partitioning (Amundsen et al. 2010, Spares et al. 2012), seasonal migration and climate change (Reist et al 2006), and temporal dynamics of anadromous salmonids in the Arctic (Tallman et a. 2013, Zhu et al. 2014). For anadromous Arctic Char, the importance of recruitment has been recognized, but information on abundance and spatial distribution by YOY char is not available till now. Despite lack of observation, our SCA model results exhibited significant differences in cohort strengths in abundance and biomass trends, accounting for the temporal variations in YOY recruits and spawning biomass. It is rather promising to notice these differences will likely influence the population projections and age-class strengths when assessing the fish population dynamics. Conventionally, constant recruitment and stable spawner-recruit relationships were assumed for the purpose of simplicity. However, this has been challenged recently by advocating the time-varying recruitment patterns derived from inter-annual fluctuations on population density, recruitment, prey resources and temperature (ACIA 2004, Lorenzen 2000, Rikardsen et al. 2000). Because of the time constraints for sample collections from the community-based monitoring program, the need for information pertaining to recruitment and spawning for Arctic Char from the Hornaday River remain.

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APPENDIX 1. TABLES

Table 1. Annual harvest for Arctic Char in the Hornaday River, incorporated from multiple information sources. Missing harvest weight was estimated by applying a factor of assumptive 2.3 kg per fish to individuals caught.

Year	Commercial		Subsistence		Sport		Total	
	individual	kg	individual	kg	individual	kg	individual	kg
1968	500	1150	1000	2300			1500	3450
1969	800	1840	1000	2300			1800	4140
1970	750	1725	1000	2300			1750	4025
1971	750	1725	1000	2300			1750	4025
1972	750	1725	1000	2300	100	230	1850	4255
1973	1151	2854	1200	2975	100	248	2451	6077
1974	229	495	1250	2702	100	216	1579	3413
1975	1500	3450	1250	2875	100	230	2850	6555
1976	3376	7765	1250	2875	100	230	4726	10870
1977	2757	6341	1250	2875	200	460	4207	9676
1978	2619	6024	1676	3856	40	92	4335	9972
1979	2954	5119	1676	2905	10	17	4640	8041
1980	2794	6426	1676	3855	10	23	4480	10304
1981	972	1583	1676	2730			2648	4313
1982	3780	8694	1676	3855			5456	12549
1983	1700	3909	1676	3854			3376	7763
1984	2650	6095	1676	3855			4326	9950
1985	1380	3179	1676	3855			3056	7034
1986	1201	2762	1676	2154			2877	4916
1987			2392	3512	10	15	2402	3527
1988			2829	8148	10	29	2839	8176
1989			2880	7042	10	24	2890	7066
1990			2369	5204	10	22	2379	5226
1991			2424	4988	10	21	2434	5009
1992			2408	5482	10	23	2418	5504
1993			1839	4611	10	25	1849	4637
1994			2290	5625	10	25	2300	5650
1995			3850	9192	10	24	3860	9216
1996			1984	4538			1984	4538
1997			1956	3856			1956	3856
1998			1686	4079			1686	4079
1999			1636	4354			1636	4354
2000			1492	3685			1492	3685
2001			1949	5121			1949	5121
2002			1589	3743			1589	3743
2003			1522	3809			1522	3809
2004			1597	4336			1597	4336
2005			665	1696			665	1696
2006			1300	3746			1300	3746
2007			724	1426			724	1426
2008			479	1030			479	1030
2009			1793	3699			1793	3699
2010			1175	3162			1175	3162
2011			1119	3392			1119	3392
2012			1513	3904			1513	3904
2013			1570	3875			1570	3875

Table 2. Summary of gillnet sets used for quantitatively accounting catch rates of Arctic Char in the Hornaday River over day-of-the-year, week and years 1997-2013.

Day-of-the-year	Week	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Sum
197	1															4			4
198																5			5
199																5			5
200			4													7			11
201			4													3			7
202			4																4
203			6													4			10
204	2		6													5			11
205			8													16			24
206			5																5
207			5																5
208			19																19
209			17													1			18
210			19	4										1		2			26
211	3		21	5										1		2			29
212			18	8	2				1					1	2	3			35
213			18	11										3	6	6			44
214		7	22	17					1					4	5	6			62
215		13	18	14		1								4	6	5			61
216		17	14	12	1	6	2	14						5	7	4			82
217		21	10	15	2	14	4	14		1	4			8	8			1	102
218	4	20	2	9	1	10	6	11	1	1	7			2	8	2	1	1	82
219		16		9	2	9	6		8	2	9				12	8	1	2	84
220		14		10	1	11	9		12	3	10		2	3	7	7		2	91
221		14		6	6	14	9		4	2	4		2	6	6			2	75
222		25		3	3	15	10	5	16	2			3	6	3	3		2	96
223		26			3	18	9	5	5	2			2	6	7	3	1	7	94
224		24			2	12	11	15	12	3	4		3	5	4	5	2	5	107
225	5	27				9	11	11	16	1	2		2	1	8	5	1	5	99
226		17			1	12	12	14		2	3		2		14	8		4	89
227		11			2	13	10	10	7	3	7		2		15	4	1	2	87
228		18			2	7	6	7	6	7	7			1	15			1	77
229		12			5	5	2	11	10	7	5			2	14		1		74
230		5			7	7	1	7	11	6	9	2			12		1	4	72
231		17			6	10	2		20	7	8	2	1		8			1	82
232	6	9			6	9	7		25	6	8	2	1		4		2		79
233		12			8	9	8		20	14	8	2	1		6				88
234		13			5	5	5		24	8	4	1	2		6				73
235		7			6	3	1		14	12	2	4			3		3		55
236		8			5	1	1		12	5	2	4	1				2	1	42
237		10			7	1	1		17	6		3	2				2	6	55
238		12			5				8	3		3					2	3	36
239	7	13			4					1		2					2		22
240		12			3					2		4							21

Day-of-the-year	Week	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Sum
241		1								3		4							8
242										2		7							9
243										2		8							10
244												8							8
245												8							8
246	8											6							6
247												2							2
248												2							2
249												2							2
205																			
251												2							2
252												3							3
253	9											3							3
254												1							1
255												1							1
256																			
257																			
258												1							1
259												1							1
Sum	9	401	220	123	95	201	133	124	250	113	103	88	26	59	186	123	22	49	2316

Table 3. Summary of mesh size (mm) and net length (m) of gillnets used for quantitatively accounting catch rates of Arctic Char in the Hornaday River during 1997–2013. NA means no available information.

Year	Mesh size (mm)						Net length (m)							Sum
	114	127	133	140	152	NA	18.3	22.9	27.4	32	36.6	45.7	NA	
1997	161	188		52				25	15			361		401
1998	57	87		75		1	4		23	15		178		220
1999	47	15		61			1	13				109		123
2000	75	20										95		95
2001	146	55							45			156		201
2002	46	52	21	14								133		133
2003	24	64	15	21								124		124
2004	56	94		97		3			5			242	3	250
2005	49	52	6			6						107	6	113
2006	33	30	22	2	16			2	2		2	97		103
2007	57	9	17		5			14				74		88
2008	22	4										26		26
2009	32	24		3							8	51		59
2010	46	96		37	7							186		186
2011	40	61		22			17	24			10	72		123
2012	15	7										22		22
2013	40	9						3				46		49
Sum	946	867	81	384	28	10	22	81	90	15	20	2079	9	2316

Table 4. Summary of fishing duration (hours) of gillnet sets used for quantitative monitoring harvest rates of Arctic Char in the Hornaday River during 1997-2013. NA means no information is available.

Hour	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
0.15		1																1
0.30		1																1
1.00	1														1			2
1.50													1					1
2.00	1	2					2	1										6
2.50															3			3
3.00					2			4						2				8
4.00			3		6			2							1	1	1	14
5.00			1		5					3			1	1	2			13
5.50					3													3
6.00	13	4	4	1	1	18	4	1	2	2			1	5		2		58
7.00					2		1	1						1	2			7
7.50															3			3
8.00	2		1	1	11		6	3	17	1			2	10	17	1	2	74
9.00	3				7					2					20			32
10.0	10		4	2	18	10	9	8		13			3	12	24	4		117
11.0					6					2				6				14
11.5					1													1
12.0	341	197	107	24	137	105	102	219	86	80	32	26	48	126	33	11	46	1720
13.0					1									5				6
14.0	1	5			1								2	12	6	3		30
16.0	12		2											3	5			22
17.0	3													1				4
18.0	14	1																15
24.0		4	1	67							56		1					129
26.0		5																5
NA								11	8					2	6			27
Total	401	220	123	95	201	133	124	250	113	103	88	26	59	186	123	22	49	2316

Table 5. Summary of mathematical models used for CPUE standardization, including generalized linear mdoels (GLM) of Poisson, Quasi-Poisson, and negative binomial regressions, as well as zero-augment models (ZAM) of hurdle, zero-inflated Poisson (ZIP) and zero-inflated negative binomial models (ZINB). Observed CPUE was the number of Arctic Char captured by a standard length of 45.72 m (50 yard) gillnet set. The covariates for CPUE standardization included year, julian week, mesh size (mm), and fishing duration (hour). The model parameters p, μ, θ were probability, mean CPUE, and shape parameter. Model coefficients β_0 and γ_0 were random intercepts, and ***β*** *and* ***γ*** *were vectors of random effects. Variables* ***x*** *were vector covariates of interests.*

Generalized linear model (GLM)

Parameter	**Equation**
Poisson	$P(y;\mu) = \dfrac{\mu^{y} e^{-\mu}}{y!}$
Negative binomial or Quasi-Poisson	$P(y;\mu,\theta) = \dfrac{\Gamma(y\ X\ \theta)}{\Gamma(\theta)\ X\ y!}\ X\ \dfrac{\mu^{y}\theta^{\theta}}{(\mu+\theta)^{y+\theta}}$ $u_i = \exp(\beta_0 + \beta_1 x_{1,x} + \ldots \beta_p x_{p,i)}$

Zero-augment model (ZAM)

Parameter	**Equation**
Hurdel	$P(y_i = 0) = 1 - P_i$ $P(y_i = k) = P_i \dfrac{\mu^{k} e^{-\mu}}{k!\,(1 - e^{-\mu})}$
Zero-inflated Poisson (ZIP)	$P(y_i = 0) = (1 - p_i) + p_i e^{-\mu})$ $P(y_i = k) = p_i \dfrac{\mu^{k} e^{-\mu}}{k!}$
Zero-inflated negative binomial (ZINB)	$P(y_i = 0) = p_i + (1 - p_i) \dfrac{\theta^{\theta}}{(\mu_i + \theta)^{\theta}}$ $P(y_i = k) = (1 - p_i) \dfrac{\Gamma(k+\theta)}{\Gamma(\theta)k!} X\ \dfrac{\mu_i^{k}\theta^{\theta}}{(\mu_i + \theta)^{k+\theta}}$ $\text{logit}(p_i) = \ln\left(\dfrac{p_i}{1 - p_i}\right) = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_n x_{ni}$ $\text{logit}(\mu_i) = y_0 + y_1\, x_{1i} + \cdots + Y_n X_{ni}$ k=1,…,∞, i=1,…,n, 0<μ<∞
Multi-model inference (MMI)	$\Delta_i = AICc - AICc_{min}$ $W_i = \dfrac{e^{-\frac{1}{2}\Delta_i}}{\sum_{i=1} e^{-\frac{1}{2}\Delta_i}}$ $\beta_{ij}^{1} = \beta_{ij}\ w_i$

Table 6. Summary of growth in length-at-age and natural mortality models used for Arctic Char in the Hornaday River. The growth parameters include asymptotic length (L_∞: mm) and weight (W_∞: g), growth rate (K, per year), and age when length=0 (t_0, year). The length-weight relationship is modeled by a power function with regression coefficients a and b. The parameter t_m is maturity-at-age and M_t is age specific natural mortality.

Paramter	Equation	Reference
Growth		Von Bertalanffy (1938)
	$L_t = L_\infty \left[1 - e^{-K(t-t_0)}\right]$	
	$W_t = W_\infty \left[1 - e^{-K(t-t_0)}\right]^b$	
	$W = aL^b$	
Natural mortality	Life history parameter model	
	$M(t) = \begin{Bmatrix} \frac{K}{1 - e^{-K(t-t_0)}}, t \le t_m \\ \frac{K}{a_0 + a_1(t - t_m) + a_2(t - t_m)^2}, t \ge t_m \end{Bmatrix}$	Chen and Watanabe (1989)
	$a_0 = 1 - e^{-K(t_m - t_0)}$	
	$a_1 = Ke^{-K(t_m - t_0)}$	
	$a_2 = 0.5K^2 e^{-K(t_m - t_0)}$	
	$t_m = \frac{1}{K} 1n \left\vert 1 - e^{Kt_0} \right\vert + t_0$	
	Length growth parameter-based model	
	$\text{Ln}(M_t)$=0.55-1.61ln(L_t: cm))+1.44ln(L_∞: cm)+ln(K)	Gislason et al. (2010)
	Weight growth parameter-based model	
	$M_t=1.92(0.2W_t)^{-0.25}$	Peterson and Wroblewski (1984)
	$M_t=1.69W_t^{-0.292}$	Lorenzen (1996, 2000)

Table 7. Depletion-based stock reduction analysis model (DB-SRA) used for estimating stochastic parameters of population dynamics in terms of catch statistics and biological parameters of the Hornaday River Arctic Char. C_t and n are a catch history in year t, and the length of catch history in years. Δ and B_0 are the relative stock status and the virgin biomass. B_{MSY} and F_{MSY} are maximum sustainable biomass at a level of fishing mortality. Parameters M and m are MSY and instantaneous natural mortality, respectively, and u is exploitation rate.

Model	Equation	Reference
Depletion-corrected average catch	$DCAC = \frac{\sum C_t}{n + \frac{\Delta}{\left(\frac{B_{MSY}}{B_0}\right)\left(\frac{F_{MSY}}{M}\right)M}}$	MacCall 2009
Stock reduction analysis	$B_t = B_{t-1} + P(B_{t-a}) - C_{t-1}$ $P(B_{t-a}) = gMSY\left(\frac{B_{t-a}}{K}\right) - gMSY\left(\frac{B_{t-a}}{K}\right)^n$ Here, $g = \frac{n^{n/(n-1)}}{n-1}, n > 0$ $P = B_{t-a}\left(P\left(B_{join}\right)/B_{t-a} + s\left(B_{t-a} - B_{join}\right)\right)$ $s = \left(1 - n\right)gmB_{join}^{n-2}K^{-n}\right)$ $u = \frac{F}{M+F}\left(1 - e^{-(F+M)}\right)$ or $u = 1 - e^{-F}$	Pella and Tomlinson 1969, Fletcher 1978, McAllister et al. 2000, Walters et al. 2006, Worm et al. (2013)

Table 8. Notation of surplus production stock assessment models to integrate time series of fishery-dependent and fisheries-independent population indices versus harvest statistics for Arctic Char in the Hornaday River.

Parameter	Equation
Model parameter	$\Theta=\{K, r, \mathrm{q}, \sigma^2, \tau^2\}$
Surplus production model	$P_t=B_t/K$
	$\frac{dB_t}{dt} = rB_t\left(1-\frac{B_t}{K}\right) - C_t$
	$\widehat{I_t} = q\ x\ B_t$
	$P_{t+1} = P_t + rP_t(1-P_t) = \frac{C_t}{K}$
Derived management quantities	$F_{\mathrm{MSP}}=r/2$
	$B_{\mathrm{MSP}}=K/2$
	$\mathrm{MSP}=(B_{\mathrm{MSP}})\times(F_{\mathrm{MSP}})=r \times K/4$

Model Notation

	Symbol	Description
Indices	T	Time step year t=1,2,…,T
Observations	C_t	Harvest landing in year t
	I_t	Catch per unit effort (CPUE) in year t
Model parameters	B_t	Estimated exploitable biomass in year t
	K	Virgin population size for growth or biological carrying capacity
	r	Intrinsic population growth rate
	E_t	Fishing effort in year t
	q	Gear specific catchability coefficient
	P_t	Depletion rate parameter for B_t/K
	σ	Standard error in processing log-depletion rate
	τ	Standard error in observed biomass indices
Derived parameters	MSP	Maximum sustainable production
	B_{msp}	Biomass at MSP
	F_{msp}	Fishing mortality at which MSP is obtained

Table 9. Notation of the statistical catch-at-age stock assessment model for the Hornaday River Arctic Char.

Indices

Symbol	Description
t	Time step year t=1,2,…,T
a	Age classes in years a={1,2,…,A}

Observed data

Symbol	Description
I_t	Survey abundance index in year t
C_t	Catch in kilogram in year t
$p_{t,a}$	Proportion of catch-at-age a and year t
wla	Length-weight relation parameter
wlb	Length-weight relation parameter
L_∞	Asymptotic length in mm
K	von Bertalanffy growth parameter
t_0	Theoretical age when length approaches zero

Derived parameter

Symbol	Description
l_a	Length-at-age a
w_a	Weight-at-age a
m_a	Maturity-at-age a
M_a	Natural mortality-at-age a
v_a	Age-specific vulnerability
f_a	Mean fecundity-at-age
r_t	Recruitment for each year
ζ_a	Age-specific survivorship
q	Survey catchability per fishing effort
s_a	Selectivity-at-age a
μ_1	Age-at-50% maturity
μ_2	Maturity-at-age function slope
τ_1	Coefficient of variation for survey abundance index
τ_2	Standard error in observed proportion-at-age
σ	Standard error of log-transformed recruitment deviations

State variables

Symbol	Description
$N_{t,a}$	Abundance in age a and year t
$B_{t,a}$	Biomass in age a and year t
$F_{t,a}$	Fishing mortality in age a and year t
$Z_{t,a}$	Total mortality in age a and year t
N_t	Abundance in year t
B_t	Biomass in year t
S_t	Spawning biomass in year t

Table 10. Details of calculations of age-specific abundance, biomass, and fishing mortality values through the maximum likelihood estimation functions.

Parameter	Equation	
Parameters to be estimated at equilibrium state		
$\Theta = (B_0, M_a, \hat{a}, \hat{\gamma}), B_0 > 0, M_a > 0$		
$\theta = (L_\infty, k, t_0, wla, wlb, \dot{a}, \dot{\gamma})$		
Life-history schedule	$L_a = L_\infty\left(1 - e^{-K(a-t_0)}\right)$ $wa = wla \times (L_a)^{wlb}$ $M_a = 1.69 w_a^{-0.292}$ $m_a = \frac{a^{u_1}}{a^{u_1} + u_2^{U_1}}$	$f_a = \frac{w_a}{1 + e^{-\frac{(\dot{a}-a)}{\dot{\gamma}}}}$ $v_a = \frac{1}{1 + e^{\frac{-(\hat{a}-a)}{\sigma_y}}}$
Population dynamics	$N_{1,a} = \bar{R}e^{-\sum_{a=1}^{A-1} Z_{1,a}}, a = 0$ $N_{t+1,a+1} = N_{t,a}e^{-Z_{t,a}}, 1 \le a \le A-1$ $N_{t+1,A} = N_{t,A-1}e^{-Z_{t,A-1}} + N_{t,A}e^{-Z_{y,A}}, a = A$ $C_{t,a} = \left[\frac{F_{t,a}}{Z_{t,a}}(1 - e^{-Z_{t,a}}) \times w_{t,a}\right]$ $P_{t,a} = \frac{C_{t,a}}{\sum_a C_{t,a}}$ $\widehat{C_{t,a}} = \frac{F_{t,a}}{M_{t,a} + F_{t,a}} N_{t,a}\left(1 - e^{-(M_{t,a}+F_{t,a})}\right)$	$B_t = \sum_a N_{t,a}W_{t,a}$ $Z_{t,a} = M_{t,a} + F_{t,a}v_{t,a}$ $F_{t,a} = q_t E_t S_a$ $S_t = \sum_{a=1}^{A} m_a B_t$ $\widehat{F_{t,a}} = \hat{q}E_{t,a}$ $\widehat{I_t} = \hat{q}B_t = \hat{q}\sum_{a=1} w_a S_a N_{t,a}$
Residuals and objective functions	$\eta C_t = \ln(C_t) - \ln(\widehat{C_t})$ $nll_C = \sum\left[T\ln(\sigma_c) + \frac{\Sigma_t(\eta C_t^2)}{2\sigma_c^2}\right]$ $\eta I_t = \ln(I_t) - \ln\left(\widehat{I_t}\right)$ $nll_I = \sum_{t \in I_t} \ln(I_t) + \frac{\eta I_t^2}{2\sigma_t^2}$	$CPUE: v_t = \sum_a N_{t,a}e^{-\lambda_t Z_{t,a}} v_a w_a$ $\sum_{a=1} P_{t,a} = 1$ $\hat{\tau}^2 = \frac{1}{(A-1)T}\sum_{t=1}^{T}\sum_{a=1}^{A} \eta P_{t,a}^2$ $nll = (A-1)T\ln(\hat{\tau}^2)$
	$\eta P_{t,a} = \ln\left(p_{t,a}\right) - \ln(\widehat{p_{t,a}}) - \frac{1}{A}\sum_{a=1}^{A}\left[\left[\ln\left(p_{t,a}\right) - \ln\left(\widehat{p_{t,a}}\right)\right]\right]$	

Table 11. Estimates of length-weight relationships and the VBGM parameters for Arctic Char in the Hornaday River. SE is standard error.

1) Fork length (FK: mm) versus round weight (RW: g)

	Mean	SE	Mean	SE	Mean	SE
FL (mm)	579.93	1.5545	561.10	1.4522	560.84	0.7003
RW (g)	2591.24	19.3123	2255.89	15.4505	2275.54	8.0890
log(a)	-11.3218	0.1034	-11.1305	0.1237	-11.1805	0.0525
b	3.0042	0.0163	2.9701	0.0196	2.9775	0.0083
a	1.21E-05		1.47E-05		1.39E-05	
r^2	0.9204		0.9018		0.9073	
n	2957		2513		13141	

2) Length-at-age growth

	Mean	SE	Mean	SE	Mean	SE
log_L_∞	6.6995	0.0505	6.6177	0.0389	6.6481	0.0456
log_K	-1.7296	0.1296	-1.7012	0.0736	-1.6771	0.0815
t_0	-9.52E-02	1.91E-01	-1.50E-07	1.50E-04	-1.40E-06	1.40E-03
log_σ	-3.6199	0.2236	-3.0468	0.2041	-3.1370	0.2236
L_∞	812.00		748.22		771.32	
K	0.1774		0.1825		0.1869	
σ	0.0268		0.0475		0.0434	

3) Weight-at-age growth

	Mean	SE	Mean	SE	Mean	SE
log_W_∞	8.7549	0.0795	8.5680	0.2175	8.6704	0.1300
log_K	-1.6571	0.0479	-1.7440	0.1351	-1.6798	0.0779
t_0	-1.97E-07	1.96E-04	-1.52E-07	1.52E-04	-1.47E-07	1.47E-04
log_σ	-2.5617	0.2236	-1.3520	0.2041	-2.0860	0.2236
W_∞	6341.69		5260.60		5827.83	
K	0.1907		0.1748		0.1864	
σ	0.0772		0.2587		0.1242	

Table 12. Estimates of natural mortality in terms of either age-specific life history or body mass parameters for the Hornaday River Arctic Char.

Age	Life history model (Chen and Watanabe 1989)			Length-at-age model (Gislason et al. 2010)			Weight-at-age model (Peterson and Wroblewski 1984)			Weight-at-age model (Lorenzen 1996)			Geometric mean		
	Male	Female	All	Male	Female	All	Male	Female	All	Male	Female	All	Male	Female	All
1	1.0046	1.0940	1.0964	2.3750	2.9689	2.7290	1.1984	1.3121	1.2285	0.6091	0.6771	0.6270	1.1488	1.3033	1.2321
2	0.5714	0.5968	0.5993	0.9575	1.1190	1.0319	0.7623	0.8344	0.7835	0.3591	0.3991	0.3708	0.6221	0.6867	0.6510
3	0.4198	0.4328	0.4355	0.5829	0.6672	0.6172	0.6005	0.6558	0.6177	0.2718	0.3012	0.2809	0.4470	0.4887	0.4647
4	0.3435	0.3522	0.3550	0.4220	0.4788	0.4442	0.5156	0.5615	0.5304	0.2275	0.2513	0.2351	0.3611	0.3928	0.3745
5	0.2981	0.3049	0.3078	0.3359	0.3796	0.3530	0.4637	0.5034	0.4769	0.2010	0.2212	0.2076	0.3108	0.3369	0.3221
6	0.2684	0.2742	0.2772	0.2837	0.3200	0.2983	0.4291	0.4644	0.4411	0.1835	0.2013	0.1896	0.2783	0.3009	0.2884
7	0.1799	0.1825	0.1869	0.2493	0.2811	0.2626	0.4047	0.4366	0.4159	0.1714	0.1873	0.1769	0.2362	0.2545	0.2451
8	0.1795	0.1825	0.1869	0.2255	0.2542	0.2380	0.3868	0.4161	0.3973	0.1626	0.1771	0.1677	0.2246	0.2418	0.2333
9	0.1792	0.1825	0.1869	0.2082	0.2348	0.2202	0.3734	0.4006	0.3833	0.1560	0.1694	0.1609	0.2159	0.2322	0.2244
10	0.1790	0.1825	0.1869	0.1953	0.2204	0.2071	0.3630	0.3886	0.3725	0.1510	0.1635	0.1556	0.2092	0.2248	0.2176
11	0.1789	0.1825	0.1869	0.1855	0.2095	0.1971	0.3550	0.3791	0.3641	0.1471	0.1588	0.1515	0.2040	0.2190	0.2123
12	0.1789	0.1825	0.1869	0.1779	0.2011	0.1894	0.3486	0.3715	0.3574	0.1440	0.1551	0.1483	0.1999	0.2144	0.2081
13	0.1789	0.1825	0.1869	0.1719	0.1944	0.1834	0.3436	0.3655	0.3521	0.1416	0.1522	0.1457	0.1967	0.2108	0.2048
14	0.1791	0.1825	0.1869	0.1671	0.1892	0.1787	0.3396	0.3605	0.3478	0.1396	0.1498	0.1436	0.1941	0.2078	0.2021
15	0.1794	0.1825	0.1869	0.1633	0.1850	0.1749	0.3363	0.3565	0.3444	0.1381	0.1478	0.1420	0.1920	0.2054	0.1999
16	0.1798	0.1825	0.1869	0.1602	0.1816	0.1718	0.3337	0.3532	0.3416	0.1368	0.1462	0.1406	0.1904	0.2034	0.1982
Mean	0.2496	0.2560	0.2606	0.2934	0.3347	0.3131	0.4395	0.4728	0.4510	0.1887	0.2055	0.1945	0.2792	0.3021	0.2909
SE	0.0552	0.0605	0.0603	0.1399	0.1753	0.1608	0.0565	0.0627	0.0580	0.0306	0.0344	0.0315	0.0622	0.0711	0.0668

Table 13. Summary of sample size (n), age range and class, mean and standard error (SE) as well as 95% confidential intervals of the age composition for the Hornaday River Arctic Char during 1989-2013. Shapiro-Wilk z-statistic was applied to test for the normality of the age composition.

Year	n	Age range	Age class	Mean	SE	-95%	+95%	z-statistic	Prob>z	Normality
1989	286	4-12	9	8.045	0.110	7.830	8.261	3.071	0.001	No
1990	169	2-12	11	7.254	0.126	7.007	7.502	-0.227	0.590	Yes
1991	234	4-11	8	7.278	0.101	7.080	7.476	2.449	0.007	No
1992	197	5-12	8	7.289	0.091	7.111	7.467	4.631	0.000	No
1993	193	4-13	10	7.881	0.091	7.702	8.060	3.430	0.000	No
1994	187	4-13	10	7.877	0.115	7.652	8.102	0.563	0.287	Yes
1995	261	3-11	9	7.054	0.101	6.855	7.252	1.902	0.029	No
1996	179	4-13	10	6.559	0.131	6.302	6.816	5.738	0.000	No
1997	184	4-10	7	6.527	0.086	6.358	6.697	4.183	0.000	No
1998	171	5-12	8	7.240	0.090	7.063	7.417	3.491	0.000	No
1999	151	2-11	10	6.404	0.107	6.195	6.613	-0.211	0.583	Yes
2000	285	4-11	8	6.719	0.063	6.595	6.843	1.938	0.026	No
2001	269	4-10	7	6.535	0.065	6.408	6.663	2.596	0.005	No
2002	195	5-13	9	7.215	0.090	7.039	7.391	5.934	0.000	No
2003	164	4-11	7	7.622	0.078	7.468	7.776	1.899	0.029	No
2004	238	5-13	8	7.782	0.075	7.634	7.929	3.584	0.000	No
2005	105	5-11	7	7.810	0.118	7.578	8.041	0.035	0.486	Yes
2006	46	5-11	7	7.717	0.203	7.319	8.115	-0.877	0.810	Yes
2007	36	4-12	8	6.167	0.277	5.623	6.711	2.958	0.002	No
2008	138	4-14	11	6.217	0.166	5.891	6.544	6.227	0.000	No
2009	51	5-9	5	6.137	0.148	5.847	6.428	3.173	0.001	No
2010	170	4-11	8	6.612	0.083	6.449	6.775	4.061	0.000	No
2011	284	4-16	12	7.585	0.077	7.433	7.736	7.380	0.000	No
2012	154	4-10	7	6.870	0.081	6.712	7.028	-0.669	0.748	Yes
2013	198	5-14	9	7.545	0.097	7.355	7.736	3.437	0.000	No
1989-2013	4545	2-16	14	7.186	0.022	7.143	7.229	8.764	0.000	No

*Table 14. Two-way ANOVA applying types I (upper) and II (lower) sums of squares to detecting the possible effects of year, Julian week, mesh size, and fishing duration on the number of char caught by a standard length of 45.72 m (50 yard) gillnet. The week was accounted during day-of-the-year 197 and 259, and the mesh sizes were graded by 114 (4.5"), 127 (5"), 133 (5.25"), 139 (5.5") and 152 (6") mm. Fishing duration varied in a range of 0.15 to 26 hours, classified by one-hour intervals. The statistical significance was marked by *** (p<0.0001), ** (p<0.001), * (p<0.05) and NS (p>0.05), respectively.*

Source	DF	Type I SS	MS	F	Pr > F	Sig
Year	16	269.782	16.861	25.960	<0.0001	***
Week	8	131.642	16.455	25.330	<0.0001	***
Mesh	4	35.037	8.759	13.490	<0.0001	***
Soak	18	50.599	2.811	4.330	<0.0001	***
Year*Week	45	229.834	5.107	7.860	<0.0001	***
Year*Mesh	31	55.431	1.788	2.750	<0.0001	***
Week*Mesh	20	27.022	1.351	2.080	0.003	**
Year*Soak	78	48.790	0.626	0.960	0.571	
Week*Soak	37	28.601	0.773	1.190	0.202	
Mesh*Soak	36	14.924	0.415	0.640	0.954	
Year*Week*Mesh	55	45.015	0.818	1.260	0.097	
Year*Week*Soak	22	14.623	0.665	1.020	0.431	
Year*Mesh*Soak	30	16.536	0.551	0.850	0.702	
Week*Mesh*Soak	15	14.678	0.979	1.510	0.094	
Year*Week*Mesh*Soak	2	2.702	1.351	2.080	0.125	
Error	1871	1215.327	0.650			

Source	DF	Type II SS	MS	F	Pr > F	Sig
Year	16	262.520	16.408	25.259	<0.0001	***
Week	8	95.480	11.935	18.373	<0.0001	***
Mesh	4	37.640	9.410	14.487	<0.0001	***
Soak	18	50.840	2.824	4.348	<0.0001	***
Year*Week	45	132.650	2.948	4.538	<0.0001	***
Year*Mesh	31	40.540	1.308	2.013	<0.001	**
Week*Mesh	20	25.110	1.256	1.933	0.008	**
Year*Soak	79	42.660	0.540	0.831	0.854	
Week*Soak	39	30.530	0.783	1.205	0.181	
Mesh*Soak	36	14.920	0.414	0.638	0.954	
Year*Week*Mesh	52	38.260	0.736	1.133	0.242	
Year*Week*Soak	22	18.870	0.858	1.321	0.145	
Year*Mesh*Soak	30	23.890	0.796	1.226	0.186	
Week*Mesh*Soak	15	14.680	0.979	1.506	0.094	
Year*Week*Mesh*Soak	2	2.700	1.350	2.080	0.125	
Residuals	1871	1215.330	0.650			

Table 15. Summary of fitted count regression models for catch rate of Arctic Char in the Hornaday River. Model coefficients estimated from generalized linear models (GLMs) and zero-augmented models (ZAMs), robust standard error for GLMs and standard error for ZAMs, statistical significance at p<0.0001 (***), p<0.001 (**), and p<0.05 (*). N is the number of estimated parameters, maximized log-likelihood, AICc, difference between AICc and minimum AICc (AICc-AICc$_{min}$), AICc weight (w_i), and the observed and expected zero catch.

	Generalized linear model (GLM)									Zero-augmented model (ZAM)								
	Poisson			Quasi-Poisson			Negative Binomial			Hurdle			ZIP			ZINB		
	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig
(Intercept)	-4.12	1.14	***	-4.12	1.14	***	-5.149	1.03	***	-2.61	1.05	*	-2.38	1.15	*	-3.60	1.00	***
1998	0.93	0.12	***	0.93	0.12	***	0.96	0.12	***	0.84	0.13	***	0.78	0.12	***	0.91	0.12	***
1999	0.94	0.14	***	0.94	0.14	***	0.88	0.14	***	0.91	0.14	***	0.85	0.13	***	0.95	0.13	***
2000	0.42	0.19	*	0.42	0.19	*	0.49	0.20	*	0.53	0.18	**	0.40	0.18	*	0.54	0.17	**
2001	0.34	0.11	**	0.34	0.11	**	0.24	0.11	*	0.50	0.11	***	0.47	0.10	***	0.47	0.11	***
2002	0.60	0.11	***	0.60	0.11	***	0.50	0.11	***	0.55	0.11	***	0.51	0.10	***	0.55	0.11	***
2003	0.93	0.15	***	0.93	0.15	***	0.86	0.14	***	1.08	0.14	***	0.97	0.13	***	1.08	0.14	***
2004	0.17	0.11		0.17	0.11		0.06	0.11		0.29	0.12	*	0.27	0.10	**	0.28	0.13	*
2005	-0.13	0.14		-0.13	0.14		-0.16	0.14		0.06	0.14		0.04	0.12		0.04	0.14	
2006	-1.03	0.13	***	-1.03	0.13	***	-1.13	0.14	***	-1.33	0.18	***	-1.12	0.16	***	-1.16	0.14	***
2007	-0.96	0.17	***	-0.96	0.17	***	-1.14	0.16	***	-0.82	0.18	***	-0.71	0.16	***	-0.95	0.18	***
2008	1.41	0.16	***	1.41	0.16	***	1.42	0.16	***	1.43	0.16	***	1.26	0.15	***	1.41	0.16	***
2009	0.49	0.16	**	0.49	0.16	**	0.42	0.16	**	0.50	0.16	**	0.49	0.14	***	0.50	0.16	**
2010	0.17	0.10		0.17	0.10		0.10	0.10		0.07	0.11		0.10	0.09		0.11	0.11	
2011	1.35	0.11	***	1.35	0.11	***	1.35	0.12	***	1.14	0.11	***	1.06	0.11	***	1.23	0.11	***
2012	1.04	0.17	***	1.04	0.17	***	0.96	0.19	***	1.00	0.19	***	0.89	0.17	***	0.98	0.19	***
2013	0.99	0.16	***	0.99	0.16	***	0.84	0.15	***	0.94	0.17	***	0.90	0.15	***	0.88	0.17	***
Mesh 2	-0.07	0.06		-0.07	0.06		-0.08	0.06		-0.05	0.06		-0.05	0.06		-0.07	0.06	
Mesh 3	-0.32	0.17		-0.33	0.17		-0.12	0.15		-0.07	0.15		-0.04	0.013		-0.11	0.14	
Mesh 4	-0.36	0.09	***	-0.36	0.09		-0.36	0.09	***	-0.17	0.09		-0.16	0.08		-031	0.09	***
Mesh 5	-0.01	0.29		-0.01	0.29		0.04	0.24		0.36	0.23		0.40	0.23		0.10	0.24	
Julian date	0.02	0.01	***	0.02	0.01	***	0.03	0.00	***	0.02	0.00	**	0.02	0.01	**	0.02	0.00	***
Soak duration	0.04	0.01	***	0.4	0.01	***	0.05	0.01	***	0.03	0.01	**	0.3	0.01	*	0.04	0.01	***

	Generalized linear model (GLM)									Zero-augmented model (ZAM)								
	Poisson			Quasi-Poisson			Negative Binomial			Hurdle			ZIP			ZINB		
	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig	Value	SE	Sig
Zero model coefficient (binomial with logist link)																		
(Intercept)										-10.66	2.16	***	9.58	2.42	***	-1.96	1.51	
1998										1.08	0.26	***	-0.95	0.28	***	1.11	1.26	
1999										0.62	0.26	*	-0.51	0.27		1.77	1.29	
2000										15.17	0.21	***	-15.17	0.22	***	-15.41	1.29	***
2001										-0.54	0.20	**	0.61	0.21	**	2.13	1.29	
2002										0.38	0.26		-0.34	0.26		0.90	1.31	
2003										-0.18	0.23		0.24	0.24		2.29	1.30	
2004										-0.530	0.20	**	0.56	0.21	**	2.12	1.27	
2005										-0.85	0.27	**	0.86	0.28	**	1.90	1.31	
2006										-0.87	0.26	***	-0.05	0.54		-14.39	1.55	***
2007										-2.06	0.38	***	1.84	0.44	***	1.28	1.94	
2008										1.63	1.05		-1.57	1.04		-1.71	8.18	
2009										0.10	0.34		-0.01	0.35		1.47	1.40	
2010										0.29	0.22		-0.30	0.24		1.18	1.61	
2011										2.69	0.44	***	-2.55	0.44	***	-16.32	1.47	***
2012										1.46	1.00		-1.42	1.01		-12.85	2.19	***
2013										0.65	0.50		-0.58	0.50		-0.43	3.02	
Mesh 2										-0.19	0.13		0.19	0.13				
Mesh 3										-0.53	0.29		0.64	0.33				
Mesh 4										-0.95	0.16	***	0.95	0.16	***			
Mesh 5										-0.73	0.45		1.23	0.52	*			
Julian date										0.05	0.01	***	-0.04	0.01	***			
Soak duration										0.11	0.02	***	-0.11	0.02	***	-0.14	0.05	**
N of parameters	23			23			24			47			46			42		
AICc	19058			NA			12033			11922			16306			11984		
W_i	0.00			NA			0.00			100.00			0.00			0.00		
Zero catch	521			521			521			521			521			521		
Expected zeros	79			NA			492			521			521			536		

Table 16. Summary of biological reference points for fisheries management, derived from the DB-SRA model for Arctic Char in the Hornaday River.

Abundance (individual)

Parameter	Mean	SD	2.50%	25%	50%	75%	97.50%
K	32339	7085	21853	27368	31302	36115	49020
OFL	2455	140	668	1512	2254	3137	5527
DCAC	2476	195	2042	2357	2493	2616	2809
M	0.2928	0.0596	0.1933	0.2502	0.2853	0.3295	0.4262
F_{MSY}/M	0.8034	0.1608	0.5369	0.6886	0.7816	0.9003	1.1552
Delta	0.5898	0.0900	0.4001	0.5286	0.5954	0.6575	0.7398
B_{MSY}/K	0.3994	0.0456	0.3122	0.3682	0.4016	0.4299	0.4897
F_{MSY}	0.2352	0.0671	0.1290	0.1876	0.2242	0.2727	0.3909
U_{MSY}	0.1805	0.0419	0.1091	0.1509	0.1747	0.2056	0.2738
N_{MSY}	12829	2791	8588	10843	12660	14326	19227
MSY	2245	434	1537	1943	2189	2486	3257

Biomass (kg)

Parameter	Mean	SD	2.50%	25%	50%	75%	97.50%
K	70744	15427	47563	59956	68440	79100	107051
OFL	5037	317	1556	3049	4556	6435	11536
DCAC	5490	434	4529	5228	5528	5801	6228
M	0.2926	0.0595	0.1929	0.2501	0.2865	0.3293	0.4251
F_{MSY}/M	0.8061	0.1610	0.5384	0.6914	0.7920	0.9033	1.1573
Delta	0.5811	0.0651	0.3980	0.5240	0.5895	0.6467	0.7162
B_{MSY}/K	0.3991	0.0456	0.3132	0.3679	0.3986	0.4296	0.4895
F_{MSY}	0.2358	0.0675	0.1288	0.1882	0.2271	0.2735	0.3919
U_{MSY}	0.1810	0.0420	0.1091	0.1512	0.1771	0.2061	0.2741
B_{MSY}	28043	6065	18776	23730	27259	31270	41836
MSY	4913	912	3423	4280	4814	5413	7046

Table 17. Comparison of a) abundance and b) biomass-based surplus production model parameters of, K, r, q, precisions for process error (σ), observation error (τ), as well as biological reference parameters of maximum sustainable yield (MSY), abundance (N_{MSY}) or biomass (B_{MSY}) and fishing mortality at MSY (F_{MSY}).

a)

	Mesh size 114 mm		Mesh size 127 mm		Both mesh sizes combined	
Variable	Mean	SD	Mean	SD	Mean	SD
Ln (K)	10.0000	0.0002	10.0000	0.0002	10.6050	0.1187
r	0.3348	0.0630	0.3341	0.0628	0.2773	0.0444
Ln(q)	-8.0045	0.1305	-8.1100	0.1295	-8.3670	0.1600
Ln(σ)	4.1345	0.2830	4.1345	0.2830	4.9030	0.1929
Ln(τ)	1.3556	0.2832	1.3740	0.2832	2.0637	0.1964
K	22026		22027		40339.8	
q	3.34E-04		3.01E-04		2.32E-04	
σ	0.1265		0.1265		0.0862	
τ	0.5077		0.5031		0.3564	
F_{MSY}	0.1674		0.1671		2797	347
N_{MSY}	11013		11013		0.1387	0.0264
MSY	1844		1840		20170	3004

b)

	Mesh size 114 mm		Mesh size 127 mm		Both mesh sizes combined	
Variable	Mean	SD	Mean	SD	Mean	SD
Ln (K)	10.4940	0.2964	10.4790	0.2852	11.2040	0.1324
r	0.3628	0.0719	0.3631	0.0720	0.3326	0.0609
Ln(q)	-7.4542	0.4755	-7.5057	0.4634	-7.3992	0.1964
Ln(σ)	4.1335	0.2833	4.1334	0.2834	4.8967	0.1941
Ln(τ)	1.2031	0.2863	1.1734	0.2860	1.9723	0.1944
K	36109		35575		73406	
q	5.79E-04		5.50E-04		6.12E-04	
σ	0.1266		0.1266		0.0864	
τ	0.5480		0.5562		0.3730	
F_{MSY}	0.1814		0.1815		0.1663	0.0265
B_{MSY}	18055		17787		36703	5175
MSY	3275		3229		6104	327

Table 18. Comparison of median and standard deviation of maximum sustainable yield (MSY) as well as corresponding abundance (N_{MSY}), biomass (B_{MSY}), spawning stock biomass SSB_{MSY}, fishing mortality (F_{MSY}), and exploitation rate (U_{MSY}) at MSY, estimated from DB-SRA, surplus production model (SPM), statistical catch-at-age (SCA) models and weighting by inverse variance (WIV) for Arctic Char.

Parameter		DB-SRA		SPM		SCA		WIV	
		Median	SD	Median	SD	Median	SD	Median	SD
Abundance	N_{MSY}	12660	2791	20170	3004	10701	3468	14635	1021
	MSY	2189	434	2797	347	2372	769	2496	154
	F_{MSY}	0.2242	0.0671	0.1455	0.0264	0.2217	0.0445	0.1838	0.0133
	M	0.2853	0.0596	0.2909	0.2673	0.2918	0.0158	0.2905	0.0119
	U_{MSY}	0.1747	0.0419	0.1179	0.0197	0.1734	0.0309	0.1474	0.0093
Biomass	B_{MSY}	27259	6065	36703	5175	24857	5487	29826	1851
	MSY	4814	912	6104	327	5586	834	5724	187
	F_{MSY}	0.2271	0.0675	0.1663	0.0265	0.2217	0.0445	0.1949	0.0133
	M	0.2865	0.0595	0.2909	0.2673	0.2918	0.0158	0.2907	0.0119
	U_{MSY}	0.1771	0.0420	0.1335	0.0197	0.1734	0.0309	0.1553	0.0094
SSB	SSB_{MSY}					3411	1126	3411	1126
	MSY					756	135	756	135
	F_{MSY}					0.2217	0.0445	0.2217	0.0445
	M					0.2918	0.0158	0.2918	0.0158
	U_{MSY}					0.1734	0.0309	0.1734	0.0309

APPENDIX 2. FIGURES

Figure 1. Map of the Paulatuk area, Northwest Territories, showing the Hornaday River (square block) and the northern portion of Tuktut Nogait National Park (shaded area).

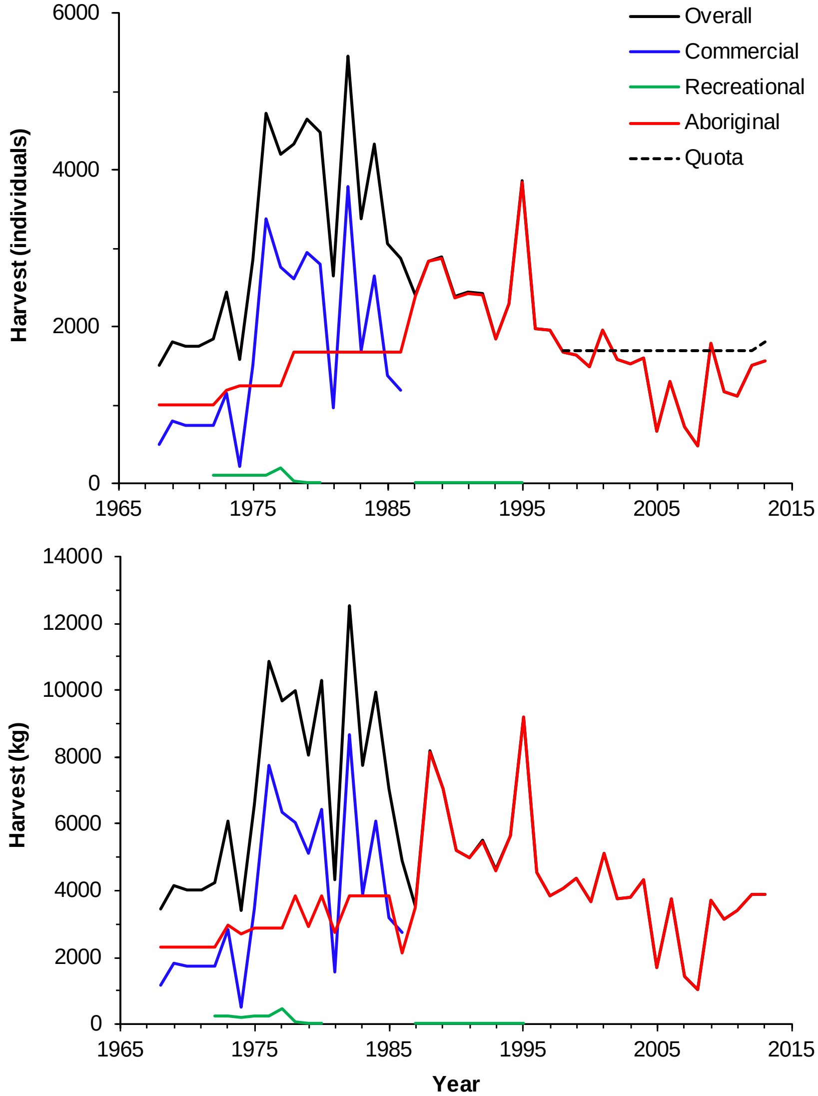

Figure 2. Harvested individuals (upper panel) and weight (kg, lower panel) for Arctic Char in the Hornaday River during 1968 through 2013. The fisheries were partitioned into commercial use from 1968 to 1986, recreational use during 1972 through 1995, and aboriginal use from 1968 through 2013. Voluntary limit began for aboriginal fisheries in 1998, expressed by broken line.

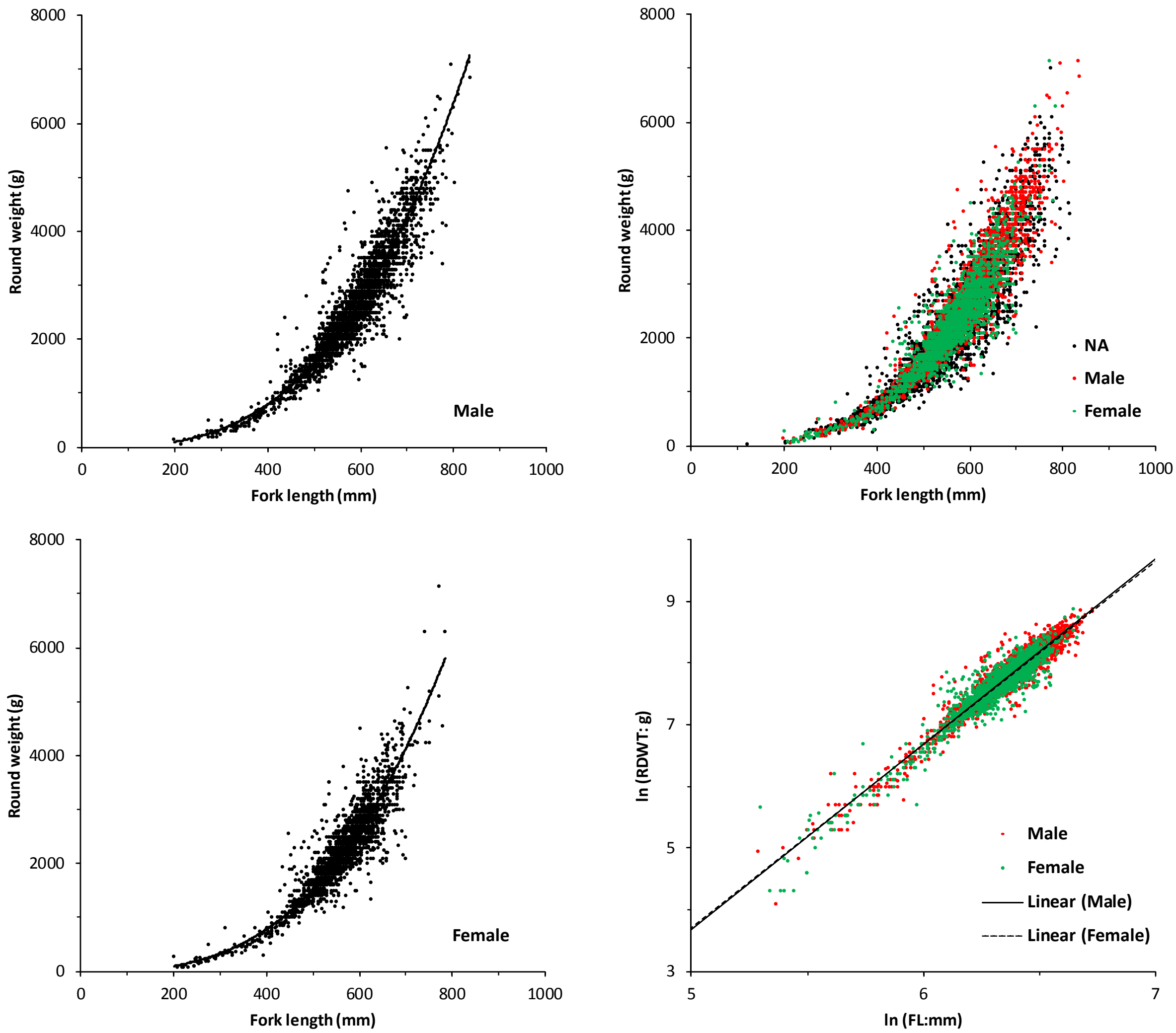

Figure 3. Relationships between round weight (W: g) and fork length (L: mm) for male (upper left), female (lower left) and combined sexes of Arctic Char (upper right) in the Hornaday River. Sexual difference was compared by using a linear relationship (solid line for male and broken line for female) between log-transformed W and L (lower right).

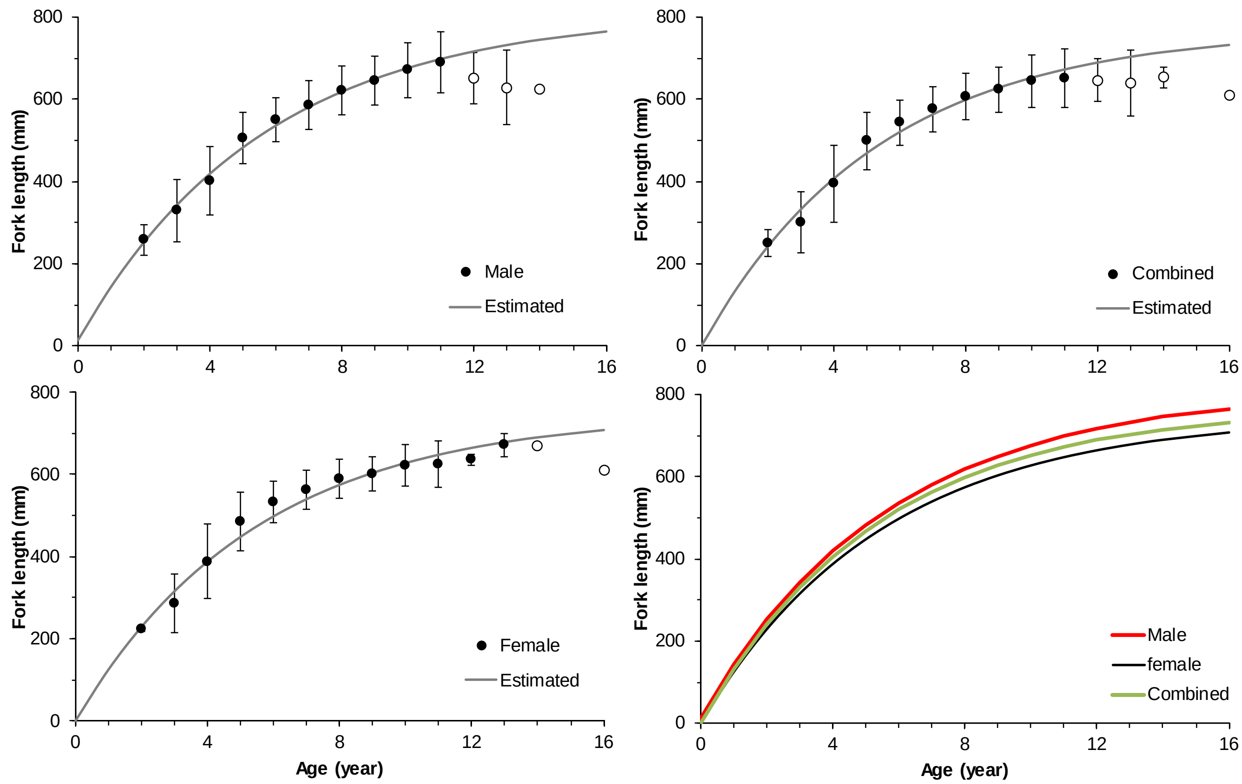

Figure 4. Growth in length-at-age for Arctic Char in the Hornaday River. The observed data were expressed by mean (black dots), one unit of standard deviation (bars) and estimated values (grey line). Data with open circles were observed and not used in growth models because of under-represented sample size.

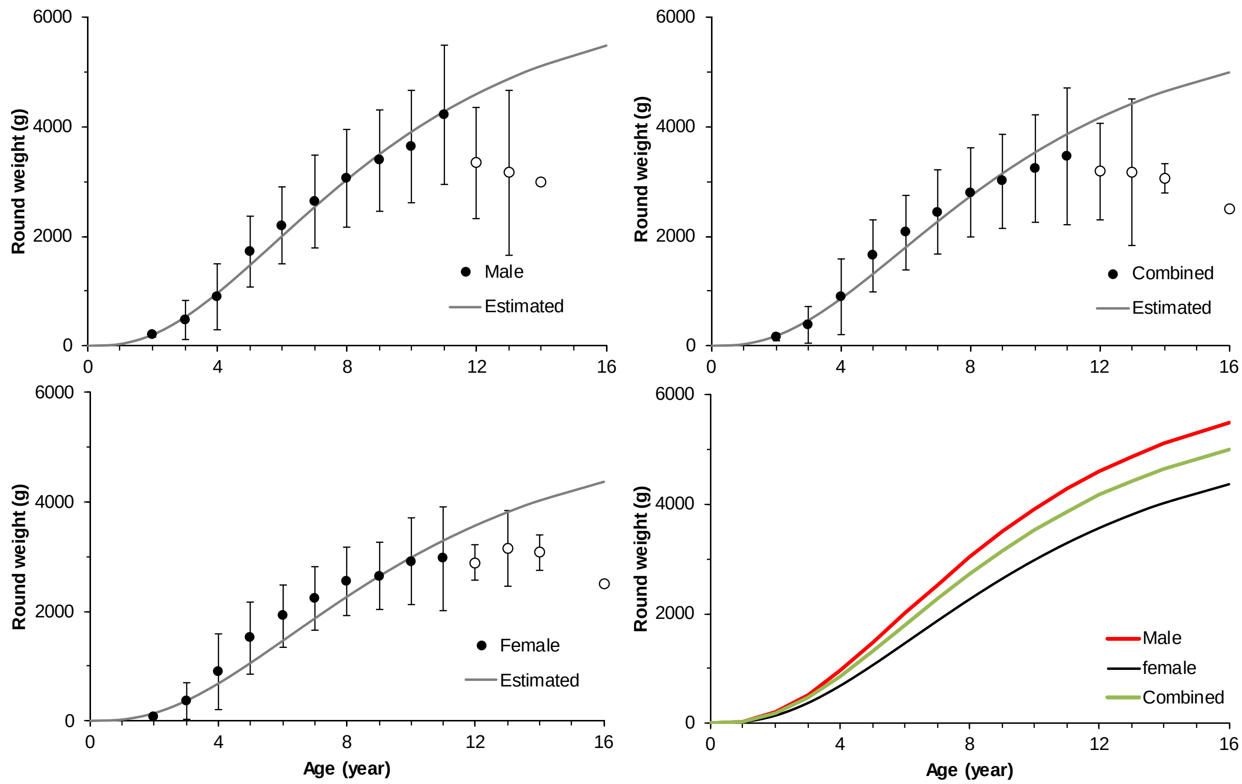

Figure 5. Growth in weight-at-age for Arctic Char in the Hornaday River. The observed data were expressed by mean (black dots), one unit of standard deviation (bars) and estimated values (grey line). Data with open circles were observed and not used in growth models because of under-represented sample sizes.

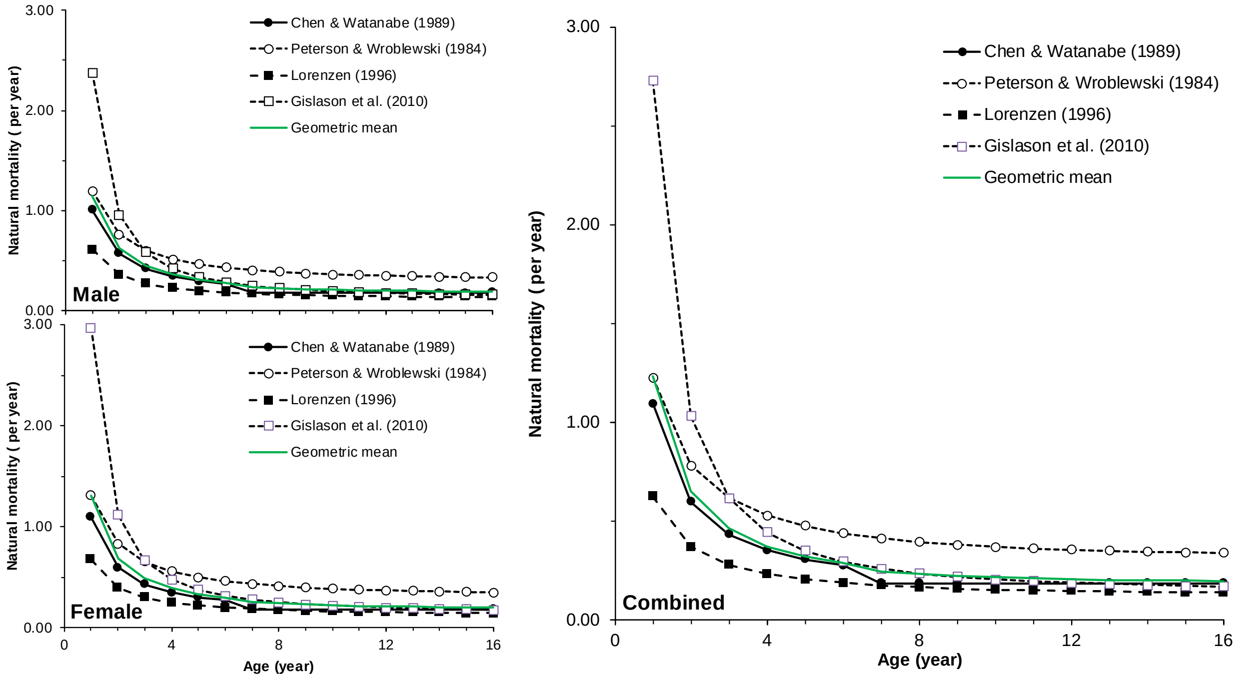

Figure 6. Comparison of natural mortality estimates using age-specific life-history parameter and body mass models for Arctic Char in the Hornaday River.

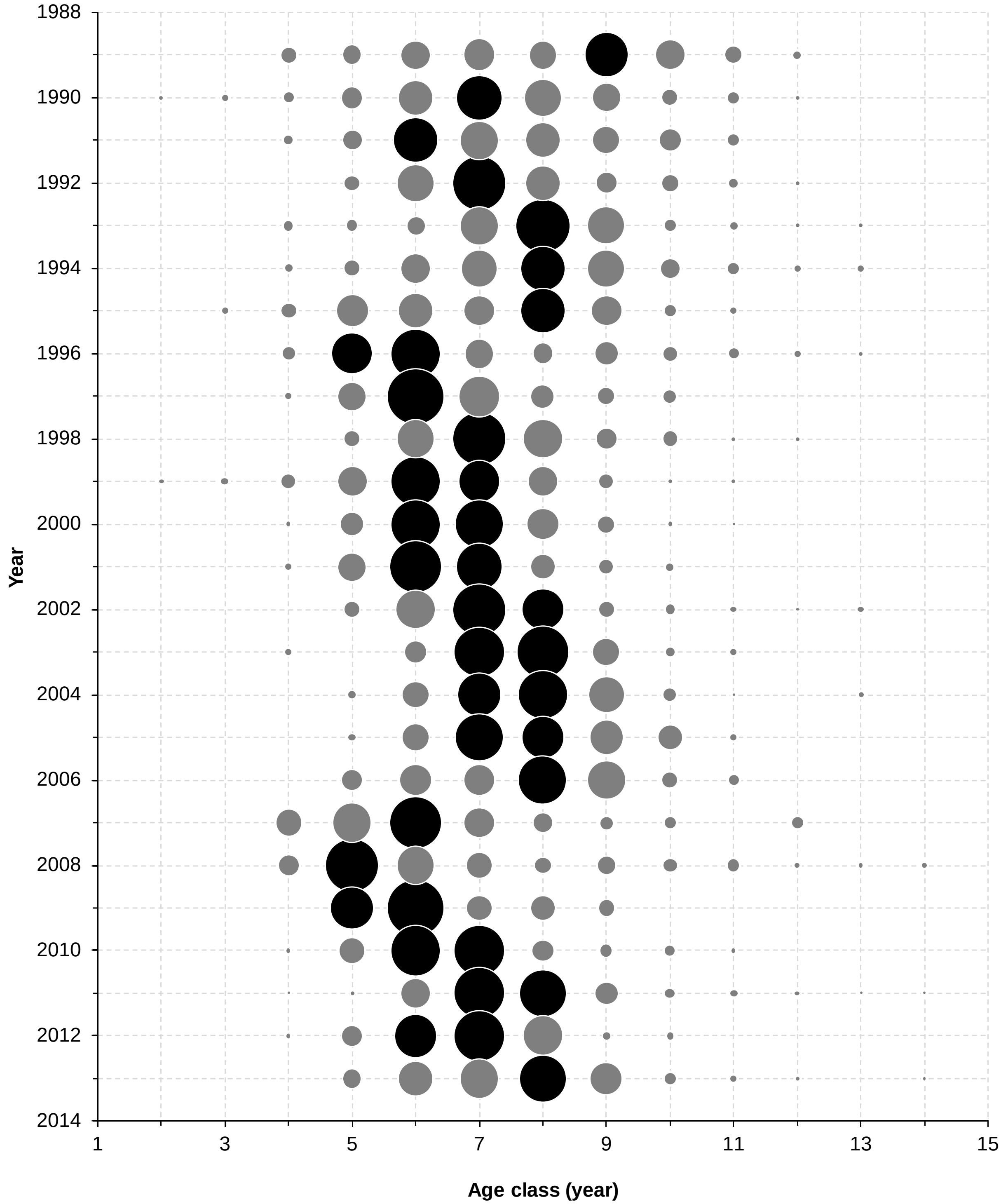

Figure 7. Proportions of catch-at-age for Arctic Char caught with gillnet mesh sizes 113-140 mm in the Hornaday River during 1989-2013. Grey and black dots are age-specific percentages less and greater than 25%, respectively.

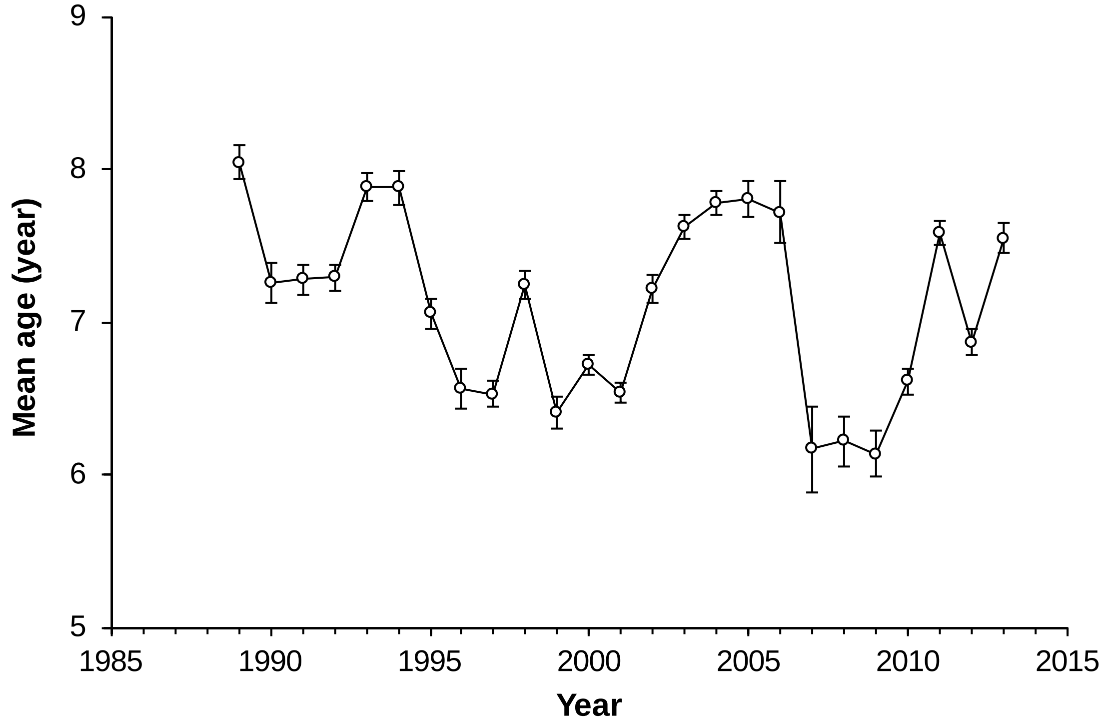

Figure 8. Variation of Arctic Char mean age plus one unit of standard error (bars) from the Hornaday River during 1989-2013.

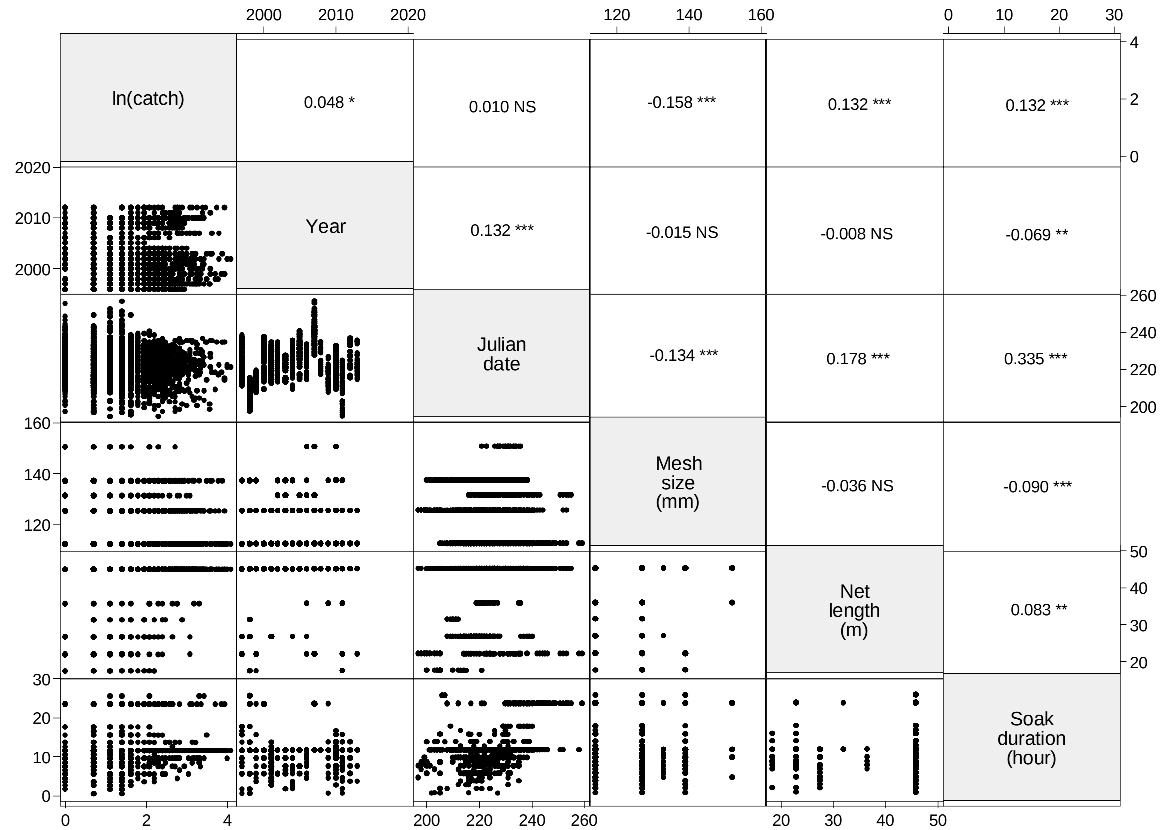

*Figure 9. Matrix graphs of the log-transformed catch rates for Arctic Char in relation to year, day-of-the-year, gillnet mesh size (mm), net length (m) and soak duration (hour). Numbers in right triangle areas indicated pair-wise correlation and statistical significance, signified by *** (p<0.0001), ** (p<0.001), * (p<0.05) and NS (p>0.05), respectively.*

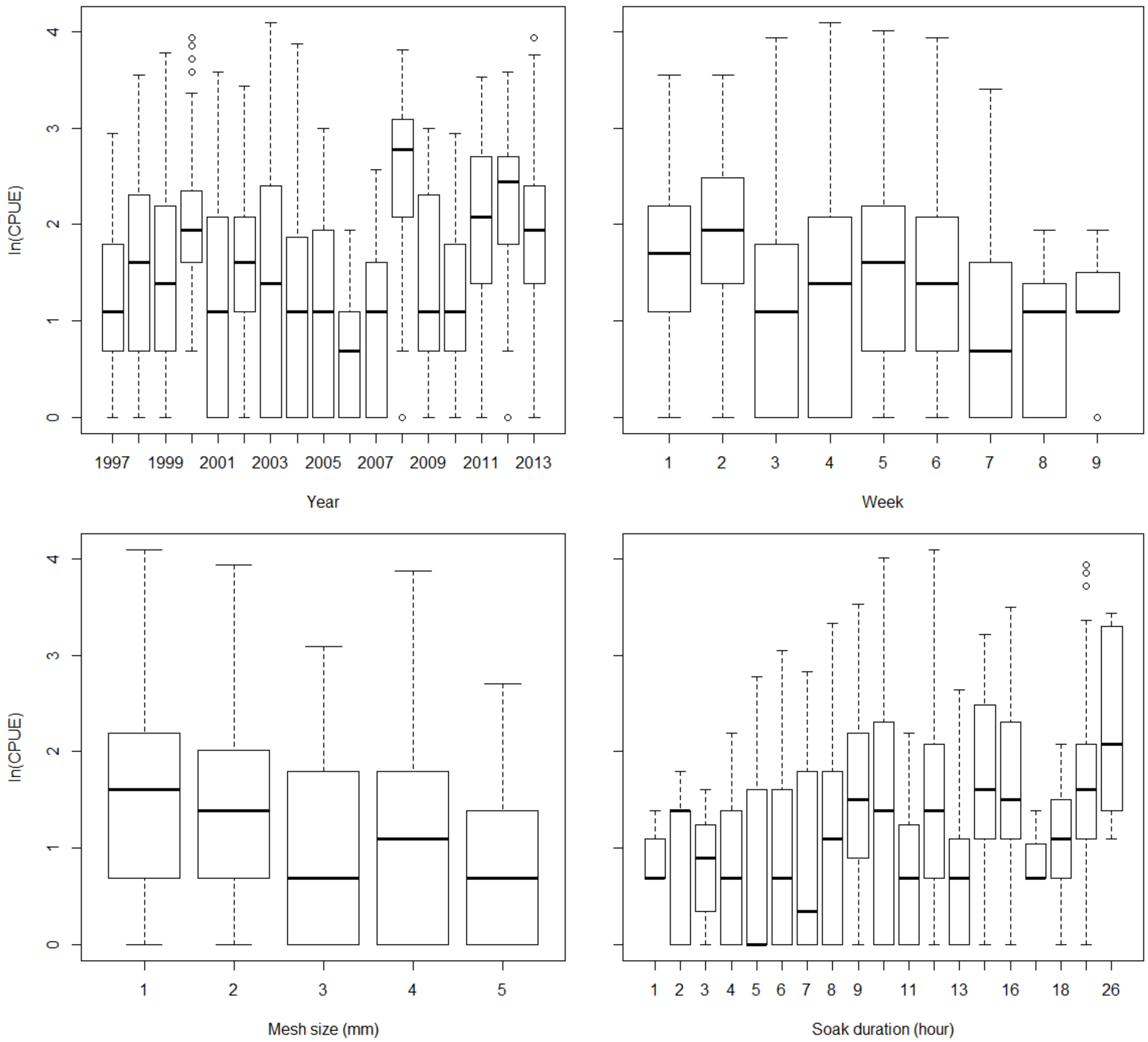

Figure 10. Bivariate explorative boxplots showing the changes of log-transformed CPUE of Arctic Char caught by gillnets against year (upper left) and codes of Julian week (upper right), mesh size (lower left) and fishing duration (lower right) panels.

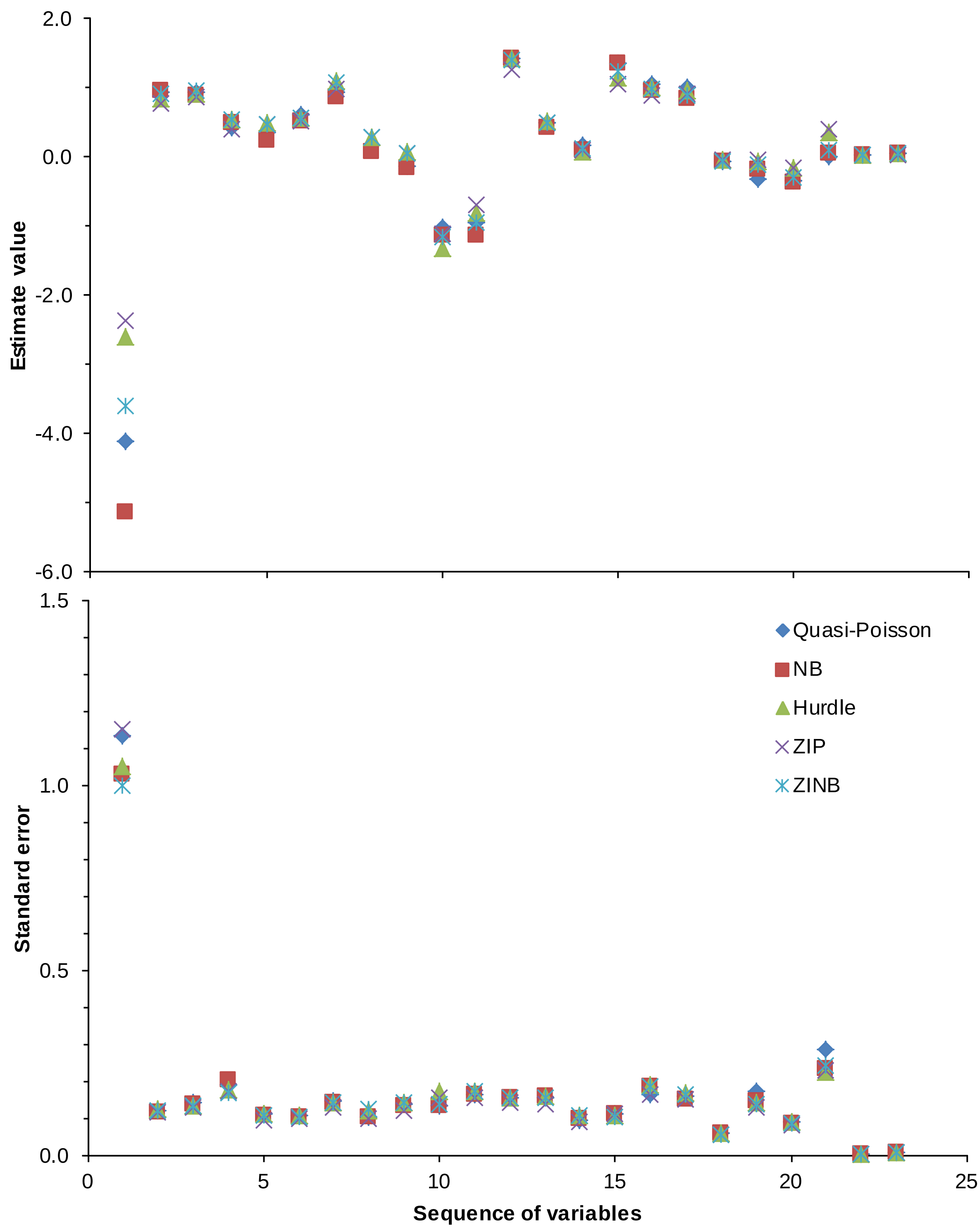

Figure 11. Comparison of regression coefficients (upper) and standard errors (lower panel) regressed by Quasi-Poisson, negative binomial (NB), hurdle (Hurdle), zero-inflated Poisson (ZIP) and zero-inflated negative binomial models (ZINB) for catch rates of Arctic Char in the Hornaday River, 1997-2013.

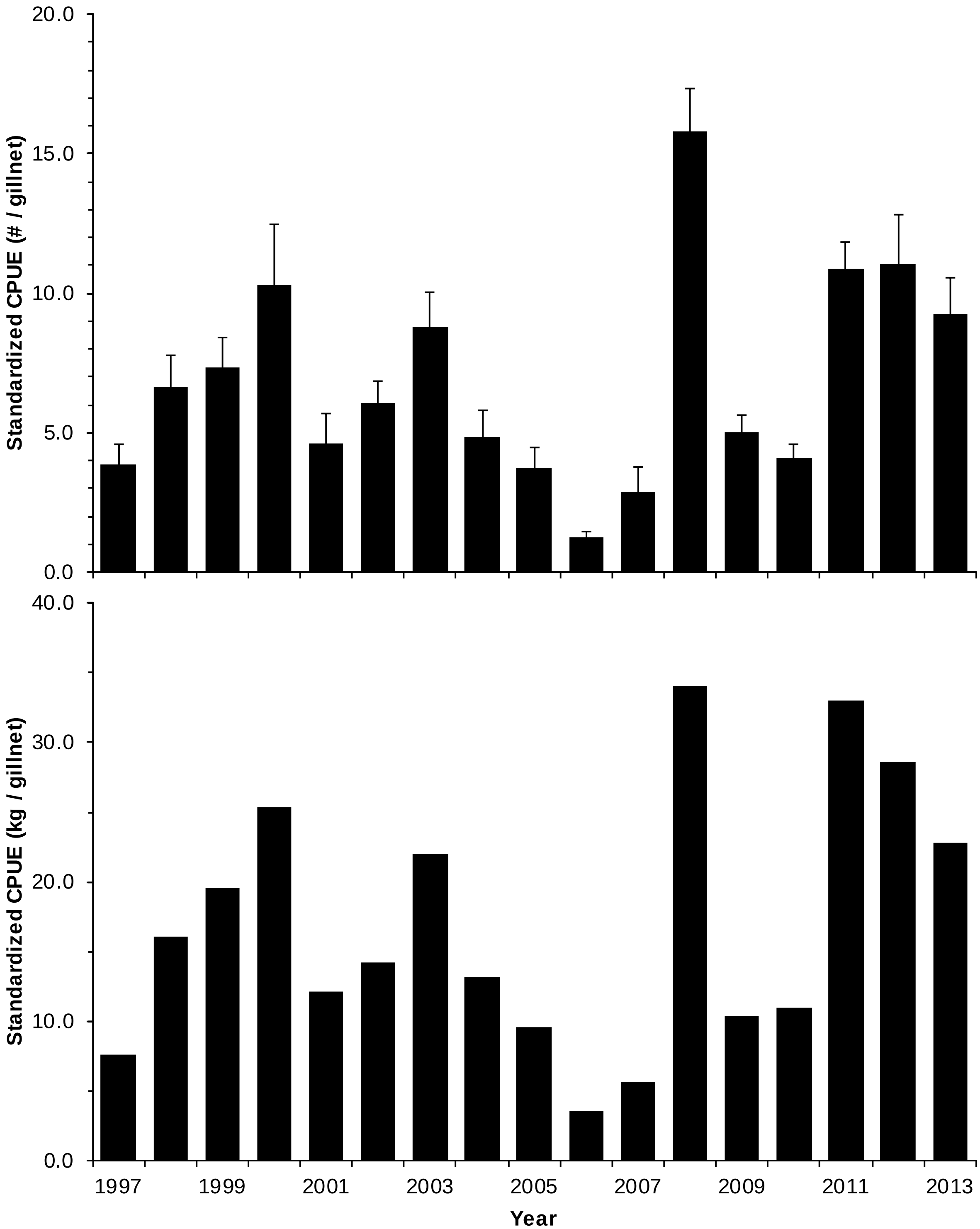

Figure 12. Temporal changes in CPUE standardized by the hurdle regression model for Arctic Char captured by 45.72 m (50 yard) net length with mesh size 114 mm gillnets for 24 hours in the Hornaday River. CPUE are expressed by individual (upper panel, mean ± SD: individuals per set) and weight (lower panel, kg).

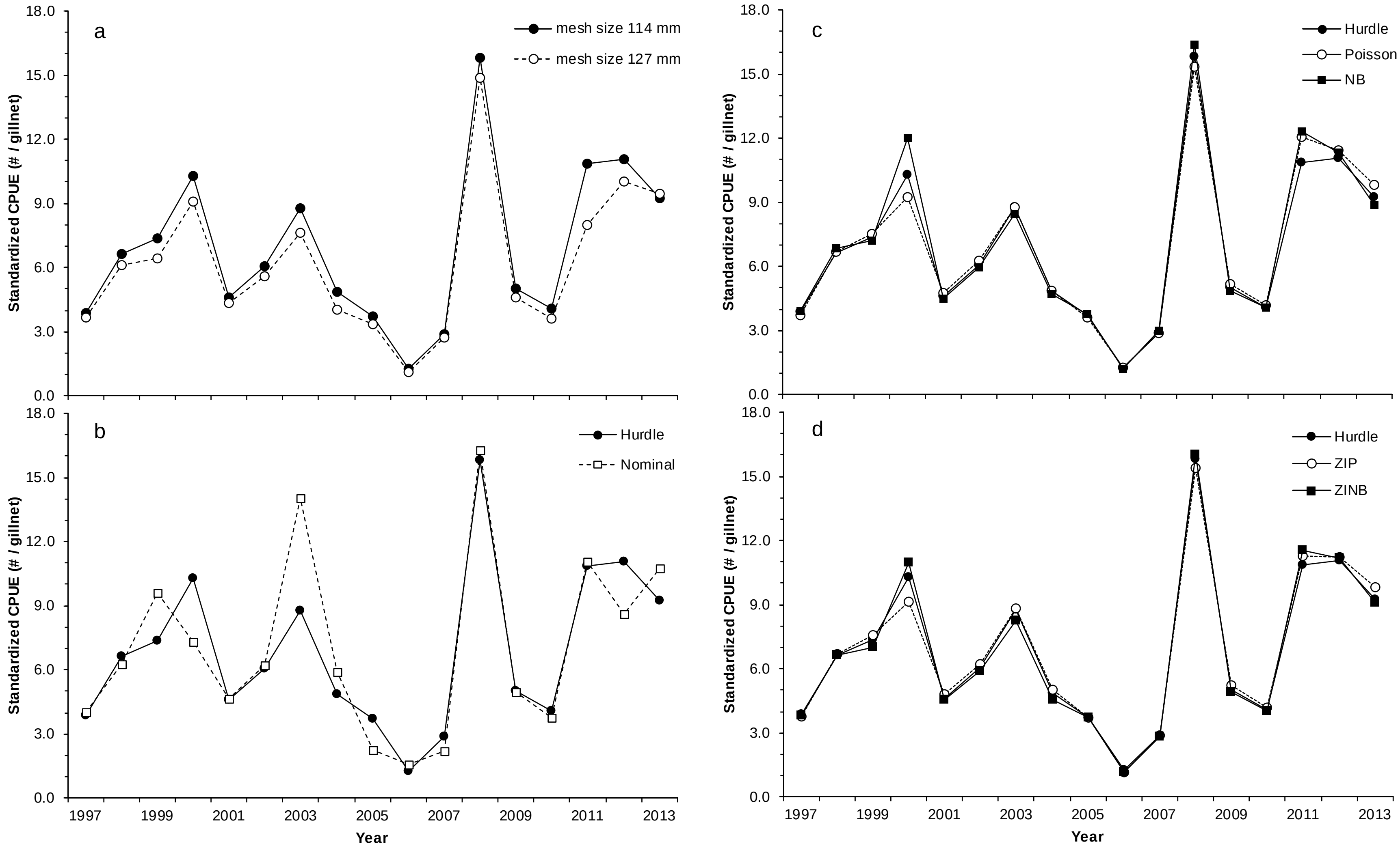

Figure 13. Comparisons of CPUE (individual per standardized gillnet) for Arctic Char in the Hornaday River from 1997-2013 for observed CPUEs by mesh sizes 114 mm and 127 mm (a), the best-fitting model and the nominal CPUEs (b), the best-fitting model (Hurdle) and the classic count-based models (c), and the best-fitting model and the two zero-augmented count models (d).

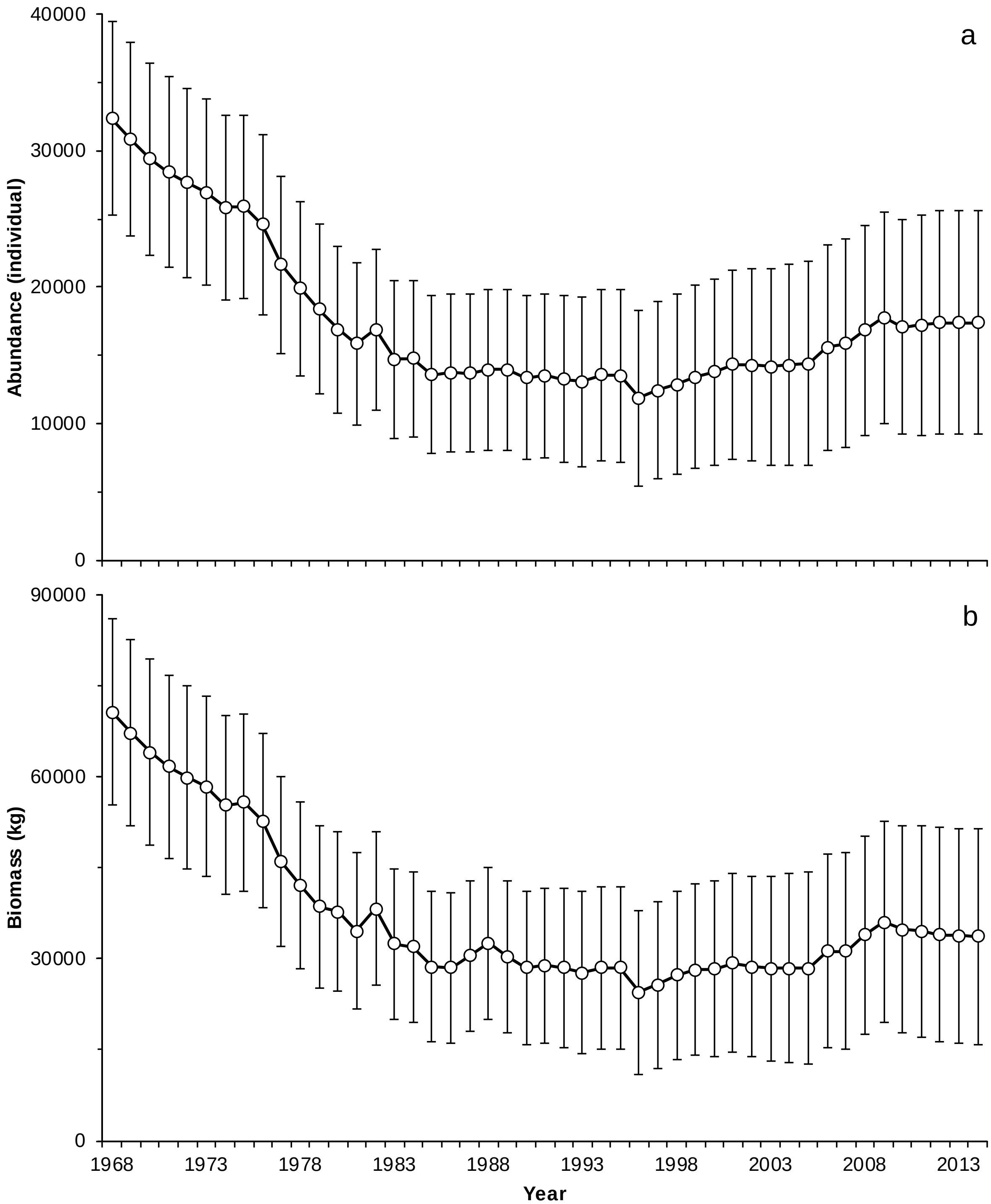

Figure 14. Trajectories of the DB-SRA model estimated (mean ± SD) abundance (a: individuals) and biomass (b: kg) for Arctic Char in the Hornaday River.

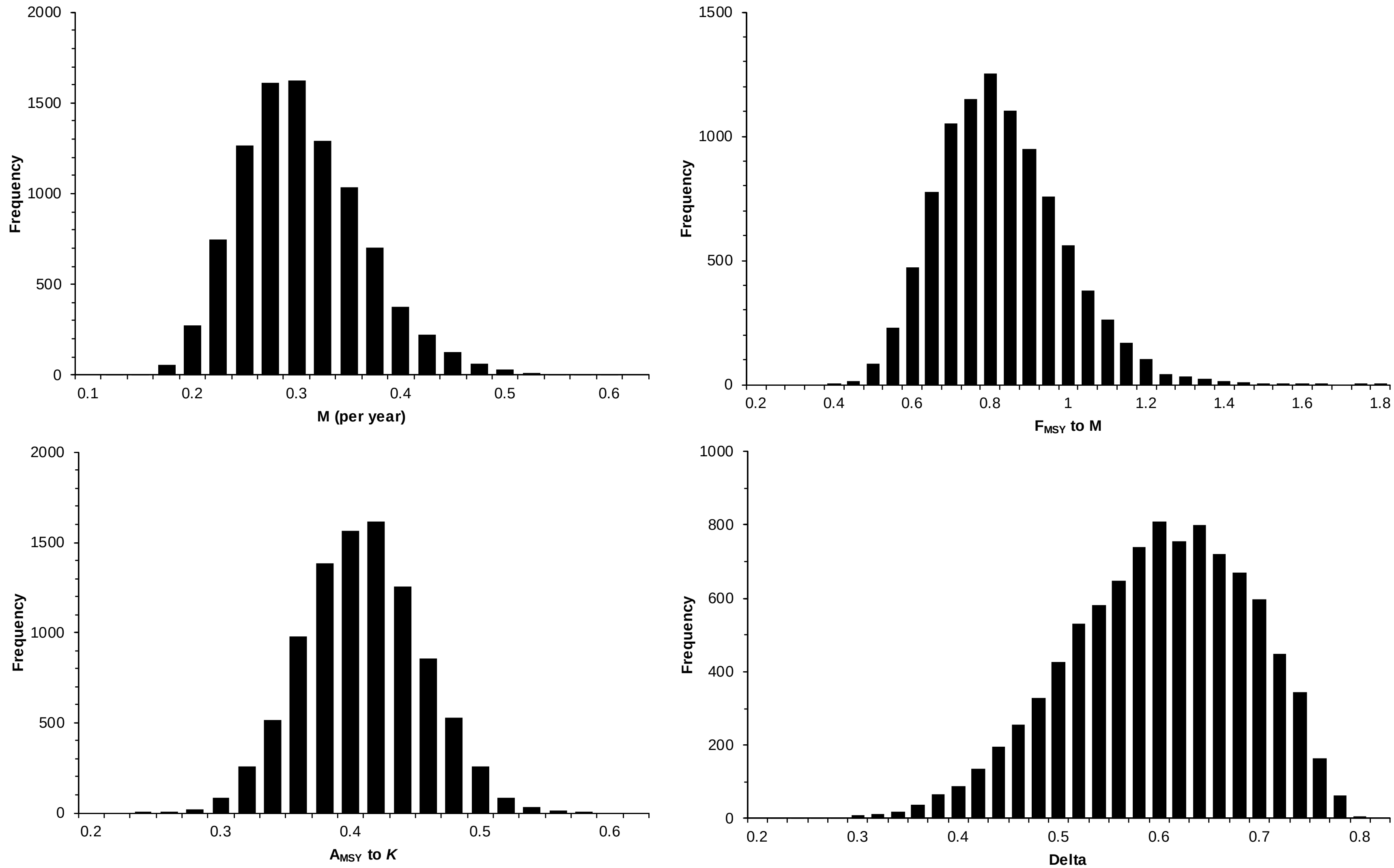

Figure 15. Parameter distributions for M, F_{MSY}/M, A_{MSY}/K, and DCAC, of the DB-SRA model for estimation of Arctic Char abundance in the Hornaday River.

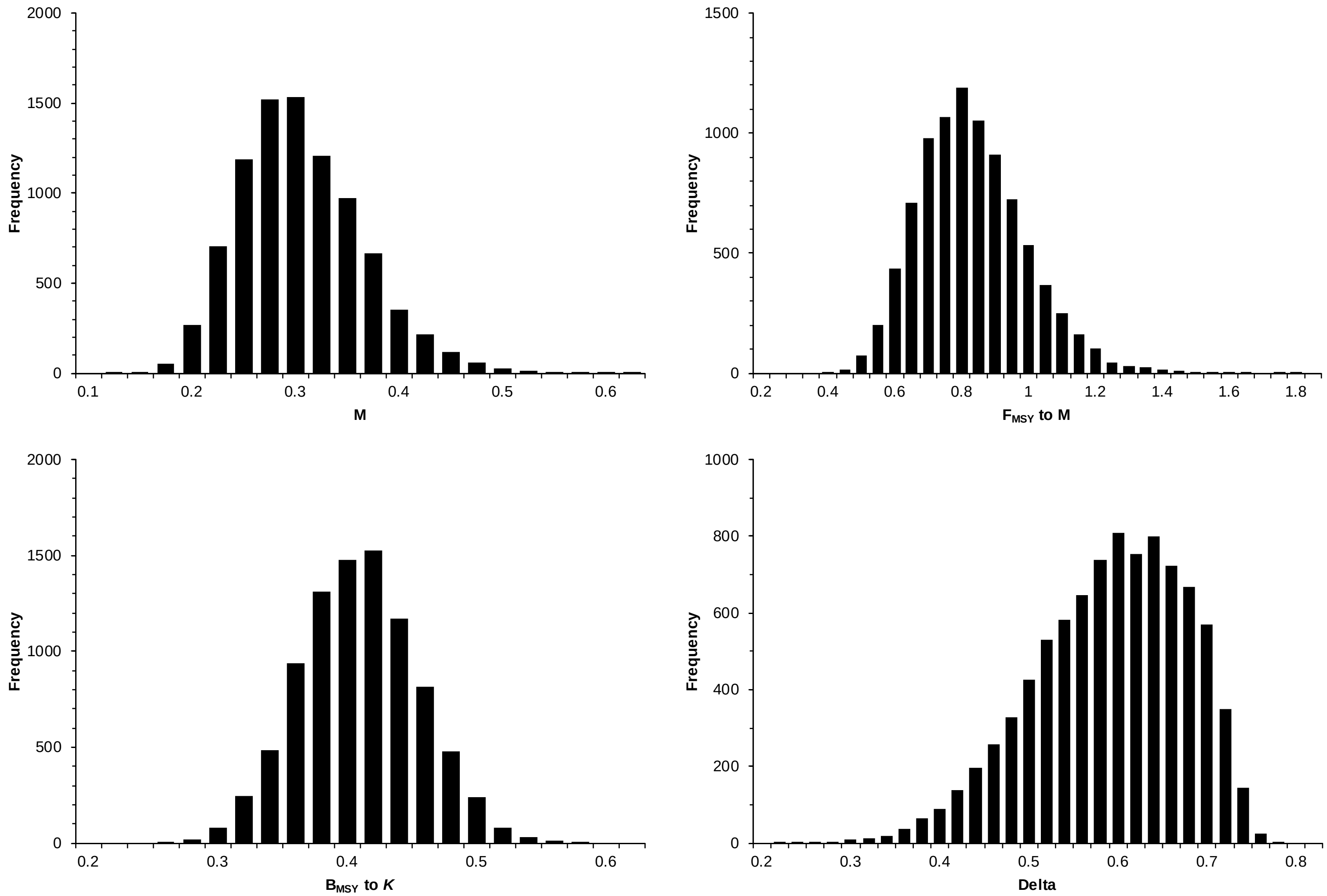

Figure 16. Parameter distributions for M, F_{MSY}/M, B_{MSY}/K, and DCAC, of the DB-SRA model for estimation of Arctic Char biomass in the Hornaday River.

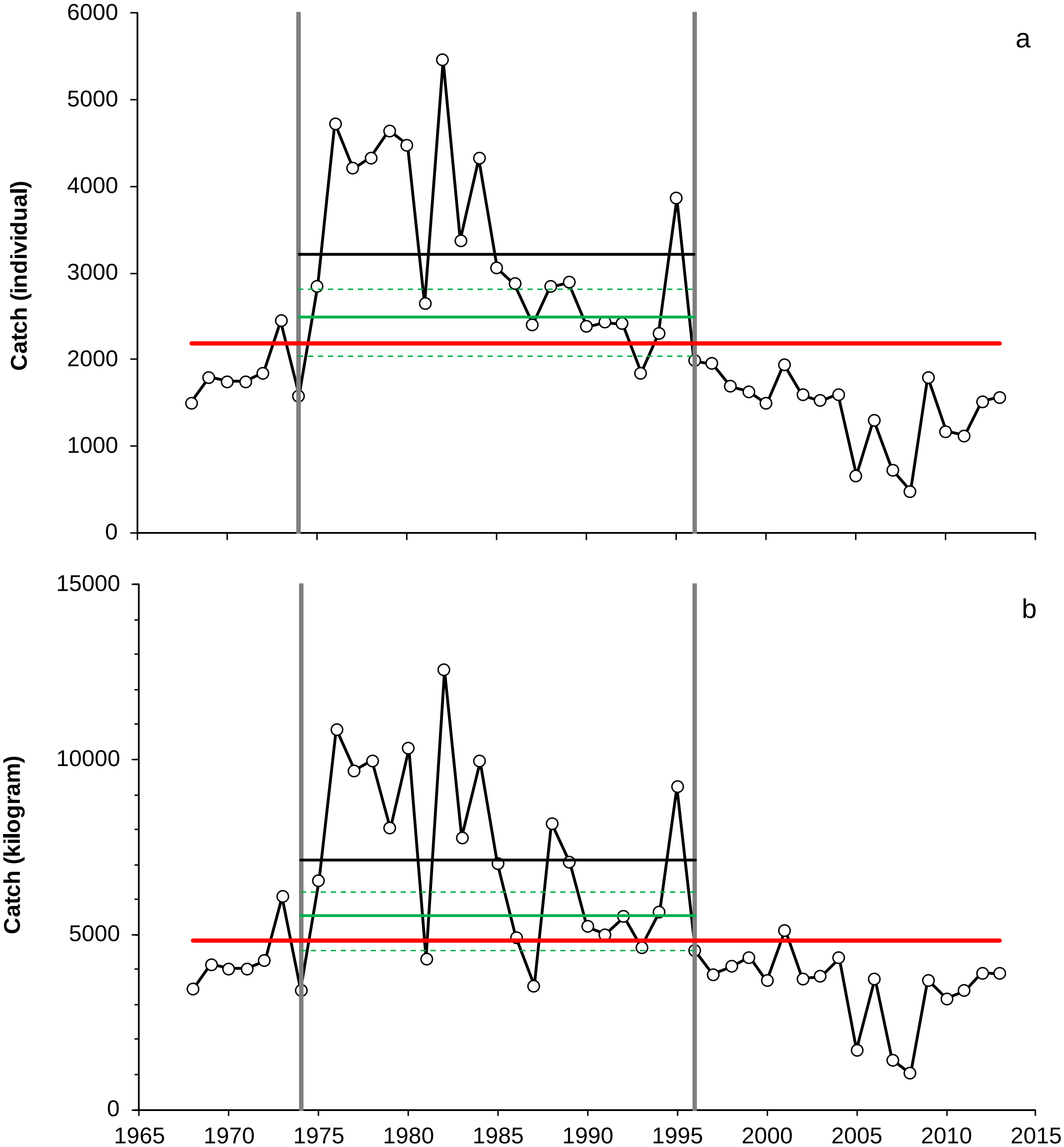

Figure 17. Annual variations of estimated abundance (a) and biomass (b) of Arctic Char, from the DB-SRA model, in the Hornaday River. Grey lines bracket years 1974-1996, over which catch was summed. Red horizontal line was MSY from the model assessment. Black horizontal line was the average. Green horizontal line is the DCAC median (solid line) and 95% confidential intervals (dashed lines) based on 10,000 non-negative simulations.

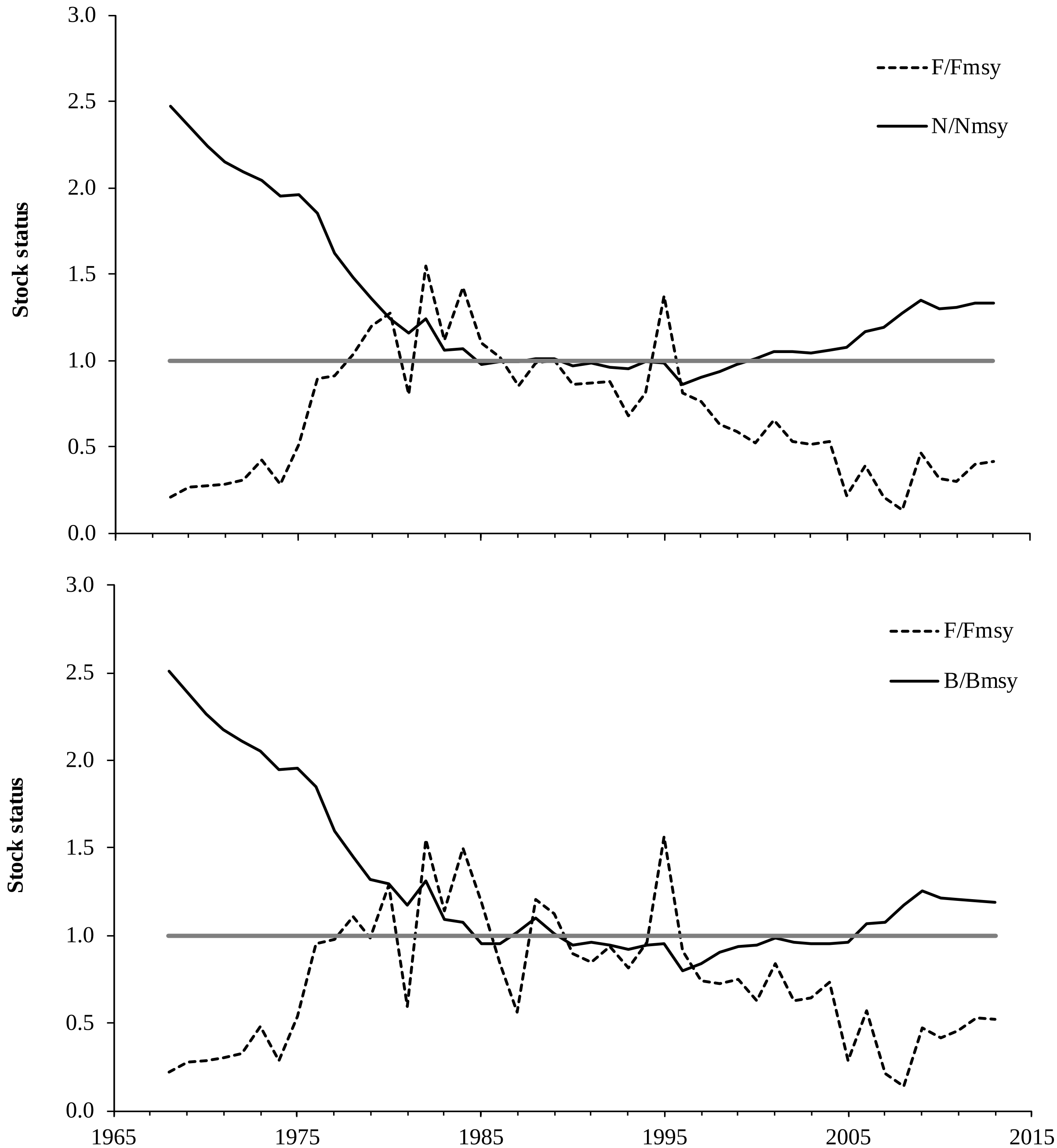

Figure 18. Graphic summary of the Arctic Char stock exploitation history from 1968-2013, demonstrating posterior median trends in stock status (N/N_{MSY} or B/B_{MSY}) and fishing status (F/F_{MSY}) by use of the DB-SRA model. The critical reference to the stock status were delineated by grey lines as abundance (upper) and biomass-specific (bottom panel) indicators.

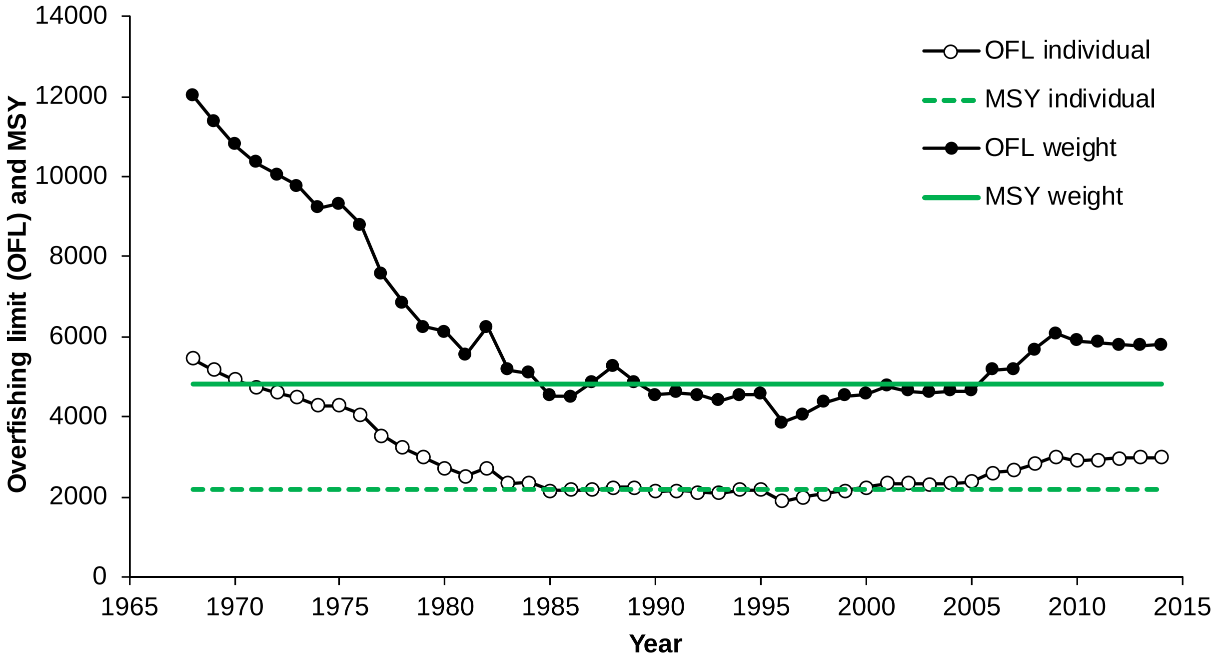

Figure 19. Comparison of fisheries management targets of maximum sustainable yield (MSY) and the overfishing limit (OFL) in connection with the precautionary reference points from the DB-SRA model for Arctic Char in the Hornaday River.

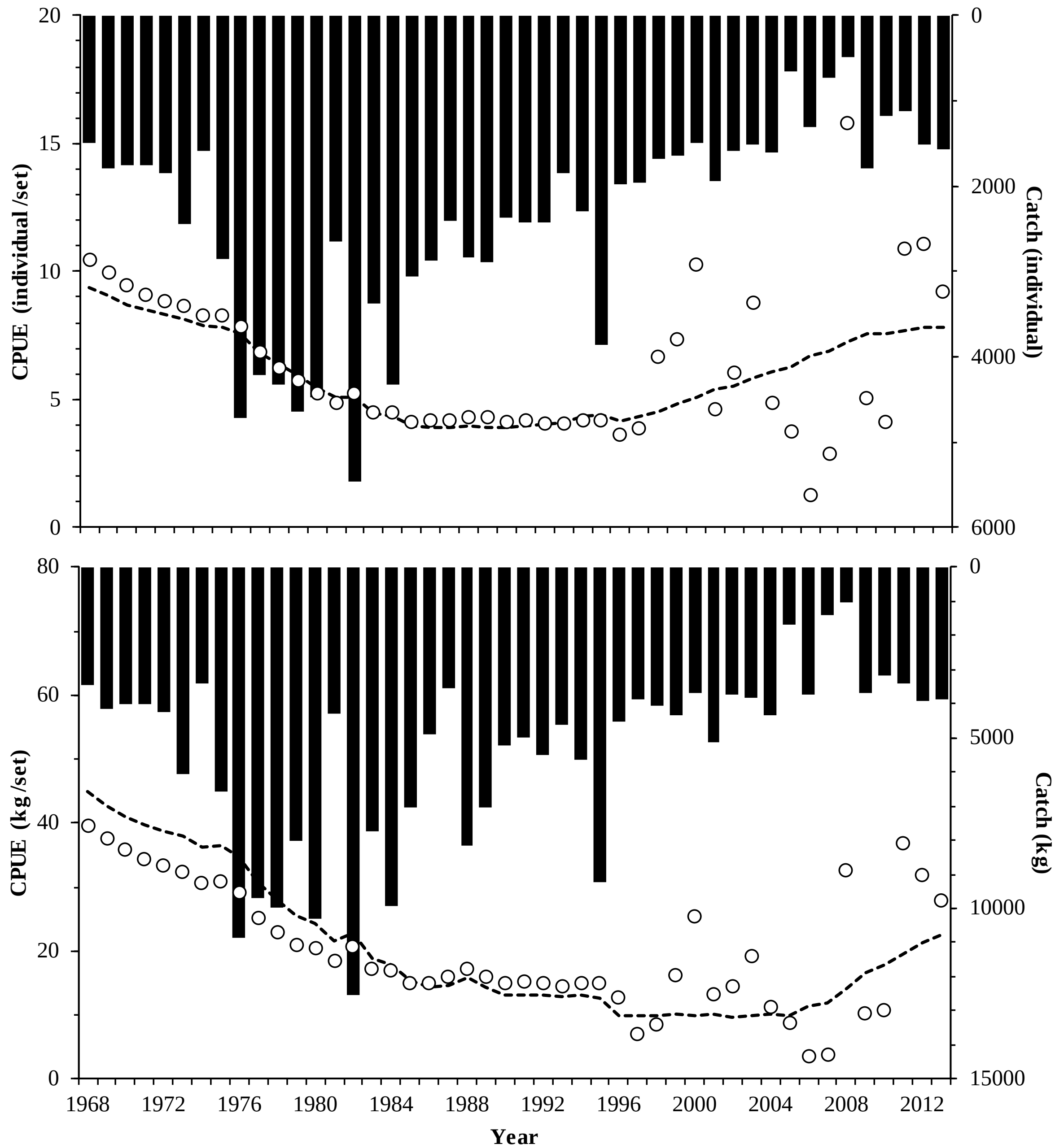

Figure 20. Comparison of the observed (circles) and projected (dashed line) CPUE and catch of individuals (upper panel) and weight (kg) (lower panel) for Arctic Char in the Hornaday River during 1968-2013.

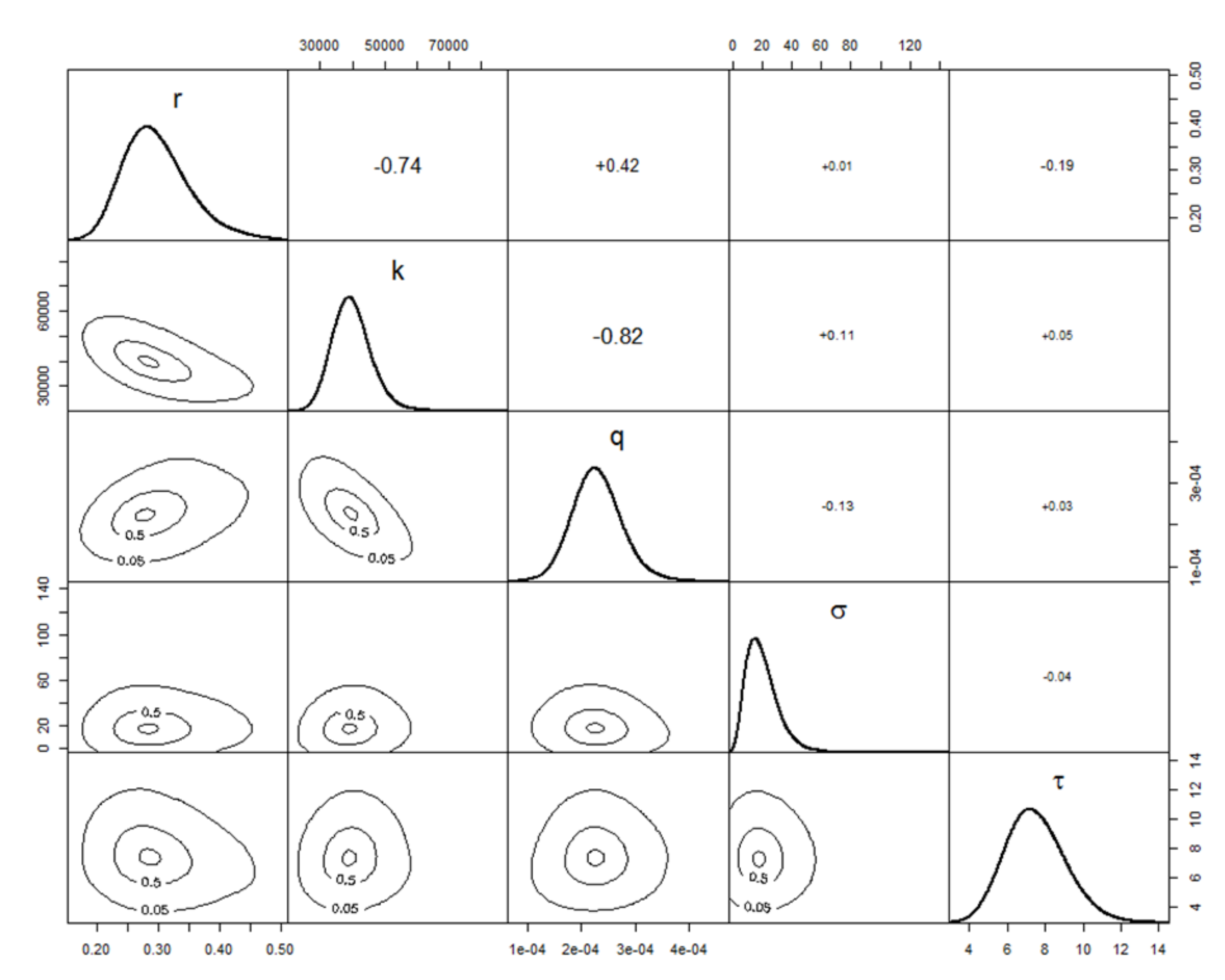

Figure 21. Parameter distributions of K, r, q, σ and τ for surplus production model of Arctic Char abundance in the Hornaday River from 1968 through 2013. Isograms indicated covariate relations and digits for spearman correlation coefficients. Two statistically significant negative relations can be seen between K and r as well as K and q.

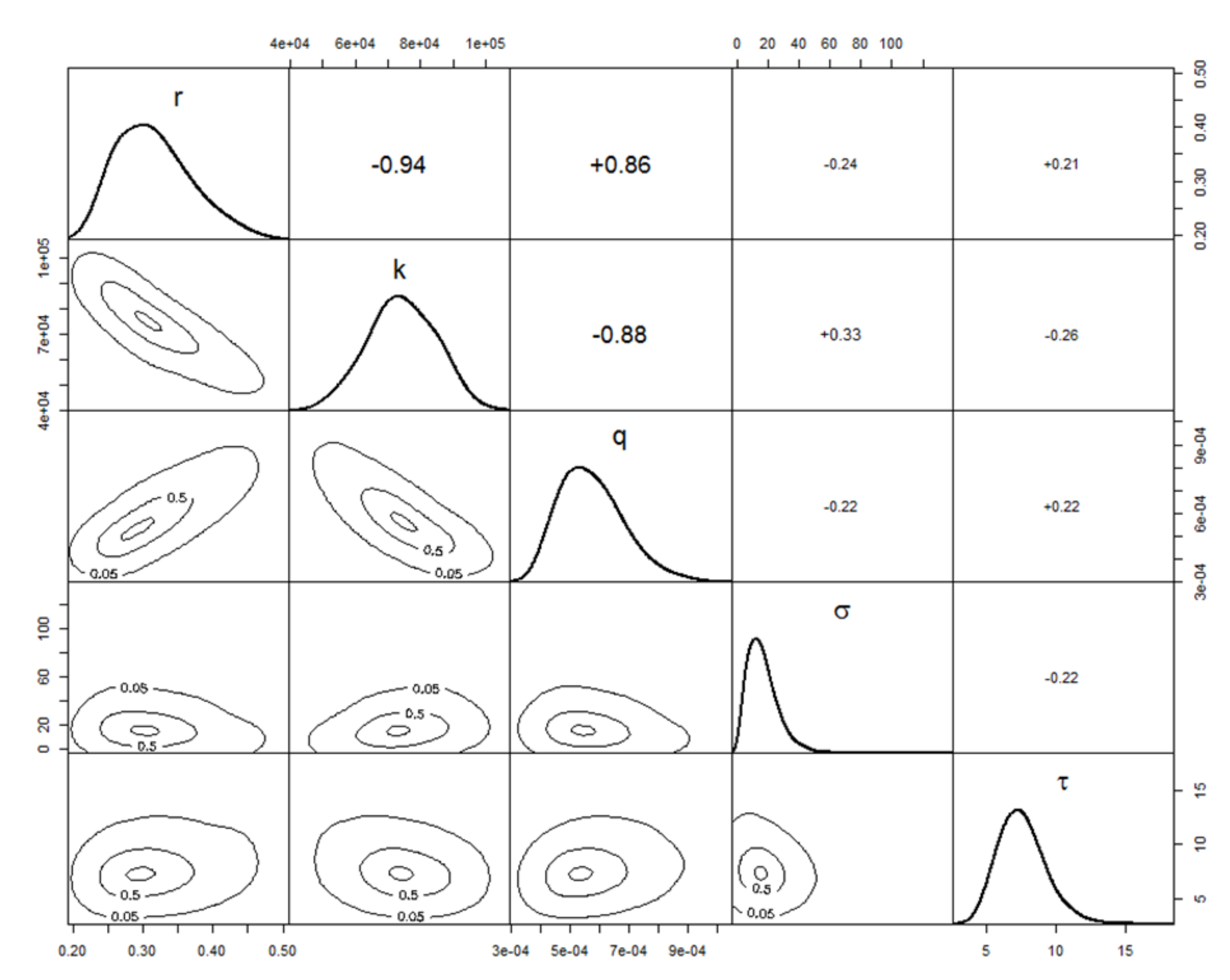

Figure 22. Parameter distributions of K, r, q, σ and τ for surplus production model of Arctic Char biomass in the Hornaday River from 1968 through 2013. Isograms indicated covariate relations and digits for spearman correlation coefficients. Two statistically significant negative relations can be seen between K and r as well as K and q, and positive correlation between r and q.

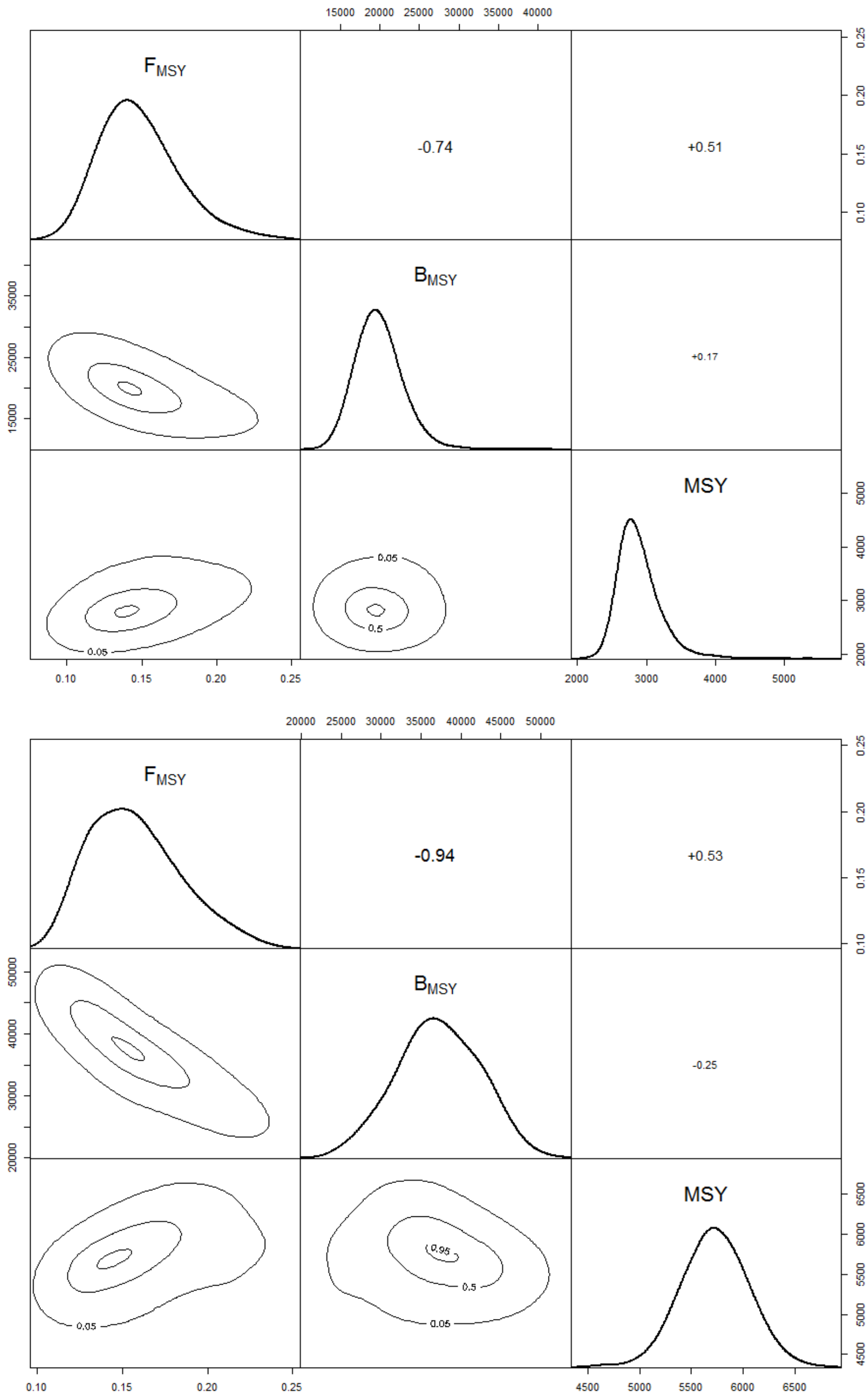

Figure 23. Parameter distributions of maximum sustainable yield (MSY) and corresponding fishing mortality (F_{MSY}) and biomass (B_{MSY}) of Arctic Char abundance (upper panel) and biomass (lower panel) in the Hornaday River. Isograms indicated covariate relations and digits for spearman correlation coefficients.

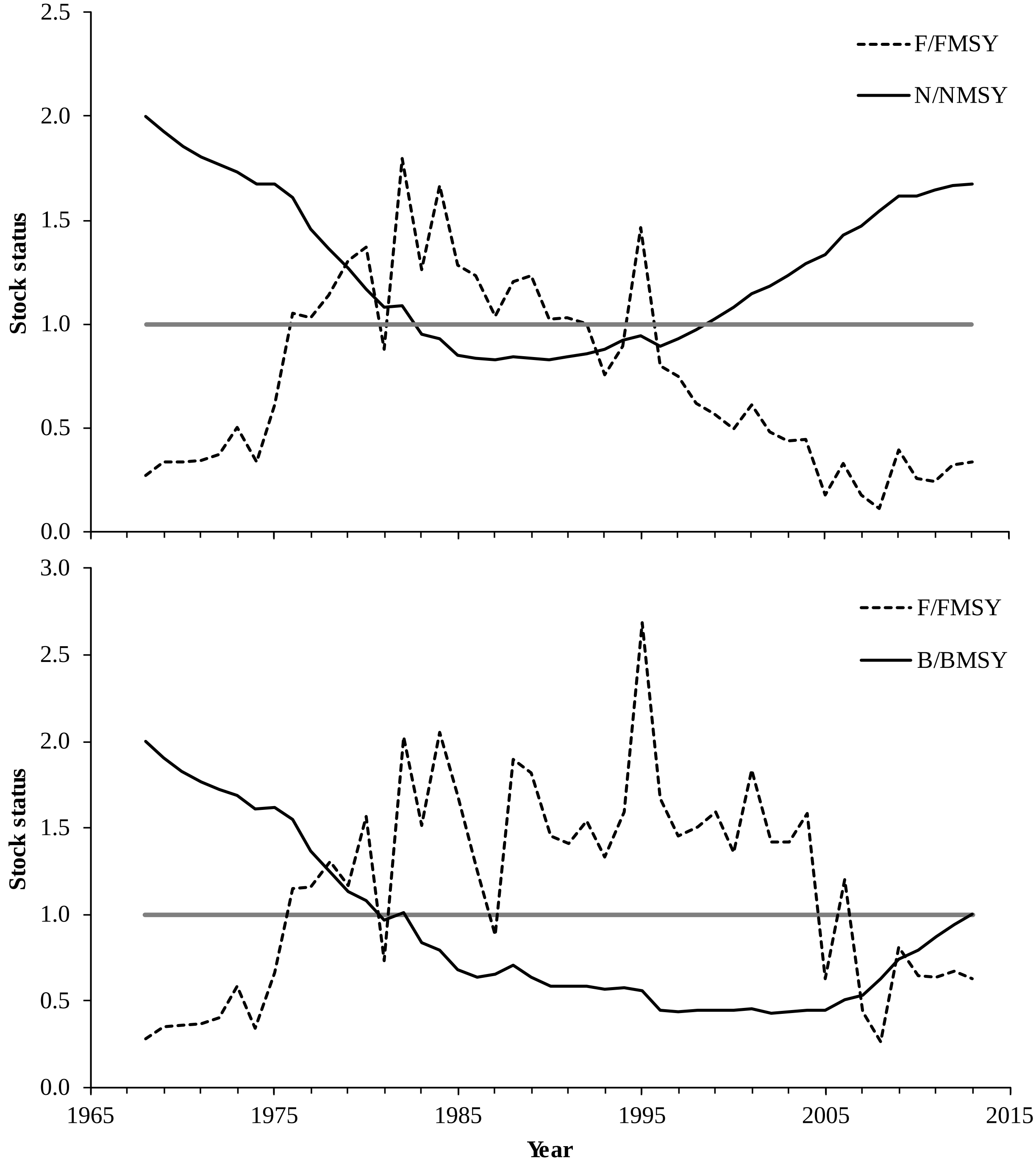

Figure 24. Graphic summary of the Arctic Char stock exploitation history during 1968-2013, shown by stock status (N/N_{MSP} or B/B_{MSP}) and fishing status (F/F_{MSP}) by SPM. The stock statuses were described by the abundance (upper panel) and biomass-specific (bottom panel) indicators.

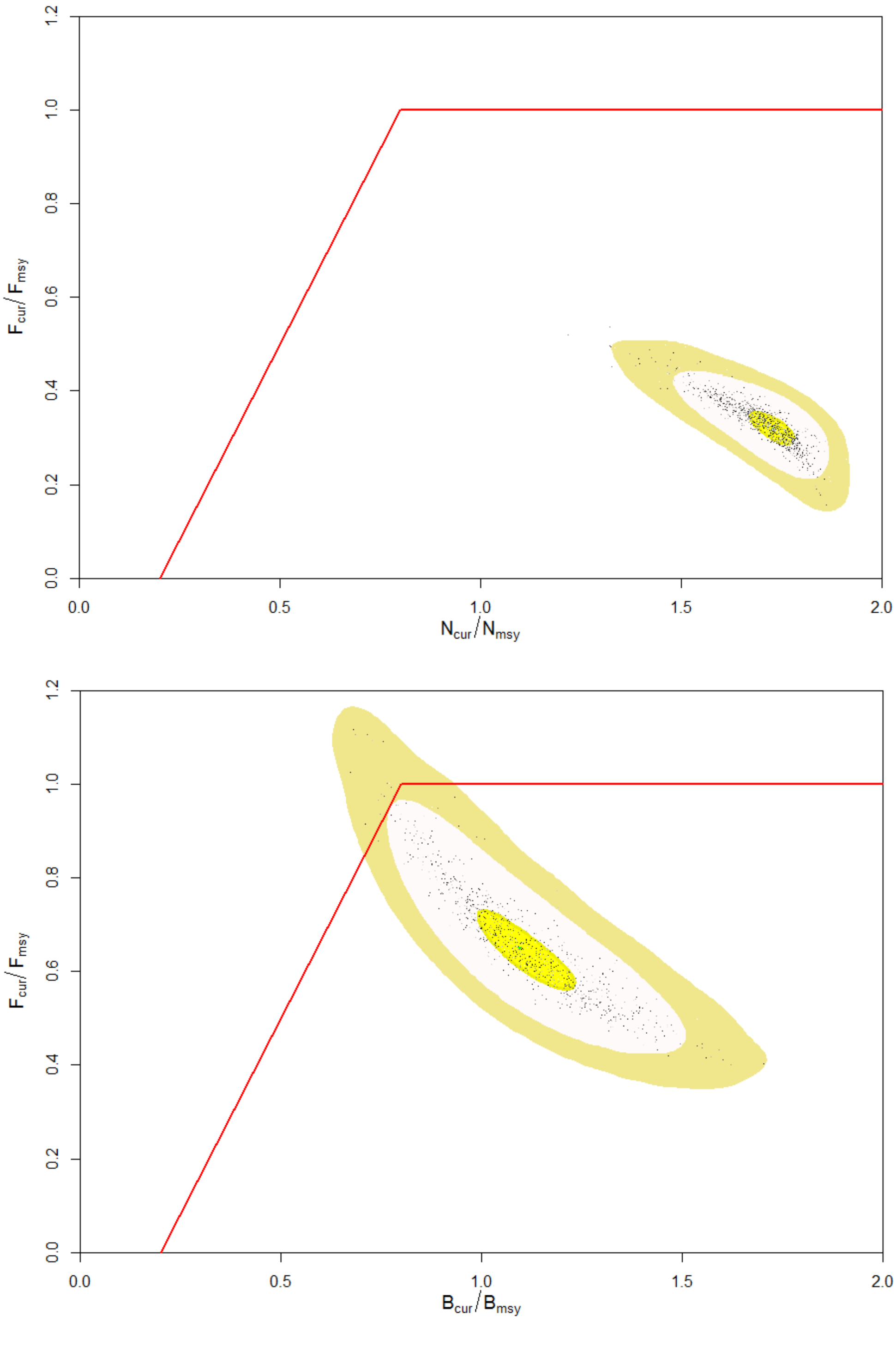

Figure 25. Graphic summary of the stock status of Arctic Char population abundance (upper panel) and biomass (lower panel) where the 'fried egg' represents uncertainty, described by the precautionary reference line (red) and simulation of current population state corresponding to the fishing status by Kobe-egg smoothing. The isograms were graded to 0.01 (yellow), 0.1 (snow) and 0.8 (Khaki), respectively.

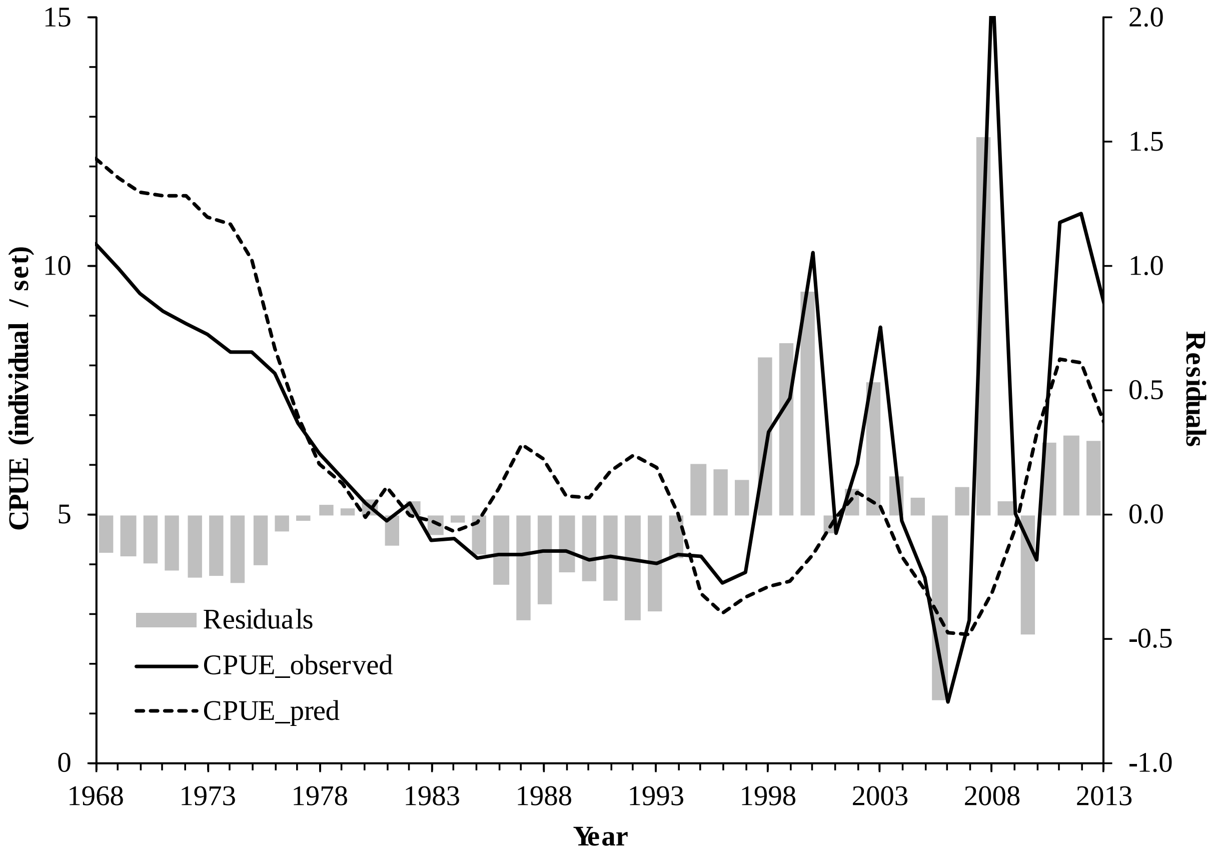

Figure 26. Comparison of observed (solid line) and predicted CPUE series (individual/gillnet set) as well as standardized residuals fitted by the SCA model. The CPUE series from 1968 through 1988 were generated in connection with parameter estimates of DB-SRA and SPM models for Arctic Char in the Hornaday River.

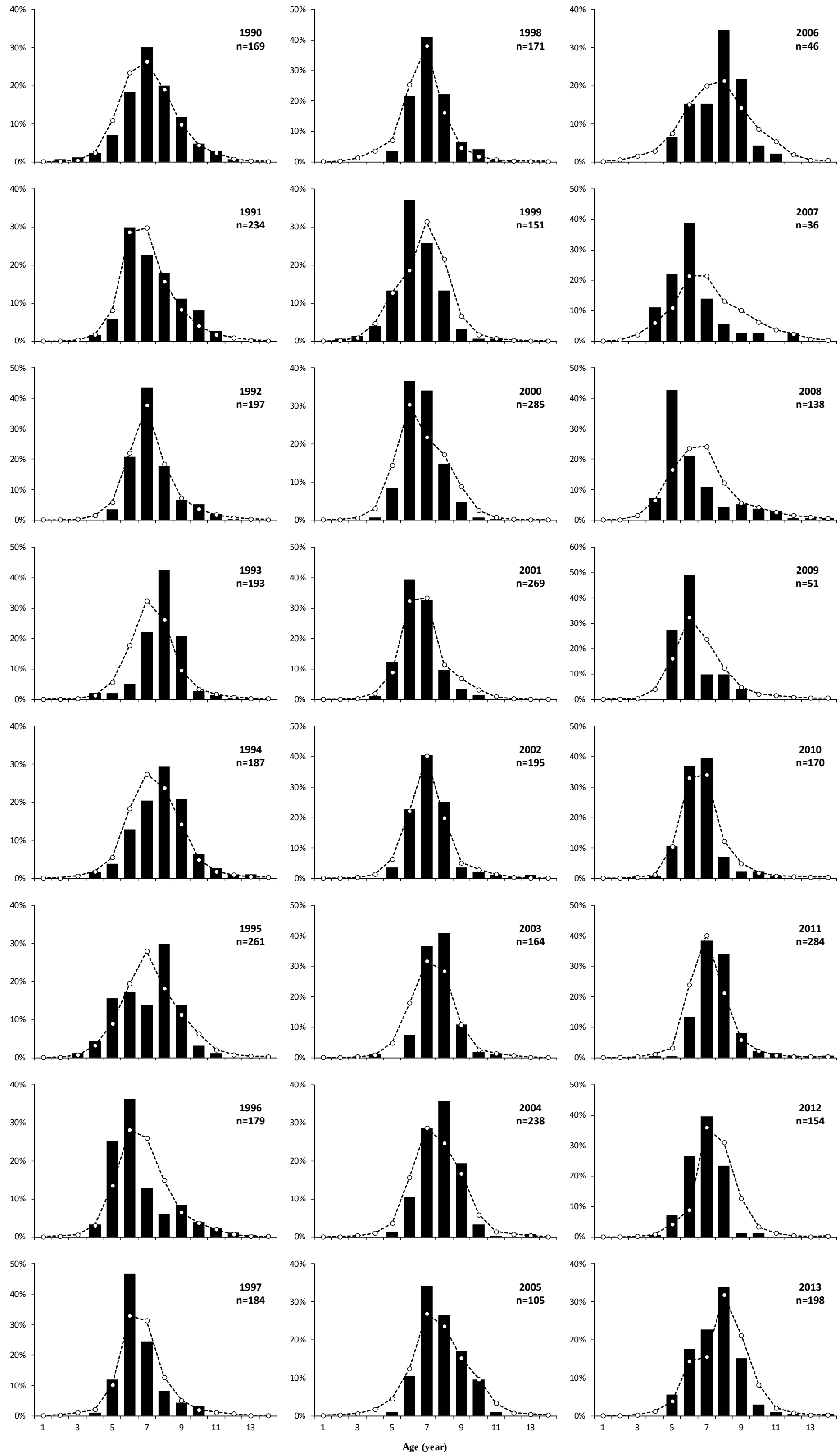

Figure 27. SCA fits (circle plus dashed line) of survey-based age composition (solid bar) for Arctic Char in the Hornaday River during 1990-2013.

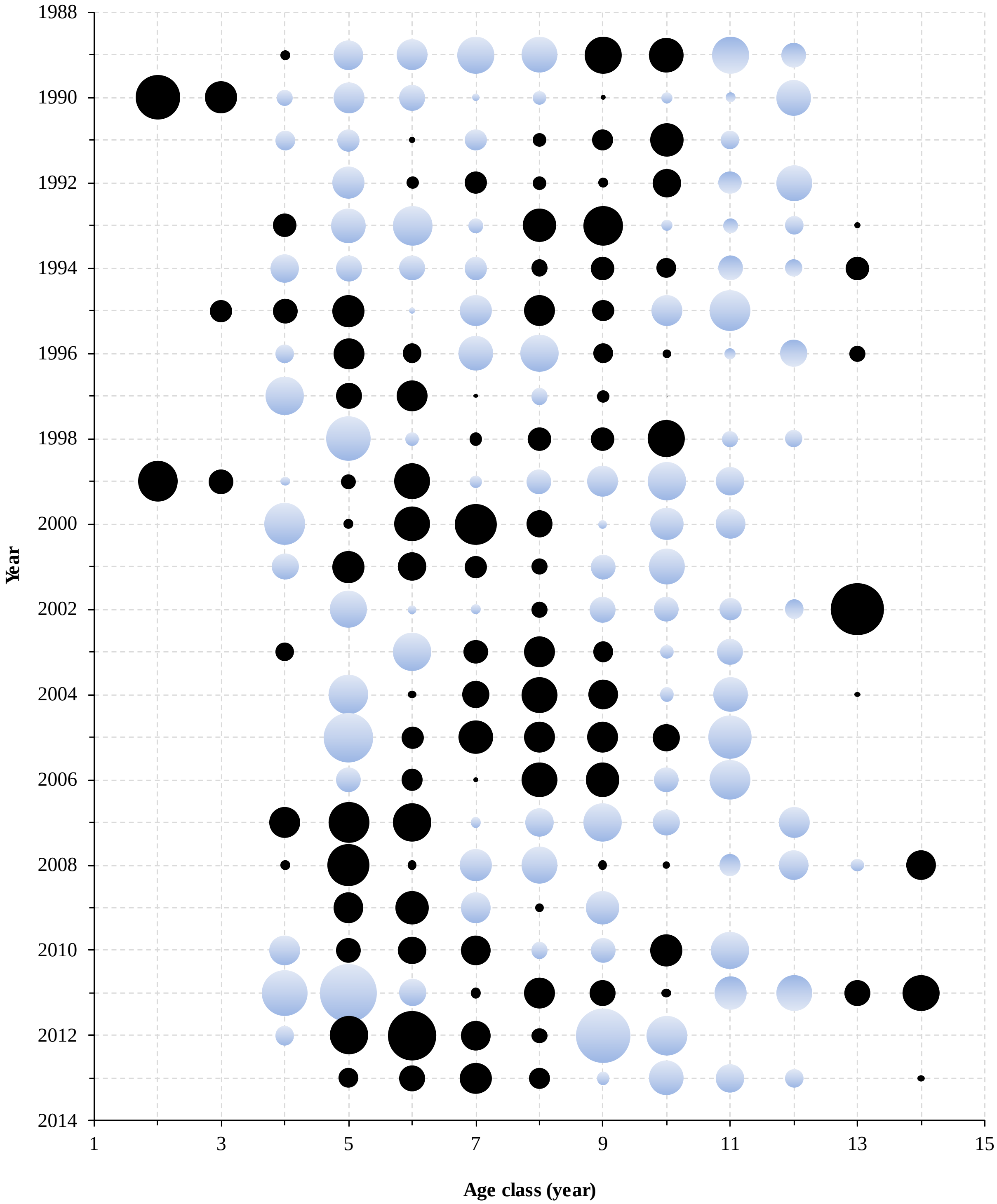

Figure 28. Bubble plots for negative (red) and positive (black) Pearson residuals between observed and predicted proportion-at-age of Arctic Char fisheries in the Hornaday River. Bubble size is set to 20.

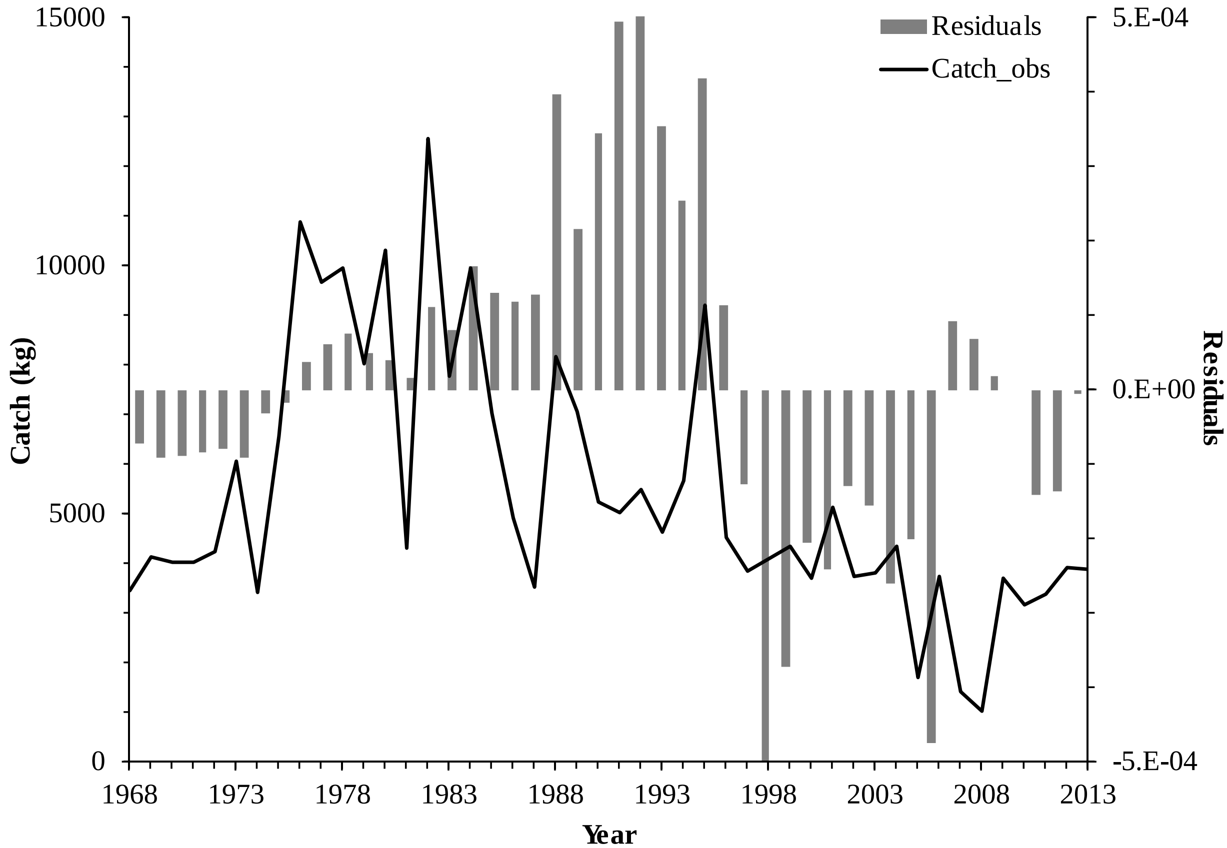

Figure 29. Changes of Pearson residuals between the observed and predicted catch for Arctic Char in the Hornaday River during 1968-2013.

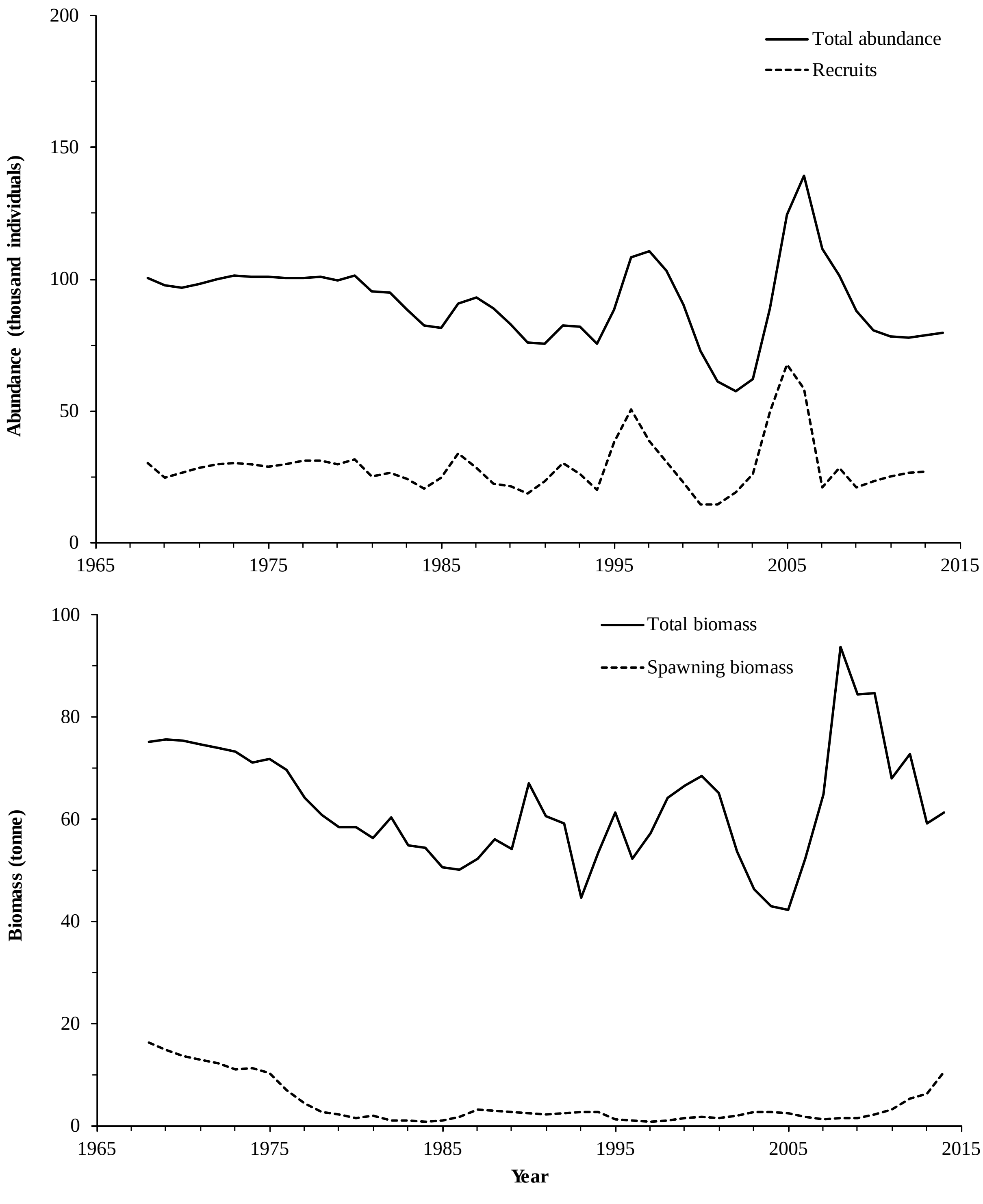

Figure 30. Changes of age-1 stock recruits and total abundance (upper panel) as well as spawning stock and total biomass (lower panel: kg) for Arctic Char in the Hornaday River.

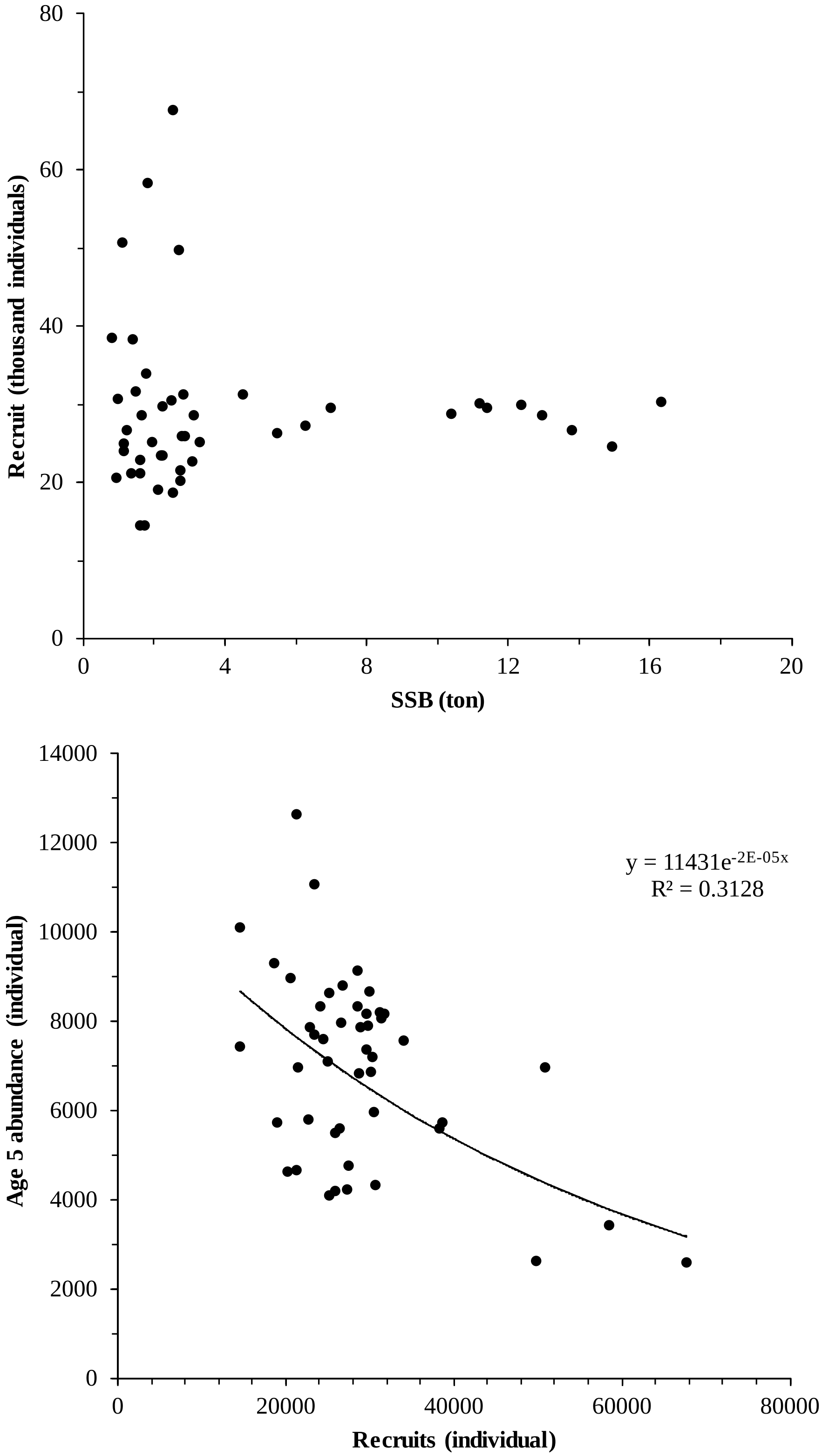

Figure 31. Relationships between spawning stock biomass (SSB: tonne, upper) versus recruits (individuals) as well as age-1 recruits versus age-5 abundance (lower panel) for Arctic Char.

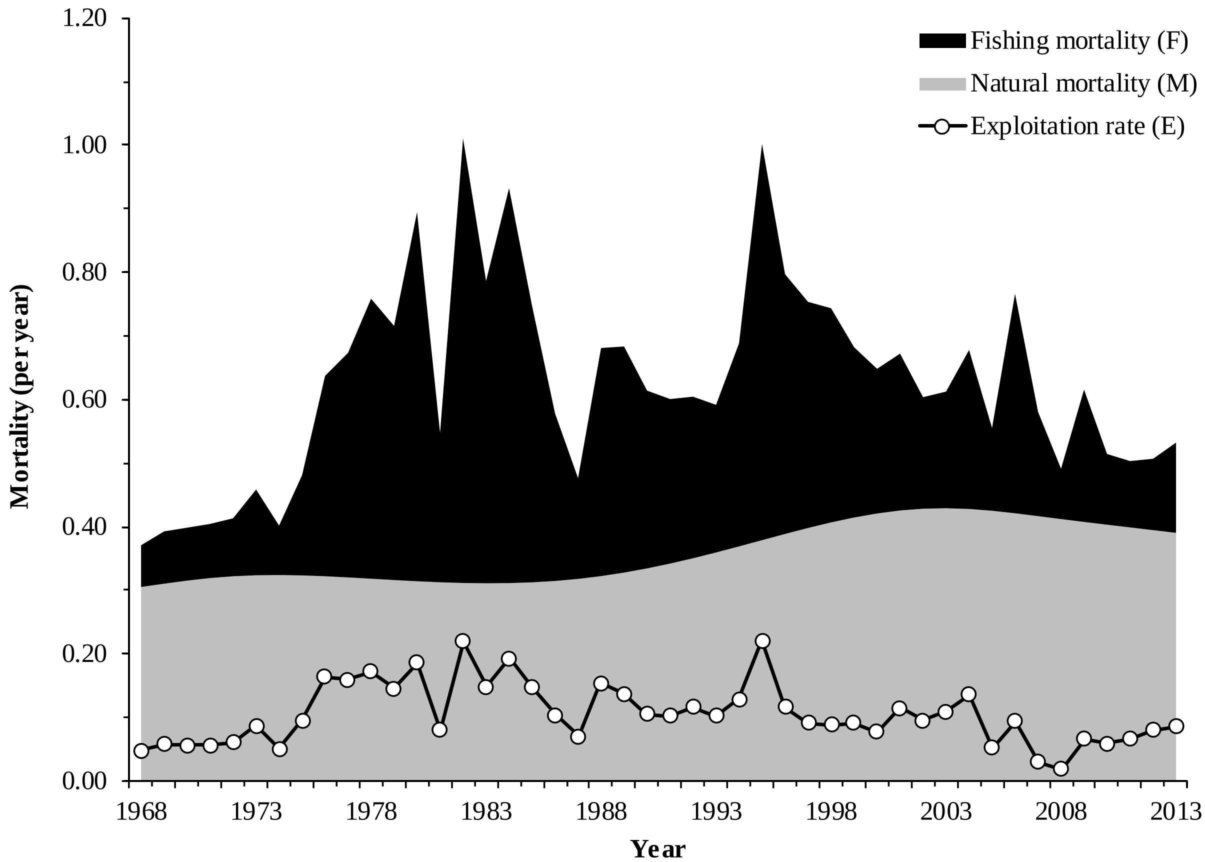

Figure 32. Graphic summaries of annual natural (M) and fishing mortality rates (F) as well as exploitation rate (E) for Arctic Char in the Hornaday River between 1968 and 2013.

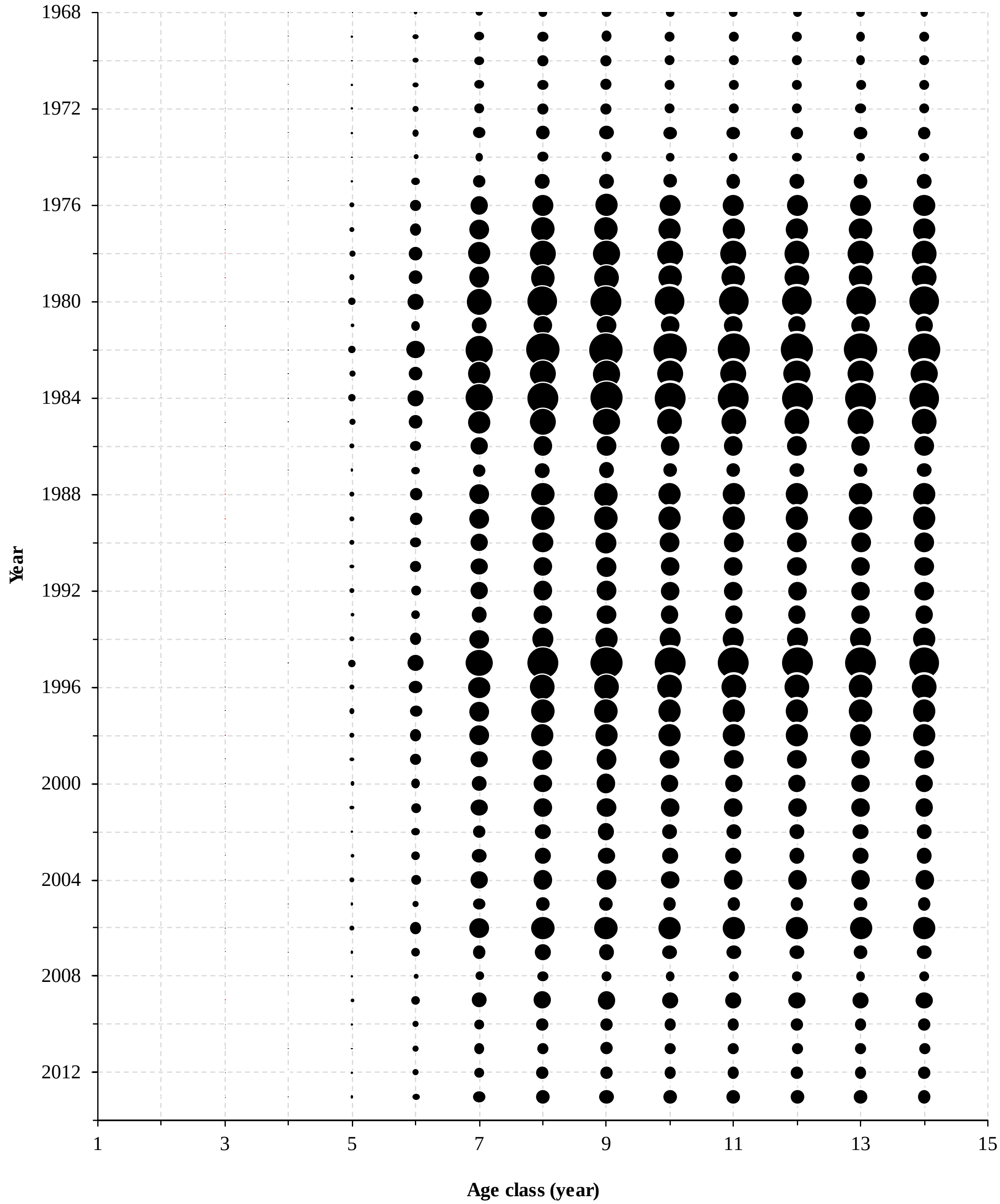

Figure 33. Maximum likelihood estimates of age-specific fishing mortality (F) for Arctic Char in the Hornaday River over years 1968-2013, expressed by bubble plots with the bubble size 12.

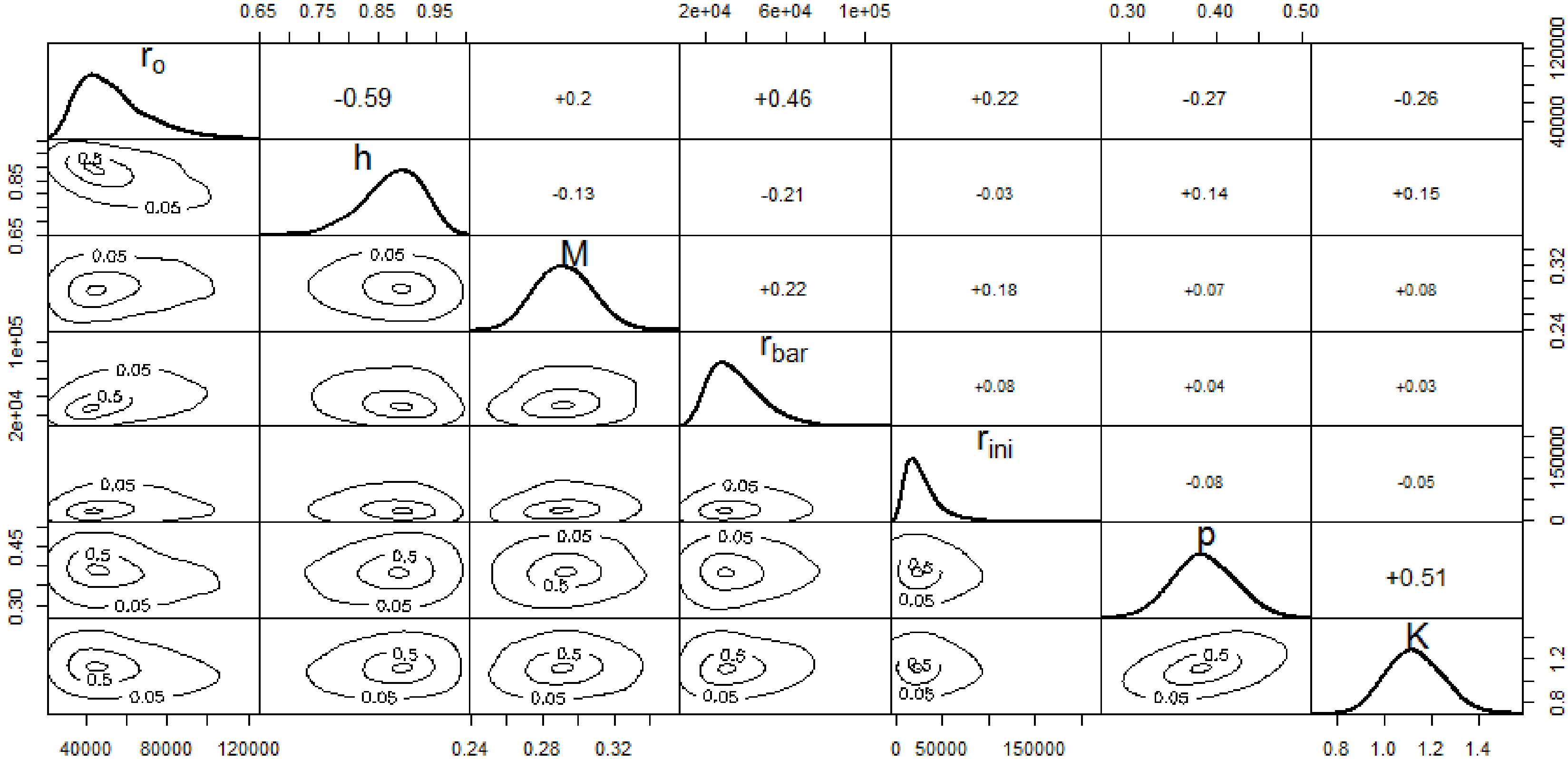

Figure 34. Probability distributions of SCA model parameters, YOY un-fished recruitment (r_0), average recruitment (r_{bar}), initial values of recruitment (r_{ini}), stock-recruitment relationship parameter (h), ratio of process to total error (p), and recruitment compensation (K) for Arctic Char in the Hornaday River. Isograms indicated covariate relations and digits for spearman correlation coefficients.

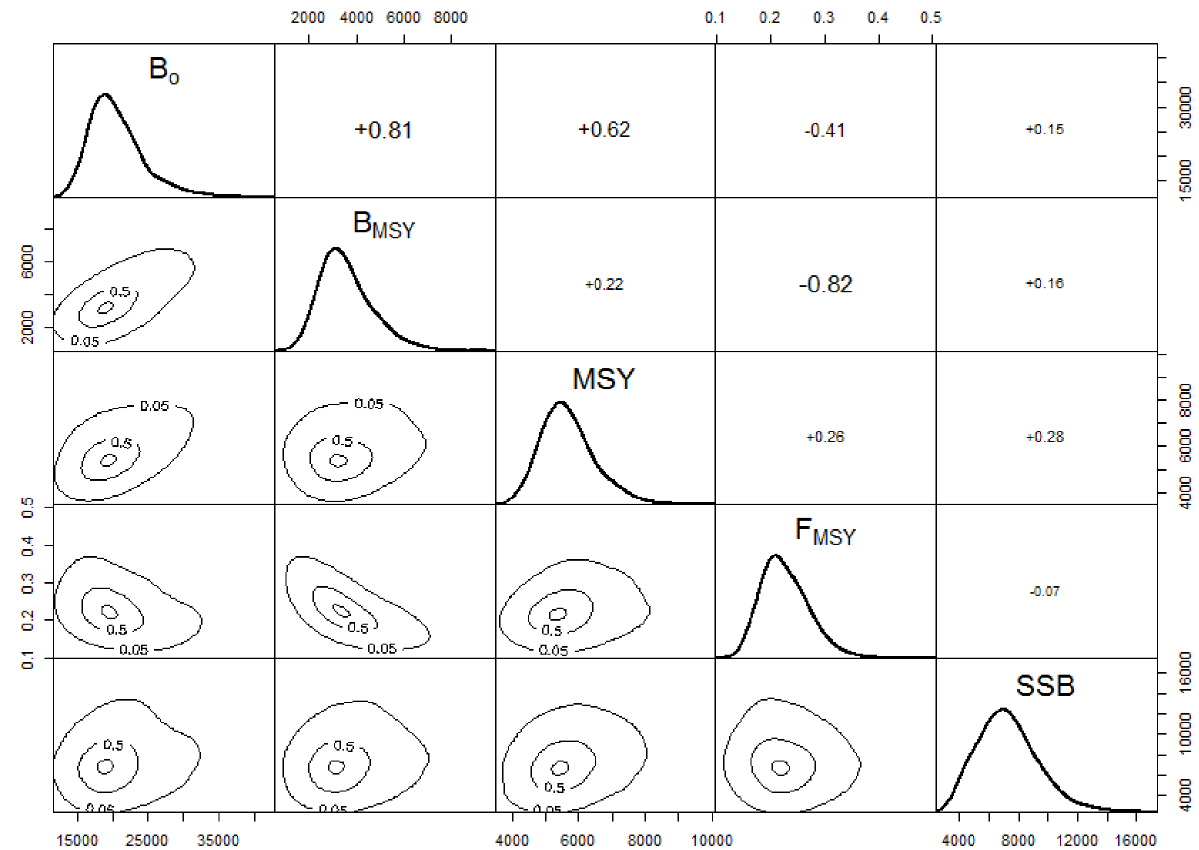

Figure 35. Probability distributions of un-fished spawning biomass (B_0), maximum sustainable yield (MSY) and corresponding fishing mortality (F_{MSY} and biomass (B_{MSY}), as well as spawning stock biomass (SSB) of Arctic Char in the Hornaday River. Isograms indicated covariate relations and digits for spearman correlation coefficients.

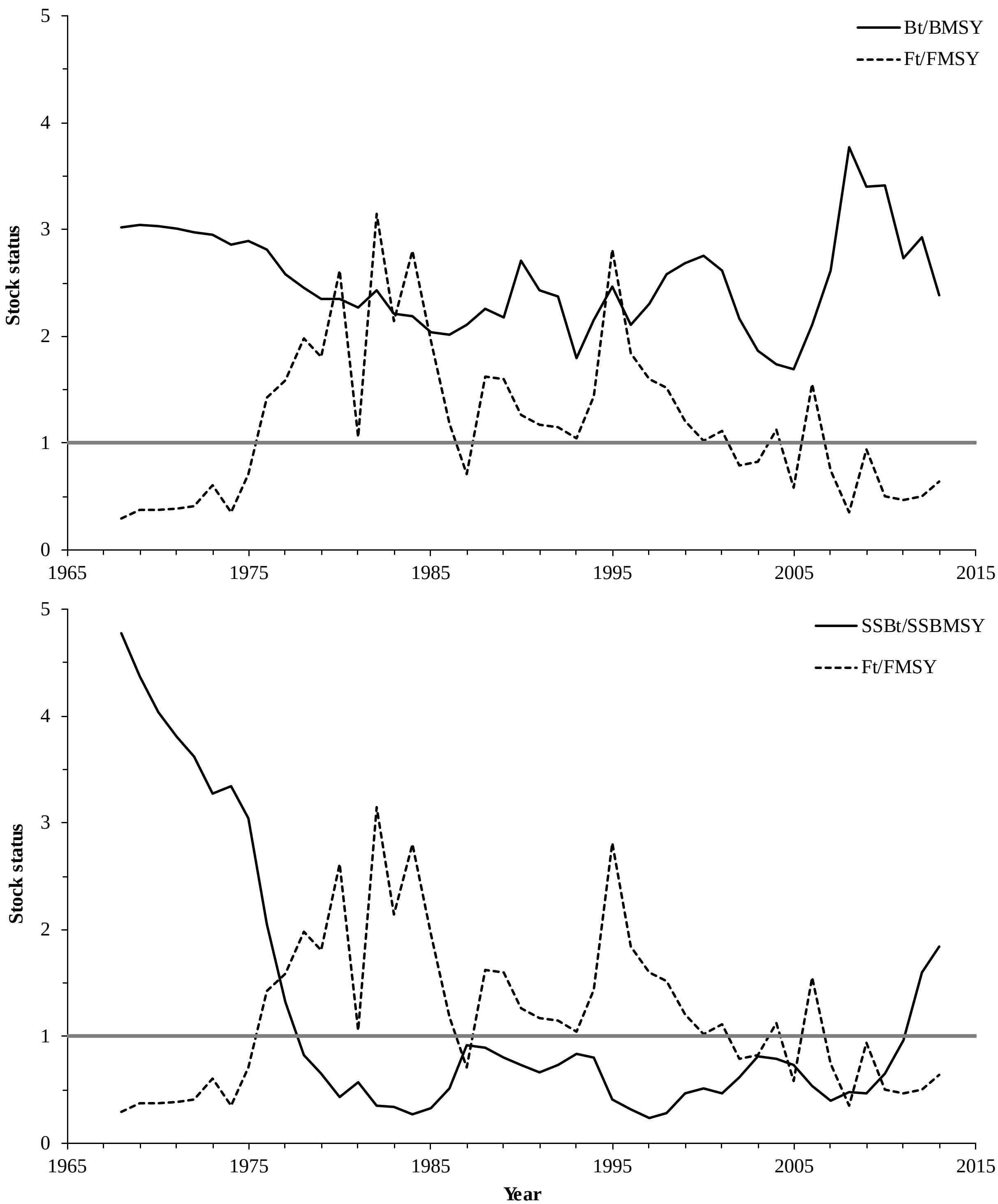

Figure 36. Stock status of total biomass (B_t) relative to B_{MSY} (upper panel) and total spawning biomass SSB_t relative to spawning biomass at SSB_{MSY} (lower panel) versus removal rates (F_t/F_{MSY}) for Arctic Char in the Hornaday River. The baseline condition (ratio=1.0) was indicated by a grey line.

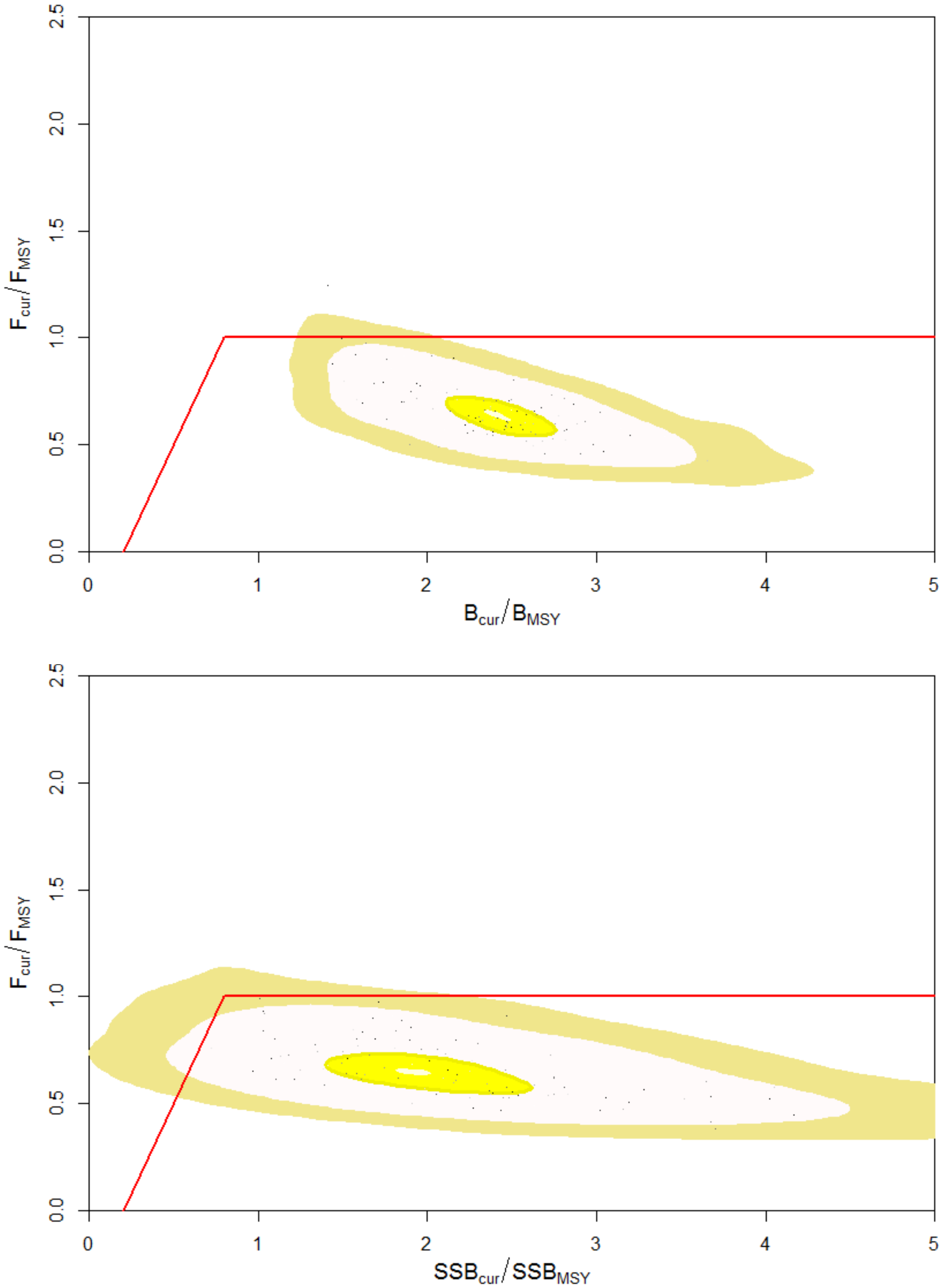

Figure 37. Graphic summary of the stock status of Arctic Char populations biomass (upper panel) and spawning stock biomass (lower panel) where the 'fried egg' represents uncertainty, described by precautionary reference line (red) and simulation of current population state corresponding to the fishing status by Kobe-egg smoothing. The isograms were graded to 0.01 (yellow), 0.1 (snow) and 0.8 (Khaki), respectively.