USING NON-TRADITIONAL METHODOLOGY TO EVALUATE THE INFLUENCE OF COMMERCIAL OPERATIONS ON GREAT SLAVE LAKE TROUT, *SALVELINUS NAMAYCUSH*

by

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A thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Biological Sciences

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Winnipeg

THESIS ABSTRACT

Multiple surveys have taken place on Great Slave Lake with the aim of collecting data on fish populations to achieve sustainable management, however, a lack of consistency and lake coverage from these investigations' limits data useability. Misinterpretations of data collected in early research likely contributed to the collapse of the Lake Trout, *Salvelinus namaycush,* stocks shortly after the commercial fishery began. The limited abundance indices available for Lake Trout, further complicated by inconsistent management areas and recording methods, prevents the incorporation of all available data into a conventional stock assessment model. Therefore, CMSY++, the most recent version of the data-limited, surplus production model, CMSY, was applied to assess the status of Great Slave Lake Trout populations. The results generated in this assessment predict that Lake Trout stocks in all current commercially fished regions are overfished, with combined Lake Trout and Lake Whitefish, *Coregonus clupeaformis*, quotas above estimated Lake Trout maximum sustainable yields. My findings indicate Lake Trout commercial harvest in recent years has surpassed the estimated maximum sustainable yield for the stock in some management areas. Inferences from modeling catch-time series of varied lengths suggest ~50 years of catch data should be sufficient for reference point estimation for these Lake Trout populations, as longer time series did not decrease uncertainty. The management areas with the most commercial harvest (Areas IW & IE) reveal the greatest uncertainty associated with biomass estimates, suggesting more data is required to better understand the current state of the stocks and any increases to quotas should not occur until this is done. Conclusions of my research support those suggested over 50 years ago; Lake Trout and Lake Whitefish, should be managed through separate commercial quotas to achieve sustainable management for these populations.

ACKNOWLEDGMENTS

Immense appreciation and thanks for my co-advisors, Dr. Kimberly Howland, and Dr. Darren Gillis for their support during the entirety of my thesis and degree completion. Your guidance, willingness to help, and belief in my abilities, has been a driving force in the success of my education and thesis. The adaptability and humour of my supervisors during uncertain times has and will always be greatly appreciated. Additional thanks for the rest of my committee members, Dr. Ross Tallman, and Dr. David Walker: thank you for your thought provoking questions, discussions, and trust in the process.

Furthermore, I would like to acknowledge the numerous commercial fishers, Fisheries and Oceans Canada team members, including Dr. Muhammad Yamin Janjua, Dr. Xinhua Zhu, Mrs. Heather Clark, and the Great Slave Lake community members, who have contributed to the data collection, and dialogue related to these fisheries. I would also like to acknowledge and thank my personal support system for their constant belief in me, you all have played an integral role in reaching this goal, and I am incredibly grateful to have you all in my corner.

A final thanks for the various funding contributors for this project which have included Fisheries and Oceans Canada, the Cumulative Impact Monitoring Program for Northwest Territories, a TESA (Technical Expertise in Stock Assessment) scholarship, and contributions from Dr. Gillis' NSERC Discovery Grant.

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CHAPTER 1: INTRODUCTION

Freshwater systems, and the organisms that occupy them, have high importance in Canada and worldwide with fish stocks providing vital protein, recreation, employment, and cultural value to many Indigenous communities and citizens (Schindler 2001; Islam and Berkes 2016; Pitcher 2016). Even with its high importance, misuse of freshwater ecosystems often occurs. Fish populations are continually compromised by overexploitation, introductions of non-native species, and by pollutants with a variety of potential impacts (Schindler 2001; Strayer and Dudgeon 2010; Fitzgerald et al. 2018). Globally, Lake Trout, *Salvelinus namaycush*, populations have already been drastically affected by anthropogenic forces, which has led to the collapse of stocks in numerous Canadian freshwater lakes, especially in more populated regions. This includes the collapse of the Laurentian Great Lakes trout stocks, influenced largely by exploitation and the unintentional introduction of lamprey (Healey 1978; Hanson 1999; Schindler 2001).

Certain freshwater locations, such as northern latitude lakes, warrant additional concern. Numerous stressors threaten these locations, but unfortunately the potential impacts of climate change are largely unknown, with baseline information often lacking in remote areas largely due to difficulties in conducting research (Evans 2000; Reist et al. 2006; Strayer and Dudgeon 2010). However, large freshwater lakes, such as North American Great Lakes including Lake Superior, Great Bear Lake, and Great Slave Lake, still have potential for high economic and cultural value (Strayer and Dudgeon 2010; Pitcher 2016). With the increasing need for food stability in the world, additional pressure on these fisheries in unavoidable (Strayer and Dudgeon 2010; Pitcher 2016). There is consensus in the literature that there is presently a need for more robust methods for assessing and managing fish stocks at every scale to ensure sustainable management of fisheries (Schindler 2001; Allan et al 2005; Fujita 2021) with even greater attention needed in the assessment of inland and Arctic fisheries (Reist et al. 2006; Lorenzen et al. 2016).

Policy makers rely on the knowledge obtained from scientists and community members to help determine the status of fish stocks and to ensure sustainability and effective management (Bentley 2015; Lorenzen et al. 2016). Values known as management reference points, often determined through simulations and models, help reveal information on current and past stock states and can also represent harvesting targets and limits (Richard and Maguire 1998; Pitcher 2016). More advanced population modeling methods to predict reference points can be utilized in situations where the fishery has a large quantity of reliable data (data-rich); in particular, abundance indices and age, or size class data (Dick and MacCall 2011; Bentley 2015; Pitcher 2016). However, this can be complicated due to data gaps in fisheries and fish populations preventing complex stock assessment models and ecosystem simulations (Bentley 2015; Reist et al. 2016; Fujita 2021). Where data accumulation has been slower and less informative, often occurring in inland and smaller scale fisheries, little information is available to make management decisions (Fitzgerald et al. 2018). These stocks are typically classified and referred to as *data-limited* or *data-poor* (Bentley 2015; Fitzgerald et al. 2018), with the terms often used interchangeably. (For the remainder of the thesis these methods will be referred to as data-limited). These data-limited stocks may still possess some information on effort and catch, but limited time-series has restricted their utility in stock status assessment (Fujita 2021).

Recently, many data-limited models with varying data input requirements have surfaced, (e.g., Dick and MacCall 2011; Cope 2013; Froese et al. 2017), providing new opportunities to assess such stocks. These models vary in their suitability on a case-by-case basis depending on factors such as: the demographic traits of the target species, available years of catches, and current depletion level (Pons et al. 2020). Due to typical data-availability, catch-based surplus production models are often determined as the best-suited modeling method in data-limited situations (Lorenzen et al. 2016; Pitcher 2016; Fitzgerald et al. 2018). A relationship between catch values and predicted biomass is interpreted by these models, with management reference points, such as the maximum sustainable yield, estimated based on this relationship (Pitcher 2016; Pons et al. 2020). Thus, many of these models require catch values as primary inputs, however, total fishery production can be complicated by misreporting, culls, and waterbodies with multiple uses (van Gemert et al. 2021), such as Great Slave Lake. Even with the various critiques that have accompanied these stock assessment methods (e.g. Walsh et al. 2018; Free et al. 2020; Pons et al. 2020); these methods have proven valuable in providing baseline information for stocks that are lacking informative data to assess status and are often seen as a building block for the development of more complex assessments (Liang et al. 2020; Pons et al. 2020; Nisar et al. 2021).

Data-limited fisheries may include those with less monetary value, lower annual catches, and fewer livelihood opportunities, and consequently have not warranted more aggressive data collection and assessment methods, but this is not always the case (Pitcher 2016; Fitzgerald et al. 2018). Great Slave Lake, in Northwest Territories, Canada, is the fifth largest lake in North America and tenth in the world (Kennedy 1956; Yaremchuk 1986), at a size of ~28,000 km^2 (Reist et al. 2016). The lake is home to fish stocks that are of high importance to not only the surrounding communities, but also to commercial fisheries that distribute catches, and their patrons worldwide (Healey 1978; McDermid et al. 2010). However, due to an unclear understanding of stock dynamics and how commercial operations could influence them, Great Slave Lake Trout were mismanaged at the onset of the commercial fishery which led to harvesting well above sustainable yields. The management of Great Slave Lake is complicated further by differences in production capabilities in lake regions due to variations in lake characteristics, including underlay, depth, island prevalence, and proximity to inflows and outflows (Keleher 1972; Zhu et al. 2017).

The lack of long-term monitoring and scientific studies at the fish population level for Great Slave Lake has resulted in data gaps that prevent the use of traditional fisheries stock assessment methods for many species, including Lake Trout (Zhu et al. 2017). Even with research investigations beginning prior to the initiation of the commercial fishery in 1944 (e.g., Rawson 1947), inconsistencies in methodology and changes to management regimes complicate the integration of historical data sets in stock assessment. Early fisheries production and studies, including those on Great Slave Lake, were conducted with small boats and hand-operated equipment (Kennedy 1950), which is quite different than methods used in current fishery work (Schindler 2001; Palomares and Pauly 2019). Additionally, initial commercial fishery operations were harvesting from a population that consisted of individuals that had been accumulating since the species established itself in the region (Keleher 1972). The use of such values can complicate analysis by creating a potential for a shifting baseline, where initial research results and conclusions may no longer be valid for the evolved system following initial harvests (Palomares et al. 2018; Schijns et al. 2021).

Although still commercially harvested, the long-lived, slow growing Lake Trout stocks of Great Slave Lake were later seen as unable to withstand extensive gillnetting associated with the commercial fishery (Bond 1974). This practice contributed to the collapse of the western basin's Lake Trout stocks, and commercial closure of some eastern lake areas during the 1970's in order to protect remaining stocks (Yaremchuk 1986). It has previously been suggested that commercially caught Lake Whitefish and Trout should be managed separately (Keleher 1972), however, a combined quota remains for these two vastly different species (Northwest Territories Fishery Regulations 2023). The desire and need for a more adequate assessment of Great Slave Lake Trout populations has been identified, as these stocks have substantial value for surrounding communities and are important to those that rely on subsistence, commercial and recreational catches, acting as a staple for all fisheries on the lake (Rawson 1951; Healey 1978; McDermid et al. 2010). It remains apparent there is still much to know about these stocks, however, recent initiatives (e.g., Government of Northwest Territories 2017) have been put forth with the aim of increasing production and the economic value of the Great Slave Lake commercial fishery.

The current project addresses the need for a more robust stock assessment to guide the management of this valuable resource, aided by a review of past research and data collection. In this study, sustainable yields and management reference points are estimated for Great Slave Lake Trout using non-traditional, data-limited, assessment methods, that have fewer data requirements than those used in data-rich fisheries (Chapter 3). Selection of appropriate methods for assessment was determined through a review and collation of available fishery data (Chapter 2). These core chapters are preceded by the current brief introduction (Chapter 1) establishing the broader perspective of the thesis and a conclusion with a short discussion (Chapter 4) to help further interpret and integrate the research.

The present research can be used to help address questions related to the productivity and sustainability of the Great Slave Lake Trout fishery, as well as provide management reference points and assist with a planned future Integrated Fisheries Management Plan for Great Slave Lake. This research not only adds to the literature on the application of data-limited methodology, but also to inland Arctic fisheries: an area of research with known data gaps (Reist et al. 2006).

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CHAPTER 2: THE ROLE OF LAKE TROUT IN THE DEVELOPMENT OF ARCTIC CANADA'S LARGEST FRESHWATER FISHERY ON GREAT SLAVE LAKE - A SYNOPSIS

Abstract

The complexities of Great Slave Lake and its fisheries (e.g., varied production abilities, and effort among regions) have added challenges to the identification of demographic trends and changes in harvested species. The need for an evaluation of stock status and health of Great Slave Lake Trout, *Salvelinus namaycush,* an important component of the largest northern commercial freshwater fishery, has been complicated by minimal research attention and monitoring of harvested populations. Historical research aimed at exploring lake productivity at the beginning of commercial operations ultimately fell short in its conclusions, contributing to the overharvest of Great Slave Lake Trout within the first decade of the fishery. Combined with lake closures and typical difficulties associated with northern research, this has resulted in sporadic temporal and spatial coverage of data for both commercial harvest and biological information. The limited available data point to the commercial fishery as historically the primary mechanism altering populations, however presently other factors may be influencing production. Uncertainty in the current state of populations, compounded with historic recollections of misunderstood harvest data, has resulted in the need for an updated assessment of these economically and culturally valuable fish stocks.

Introduction

Great Slave Lake in Northwest Territories (NT), Canada (Figure 2.1), has multiple fish stocks that are culturally valuable to surrounding communities and important to those that rely on the multiple fishery types on the lake (Rawson 1951; Healey 1978; McDermid et al. 2010). Commercial, recreational, as well as subsistence fisheries occur on Great Slave Lake with Lake Trout, *Salvenius namaycush* (Walbaum, 1792), being an important component of all three (Kennedy 1956; Keleher 1962; Zhu et al. 2017). The Great Slave Lake commercial fishery is exceptionally valuable for NT given its proportionally high landings for the entire territory (Sinclair et al. 1967; Day and Low 1992).

As a result of the historic Pleistocene glaciation (8,000 – 12,000 years ago), large lakes of northern Canada, such as Great Slave Lake are considered relatively young ecosystems with limited known anthropogenic influences (Johnson 1976; Hendendorf 1982; Evans 2000). However, recent research indicates effects of climate change have begun to appear (e.g., Ruhland et al. 2023). Characteristics of the watersheds surrounding the Northern Great Lakes include largely undeveloped regions with low populations and industrialized areas only established in a few cities (Evans 2000). Largely unexploited, there are many valuable resources and recently developed extraction industries located in the surrounding areas. However, northern waterbodies are becoming increasingly susceptible to environmental concerns, with the response of individual ecosystems, largely unknown (Strayer and Dudgeon 2010; Reist et al. 2016).

Compared to other northern fisheries, Great Slave Lake is considered unusual, in that, periodically, since the onset of the commercial fishery, some biological information for harvested species has been collected (Bond and Turnbull 1973; Day and Low 1992). Domestic and local fisheries have existed since the first settlers inhabited the shorelines, with the Great

Slave Lake commercial fishery beginning in 1945 (Keleher 1962). The first twenty years of the fishery saw rapid expansion with exploitation of the long-accumulated fish stocks in all areas of the lake (Bond 1974). This resulted in changes to Lake Trout production, and population demographics (e.g., decreased average weight) within the first ten years of commercial operations (Keleher 1962, 1972a, 1972b). By the early 1970's the Lake Trout commercial fishery in the western areas of the lake experienced catch rate declines that forced a shift in the primary target species to Lake Whitefish, *Coregonus clupeaformis*, and ultimately influencing the management decision to close the East Arm to commercial fishing in November 1974 (Moshenko et al. 1978; Yaremchuk 1986; Low 2006). Findings of historic Great Slave Lake fishery-independent experimental netting revealed Lake Trout accounted for 10% of the fish community by numbers, and 46% by weight (Rawson 1949). However, by 1972, similar fishery-independent experimental netting results suggested that Lake Trout accounted for 2.3%, and 6.5%, of fish community by numbers, and by weight, respectively (Bond and Turnbull 1973), while recent experimental net survey data estimate Lake Trout species composition at 0.6% of the fish community by numbers, and 6.6% by weight (Zhu et al. 2017).

There have been few scientific investigations in relation to stock assessment and status of Lake Trout in this system despite previous investigations into production capabilities of the lake, the early onset of the fishery, the known crash of Lake Trout, and the acknowledgement of a need for additional assessments of Great Slave Lake Trout (Healey 1978; Yaremchuk 1986; Low 2006). Furthermore, most studies on this and other species, in general, focus on the southern portion of their ranges and are extremely limited for northern freshwater bodies (Schindler 2001; Callaghan et al. 2016; Palomares et al. 2020). Success and certainty in the identification of demographic trends and yield estimates for Great Slave Lake stocks are further complicated for multiple reasons. This includes the unique traits and distributions of fish populations, which have evolved due to the lake's vast size and variation in physical features in different areas (Rawson 1951; Zhu et al. 2017). Other challenges for assessment include the relatively remote location of the lake, inconsistent data collection needed to determine and identify trends in demographic rates, changes to management and administration areas, and a lack of consistency in fleet involvement and harvesting records. Nonetheless, recently there has been increasing interest in commercial operations from an economic development standpoint driven by initiatives to revitalize the commercial fishery (e.g., Government of Northwest Territories 2017). Furthermore, there is increasing concern for the possible implications of climate change on this and other freshwater systems (Schindler 2001; Ruhland et al. 2023). These factors combined reinforce the need for better understanding of this commercially, and culturally, valuable species, in addition to evaluating sustainable harvest levels. The following is an extensive review and synthesis of available Great Slave Lake fishery information with an emphasis on Lake Trout data and research. The first thirty years of the commercial fishery are thoroughly explored to help reveal the major influences that were associated with declines in Great Slave Lake Trout stocks. The goal of this chapter is to provide previous interpretations of historical data, identify knowledge gaps, and background for future stock assessments aimed at Lake Trout.

Study Location – Great Slave Lake

Site Description

Great Slave Lake (Figure 2.1), a freshwater waterbody, is a member of the chain of inland lakes from 50°N to 63°N known as the Northern Canada Great Lakes (Evans 2000). Specifically, the lake lies at 61-63°N and 109°-117°W, with Great Bear Lake residing approximately 300 km to the Northwest (Kennedy 1956). The climate of the area has been described as northern continental/subarctic (Kennedy 1956; Bond 1974; Yaremchuk 1986). Great Slave Lake, the fifth largest lake in North America and tenth in the world, drains into the Mackenzie River; the Slave River is the lake's biggest input (Figure 2.1) (Kennedy 1956; Yaremchuk 1986; Zhu et al. 2017). The lake has a drainage area of 958 300 km^2, a surface area of 27 195 km^2 (Bond 1974), an elevation equal to 156 m (Hendendorf 1982; Reist et al. 2016), and is part of the 4200 km long Mackenzie River drainage system (Rawson 1950; Zhu et al. 2017). Great Slave Lake belongs to the Peace-Athabasca-Slave-Mackenzie River system, which carries water originating from snow/ice of the Rocky Mountains, and eventually drains into the Arctic Ocean (Schindler 2001). The major outflow of Great Slave Lake, the Mackenzie River, is reached from the lake by channels running on either side of Big Island in the southwestern region (Keleher and Meeker 1962). The average water residence times are 7 and 12 years for the western basin and whole lake, respectively (Rawson 1950).

Given the northern location, and youth of the system, development in the surrounding area has been slow, however, small communities exist around the lake with various infrastructure associated with exploration. Hay River, a predominant Great Slave Lake community, is located on the largest of nine islands that make up the Hay River delta, Vale Island, along the southern shoreline at the inlet of the river. Yellowknife, and Gros Cap are situated along the northern shore, while Fort Resolution (Figure 2.1), is on the southeastern shore. Taltheilei Narrows (separating Christie and Mcleod Bay), Reliance, and Lutselk'e (Figure 2.1) are all communities located along the northern east arm of Great Slave Lake (Keleher and Meeker 1962; Sinclair et al. 1967; Northwest Territories Fishery Regulations 2023). Access to these areas has gradually increased with the development of infrastructure. These developments include the completion of

Mackenzie Highway connecting Hay River to Grimshaw, Alberta in 1948 (Keleher 1962), Yellowknife Highway connecting Yellowknife to the Mackenzie Highway system in 1960 (Prince of Wales Northern Heritage Centre 2022), and the completion of the Liard Highway connecting Alaska to the Mackenzie Highway in 1984 (Dene Nation 2022).

Like many other northern regions, NT was largely settled due to the exploitation of mineral resources (Silke 2009). Numerous mines have operated in the vicinity of Great Slave Lake since the 1800's and have been a major influence on development around the lake. In the 1890's gold was first discovered in the Yellowknife River, while lead and zinc ore were found at Pine Point (Figure 1), leading to the first geological survey of Great Slave Lake in the early 1900's (Silke 2009; Cott et al. 2016). Gold prospector success in Yellowknife Bay throughout the 1930's resulted in the construction of a settlement, that later became the city of Yellowknife, by 1936, and the Con Mine gold mine in 1938, among other mining operations (Figure 2.1) (Silke 2009). Giant and Discovery mines (Figure 2.1) were formed following World War II and the discovery of additional gold availability around the community of Yellowknife (Silke 2009). Diamond mines opened as a result of diamond discoveries in 1991-92, including the Ekati Mine in 1998, however, throughout the 1990's-early 2000's many other mineral operations ceased, including the closure of the last remaining gold mine, Giant Mine, in 2004 (Silke 2009). These examples are not an extensive list of mining operations that have occurred in areas around Great Slave Lake and given the vast size of the northern territories future mineral extraction is likely (Silke 2009). Resource exploration in the form of mining has not only had a major influence on development around the lake but also research, such as environmental assessments aimed at evaluating mineral exploration effects on water quality and fish health (e.g., Palmer et al. 2015; Cott et al. 2016).

This glacial-origin lake formed during the Pleistocene glaciation, one of the most important processes in the development of large inland lakes in European and North American middle-northern latitudes (Hendendorf 1982). The lake resides along a contact line between two different types of geological base that has led to the formation of multiple unique physiographic areas that can more generally be broken up into the East Arm and the Main Basin or West Arm (Kennedy 1956; Bond 1974; Zhu et al. 2017). Mixed sedimentary igneous origin bedrock from the Proterozoic era underlays the southeast area of the lake, while the East Arm underlay is the product of a Proterozoic era fold belt combined with metamorphic rocks with gabbro and diabase intrusions overlain by sediment (Zhu et al. 2017). The Canadian Shield underlay found in the northeast area of the lake formed from Archean peneplain made up of sedimentary-volcanic greenstone belts and granites (Keleher 1972; Zhu et al. 2017). The oligotrophic nature of Great Slave Lake implies it has low photosynthetic production and nutrient content in comparison with other aquatic systems (Evans 2000; Krohne 2015). Differences in geographical characteristics and sources of water inputs between lake regions, have resulted in fish habitat with varying suitability for native species, thus having a large influence on Great Slave Lake fish distributions (Rawson 1950).

Rivers entering Great Slave Lake from Canadian Shield areas (e.g., Yellowknife River) are mainly cold, clear, and rapidly flowing, while those from southern origins, such as the Slave River, are generally brown, slower moving waters with high silt loads (Rawson 1950; Bond, 1974; Day and Low 1992). These incoming waters affect the limnology in different basins of the lake, resulting in variations in turbidity/water clarity, water temperature and primary production; all of which influence aquatic communities and the life histories of native fish species that depend on them (Rawson 1950). The primary input, the Slave River, carries waters from northern British Columbia and Alberta to Great Slave Lake and is responsible for 87% of total annual discharge into the lake (Zhu et al. 2017). The deepest waters are generally in the East Arm with maximum recorded depths of 614 m (Rawson 1950; Hendendorf 1982; Evans 2000), and 625 m (Bond 1974; Day and Low 1992). In contrast, the West Arm is shallower with soft substrates and maximum and average depths of 165 m and 42 m, respectively (Rawson 1950; Bond 1974; Day and Low 1992). Another unique area of Great Slave Lake is Yellowknife Bay: a large, relatively deep area considered somewhat isolated from the Main Basin by an underwater ridge located between the East and West Mirage Islands (Rawson 1950).

The long cold winters experienced around Great Slave Lake are contrasted with short summers, however, with long days of sunlight (Rawson 1950); a climate which is common to all lakes of the area (Johnson 1976). Early studies on the lake revealed water temperatures vary between years and locations around the lake, surrounding rivers and creeks, with break-up generally occurring in late May to Early June (Keleher and Meeker 1962). Great Slave Lake remains iced covered for approximately five and a half months of the year, with the Main Basin historically being ice free by June 15th on average, while the Hearne Channel (Figure 2.1) remains iced over for approximately one-week longer, and the East Arm bays remaining ice covered two weeks to a month longer than the Main Basin (Rawson 1950; Keleher and Meeker 1962). The freezing and break-up process on Great Slave Lake has historically occurred over a period of approximately two and a half months on either end of the ice-covered season (Rawson 1950). Ice begins to form first in the surrounding rivers in early October, followed by the smaller, shallow bays, around October 15, continued by the larger bays, around December 1st (Rawson 1950). Historical records indicate the Main Basin is completely ice covered by January 1st, a crucial factor in facilitating transportation around the lake as it allows isolated communities the ability to move further out and access additional resources (Rawson 1950). Additional facts on Great Slave Lake and its diversity can be found in Appendix I.

Fish Distribution & Key Species

Similar to many other arctic freshwater systems, Lake Trout and Lake Whitefish have been, and remain, primary components of the Great Slave Lake ecosystem (Johnson 1976; Zhu et al. 2017). During the initial studies of Great Slave Lake, twenty-one species of fish were identified, including Lake Whitefish, Inconnu (*Stenodus leucichthys*), and Lake Trout, however by 1956 an additional fish species, Yellow Perch (*Perca* flavescens), was discovered (Rawson 1951; Kennedy 1956). Little attention was paid to shallow waters and therefore other nearshore species may have been missed in earlier surveys (Rawson 1950). By the 1970's, the number of identified species grew to twenty-five, with nine species common in commercial catches, and Lake Trout and Lake Whitefish dominating (90% of catch) during the first twenty years of the fishery (Keleher 1972a). This is typical of Arctic lakes, where Lake Whitefish and Lake Trout have been reported to comprise nearly 95% fish biomass (Johnson 1976). A recent publication lists a total of 32 naturally occurring fish species in Great Slave Lake (Reist et al. 2016).

Study Species – Lake Trout, *Salvelinus namaycush*

Distribution

Lake Trout are a common member of the Salmonidae family of fish, found throughout freshwater lakes in North American, however, semi-anadromous populations have been documented at the northern limits of their range (Scott and Crossman 1973; Kissinger et al. 2016). This species is widespread throughout North America, with the natural range consistent with the locations of glaciation during the Pleistocene era (Lindsey 1964; Scott and Crossman 1973). Throughout Canada, Lake Trout populations occur in clusters in Southwest Nova Scotia & New Brunswick, Northern Quebec, and some parts of Labrador but do not reach the island of Newfoundland (Lindsey 1964; Scott and Crossman 1973). They are also found in Northern Manitoba, Saskatchewan, and British Columbia, and Southwest and Northeast Alberta (but are relatively absent from the central areas of the province) (Lindsey 1964; Scott and Crossman 1973). Lake Trout are widely distributed through much of Ontario, the Yukon, and Northwest Territories, as well as some Arctic Islands, including Baffin, Victoria, and Banks, in addition to lakes in Alaska (Lindsey 1964; Scott and Crossman 1972). Lake Trout presence in the southern areas of their range is restricted to deep, cold-water lakes, but they are capable of surviving in shallower waters in the northern areas they occupy (Daly et al. 1962; Lindsey 1964). Lake Trout can be found in the Hudson (New York) and Missouri (Montana) Rivers, in addition to a few Minnesota and Wisconsin lakes, and have been added to bodies of water as introduced populations elsewhere in North America and the world, including New Zealand and Sweden (Daly et al. 1962; Lindsey 1964; Scott and Crossman 1973). Unable to tolerate low levels of dissolved oxygen, and high levels of turbidity, Lake Trout within Great Slave Lake have been noted to avoid areas associated with high turbidity, such as the outlet of the Slave River (Zhu et al. 2017).

Appearance & Biology

Lake Trout are a large, long-lived, predatory fish, feeding primarily on other fish (Daly et al. 1962; Scott and Crossman 1973; Zimmerman et al. 2009) and reach a total length between 381-900mm, depending on the population (Daly et al. 1962; Moore and Bronte 2001;

Zimmerman et al. 2006). In general, the colours of Lake Trout range from light green/grey to dark green/brownish colour, sometimes almost black, on most of their body with light spots throughout the darker background and a lighter coloured underbelly (Scott and Crossman 1973; Government of Northwest Territories 2023). In the early 1960's, the largest recorded Lake Trout in North America was believed to be caught in 1864 in Grand Haven, Michigan, and weighed 88 lbs (~40 kgs), while the record for Great Slave Lake was 66.5 lbs (~30 kgs) (Keleher 1961). In a Great Slave Lake specific study, 68% of 217 sampled Lake Trout had stomach contents containing fish material, with terrestrial insects and aquatic invertebrates also being common (Zimmerman et al. 2009), although other prey, including small songbirds, have been found in stomachs of Lake Trout from some populations (Daly et al. 1962).

Multiple body forms with varying body shapes have been identified for the species. In general, the separation of Lake Trout body form has been classified into three morphotypes: a lean, a siscowet (fat), and a humper or banker Lake Trout, although previous additional forms were noted in other regions, such as the Laurentian Great Lakes (Moore and Bronte 2001; Zimmerman et al. 2006, 2009). In general, large, more streamlined, lean Lake Trout (>60 cm) have a lower lipid concentration and are found in shallower waters than siscowets (Moore and Bronte 2001; Zimmerman et al. 2006). In comparison, large siscowets have higher lipid concentration and a thicker, longer caudle peduncle which may allow them to swim longer and employ burst movements to capture prey in the waters where they typically occur (Moore and Bronte 2001; Zimmerman et al. 2006). A third intermediate form, the humper, has median lipid content and is commonly located in offshore shoals (Moore and Bronte 2001; Zimmerman et al. 2006). Moore and Bronte (2001) found a mean capture depth for lean, humpers, and siscowets in Lake Superior of 88 m (±5 m), 100 m (±5 m), 124 m (±5 m), respectively. Zimmerman et al.

(2006) found that individuals needed to reach a standard length of 43 cm to distinguish between the three measured body characteristics in their study of East Arm Great Slave Lake Trout. Generally, after this point (43 cm), body developments began that lead in the direction of either a lean, more shallow water morph, or a larger, siscowet form (Zimmerman et al. 2006) (additional information on study in the *History of Great Slave Lake Research* section and Appendix I, Table 3).

Lake Trout generally possess slow growth rates and mature relatively late in life, with these conditions being even more extreme in the cold waters of Great Slave Lake East Arm (Low 2006), although demographic rates vary greatly between populations throughout their range (Daly et al. 1962; McDermid et al. 2010), and between morphs (Chavarie et al. 2016; Hansen et al. 2016). Early reviews suggested age at maturity from 6-13 depending on the population (Daly et al. 1962; Scott and Crossman 1973), with East Arm Great Slave Lake Trout maturing between 7-14 years (Yarmechuk 1986). A recent study conducted on Great Bear Lake, NT, found the youngest mature Lake Trout in their sample to be 9, and the oldest to be 60 years (Chavarie et al. 2016), although true natural age is hard to determine given the longevity of the species.

Lake Trout are iteroparous, spawn in fall and lay their eggs on well-sorted, rocky substrates of inland lakes, where their eggs can fall into crevices between the pebbles (Daly et al. 1962; Power 1978; Callaghan et al. 2016). Unlike other species in the Salmonid family, Lake Trout lay their eggs directly on bottom substrate and provide no parental care (Daly et al. 1962; Callaghan et al. 2016). Timing of spawning (and hatching) can vary from lake to lake, with stocks in northern lakes spawning as early as September, and populations in the south, as late as November (Scott and Crossman 1973; Callaghan et al. 2016). Hatching usually occurs 4-5 months later, in the spring, although June hatching has been reported for populations near the northern limits of the species (e.g., Great Bear Lake) (Scott and Crossman 1973). Hybridization between Lake and Brook Trout, resulting in the subspecies, Splakes, has been reported (Daly et al. 1962; Scott and Crossman 1973).

Common parasites of Lake Trout include Tape Worms, Horny-Headed Worms, Flukes, and Lamprey, among others, with their prevalence and effect varying greatly throughout their range (Daly et al. 1962; Scott and Crossman 1973). Lake Trout can be heavily influenced by the presence of parasitic Lamprey, which can act as a limiting factor for some stocks, (e.g., in the Laurentian Great Lakes) (Daly et al. 1962). Northern Lamprey, *Entosphenus japonicus septentionalis*, naturally coexist with Great Slave Lake Trout but these native species are smaller (Rawson 1951) than those found in systems such as the St. Lawrence and Laurentian Great Lakes which has seen Lake Trout populations devastated by lamprey predation (Lindsey 1964).

Great Slave Lake Fisheries

Great Slave Lake Domestic & Local Fisheries

Sport and domestic fisheries have contributed to the social and economic development of the Great Slave Lake area (Sinclair et al. 1967). Domestic and local fisheries likely occurred since the first settlers inhabited the shores, especially around the area of Lutselk'e in the East Arm, a first nations community with a long history of subsistence fishing (Kennedy 1956; Keleher 1962; Low 2006). Both, organized and unorganized (individuals who fish for themselves, their families, and/or dog(s)) domestic fisheries exist on Great Slave Lake (Sinclair et al. 1967). In the latter case, local fishers have historically been assisted by various organizations through purchase or rentals of boats and equipment, and through the purchasing of surplus catches (Sinclair et al. 1967). Surplus catches were then marketed to other residents with the goal of increasing efficiency and reducing fish wastage (Sinclair et al. 1967).

Prior to 1945, the first year of summer season commercial fishing, ~230,000 – 450,000 kg were estimated to have been taken annually for local use, with 80% of this going towards food for dog sled teams (Kennedy 1956; Sinclair et al. 1967). However, by the time commercial fishing commenced most dog sled teams had been replaced by snowmobiles for winter transport, lessening the need for canine food harvest as part of the domestic fishery (Kennedy 1956). It is uncertain whether estimates of local harvest prior to 1945 included fish harvested under the early local consumption licenses (started by the Department of Fisheries in the 1930's), which could have been substantial. For example, licences granted to three individuals in 1940 resulted in a combined catch of 50 Lake Trout, 4,640 Lake Whitefish, 4,900 Inconnu and 5,500 Suckers (*Catostomus* sp.) (Keleher 1962). Winter commercial fishing officially began in 1946, although it is believed that during March of 1944, a single Albertan resident who used the winter road to access Great Slave Lake, harvested a small amount (~770 kg of Lake Whitefish and 136 kgs of Lake Trout), and returned to Alberta (Keleher 1962), although it is unclear if these were marketed.

Great Slave Lake Recreational Fishery

Great Slave Lake is home to a prevalent sport fishery with high community and economic values, largely centered around Lake Trout (Sinclair et al. 1967; Low 2006). Other species such as Arctic Grayling (*Thymallus arcticus*), Inconnu, Walleye (*Stizostedion vitreum),* and Northern Pike (*Esox Lucius*) are also fished, with Trout and Grayling being most common in the East Arm (Keleher and Meeker 1962; Sinclair et al. 1967). Sport fishing, defined as fishing for pleasure, not for sale or trade, is accomplished through many harvesting methods on Great Slave Lake, including angling (hook and line fishing), spear, and dip netting (Sinclair et al. 1967; Government of Northwest Territories 2023), primarily from shore or small vessels (Keleher and Meeker 1962). Prior to the creation of sport lodges and investments in a tourist-focused sport fishery along the East Arm, other areas of the lake were noted popular for recreational fishing, including Hay River, Mackenzie River, Yellowknife Bay, and Fort Resolution, in addition to, Yellowknife, Taltheilei Narrows, Reliance and Snowdrift (Figure 2.1) (Sinclair et al. 1967).

Hay River, one of three large rivers along the south shore of Great Slave Lake, remains a popular destination for the majority of recreational angling, outside the East Arm lodge industry, due to ease of access via the Mackenzie Highway and proximity to Alexandra and Louise Falls (Figure 2.1). These areas are known scenic attractions in addition to common recreational fishing areas (Keleher and Meeker 1962). The primary species captured in this region were historically Walleye, Northern Pike, and Inconnu in the spring, while the outlet of the Mackenzie River is known for its production of Grayling and large Pike (Keleher and Meeker 1962). Yellowknife Bay, and further up the North Arm were commonly trolled for Lake Trout with increased popularity following the completion of a summer road in 1961 (Keleher and Meeker 1962). Impediments to the expansion of the sport fishery have included limited access by tourists due to sparce infrastructure, high costs associated with air travel and lodging, the remote setting requiring large travel distances, and the generally short season with limited opportunities for guests and workers associated with lodges and guided fishing operations (Sinclair et al. 1967).

Of the sport fish, Lake Trout are the most vulnerable to over-harvesting for several reasons, including their relatively late age of maturity, and slow growth rates, however Great Slave Lake is known for producing large Trout, with individual fish commonly weighing over 20 kg (Low et al. 1999; Low 2006). Participation in the recreational fishery requires the purchase of a license that is valid from April 1st till March 31st the following year, however, it has been noted that there may be inconsistencies present between involvement in the fishery and the issuing of licenses, especially in the early years of the fisheries (Keleher and Meeker 1962; Government of Northwest Territories 2023). Previous angler surveys have been conducted by DFO, indigenous organizations and local communities and a current reward program is in place for the return of tagged fish information (Government of Northwest Territories 2023). An early review of recreational license sales in NT and participation in sport fishing revealed that most effort exerted by sport fishers in NT at the time occurred on Great Slave Lake (Keleher and Meeker 1962).

Most sport fishing for the former Mackenzie District of NT (the area that now makes up most of NT) was associated with the sport lodges of both Great Bear and Great Slave Lakes providing numerous employment opportunities as guide and lodge workers (Sinclair et al. 1967). The first official recreational fishing lodge on Great Slave Lake, known as the Great Slave Lodge, was established in 1938, originally as a camp for the owner, C.C. Plummer, and a limited number of guests (Keleher and Meeker 1962). By the 1960's the lodge operated as a business with increased available accommodations from 12 guests to 38 in 1961 (Keleher and Meeker 1962). Additional sport lodges were constructed along the East Arm in the 1960's; the first being built in the Snowdrift area in 1960, with another three builds to follow (Falk et al. 1973; Yarmechuk 1986). Sport fishing at Snowdrift allows for anglers to reach Christie Bay, Stark Lake and River, in addition to Snowdrift Lake and River, which historically added to the popularity of the location (Keleher and Meeker 1962). Another East Arm recreational fishing area includes Fort Reliance at the far east end of Great Slave Lake (Figure 2.1) (Keleher and

Meeker 1962). Areas around the many islands of the lake are prevalent recreational fishing areas as the land masses provide shelter and safer traveling for smaller vessels (Yarmechuk 1986). By 1980, seven sport lodges were in operation on the East Arm of Great Slave Lake, with total guest capacity estimated as 147; between 1980 and 2000, the Arctic Star Lodge burnt down, but the addition of Morin Outfitters kept the number of sport lodges in 2000 at seven with an estimated capacity of 128 anglers (Low 2006).

Participants of the Great Slave Lake sport fishery, from the initial years until the mid-1970's, experienced high possession limits that were frequently filled (Low 2006). However, from the mid 1970's until the end of the 1990's, lodge guests often practised catch and release for most fish encountered, but did retain some small Lake Trout for lunches, as well as large individuals, considered "trophy fish" (Low 2006). Lake Trout limits in place for Great Slave Lake anglers for the years 1973, 1974, 1979, 1991, 2003, and 2022 can be found in Table 2.1. (Other sport fishery specific information and research can be found in Appendix I, Table 3).

Great Slave Lake Commercial Fishery

Fishery Development until the Crash of Commercial Lake Trout

Interest in operating a commercial fishery out of Great Slave Lake is thought to have begun as early as 1929 when the Great Slave Lake Fishing Company was created with plans to commercial fish in the winter, although these plans were never acted on (Keleher 1962; Day and Low 1992). Numerous companies expressed the desire to commercially fish Great Slave Lake between the 1930's-1940's, however, commercial fishing on the lake was not officially enacted until 1945 (Kennedy 1956; Keleher 1962; Day and Low 1992). Prior to the kick-off of the fishery, in February 1942, a commercial limit was arbitrarily set at 450 tonnes dressed weight, 540 tonnes round weight, for the primary marketable species, Lake Whitefish and Lake Trout, albeit unclear how this value was chosen as no previous investigation into lake production had occurred (Keleher 1962; Day and Low 1992). The first summer season consisted of only one and a half months of commercial operations, while the commercial harvest during the winter 1945-1946 can be considered trivial (Kennedy 1946). Prior to the start of the first official commercial season, on May 1, 1945, McInnes Products Corporation (McInnes) requested an increase to the commercial limit, indicating that even 900 tonnes dressed weight was too low given the lake's size (Keleher 1962). This request, originally denied as the policy in place required that the first commercial season be complete prior to any increase in quota, was repeated by McInnes on June 29th, of the same year (Keleher 1962).

Commercial fishing of Great Slave Lake began on July 29, 1945, with the original fishing grounds corresponding with the location of the first (and initially only operational) fish plant on the lake, the McInnes Products Corporation Ltd centrally located at Gros Cap (Kennedy 1956; Keleher 1962; Sinclair et al. 1967). Twenty 28-foot, wooden hulled boats, originally used for the exploitation of Lake Athabasca, made up the 1945 summer fishing fleet (Day and Low 1992). Less than one month into commercial operations, on August 20th, 1945, McInnes received information that on the recommendation of Dr. D. S. Rawson, the quota had been increased to over 907 tonnes dressed weight: ultimately going against the policy in place (Keleher 1962). In the first year of commercial fishing operations, the only company involved, McInnes, surpassed the initial quota (540 tonnes), and over 680 tonnes round weight of commercial species were harvested in the short season (Keleher 1962). Given continued pressures from fishing companies and based on findings from the first two years of fish community research investigations on Great Slave Lake, on May 17, 1946, the combined annual lake quota for Lake Whitefish and

Lake Trout was increased to ~1,905 tonnes round (~1,590 tonnes dressed) weight; this quota was below additional requests made by McInnes (Rawson 1951; Kennedy 1956; Keleher 1962; Table 2.2).

In the summer of 1948, an all-weather road was constructed (Mackenzie Highway) that connected the city of Hay River with the network of Albertan roadways, enabling the involvement of other fish companies and lowering the importance of the Gros Cap plant (Keleher 1962; Kennedy 1956; Sinclair et al. 1967). Additionally, during the 1948-1949 season, the commercial winter quota was increased, resulting in a new annual quota of ~3200 tonnes dressed weight (Keleher 1962; Keleher 1972a). The annual quota for Lake Whitefish and Lake Trout was further increased to ~4100 tonnes round weight prior to the start of the 1949 commercial season with 56 % being allotted to summer catches and 44 % to winter, and further divisions by management areas; this was also the first time the quota was officially given in terms of round weight, where it was previously given as dressed weights (Keleher 1962) and (later scaled via conversion factors). The rise in quota, along with the completion of the Mackenzie Highway, undoubtedly increased interest in, and expansion of, the Great Slave Lake commercial fishery from outside companies, resulting in the greatest number of operators and, coincidentally, the peak commercial catch during the 1949 season (Keleher 1962; Bond and Turnbull 1973; Day and Low 1992). In these early years, only Lake Whitefish and Lake Trout were restricted to a combined quota (Keleher 1962), however other fish were marketed at various times. For example, in the 1948 commercial summer season Inconnu and Walleye entered the market (Kennedy 1950). By 1956 Northern Pike were also marketed, along with Cisco, Burbot, Sucker, American Grayling, Round Whitefish, and Goldeye, which were additionally sold to some degree (Kostelnuk and Roberts 1957).

Gillnets, of legal mesh size at the time (5.5 inch or 13.9 cm stretched), were the only harvesting method utilized in the commercial fishery (Kennedy 1956; Keleher 1972a) with methods changing little in the first twenty years of commercial operations (Keleher 1972a). Methodology for setting gillnets generally involved placement on sloping bottom, therefore depth is often reported as a range to best display true information in relation to net placement (e.g., Table 27 in Kennedy (1946)). Two different net materials, cotton, and nylon were utilized in the history of the commercial fishery on Great Slave Lake (Kennedy 1956). It is believed that until 1949 only cotton nets were used, but by 1951 Hay River fishers used nylon nets for 75% of all fishing, while Gros Cap fishers continued using cotton until the end of ~1952 (Kennedy 1956). Apart from the Gros Cap and Northwest areas which included nets set at shallower depths during the pre-spawning period for Lake Trout and Lake Whitefish (September, as shallow as 5 ft), nets were set at similar depths in all areas and time periods (Kennedy 1946). The net placement depth range for the 1947 summer season was 10-150 ft (~3-46 meters) (Kennedy 1950).

The most prevalent boat used during the 1949 commercial season was a 28-32 ft long boat with a 7 ft beam, a style originally designed for Lesser Slave Lake, with the 40 ft long, 14 ft beam *Riverton Boat* (designed for Lake Winnipeg), also being common (Kennedy et al. 1951). In general, two to four fishers were present in each boat that operated during the fishery in the early years (Kennedy 1946, 1956; Keleher et al. 1962). Due to heavy winds and rain, commercial fishing was intermittent during July 1949, with operations out of Windy Bay ceasing temporarily from July 30th – August 8th due to the washing out of roadways (Kennedy et al. 1951). Vessels used in the original McInnes fishing fleet were found to be too small and by 1958 were replaced by 37 ft boats (Day and Low 1992). Historical transportation of fish to the McInnes plant occurred as follows: a fisher's catches were bought, frozen, and sent off on refrigerated barges to a location near Fort Smith, NT (Kennedy et al. 1951; Kennedy 1956). The fish were then moved by multiple methods until ultimately ending up in Waterways, AB (Kennedy 1956).

From 1950-1956 the commercial fishery saw a brief period of stabilization for some commercial species, such as Lake Trout, as more fish plants opened, and participants explored new grounds and exerted effort in areas previously not commercially fished (Kennedy 1956; Keleher 1972a). In 1957, Lake Trout commercial catches declined from ~1,200 to ~900 tonnes round weight of commercial harvest (Keleher 1972a). Throughout the 1960's, Lake Trout commercial catch continued to decline, with the whole lake catch reaching a low of ~100 tonnes in the 1968-1969 season (Keleher 1972a).

Various commercial fishery changes occurred throughout the 1960-1970's, including changes to administration areas, lake closures, quotas, and composition of catch, with most of the management measures aimed at protecting Lake Trout stocks and limiting competition with the recreational and domestic fisheries (Sinclair et al. 1967; Day and Low 1992). These changes included the reduction of the Lake Whitefish and Lake Trout whole lake quota to ~2300 tonnes in 1971, when the Freshwater Fisheries Market Corporation (FFMC) (established in 1969), took over all purchasing of Great Slave Lake commercial species (Bond and Turnbull 1973; Day and Low 1992). In the following summer season, a Lake Trout sub-quota for Area VI was put in place (Bond and Turnbull 1973; Day and Low 1992). Four fish processing plants operated throughout the 1970's – 1990's with only the Hay River plant operating year-round (Bond 1975; Day and Low 1992). The plant located at Simpson Islands closed in 1991, the Moraine Bay plant in 2005, Wool Bay in 2008, and in 2007 the Hay River plant began only processing in the summer season (VanGerwen-Toyne et al. 2012).

Commercial fishery involvement, landings, and composition of catch, continued to vary greatly during the first twenty years of the commercial fishery, with the lowest production seen ever in 1972, a 41% reduction from the previous year (Bond and Turnbull 1973). This reduction was largely attributed to the Lake Trout Area VI sub-quota, which was reached on August 12, 1972, as 55% of all commercial Lake Trout were harvested from Area VI that season (Bond and Turnbull 1973). By this time, Lake Trout were nearly absent from the western areas of the lake and considered incidental in catches (Bond and Turnbull 1973).

For the 1974 season the separation of annual quota into summer and winter seasons was abolished resulting in the ~2300 tonnes Lake Whitefish and Lake Trout quota representing the entire 1974-1975 commercial fishing season (Bond 1975). In 1974, it was decided that following reaching the current Area VI sub-quota, the area would be closed to commercial fishery operations (Bond 1975). In November of 1974, before the start of the winter 1974 and subsequent summer 1975 season, Area VI was officially closed to commercial fishery operations to protect Great Slave Lake Trout stocks and the recreationally fishery they help support (Bond 1975; Day and Low 1992). Additional quota changes occurred from 1975-2000's but these were relatively minor ranging from ~2175 (1974-76) to a low of ~1545 tonnes (1976-78) (Table 2.2).

Historically, the summer commercial fishery, which produced ~two-thirds an entire year's commercial harvest, began when the lake was free of ice, (~mid June), and operated until ~mid-September, marking the end of the regulated season (Kennedy 1956; Jennes 1963). In later years the season began as early as May 16th and ran until September 25th with exact dates largely affected by weather conditions (Keleher 1972a; Day and Low 1992). A winter and summer commercial fishing season do not represent a single calendar year, but rather the winter season of one year and the following summer, resulting in a typical fishing year operating from

~November 1st to October 31st the following year (Day and Low 1992; Northwest Territories Fishery Regulations 2023). No significant changes in fishing practices occurred in the first twenty years of the fishery, with the major differences between the initial fishery and twenty years later being changes in the fishing fleet through upgrades to larger vessels with accessories to aid success (Keleher 1972b). Initial fishery involvement was largely influenced by water transport, and later by the development of infrastructure, including road and harbour development (Jennes 1963; Keleher 1972b).

Traditionally the winter commercial fishery ran from December 1st until March 31st, in areas exclusively near Hay River in and relied heavily on snowmobiles once they became available (Kennedy 1956; Jennes 1963). Exact dates for the winter fishery varied from year to year as they are reliant on ice formation in the fall and break up in the spring (Day and Low 1992). Methods used in the winter commercial fishery were essentially the same as other Canadian commercial fisheries at the time: using gillnets (5.5 inch (13.9 cm) stretched, 100-yard long) through ice holes, set at depths between 20 and 120 meshes deep, with the majority being between 30-40 meshes deep (Kennedy and Hewson 1951). During extremely cold temperatures, fishers were required to move their nets constantly as fish become increasingly dormant as temperatures decline, however, higher winter market prices, compensated for the extra effort required (Jennes 1963). Generally, commercial fishers did not establish field camps in the winter, and instead maintained cabooses on the lake bringing catches to Hay River primarily via snowmobile (Keleher 1972a). The primary marketed species in the initial winter seasons of the commercial fishery were Lake Trout, Lake Whitefish, and Inconnu, with Pike and Walleye also entering the winter market in 1950 (Kennedy and Hewson 1951), and Burbot, Pike, Longnose Sucker and Cisco additionally sold to some degree (Wheaton 1951a).

Boundary Revisions & Changes to the Representation of Data

Great Slave Lake has been divided into management areas for most of the commercial fishery, however, the number and size of these areas has varied throughout the progression of the fishery (Appendix I, Table 2). From 1945, the first year of commercial fishing, until 1948, Great Slave Lake was designated and managed as one large waterbody, although commercial participants generally stayed close to the regions of Gros Cap and Hay River (Keleher 1962). Based on the first three years of scientific investigation on the lake, it was concluded that although effort was appropriate, only a small area of the lake was being exploited with no signs of overfishing, therefore if effort were to be distributed more evenly over the entire lake, the initial quota could be doubled (Rawson 1947; Kennedy 1956). The lake was subsequently divided into three management areas, each with an assigned quota in 1949 (Kennedy 1956; Keleher 1962). The 1949 subdivisions were short lived and in 1950 the lake was further divided into five management areas for the full year (Keleher 1962). In 1951, the lake was again subdivided for the full commercial fishing season, however, this time as four management areas (Kennedy 1956; Keleher 1962; Sinclair et al. 1967; Appendix I, Table 2).

Great Slave Lake administration areas remained largely unchanged from 1951 until 1963 (Keleher 1962) when Area I was further subdivided into Area IE and IW (Sinclair et al. 1967). Additional boundary and nomenclature changes occurred throughout the 1970's, the most notable modification being the addition of Area VI (far northeast arm) in 1971 and the area specific sub-quota intended to limit commercial removals of Lake Trout. Following the advice of the Great Slave Working Group (1969) and recommendations of Bond (1974), Area VI was eventually closed to commercial harvesting in November of 1974 (Yaremchuk 1986; Low et al. 1999). Management areas remained relatively unchanged until 1979, when a boundary addition in Area II spilt the region into Areas II and III creating the management areas used in the present day (Moshenko and Low 1980; Roberge et al. 1982; Northwest Territories Fishery Regulations 2023).

Along with current Great Slave Lake management areas differing drastically from those used during the initial ten seasons, commercial fishery research has been collected and reported in varying ways since the first surveys in 1944 creating challenges for the creation of complete, standardized time series for fishery modeling and assessments (Table 2.3). For the 1946 and 1947 commercial seasons, biological and catch data are analyzed and summarized under areas described as: West, Northwest, Gros Cap, East, and the Island Area, (Kennedy 1946; Appendix I, Table 2). Although these areas cover the fishing grounds in use during that period, they do not account for the southern half of the lake as not all areas had been subject to commercial or sampling operations yet. In subsequent years, Great Slave Lake commercial operations and research shifted to using areas defined based on underlying physiologic/ habitat characteristics, resulting in thirteen designations with no relation to initial management areas in place at the time (e.g., Kennedy (1950)), or those currently in use. Other aspects of analysis and investigation on the lake throughout the first ten years of fishing, divided the lake into three areas (e.g., Rawson (1951)).

This variation in management zones and associated data collection and reporting methods, combined with differences in fish communities and production capabilities in numerous areas of the lake (Keleher 1972b), make it difficult to translate early information into values which can be compared to those collected according to the current management zones. This limits the length of time-series available for commercial catch (a common stock assessment input) for the current management areas, adding uncertainty to maximum sustainable yield estimates, as not all data are useable. Additional details regarding the Great Slave Lake commercial fishery based on early historical research technical reports are included in Appendix I, Table 1. These facts, although not incorporated in the current stock assessment (Chapter III) may hold value for future investigations of the fishery.

Present Commercial Fishery

Great Slave Lake is currently divided into seven commercial management areas (Appendix I, Table 2), with harvesting data and research survey data generally summarized and presented as such. Lake Whitefish, and Lake Trout are the primary targets of the commercial fishery, although relative importance of each has varied greatly throughout the more than 75-year commercial fishery (Keleher 1972; Day and Low 1992; Northwest Territories Fishery Regulations 2023). Lake Whitefish and Lake Trout continue to be regulated through a combined quota for each of these management areas (Table 2.4) (Northwest Territories Fishery Regulations 2023). All Great Slave Lake management areas are closed to commercial fishing from May 15th to 30th to accommodate the spawning seasons of various spring spawning fish species, while Area VI remains closed year-round to commercial fishing (Bond 1975; Day and Low 1992; Northwest Territories Fishery Regulations 2023). In addition to these closures, there are multiple commercial fishery exclusion zones in various seasons and areas of the lake, including around Fort Resolution, Hay River, and regions around the community of Behchokǫ.

History of Previous Great Slave Lake Research

Overview of Previous Research Conducted on Great Slave Lake

Great Slave Lake is unique in that the commercial fishery and the target species have been monitored to some degree for the entirety of the fishery (Keleher 1972a; Day and Low 1992), however, as noted in Kennedy (1946), official monitoring of the commercial fishery from a research standpoint began in 1946, as the harvest in 1945 was considered mere. In the initial years of the Great Slave Lake commercial fishery, the Fisheries Research Board conducted annual monitoring and reporting (e.g., Kennedy 1946, 1950), with various aspects of the fishery studied consistently over two decades (1945-1964) (Keleher 1972a). A large majority of studies during the initial 10 years (e.g., Kennedy 1950; Wheaton 1951; Scott 1954) focused on Lake Trout given the importance of the species role in the commercial fishery at the time (Appendix I, Table 1). These early studies were supplemented by research on the limnology and fish production capacity of the lake (e.g., Rawson 1947, 1949, 1950, 1951; Kennedy 1954). The data from this early experimental research was often combined in summaries with data obtained from sampling commercial catches. Thus, separating the early year's fishery research into fishery dependent and independent information remains difficult since many data summaries are presented using mixed information from commercial and experimentally caught fish (e.g., Kennedy 1954).

Kennedy (1956) provides an in-depth review of the first ten years of commercial fishing operations and results of the associated scientific studies, while results of a multi-species tagging program from the same period are published in Keleher (1963). Keleher et al. (1962) provides more detailed information on the historical composition of the commercial fishing fleet, while Keleher (1962) reviews previous Great Slave Lake commercial fishery regulations, as well as those in place at the time of publication. General information on fisheries (e.g., harvest) and the organizational structure (e.g., market price, and license sales) of those throughout the Mackenzie district (majority of area that makes up current NT) can be found in Sinclair et al. (1967). Keleher (1972a) reviews the first twenty years of the commercial fishery, with some special attention paid to the salmonid stocks of Great Slave Lake, and additional information for both the commercial fishery and Lake Trout stocks in a supplementary document (Keleher 1972b). As a continuation to the first twenty years of scientific research on Great Slave Lake and based on suggestions from the Great Slave Lake Working Party (1969), a long-term study to collect data on the commercial fishery was initiated in 1971 (Bond and Turnbull 1973; Moshenko et al. 1978). Aspects of this research included both fishery dependent methods, in the form of fish plant sampling, and independent methods through experimental netting.

For multiple reasons, such as difficulties associated with remote research and likely the lack of Lake Trout in commercial catches following the mid -1970's, there was a shift in research focus to Lake Whitefish, with Lake Trout receiving limited attention in commercial fishery studies from the late 1970's to early 2000's, save for a few exceptions. Research on the Great Slave Lake domestic and sport fisheries was relatively scarce considering its long history and high socioeconomic value. Nonetheless, a few documents were produced summarizing the research that has occurred on the Great Slave Lake recreational fishery, including: Keleher and Meeker (1962), Keleher (1964), Yarmechuk (1986), Thompson et al. (1988), Low et al. (1999), and Low (2006). Although sparse, some past research was also conducted on the domestic fisheries (e.g., Keleher and Haight 1959).

Fishery Independent Studies

The first fishery independent investigation into the biological resources of Great Slave Lake took place from 1944-1947 (Rawson 1947, 1949; Kennedy 1956). The study goal was to evaluate the lake's capacity for fish production to achieve proper management of commercially harvested fish, since prior to 1945, only local subsistence and sport fishing occurred (Rawson 1951; Kennedy 1956). This research was facilitated through the 1943 formation of the North Pacific Planning Project charged with determining the value of northern resources in North American, so that this information would be available in case of military action in the area (Keleher 1962).

All species in the initial research study were collected by 1.5-5.5 inch (3.8-13.9 cm) stretched mesh gillnets, as well as 'seines', and small mesh-trawls, however the smallest of fish caught through the latter two methods contributed little statistical information to the study (Rawson 1951). Gillnet mesh sizes were selected to capture a range of sizes for most species from youngest to the legal size for commercial fisheries with nets typically set for 24 hr in eleven target areas based on proximity to shorelines and the surrounding communities (e.g., Table 3 in Rawson 1951). From 145-gillnet sets (1944-1947), 11,620 fish were caught weighing in at 19,742 lb (~8955 kg) with Cisco, Lake Whitefish, and Lake Trout being dominant (Rawson 1951). Ciscoes were the most numerically abundant, however Lake Trout represented the greatest dominance by biomass representing only 10% of the species composition based on the number of individuals but 46% by biomass (Rawson 1951). Based on the food chain/ web in Great Slave Lake, it was suggested that it is unlikely much competition for food occurs by the three dominant species (Rawson 1951).

In a follow-up fishery independent study in 1972, 22 experimental net sets of varying mesh sizes (1.5-5.5 inch (3.8-13.9 cm)), and placement depths, resulted in the harvest of 3340 individual fish, with Lake Whitefish being most plentiful, followed by Cisco, while Lake Trout only accounted for 2.3% of individuals and 6.5% of total biomass, indicating a major shift in the composition of Great Slave Lake fish species (Appendix I, Table 2) (Bond and Turnbull 1973). At both the Moraine Bay and Hay River sampling sites, only a single Lake Trout was caught at each location, while 4.3% of all individual fish caught at Union Island were Lake Trout, revealing how Lake Trout had become essentially commercially extinct in western waters of Great Slave Lake (Bond and Turnbull 1973; additional details on study in Appendix I, Table 1).

Fishery Dependent Studies

The Great Slave Lake commercial catch was monitored consistently in the early years (~1945-1955) of the fishery, with the goal of establishing a long-term fishery dependent program that could follow trends in fish populations, with special attention to undesirable influences of the commercial harvest (Kennedy 1946). Information gathered in 1945, the first year of commercial fishing, was negligible given the one and a half-month season, but from 1946 onward approximately yearly publications were produced (summarized in Tables 2.5, 2.6 and Appendix I, Table 1). In these investigations standard gillnets were 100 yards by thirty meshes deep (~nine feet), usually fished in gangs of three (300 yards), with 30/6 cotton 5.5-inch (13.9 cm) mesh (stretched) treated with copper oleate (Kennedy 1946). A standard gillnet left for one night, was considered the natural unit of effort, and for the first couple years of the fishery, nets were generally only left for one night as fishers were mainly fishing close to shore (Kennedy 1946). By 1948 the unit considered as effort changed slightly: one unit of effort was equivalent to one 100-yard gillnet (30/6 or 36/6 cotton web, 5.5-inch mesh) thirty meshes deep for one night, however, time in water could be longer (Kennedy 1950). Participants of the fishery were allowed to fish up to 1000 yards/ person working on a boat (Kennedy 1946). Winter fishing also occurred in the early years of the Great Slave Lake commercial fishery and research investigations (sampling catch and participant interviews) during this season began in the 1948-1949, but no attempt was made to estimate total winter catch and effort, nor were any recommendations presented (Kennedy 1950; Kennedy and Hewson 1951).

Sampling of catch in early studies was done in a matter that was deemed random, but not independent of the commercial fishery (Kennedy 1946) and reports included weights of commercially caught fish (dressed and estimates of converted round weights), weight frequency distributions for key species (Lake Trout and Lake Whitefish, mainly), in addition to estimates of effort, availability, as well as tagging results, and meteorological and limnological data (Kennedy 1946, 1950; Kennedy et al. 1951). Once docked, fish were divided according to species by the fishers and weighed by the buyer, which in the early years of the fishery until 1948, was McInnes, who operated from the only fish plant located centrally at Gros Cap (Kennedy 1946, 1950). Sample boxes were then selected at random for the areas being investigated (Kennedy 1946). In these reports, the catch per unit of effort, referred to as availability, is defined as the round weight of fish caught by the commercial fishery per unit of effort (one net-night) (Kennedy 1946, 1950). This value is also termed Fishing Success (FS-Index) in Kennedy (1956). To account for fish discarded by commercial fishers, interviews were conducted daily to form an estimate of fish not sold; this was then added to the estimates of total catch; information on depths fished was also obtained from commercial fishery participants (Kennedy 1946). Some season specific details from these early reports and observations (e.g., comments on effort, estimates of fleet size, etc.) regarding the entire commercial fishery are summarized in Appendix I, Table 1, with general conclusions presented in the subsequent sections, followed by Trout-specific details from these investigations (Tables 2.5 and 2.6).

Changes in Availability of Commercial Species

Commercial fish availability generally increased as distance from Gros Cap (the only fish plant at the time) increased, and as the season progressed (Kennedy 1950). Overall, there was minimal change in the availability of commercial species from 1945 - 1948, as the increased overall catch was attributed to fishery expansion to new grounds (e.g., East Arm in 1947) where local availability was higher than areas previously targeted (Kennedy 1948, 1950). In 1950, following the analysis of the 1948 season, it was concluded that although catch per unit of effort (CPUE) had increased, total production and effective effort were, in fact, decreasing due to harvesting difficulties, however, commercially exploited fish were reported to show no signs of change in size or availability (Kennedy 1950). In the analysis of the 1949 commercial season, it was noted that availability appeared marginally lower than previous years which could be interpreted as a decrease in abundance due to commercial operations (Kennedy et al. 1951). Nonetheless, Kennedy et al. (1951) supported the previous year's conclusion that no change in average size was occurring for any commercial species.

Other factors that historically influenced effort and associated availability included weather and the distance to basecamp. Nets were more often cleared daily when weather was calm, as some fishers considered wind in their decisions to not venture as far or leave nets out longer (Kennedy 1950). However, effects on production associated with wind were negligible in areas sheltered from the east, such as research subdivision K, while the effect of wind was noticeable in area E (Appendix I, Table 2), unprotected from prevailing winds (Kennedy 1950). Distance from basecamp and shore was also a factor in estimates of availability, as some areas, such as E and M (Appendix I, Table 2), were impossible to clear daily given their distance from Gros Cap (Kennedy 1950).

The 1950 summer season saw further declines in commercial availability of key species, particularly Lake Trout, at the western end of the lake (statistical Areas A and D, Appendix I, Table 2), however, there was still some question as to whether seasonal fluctuations were responsible (Wheaton 1951b). Following the analysis of the 1951 summer season, Wheaton and Kennedy (1952) concluded that availability for all Great Slave Lake commercial fish had decreased by ~25% and that it may represent an actual decline in standing stock. However, since they did not observe a consistent change in size or demographic rates of commercial harvested species, it was considered unlikely that a true decline in standing stock had occurred (Wheaton and Kennedy 1952) and in 1953 it was suggested that areas fished the longest may be reaching an equilibrium point (Kennedy et al. 1953).

Following the analysis of the 1955 commercial summer season Scott (1956) presented evidence, although controversial at the time, revealing that a greater quantity of the primary commercial species (Lake Trout and Whitefish) had been removed than what Great Slave Lake could produce, and population declines were evident. The basis behind these conclusions included: the noticeable decrease in average size in all areas without a trend towards stabilization, maximum age in fish of similar size had decreased by approximately four years since 1945, and there was sustained decrease in catch in weight per net of Lake Trout and Whitefish (Scott 1956). Given these findings and the expectation of increased fishing pressure Scott (1956) recommended reducing the annual quota from the existing ~4080 tonnes (9 million lb) to ~3630 tonnes (8 million lb) to allow stocks to reach a production equilibrium consistent with the maximum sustainable yield. However, a "*special note"* added to the end of Scott's (1956) recommendations by Director W.A. Kennedy, stated (pg. 10, paragraph 3):

"…desirable to put on record…Mr. Scott's opinion as expressed…particularly since he is no longer connected with the Fisheries Research Board…the fact his ideas are given…is not to be interpreted as representing an official recommendation. Our official policy is still that of recommending no change in the over-all catch limit for Great Slave Lake".

Following this recommendation, more detailed information involving analyses from the first scientific study, as well as official conclusions from the first ten years of research, were published in Kennedy (1956). This study divided the lake into thirteen areas for analysis and determined a measure of area-specific fishing success (referred to as the FS index), comparable to an availability or CPUE estimate, for the first ten years of commercial operations (Kennedy 1956). Effort was determined through interviewing fishers either when encountered on the water, or while a research member accompanied a boat for an entire day's fishing efforts to ascertain number and duration of net sets, and the quantity of commercial versus non-commercial species caught and culled. Answers from these questions as well as weight records from fish companies (from which an attempt was made to account for dressed versus non-dressed submissions) were used to calculate the FS index (Kennedy 1956). Assuming proportionality, an attempt was also made to estimate the catch and discards from fishers not interviewed; these were combined with fish plant records to estimate total annual catch (Kennedy 1956). This research investigation was considered to have performed adequate inquires to estimate the percentage of fishing effort applied over any one of the statistical areas (Kennedy 1956). Checking out-port records from fish plants to assess consistency with records given for fish purchased from fishers was a means to improve reliabilities of these estimates (Kennedy 1956).

Key findings following the completion of the first decade of the commercial fishery on Great Slave Lake were that fishing effort generally increased annually from 1945-1954, while fishing success only increased over the first few years, followed by a noticeable decrease (Kennedy 1956). However, it was noted that memories regarding catch and effort can be fairly unreliable and the relationship between fishing success and effort fluctuated inconsistently, possibly due to the use of limited data, particularly at the beginning of the fishery (Kennedy 1956). Although it appears likely the initial increase in success was related to the exploration of new grounds, the use of better gear, and improved techniques could also have contributed (Kennedy 1956). Observations from FS index patterns among fishers using different net materials (cotton vs nylon) suggest that techniques (rather than gear) were primarily responsible for differences in success (Kennedy 1956). Ultimately, this decade long study concluded that since there were no changes in mortality or growth rate in the commercially important species investigated (Kennedy 1954; Kennedy 1956); the ongoing Great Slave Lake commercial fishery was not likely to deplete the primary commercial species (Kennedy 1956). The Fisheries Research Board continued yearly monitoring of the commercial fishery following Kennedy's (1956) summary, although reporting was less consistent through the 1960's. By 1967, it was concluded that the commercial fishery had experienced declines in catch (Sinclair et al. 1967).

As a follow-up to the yearly Fisheries Research Board data collection, Keleher (1972a) summarized and analyzed the research carried out on Great Slave Lake during the first twenty years of commercial operations with special attention to the Salmonid community (additional information published in the supplementary document, Keleher (1972b)). Methods of data collection during this stage of research mostly occurred at field stations and mirrored fishing patterns through seasons and throughout the study (Keleher 1972a). Information on fish sold was obtained from company records, while fisher interviews were used to estimate culled fish and effort (number of nets used), and biological samples (size data and scale samples) were acquired through sampling catches once companies purchased them from fishers (Keleher 1972a). Results were presented in relation to commercial Lake Whitefish and Lake Trout (with some conclusions for minor species), as well as by the thirteen statistical areas used previously in Kennedy (1956). This summary helped reveal how unevenly divided overall catch was between the two species, in addition to among areas, throughout the twenty-year history (Keleher 1972a, b). Statistical areas A, D, E, and M (Appendix I, Table 2) produced more than 50% of all Lake Trout commercially caught from 1945-1964, with Lake Whitefish being primarily caught in the West and Lake Trout in the East, largely related to the physiographic differences between these areas of the lake (Keleher 1972a). From 1945-1964, more than 500,000 individuals of combined Lake Whitefish and Lake Trout were weighed and examined for trends which indicated a slight decrease in seasonal average weight, with commercial fishing implicated as the lone cause of this change (Keleher 1972a, b).

Other findings from the twenty year retrospective analysis included that estimated effort (defined as the number of 100-yards gillnets set, regardless of time spent in water and equivalent to total-net-nights defined in Kennedy (1956)) exerted by the commercial fishery in 1945 was 7 times less than the effort in 1964 (estimated as 125,000 nets for the summer fishery) (Keleher 1972a), with high variability among regions. Based on a visual representation of the year commercial fishing began in each of the statistical areas (Appendix I, Table 2), the western portion of Great Slave Lake (areas A-H), experienced a general increase in effort until approximately 1954, while the eastern portion, areas L-O, experienced relatively low effort (less than 10,000 nets/summer) up to this time, followed by an increase for approximately three years (Keleher 1972a). Over the same time period CPUE was found to have decreased for ten of the thirteen (eleven for Lake Trout only) statistical areas explored for both Lake Whitefish and Lake Trout (Keleher 1972a).

Despite some limitations of data in the early years (lower sample sizes, higher variability, and uneven coverage of lake sampling), it was apparent exploitation had resulted in changes to commercially fished stocks and that initial observations and conclusions were likely inaccurate (Keleher 1972a, b). For example, the 1948 decision to double the commercial Lake Whitefish and Lake Trout quota appeared to be based on fishing indices that did not truly represent the state of the stocks. Initial high catches and associated perceived high fishing success were merely temporary conditions associated with exploitation of long-accumulated stocks of Great Slave Lake (Keleher 1972a). This observation, together with the vast physiographic differences among regions of the lake (e.g., some areas were too deep for the production values generated based on other areas) led Keleher (1972a) to express concern regarding the pooled Lake Whitefish and Lake Trout quota, as it was apparent the maximum sustainable yield (MSY) had been overestimated. This led to the recommendation that the commercial quota should be set based on biological data rather than societal economics (Keleher 1972a).

As a continuation from the initial twenty years of research (~1945-1964) led by the Fisheries Research Board, a multi-year monitoring program on Great Slave Lake was implemented in 1971 with the aim of collecting information valuable for the successful management of the commercial fishery (Bond and Turnbull 1973; Moshensko et al. 1978; Day and Low 1992). The four primary objectives of this study were to: i) maintain records of commercial harvests by management area, species, and weight, ii) estimate CPUE and culls, iii) monitor biological data for change in size and demographic rates, with a focus on Lake Whitefish, and iv) determine populations structure of numerous species (Bond and Turnbull 1973; Moshenko et al. 1978). The first three years of this monitoring program are summarized in Bond and Turnbull (1973), Bond (1974) and (1975), and focus on the primary commercial species, Lake Whitefish and Lake Trout. Given the closure of the Area VI to commercial fishing in 1974, the area responsible for the majority of commercial Lake Trout harvests, the remainder of these reports (e.g., Moshenko et al. (1978); Moshenko and Low (1980), and Roberge et al. (1982)) reveal very little regarding trout stocks, although details of other species and the fishery are provided.

Lake Trout Specific Data and Studies

Lake Trout biological information from the beginning of the commercial fishery are available in the previously described historic Fisheries Research Board technical reports including studies of Rawson (1951), Wheaton (1951), Kennedy and Hewson (1951), and Scott (1956). Lake Trout specific details from these reports are summarized in the following sections and Tables 2.5-2.6.

Demographic Data and Trends

Average size for commercial species was investigated through borrowing fish, with attention given to minimize the time fish spent out of the water and away from owners, and therefore only weights were recorded (Kennedy 1956). Based on these data, a general decrease in average weight was observed in sampled Lake Trout, from 3.6 kg (7.9 lb) in 1945, to 2.9-3.0 kg

(6.5-6.6 lb) in 1954-1956 (Kennedy 1956), although sample sizes varied greatly annually (Table 2.5). A similar pattern was observed for Trout sampled during the winter commercial fishery, however conclusions stated that the observed change in average size should be interpreted with caution (Kennedy 1956). In the early 1950's the largest recorded Lake Trout individual(s) caught on Great Slave Lake were 30.2 and 29.9 kg, in 1954 and 1955, respectively (Keleher 1961). Although weight was primarily used to assess changes in body size over time, Kennedy (1954) developed the following length-weight relationships (log length vs log weight) for Lake Trout at different maturity stages: Immature: $y = 0.000238x^{3.16}$, and Mature: $y = 0.000413x^{3.02}$, where y is the weight in pounds and x is fork length in inches. Ultimately, 88,928 Lake Trout were analyzed in the early years of the commercial fishery with conclusions suggesting Lake Trout spawning may occur in the northeast, and evidence that larger Lake Trout concentrate at greater depths (Kennedy 1956), which may be indication of different Lake Trout body morphs; a topic later studied in the 2000's (Zimmerman et al. 2006, 2009).

States of maturity were determined from Lake Trout obtained from the Gros Cap location during 1946 (Kennedy 1954; (Appendix I, Table 2; location V in Kennedy (1954) fish scale sampling locations map)) and due to its approximately central location on the lake, were assumed to be representative of the whole area. Based on this study, Lake Trout were found to reach 50 % maturity at age eight when their average weight and length were, 1.2 kg (2.7 lb) and 46.7 cm (18.4 in), respectively. From a sample of 412 standard-gang caught trout from a variety of locations on the lake, an approximately equal sex ratio was found (Kennedy 1954). This is supported by results of experimenting netting included in Bond and Turnbull (1973), who found a sex ratio for Lake Trout sampled at Union Island of 1.042.

Results of early research suggest annual growth of individual Lake Trout takes place mainly between June and September, however results based on different sampling locations indicate that in areas where waters warm more quickly, growth of Trout may begin sooner (Kennedy 1954). Given noticeable differences in growth rates found in this study, it was decided the best way to group sampling stations (and associated sampled fish) was by western and eastern locations (Kennedy 1954). From this separation, Kennedy (1954) concluded Great Slave Lake Trout from the western locations grow faster and were approximately 75% larger (for fish past maturity, 9-15 years old) than those in the east areas based on scaled-aged samples.

Mortality rates for Lake Trout in early years of the fishery were examined through an analysis of scale-aged fish from the commercial catch (Kennedy 1954). Given the timing of the study in relation to the start of commercial fishing, it was concluded that these mortality rate estimates (instantaneous total mortality: .33 for fish aged 10, .39 for age 15 and .49 for age 20) could be used as priors for unexploited trout populations with similar characteristics (Kennedy 1954). Given that estimated mortality rates were extrapolated from catch curves and based on scale ages (known to underestimate ages of older fish in many species, especially those that are long-lived like Trout), caution is given for using these estimates for further extrapolation (Kennedy 1954).

Using catch curves created from all the age-class data available (1946-1952) in Tables V and VI in Kennedy (1954) and applying the “chapmanRobson” function in the FSA “R” package (Ogle et al. 2021), I calculated total mortality, Z, for the Western (I, II, and III), and Eastern (IV, V, VI, and VII) sampling stations. An instantaneous total mortality (Z) value of 0.37, and a survival (S) of 0.69 was found for the western sampled Lake Trout, while a Z of 0.45, with a S of 0.64 was found for Lake Trout sampled from the east. Additional information regarding Lake

Trout instantaneous total mortality was generated by Yaremchuk (1986) based on a recreational survey in the East Arm between 1972-1980 with values ranging from 0.11-0.33 produced through otolith-based, catch curve analysis (Appendix I, Tables 3 and 4).

Movement Patterns

Between the years of 1946-1955, 3629 fish of various species in Great Slave Lake were tagged and subsequently released, of which 505 were later recovered (Keleher 1963; Appendix I, Table 2 and Table 5). It was also noted that two Cisco and one Lake Trout were consumed by a recaptured Lake Trout (Keleher 1963). The majority of fish (all except six recaptures) handled in this study were caught by means of gillnets consisting of seven mesh sizes with a total of 93 tagging days for Lake Trout (Keleher 1963). The longest period from tag to recapture for an individual Lake Trout in this study was 4027 days (Keleher 1963). This Lake Trout was tagged near Christie Bay (current management area VI) over eleven years previously and recaptured a mere 1.6 km away in 1958 (Keleher 1963). This example demonstrates the short distances generally found between fish tag and recapture locations with 50% recaptured within eight km and 65% within 16 km of their original tagging locations, although occasional longer distances were noted (Keleher 1963). Keleher (1963) drew attention to the observation that Lake Trout released in the East Arm moved very little before recapture, while those released in the southeast corner of north arm were considered “exceptionally mobile”. Keleher (1963) concluded that the Great Slave Lake fish populations for the species tagged in the greatest numbers (Lake Whitefish and Lake Trout) are generally sedentary as indicated by the relatively long time periods, and short distances moved, between release and recapture.

General Patterns in Composition of Catch

Early experimental netting demonstrated that the average length of Lake Trout caught in various gill net mesh sizes (1.5-5.5 inch or 3.8-13.9 cm) showed a pattern of increase with mesh size (Rawson 1951). The greatest number of Lake Trout were caught in the 3 inch (7.6 cm) mesh size, but it was noted that many trout in the smaller mesh sizes were caught as a result a baiting effect from fish already entangled in nets (Rawson 1951). The proportion of Lake Trout in commercial catch compared to Lake Whitefish was found to be greater during the summer season than the winter season, with the hypothesis that seasonal differences were due to depth segregation between the two species (e.g., occupying different depths). Kennedy (1956) corroborated this idea by noting that the greater proportion of Lake Trout in catches compared to Lake Whitefish was less extreme during the winter season and suggested that during this season the two species are less separated by depth than they are in the summer. He further hypothesized that although Lake Trout fishing success tends to increase as the summer season progresses, this may be due to increased catchability seen in concentrated fish groups during spawning later in the summer (Kennedy 1956). Fishing success (FS index) was also noted to vary geographically with the FS index for Lake Trout tending to show a pattern of consistent increase in the north-east direction of the lake versus the south-west during the early years of commercial fishing (Kennedy 1956). However geographic patterns may have been influenced, in part, by socioeconomics as McInnes, the primary purchasing company at the time, saw Lake Whitefish and Inconnu as nuisance species, with their primary interest being Lake Trout. Therefore, participants were encouraged to fish in areas where Lake Trout availability appeared higher (Kennedy 1950).

Changes in Availability

In the review after the first ten years of the commercial fishery, Kennedy (1956) found that the Lake Trout FS index (previously defined) had declined to approximately half what it was at the beginning of the fishery (see details of changes in Lake Trout availability in Table 2.6), with the whole summer Lake Trout FS index decreasing from 68 lb (~31 kg) per net-night in 1947 to 37 lb (~17 kg) in 1951. In 1951 it was hypothesized that an observed decrease in Lake Trout availability (e.g., Summer 1950) may be a result of poor conditions and seasonal fluctuations, rather than population depletion, and that next year's conclusions should be used to validate the decrease (Wheaton 1951a). A further reduction can be seen from 1953 to 1954 of 45 lb (~20 kg) to 22 lb (10 kg) per net-night, respectively. However, this extreme low was attributed to uncharacteristically poor trout fishing conditions during the 1954 summer season, enforced by the plume of the warm, high silt, Slave River water that spread further out than in previously monitored seasons (Kennedy 1956).

For the 1956 summer season the estimated availability of the primary harvested species, Lake Whitefish and Lake Trout, was one-third the 1947 estimate, being the lowest in the ten years of commercial fishing (Kostelnuk and Roberts 1957). This downward trend continued into the next decade of fishing with a 93% reduction in Lake Trout CPUE over the 20-year period, although average size and CPUE varied among locations on Great Slave Lake (Keleher 1972a). At this time effects of exploitation were still relatively unclear; however, it was noted by Keleher (1972a) that overfishing had drastically affected the Great Slave Lake Trout stocks. It was concluded that this long-lived species was unable to withstand the extensive gillnetting associated with the commercial fishery and as a result, suggestions to manage the situation were made. These included reductions to quotas, the separation of Lake Whitefish and Lake Trout quotas, and changes to harvesting seasons (e.g., harvest Lake Whitefish during the winter months when Lake Trout appeared less at risk) (Keleher 1972a).

Following results of the 1972 summer commercial season and research analysis it was found that Lake Trout production had decreased to a level that was unlikely to be able to rebound without restricting commercial operations in some areas (Bond and Turnbull 1973). Lake Trout accounted for 2.3% of the catch (numbers) and 6.5% of the total weight in the results of 22 experimental net sets from 1972 (Bond and Turnbull 1973). Similar results were found by Zhu et al. (2017) experimental netting (2011-2016) who reported an estimate of 0.6% for Lake Trout species composition by numbers, and 6.6%, by weight (Zhu et al. 2017). Previously, Rawson (1951) had found that Lake Trout accounted for 10% of the species composition based on the number and 46% by biomass, although a much larger sample size was used by Rawson (1951) than by Bond and Turnbull (1973). Bond and Turnbull (1973) suggested that the East Arm, specifically current management Area VI, should be closed to commercial operations within two years and reserved for the culturally and economically valuable recreational fishery. Area VI remained open for the following season, 1973, with a Lake Trout annual sub-quota, surpassed by 4050 kg (8,931 lb) and consequently closed to the commercial fishery on July 12th (Bond 1974). The same sub-quota was in place for the 1974 season and when reached in May 1974, resulted in the closure of Area VI for the following winter season (Bond 1975); this closure remains in effect (Northwest Territories Fishery Regulations 2023).

Additional Fishery Research with Great Slave Lake Trout Information

Periodic studies were carried out on Great Slave Lake recreational fisheries from 1961-2005 in response to concern regarding the state of fish stocks following increasing interest in the lake's sport fishery, largely focused on Lake Trout in the East Arm (Appendix I, Table 3). These included a sport-fishery specific creel census survey undertaken at the Great Slave Lodge, located in the East Arm along the Taitheilei Narrows in 1961 (Keleher and Meeker 1962). This was followed by Great Slave Lake recreational fisher research surveys in the 1970's (e.g., summarized in Yaremchuk 1986), in addition to later sport fishery studies completed on Great Slave Lake East Arm in the years 1986, 1994, and 2005 (Low et al. 1999; Low 2006). However, unlike previous East Arm surveys, itinerant Lake Trout fishers who were not supported by guides or stayed at lodges, were the focus of these later studies (Low et al. 1999; Low 2006).

Conclusions of these studies should be interpreted carefully due to acknowledged sampling and response bias', including sampling taking place over limited lake coverage and locations varying annually, inaccurate responses submitted by anglers, and a lack of response (Low 2006). However, observations in Low (2006) supported the belief that the East Arm Lake Trout populations in Area VI (closed to commercial fishing) could support the current effort exerted by the sport fishery. The survey also demonstrated a means for DFO to continue gathering data from itinerant anglers using the East Arm of Great Slave Lake, acknowledging that improvements to data collection, and angling methods could likely be made (Low 2006). Angler related release mortality was recommended as a priority of future research, in addition to providing access to education on lowering catch and release mortality (Low 2006). Low (2006) suggested a future survey should aim to increase response rate and estimate harvest trends and catch for the entire East Arm. Suggestions from Low et al. (1999) and Low (2006) have since been adapted into legislation as barbless hooks are mandatory, and education material related to reducing angler caused mortality is included in the current sport fishery regulations (Government of Northwest Territories 2023).

Although sparse, other types of biological research have occurred on Great Slave Lake Trout populations in the past two decades. For example, Zimmerman et al. (2006) and (2009) (Appendix I, Table 3) examined phenotypic variation in East Arm Lake Trout through a method of photographing and measuring body landmarks on individual Lake Trout. Results revealed significant differences in three out of four traits explored for large-bodied Lake Trout, and that this divergence occurs when an individual reaches a standard length of approximately 43 cm (Zimmerman et al. 2006). In addition, they reported that the diversification of traits revealed at least two phenotypically diverse Lake Trout body forms (a lean and a siscowet (fat)) in Great Slave Lake, generally occupying different water depths, although whether these groups differ genetically has yet to be explored (Zimmerman et al. 2006). Zimmerman et al. (2009) further explored Great Slave Lake Trout phenotypic diversity with an emphasis on assessing the possibility of resource partitioning between forms, and related physical characteristics (e.g., head shape).

Zimmerman et al. (2009) found large Lake Trout (> 43 cm standard length) had two groupings (siscowet and lean) based on both head and body shape, whereas smaller Lake Trout (< 43 cm standard length) only revealed one grouping based on body shape and two morphological groupings based on head shape: Group One individuals having shorter snouts, a higher placement of eyes, and deeper posterior head area, than Group Two individuals. Fifteen individuals were classified as a third morph, humpers (all in the small size class), characterized by having thinner abdominal walls, eyes located higher on dead and deep mid-body profiles (Zimmerman et al. 2009). However, these fifteen individuals were not considered morphologically distinct in terms of head or body shape, nor resource partitioning from the small size class Lake Trout in the siscowet classification (Zimmerman et al. 2009). It was therefore concluded, the true existence of a distinct third morphotype, beyond the lean and siscowet-like forms previously identified in Zimmerman et al. (2006), could not be confirmed for Great Slave Lake (Zimmerman et al. 2009). Within each morph, buoyancy was found to be three times greater in large-bodied individuals versus small, with capture depths varying between sizes classes and among morphs (Zimmerman et al. 2009). Large siscowet-form Lake Trout were caught at deeper depths than large leans, but at similar depths to small-siscowets and small leans (Zimmerman et al. 2009). Sculpins and coregonines were common prey for all trout with 68% of all stomach contents containing fish, however several large-bodied leans were found to specialize on terrestrial insects, while a single small siscowet specialized on benthic invertebrates (Zimmerman et al. 2009). Ultimately Zimmerman et al. (2009) concluded that both lean and siscowet-form Great Slave Lake Trout experience a shift from benthic to pelagic feeding at ~43cm standard length, made evident by staple isotope analysis, however for lean morphs this occurs through a movement to shallower feeding areas, while siscowets transition through utilizing different available prey.

Recent data collection on Great Slave Lake, including Lake Trout-specific surveys have been occurring for the past decade through work of local fishers, research organizations, and the Department of Fisheries and Oceans (DFO), Canada. Fishery dependent data has been collected beginning in 2010 through fish plant sampling and commercial fisher logbook data (DFO 2024). This research included the analysis of Lake Trout catches, fork length, weight, age, sex, and maturity, although not all information is complete for all data entries, with logbook data currently being validated. Since 2011, DFO has conducted semi-regular summer season, multispecies, multi-mesh, gill-net surveys on Great Slave Lake (Zhu et al. 2017, Appendix I, Table 3), with a fall-season Lake Trout spawning index survey initiated in 2017. Worldwide events have impacted some aspects of data collection in recent years, limiting available data in some survey years. Nonetheless, information obtained from these surveys for various Great Slave Lake species has, and is currently, being reviewed and analyzed to assess stock status (e.g., abundance data used in Chapter 3).

Summary

The long history of commercial fishing on Great Slave Lake has consisted of varying vessels of size and type, number of participants, including buyers and sellers, and different controlling management parties which has created challenges for the collection and interpretation of data (Keleher 1972a; Day and Low 1992). This enforces the need for more systematic stock assessments and research investigations into the health of valuable fish stocks. The need remains for a synoptic analysis and time series investigation approach to available data by means of predictive modeling (Day and Low 1992). This need extends to Lake Trout, a staple of the commercial, subsistence, and recreationally fisheries, and thus of substantial value (Rawson 1951; Healey 1978a; McDermid et al. 2010).

Extreme variability in demographic rates is observed from populations throughout the native range of Lake Trout, including vast difference in recorded ages and associated sizes of Lake Trout from populations in their southern range, as compared to those in their northern range. This adds uncertainty to stock assessment methods that synthesize information from other sources and extrapolate for understudied populations. Therefore, future research aimed at Great Slave Lake Trout should collect data that enables estimates of demographic rates specific for Great Slave Lake populations, with greater certainty. Moreover, data collection should continue to operate in a manner that follows commercial fishery operations, in addition to research that helps determine the structure of populations within Great Slave Lake. This is required to estimate area specific quotas that are based on biologically distinct populations within the lake. Acknowledgement has been made that rebuilding the Great Slave Lake commercial fishery will take time (Keleher 1972a; DFO 2014; Government of Northwest Territories 2017), however pressure to increase commercial operations is still occurring (Yarmechuk 1986; Government of Northwest Territories 2017). Recent higher catches (e.g., 2018, catch data from DFO Fisheries Resource Management and DFO Fisheries Management and Harvest Information System (FMHIS) database; Chapter 3) should be interpreted with caution, as there are risks of misinterpreting an increase in effort following the initiative to revitalize the commercial fishery enacted in 2017. Given the history of data interpretations for this stock, it would be prudent to limit further increases in annual harvest, until stock assessment estimates reveal the current status of the Great Slave Lake Trout populations to be sitting at a healthy, rebuilt stage.

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Tables and Figures

Table 2.1: History of Great Slave Lake recreational license catch and possession limits for Lake Trout

Year	Daily	Possession	Reference
1973	5	10	Low 2006
1974	3	5	Low 2006
1979*	2	3	Low 2006
1991*	2	3	Low 2006
2003**	1	2	Low 2006
2022-2023***	2	3	Government of Northwest Territories 2022

* 1 Lake Trout in possession may be larger than 70cm fork length

** Trophy management area of the East Arm only (Area VI)

***1 Lake Trout can be taken from Area VI as part of daily limits; 2 can be from Area VI as part of possession limit, and 1 Lake Trout in possession may be larger than 70cm fork length

Table 2.2: History of Great Slave Lake Whitefish and Trout combined commercial quota; from 1949 onward, all quotas are given as round weights.

Year	Annual Whole Lake Quota (Tonnes, t)	Reference	Comments
1942-1944	~544 (round) ~454(dressed)	Keleher 1962	- Arbitrarily set in 1942, pre commercial operations
1944-1945	*Opening Quota:* ~544 (round) ~454(dressed) *After increase Aug 1945:* ~1089 (round) ~907 (dressed)	Keleher 1962; Day and Low 1992*	- Following 1944 survey, in December 1944 Rawson made quota recommendation of ~1360 - ~2270 t* - McInnes requested increase on May 1, 1945 (repeated June 29): before commercial fishing began - When summer season opened quota was still ~454 t; increased in August 1945, (a few days into the season), going against policy that completion of commercial season was needed before increase - In October 1945, McInnes relayed intentions to request further increase to ~136 t dressed for summer allocation the for 1946-1947 season

1945 -1948	*Opening Quota:* ~1089 (round) ~907 (dressed) *After increase May 1946:* ~1905 (round) ~1590 (dressed)	Keleher 1962	- May 17, 1946, limit increased: ~455 t to winter & ~1135 t dressed allotted to summer, with carry over allowed - McInnes expressed discontent for not being granted ~1360t dressed for summer allocation - 1946 quota carried onto 1947-1948 season based on Demsey's recommendation and approval of Kennedy and Rawson - Dempsey suggested no further increase should be granted until biological understanding of south shore populations increases
1948-1949	*Opening Quota:* ~1905 (round) ~1590 (dressed) *After quota increase Jan 1949:* ~3175(round) ~ 2680 (dressed)	Keleher 1962	- After back-and-forth recommendations and opinions, the winter quota was increased experimentally during the season with widespread repercussions - Mixed reactions from involved companies: McInnes & Menzies objected but it was the belief of Dempsey this was due to concern for summers availability - Ripple effect of increase felt by Manitoba Government as it weakened Whitefish market in the province in addition to supplies that were contracted out based on the previous quota

1949-1955	~4080 (round)	Keleher 1962	- Quota was proposed by Rawson and supported by Kennedy through the main conclusions of the research study (e.g., no change in average size, CPUE, etc.)
			- Decision was met with many opinions, mainly those disagreeing:
			  - McInnes did not agree that the limit could be sustained
			  - Deputy Commissioner of NT believed previous limit was sufficient for need, and limit should remain unchanged to assess effect on fish populations
			  - Prairie Fisheries Federation opposed, largely related to effect of previous winter quota increase
			  - Rawson agreed with previous increase but expressed concern it wasn't maintained for a minimum of two seasons and sampling as a precaution to notice influence was risky
			  - Dempsey appeared to support Kennedys conclusions

1955-1956	~4080	Keleher 1962; Sinclair et al. 1967	- 1955 & 1956: the Yellowknife Brand of NT Fish and Game Association requested commercial fishing be prohibited in East Arm sections → a request that was heard as early as

			1942 → this request was denied - 1956: the biologist studying Great Slave Lake, D.C. Scott (from April 1953 till his resignation in May 1956), made suggestion quota be reduced to ~3630
1956-1970	~4080	Day and Low 1992	
1970-1973	*Opening Quota:* ~4080 *After decrease spring 1971:* ~2260	Day and Low 1992	- Following the analysis of the first 20 years of commercial operations, the quota was reduced in the spring of 1971
1973-1974	~2260	Day and Low 1992	- Although overall quota was not reduced, in May 1974, the Area VI quota was reduced by ~90 tonnes (to protect East Arm Lake Trout), with that amount allotted to other areas
1974-1976	~2175	Bond 1975; Day and Low 1992; Read and Taptuna 2003	- In November 1974, before the start of the season, Area VI was closed to commercial operations, resulting in a quota reduction, kept at this level for two seasons
1976-1978	~1545	Read and Taptuna 2003	- Quota was reduced due to reductions in Areas II, IV and V, with IE and IW quotas unchanged from previous year
1979-1980	~1615	Read and Taptuna 2003	- Quota increased due to additions to Area V

1978-1979	~1680	Read and Taptuna 2003	- Quota increased due to additions to Area V
1980-1981	~1680	Read and Taptuna 2003	- Small changes to area quotas but negligible over all (total in kg 1979-80 = 1,681,818, total in kg 1980-81 = 1,681,900)
1981-1982	~1720	Read and Taptuna 2003	- Quota increased due to additions to Area III
1982-1985	~1680	Read and Taptuna 2003	- Quota decrease due to reductions to Area III
1985-1986	~1710	Read and Taptuna 2003	- Quota increased due to additions to Area III
1986-1990	~1680	Read and Taptuna 2003	- Quota reduced due to reductions to Area III
1990-1996	~1730	Read and Taptuna 2003	- Quota increased due to additions to Area III
1996-1997	~1750	Read and Taptuna 2003	- Quota increase due to additions to Area IW
1997-2002	~1730	Read and Taptuna 2003	- Quota reduced due to reductions to Area IW

Table 2.3: A summary of Great Slave Lake current and past management areas, and the regions they share with the areas used from ~1951-1972, as well as the 13 statistical areas used by Kennedy (1956). Additional columns indicate the year commercial operations began, the year the greatest and second greatest commercial catches from that area occurred, in addition to a description of the general lake location (e.g., northwest/NW, south/S, etc.). Data from Kennedy (1956), and Keleher (1972a, b). Note: See Appendix I, Table 2 - maps for lake area designations referred to below.

Statistical Area	Current Management Area	Areas 1951-1971	Lake Area	Year Opened	Year of Peak Yield	Second greatest peak yield	# of years between opening and peak yield
F	IV	3(~50%), 4 (~50%)	Upper half of NW Arm		1952	1953	7
G	IV	3	N Central		1946	1954	1
H	IV, V	3 (~95%) 4 (~5%)	N Central	1945	1946	1949	1
K	IV, V (mostly V)	3	East Arm Entrance to Main Basin		1945	1949	0
E	II, IV	2 (~33%), 4 (~66%)	Lower half of NW Arm		1949	1951	3
A	I, III	1(~55%), 2(~45%)	S Coast of Main Basin	1946	1951	1952	5
M	VI	3	Northern Side of S portion of East Arm		1948	1956	2
D	I, III	1(~33%), 2(~66%)	W Coast of Main Basin	1947	1949	1950	2
L	VI	3	Southern Side of S portion of East Arm	1948	1955	1949	7
C	II, III (mostly II)	2 (~66%), 4 (~33%)	Central Main Basin	1949	1953	1960	4
B	II, III, IV, V	3(~90%)	E Coast Main Basin	1950	1950	1951	0
N	VI	3	Southern Side of N portion of East Arm	1952	1956	1958	4
O	VI	3	Northern Side of N portion of East Arm	1954	1954	1958	0
			Average # of years between opening and peak:				3

Table 2.4: Current Great Slave Lake commercial management areas and associated Lake Trout and Whitefish combined quotas. Quotas are taken from Northwest Territories Fishery Regulations (2023) and area given as kilograms, round weight.

Management area	**Combined Lake Trout & Whitefish Commercial Fishery Quota**
IW	227,300
IE	318,200
II	318,200
III	45,500
IV	409,100
V	363,600
VI	Closed

Table 2.5: Information on Lake Trout average size obtained from the early technical reports covering the research investigations on the Great Slave Lake Commercial Fishery. Note: See Appendix I, Table 2 maps for lake area designations referred to below.

Season	# Lake Trout Sampled for Weight	Comments On Size	Reference
Summer 1947	4442	- Tendency for size to decrease through the season; also noted in the previous season - Decreased size from west to east	Kennedy 1948
Summer 1948	4721	- Tendency for Lake Trout from the west fishing grounds, and caught early in the season, to be larger than those caught later	Kennedy 1950
Summer 1949	5349	- Average size tended to decrease from E to M, as in previous season - Tendency to decrease from E to A, new for the season, however A was not fished prior to season - No indication that average size changed since 1945	Kennedy et al. 1951
Summer 1950	6699	- The average size of sampled Lake Trout lower than the previous summer and winter	Wheaton 1951b
Summer 1951	9405	**-** No consistent difference in average size was apparent at any time and place from 1945-1951	Wheaton and Kennedy 1952

Summer 1952	16,333	-The inconsistent changes in average size since the initiation of the commercial fishery make a true change difficult to detect - Average size of measured Lake Trout decreased by 20% in some areas (e.g., G).	Kennedy et al. 1953
Summer 1953	16,275	- Average size at Whole Lake scale was 7.0 lbs (~3.2 kg); similar Whole Lake average size in 1952, but this was notably smaller than previous years - An increase in average size in Area D and F, and a clear decrease in G	Scott 1954
Summer 1954	17,518	- Average size for Whole Lake decreased to ~6.5lb (~2.9 kg)	Scott and Hanson 1955
Summer 1955	12,382	- Greater % samples taken from east arm (known for large Trout), yet average size still decreased in most areas - Whole Lake average size ~6.5 lb (~2.9 kg)	Scott 1956
Summer 1956	18,607	- Whole Lake average size ~6.6 lb (~3.0 kg)	Kostelnuk and Roberts 1957

Table 2.6: Information on Lake Trout availability obtained from the early technical reports covering the research investigations into the Great Slave Lake Commercial Fishery. Note: See Appendix I, Table 2 maps for lake area designations referred to below.

Commercial Season	Comments On Availability	Reasoning Provided by Authors	Reference
Summer 1945	- Noticeable increase in Lake Trout availability in most places (except Gros Cap) in September	- Hypothesized to be associated with pre-spawning behaviour	Kennedy 1946
Summer 1946	- Apparent decrease in availability of each species from 1945	- Too little information about significance of fluctuations in availability to say if decrease is significant	Kennedy 1946
Summer 1947	- Lake Trout availability tended to increase as season progressed (unlike other species)	- May be result of special effort and attention paid to capture small Lake Trout	Kennedy 1948
Summer 1948	- Lake Trout availability tended to increase with distance from Gros Cap - Sight tendency for Lake Trout to increase while Whitefish decrease as season progresses	- Little change since 1945 in availability at any particular area/time period with the increase in overall catch mostly a result of expanding to areas of greater availability	Kennedy 1950

Summer 1949	- In general, availability appeared to be lower than previous seasons	- The decrease in availability could be seen as a decrease in abundance, however, previously availabilities have varied enough this this decrease can presumably be seen as a deviation from the norm	Kennedy et al. 1951
Summer 1950	- Lower availabilities of Lake Trout when compared with the previous season, particularly in subdivisions A and D	- It is hypnotized that this decrease may be associated with seasonal fluctuations, and the following years season should be used to clarify - Suggest recommendations regarding a boundary relocation and quota change to prevent depleting areas A and D	Wheaton 1951a
Summer 1951	- Decreased availability of Lake Trout was found for areas E, K and M compared to previous years	- Data from area E may be misleading as only the northern end of the region was sampled - Little fishing was carried out in K which may have also influenced the decreased availability - Overall whole lake availability from 1945-1951 decreased by 25% potentially indicating a decrease in standing stock. However, since no change in average size/morality rate	Wheaton and Kennedy 1952

		has been found, a standing stock decreased appears unlikely. - Relationship between availability and standing stock still unclear with hopes that continued data collection may clarify this interaction	
Summer 1952	- Whole lake availability was estimated at being the same as 1951, but in general there does appear to be a decrease in availability since the start of commercial fishing	- Hypothesized that a stable equilibrium state may be being reached in areas fished the longest (e.g., Area G – has had ~same CPUE for the last 4 years, with that being 2/3 the original value)	Kennedy et al. 1953
Summer 1953	- Overall, area A availability was slightly higher than previous years but varied from west-east - Areas C and E with lower availability → effort and catch also much lower - In Area D lower availability than previous years for Lake trout in June/July resulted in lower effort in the area for the remainder of the year - In F, Lake Trout production	- Harvest from the western region of Area A occurred at beginning of season, rather than in September in 1952, therefore availability was lower as expected since it did not overlap with spawning - Attributed lower production in L to a diversion of fishing effort to Area G, H, and N rather than actual decreased availability	Scott 1954

	was lower in June, July, and September, than it was in August - Greatest decrease in production witnessed in area L - No change in availability of Lake trout in area M from previous year		
Summer 1954	- Availability of Lake trout decreased from 45 lb (~ 20 kg) per net-night in 1953 to 22 lb (~10 kg) in 1954 - This new low in availability is 40% than the previous low in 1951 - Area E was the only area with higher availability than previous year	- Decrease in availability was greatest in Areas F and N	Scott and Hanson 1955
Summer 1955	- Availability of Lake Trout for Whole Lake was ~20 lb (~9 kg) per net night - Availability decreased to ~6 lb (~2.7 kg) per net-night in all areas except A, D, N and F	- Increase in availability in A and D was attributed to 2 new companies fishing in the area	Scott 1956
Summer 1956	- Availability of Lake Trout for	*N/A*	Kostelnuk and

	whole lake was ~20 lb (~9 kg) per net - Areas G and L had a slight increase in availability from 1955 and Area B had the same availability as 1955; all other areas had decreased availability (e.g., A by 98.5% and K by 90%)	*Essentially no reasoning for availability patterns provided in Kostelnuk and Roberts (1957)*	Roberts 1957

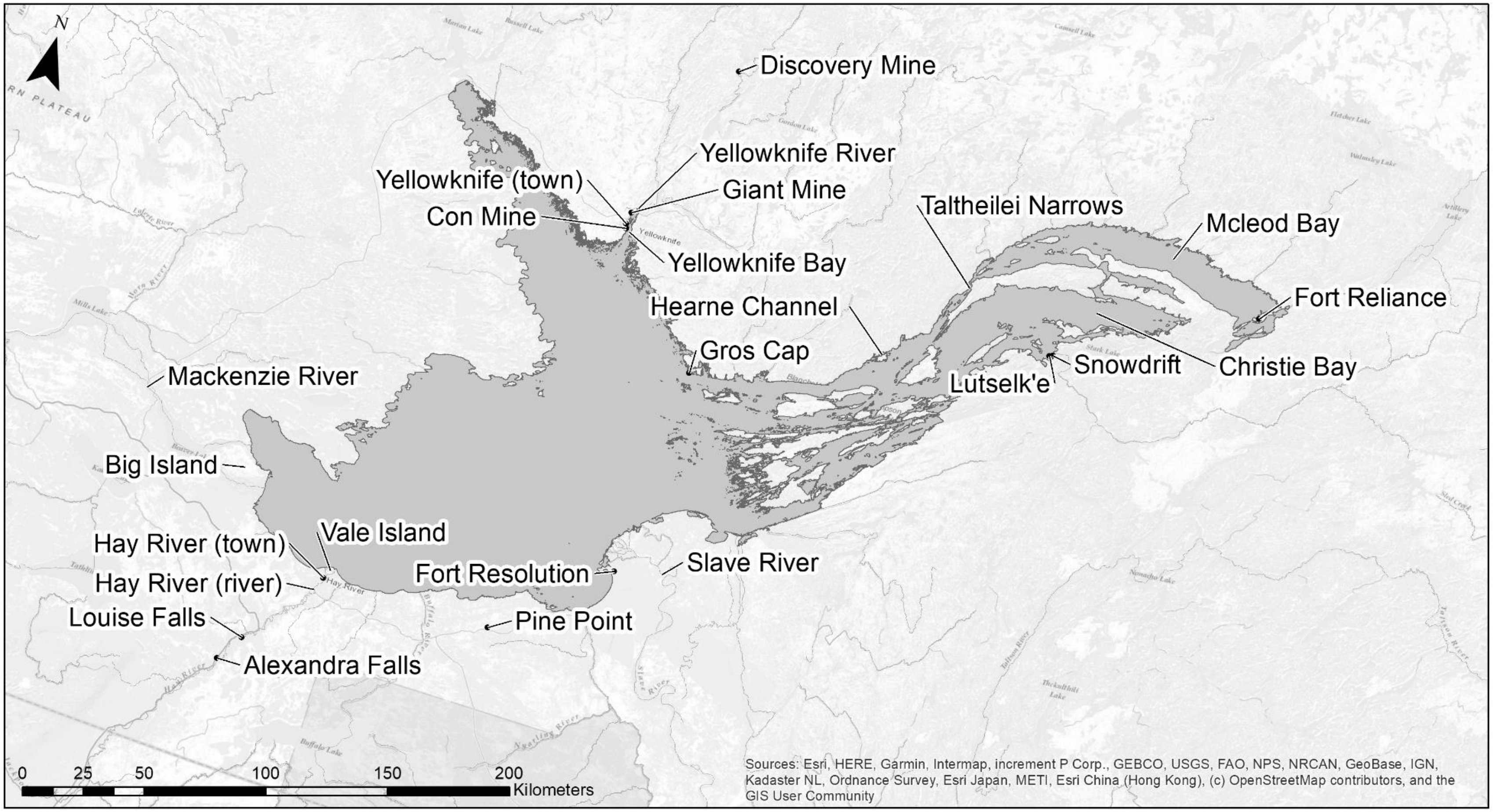

Figure 2.1: Great Slave Lake, Northwest Territories and the locations mentioned in text.

CHAPTER 3: CAN A DATA-LIMITED STOCK ASSESSMENT SHED LIGHT ON THE UNKNOWN STATE OF A NORTHERN FISHERY STOCK? – AN ASSESSMENT OF GREAT SLAVE LAKE TROUT USING CMSY++

Abstract

Great Slave Lake Trout commercial catches have increased gradually from 2007-2018; however, a formal stock assessment is required to determine whether a true increase in stock biomass has occurred. Current stock status of Great Slave Lake Trout was investigated by assembling 50 years of commercial catch data and applying the data-limited stock assessment software, CMSY++. The results estimate that Lake Trout stocks in two of six current management areas are overfished, two are severely overfished, and the remaining two stocks are collapsed based on commonly used definitions for estimates of current biomass relative to the biomass at the maximum sustainable yield (MSY). An assessment of the combined Areas IW and IE spanning a harvest time-series of 70 years, estimates the stocks at the same state as the shorter, 50 year series, adding confidence to the area-specific predictions. The area-based assessments where both BSM and CMSY could be applied also produced similar estimates. However, the longest time series available (~75 years) at the entire lake level revealed drastically different estimates compared to the truncated series (~50 years), adding caution to estimates produced at the whole lake level. Model estimates of Lake Trout MSYs were well below the current pooled quotas in place for Lake Trout and Whitefish in all management areas, with results suggesting Lake Trout commercial harvest in recent years has surpassed the estimated MSY for the species in some areas. The current assessment of this commercially and culturally important species provides the first quantitative estimate of stock biomass and exploitation level

in Canada’s most northern freshwater fishery, Great Slave Lake. The assessment reference points that I determined support caution in further increasing allowable catch and justify the future development of species-specific quotas for this fishery. Nonetheless, given uncertainty inherent in catch only methods there is a strong need for more comprehensive data from this fishery to enable more robust assessment models and ensure future sustainable harvests.

Introduction

Freshwater fish have high importance in Canada and worldwide producing a vital protein source, recreational opportunities, and a valued cultural resource to many Indigenous communities (Schindler 2001; Islam and Berkes 2016). However, many of these fish stocks are being compromised by overexploitation, introductions by non-native species, and by pollutants, among many other anthropogenic influences, adding to the need for a better understanding of these resources (Schindler 2001; Allan et al. 2005; Brander 2010). Great Slave Lake, in Northwest Territories (NT), Canada, has Lake Trout (*Salvelinus namaycush*) populations that are culturally valuable to surrounding communities and important to those that rely on subsistence, commercial, and recreational catches (Rawson 1951; Healey 1978). In addition to being a staple for these various types of fisheries on Great Slave Lake, the species is a valuable component of fisheries throughout their range (Healey 1978; Callaghan et al. 2016; McDermid et al. 2010).

Lake Trout are a key component of the Great Slave Lake commercial fishery which has been operational since 1945. It was the dominant species during the first twenty years of the fishery, when it made up 90% of commercial take (Keleher 1972), however this contribution level was not sustained. Great Slave Lake Trout commercial production declined from a peak of over 1800 tonnes for the 1948-1949 season to ~85 tonnes by the 1971-1972 fishing season (Keleher 1972). Management Area VI in the East Arm of the Lake was closed to commercial fishing in the 1970’s when it became evident that Lake Trout stocks were becoming nearly commercially absent in some areas, unable to withstand commercial gillnetting (Keleher 1972; Bond 1975; Day and Low 1992). This closure was largely enacted to protect Lake Trout stocks and the lucrative recreational fishery they support (Bond 1975; Yarmechuk 1986). Despite this closure, commercially caught Lake Trout have remained at a fraction of original production through the beginning of the 21st century, and only accounted for ~20% of the Lake Whitefish and Lake Trout total catch for the 2019-2020 commercial season (~66 tonnes Lake Trout and ~258 tonnes Whitefish) (Catch values from DFO Fisheries Management and Harvest Information System (FMHIS)). Yet, the two species are still managed through a combined commercial quota (Northwest Territories Fishery Regulations 2023), as they have been since the inception of the fishery in 1945 (Keleher 1962). Environmental changes and other anthropogenic influences (e.g., climate change) may further influence species distributions and productivity of this and other freshwater ecosystems (Schindler 2001; Brander 2010; Poesch et al. 2016) with the extent of impacts largely unknown (Reist et al. 2006; Strayer and Dudgeon 2010).

Models and simulations that estimate reference points, such as the Maximum Sustainable Yield (MSY), are a conceptual foundation for stock assessments and used to evaluate available fishery data and help determine preferred management options (Free et al. 2020; Pantazi et al. 2020; Pons et al. 2020). Reference points can be used to reveal information on current and historical fishery status, responses to past policy, and how a stock may respond to future changes in management or policy (e.g., quota changes) (MacCall 2009; Lorenzen et al. 2016; Walsh et al. 2018). These models generally require catch values and estimates of stock specific characteristics, such as growth rates, in addition to indices of relative abundance, (e.g., catch per unit of effort (CPUE)) (Dick and MacCall 2011; Maunder and Piner 2015; Froese et al. 2017). The long history of Great Slave Lake fisheries, varying spatial exploitation, vessels and abilities, and inconsistent divisions of management areas and research regions have led to difficulties in the assessment of historical data sets and management of fish stocks; a common occurrence in this and other mixed-use fisheries (Keleher 1972; Day and Low 1992; van Gemert et al. 2022). Recent catch-based assessment models have been developed that no longer require the extent of information and data sources of traditional fisheries models but are still capable of producing estimates of fishery reference points (Froese et al. 2017; Fitzgerald et al. 2018; Free et al. 2020). These data-limited methods are primarily mathematical models where MSY is based on the estimated historical relationship between catch and biomass (Pitcher 2016; Pons et al. 2020; Williams et al. 2002). Of these models, CMSY (Froese et al. 2017), has proven reliable in providing baseline stock information for fisheries management through the generation of reference points and estimates of relative stock size with minimal input data (Liang et al. 2020; Nisar et al. 2021).

The highly valued Great Slave Lake Trout populations are relatively data-limited, with a limited time-series of commercial harvest totals for current management areas, in addition to few research studies on the demographic characteristics of commercial fish species over the more than 75-year fishery (Yaremchuk 1986; Low 2006; Zhu et al. 2017). The objectives of this chapter are to: i) estimate the current state of Great Slave Lake Trout stocks and ii) to determine if current harvesting levels align with the management goal of rebuilding stocks to support commercial, subsistence, and recreational fisheries (Keleher 1972; Government of Northwest Territories 2017).

Methods

CMSY Stock Assessment Model

Surplus production models account for all individuals in a population as a single measure of biomass and have been developed to determine the ideal annual effort level (F_{MSY}) and yields that can be removed from a population without influencing the long-term productivity of the fish stock (MSY) (Varghese et al. 2020). Catch-MSY, first introduced by Martell and Froese (2013), utilizes one of the most common surplus production models, the Schaefer model (Schaefer 1954). The first rendering of the Catch-MSY model was later modified to account for the early model's shortcomings (e.g., a biased estimate for unexploited stock size, B_0 (Froese et al. 2017; Ju et al. 2020; Pons et al. 2020)); resulting in the new assessment model, CMSY (Froese et al. 2017). The theory behind this modeling approach is that a specific carrying capacity, k, exists for every ecosystem with the biomass of a given stock at this point being ~B_0, the unfished biomass level. If the biomass is reduced, the population has the capability to grow as a function of the current population size, its per capita intrinsic growth rate (r), and the limit k (Froese et al. 2017; Froese et al. 2023). With this in mind, CMSY assumes that a stocks biomass (B_t) from one year (t) to the next (t+1), B_{t+1}, follows Equation (1) (Schaefer 1954, 1957; Froese et al. 2017):

(1) $$B_{t+1} = B_t + r\left(1 - \frac{B_t}{k}\right)B_t - C_t,$$ where C_t is catch at time, t.

A common concept in fisheries population dynamics is that of depensation at low stock sizes (Meyers et al. 1995; Froese et al. 2017). It is assumed low levels of recruitment are associated with low population sizes, potentially related to the Allee effect causing disproportionately reduced feeding, survival, or reproductive success at very low population sizes (Meyers et al. 1995; Liang et al. 2020; Varghese et al. 2020). To address this issue, CMSY conditionally replaces Equation 1 with Equation 2, which assumes a linear decline in recruitment when biomass falls below half the biomass that enables fish stocks to support the MSY, $.5B_{MSY}$ or ~ 0.25k (Froese et al. 2017; 2023; Liang et al. 2020).

(2) $$B_{t+1} = B_t + 4\frac{B_t}{k}r\left(1 - \frac{B_t}{k}\right)B_t - C_t \mid \frac{B_t}{k} < 0.25$$

The second term in Equation 2 accounts for the reduced recruitment through the linear decline of *r* and further reduces the estimate for F_{MSY}, which is calculated at ~.05r (Ricker 1975; Froese et al. 2023; Nisar et al. 2021).

In similar fashion to other data-limited modeling methods, CMSY requires input distribution ranges for some population demographic traits, in addition to a time-series of catches (Fitzgerald et al. 2018; Froese et al. 2017; Ju et al. 2020). A range for r, also known as resilience and defined as the maximum net productivity for the population, is additionally needed for this model to estimate reference points (Froese et al. 2017). Input estimates of prior ranges for the ratio of current level biomass (B) to unfished biomass (k) at the beginning, middle (optional), and end of the time-series are used in conjunction with catch values to determine valuable management reference points (Froese et al. 2017; Ju et al. 2020; Nisar et al. 2021). Drawing on the input distributions for r and k, the Schaefer model is run repeatedly (10,000 times in the present study) to estimate annual biomass from valid r-k pairs (Froese et al. 2017; Nisar et al. 2021).

Possible pairs for the populations r and k values are drawn randomly from their priors and considered valid for final analysis if the biomass trajectories from the pair are within levels of observed catches (Froese et al. 2017; Ju et al. 2020; Nisar et al. 2021). Accepted pairs of r-k variables are determined using a set of rules for evaluating biomass trajectories. For example, a pair is considered viable as long as a biomass smaller than 0.01 k is not projected over the time series (population trajectory crash), pairs do not allow the stock to exceed carrying capacity, and projected results are consistent with input estimates for the relative biomass (B/k), and k ranges (Froese et al. 2017, 2023; Nisar et al. 2021). The most probable r-k pair is then selected as the geometric mean from the density distributions created through the repeated sampling worked into the model (Nisar et al. 2021). Management reference points, MSY, F_{MSY}, B_{MSY} (stock biomass at MSY), B/B_{MSY} (ratio of estimate of current biomass over biomass required at MSY), and the ratio of current fishing pressure to the fishing pressure estimated at MSY (F/ F_{MSY}) can then be generated from simple equations using r and k (Ricker 1975; Froese et al. 2017; Ren and Liu 2020). Numerical outputs are supplemented with multiple visuals, including a form of stock status plot known as a Kobe plot, which summarizes the progression of estimated state of a fishery through time, along with the probability of the current stock falling into differing fishery states (Maunder and Aires-da-Silva 2014; Froese et al. 2021).

Further advancements have been made to the Froese et al. (2017) CMSY model with the creation of the software, CMSY++ (Froese et al. 2021, 2023), the primary assessment method used in the present study of Great Slave Lake Trout. The main differences between the original CMSY model (Froese et al. 2017) and the improved CMSY++ (Froese et al. 2021, 2023) is that the latter includes the use of an artificial intelligence (AI) that uses catch values to make a prediction for biomass priors (B/k), instead of the inclusion of expert opinion on stock size. However, CMSY++ still allows other sets of priors (e.g., expert opinion-based) to be used if preferred (Froese et al. 2021, 2023). The model's AI is a neural network that predicts default B/k priors based on catch relative to the model's prior estimate of MSY, using patterns from 400 unique test stocks from a variety of species (Froese et al. 2023). Additionally, CMSY++ uses a complete Bayesian Markov Chain Monte Carlo (MCMC) methodology for its model estimates, instead of the previous version's use of the Monte Carlo approach for the CMSY model (Froese et al. 2017, 2021). The model executes faster as a result of these updates, and options for additional graphical outputs have been added (Froese et al. 2021). Other improvements to the model include a quicker and more streamlined method of determining the best r-k combinations through the inclusion of multivariate normal priors in log space instead of the uniform prior distributions used for determining values of r and k in previous versions (Froese et al. 2017, 2021, 2023).

An additional stock assessment model, the Bayesian state-space Schaefer Model (BSM), is commonly used in conjunction with CMSY, or on its own (Meyer and Millar 1999). However, the application of BSM is limited to stocks that have some index of abundance available as input (Froese et al 2017, 2023; Nisar et al 2021), therefore it's use in any study is conditional on the availability of consistent and reliable abundance indices for each stock in a given administration area from either the fishery or an independent survey.

All modeling scenarios in the current study were completed using the software R (R Core Team 2022) version 4.0.4, the most recent version of the CMSY++ software (Froese et al. 2021, 2023), in association with a variety of packages as required with CMSY++: (0.7-1), coda (0.19-4), parallel (4.0.4), gplots (3.1.3), mvtnorm (1.1-3), snpar (1.0), neuralnet (1.44.2), and conicfit (1.0.4). The CMSY++ script used is available at https://oceanrep.geomar.de/id/eprint/52147/, and in Appendix III, with an example of the R output from the current assessment also included in Appendix III. Results of the CMSY assessment model within the CMSY++ software are referred to as "CMSY model results/estimates" in the following sections, however, "CMSY++" is used to more generally refer to the updated 2021/2023 software.

Fisheries Data and Model Requirements

A comprehensive review of historic and current literature on the Great Slave Lake fisheries, with an emphasis on Lake Trout, has led to an in-depth understanding of how the lake's commercial and recreational fisheries have progressed, in addition to the differences in limnology throughout this vast system (Chapter 2). Great Slave Lake is generally oligotrophic in nature, with this state exacerbated in the East Arm (management Areas V and VI), especially in Christie and McLeod Bays (Rawson 1950; Evans 2000; Low 2006). The East Arm along with some of the northeast shore of Main Basin has a Precambrian rock underlay, known as the Canadian Shield (Rawson 1950; Keleher 1972; Bond 1974), while the western portion of the lake has an alluvial plain underlay referred to as the Mackenzie Lowlands (Rawson 1950; Bond 1974). Differences in areas are not limited to underlay, as maximum depth, water temperature, turbidity, prevalence of islands, in addition to productivity levels and composition of fish communities, differ throughout Great Slave Lake (Rawson 1950; Kennedy 1956; Zhu et al. 2017). Furthermore, Lake Trout within Great Slave Lake have been recorded as being sedentary individuals, generally remaining in the same lake region throughout their life (Keleher 1963). These stock demographics, and regional variations in lake characteristics led to the decision to base stock analyses on a finer spatial scale than that of the entire lake through modeling of current fishery management areas (Figure 3.1).

Due to historical changes in the lake’s management areas, the methods for presenting data, and changes to management, much of the early commercial fishery information for Great Slave Lake is difficult to translate into values comparable with that of the present fishery. Despite the high value of fish stocks, monitoring records are limited, and require methods for stock assessment tailored to their data availability. As a result of changes to management areas and consequent lack of spatially consistent harvest data from early years, the most logical commercial catch time-series begins in 1972 for Areas IW and IE, 1974 for Areas IV & V, while the appropriate time-series for Areas II and III begins in 1979, following the most recent management area change which occurred before the start of the 1979 winter commercial fishing season. Catch inputs for CMSY++ used in the Great Slave Lake Trout stock assessment included annual catch information by management area obtained from DFO Fisheries Resource Management and DFO Fisheries Management and Harvest Information System (FMHIS) database (Appendix II, Table 1).

As suggested by both the digital reference source, Fishbase (Froese and Pauly 2023), and Froese et al. (2017) for slow growth, long-lived species, such as Lake Trout, a range of 0.05 - 0.5 was used in all modeling scenarios as the proxy for r, representing low resilience. Model explorations were run using default B/k values (ratio of current biomass to carrying capacity) at the beginning, middle, and end of the time-series estimated by the built-in neural network of CMSY++, in addition to set B/k values based on expert opinion (pers. comm., Dr. M. Y. Janjua, Fisheries and Oceans Canada, Winnipeg, MB, January 11, 2023) and previous fishery knowledge (Chapter 2). The latter were included due to the perceived initial low catches, which resulted in model outputs being accompanied by a warning message when using neural network-estimated B/k inputs at the beginning of the series (1970's) for all individual management areas (results not included). The warning (generally) stated:

"Attention: Low catch in 1975 may indicate either depleted or unexploited biomass.
Set startbio in ID file to 0.01-0.2 or 0.8-1.0 to indicate depleted or unexploited biomass.
Else, set start year in ID file to 2009 to avoid uncertainty".

Therefore, given previous knowledge of the fishery (e.g., catch time series beginning after the crash of the Lake Trout commercial fishery in the western areas of the lake) a B/k input prior for the beginning of the time series was set at 0.01 - .02 to indicate a very strong depletion level (Froese et al. 2021), for Areas IW, IE, II, III, VI, & V. Additional support for the selection of this input comes from Froese et al. (2021) descriptions of stock status based on B/k ranges. They suggest low abundance in previously high producing areas, collapsed stocks or closed areas, or unprofitable situations (e.g., early companies urged fishers to venture further out when areas began failing to meet production expectations (Kennedy 1950)), potentially indicate a B/k range 0.01-0.2 (Froese et al. 2021). These factors were all found throughout the history of the Great Slave Lake Trout fishery. Given that the present state of the fishery is unknown and currently under investigation, the B/k values at the end of the time series were not set. Instead, the model's neural network was utilized to estimate a prior based on the history of catches provided. A summary of the modeling inputs used for the CMSY analysis for the individual management areas and their input condition labels used in analysis can be found in Table 3.1.

Sensitivity Analysis

To explore the model's dependence on informative priors, multiple scenarios were run for each of the lake management areas by altering the B/k inputs, in addition to exploring outputs at different spatial scales (e.g., Whole Lake versus individual management areas) (Table 3.1). For the individual lake management areas with available catch time-series (IW, IE, II, III, VI, V) beginning in the 1970's, well after initiation of the commercial fishery, two initial B/k ranges were explored: condition i – a narrow B/k input of 0.01-0.2 at the beginning of the time series, and condition ii – a wider, more uncertain, B/k input of 0.01-0.4. The B/k at the end of the time series was left open for the model to estimate. Condition ii, the wider B/k at the beginning of the series, was chosen based on input from an expert on the fishery whom suggested the initial B/k range, 0.01-0.2 (suggested by the model's warning statement when the B/k input at the beginning of the time series was not set), may be too limiting for some areas as fisheries were being abandoned at the time and thus low catches could, in part, be associated with reduced effort (pers. comm., Dr. M. Y. Janjua, Fisheries and Oceans Canada, Winnipeg, MB, January 11, 2023). Some areas still produced relatively high catches in the 1970's - 1980's, such as Area V that still produced between ~70 – 100 tonnes annually from 1976 – 1986, furthering the possibility stocks in these locations may not be as depleted as implied by the narrow B/k input, condition i.

In the case of management areas IW and IE where biomass-per-unit-effort (BPUE) data were available from the integrated summer multi-species monitoring program held on Great Slave Lake Main Basin, (June-August 2011–2019, 2022) (Zhu et al. 2017; Zhu et al. 2023, Fisheries and Oceans Canada, unpublished), the BSM model associated with Froese et al.'s (2021, 2023) CMSY++ software (which contains both the most recent CMSY model, and BSM) was used to allow for comparison with CMSY outputs. The BSM model inputs for areas IW and IE can be found in Table 3.1, with the BPUE index values in Appendix II, Table 3. For each area (IW and IE), scenarios using the available biomass indices were run with both previously used B/k inputs: 0.01-0.2, and 0.01-0.4.

CMSY modeling scenarios were completed for the entirety of Great Slave Lake utilizing the longest time series of catches available which is at the whole lake spatial scale beginning from commercial fishery inception in 1945 (catch values in Appendix II, Table 2). In addition to allowing the neural network of CMSY++ to estimate B/k priors, the B/k range used for the time-series' that begin at the initiation of commercial fishing (1945) was set at 0.5-0.9, as it is believed the fishery was underdeveloped and underfished at this time. According to Froese et al. (2017, 2021) the range of 0.05-0.9 can be used as a default for prior biomass if there is an assumption that biomass at the time is relatively high. Additionally, due to the influence of

World War II on fisheries worldwide resulting in the recovery (e.g., reinvolvement in fisheries abandoned due to war efforts), or the introduction of new fisheries following the war, the high initial biomass range of 0.05-0.9 has been determined as an appropriate proxy for catch series inputs beginning before 1960 (Froese et al. 2021). This seems like a logical proxy for this fishery given that the year commercial fishing commenced aligns with the completion of WWII, and the knowledge that multiple mining operations began in the years following the war (Silke 2009), both suggesting an influx of interest in the resources of the area. For all the whole lake stock assessment scenarios, the B/k's at the end of the series were estimated by the model's neural network (Table 3.1). To explore the effect the closure of Area VI may have had on production, a catch series beginning in 1975, the year following Area VI's closure to commercial fishing, was also completed at the whole lake level, allowing the neural network to estimate both the initial and end prior for B/k (Whole Lake modeling condition iv), in addition to setting B/k at the beginning of the series to 0.01-0.4 (Whole Lake modeling condition v), indicating low relative biomass.

Although the commercial fishery officially began in 1945, the ideal commercial catch series available for the current management areas begins in the 1970's following the collapse of commercially caught Lake Trout in western regions of the lake (Bond 1974), limiting the useable catch data. By digitizing a historical figure (Figure 4 in Bond and Turnbull (1973)) a time series of approximate commercial catch for the entirety of Area I (western and eastern portions) was created, adding 20 years of Area I (IW and IE) catches that were previously not tabulated in historic literature (Appendix II, Table 2). This lake region, and associated recreated catch time series, provide a 70-year time series that is useable on a smaller spatial scale than previously available, yet, still beginning after the peak catches occurred for the stock in this area. Modeling scenarios for Area I were run using catch inputs of 1952 – 1971, 1972 – 2022, and 1952 – 2022, to examine the sensitivity of results to catch time-series lengths.

Similar to the previous modeling scenarios that utilized the shorter 1970's - 2022 time-series, when running the Area I 1972 – 2022 input condition, the model produces the same previously quoted error code when allowing the neural network to estimate the B/k at the beginning of the time series (results not shown). Therefore, the analysis was performed using set B/k inputs of both 0.01-0.2 and 0.01-0.4. Outputs produced using the longer time-series can be compared to the series beginning in the 1970's to reveal whether the model predicts the state of the stock at similar levels in both scenarios, helping to evaluate the appropriate time series length for these stocks. Additionally, the 1952 – 1971 time series for Area I was run to compare the model's estimate of the B/k at the end of the time series (1971), to the B/k inputs (0.01-0.2; 0.01-0.4) selected for the beginning of the 1970's – 2022 time-series for area-wise modeling. The CMSY modeling inputs for the Whole Lake and Area I assessments are summarized in Table 3.1.

An added benefit of the CMSY++ version of the Schaefer surplus production model is that it allows for the generation of retrospective analyses results and plots (Froese et al. 2021). This can be used to determine whether a retrospective discrepancy exists (e.g., biomass trajectories using most recent catches varying from those using truncated time-series) (Froese et al. 2021). If the series for the assessment using all years of data appears to stray from those produced when omitting recent year's data, then a strong retrospective discrepancy exists, and fisheries management should take this into account when interpreting the assessment. For this stock assessment, the retrospective analyses were performed using 1-3 years less of data than in the initial modeling condition and plots were generated to compare the estimates for F/F_{MSY}, and B/B_{MSY} generated with the full versus the different, shorter, time-series (Froese et al. 2021).

Results

CMSY Stock Assessment Model

The CMSY results of this study estimate MSY's for Great Slave Lake Trout at levels substantially lower than current Lake Trout and Lake Whitefish combined commercial quotas in all the current management areas, Figure 3.2. Furthermore, commercial catches in the management areas with most of the Lake Trout commercial harvest, IW, and IE, have in recent years surpassed the estimated MSY's, while likely harvesting below MSY in recent years in other regions, such as Area V (Figure 3.2). The values of B/B_{MSY}, produced by the CMSY stock assessment method estimate the current biomass level in all management areas below the biomass required at MSY, with stocks in various states of being overfished according to terms used by Palomares et al. (2018) and modified in Ju et al. (2020) to describe stock status based on predicted B/B_{MSY} ranges (Table 3.2).

The CMSY model estimated MSY for management Area IW at approximately half the MSY estimate for Area IE, with associated B_{MSY}'s following the same pattern (e.g., ~1080 (742 – 2040) t for IW and ~1990 (1370 – 3670) t for IE (Figure 3.3)). For both IW and IE the estimated MSY values from input condition ii (wider range for the initial B/k), were marginally more conservative than the narrower B/k input condition i, however confidence limits overlapped substantially in all lake areas assessed. Given the added uncertainty in model inputs, common to data-limited fisheries, the more conservative results based on input condition ii are presented in the following stock assessment summary (results from all CMSY and BSM analyses are summarized in Appendix II, Table 4). Biomass in 2022 was estimated below B_{MSY} for both Areas IW and IE based on the CMSY model (Figure 3.4). These values fall within the overfished stock status state (B/B_{MSY} range between 0.5 – 0.8) as described by Palomares et al. (2018) (Table 3.2). The ratio for fishing mortality in 2022 to fishing mortality at MSY was estimated at ~1 for Areas IW and IE, suggesting current fishing mortality is at the level corresponding to the predicted MSY (Figure 3.5). The CMSY results indicate that current stock status for Area IW (based on input condition ii) is on the boundary of the $F=F_{MSY}$ line, while being mostly below the $B=B_{MSY}$ boundary, as shown in Figure 3.6a, the Kobe Plot output for Area IW. The CMSY model stock status plots for Areas IW and IE indicate the 2022 stock health is in a state of either overfishing an overfished stock (red) or being overfished, but with fishing at a level that should allow stock recovery (yellow), with a very small likelihood the current stock falls in the area where biomass is equal to or greater than B_{MSY} (e.g., 0.2% probability for IW stock in 2022 based on input condition ii) (Figure 3.6a).

The CMSY model produced estimates of both MSY and B_{MSY} for Great Slave Lake management Areas II and III that were substantially lower than the estimates for Areas IW and IE (Figure 3). The model indicates that Area II Lake Trout biomass in 2022 is less than 20% the biomass required for MSY, which corresponds to a collapsed stock state (Figure 3.4) (Palomares et al. 2018), as indicated by the B/B_{MSY} at ~0.2 (0.08 – 0.4). The associated F/F_{MSY} predicted by the model for Area II suggests that the current fishing effort in this area should allow for recovery (Figure 3.5). However, the upper range of the confidence interval associated with all the F/F_{MSY} estimates (Figure 3.5), reveal uncertainties associated with effort and the Lake Trout stocks in general, largely due to the lack of effort data to predict fishing mortality more accurately. The stock status plots produced for both initial input conditions for Area II also indicate the current fishing mortality in this area should allow the stock to recover, however the stock appears to still be at an overfished state from previous exploitation (Figure 6b). For Area III, the CMSY model estimate for B/B_{MSY} corresponds to a severely overfished stock state ($B/B_{MSY} > 0.2 – 0.5$) (Palomares et al. 2018; Ju et al. 2020). Similarly, stock status plots for both initial input conditions for Area III suggest overfishing is occurring on an already overfished stock (red region) with a likelihood of over 50%, and a 0% likelihood of the stock falling into the categories that indicate either a healthy stock, not depleted by overfishing (green region), or a recovered/healthy stock likely to be depleted by overfishing (orange region) (Figure 3.6b).

Similar to Area III, the predicted ratio of current biomass to biomass at MSY for Area IV of ~0.3 (0.1 – 0.5) indicates a state of being severely overfished (within the range of 0.2 – 0.5; Ju et al. 2020), while Area V is estimated to be collapsed ($B/B_{MSY} < 0.02$) (Figure 3.4). The CMSY model predicts that the current fishing mortality in Area IV (F_{2022}/F_{MSY} at ~2.9 (0.9 – 14.4)) is almost three times the fishing mortality required for MSY (Figure 3.5), with the lower interval being close to 1, suggesting that there is a small probability current fishing mortality is lower than or equal to F_{MSY}. Stock status plots indicate Lake Trout in Area IV are overfished and continue to be overfished, with a >90% probability for both initial input conditions (Figure 3.6b). For management Area V, the CMSY estimate for B_{2022}/B_{MSY} suggests current biomass is at only ~20% $B_{MSY,}$ however, the low F/F_{MSY} value indicates current fishing effort in this area should allow for stock recovery (Figure 3.4 and Figure 3.5). Nonetheless, the current Area V biomass prediction estimate places the stock in the collapsed category according to Palomares et al. (2018). The estimate for stock status indicates the Lake Trout in Area V are currently being fished at a rate that should allow the stock to recover, however the stock is still at an overfished state from previous exploitation (yellow region) with >90% probability (Figure 3.6b).

Sensitivity Analysis

In general, widening the B/k range used as input to indicate the state of the stock at the beginning of the time series has the effect of producing slightly more conservative results for management reference points with lower central r values, and higher values for biomass required at MSY (Appendix II, Table 1). For example, the CMSY models estimate of B_{MSY} for Area IE with a B/k input at the beginning of the series of 0.01 – 0.2 (input condition i) is ~1500 t (1050 – 2660 t), while the B_{MSY} estimate with a B/k input at the beginning of the series of 0.01 – 0.4 (input condition ii) was ~1990 t (1370 – 3670 t) (Figure 3.3). This pattern was consistent across all Great Slave Lake management areas (Figure 3.3). These more conservative results with greater uncertainty (wider intervals) in the majority of estimates are logical given the added uncertainty associated with the broader input values. Nonetheless, overlapping 95% credible intervals can be seen for all reference points produced for all individual management areas, indicating no discernible difference among them (Figures 3.3 - 3.5).

Reference point estimates for MSY and B_{MSY} produced by the BSM model for Areas IW and IE were similar to those produced by CMSY (Figure 3.7) with overlapping credible intervals for both management areas IW & IE, adding confidence to the CMSY estimated reference points. A similar pattern of agreement among estimates produced by CMSY and BSM was seen with the other reference points (e.g., K, B/B_{MSY}, stock status as indicated by Kobe Plots, etc., Appendix II, Table 4) although uncertainty was not decreased by using additional fishery data in the form of an abundance index (BPUE). Furthermore, slightly wider credible intervals for the

BSM estimates of fishing mortality at MSY indicate that inclusion of fishery-independent derived BPUE indices did little to improve reference point estimates in this particular assessment.

Altering the length of catch time series used as input for CMSY at the Whole Lake scale had the greatest impact on results compared to any other form of model exploration. The longest time series of catches available for Great Slave Lake produced reference point values for MSY and B_{MSY} higher than those produced using the catch series beginning in 1975 (Figure 3.8). The estimates of MSY and B_{MSY} for Whole Lake modeling using the time series beginning in 1945, and ending in either 1975 or 2022, were approximately equal, with overlapping credible intervals for all input conditions with catch data beginning in 1945 (i-iii), however these estimates were significantly different than those produced using the catches beginning in 1975 (iv-v) (Figure 3.8). For example, the model estimates MSY for Whole Lake condition i (catch series length from 1945 – 1975 and a B/k prior at the beginning of the series of 0.5-0.9) at 916 (627 – 1450) t, was substantially higher than the MSY produced for Whole Lake condition iv (catch series length from 1975 – 2022 and a B/k prior at the beginning of the series estimated by the model) at 106 (75.6 – 151) t. The estimates of the state of the stock, based on the Whole Lake Kobe Plot outputs for conditions iii (catch series length from 1945-2022 and a B/K prior for the beginning of the series of 0.5-0.9), and iv (catch series length from 1975-2022 and a B/K prior for the beginning of the series estimated by the model), were similarly very different across catch-series lengths, with input conditions i, and ii, predicting Lake Trout considered at the Whole Lake scale are overfished, but with a fishing mortality that should enable stock recovery (yellow region). Input condition iii predicts that the stock (Whole Lake scale) has an approximately 50% likelihood of being at either a state of fishing an overfished stock, or underfishing (allowing for recovery) an overfished stock, while both conditions iv and v predict a currently healthy stock (green region) (Figure 3.9; Appendix II, Figure 4).

In contrast to model sensitivity results at the Whole Lake scale, the incorporation of a longer time series of catch data (starting in 1952) for Area I (pooled Areas IW and IE), did not affect reference point estimates or level of certainty in results as indicated by similar central values and approximately equal, overlapping credible intervals associated with estimates of MSY and B_{MSY} (Figure 3.10). Additionally, the estimated state of the stock (B/B_{MSY}) was similar for all Area I input conditions, although B/B_{MSY} using the catch series from 1952 - 2022 (iv) produced a lower central value than those beginning in 1972 (ii, iii) (Appendix II, Table 4). For example, B/B_{MSY} was estimated at ~.7 (.4 – 1.1) for Area I with a catch series input beginning in 1972, and at ~.5 (.3 - .8) for the series beginning in 1952 (Appendix II, Table 4; Figure 3.10).

The catch time series input of 1952 – 1971 for Area I was run utilizing the model's ability to estimate the B/k at the end of the time series (1971) (input condition i), with the year(s) immediately following (1972, 1974, 1979) being the beginning year(s) for the Lake Trout assessment of the current management areas. Using this input condition, the model produced an estimate of 0.08 – 0.35 for the B/k at the end of the time series (1971), falling more completely in the B/k prior input range of 0.01 – 0.4 (condition ii) versus 0.01 – 0.2 (condition i) used for the area wise modeling explorations with catch time series' beginning in the 1970's (IW, IE, II, III, IV, & V). Furthermore, the models estimate for B/B_{MSY} in 1971 was ~0.55 (.3 - .8), or ~50% of the biomass required at MSY, which translates to ~25% carrying capacity, falling within the 0.01-0.4 range (1-40% of carrying capacity biomass). This observation adds support for the choice of model inputs and specifically the use of the expert opinion range of 0.01-0.4 for the B/k at the beginning of the series in the 1970's.

An additional form of sensitivity analysis for this Great Slave Lake Trout stock assessment comes from the retrospective modeling. The results of which reveal a retrospective discrepancy exists for Areas IW and IE, indicating this model may not be able to reliably convey future population dynamics of this fishery with the available data, in contrast to Area V, which lacks a retrospective discrepancy (Figure 3.11). Similar retrospective analysis results for Areas II, III and IV (Appendix II, Figure 6) suggest minor discrepancies, however patterns more closely resembled that of Area V rather than Areas IW and IE. Results of the BSM analysis for Area IW and IE reveal the same retrospective pattern (Appendix II, Figure 7) when removing the last 1-3 years of catch values, however with slightly different estimates of biomass and fishing effort.

Discussion

The findings from this study suggest existing fishery management strategies are unlikely to facilitate rebuilding of Lake Trout stocks in most of Great Slave Lake. The current assessment reveals that the combined commercial quota for Lake Trout and Lake Whitefish lies well above the CMSY predicted MSY's for Lake Trout in all commercially producing management areas (IW, IE, II, III, IV and V). This suggests the potential for further declines in production and stock collapse at current harvesting rates (Allan et al. 2005) under a shared quota with Lake Whitefish as the two species are known to have very different demographic characteristics (Reist et al. 2006), and response to harvest. Additionally, the estimates of MSY for the areas with the majority of current Lake Trout production (IW and IE) have been surpassed by commercial catches in recent years. Conclusions of this study reinforce the need for ensuring stock assessments interpret historic fishery data in the context of potential temporal changes in catch regimes and at appropriate spatial scales that align with actual stock characteristics and harvesting patterns.

Current management strategies do not consider the presence of different morphs within the Lake Trout populations, although available research has suggested the existence of such within the Great Slave Lake system (e.g., Zimmerman et al. 2009; Hansen et al. 2016), which may influence reference point estimates. Multiple body forms have been identified, with at least three (lean, a siscowet (fat) and a humper (banker)) being common in Lake Trout throughout their range in Great Slave Lake as well as other large lakes (Moore and Bronte 2001; Zimmerman et al. 2006, 2009). Along with visual differences, life history traits (e.g., growth rate), as well as habitat use/water column position, are known to vary between forms, including those in Great Slave Lake (Moore and Bronte 2001; Zimmerman et al. 2006; Hansen et al. 2012 and 2016; Chavarie et al. 2016). Since surplus production models, such as CMSY, assume all individuals in the assessed population have the same demographic characteristics and are treated as a single biomass unit (e.g., based on total population weight) (Varghese et al. 2020), deviations from this would result in added uncertainty in reference point estimates. If certain morphs contribute more to production values than others this should be considered in modeling, however, given that the percentage of unique Lake Trout morphs within Great Slave Lake stocks is not known, the estimation of unique MSY's for individual morphs is not currently possible. Populations consisting of multiple genotypes have added concern considering that anthropogenic influences such as climate change may lead to the loss of certain sub-populations due to varied resilience (Brander 2010). Future research on stock structure is clearly needed to better understand intraspecific variation in key demographic traits to better inform management of fisheries on this sensitive and valuable arctic species.

Ratios for B/B_{MSY} are commonly translated into terms and definitions in fisheries science to classify estimates of biomass and the state of stocks for assessments across the world (Ju et al. 2020; Laing et al. 2020; Nisar et al. 2021), including by Palomares et al. (2018) who compared the average B/B_{MSY} over a 4-year period for over 1500 stocks to assess the global status of fisheries. Based on the CMSY estimates of B/B_{MSY}, current Great Slave Lake Trout stocks in all commercially fished management areas are in overfished states according to definitions set in Palomares et al. (2018). These results predicting overfished states for all assessed stocks are similar to previous studies using similar methodology (e.g., Ju et al. 2020; Laing et al. 2020; Demirel et al. 2020). Values for B/B_{MSY} found by Demirel et al. (2020) for 46/54 (85%) of analyzed stocks from the Black, Marmara, and Levantine Seas revealed various states of being overfished. Ju et al. (2020) examined 16 commercial stocks in offshore Taiwan waters with their assessment producing B/B_{MSY} values that showed collapse for ten stocks, two of which were at the severely overfished and overfished states, while one stock was classified as slightly overfished and another single stock as healthy (B/B_{MSY} >= 1). Of the 15 fish and invertebrate species from various waterbodies in China, Japan, and South Korea, assessed by Liang et al. (2020), two were collapsed, three were grossly overfished, nine were overfished, and one was slightly overfished, while none were considered at a healthy state according to B/B_{MSY} values. Although many of these previous assessments are from marine systems, the lack of distinction between underlying properties of these and freshwater lakes and rivers in the context of assessment modeling, enable the application of the same methods across a broad spectrum of aquatic systems (Pitcher 2016).

Previous literature has emphasized the need for sensitivity analysis with data-limited approaches, as with any stock assessment modelling methods, particularly to explore model dependency on priors. For example, Sweka et al. (2018) incorporated multiple alterations to model inputs (e.g., age of maturity, B/k values) in their sensitivity analyses and application of DB-SRA. Pons et al. (2020) evaluated 8 different catch-based and length-based stock assessment modelling methods (including CMSY) and based performance largely on each model's response to variations in life history demographics (e.g., long, medium, or short-lived species) and current depletion level (e.g., heavily, moderate, or lightly fished) of assessed stocks. Advantages of expert opinion versus model-based predictions on intermediate and end B/k ratios were explored in Schijns et al. (2021), in addition to changes in carrying capacity and responses of CMSY and BSM through altering the length of catch time-series used as inputs. The latter approach was helpful in the current assessment for understanding the contribution and importance of Area VI (now closed), and the extent of the long-accumulated stock, to the commercial fishery.

The incorporation of the full time series at the Whole Lake scale had the greatest impact to modeling outputs of any sensitivity analyses in the current assessment with results suggesting changes in commercial regimes reflect changes in carrying capacity (Schijns et al. 2021). The CMSY estimate for Whole Lake MSY and B_{MSY} using the truncated catch series following the 1974 closure of Area VI (input conditions iv and v) were significantly lower than those predicted using catch values that included the now closed management area (input conditions i – iii). This was the only instance where the CMSY model outputs did not have overlapping credible intervals across different input scenarios for any given area. With this is mind, the evaluation of any lake area utilizing the entire time series beginning in 1945 includes a period when the fishery was exploiting the long-accumulated stock, followed by a collapse of the Lake Trout commercial fishery in the 1970s in the western areas, and the closure of Area VI (East Arm), the area responsible for most of Lake Trout commercial production at the time (Bond 1975). Although the finer-spatial scale time-series (e.g., current management area scale) does not incorporate all available data, it appears to better capture the current state of the lake than the full commercial catch series. Multiple reasons may explain this including an actual change in carrying capacity as a result of continued commercial pressures or climate change which alter the distributions of species and habitat availability, the removal of the pre-commercial operations accumulated standing stocks, in addition to the fact that the commercial harvested lake area for the full series of Whole Lake catches includes Area VI (closed to the commercial fishery in 1974) thus changing the total area from which the catches were obtained following this closure. This spatial reduction in the commercially fished area of Great Slave Lake cannot be inferred by the model when using the entire whole lake catch series. These conclusions demonstrate the importance of performing analyses at finer spatial scales and setting individual management area quotas given the substantial difference in productivity of different areas, lending support for the choice of catch time-series and spatial scales assessed in the current study.

Where both data-limited modeling results and BSM results are available, past research has suggested the BSM estimates should be used for management advice given that they often produce more precise reference points (Varghese et al. 2020). This was not the case in the current assessment. The BSM model has been used for assessing data-limited to data moderate stocks when knowledge of relative abundance data, in addition to a time series of catches and information surrounding input parameters, are known, and has been shown to add value in situations where catch records and time series are incomplete (Froese et al. 2017, Meyer and Millar 1999, Ju et al. 2020). Where relative abundance data is available, it has been common practice to compare results produced by both the CMSY and BSM models (e.g., Varghese et al. 2020; Ju et al. 2020; Ren and Liu 2020), with BSM, in many cases, producing estimates with smaller credible intervals and consequently being favoured in provision of management advice (Varghese et al. 2020). Ren and Lie (2020) found that the two methods were able to produce agreeable estimates for r, k, MSY, and B/B_{MSY} for 7/7 data-limited stocks explored in their study, with BSM estimate intervals being narrower, decreasing uncertainty and providing greater precision. Similar results for reference point estimates between the two methods were also reported by Ju et al. (2020). Thus, the agreement of BSM reference points estimates with those of the CMSY model in the case of the current assessment of Lake Trout in Areas IW and IE, appears logical and consistent with other data-limited assessments that have employed these methods. However, unlike Ren and Lie (2020), and Varghese et al. (2020), the credible intervals of the BSM model estimates in the current study were not narrower in general, in fact, they were noticeably wider for estimates of B_{MSY} and F_{MSY} (Figure 7; Appendix II, Table 4), possibly because of uncertainties in the added BPUE index (Appendix II, Table 3).

As the development of data-limited methods has increased (e.g., Dick and MacCall 2011; Cope 2013; Pedersen and Berg 2017) so have the associated critiques (e.g., Walsh et al. 2018; Free et al. 2020; Pons et al. 2020). They consist of varying criticisms, such as the reliance on informative priors and the need for sufficiently long time-series with high levels of contrast, which may vary in availability depending on the stock. Multiple authors have stressed the importance of longer time series particularly when using data limited modeling methods for long-lived species (Walsh et al. 2018; Pons et al. 2020), like Lake Trout (Scott and Crossman 1973), where time series should be close to the maximum age of the species (Walsh et al. 2018; Pons et al. 2020). Often for accurate estimates of the carrying capacity of a lake, fisheries scientists require temporal contrast in catch data and a long enough series to expose population dynamics (Bentley 2015). Being a long-lived species, with slow growth rates, true maximum age is difficult to determine for Lake Trout (Daly et al. 1962) but has been reported as 34 years (McDermid et al. 2010) for some populations and up to 67 years (Gallagher et al. 2021) for others. However, in the current study, sensitivity analyses to test effect of time-series length on Area I (the only area consistently fished within the same management boundaries since near the start of the fishery) resulted in overlapping MSY estimates for all input conditions, indicating that the addition of 20 years of catch data, had little influence on reference point estimates. This suggests that although the ideal inputs for individual lake areas required use of catch series beginning in the 1970's, resulting in less than 50 years of catch data, this may be sufficient for the assessment of these stocks.

The CMSY estimates of F/F_{MSY} either equal to (Areas IW, IE, III) or substantially greater than 1 (Area IV) suggests current fishing mortality is at or above the fishing mortality required for MSY in most current commercial areas. These values are contrasted with the low F/F_{MSY} estimate (substantially less than 1) for Area V. This is likely related to various changes in commercial effort and production in the East Arm (Areas V and VI), including the closure of the commercial fishery in the nearby Area VI in 1975, and the closure of the Simpson Islands fish plant in 1991 resulting in less commercial fishing effort being exerted in Area V in the subsequent years (Low 2006; VanGerwen-Toyne et al. 2012). Other plant closures that have occurred in the last 20 years that have likely influenced production include the Moraine Bay plant near Areas IE and II in 2005, and the Wool Bay plant (Area VI) in 2008 (VanGerwen-Toyne et al. 2012). Thus, the limited catches, and associated low effort from Area V for over the last decade adds another layer of uncertainty to the estimate of current stock size as status may not be adequately reflected by commercial catches.

Limitations with the data series and analyses are also indicated by retrospective analysis results which demonstrate the greatest retrospective discrepancy is occurring in Areas IW and IE, where the most Lake Trout production has occurred in the last decade (FHMIS database). Given this discrepancy, implying uncertainty in the input data and associated model reference points, it is recommended that catch values be validated before allowing increased quotas (Froese et al. 2021). Northern Great Lakes fisheries, such as this, often support livelihoods of local residents, and provide much needed protein for the surrounding community (Pitcher 2016), however worldwide events have the potential to not only influence catches due to the availability of fish, but additionally impact involvement by fishers and associated effort. For example, the COVID-19 epidemic had an influence on all aspects of life from 2020 onward such as traffic in and out of the communities surrounding Great Slave Lake, while the town of Hay River was further devasted by flooding in 2022 and continued to be devastated by forest fires in 2023, along with all other communities of the area. Outside forces such as these can influence effort and production but are unable to be interpreted by the current assessment model. Such events may help explain observed discrepancies in retrospective patterns. The lack of divergence in the retrospective analysis of other areas must additionally be interpreted with caution given the observed low exploitation and negligible catches, means there is limited data to inform the model on the state of the stock.

Another important consideration related to catches for this fishery is recreational and subsistence fishing since multiple outfitters and communities are present on the lake (Low 2006; Low et al. 1999). Recreational and subsistence fisheries have occurred on Great Slave Lake for as long as human inhabitants have lived there, with commercial activity only officially beginning in 1945 (Keleher 1962) and investments and infrastructure added to the recreational fishery throughout the 1960's aided by the development of multiple East Arm sport fishing lodges (Falk et al. 1973; Yarmechuk 1986). Various authors have suggested the importance of incorporating all catch values in stock assessment where possible (Fitzgerald et al. 2018; Lorenzen et al. 2016; van Gemert et al. 2022). Thus, angler catch may also be a vital component for estimating total catch per year given the importance of recreational fisheries on Great Slave Lake (Yaremchuk 1986), although these values are currently unknown. Furthermore, data-limited fisheries may lack accurate estimates of culls and misreporting is common, with stocks distributed across more than one economic region (e.g., management area) (Ju et al. 2020). Genetic investigations are currently underway that may help determine the dynamics of stocks across the current areas (Won et al. 2022, unpublished) and may lead to future resolution of biologically relevant Lake Trout management areas and division of catch data used in the estimation of reference points. In addition, a commercial log-book validation program (DFO 2024, unpublished) that should help confirm commercial effort and associated by-catch and discards. This information can be used to aid in the validation of catch inputs and assist in evaluating estimates of stock status through the re-application of the current methods and potential use of more data intensive methods that can incorporate commercial abundance indices, including BSM, across all lake areas. With an ever-changing climate, and further anthropogenic influences inevitable, more certain values for total harvest over all levels of fisheries for these northern fish populations, will be invaluable and necessary to predict stock status with greater certainty.

The prolonged sustainability of fisheries requires the conservation of biodiversity integrated with fisheries management (Allan et al. 2001). Data limited assessment is recognized as an important first step in the development of stock assessment (Cope 2013; Pons et al. 2020), as many sources have stated the value of using data-limited methodology as a building block toward more intensive methods (Bentley 2015; Cope 2013; Pons et al. 2020). It is suggested caution should be given for the management of species at the northern edge of their ranges (Power 1978), however, until recently most research on Lake Trout occurred at the southern half of their range, with the level of attention to northern lakes, including Great Slave and Great Bear Lakes in Northwest Territories, previously considered abysmal (Schindler 2001). With inevitable increases in pressure on already strained food systems (Pitcher 2016), concern for food security worldwide (Islam and Berkes; 2016), and recognized gaps in freshwater fisheries research (Strayer and Dudgeon 2010; Reist et al. 2016), it seems appropriate to value conclusions of even data-limited stock assessments, especially in systems that may just be beginning to see anthropogenic impacts. Species-specific commercial quotas are recommended for the sustainable management of Great Slave Lake Trout, in addition to the determination of stock-specific abundance indices potentially guided by future genetic results (e.g., Won et al. 2022, unpublished) to determine the distribution of unique Lake Trout stocks within the lake. This contribution not only reinforces the need for a better understanding and valid baseline information for fisheries assessment, but it also shows the utility in applying CMSY++ to assessing valuable data-limited fisheries in Canada. The current research adds to the literature base on the application of these types of methods which are especially limited in northern ecosystems where climate change may just be beginning.

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Table and Figures

Table 3.1: The CMSY and BSM model inputs used for Great Slave Lake Trout area-wise, whole lake, and Area I (IW & IE) analysis. This includes catch-series lengths, the estimates of B/k at the beginning of the time series and the end (if value is italicized, B/k estimated by model, no input included), and the years of the BPUE index used for the BSM assessment of IW and IE. A narrow, low value B/k input (0.01 – 0.2) is indictive of an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20%, and a wide, low value B/k input (0.01 – 0.4) indicates greater uncertainty by implying the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. Alternatively, a high value B/k input (0.5-0.9) implies a relatively unexploited stock, with the proportion of biomass at the beginning of the time series relative to the carrying capacity between 50-90%; this input is reserved for assessments using catch inputs beginning at the initiation of commercial operations.

	Catch Series	**B/k Start**	**B/k End**	**Condition Reference ID**
Primary Analysis Inputs				
IW	1972 - 2022	0.01 – 0.2	*0.136 - 0.468*	IW – CMSY – i
		0.01 – 0.4	*0.136 - 0.468*	IW – CMSY- ii
IE	1972 - 2022	0.01 – 0.2	*0.191 – 0.585*	IE – CMSY- i
		0.01 – 0.4	*0.191 – 0.585*	IE – CMSY – ii
II	1980 – 2022	0.01 – 0.2	*0.016 – 0.213*	II – i
		0.01 – 0.4	*0.016 – 0.213*	II – ii
III	1980 – 2022	0.01 – 0.2	*0.0786 – 0.346*	III – i
		0.01 – 0.4	*0.0786 – 0.346*	III – ii
IV	1974 – 2022	0.01 – 0.2	*0.0881 – 0.366*	IV – i
		0.01 – 0.4	*0.0881 – 0.366*	IV – ii
V	1974 – 2022	0.01 – 0.2	*0.012 – 0.204*	V – i
		0.01 – 0.4	*0.012 – 0.204*	V – ii
Sensitivity Analysis Inputs				

	Whole Lake Analysis				
Whole Lake	1945 – 1975	0.5 – 0.9	*0.0301 – 0.243*	Lake – i	
	1945 – 2022	*0.384 – 0.792*	*0.024 – 0.23*	Lake – ii	
		0.5 – 0.9	*0.024 – 0.23*	Lake – iii	
	1975 – 2022	*0.226 – 0.658*	*0.47 – 0.839*	Lake – iv	
		0.01 – 0.4	*0.47 – 0.839*	Lake – v	
	Area I (West and East regions combined)				
Area I	1952 – 1971	*0.247 – 0.702*	*0.0817 – 0.352*	AreaI – i	
	1972 – 2022	0.01 – 0.2	*0.186 – 0.573*	AreaI – ii	
		0.01 – 0.4	*0.186 – 0.573*	AreaI – iii	
	1952 – 2022	*0.281 – 0.735*	*0.123 – 0.44*	AreaI – iv	
	BSM Inputs –Areas IW & IE				
				BPUE Index Years	
IW	1972 – 2022	0.01 – 0.2	*0.136* - *0.468*	2011 – 2019, 2022	IW – BSM -i
		0.01 – 0.4	*0.136* - *0.468*	2011 – 2019, 2022	IW – BSM -ii
IE	1972 – 2022	0.01 – 0.2	*0.191 – 0.585*	2011 – 2019, 2022	IE – BSM-i
		0.01 – 0.4	*0.191 – 0.585*	2011 – 2019, 2022	IE – BSM-ii

Table 3.2: Explanation of stock status classification (collapsed, severely/grossly overfished, overfished, slightly overfished, and healthy (Palomares et al. 2018)) used to describe Great Slave Lake management areas based on CMSY estimates of B/B_{MSY}. Area-wise estimates of B/B_{MSY} given are based on a wide B/k input (0.01 – 0.4) at the beginning of the time series, indicating that the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%, with credible intervals associated with the estimate given in parentheses.

Stock Status Classification	**Collapsed**	**Severely Overfished**	**Overfished**	**Slightly Overfished**	**Healthy**
Ratio of B/B_{MSY}	*0.01 – 0.2*	*0.2 – 0.5*	*0.5 – 0.8*	*0.8 – 1.0*	*> 1.0*
Great Slave Lake CMSY Area Estimate of B/B_{MSY}	**II** – 0.194 (0.082 – 0.39) **V** – 0.175 (0.066 – 0.361)	**III** – 0.352 (0.17 – 0.665) **IV** – 0.301 (0.144 – 0.544)	**IW** – 0.564 (0.304 – 0.847) **IE** – 0.673 (0.354 – 1.03)	-	-

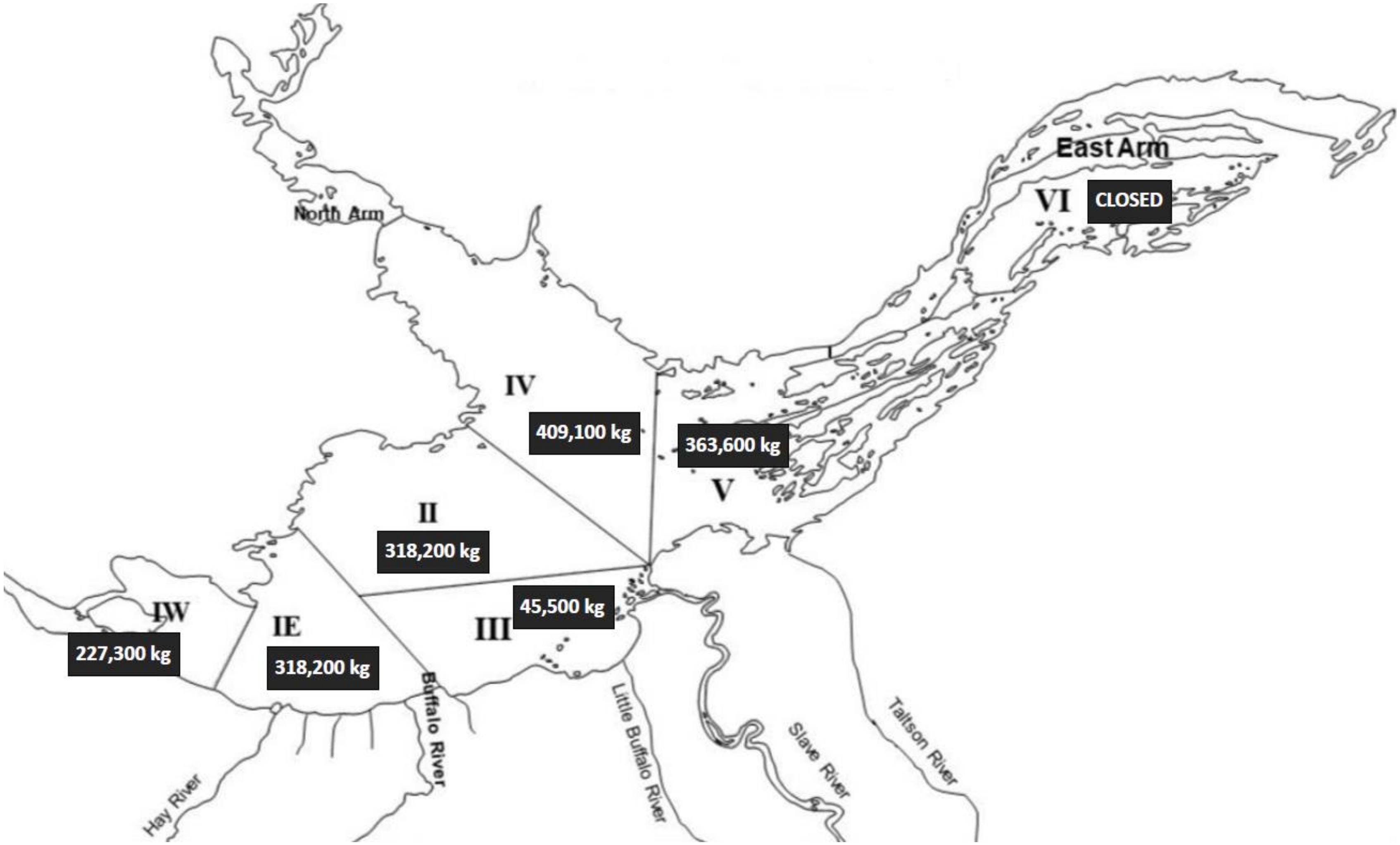

Figure 3.1: Great Slave Lake region with current management areas and 2022-2023 commercial Lake Trout and Lake Whitefish combined quotas

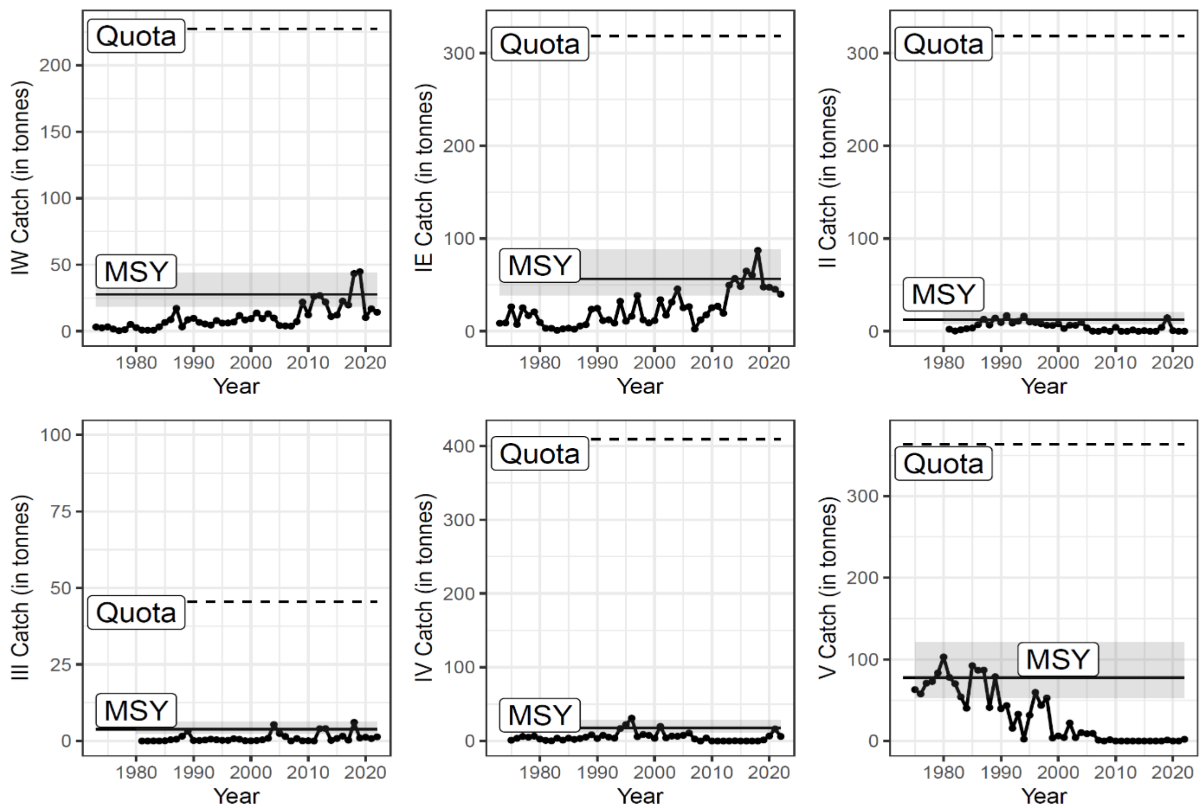

Figure 3.2: CMSY estimates of MSY (solid line) for each management area (IW, IE, II, III, IV and V) with a B/k input at beginning of time series of 0.01-0.4, indicating that the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%, indicated a relatively depleted stock. The 95% credible intervals associated with the MSY estimate are indicated by the grey shaded region, the time series of commercial catches indicated by the black line & points, and the 2022-2023 Area-Wise Lake Trout and Whitefish pooled quota indicated by the dashed black line. The year in along the x-axis, and the commercial catch, in tonnes, along the y-axis.

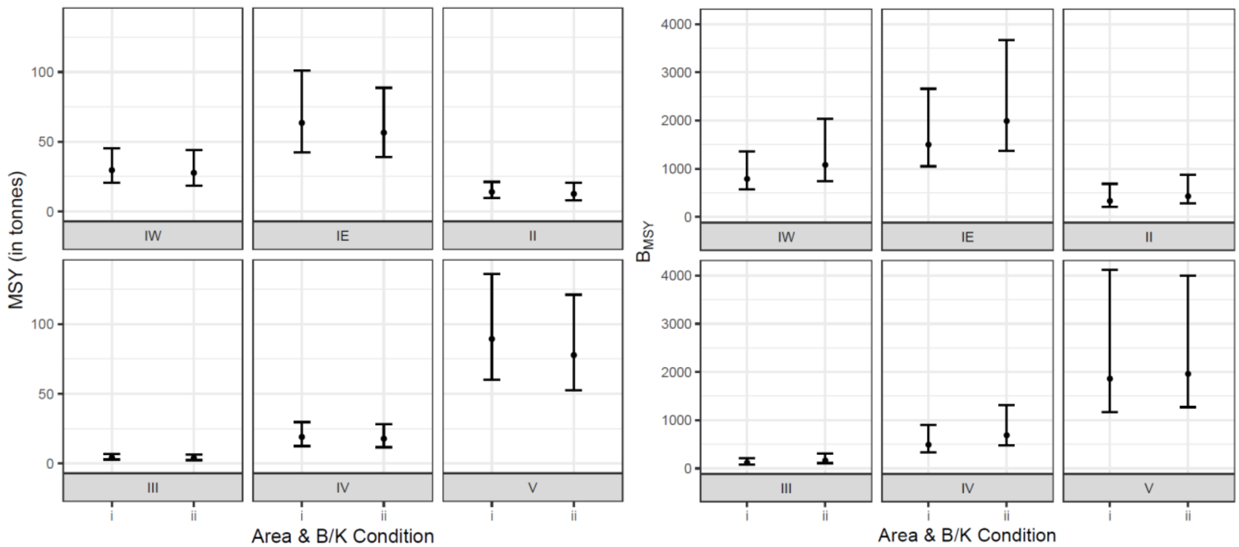

Figure 3.3: CMSY estimates of MSY and B_{MSY} in tonnes for each management area (IW, IE, II, III, IV and V) under two initial conditions: a B/k input at the beginning of the time series of 0.01-0.2 (i), and 0.01-0.4 (ii). A narrow, low value B/k input (0.01 – 0.2) is indictive of an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20%, and a wide, low value B/k input (0.01 – 0.4) indicates greater uncertainty by implying the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. The 2.5th and 97.5th percentile credible intervals associated with the estimate indicated by black error bars. The area and the B/k condition are along the x-axis, and the MSY and B_{MSY} estimates in tonnes, along the y-axis.

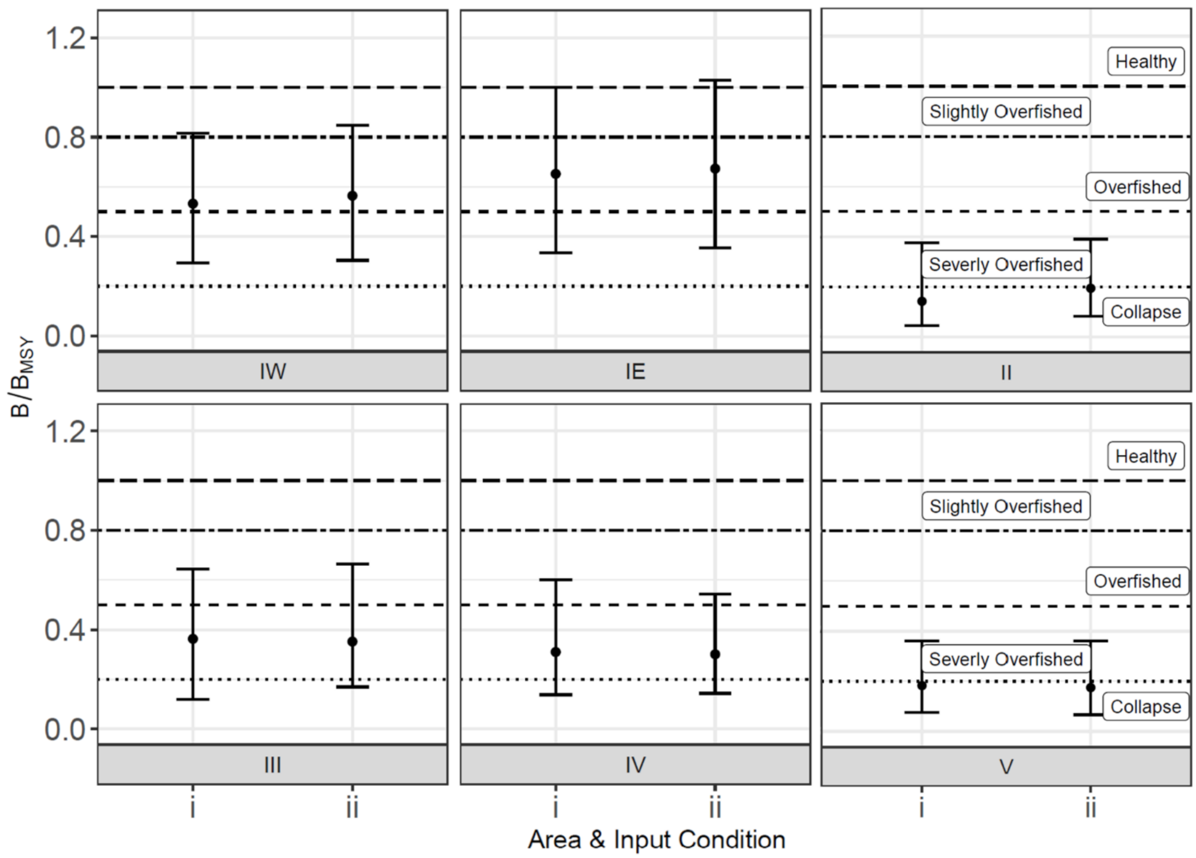

Figure 3.4: CMSY estimates for the ratio of current stock biomass over the estimated biomass at MSY, B/B_{MSY}, in 2022 for individual Great Slave Lake management areas (IW, IE, II, III, IV and V) under two initial conditions: a B/k input at the beginning of the time series of 0.01-0.2 (i), and 0.01-0.4 (ii). A narrow, low value B/k input (0.01-0.2) is indictive of an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20%. A wide, low value B/k input (0.01-0.4) indicates greater uncertainty by implying the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. The 2.5th and 97.5th percentile credible intervals associated with the estimate indicated by black error bars. Management area and B/k input condition are along the x-axis, and B/B_{MSY} along the y-axis. The region below the dotted line represents stock collapse (B/B_{MSY} = 0

– 0.2), region between the dotted and short dashed lines represent stocks that are severely overfished (B/B_{MSY}= 0.2 – 0.5), region between the short dashed and dot-dashed line presents stocks that are overfished (B/B_{MSY} = 0.5 – 0.8), region between dot-dashed and long dashed lines representing slightly overfished stocks (B/B_{MSY} = 0.8 – 1.0), while the region above the long dashed line represents healthy stocks ($B/B_{MSY} \geq 1$). Exploitation categories are taken from Palomares et al. (2018) & Ju et al. (2020).

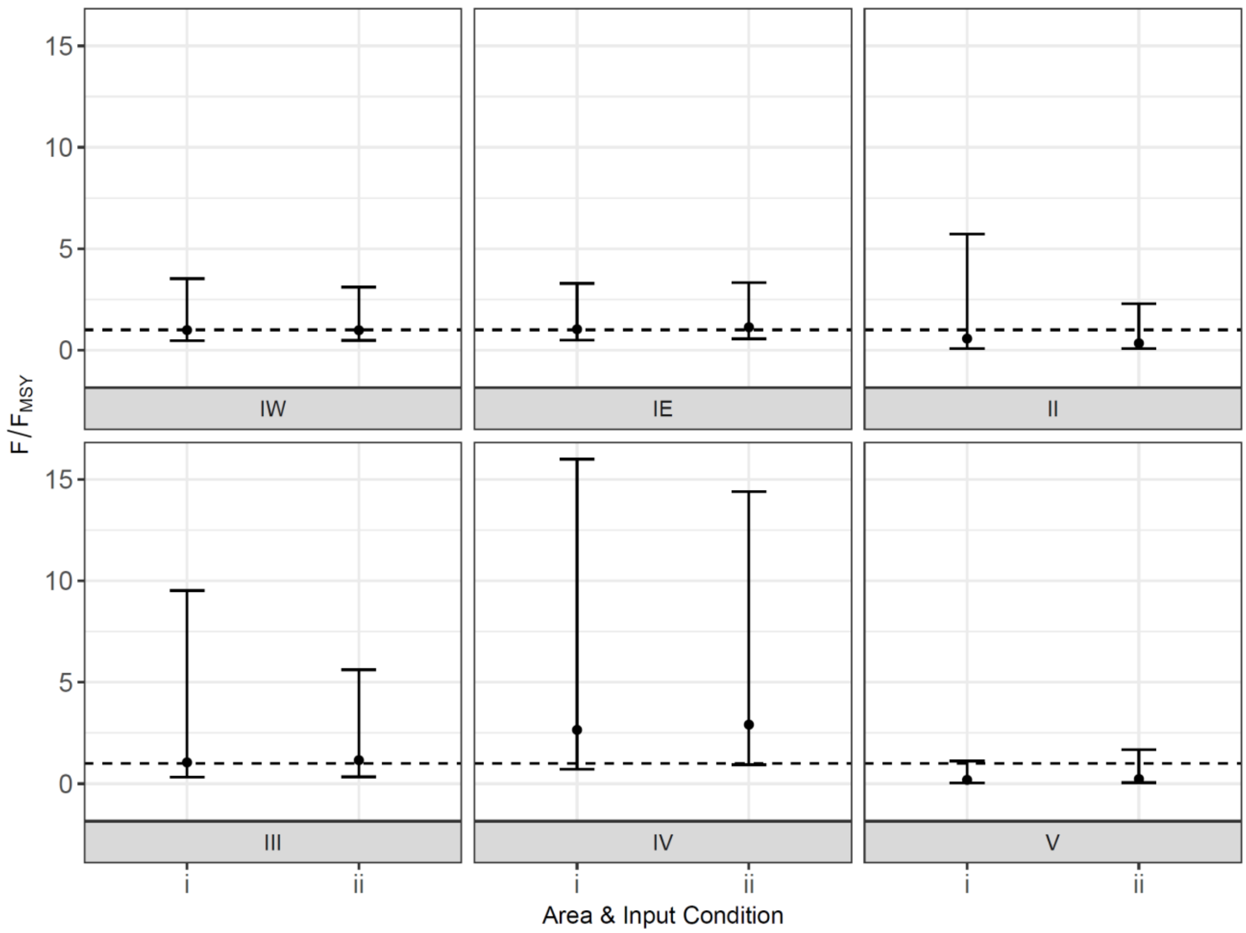

Figure 3.5: CMSY estimates for the ratio of fishing mortality in 2022 over the fishing mortality at MSY, F/F_{MSY} for individual Great Slave Lake management area under two initial conditions: a B/k input at the beginning of the time series of 0.01-0.2 (i), and 0.01-0.4 (ii). A narrow, low value B/k input (0.01-0.2) is indictive of an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20%, and a wide, low value B/k input (0.01-0.4) indicates greater uncertainty by implying the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. The 2.5th and 97.5th percentile credible intervals associated with the estimate indicated by black error bars. Management area & B/k input condition are along the x-axis, and the estimate for F/F_{MSY}, along the y-

axis. The dotted line indicates $F=F_{MSY}$, where regions above the line are harvesting above F_{MSY}, and below the line are harvesting below F_{MSY}.

a) b)

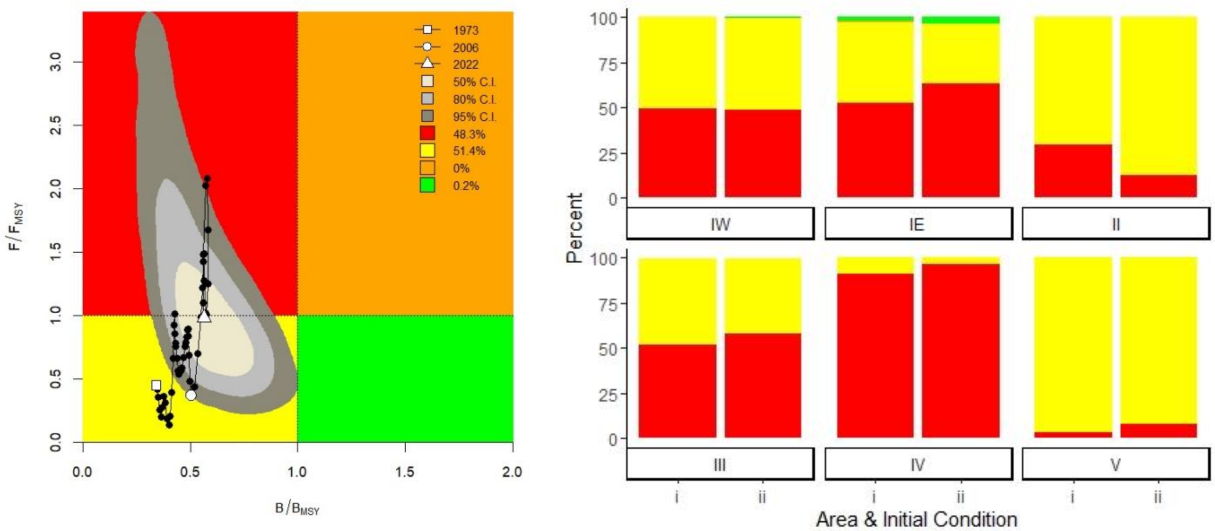

Figure 3.6:

a) CMSY produced Kobe phase plot for Area IW with a B/k at the beginning of the series set at 0.01 – 0.4, representing a depleted stock size where the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. The time series of the fishing is represented by the line connecting annual points. Fishing pressure, F/F_{MSY}, is on the y-axis, and the stock status, B/B_{MSY}, is along the x-axis. The red region indicates a stock being overfished at an overfished state, with biomass too low to produce MSY's. The orange region indicates a recovered/healthy stock soon to be depleted by overfishing, the yellow represents a stock that is experiencing fishing pressures that allows recovery, however the stock has not yet recovered. The green region indicates a healthy stock, not depleted by overfishing. The percentages given in the legend of the plot correspond to the probability of the final year's stock status falling in each of the four regions.

b) Bar graph visualization of Kobe plot area likelihood percentage the correspond with the probability of the final years stock status falling in each of the four phase plot regions, for each management area (IW, IE, II, III, IV and V) and initial B/k input condition: 0.01-0.2 (i), and 0.01-0.4 (ii).

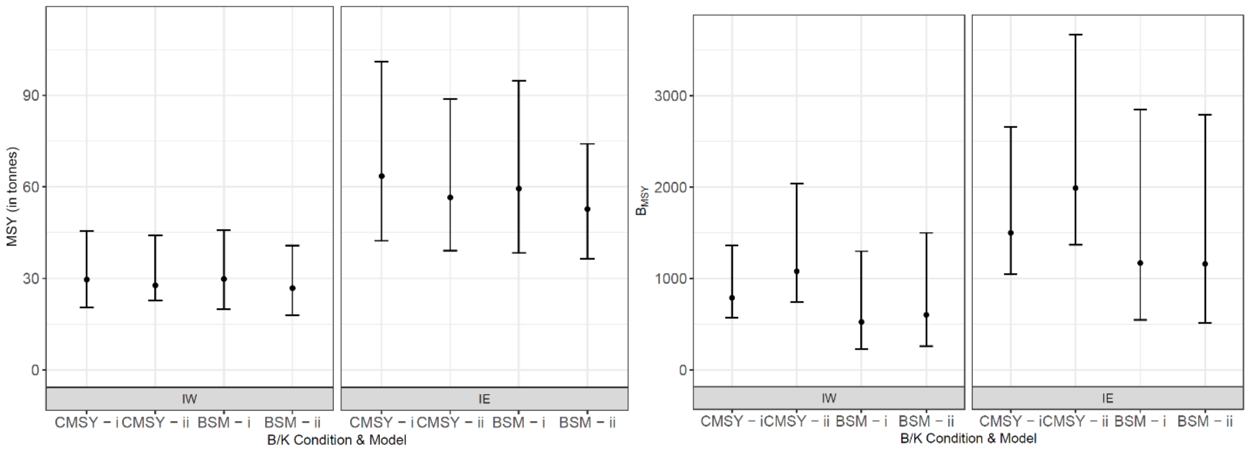

Figure 3.7: CMSY & BSM estimates of MSY and B_{MSY} (in tonnes) for management areas IW and IE, under four initial conditions: a narrow (CMSY-i) and a wide (CMSY-ii) B/k input condition at the beginning of the time series using CMSY, and a narrow (BSM-i) and a wide (BSM-ii) B/k input condition using BSM. A narrow, low value B/k input (0.01 - 0.2) is indictive of an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20%. A wide, low value B/k input (0.01- 0.4) indicates greater uncertainty by implying the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%. The 2.5th and 97.5th percentile credible intervals associated with the estimate indicated by black error bars. The area and the input condition are along the x-axis, and the MSY and B_{MSY} estimates, along the y-axis.

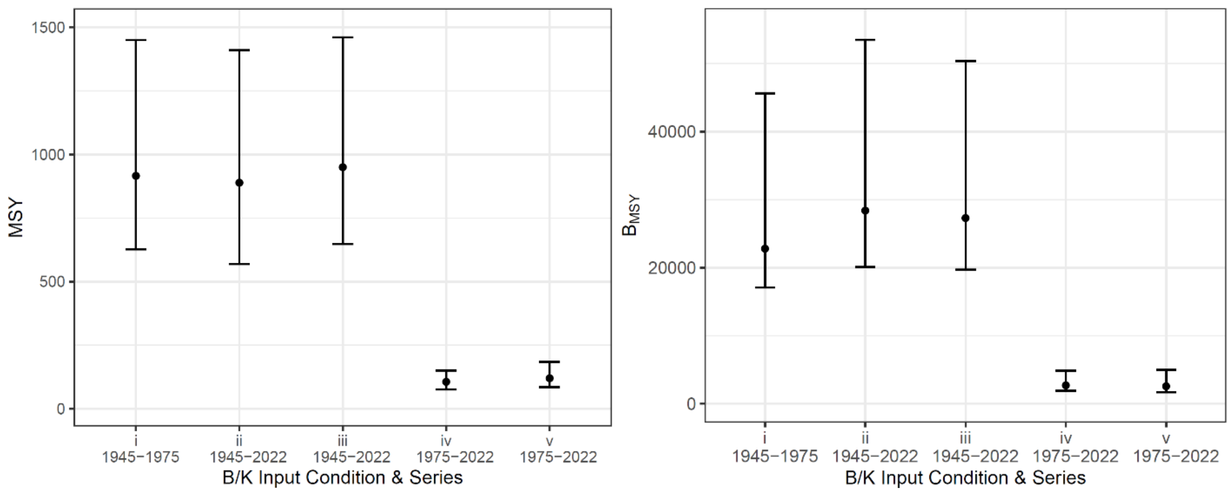

Figure 3.8: CMSY estimates of MSY and B_{MSY} (in tonnes) for Great Slave Lake using the whole-lake commercial catch series under varying conditions. For input condition i) the catch series used was from 1945 – 1975, with a B/k input at beginning of series estimated by model. Input conditions ii) and iii) had a time series of 1945 -2022, with a B/k input at the beginning of the series of 0.5 – 0.9 for input condition ii, indicating the proportion of biomass at the beginning of the series relative to carrying capacity is between 50-90% (new fishery). The B/k input at the beginning of the time series was estimated by the model for input condition iii. The catch series used for input conditions iv) and v) was from 1975 – 2022, with a B/k input at the beginning of time series estimated by the model for iv), and set to 0.01 – 0.4 for v), indicating the proportion of biomass at the beginning of the series relative to carrying capacity is between 1-40%. The 95% credible intervals associated with the estimates are indicated by the black error bars around each point. The time series used (in ascending order by starting year) and the input condition are along the x-axis, and the MSY and B_{MSY} estimates along the y-axis.

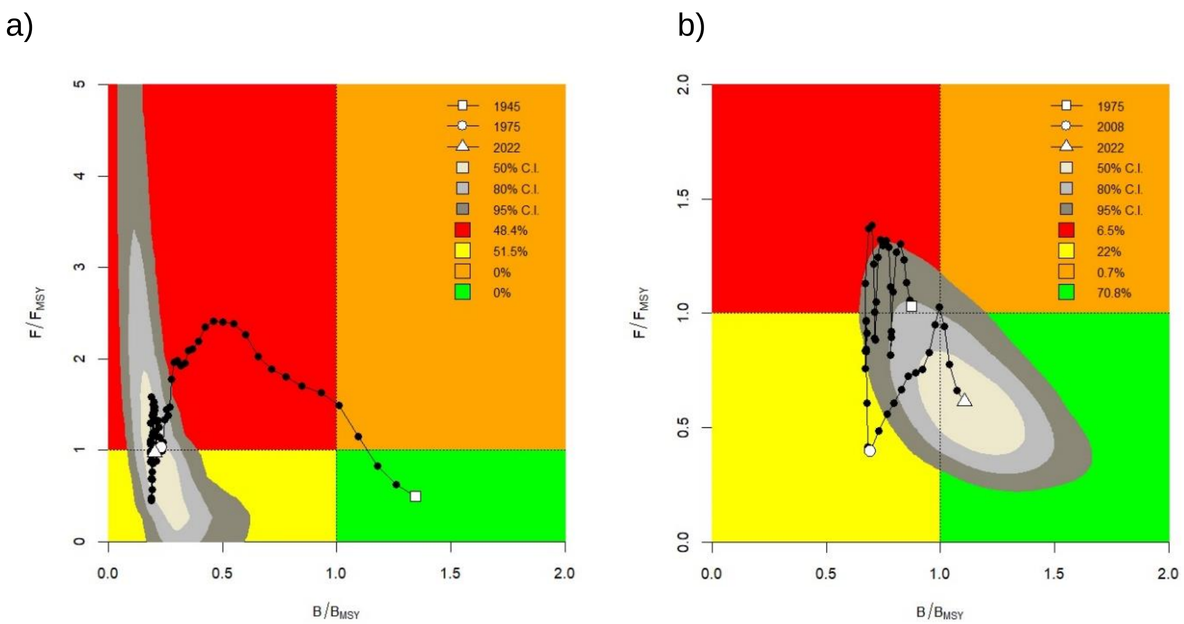

Figure 3.9: Kobe plot outputs for Great Slave Lake whole lake scale CMSY modeling.

- ***a)*** Input condition iii: The inputs used were the 1945-2022 catch series with an initial B/k input of 0.5-0.9, indicating the proportion of biomass at the beginning of the series relative to carrying capacity is between 50-90% (new fishery).
- ***b)*** Input condition iv: The inputs used were the 1975 – 2022 catch series, with the B/k at the beginning of the series estimated by the model. The ratio of the estimate of current fishing effort to fishing effort at MSY is on the y-axis, and the ratio of the estimate of current stock biomass over the estimated biomass at MSY along the x-axis.

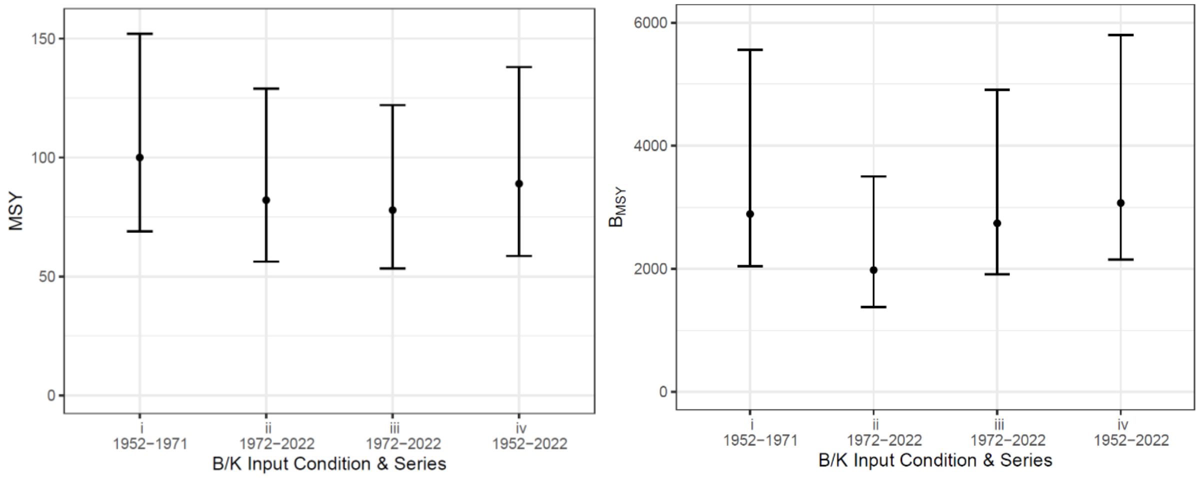

Figure 3.10: CMSY estimates of MSY, and B_{MSY} (in tonnes) for management Area I (Western and Eastern portions), for four different B/k and catch series input conditions. Input condition i) has an initial B/k estimate by the model with a time series from 1952-1971 (~7 years since fishery initiation), ii) has an initial B/k of 0.01-0.2 indicating an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20% and a time series input on 1972-2022 (~30 years since fishery initiation), iii) has an initial B/k of 0.01-0.4, indicating greater uncertainty in the estimate of biomass at the beginning of the time series relative to carrying capacity by estimating the range between 1-40%, with a time series input on 1972-2022. Input condition iv) has an initial B/k input estimated by model, with a time series input of 1952-2022. The 95% credible intervals associated with the estimates are indicated by the black error bars. The time series used (in ascending order by series length) and the input condition are along the x-axis, and the MSY and B_{MSY} estimates, along the y axis.

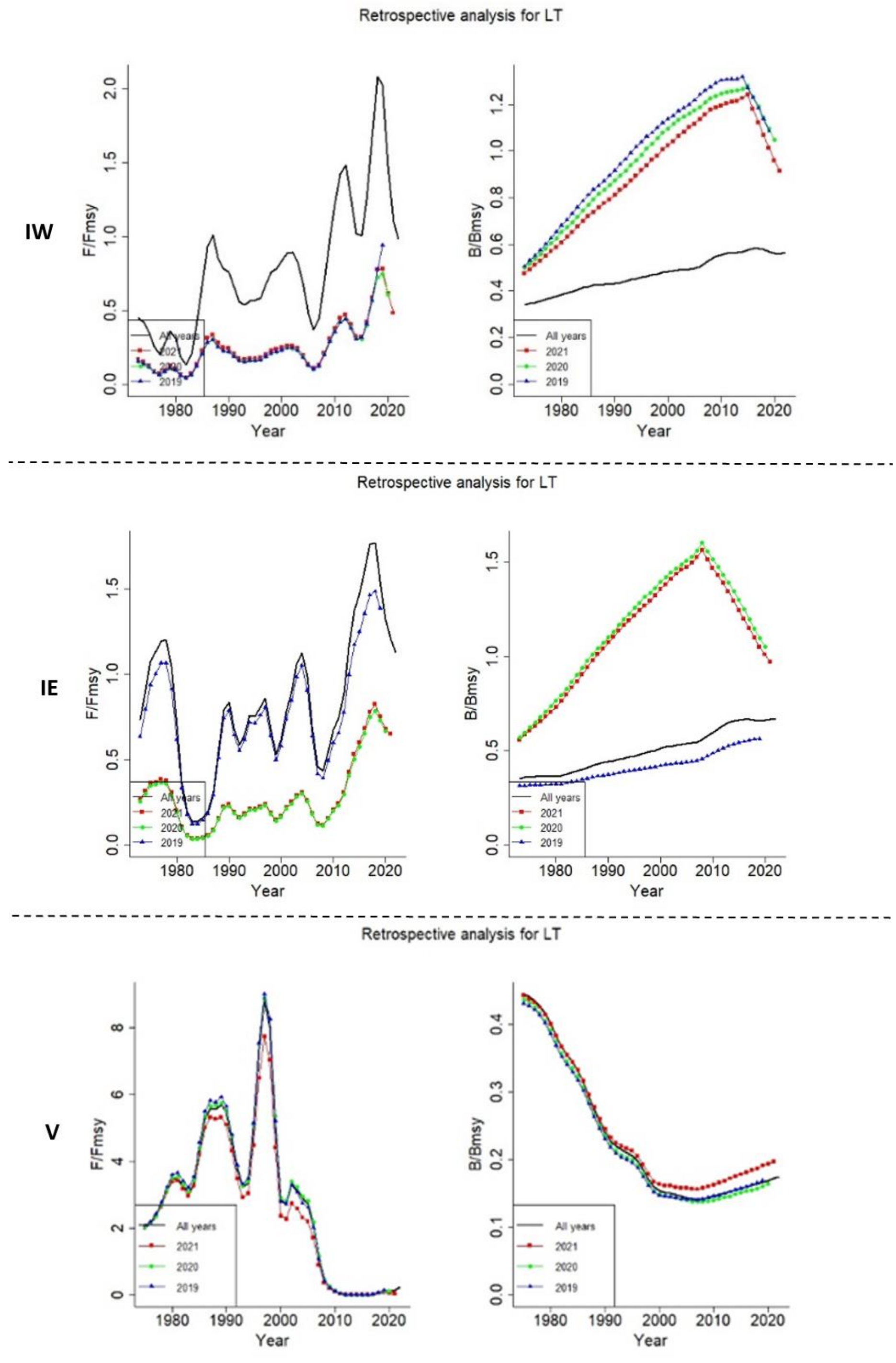

Figure 3.11: CMSY produced retrospective analysis results for management areas IW, IE, and V. Time series of estimates of fishing pressure (F/F_{MSY}) and relative stock size (B/B_{MSY}) when the final 1-3 years of catch are omitted from analysis are compared to those when

all years of catch data area used. A wide B/k input (0.01-0.4) condition at the beginning of the time series, representing an exploited stock size where the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%, was used to produce these results.

CHAPTER 4: CONCLUSION - INTERPRETING THE COMPLEX HISTORY OF THE GREAT SLAVE LAKE TROUT AND INFERRING THE CURRENT STATE OF POPULATIONS

Great Slave Lake fisheries have had a complex history, particularly the more than seventy-five-year long commercial fishery, with Lake Trout populations having an important role within all levels of fishing activities. These fisheries grant opportunities to community members in areas where other economic sectors may be lacking and can be considered safety-nets for income and sustenance (Lynch et al. 2016). The presence of long-accumulated stocks in these regions is often considered an unexploited resource with high economic value; a factor that aided in initially enticing people to explore arctic regions (Johnson 1976). Inland fisheries, such as Great Slave Lake, are considered good indicators of environmental change acting in a fundamental role for entire ecoregions (Lynch et al. 2016) with Lake Trout filling a primary role in many commercial and recreational fisheries in freshwater lakes of Canada (Johnson 1976; McDermid et al. 2010; Callaghan et al. 2016). However, many stocks have felt the impact of anthropogenic influence, including exploitation and invasives, such as the Laurentian Great Lakes (Healey 1978; Hanson 1999; Schindler 2001), and a need for a current evaluation of the health of Great Slave Lake fish populations has been previously identified (Yaremchuk 1986; Low 2006).

The knowledge base for Great Slave Lake fish populations can accurately be described by Fujita's (2021) definition of data-limited fisheries which states they posses "*stocks that are unassessed… either lack resources to analyze (*available*) unprocessed data or have some data but not enough* (for) *conventional stock assessment".* Common in many inland fisheries, this could be due to multiple reasons including time series that are too short to reveal information on stock status and true fishing mortality, or a lack of effort data, and/or age-structure (Lynch et al. 2016; Palomares et al. 2020; Fujita 2021). Considering the wealth of available information on these populations contained within Chapter 2 that is not currently utilized in stock assessment (Chapter 3), the latter part of Fujita's (2021) definition seems fitting: some data but not enough for conventional assessment.

The data obtained and inferred from initial research investigations conducted on Great Slave Lake has not always provided clear results, possibly leading to the mismanagement of the lake in the initial years of the fishery. For example, as part of conclusions drawn from the initial research investigations on Great Slave Lake, Kennedy (1956) made comparisons between Great Slave Lake and Lake Erie to help justify quotas. This evaluation comes with assumptions that may have aided in early decision-making errors for Great Slave Lake Trout stocks. Kennedy (1956) concluded that for Lake Erie to produce six times more fish than Great Slave Lake, 200 times the effort would be required than was on Great Slave Lake. This conclusion was made without reference to when commercial operations began on Lake Erie, an important factor when considering the exploitation of accumulated fish stocks. Commercial fishing began on Lake Erie in 1815 in shallow areas, using relatively primitive gear with improvements to gear in 1850 that enabled fishing operations to occur further from shore (Applegate and Meter 1970). This fact adds considerable doubt to Kennedy's (1956) comparison. At the time of Kennedy's (1956) comparison, Lake Erie had already been subjected to over 100 years of commercial operations, thus, the accumulated standing stock would have been exploited long ago. Commercial operations in Great Slave Lake during the 1950's were recently initiated and were likely utilizing the long-accumulated stock at the time these observations were made. Thus, it appears unlikely

Great Slave Lake can produce at the levels initially proposed. Additional issues arise with comparisons between Northern Great Lakes and other, more southern, Great Lakes in North America since fish, such as Lake Trout and Lake Whitefish, experience slower growth rates in colder climates, on top of a shorter open water season, both of which influence fish production (Keleher 1962; Brander 2010).

Uneven distribution of effort throughout the years, compounded with commercial fishing not being active in lake all areas until after the Lake Trout commercial catch peak, further complicates the detection of trends and interpretation of harvest data. Largely due to the commercial fishery closure in Area VI in 1974, differences between fishing effort and capture styles among Great Slave Lake areas has always occurred (e.g., primarily angling in Area VI, gillnetting in others) (Bond 1974; Yaremchuk 1986; Government of Northwest Territories 2022). The availability and locations of fish plants and accessibility by participants of the fishery (Kennedy 1956; Keleher 1972a; Government of Northwest Territories 2017), additionally complicates past and present effort estimates already obscured by varied production capabilities throughout lake regions.

Some areas, such as statistical areas K and B (used in previous statistical analysis; Chapter 2; Appendix I, Table 2), are likely to have begun with a relatively small standing stock in comparison to other areas, such as F. This is inferred from the peak commercial catch occurring the same year fishing operations began in K and B, versus a 7- year lag between first year and year of peak yield for area F (Keleher 1972b) (Chapter 2; Table 2.3). This comparison reveals the disproportional production capabilities among regions of Great Slave Lake. Added support for this comes from the recognition that the fishery had additional influences the year commercial catch was the highest (1949). Fishing operations only covered ten of the thirteen historically used statistical areas (Keleher 1972a) during the 1949 season. In the same year commercial operations were forced to temporarily stop due to the washing out of roadways and were noted as being sporadic during July as weather often prevented fishers from lifting nets daily (Kennedy et al. 1951). This shortened the season but apparently did not limit harvest. These factors all contribute to difficulties in establishing population demographics and compiling complete catch and effort series that extend to the beginning of the fishery for the current management zones.

Availability of Lake Trout in any one subdivision (thirteen historical statistical analysis areas; Appendix I, Table 2) decreased by ~25% within a short period from entering the commercial fishery (Kennedy 1950), making it apparent Great Slave Lake Trout populations were altered soon after commercial harvesting began. When fishery operations began, expectations from commercial participants were high given the available previously unexploited stocks (Keleher 1972a). However, catches around Gros Cap failed to meet expectations and fishers were encouraged to venture further out (Kennedy 1950). With the added travel time, required equipment, and difficulties associated with venturing further out (e.g., daily net clearing), fishery effort decreased over the first few years (Kennedy 1950). Given the obvious decrease in effort, suggestions were made to base boats in areas that could ensure daily net clearing, and setting up base camps around the lake became common practise (Kennedy 1950). Upon the re-evaluation of the first ten years of fishery data, Keleher (1972a) reported that commercial exploitation had, in fact, altered the Lake Trout populations, a conclusion that was missed in previous investigations (e.g., Kennedy 1956). Keleher (1972a) cautioned that Great Slave Lake Trout production had been pushed to the point of becoming essentially commercially extinct in western areas of the lake, with a population decrease that was unlikely to be able to rebound without putting additional restrictions on commercial operations (Bond and Turnbull 1973).

The ever-evolving CMSY stock assessment method (Froese et al. 2017) (most recent software version termed CMSY++ contains the most recent version of CMSY, as well as a Bayesian state-space Schaefer Model, BSM) (Froese et al. 2021, 2023) were developed in an attempt to combat the lack of available assessment models for systems, such as Great Slave Lake, and have been utilized in the present assessment to produce biomass trajectories and reference point estimates for Lake Trout populations. Given the data requirements of the model, and the long history of catch records with a high degree of contrast in high and lows catches for commercially caught Lake Trout, models of this sort have potential to be of great value in the present situation. This type of catch contrast is a recognized component of accurate carrying capacity estimation (Bentley 2015). However, as CMSY uses high catches regardless of effort (no incorporation of abundance indices), this contrast can be misleading. Therefore, understanding the development of the fishery is vital for interpreting modeling results, as difficulties in precisely predicting carrying capacity are recognized challenges of the CMSY assessment model (Schijns et al. 2021).

The CMSY++ software used in this study illustrates the rapid expansion and initial high catches of the commercial fishery when utilizing the whole lake catch series for Great Slave Lake, as seen in Chapter 3, Figure 3.9. This is followed by stock depletion through harvesting above MSY ($F/F_{MSY} > 1$) appearing within four years of the commercial fishery initiation, visible on the Kobe plot. This coincided with the knowledge that effort was rapidly increasing and was still high when the initial low Lake Trout catches were first observed, indicating a collapsing stock. By ~1948 harvesting rates were already deemed too high according to the Kobe plot results (Figure 3.9), which show the point for this period in the orange zone of the plot (overfishing an underfished stock). By ~1950 the estimated harvesting level was above the estimated maximum sustainable level and the stock size was already depleted to the point of being below the biomass needed for MSY. By 1956, the fishery was pronounced to “have no new grounds to explore” (Bond and Turnbull 1973); this year coincided approximately with the highest fishing effort value in Figure 3.9, followed by a brief period of stabilization in terms of effort at ~2.5 F/F_{MSY}. Lower fishing effort was assumed to be occurring following this period, however, as CMSY is not considering effort in this series, this may be misleading as similar effort may produce lower catches as stocks are depleted.

Initial high harvests associated with commercial fishery production were a result of depleting the long-accumulated stocks not yet influenced by commercial gillnetting. This has the potential for creating a shifting baseline for this fishery, and limiting conclusions that can be drawn from the end of the series in whole lake modeling. Therefore, even though the present assessment model can interpret the initial development of the fishery, outside influences not accounted for in modeling, (e.g., effort, changes to the commercially harvestable lake region via. management, changes to ecosystem via. climate change), may be missed in the latter part of the series. Nonetheless, even uncertain outputs can still reveal fisheries information. Catches and management regimes may reflect changes to carrying capacity (Schjins et al. 2021), as exposed through the whole lake analysis in the present assessment (Chapter 3).

To better interpret the influence of fisheries on systems and achieve sustainable management, the integration of historical knowledge in assessment has proven vital (Palomares et al. 2020; Schijns et al. 2021). This further reinforces the need for realistic priors, as with any Bayesian application (Palomares et al. 2020; Bouch et al. 2021) and the importance of Chapter

3’s sensitivity analysis that explored widening the estimate for the ratio of biomass at the end of time series relative to carrying capacity (B/k). If default priors are too constraining, recently recovered biomass obtained through management actions indicated by low stable catches at the end of a time series, can only be perceived by the CMSY model as low biomass due to previously high fishing mortality (Bouch et al. 2021). Thus, certain plausible trajectories that involve biomass above the restricted prior may be rejected due to constraints in the B/k inputs. This has been shown in Bouch et al. (2021) application of CMSY which resulted in pessimistic results when compared to the available data-rich assessment. However, in Bouch et al. (2021) assessment, priors were only based on the default rules available in Froese et al. (2017), not the neural network of the more advanced 2021/2023 CMSY++ software (Froese et al. 2021, 2023), nor altered to follow expert opinion on the assessed systems. Bouch et al. (2021) recognises that in their study, like the present, the obtainable data time series generally lack a period when biomass is high and fishing pressure is low. This type of situation may be inferred via. the use of expert knowledge on the system: a well-established and accepted part of analysis in fisheries science (Palomares et al. 2020).

In future modeling efforts, predictive scenarios that do not consider anthropogenic influences (e.g., habitat loss, invasive species) when creating future projections should be considered overly optimistic considering their probable influence (Demirel et al. 2020). Rapid human population growth and the resulting need for dependence on fresh water, has resulted in negative anthropogenic influences worldwide with responses of individual ecosystems largely unclear (Strayer and Dudgeon 2010; Reist et al. 2016). As recently as 2016, Great Slave Lake Trout populations were thought to only largely be affected by exploitation (Reist et al. 2016), mostly in the form of commercial gillnetting, although, with current production at a fraction of historic values (Government of Northwest Territories 2017). However, more recent research (e.g., Ruhland et al. 2023) has suggested other anthropogenic influences such as climate change are being felt by the Great Slave Lake ecosystem.

Future research should aim at determining assessment methods that produce climate projections (Fujita 2021), and habitat suitability models that can help more accurately predict k (Bentley 2015), in data-limited situations in order to help ensure success of these valuable populations. Rawson (1950) notes that the presence of storms had a strong influence on water temperature mixing and had the ability to disrupt gillnetting operations. Climate change may contribute to this further by an increase in the prevalence of storms, and other unpredictable influences (Schnidler 2001; Callaghan et al. 2016). Additionally, the oligotrophic nature of Great Slave Lake suggests this ecosystem has a lower ability to regulate additions of acid (Evan 2000; Krohne 2015; Zhu et al. 2017), and thus environmental change, compared to other water bodies.

Previous management actions have been criticized for enabling changes to regimes (e.g., quotas) before having reached previously identified recovery points (Hutchings et al. 2021), with uncertainty a poor reason for inaction (Strayer and Dudgeon 2010; Bentley 2015). Furthermore, suggestions of the present research (e.g., enacting species-specific, area-wise quotas) are supported by those proposed over 50 years ago (Keleher 1972a). With this idea in mind, it seems vital to acknowledge that the current retrospective discrepancies in the assessment results (Chapter 3) for the management areas with the greatest production in the past decade (Areas IW and IE) are currently attributed to unknown causes. An evaluation of true total harvest and effort (e.g., through log-book data) will help clarify data inputs and potentially decrease uncertainty in the estimation of stock status, as mentioned in Chapter 3. However, presently it also appears crucial to consider factors outside of fishery operations that may be influencing stocks. Even with the uncertainty associated with data-limited models (Chapter 3), the complicated history, high economic and cultural value, and the apparent potential for future detrimental influences on this valuable resource, indicate that conclusions of this study should be considered for the sustainable management of Great Slave Lake Trout. This research has accomplished the goals of data-limited modeling by providing an interpretation of fishery development for this complex system that can aid managers in understanding population altering processes, in addition to serving as a building block for future assessments (Bentley 2015; Pons et al. 2020).

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Appendix I (Chapter 2)

A. I. Table 1: Great Slave Lake commercial fishery details on fleet, effort, availability, and seasonal considerations based on historical research technical reports (Note: If reference is included in column heading, the reference applies to entire column, unless additional footnote included. See Appendix I, Table 2 maps for lake area designations referred to below).

SEASON	**NUMBER OF BBOATS (SKIFFS)**[1]	**SUMMER SEASON START (END) DATE**	**ESTIMATE OF FLEET SIZE (# OF FISHERS)**[3]		**NOTES ON EFFORT**	**NOTES ON AVAILABILITY**	**NOTES ON SEASON**
			Summer	**Winter**			
1944-1945	20	July 29[2] (~September 15)			- Only participating company was McInnes[2]		
1945-1946	22				- 19 boats belonged to McInnes: with the majority having the capacity of ~2268 kg[4]	- Decrease in availability for all species from 1945-1946 - Too little information about significance of fluctuations in availability to say if decrease is significant[4]	
1946-	18					- Greater availability in 1947 than	- Throughout the season, Lake

1947						1946 for both Lake Whitefish and Lake Trout - Increased availability partially due to increased effort in east[5]	Trout availability tended to increase, while Inconnu and Whitefish tended to decrease[5]
1947-1948	21				- One unit of fishing effort = one gill-net, 100 yards in length (30/6 or 36/6 cotton web) 5.5-inch mesh, 30 meshes deep / 1 night (although sometimes longer)[6]	- Area H had the lowest availability overall - E, F and M consistently had the highest availability 1948[6]	- Availability appeared largely influenced by weather - Low catches were common on calm days, while moderate winds seem to improve fishing success[6]
1948-1949	63	June 28 (September 15)[8]			- Average lift interval = ~ 2.6 nights during winter season[7] -7 McInnes boat were based out of Caribou Bay from mid-July to mid-August[8] - Intensive fishing occurred in the waters surrounding Hay River until July 13th when the area quota was reached; following this all companies	- In general, availability was slightly lower than previous years[7]	- Supply of ice was an issue for all except Hay River fishers - Sporadic July fishing due to heavy winds - No significant change in average size of any commercial species[8]

					moved north setting up base camps in Windy Bay, except Inland Fisheries who posted at Moraine Point[8]		
1949-1950	57	June 18(September 15)[9]		1000[10]		- Availability of Whitefish remained the same as previous year, however Lake Trout availability was lower[9]	- No significant change in average size of any commercial fish[9] - Declines in A and C suggest too large a percent of fishing occurs around Hay River[9]
1950-1951	61	June 21 (September 15)[11]		320[10]	- Overall summer season effort = 39,287 net-nights[11] (*Effort estimation defined in 1947-48 row & in *Fishery Dependent Studies*)	- 25% decrease in overall availability for all species since fishery inititaition[11]	- Data so far do not represent a clear relationship between standing crop and availability[11]
1951-1952	53	June 16 (September 15)[12]		393	- Overall summer season effort = 62,000 net-nights[12]		
1952-1953	40	June 28 (Septemb		255	- Overall summer season effort = 45,000 net-nights[13]	- Estimated availability of commercial species in Area G	- Poor market at beginning of season [13]

		er 15)[13]			- Decreased effort in D, E and L and an increase in A, F, and N, relative to 1951-1952[13]	~equal for last 4 years, stabilizing at roughly two thirds the original[13] - A decreasing trend was apparent for availability and average size of primary commercial species[13] - FS Index for Whitefish and Lake Trout combined estimated at 72 lb (~33 kg) per net-night; ~ the same as previous two seasons[13] - Availability of Lake Trout 45 lb (~20 kg) per net-night[1] (*FS estimation defined in *Fishery Dependent Studies*)	- Large increase in effort and availability in N, but this was the first-time the north side of N was commercially fished[13] - Greatest decrease in catch in Area L, but due to effort divided amount G, H and N, not decreased availability[13]
1953-1954	50 (6)	June 155 (September 15)[14]		304	- Overall summer effort = 80,993 net-nights[14] - Majority of effort exerted in E, F and G, with O commercially fished for the first time[14]	- FS Index for Lake Whitefish and Lake Trout combined estimated at ~49 lb (~22 kg) per net-night - Availability of Lake Trout ~22 lb (~10 kg) per net night - Area E only area with higher A than previous seasons[14]	- Warm weather, larger operations, and ice shortages forced a single company to cease operations for 3 days, and other companies to end their season early[14] - Suggests increase in East

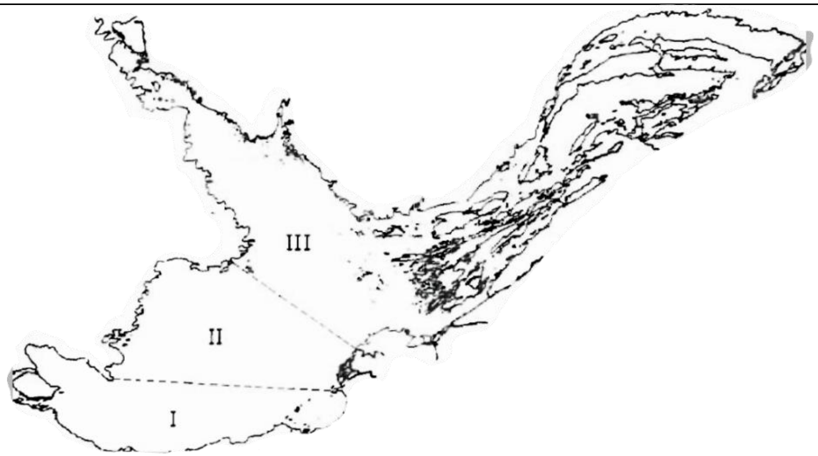
							Arm rough fish was related to the warm, muddy inputs from the Slave River being spread further than usual [14]
1954-1955	64 (6)	June 10 (September 15)[15]	404	399	- Effort was 57.7 % higher than previous year[15]	- FS Index for Lake Whitefish and Lake Trout was ~39 lb (~17 kg) /net[15]	-Lowest market prices thus far, and as a result all companies operated at lower capacity than previous years - More efficient ice supply ensured fewer fish spoiled[15]
1955-1956	65 (4)	June 16 (September 15)[16]	189	404	- Overall effort estimated at 9.8 % higher than previous year[16]	- FS Index for Lake Whitefish and Lake Trout was ~35 lb (~16 kg) /net[16]	- Some boats equipped with net lifters for the first time[16]
1956-1957	68 (9)		216		*Research/Data Gap for availability & effort 1957 - 1964*		
1957-1958	57 (7)		218				
1958-			270	276			

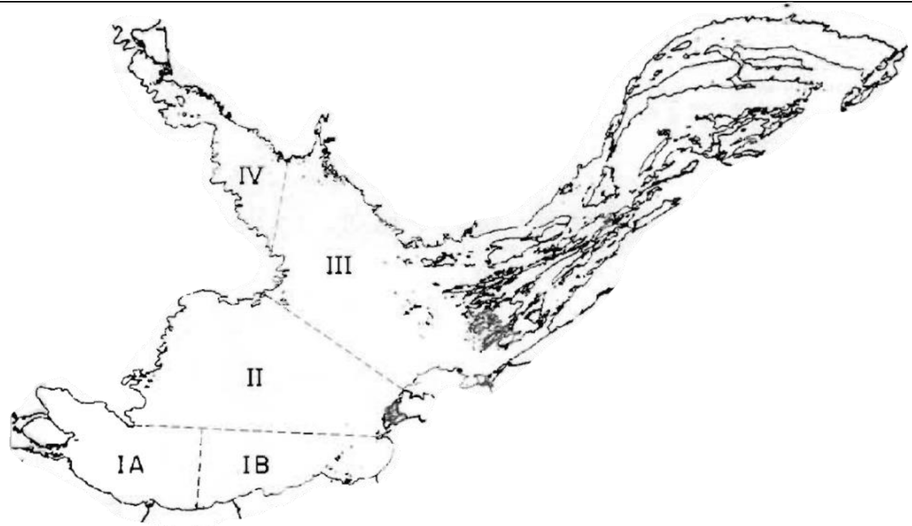
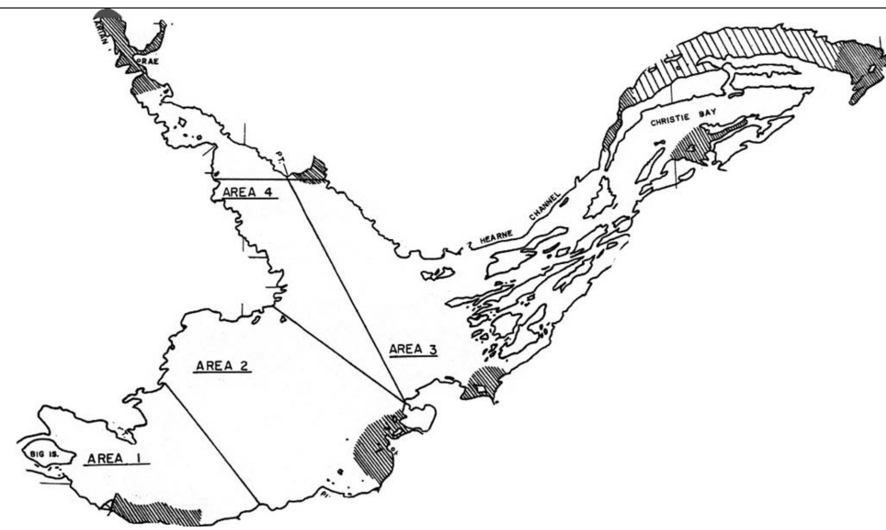
1959								
1959-1960			210	262				
1960-1961			193	159				
1961-1962			264	150				
1962-1963			327	232				
1963-1964			209	205	- Estimate of overall summer effort = 125,000 net nights[17]			
1964-1971	*Research/Data Gap 1964-1971*							
1971-1972						- Results of 22 experimental net sets: → Hay River (7 nets) = 1 Lake Trout (0.9 kg); 0.1 % by numbers; 0.1 % by wt → Moraine Bay (4 nets)		

						= 1 Lake Trout (0.8 kg); 0.1 % by numbers; 0.2 % by wt → Union Island (11 nets) = 49 Lake Trout (121.6 kg); 4.3 % by numbers; 14.0 % by wt[18]	
1972-1973	18 (56)[19]		128[19]		- Estimate of overall summer effort was 74,457 gillnets set between June 1st – October 21st - 60% of all catch in commercial gillnets consisting of species primarily discarded by fishers, (e.g., burbot, suckers, and ciscoes)[19]		- An increase of 3.3% in total catch from the previous season - Increase was attributed mainly to higher catches of minor species, including inconnu, pike, and walleye[19]

1) Keleher et al. 1962
2) Keleher 1962
3) Sinclair et al. 1967
4) Kennedy 1946
5) Kennedy 1948
6) Kennedy 1950
7) Kennedy and Hewson 1951
8) Kennedy et al. 1951
9) Wheaton 1951a
10) Wheaton 1951b
11) Wheaton and Kennedy 1952
12) Kennedy et al. 1953
13) Scott 1954
14) Scott and Hanson 1955
15) Scott 1956
16) Kostelnuk and Roberts 1957
17) Keleher 1972a
18) Bond and Turnbull 1973
19) Bond 1974

A. I. Table 2: Great Slave Lake commercial fishery administration areas, research, and analysis division maps used from 1945 – present day.

Commercial fishery administration area division maps:		
Seasons in Effect	**Source & Major Management Area Changes**	**Areas**
Summer 1949	Keleher 1962	

1949 – 1950	Keleher 1962	
1950 – 1962	Jennes 1963 *shaded areas closed to commercial fishing	

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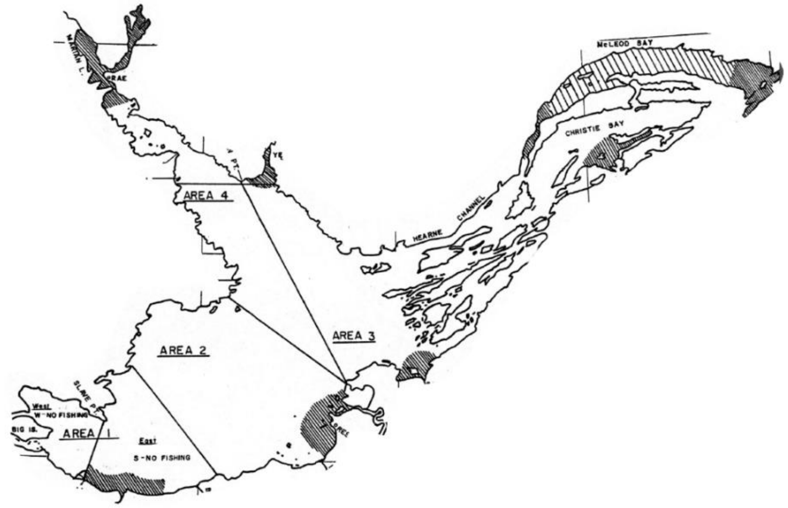
<td>1962 – 1971</td>
<td>Jennes 1963

Major change:

- addition of West and East to Area I; each with an assigned quota in addition to no commercial fishing in West during the winter, and during summer for the East

*shaded areas closed to commercial fishing</td>
<td>
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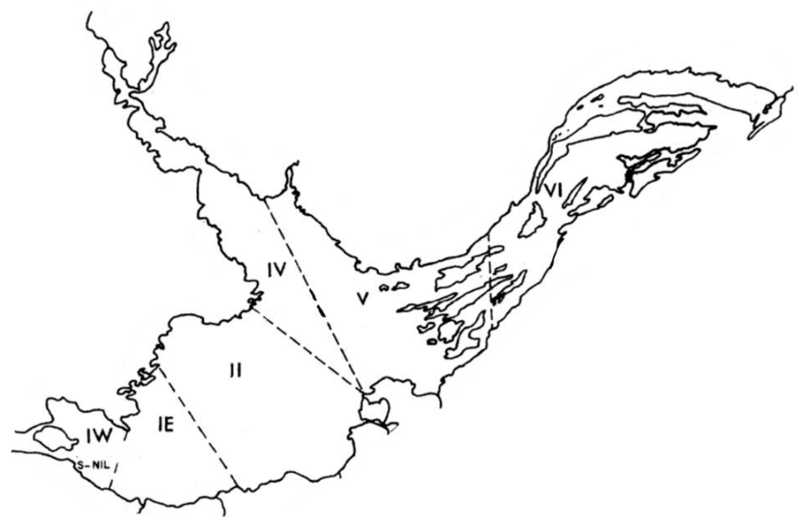
<td>1971 – 1972</td>
<td>Bond and Turnbull 1973

Major changes:

- open winter season in IW, closed summer; open summer season IE

- boundary added in east arm, splitting Area 3 into areas V and VI

*areas closed to commercial fishing not included in map</td>
<td>
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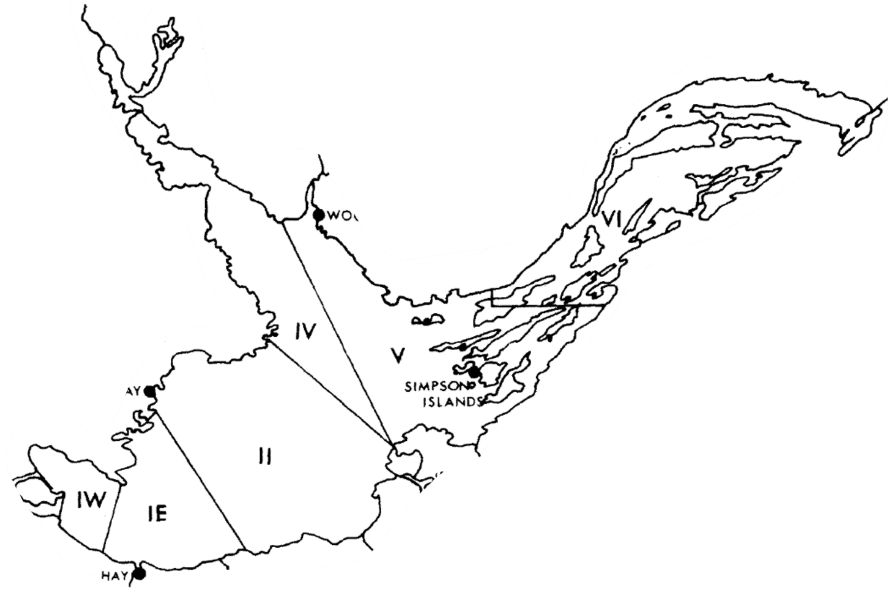
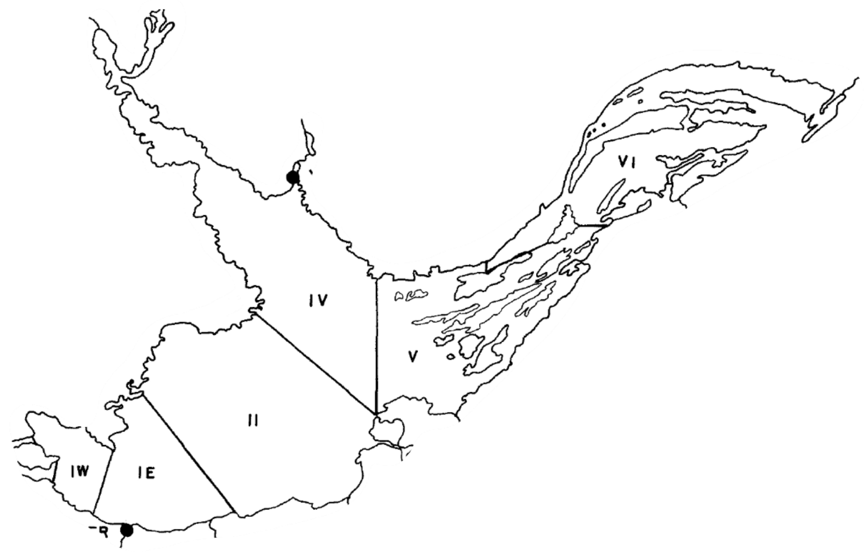
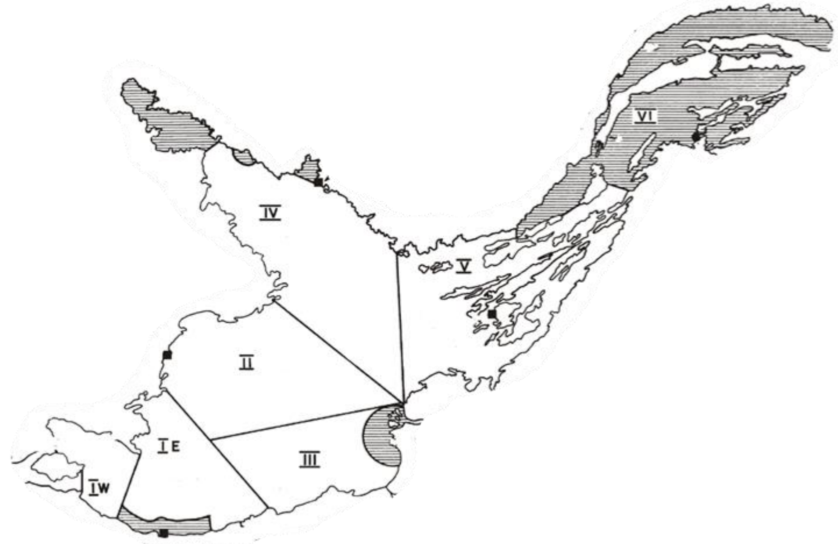
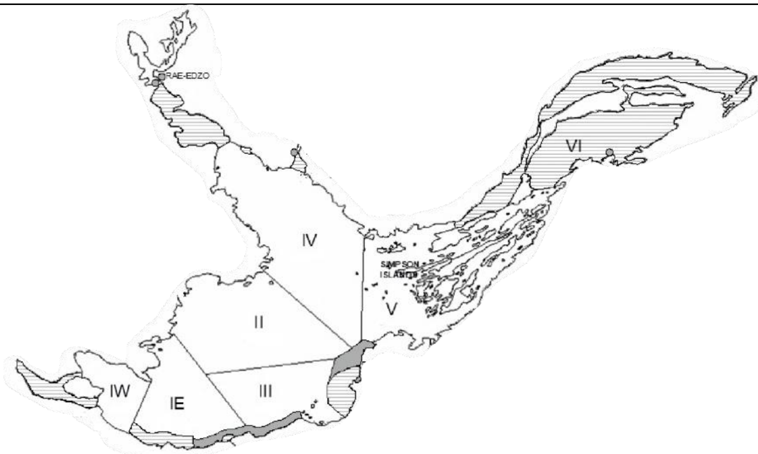
1972 – 1974	Bond 1975 Major changes: - boundary between V and VI *areas closed to commercial fishing not included in map	
1974 – 1978	Bond 1975 Major changes: - boundary between IV and V - boundary between V and VI *areas closed to commercial fishing not included in map	

1979 – present day	Roberge et al. 1982 Major change: - boundary added in II, leading to the addition of area III *shaded areas closed to commercial fishing *black squares = locations of fish plants operating at the beginning of the period	
1979 – onward, with more recent water closures included	Zhu et al. 2016 *Fully shaded regions are closed to commercial fishing during the spring * Partially shaded regions are closed to commercial fishing year-round	
Commercial fishery research and analysis division maps:		

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<tr><th>Years
Used</th><th>Source & Map Use</th><th></th></tr>
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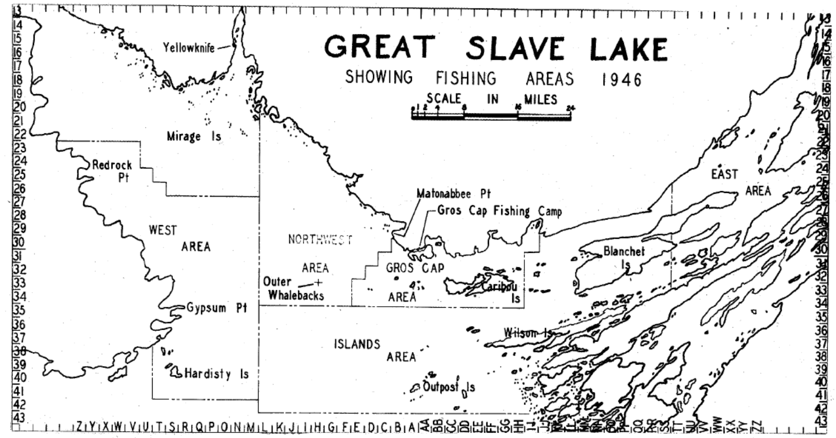
Original commercial fishing locations/divisions of first two years of research data</td><td>
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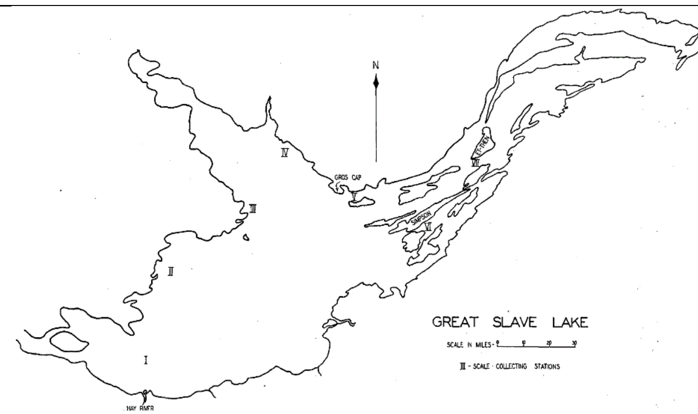
<tr><td>1946 - 1952</td><td>Kennedy 1954
Fish scale sampling locations – Early Research</td><td>
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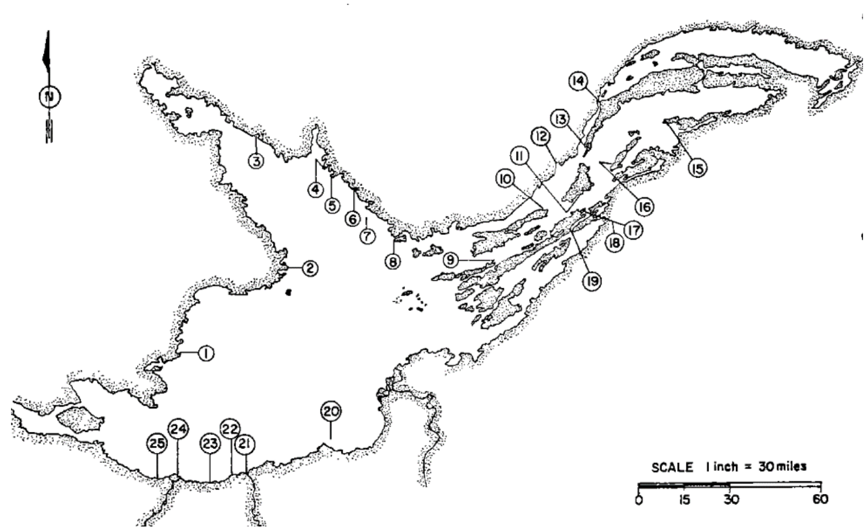
<td>1945-1955</td>
<td>Keleher 1963

Tagging site locations from early research</td>
<td>
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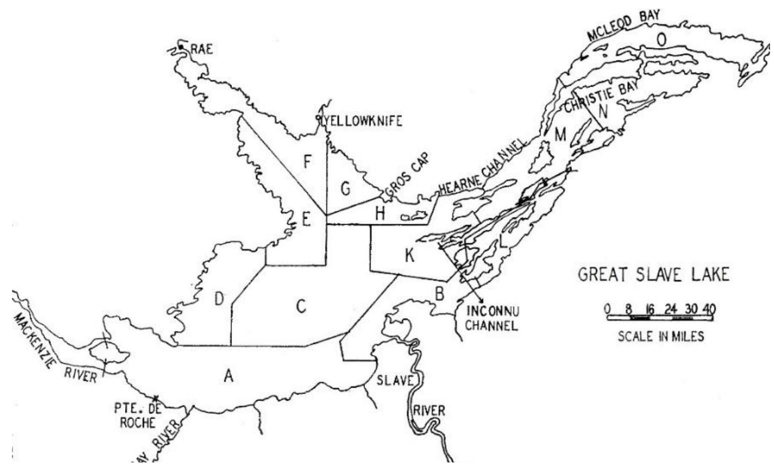
<td>1946-1964</td>
<td>Kennedy 1956

13 Statistical Areas used in early analysis</td>
<td>
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<td>1972</td>
<td>Bond and Turnbull 1973

Experimental net sampling locations</td>
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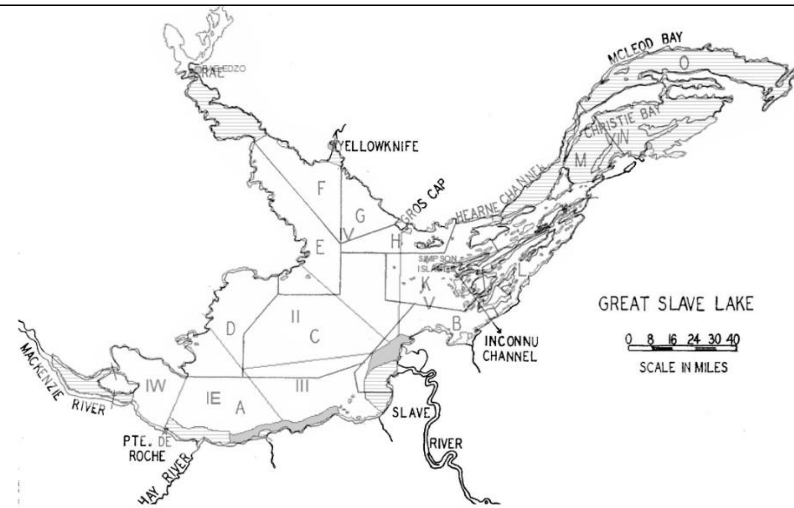
<td>Maps from Kennedy 1956 and Zhu et al. 2016

An overlay of the 13 statistical areas with the current management divisions</td>
<td>
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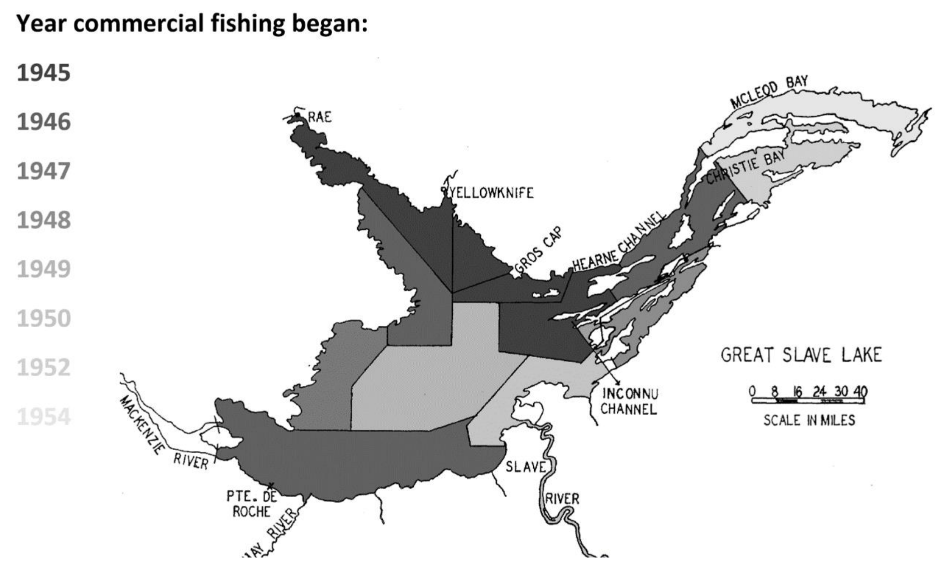
	Map from Kennedy (1956); information from Keleher (1972a) The year commercial fishing began in each of the 13 statistical areas with the darkest areas fished the longest	

A. I. Table 3: Additional details from research on Great Slave Lake characteristics, the recreational fishery, and other scientific studies

LAKE CHARACTERISTICS		
Turbidity	**Historic Research**	**Present Day Research**
Lake Transparency Measured through: - water clarity via. Seechi disc readings (Rawson 1950) - scattered light at 90° from an incident light beam, known as the Nephelometric Turbidity Unit (NTU) (USGS 2017)	- In the main lake, 1% incident light was recorded at a depth of 9-10 meters, 4-13 meters, and 10-17 meters in Christie and McLeod Bay's, respectively (Rawson 1950). - The greater maximum depths 1% incident light were recorded in for the East Arm bay's helps indicate the presence of deeper, clearer waters as suggested by the associated underlay, inflows, and maximum depths of these versus other, main lake, areas (Rawson 1950).	- Zhu et al. (2017) evaluated GSL turbidity and found turbidity readings between .1-80 NTU, with an average of 7.89 ± .28 NTU. Zhu et al. (2017) - Higher turbidity was recorded at major Great Slave Lake tributaries, such as the Slave River, in the upper water column (0-5 meters), but as well as penetration of turbid water masses into deeper zones for areas near the Slave

		River discharge. In contrast, waters in the large, deep, open areas offshore remain relatively clear at greater depths (Zhu et al. 2017).
Air & Water Temperature	- A mean annual air temperature of -5°C, was recorded in the initial research investigations suggesting a sub-arctic climate (Rawson 1950). - Average surface water temperatures on the lake during mid summer have been found to be 14°C offshore, in the Main Lake, and 16°C inshore, within 4.8 kilometres (3 miles) of the shoreline, with various gradients experienced in different areas of the lake (Rawson 1950). - Rawson (1950) found a range of 1.3-19.5°C for surface water temperature during the multiple years and seasons of observations (n=300), with daily fluctuations of 3-8°C; the strength of wind being the greatest influence in this diurnal variation	- A range of water temperatures from 3.05°C – 22.3°C in the lower water column and surface water, respectively, with an average temperature of 10.03 ± 4.91 °C (Zhu et al. 2017). - Zhu et al. (2017) found no significant variation in water temperature by year for the western basin, the area with most consistent year-to-year sampling (df = 5, f = .75, p =

				0.58).
Other		- Rawson (1950) found an average dissolved mineral content, with concentrations of calcium and bicarbonate being dominate, of 150ppm (140-160pmm) for the Main Lake, while Christie and McLeod Bay's in the East Arm had 111ppm and 22ppm, respectively; this further reveals the extreme oligotrophic nature of the east arm. - Sixty-thousand tons of dissolved minerals enter the lake per day through the Slave River, with this increased by 40,000 tons of suspended silt during the warmer months (Rawson 1950). - It has been hypothesized that the lower mineral concentration in certain areas of the lake compared to others is due to those areas only receiving waters from areas of Precambrian origin, such as McLeod Bay in the East Arm, while the Main Basin waters come from a variety of geological underlays (Rawson 1950).		
Citation	**Summary**	**Study**	**Results**	**Discussion**
RECREATIONAL FISHERY RESEARCH				
Keleher and Meeker 1962	Creel census angler survey undertaken at the Great Slave Lodge, located in the	- 1961 creel census, in addition to limited experimental angling, a summary of license sales, and a general review of the sport fishery - Most of the creel census data was	- 106 Lake Trout weights were recorded - 23 caught through nighttime experimental angling performed by the research team; average of	- Best single angling session in the Crater Bay region where 8 Lake Trout were caught in a 7-hour period - Due to inconsistencies in

	East Arm along the Taitheilei Narrows	collected by interviewing anglers or guides upon returning from a day of fishing - Questions asked ranged from gear and equipment type to location and best guess of depth in which the anglers caught the most fish - Lake trout biological information obtained through both experimental angling by the research team and recording the weight of harvested fish that anglers returned to the lodge with; given that returns were subject to angler selection, the sample should not be considered random	1.45 kg (3.2 lb), and a range of .45 - 3.18 kg (1 - 7lb) - the average and range of 83 Lake Trout recorded from lodge guests catches were 5.94 kg (13.1lb), and .45 – 17.24 kg (1 – 38lbs), respectively -Total catch and effort for the sport fishery around Taltheilei Narrows in 1961 was estimated at ~3,000 rod-angling hours to produce 2,600 fish, or on average ~30 hours for 26 fish per each of the 100 anglers included in the census. - Twenty-three Lake Trout, 40 Northern Pike, and 21 Grayling were caught in 74.5 hours of	recording, participation in licensing programs, and likely bias associated with some regions, minimal conclusions related to license sales and total angling involvement are made - If a desire exists to increase participation in the sport fishery of the East Arm additional infrastructure needs to be added to increase accessibility from Yellowknife Highway to Great Slave Lake

			experimental angling	
Yaremchuk 1986	From 1972-1980 a multi-year monitoring program, with the objective of determining the sport fishing industry lodges harvesting level on fish stocks, took place on both Great Slave	- Data collection, included a creel census, biological sampling through analysis of angler catches, similar to that of Keleher and Meeker (1962), in addition to experimental gill-netting, and fish tagging - Great Slave Lake East Arm lodges present at the time that were involved in the survey include: Arctic Star Lodge, Frontier Fishing Lodge, Plummer's Great Slave Lake Lodge, Indian Mountain Lodge, and Trophy Lodge - Fork length and round weight were recorded from fish anglers returned to lodges in addition to recording	- This paper summarizes the results of individuals years data reports including Falk et al. (1973), (1981); Gillman and Roberge (1982) - The yearly natural mortality rate for East Arm Lake Trout is estimated to be approximately 9% - The current yield by sport fishermen is estimated to be below the maximum sustainable yield for the area, however, were likely very close to the maximum - Ultimately conclude the creel census is a poor means of monitoring populations due to biases associated with sampling	- Suggested that there is no room for expansion of the sport fishing industry of the East Arm as further exploitation will decrease large Lake Trout standing stock - Area VI should remain closed to commercial gillnetting - To better understand and manage this resource, limits to catch and angler participation should be in place - Research to further understand Lake Trout stocks and their socio-economic value should be completed

	and Great Bear Lakes	biological information from individuals caught during experimental netting - 38 mm stretched mesh gill nets, chosen to limit netting mortality, set near the lodges were used for the researcher-led experimental netting	however, length data gathered by guides could be useful if consistently taken throughout the season	- Continued monitoring of recreational stocks through collection of length data should be sufficient
Thompson et al. 1988	- Angler creel census: trial study conducted at Plummer's Lodge in 1983 and 1984 as a cost-effective alternative to the creel census	- Catch and effort information was collected from lodge patrons through a diary program that asked anglers to record the amount of time spent angling, fish caught, kept, consumed, and released, and from approximately which area of the lake fishing occurred	- In the 2 years of the study it was estimated that 423 guests caught a total of 7,798 fish in 11,754 hours of angling	- Ultimately, the lack of additional studies of the same nature adds uncertainty to the success of this pilot study, although some information was gathered

Low et al. 1999	- Studies of the Sport fishery of East Arm Great Slave Lake completed in the years 1986, 1994 - Unlike previous East Arm surveys, itinerant Lake Trout fishers who were not supported by guides or staying at lodges, were	- Main purpose of study was to determine the participation and success of itinerant anglers to include them in the management plan for Lake Trout, in addition to determining if change had occurred in the 6-year interval -Base camps were set up by DFO teams at 62°19’15” N and 111°55’30” W and 61°59’40” N and 113°14’3’00” W in 1986 and 1994, respectively - Two fishery technicians a season traversed reachable commonly frequently fishing areas of the east arm anglers by boat - When anglers were encountered questionnaires were handed out asking participants to return these with their	- 155 legible, completed questionnaires of 274 given out to anglers in 1986 (56.6 % return rate), and 156 returned of the 587 distributed from 1994 (26.6 % return rate) - Results revealed that itinerant anglers in the East Arm who returned surveys in 1986 caught 1,859 Lake Trout and kept 403 (21.7 %) of these; in 1994, 1,961 Lake Trout were recorded with 337 (17.2 %) of those kept - In 1986 Lake Trout made up 79% of the overall iterant angler catch estimate, slightly lower than in 1994, when Lake Trout accounted	- Estimates of total harvest between the 1986 and 1994 assessments support observation that increased angler interest and harvest had increased - An increase in estimated mortality associated with Lake Trout harvest (25% in 1986 to 34% in 1994) was found - Suggested a new management plan be drafted for the East Arm trophy fishing industry in order to maintain the high quality of harvested fish, in addition to requesting the mandatory use barbless hooks for the Great Slave Lake sport fishery, and

	the focus	catch information, in addition, a 1986 creel census revised from Falk et al. (1973) was conducted consisting of direct sampling of anglers catch by DFO staff, took place and biological sampling of fork length, round weight, sex, maturity, stomach contents, and sagittal otoliths for aging 110 Lake Trout using methods described in Falk et al. (1982)	for 75% of the catch - Results of biological sampling 110 Lake Trout revealed an average fork length and round weight of 655 mm (510 – 968 mm range), and 3,771 g (1,050 – 12,500 g range), with a mean age of 15.6 years (11 – 22-year range) and an average condition factor (K) of 1.25 - The averages for males and females were 621 mm (511 – 955 mm range) and 670 mm (495 – 848 mm range) for fork length, respectively, while the averages for weight were 3118 g (1580 – 10,200 g range) for males and 3871 g (1230 – 8400 g range) for females	proposing future research should aim at estimating all the itinerant anglers, lodge-based and other subsistence fishery harvest levels in the same year, for multiple years in order to more accurately estimate the optimum harvesting level for Area VI Lake Trout

Low 2006	Survey similar to Low et al. 1999, conducted in 2005	- At end of 1990's Lutsel K'e First Nation, also revealed growing concern for the increased angler presence in the East Arm - Itinerant angler monitoring program focused on 4 primary species (Lake Trout, Northern Pike, Arctic Grayling, and Walleye) carried out by members of the Lutsel K'e First Nations - Methods included advertising for anglers to visit two local field workers, in addition to handing out surveys for the season to itinerant anglers by patrolling common angling grounds deemed popular by tradition and current popularity	- In 2005, Lake Trout accounted for 84% of the catch said to have been caught by itinerant anglers who returned surveys, and had a release rate of 90.7%, up from the estimated 78.3% in 1986	- Even with the relatively small sample size of returned surveys for some years, (e.g., n = 42, 2005), the information on species composition, release rates, and catch per unit of effort, are suggested to represent all east arm itinerant fishers, however, extrapolating information for an estimate of total harvest is cautioned as invalid

OTHER RESEARCH OF RELEVANCE TO THE GREAT SLAVE LAKE FISHERY				
	Summary/Objectives		**Relevance/Results/Suggestions**	
Zimmerman et al. 2006	Zimmerman et al. (2006), and the follow-up study, Zimmerman et al. (2009), examine morphological variation of Lake Trout specific to the East Arm through photographing	-The objectives were to evaluate whether a relationship exists between the body size of Lake Trout and 4 traits (weight converted to weight in water (buoyancy), colour, fin length and body shape), to determine the size at which phenotypic distinction becomes apparent, as well as determine the capture depth phenotype relationship	- Based on 72 Lake Trout caught from August 2001-2002 significant differences were observed in the diversification of 3 out of 4 traits explored (all except colour) for large, bodied Lake Trout - This divergence became apparent at a standard length of approximately 43cm	- Suggest that siscowet Lake Trout, which exhibit longer pectoral fins, may have a higher percentage of species, such as *Mysis* sp. and coregonines, in their diet as consequence of occupying a deeper depth. High lipid content, of these prey species, would help reinforce the lower percent buoyancy exhibited by these forms
Zimmerman et al. 2009		- In addition to visual analysis of body morphs, Zimmerman et al.'s (2009) investigation was complemented with analysis on capture depth, buoyancy,	- 217 Lake Trout from Christie Bay, divided into small (less than 43cm) and large (greater than 43cm) groups, were analyzed by model-	- Resource partitioning was more evident within, than between, habitat groupings (e.g., benthic (small trout) and pelagic

	sampled individuals and using a landmark system to perform body measurements	diet through stomach content analysis, and stable isotopes	based cluster analysis based on information from body landmarks, similar to the photographing procedure used by Zimmerman et al. (2006) - Large Lake Trout in one group were considered to be a siscowet form, possessing a shorter snout, eyes located higher on their heads, a deeper posterior head region, and a shorter head, deeper mid-body and thick caudal peduncles when compared to a second group (considered to be a lean form)	(large trout)) - The lean morph transitioned to pelagic feeding at shallower depths, while the siscowet morph shifted feeding at the same depths it was previously occupying with accompanying changes in fat concentration and body profile - Results showed that small Lake Trout are benthic feeders with resource portioning occurring within this habitat At approximately 43cm standard length, both Great Slave Lake lean and siscowet Trout experience a shift to pelagic

				feeding supplemented by morphological and buoyancy diversification
Sinclair et al. 1967	- A summary of the fisheries of the entire Mackenzie District of NWT from 1958-1964, as commercial operations extended to other waterbodies of the district in 1961, with some special attention paid to Great Slave Lake, however, no new firsthand data is included			
Day and Low 1992	- A summary the Great Slave Lake commercial fishery from the aspect of Lake Whitefish		- Given the lack of separation in quotas between Lake Whitefish and Trout, in addition to the shift in which species makes up most of the commercial harvest, valuable Lake Trout commercial fishery specifics are included	
Zhu et al. 2017	- From 2011-2016 various aspects of Great Slave Lake were studied with the goal of addressing community and management concerns regarding the impacts of the fisheries largely in relation to the prolonged sustainability and productivity of the aquatic ecosystem - Aspects of data collection for this study included environmental variable such as water temperature and		-The 6-year study, revealed through a two-way ANOVA test that water temperature differed significantly by management area ($df=5$, $f=25.23$, $p<.0001$) and depth strata ($df = 7$, $F = 82.85$ $p <0.0001$). - Other area specific details on water temperature from this study can be found in Figures 3-5 in Zhu et al. (2017). - Depth sampling showed that the current management area with the shallowest average depth was area IW ($9.96 \pm .37$m) and area IV was	

	turbidity, in addition to lower trophic level and fish species sampling	the deepest on average (63.53 ± 1.61m) **-** Area V, east of the Slave River, was also noted as a shallow area of the lake; for some important fish species on the lake, these shallower areas with warmer water temperatures fulfill important thermal requirements

A. I. Table 4: A summary of demographic information obtained from Tables 6 & 7 in Yarmechuk (1986) revealing the results of the East Arm recreational fishing survey that took place out of the available lodges (Frontier, Plummers, Indian Mountain, Arctic Star, and Trophy Lodge).

Age at Maturity		Frontier Lodge	Plummers GSL	Indian Mountain	Arctic Star	Trophy Lodge
	1973					
1st		7	9		12	
100%		17	12		14	
	1974					
1st		7	12		14	12
100%		16	29		16	12
	1975					
1st		8				
100%		20				
	1976			11		
1st				19		
100%						
	1977					
1st			12			
100%			21			
	1978					
1st					13	
100%					21	
	1979					
1st						13
100%						20
	1980					
1st		9				
100%		9				
Mean Length mm (1- angled, 2- gillnet)		**Frontier Lodge**	**Plummers GSL**	**Indian Mountain**	**Arctic Star**	**Trophy Lodge**
	1972	564 (n=879)	699 (n=974)		517 (n=40)	
	1973	549 (n=765)	612 (n=572)		568 (n=46)	
	1974	563 (n=543)	641 (n=636)		667(n=34)	517(n=28)
	1975	609 (n=926)				
	1976			607(n=342)		
	1977		627 (n=454), 572 (n=679)			
	1978				576 (n=384), 553 (n=682)	
	1979					559 (n=114), 586 (n=513)
	1980	649 (n=222), 478 (n=525)				

Mean Age (1- angled, 2- gillnet)		**Frontier Lodge**	**Plummers GSL**	**Indian Mountain**	**Arctic Star**	**Trophy Lodge**
	1972					
	1973	12.5 (n=689)			16.8 (n=43)	
	1974	12.5 (n=516)			15.2 (n=11)	14.5 (n=28)
	1975	14.7 (n=774)				
	1976			15.6 (n=329)		
	1977		17.0 (n=428), 11.1 (n=171)			
	1978				21.4 (n=357), 13.6 (n=172)	
	1979					19.3 (n=106)
	1980	18.9 (n=222), 7.9 (=72)				
Z – Mortality (1- angled, 2- gillnet)		**Frontier Lodge**	**Plummers GSL**	**Indian Mountain**	**Arctic Star**	**Trophy Lodge**
	1972					
	1973	0.33	0.26		0.14	
	1974	0.32	0.16			
	1975	0.33				
	1976			0.29		
	1977		.19, .33			
	1978				0.18	
	1979					.11, .17
	1980	0.2				

A. I. Table 5: Select Lake Trout tagging, and recapture data obtained from Tables I, II & III in Keleher (1963).

From Table I; Great Slave Lake Trout Tagged and Recaptured in parenthesis

Common Name	*1946*	*1947*	*1953*	*1954*	*1955*	*Total*
Lake Trout	77 (10)	504 (139)	228 (24)	22 (7)	171 (39)	1002 (221)

From Table II; Great Slave Lake Trout Recovered in Relation to Calendar Year

Year	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*Total*
Lake Trout	97	55	34	11	8	5	2	n/a	2	4	n/a	1	219

From Table III; Lake Trout Statistics for Days at Large for Fish Recaptured

	n	Total	Mean	Median	Max
Lake Trout	213	100,392	471	327	4027

Appendix II (Chapter 3)

Additional tables and figures associated with the CMSY stock assessment of Great Slave Lake Trout

A. II. Table 1: Area-wise Lake Trout commercial catch (metric tons) for Great Slave Lake. Data from DFO Fisheries Resource Management and DFO Fisheries Management and Harvest Information System (FMHIS) database.

Year	IW	IE	II	III	IV	V
1972-73	3.222	8.703				
1973-74	2.565	9.019				
1974–75	3.333	26.396			1.031	62.941
1975–76	1.677	7.466			3.631	57.645
1976–77	0.424	25.375			6.142	70.888
1977–78	1.199	17.014			5.124	72.848
1978–79	5.215	21.004			6.618	83.363
1979–80	2.723	9.569	3.872	0	2.591	102.9
1980–81	0.875	3.227	2.245	0.002	0.835	78.004
1981–82	0.765	3.225	0.329	0	0.234	70.226
1982–83	0.767	1.022	1.589	0.028	3.779	54.048
1983–84	3.357	2.591	2.846	0.018	1.189	40.154
1984–85	6.643	3.338	3.495	0.075	3.75	92.293
1985–86	8.746	2.283	7.123	0.404	2.189	86.69
1986–87	17.236	5.737	13.035	0.575	3.429	86.857
1987–88	3.297	7.151	6.845	1.567	5.301	41.094
1988–89	8.71	23.79	14.317	3.207	8.476	78.724
1989–90	9.78	24.704	9.501	0.176	3.419	39.638
1990–91	6.682	11.534	16.949	0.181	7.756	43.422
1991–92	5.502	12.482	8.876	0.323	5.32	15.664
1992–93	4.682	8.797	10.78	0.597	3.838	32.869
1993–94	8.053	32.291	16.386	0.413	16.811	2.271
1994–95	6.163	10.843	10.102	0.225	22.271	31.618
1995–96	6.254	16.148	9.483	0.216	30.88	59.563
1996–97	6.924	38.624	8.084	0.745	5.871	43.687
1997–98	11.884	12.373	6.536	0.556	8.91	52.755
1998–99	8.532	9.015	6.322	0.083	7.655	3.691
1999–00	9.484	11.557	8.161	0.058	3.653	6.214
2000–01	13.792	34.08	3.037	0.163	19.865	4.299
2001–02	9.538	17.298	6.632	0.388	4.217	22.026
2002–03	13.185	31.421	6.459	0.883	6.662	4.173
2003–04	10.006	45.634	9.592	5.374	6.423	10.281
2004–05	4.321	25.374	3.665	2.467	7.699	8.908
2005–06	4.093	26.592	0.204	1.463	10.813	9.365
2006–07	3.887	2.451	0	0.031	2.66	1.002
2007–08	7.245	12.338	1.518	0.803	0	0
2008–09	21.9	17.68	0	0.06	4.08	1.59
2009–10	12.32	25.48	4.29	0.09	0	0
2010–11	26.21	27.11	0	0	0	0
2011–12	26.89	19.43	0	4	0	0
2012–13	21.93	49.77	1.41	4.04	0	0

2013–14	11.07	56.94	0	0.2	0.25	0
2014–15	12.19	48.31	0.71	0.83	0	0
2015–16	22.63	64.93	0	1.6	0	0
2016–17	19.74	60.53	0	0.28	0	0
2017–18	43.38	87.16	4.15	6.08	0	0
2018–19	44.76	47.78	14.56	0.98	1.43	1.23
2019–20	10.35	47.51	0.71	1.23	6.74	0
2020–21	16.95	45.33	0.04	0.81	16.29	0
2021–22	14.33	39.95	0.07	1.36	6.16	2.06

A. II. Table 2: Whole Lake and Area I (IW & IE) Lake Trout commercial catch (metric tons) in Great Slave Lake. Whole lake catches were obtained from DFO Fisheries Resource Management till 1971, Area I 1952 – 1972 catch values were recreated from Figure 4 in Bond and Turnbull (1973), and the 1972 onward values for both areas were obtained from DFO Fisheries Management and Harvest Information System (FMHIS) database.

	Whole lake	**Area I (IW + IE)**		**Whole lake**	**Area I (IW + IE)**
1944-45	483.51		**1983–84**	50.155	5.948
1945-46	734.118		**1984–85**	109.594	9.981
1946-47	755.91		**1985–86**	107.435	11.029
1947-48	992.898		**1986–87**	126.869	22.973
1948-49	1822.81		**1987–88**	65.255	10.448
1949-50	1155.884		**1988–89**	137.224	32.5
1950-51	1257.126		**1989–90**	87.218	34.484
1951-52	1344.748	160.5442	**1990–91**	86.524	18.216
1952-53	1090.508	115.1927	**1991–92**	48.167	17.984
1953-54	1119.564	102.9478	**1992–93**	61.563	13.479
1954-55	1293.9	126.9841	**1993–94**	76.225	40.344
1955-56	1187.21	95.2381	**1994–95**	81.222	17.006
1956-57	898.92	126.9841	**1995–96**	122.544	18.4566
1957-58	914.356	150.1134	**1996–97**	103.935	44.7817
1958-59	774.07	122.9025	**1997–98**	93.014	20.79098
1959-60	497.13	104.3084	**1998–99**	35.298	15.75736
1960-61	485.326	68.02721	**1999–00**	39.127	20.6612
1961-62	532.088	44.44444	**2000–01**	75.236	46.0335
1962-63	316.892	61.22449	**2001–02**	60.099	25.7072
1963-64	302.818	42.17687	**2002–03**	62.783	37.8345
1964-65	368.648	40.36281	**2003–04**	87.31	46.93945
1965-66	267.86	48.52608	**2004–05**	52.433	27.18371
1966-67	302.818	113.3787	**2005–06**	52.529	29.67678

1967-68	121.672	56.68934	**2006–07**	10.031	6.338
1968-69	136.2	58.04989	**2007–08**	21.904	18.36856
1969-70	222.914	57.14286	**2008–09**	45.315	30.9142
1970-71	146.188	17.68707	**2009–10**	42.179	35.4912
1971-72	85.757	17.68707	**2010–11**	53.323	53.3234
1972-73	92.072	11.92431	**2011–12**	50.32	44.4204
1973-74	110.789	11.58381	**2012–13**	77.15	67.3353
1974–75	99.41	29.72974	**2013–14**	68.465	64.7354
1975–76	82.625	9.142652	**2014–15**	62.034	57.6026
1976–77	108.177	25.79855	**2015–16**	89.16	81.3131
1977–78	105.57	18.21312	**2016–17**	80.546	75.9122
1978–79	121.039	26.21895	**2017–18**	140.764	130.5422
1979–80	121.655	12.29205	**2018–19**	109.51	92.543
1980–81	85.188	4.102	**2019–20**	66.536	57.86
1981–82	74.779	3.99	**2020–21**	79.42	62.28
1982–83	61.233	1.789	**2021–22**	66.019	54.28

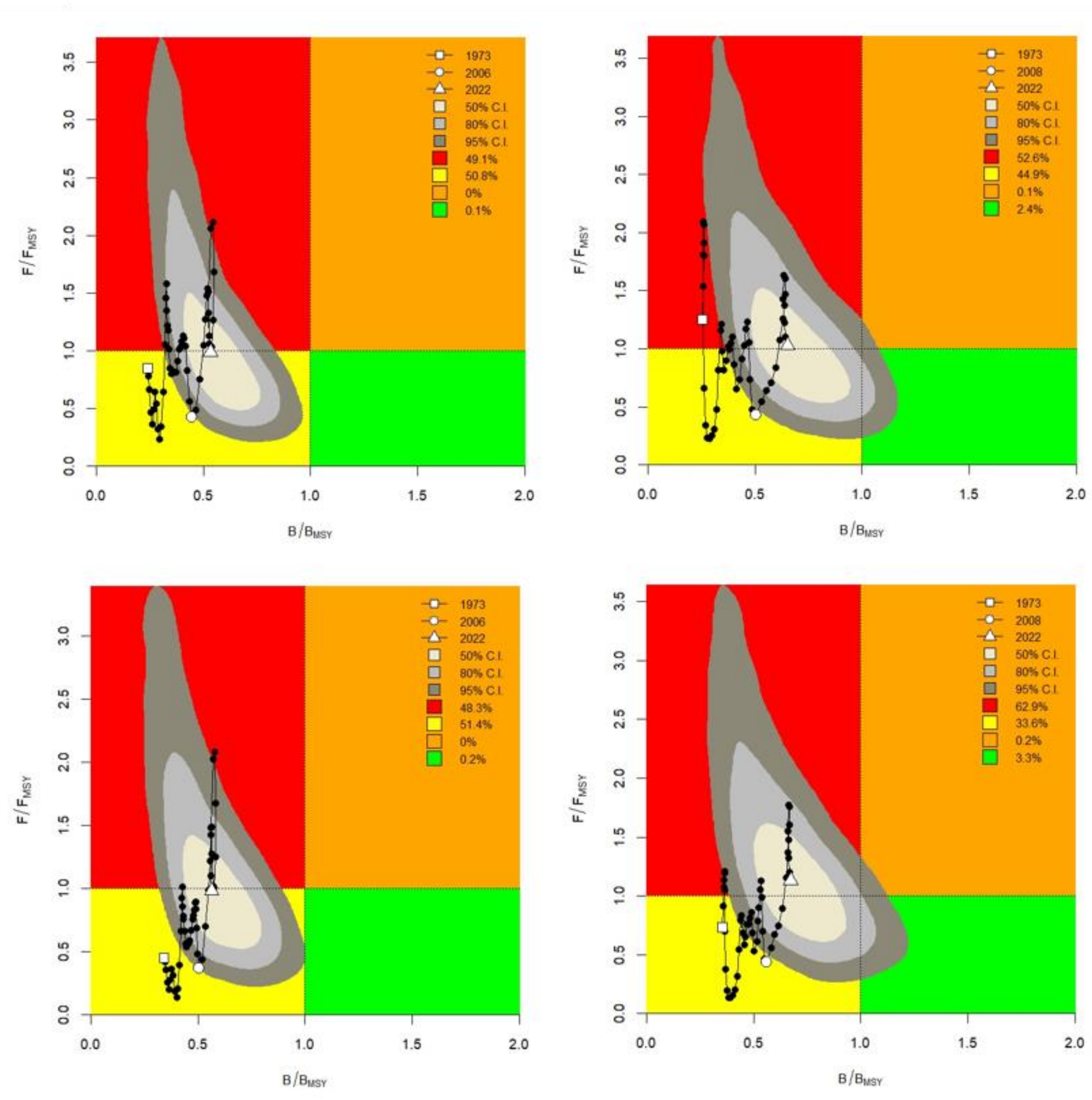
A. II. Table 3: BPUE inputs for the sensitivity analysis of IW and IE using BSM. Values from Zhu et al. 2017 and Zhu et al. 2023, Fisheries and Oceans Canada, unpublished.

	IW	**IE**
2011	0.0109	0.0016
2012	0.0000	0.0208
2013	0.0246	0.0071
2014	0.0000	0.0621
2015	0.0073	0.0315
2016	0.0003	0.0351
2017	0.0000	0.0293
2018	0.0024	0.0160
2019	0.0351	0.0576
2022	0.2518	0.0089

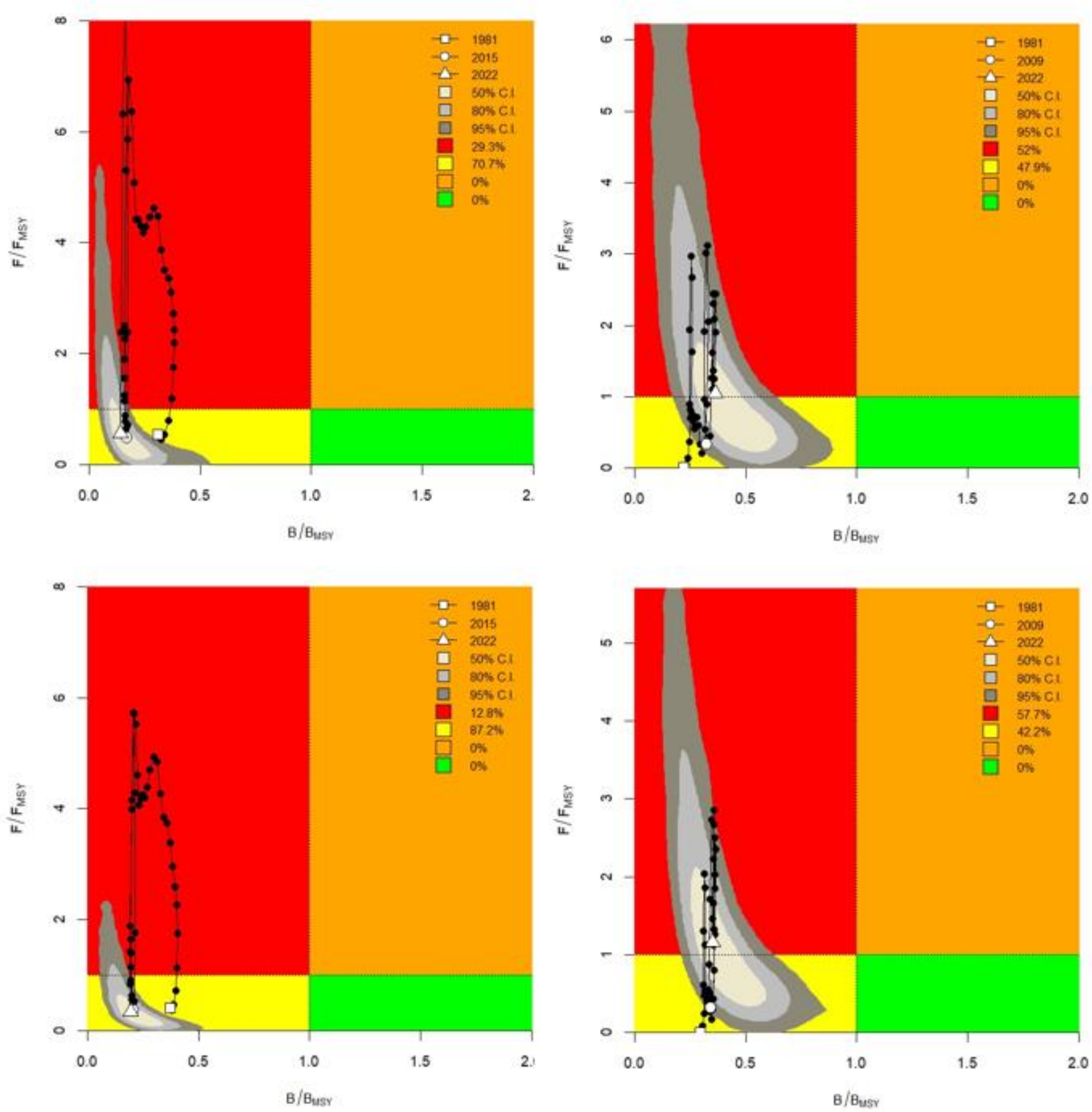
A. II. Table 4: CMSY & BSM model outputs and reference points for all Great Slave Lake Trout assessment scenarios, including model estimates for r, k, MSY and B_{MSY}, with credible intervals, and the model's estimate of B/B_{MSY} and F/F_{MSY} at the end of the time series.

Area	Condition Reference	MSY	95% C.I.	B_{MSY}	95% C.I.	B_{FINAL}/B_{MSY}	95% C.I.	F_{MSY}	95% C.I.	F_{MSY} (if B_t less than .25k)	95% C.I.	F_{FINAL}/F_{MSY}	95% C.I.	r	95% C.I.	k	95% C.I.
IW	*IW – CMSY - i*	29.6	20.5 – 45.4	789	572 – 1360	0.532	0.293 – 0.815	0.0371	0.023 – 0.051	NA		0.989	0.463 – 3.53	0.0742	0.0461 – 0.102	1600	1140 – 2730
	IW – CMSY - ii	27.7	18.5 – 44.0	1080	742 – 2040	0.564	0.304 – 0.847	0.0256	0.0156 – 0.0351	NA		0.983	0.476 – 3.11	0.0512	0.0312 – 0.0702	2160	1480 – 4080
	IW – BSM - i	31.6	20.5 – 50.3	525	231 – 1300	0.573	0.298 – 0.882	0.0574	0.0245 – 0.118	NA		0.932	0.434 – 3.2	0.115	0.049 - 0.237	1050	462 - 2590
	IW – BSM -ii	26.8	17.9 – 40.8	603	260 – 1500	0.544	0.273 – 0.842	0.0446	0.0195 – 0.0967	NA		1.11	0.531 – 4.09	0.0892	0.0389 - 0.193	1210	520 - 3000
	Average CMSY	**28.65**		**934.50**		**0.55**		**0.03**				**0.99**		**0.06**		**1880.0**	
	Average BSM	**29.2**		**564**		**0.5585**		**0.051**				**1.021**		**0.1021**		**1130**	
IE	*IE – CMSY- i*	63.5	42.3 – 101	1500	1050 - 2660	0.652	0.333 – 1.0	0.0424	0.0258 – 0.0593	NA		1.03	0.496 – 3.29	0.0848	0.0517 - 0.119	2990	2090 - 5310
	IE – CMSY - ii	56.5	39.1 – 88.7	1990	1370 - 3670	0.673	0.354 – 1.03	0.0284	0.0171 – 0.0389	NA		1.13	0.563 – 3.33	0.0567	0.0343 - 0.0777	3990	2750 - 7330
	IE – BSM-i	59.4	38.3 – 94.7	1170	547 - 2850	0.66	0.336 – 1.05	0.0507	0.0217 – 0.108	NA		1.1	0.507 – 3.8	0.101	0.0433 - 0.215	2340	1090 - 5700
	IE – BSM-ii	52.7	36.4 – 78.1	1160	517 - 2790	0.645	0.337 – 1.03	0.0454	0.0202 – 0.1	NA		1.28	0.598 4.03	0.0908	0.0404 - 0.2	2320	1030 - 5590
	Average CMSY	**60.00**		**1745.00**		**0.66**		**0.04**				**1.08**		**0.07**		**3490**	
	Average BSM	**56.05**		**1165**		**0.6525**		**0.0481**				**1.19**		**0.0959**		**2330**	
II	*II – i*	14	9.57 - 21.2	331	211 - 687	0.142	0.0453 – 0.375	0.0422	0.0217 – 0.0635	0.012	0.00616 – 0.018	0.57	0.0832 – 5.72	0.0844	0.0434 – 0.127	662	422 – 1370
	II – ii	12.6	8.09 - 20.4	429	282 - 876	0.194	0.0819 – 0.39	0.0293	0.0159 – 0.0428	0.0113	0.00617 – 0.0166	0.34	0.0746 – 2.29	0.0586	0.0319 – 0.0856	858	565 – 1750
	Average	**13.30**		**380.00**		**0.17**		**0.04**		**0.01**		**0.46**		**0.07**		**760.00**	
III	*III – i*	4.27	2.78 - 6.76	120	81.8 - 214	0.363	0.12 – 0.645	0.0355	0.0203 – 0.0513	0.0258	0.0148 – 0.0373	1.05	0.318 – 9.52	0.071	0.0407 – 0.103	240	164 – 428
	III – ii	3.87	2.45 - 6.39	163	109 - 304	0.352	0.17 – 0.665	0.0237	0.0138 – 0.0346	0.0167	0.00969 – 0.0243	1.16	0.34 – 5.62	0.0473	0.0275 – 0.0692	327	219 – 607
	Average	**4.07**		**141.50**		**0.36**		**0.03**		**0.02**		**1.11**		**0.06**		**283.50**	
IV	*IV – i*	19	12.5 - 29.6	490	336 - 898	0.31	0.138 – 0.601	0.0387	0.0224 – 0.0558	0.0239	0.0139 – 0.0345	2.65	0.715 – 16	0.0773	0.0448 – 0.112	981	672 – 1800
	IV – ii	17.8	11.6 - 28.1	687	475 - 1310	0.301	0.144 – 0.544	0.026	0.0147 – 0.0373	0.0156	0.00884 – 0.0225	2.91	0.932 – 14.4	0.0519	0.0294 – 0.0747	1370	950 – 2620
	Average	**18.40**		**588.50**		**0.31**		**0.03**		**0.02**		**2.78**		**0.06**		**1175.5**	
V	*V – i*	89.3	60.1 - 136	1860	1170 - 4120	0.183	0.0767 – 0.361	0.0479	0.0222 – 0.0759	0.0175	0.00813 – 0.0277	0.188	0.0426 – 1.12	0.0958	0.0445 – 0.152	3730	2350 – 8240
	V – ii	77.7	52.4 - 121	2320	1510 - 4840	0.175	0.0663 – 0.361	0.0335	0.0172 – 0.0499	0.0117	0.00602 – 0.0175	0.23	0.0502 – 1.68	0.067	0.0344 – 0.0999	4640	3020 – 9690
	Average	**83.50**		**2090.00**		**0.18**		**0.04**		**0.01**		**0.21**		**0.08**		**4185.0**	
Whole Lake	*Lake – i*	916	627 - 1450	22800	17100 - 45600	0.305	0.147 – 0.536	0.0402	0.0211 – 0.0554	0.0245	0.0129 – 0.0338	0.584	0.177 – 2.72	0.0803	0.0422 - 0.111	45600	34200 - 91300
	Lake – ii	889	569 - 1410	28400	20100 - 53500	0.238	0.103 – 0.481	0.0313	0.0173 – 0.0464	0.0149	0.00822 – 0.0221	0.712	0.16 – 4.11	0.0626	0.0346 - 0.0929	56800	40300 - 107000

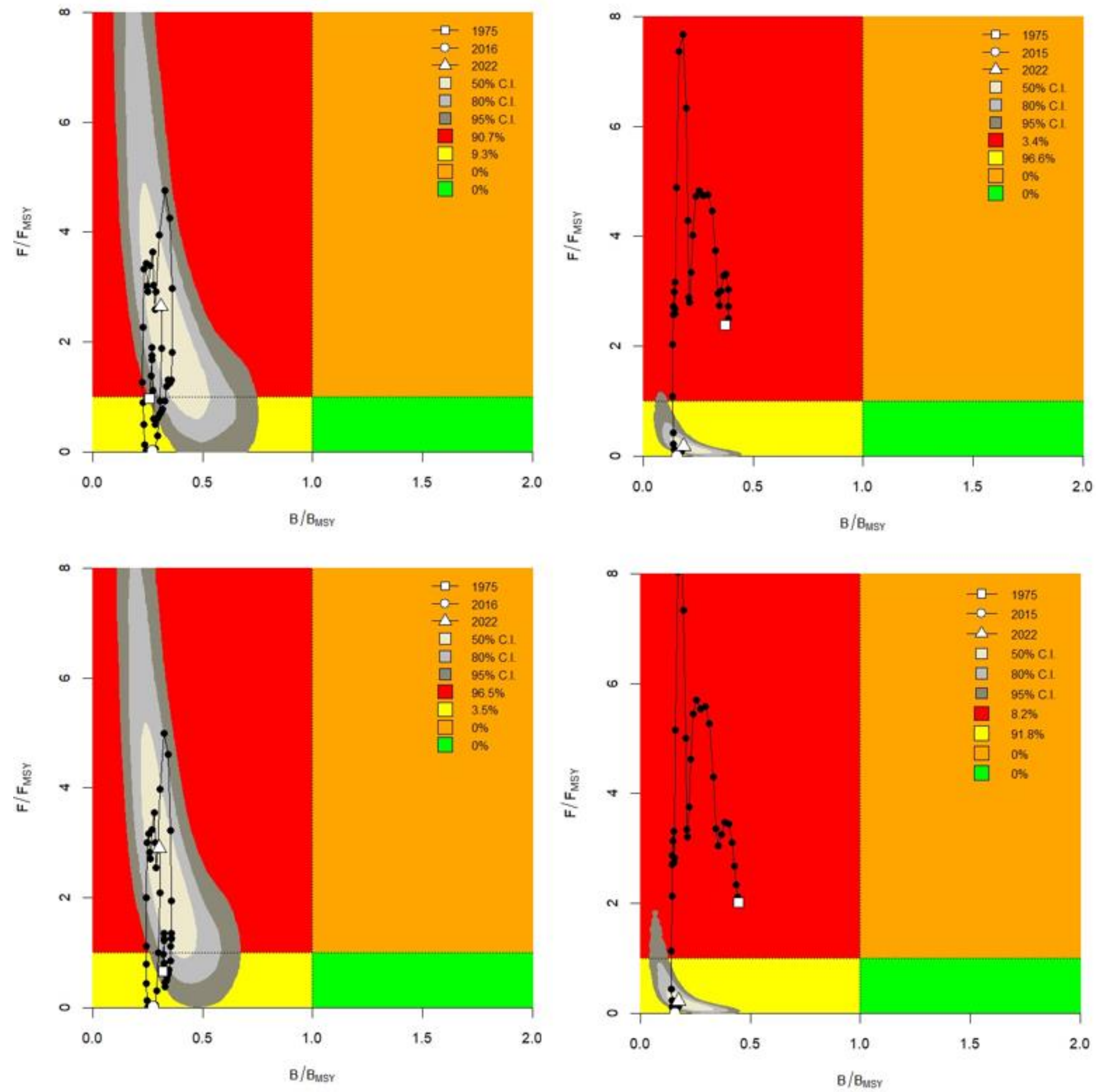
	Lake – iii	950	648 - 1460	27300	19700 - 50400	0.221	0.08 – 0.46	0.0348	0.0193 – 0.0493	0.0154	0.00852 – 0.0218	0.762	0.154 – 6.25	0.0697	0.0385 - 0.0986	54500	39300 - 101000
	Lake – iv	106	75.9 - 151	2700	1920 - 4850	1.1	0.749 – 1.48	0.0391	0.0222 – 0.0541	NA		0.615	0.338 – 1.17	0.0782	0.0445 - 0.108	5400	3840 - 9700
	Lake – v	120	85.2 - 185	2570	1700 - 4970	1.07	0.767 – 1.45	0.0467	0.027 – 0.0651	NA		0.549	0.29 – 1.01	0.0935	0.054 - 0.13	5130	3410 - 9930
	Average i-iii	**918.33**		**26166.67**		**0.25**		**0.04**		**0.02**		**0.69**		**0.07**		**52300**	
	Average iv-v	**113.00**		**2635.00**		**1.09**		**0.04**		**NA**		**0.58**		**0.09**		**5265**	
Area I (W&E)	*AreaI – i*	100	69 - 152	2890	2040 - 5560	0.554	0.309 – 0.806	0.0347	0.0189 – 0.0492	NA		0.675	0.334 – 2.24	0.0693	0.0378 - 0.0984	5790	4080 - 11100
	AreaI – ii	82.1	56.3 - 129	1980	1380 - 3500	0.724	0.404 – 1.09	0.0415	0.0259 – 0.0569	NA		0.976	0.498 – 2.44	0.083	0.0517 - 0.114	3960	2750 - 6990
	AreaI – iii	77.9	53.4 - 122	2740	1910 - 4910	0.73	0.432 - 1.1	0.0285	0.0173 – 0.0394	NA		0.997	0.486 – 2.33	0.0569	0.0346 - 0.0788	5470	3810 - 9830
	AreaI – iv	89	58.6 - 138	3070	2150 - 5800	0.524	0.263 – 0.842	0.029	0.0159 – 0.0415	NA		1.3	0.589 – 5.03	0.0579	0.0319 - 0.0829	6140	4310 - 11600
	Average	**87.25**		**2670.00**		**0.63**		**0.03**				**0.99**		**0.07**		**5340**	



A. II. Figure 1: CMSY produced Kobe plots for Area IW & IE commercially caught Lake Trout for input conditions i, and ii. Input condition i) (IW - top-left; IE – top-right) has an initial B/k input of 0.01 – 0.2 with a time series from 1972 – 2022. Input condition ii) (IW – bottom - left; IE - bottom - right) has an initial B/k of 0.01-0.4 indicating greater uncertainty in the estimate of biomass at the beginning of the time series relative to carrying capacity by estimating the range between 1-40%, with a time series input of 1972 – 2022. In both input conditions the B/k at the end of the time series was estimated by the CMSY++ model.

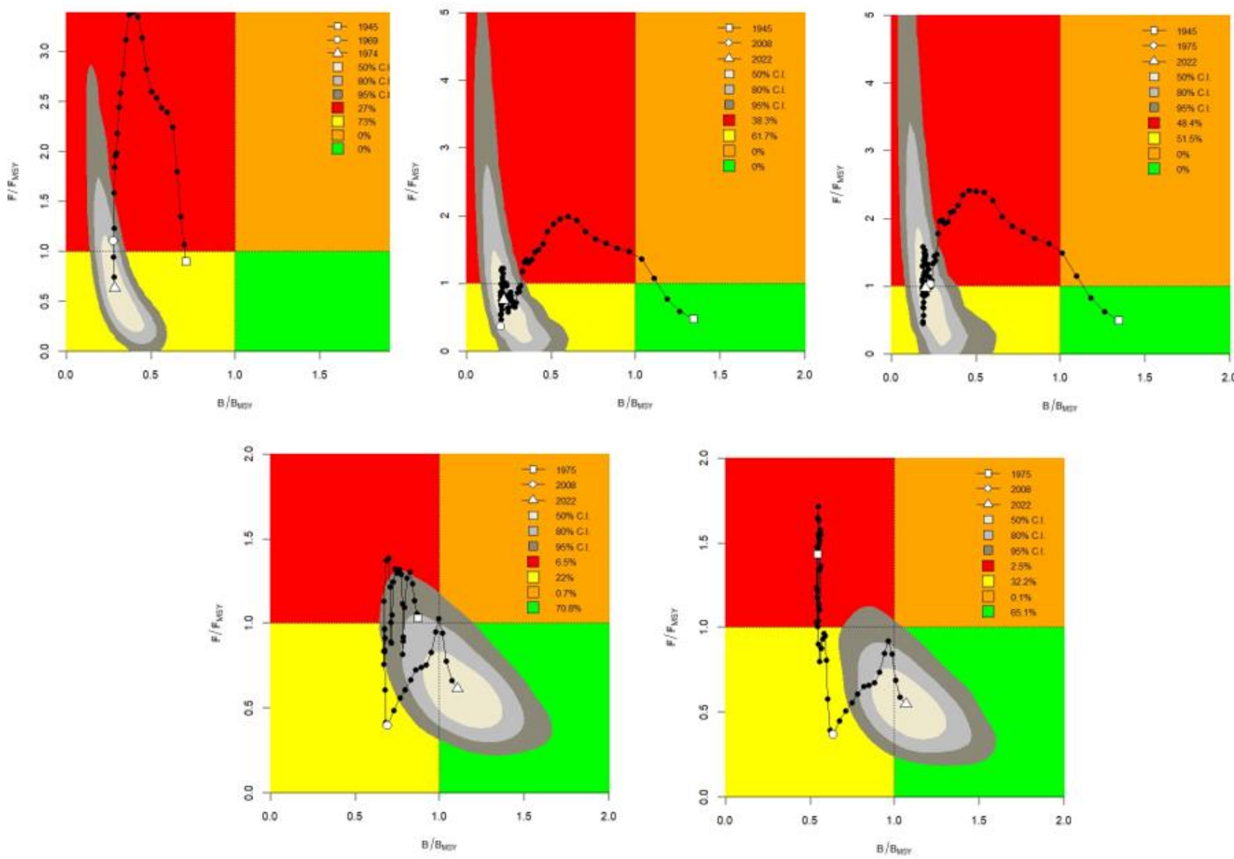


A. II. Figure 2: CMSY produced Kobe plots for Area II & III commercially caught Lake Trout for input conditions i, and ii. Input condition i) (II - top-left; III – top-right) has an initial B/k input of 0.01 – 0.2 with a time series from 1980 – 2022. Input condition ii) (II – bottom - left; III - bottom - right) has an initial B/k of 0.01-0.4 indicating greater uncertainty in the estimate of biomass at the beginning of the time series relative to carrying capacity by estimating the range between 1-40%, with a time series input of 1980 – 2022. In both input conditions the B/k at the end of the time series was estimated by the CMSY++ model.

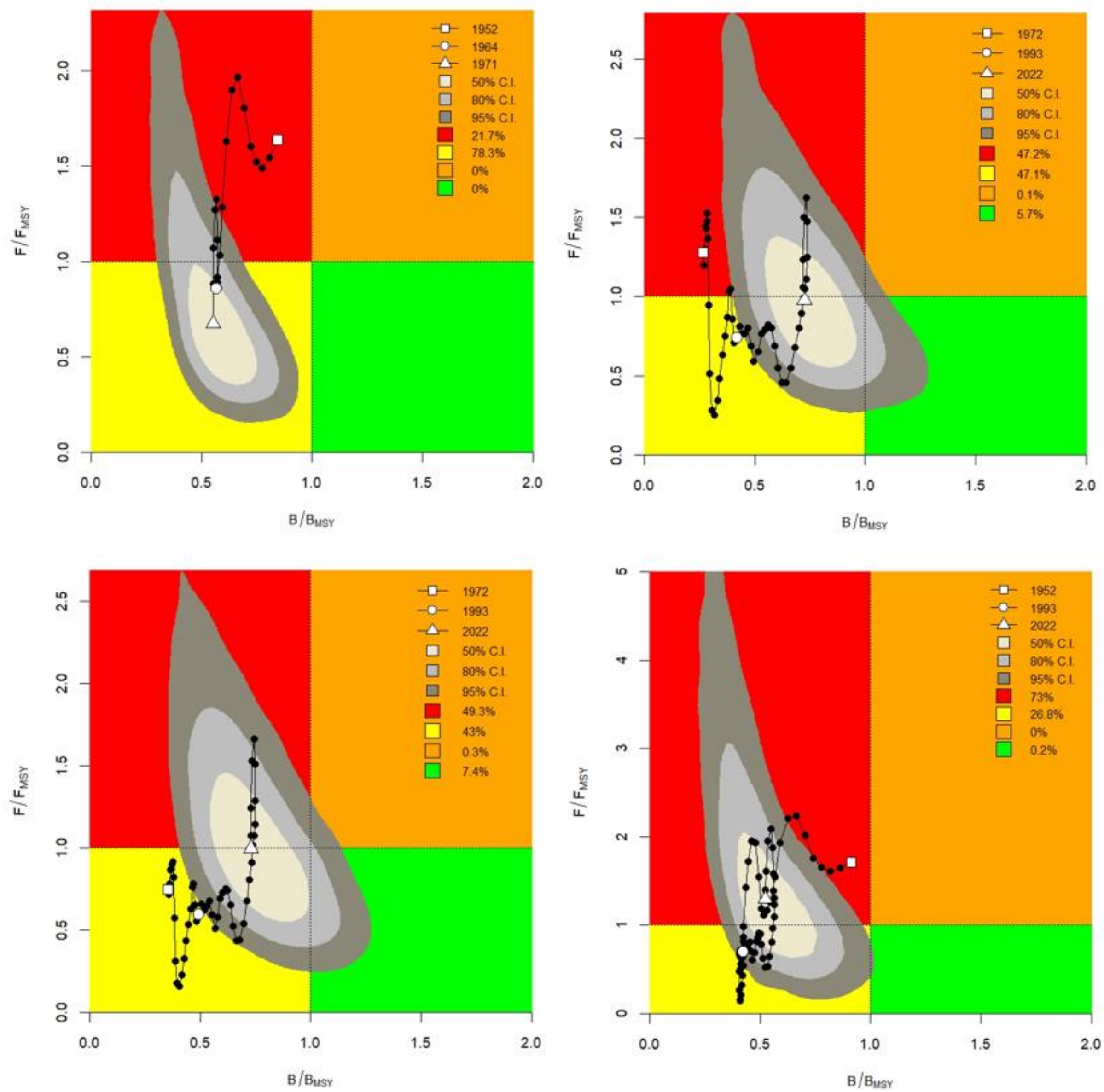


A. II. Figure 3: CMSY produced Kobe plots for Area IV & V commercially caught Lake Trout for input conditions i, and ii. Input condition i) (IV - top-left; V – top-right) has an initial B/k input of 0.01 – 0.2 with a time series from 1974 – 2022. Input condition ii) (IV – bottom - left; V - bottom - right) has an initial B/k of 0.01-0.4 indicating greater uncertainty in the estimate of biomass at the beginning of the time series relative to carrying capacity by estimating the range between 1-40%, with a time series input of

1974 – 2022. In both input conditions the B/k at the end of the time series was estimated by the CMSY++ model.

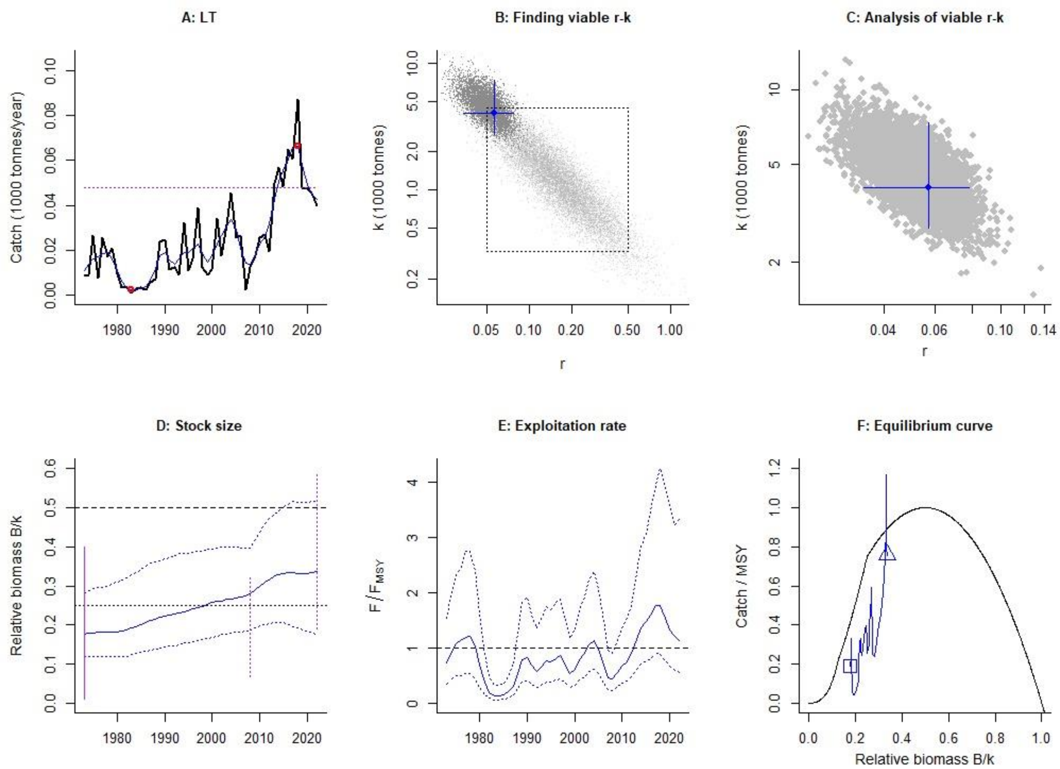


A. II. Figure 4: CMSY produced Kobe plots for all Great Slave Lake commercially caught Lake Trout for Whole Lake input conditions i-v. Input condition i) (top-left) has a time series input of 1945-1975 with an initial B/k of 0.5-0.9, and an end B/k estimated by the model. Input conditions ii) and iii) have a time series input of 1945-2022. Input condition ii) (top-middle) has an initial and end B/k estimated by the model. Input condition iii) (top-right) has an initial B/k input of 0.05-0.9, and an end B/k estimated by the model. Input conditions iv) and v) have a time series input of 1975-2022. Input condition iv) (bottom-left) has an initial and end B/k estimated by the model, and input condition v) (bottom-right) has an initial B/k input of 0.01-0.4, and an end B/k estimated by the model.

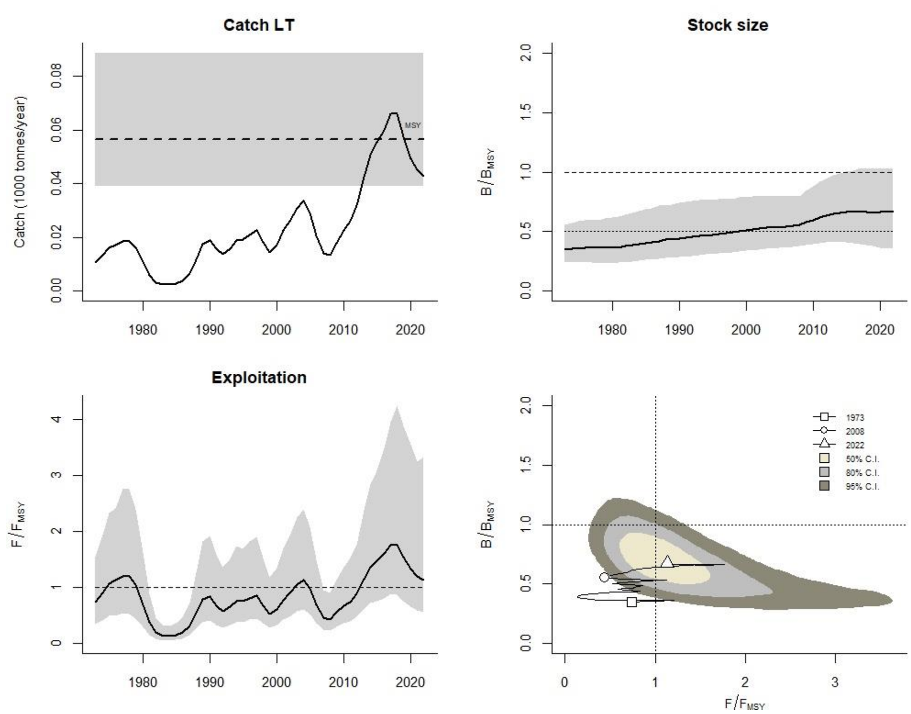


A. II. Figure 5: CMSY produced Kobe plots for Area I (IW & IE) commercially caught Lake Trout for input conditions i-iv. Input condition i) (top-left) has an initial B/k estimate by the model with a time series from 1952-1971 (~7 years since fishery initiation), ii) (top-right) has an initial B/k of 0.01-0.2 indicating an extremely depleted stock with the proportion of biomass at the beginning of the time series relative to the carrying capacity estimated between 1-20% and a time series input on 1972 – 2022 (~30 years since fishery initiation), iii) (bottom-left) has an initial B/k of 0.01-0.4, indicating greater uncertainty in the estimate of biomass at the beginning of the time series relative to carrying capacity by estimating the range between 1-40%, with a time series input on 1972 – 2022. Input condition iv) (bottom-right) has an initial B/k input estimated by model, with a time series input of 1952 -2022.

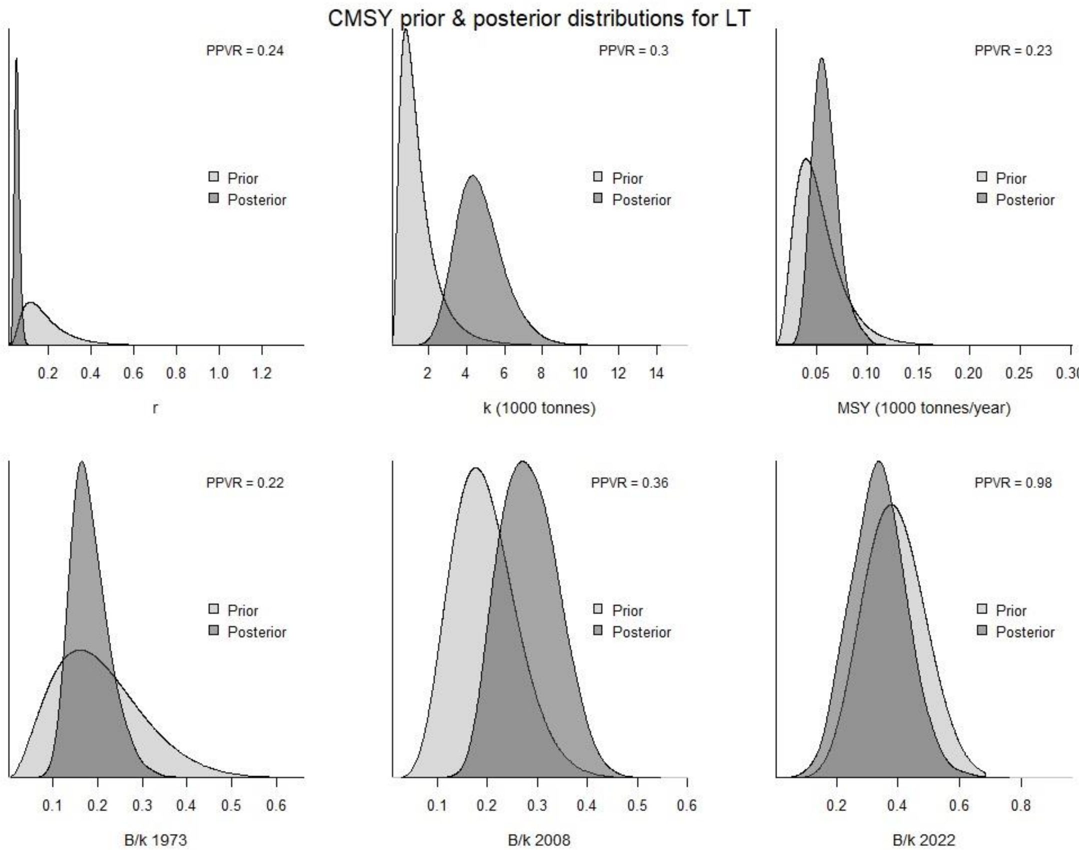
a)


A: LT
Catch (1000 tonnes/year)
B: Finding viable r-k
k (1000 tonnes)
r
C: Analysis of viable r-k
k (1000 tonnes)
r
D: Stock size
Relative biomass B/k
E: Exploitation rate
F/F_MSY
F: Equilibrium curve
Catch / MSY
Relative biomass B/k

b)


Catch LT
Catch (1000 tonnes/year)
MSY
Stock size
B/B_MSY
Exploitation
F/F_MSY
B/B_MSY
F/F_MSY
1973
2008
2022
50% C.I.
80% C.I.
95% C.I.

c)

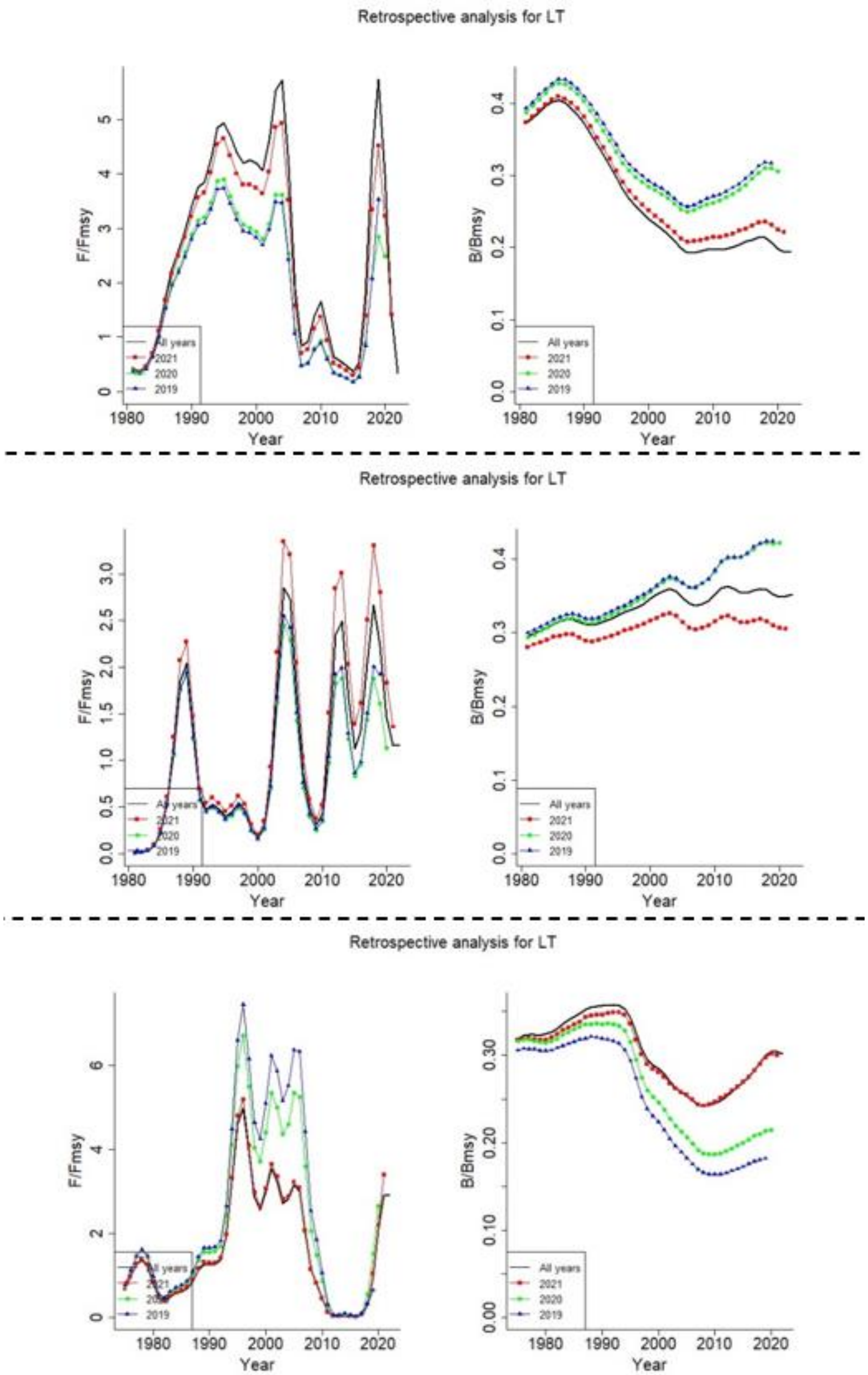


A. II. Figure 6: CMSY graphics produced for the assessment of Great Slave Lake Trout in management area IE, modeling scenario CMSY - II. The inputs used were a 1972-2022 catch time series, and an initial B/k of 0.01-0.4.

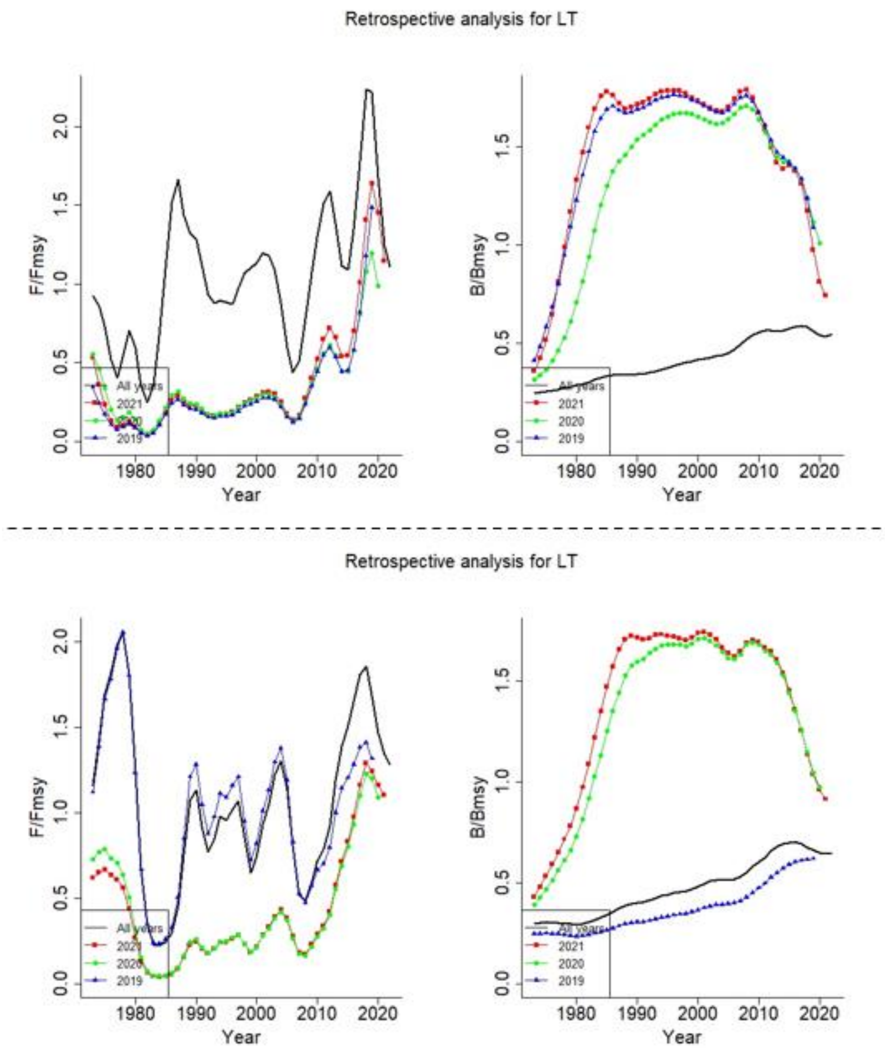
a) (A) shows the time series of catches (blue line indicating smoothed data), with the dashed purple line showing the prior estimate for MSY, and the red dots indicating catch high and lows. (B) is the explored log r-k space, with light grey portion showing non compatible pairs, with the dark grey the r-k pairs found by the model to be compatible. (C) shows only a portion of the r-k space; with blue cross showing most probable r-k pair from the CMSY estimate with associated with 95% credible intervals. The solid horizontal blue line in (D) reveals the median of the biomass trajectories estimated by CMSY with dotted blue horizontal lines indicating the 2.5th and 97.5th percentiles, the vertical lines represent the priors for biomass ranges, with dotted lines being values estimated by neural network; the dashed black line and the dotted black line represent values at B_{MSY} = 0.5k, biomass corresponding to MSY, and 0.5B_{MSY} (or .25k) equal to the biomass below which point may have reduced recruitment due to low stock sizes, respectively. (E) shows the median exploitation (F/F_{MSY}) as a blue curve, with the dotted curves indicating the 2.5th and 97.5th percentiles. (F) shows the Schaefer equilibrium curve of catch relative to MSY (y-axis) vs. biomass relative to k (x-axis); indent on right side of parabola represented values below .25k which assume linear decline of surplus production due to reduced recruitment at depleted stock sizes.

b) CMSY produced management plots for IE, modeling scenario CMSY – II showing the catch-time series with estimated MSY, the estimated biomass (B/B_{MSY}), and exploitation trajectories (F/F_{MSY}), and the predicted Kobe plot.

c) Comparison of prior and posterior densities (same area under curves) for resilience or productivity (r), unexploited stock size (k), maximum sustainable yield (MSY), and relative stock size (B/k) at the beginning, the end, and an intermediate year of the available time series of catch data. All 6-graphs representing area IE, scenario CMSY-ii (PPVR value indicates the posterior to prior ratio of variances).



A. II. Figure 6: CMSY produced retrospective analysis results for management areas II (top), III (middle), and IV (bottom). Time series of estimates of fishing pressure (F/F_{MSY}) and relative stock size (B/B_{MSY}) when the final 1-3 years of catch are omitted from analysis are compared to those when all years of catch data area used. A wide B/k input (0.01 – 0.4) condition at the beginning of the time series, representing an exploited stock size where the proportion of biomass at the beginning of the time series relative to the carrying capacity is between 1-40%, was used to produce these results.



A. II. Figure 7: CMSY++ produced retrospective analysis results for management areas IW (top) and IE (bottom) based on the BSM stock assessment model. Time series of estimates of fishing pressure (F/F_{MSY}) and relative stock size (B/B_{MSY}) when the final 1-3 years of catch are omitted from analysis are compared to those when all years of catch data area used. A wide B/k input (0.01 – 0.4) condition at the beginning of the time series, representing an exploited stock size where the proportion of biomass at the beginning of the time series relative to the carry capacity is between 1-40%, was used to produce these results.

Appendix III (Chapter 3)

An example of the CMSY++ R script output*. (Input code follows)*

Management Area IE – input condition ii, with retrospective analysis included.

Processing LT , Salvelinus namaycush
* CMSY retrospective analysis for LT has been enabled
* Retrospective analysis: step n. 1/4. Range of years: [1973 - 2022]
startbio= 0.01 0.4 expert , intbio= 2008 0.0671 0.321 default , endbio= 0.191 0.585 default
Running MCMC analysis with only catch data....

Species: Salvelinus namaycush , stock: LT , Lake Trout
Lake Trout
Region: Great Slave Lake , Area_IE
Catch data used from years 1973 - 2022 , abundance = None
Prior initial relative biomass = 0.01 - 0.4 expert
Prior intermediate rel. biomass= 0.0671 - 0.321 in year 2008 default
Prior final relative biomass   = 0.191 - 0.585 default
Prior range for r = 0.05 - 0.5 default , prior range for k = 0.329 - 4.44 , MSY prior = 0.0479

Results of CMSY analysis
----
r   = 0.0567 , 95% CL = 0.0343 - 0.0777 , k = 3.99 , 95% CL = 2.75 - 7.33
MSY = 0.0565 , 95% CL = 0.0391 - 0.0887
Relative biomass in last year = 0.336 k, 2.5th perc = 0.177 , 97.5th perc = 0.516
Exploitation F/(r/2) in last year = 1.13 , 2.5th perc = 0.563 , 97.5th perc = 3.33

Results for Management (based on CMSY analysis)

Mangement results based on CMSY because abundance data seem unrealistic
Fmsy = 0.0284 , 95% CL = 0.0171 - 0.0389 (if B > 1/2 Bmsy then Fmsy = 0.5 r)
Fmsy = 0.0284 , 95% CL = 0.0171 - 0.0389 (r and Fmsy are linearly reduced if B < 1/2 Bmsy)
MSY = 0.0565 , 95% CL = 0.0391 - 0.0887
Bmsy = 1.99 , 95% CL = 1.37 - 3.67
Biomass in last year = 1.5 , 2.5th perc = 0.728 , 97.5 perc = 2.85
B/Bmsy in last year = 0.673 , 2.5th perc = 0.354 , 97.5 perc = 1.03
Fishing mortality in last year = 0.0284 , 2.5th perc = 0.0142 , 97.5 perc = 0.0617
Exploitation F/Fmsy = 1.13 , 2.5th perc = 0.563 , 97.5 perc = 3.33

Stock status and exploitation in 2022
Biomass = 1.34 , B/Bmsy = 0.673 , F = 0.0298 , F/Fmsy = 1.05
Comment: Catch Time-Series: DFO FMHIS database
----
* Retrospective analysis: step n. 2/4. Range of years: [1973 - 2021]
startbio= 0.01 0.4 expert , intbio= 2008 0.714 0.973 default , endbio= 0.144 0.486 default
Running MCMC analysis with only catch data....

Species: Salvelinus namaycush , stock: LT , Lake Trout
Lake Trout
Region: Great Slave Lake , Area_IE
Catch data used from years 1973 - 2021 , abundance = None
Prior initial relative biomass = 0.01 - 0.4 expert
Prior intermediate rel. biomass= 0.714 - 0.973 in year 2008 default
Prior final relative biomass   = 0.144 - 0.486 default
Prior range for r = 0.05 - 0.5 default , prior range for k = 0.495 - 6.44 , MSY prior = 0.0709

Results of CMSY analysis
----
r   = 0.0865 , 95% CL = 0.0471 - 0.125 , k = 3.38 , 95% CL = 2.19 - 6.98
MSY = 0.0731 , 95% CL = 0.0481 - 0.118
Relative biomass in last year = 0.486 k, 2.5th perc = 0.307 , 97.5th perc = 0.635
Exploitation F/(r/2) in last year = 0.654 , 2.5th perc = 0.343 , 97.5th perc = 1.36

Results for Management (based on CMSY analysis)

Mangement results based on CMSY because abundance data seem unrealistic
Fmsy = 0.0433 , 95% CL = 0.0235 - 0.0624 (if B > 1/2 Bmsy then Fmsy = 0.5 r)
Fmsy = 0.0433 , 95% CL = 0.0235 - 0.0624 (r and Fmsy are linearly reduced if B < 1/2 Bmsy)
MSY = 0.0731 , 95% CL = 0.0481 - 0.118
Bmsy = 1.69 , 95% CL = 1.09 - 3.49
Biomass in last year = 1.97 , 2.5th perc = 0.946 , 97.5 perc = 3.74
B/Bmsy in last year = 0.972 , 2.5th perc = 0.614 , 97.5 perc = 1.27
Fishing mortality in last year = 0.0239 , 2.5th perc = 0.0119 , 97.5 perc = 0.0538
Exploitation F/Fmsy = 0.654 , 2.5th perc = 0.343 , 97.5 perc = 1.36

Stock status and exploitation in 2022
Biomass = , B/Bmsy = , F = , F/Fmsy =
Comment: Catch Time-Series: DFO FMHIS database
----
* Retrospective analysis: step n. 3/4. Range of years: [1973 - 2020]
startbio= 0.01 0.4 expert , intbio= 2008 0.714 0.973 default , endbio= 0.159 0.516 default
Running MCMC analysis with only catch data....

Species: Salvelinus namaycush , stock: LT , Lake Trout
Lake Trout
Region: Great Slave Lake , Area_IE
Catch data used from years 1973 - 2020 , abundance = None
Prior initial relative biomass = 0.01 - 0.4 expert
Prior intermediate rel. biomass= 0.714 - 0.973 in year 2008 default
Prior final relative biomass   = 0.159 - 0.516 default
Prior range for r = 0.05 - 0.5 default , prior range for k = 0.494 - 6.43 , MSY prior = 0.0709

Results of CMSY analysis

----
r   = 0.0922 , 95% CL = 0.0489 - 0.134 , k = 3.21 , 95% CL = 2.16 - 6.8
MSY = 0.0741 , 95% CL = 0.0484 - 0.121
Relative biomass in last year = 0.527 k, 2.5th perc = 0.324 , 97.5th perc = 0.678
Exploitation F/(r/2) in last year = 0.666 , 2.5th perc = 0.348 , 97.5th perc = 1.35

Results for Management (based on CMSY analysis)

Mangement results based on CMSY because abundance data seem unrealistic
Fmsy = 0.0461 , 95% CL = 0.0244 - 0.0671 (if B > 1/2 Bmsy then Fmsy = 0.5 r)
Fmsy = 0.0461 , 95% CL = 0.0244 - 0.0671 (r and Fmsy are linearly reduced if B < 1/2 Bmsy)
MSY = 0.0741 , 95% CL = 0.0484 - 0.121
Bmsy = 1.61 , 95% CL = 1.08 - 3.4
Biomass in last year = 2.06 , 2.5th perc = 1.02 , 97.5 perc = 3.75
B/Bmsy in last year = 1.05 , 2.5th perc = 0.648 , 97.5 perc = 1.36
Fishing mortality in last year = 0.0251 , 2.5th perc = 0.0128 , 97.5 perc = 0.0537
Exploitation F/Fmsy = 0.666 , 2.5th perc = 0.348 , 97.5 perc = 1.35

Stock status and exploitation in 2022
Biomass = , B/Bmsy = , F = , F/Fmsy =
Comment: Catch Time-Series: DFO FMHIS database
----
* Retrospective analysis: step n. 4/4. Range of years: [1973 - 2019]
startbio= 0.01 0.4 expert , intbio= 2008 0.0486 0.282 default , endbio= 0.187 0.575 default
Running MCMC analysis with only catch data....

Species: Salvelinus namaycush , stock: LT , Lake Trout
Lake Trout
Region: Great Slave Lake , Area_IE
Catch data used from years 1973 - 2019 , abundance = None
Prior initial relative biomass = 0.01 - 0.4 expert
Prior intermediate rel. biomass= 0.0486 - 0.282 in year 2008 default
Prior final relative biomass   = 0.187 - 0.575 default
Prior range for r = 0.05 - 0.5 default , prior range for k = 0.491 - 6.47 , MSY prior = 0.0709

Results of CMSY analysis
----
r   = 0.0521 , 95% CL = 0.0305 - 0.0713 , k = 6.1 , 95% CL = 4.37 - 11.6
MSY = 0.0794 , 95% CL = 0.0528 - 0.132
Relative biomass in last year = 0.282 k, 2.5th perc = 0.152 , 97.5th perc = 0.457
Exploitation F/(r/2) in last year = 1.39 , 2.5th perc = 0.636 , 97.5th perc = 4.51

Results for Management (based on CMSY analysis)

Mangement results based on CMSY because abundance data seem unrealistic
Fmsy = 0.026 , 95% CL = 0.0152 - 0.0356 (if B > 1/2 Bmsy then Fmsy = 0.5 r)
Fmsy = 0.026 , 95% CL = 0.0152 - 0.0356 (r and Fmsy are linearly reduced if B < 1/2 Bmsy)

MSY = 0.0794 , 95% CL = 0.0528 - 0.132
Bmsy = 3.05 , 95% CL = 2.18 - 5.79
Biomass in last year = 2.08 , 2.5th perc = 1.01 , 97.5 perc = 3.87
B/Bmsy in last year = 0.565 , 2.5th perc = 0.304 , 97.5 perc = 0.913
Fishing mortality in last year = 0.0306 , 2.5th perc = 0.0153 , 97.5 perc = 0.0664
Exploitation F/Fmsy = 1.39 , 2.5th perc = 0.636 , 97.5 perc = 4.51

Stock status and exploitation in 2022
Biomass = , B/Bmsy = , F = , F/Fmsy =
Comment: Catch Time-Series: DFO FMHIS database

***An example of the CMSY++R script used to produce reference points and outputs*.**

Original code taken from Froese et al. 2021, available in the supplementary information online at: https://oceanrep.geomar.de/id/eprint/52147/

```
# CMSY ++
# New Comments - HNC ; May 2023
# Great Slake Lake, Area IE - 1972-2022 - Srt Bio  - set .01 -.4
# Catch from DFO FMHIS database
#
#-------------------------------------------------------------------------------------------
## CMSY and BSM analysis ----
## Developed by Rainer Froese, Gianpaolo Coro and Henning Winker in 2016, version of January 2021
## PDF creation added by Gordon Tsui and Gianpaolo Coro
## Correction for effort creep added by RF
## Multivariate normal r-k priors added to CMSY by HW, RF and GP in October 2019
## Multivariate normal plus observation error on catch added to BSM by HW in November 2019
## Retrospective analysis added by GP in November 2019
## Bayesian implementation of CMSY added by RF and HW in May 2020
## Slight improvements to NA rules for prior B/k done by RF in June 2020
## RF added on-screen proposal to set start.year to medium catch if high or low biomass is unclear at low
catch
## Alling notation and posterior compuations between CMSY++ and BSM done by HW in June 2020
## RF fixed a bug where some CMSY instead of BSM results were wrongly reported for management,
October 2020
## RF updated cor.log.rk to -0.76 based and MSY.prior based om max.ct, based on a analysis of 240+
global stocks
## HW added use of MSY.prior to predict k.prior in JAGS
## RF and GP reviewed and improved B/k default priors, adding neural network
## HW added beta distribution for B/k priors
## GP added ellipse estimation (lower right focus) of most likely r-k pair for CMSY
##-------------------------------------------------------------------------------------------

# Automatic installation of missing packages
list.of.packages <-
c("R2jags","coda","parallel","foreach","doParallel","gplots","mvtnorm","snpar","neuralnet","conicfit")
new.packages <- list.of.packages[!(list.of.packages %in% installed.packages()[,"Package"])]
if(length(new.packages)) install.packages(new.packages)
```

```
library(R2jags)  # Interface with JAGS
library(coda)
library(gplots)
library(mvtnorm)
library(snpar)
library(neuralnet)
library(conicfit)

#-----------------------------------------
# Some general settings ----
#-----------------------------------------
# set.seed(999) # use for comparing results between runs
rm(list=ls(all=FALSE)) # clear previous variables etc
options(digits=3) # displays all numbers with three significant digits as default
graphics.off() # close graphics windows from previous sessions
FullSchaefer <- F    # initialize variable; automatically set to TRUE if enough abundance data are
available
n.chains     <- 2 # number of chains to be used in JAGS, default = 2
# setwd(dirname(rstudioapi::getActiveDocumentContext()$path)) # set working directory to source file
location
#HNC commented out setwd because individually set directory (eg to area I)
#-----------------------------------------
# Required settings, File names ----
#-----------------------------------------
catch_file  <- "IE_Catch_73-22_CMSY++.csv" #" file containing "Stock", "yr", "ct", and optional "bt"
id_file     <- "LT_ID_IE_73_22_CMSY++_srtbio01-4.csv" #
nn_file     <-  "ffnn.bin" # file containing neural networks trained to estimate B/k priors
outfile     <- paste("Out",format(Sys.Date(),format="%B%d%Y_"),id_file,sep="") # default name for
output file

#----------------------------------------
# Select stock to be analyzed ----
#----------------------------------------
stocks      <-NA #
# If the input files contain more than one stock, specify below the stock to be analyzed
# If the line below is commented out (#), all stocks in the input file will be analyzed
# stocks <-"Blacknose shark - Atlantic"  #"Alop_sup_Indian"  #"Acadian redfish - Gulf of Maine /
Georges Bank"# "Hogfish - Florida Keys / East Florida"  #"Splitnose rockfish - Pacific Coast"
#"Acadian_redfish"  # "ple.27.7d" #"cod.27.1-2coast"#"cod.27.7e-k" # "Acadian redfish - Gulf of Maine /
Georges Bank"  #c("Greenspotted rockfish - Pacific Coast")
# HNC -  only 1 stoc, comment out
#-----------------------------------------
# General settings for the analysis ----
#-----------------------------------------
CV.C         <- 0.15  #><>MSY: Add Catch CV
CV.cpue      <- 0.2 #><>MSY: Add minimum realistic cpue CV
sigmaR       <- 0.1 # overall process error for CMSY; SD=0.1 is the default
cor.log.rk   <- -0.76 # empirical value of log r-k correlation in 250 stocks analyzed with BSM (without r-k
correlation), used only in graph
rk.cor.beta  <- c(2.52,3.37) # beta.prior for rk cor+1
```

```
nbk        <- 3 # Number of B/k priors to be used by BSM, with options 1 (first year), 2 (first &
intermediate), 3 (first, intermediate & final bk priors)
bt4pr       <- F # if TRUE, available abundance data are used for B/k prior settings
auto.start   <- F # if TRUE, start year will be set to first year with intermediate catch to avoid ambiguity
between low and high bimass if catches are very low
ct_MSY.lim   <- 1.21  # ct/MSY.pr ratio above which B/k prior is assumed constant
q.biomass.pr <- c(0.9,1.1) # if btype=="biomass" this is the prior range for q
n           <- 10000 # number of points in multivariate cloud in graph panel (b)
ni          <- 3 # iterations for r-k-startbiomass combinations, to test different variability patterns; no
improvement seen above 3
nab         <- 5 # recommended=5; minimum number of years with abundance data to run BSM
bw          <- 3 # default bandwidth to be used by ksmooth() for catch data
mgraphs      <- T # set to TRUE to produce additional graphs for management
e.creep.line <- F # set to TRUE to display uncorrected CPUE in biomass graph
kobe.plot    <- T # set to TRUE to produce additional kobe status plot; management graph needs to be
TRUE for Kobe to work
BSMfits.plot <- F # set to TRUE to plot fit diagnostics for BSM
pp.plot      <- T # set to TRUE to plot Posterior and Prior distributions for CMSY and BSM
rk.diags     <- F #><>MSY set to TRUE to plot diagnostic plot for r-k space
retros       <- T # set to TRUE to enable retrospective analysis (1-3 years less in the time series)
save.plots   <- T # set to TRUE to save graphs to JPEG files
close.plots  <- T # set to TRUE to close on-screen plots after they are saved, to avoid "too many open
devices" error in batch-processing
write.output <- F # set to TRUE if table with results in output file is wanted; expects years 2004-2014 to
be available
write.pdf    <- F # set to TRUE if PDF output of results is wanted. See more instructions at end of code.
select.yr    <- 2022 # option to display F, B, F/Fmsy and B/Bmsy for a certain year; default NA
write.rdata  <- F #><>HW write R data file

#---------------------------------------------
#  FUNCTIONS ----
#---------------------------------------------
#-----------------------------------------------------------------------------------
# Function to create multivariate-normal distribution for r-k, used only in graphs
#-----------------------------------------------------------------------------------
mvn   <- function(n,mean.log.r,sd.log.r,mean.log.k,sd.log.k) {
  cov.log.rk <- cor.log.rk*sd.log.r*sd.log.k # covariance with empirical correlation and prior variances
covar.log.rk = matrix(NA, ncol=2,nrow=2)   # contract covariance matrix
  covar.log.rk      <- matrix(NA, ncol=2,nrow=2) # covariance matrix
  covar.log.rk[1,1] <- sd.log.r^2               # position [1,1] is variance of log.r
  covar.log.rk[2,2] <- sd.log.k^2               # position [2,2] is variance of log.k
  covar.log.rk[1,2] = covar.log.rk[2,1] = cov.log.rk     # positions [1,2] and [2,1] are correlations
  mu.log.rk  <- (c(mean.log.r,mean.log.k))      # vector of log.means
  mvn.log.rk <- rmvnorm(n,mean=mu.log.rk,sigma=covar.log.rk,method="svd")
  return(mvn.log.rk)
}

#------------------------------------------------------------
# Function to run Bayesian Schaefer Model (BSM)
#------------------------------------------------------------
bsm   <- function(ct,btj,nyr,prior.r,prior.k,startbio,q.priorj,
```

```
              init.q,init.r,init.k,pen.bk,pen.F,b.yrs,b.prior,CV.C,CV.cpue,nbk,rk.cor.beta,cmsyjags) {
  #><> convert b.prior ranges into beta priors
  bk.beta = beta.prior(b.prior)

  if(cmsyjags==TRUE ){ nbks=3 } else {nbks = nbk} # Switch between CMSY + BSM

  # Data to be passed on to JAGS
  jags.data        <- c('ct','btj','nyr', 'prior.r', 'prior.k', 'startbio', 'q.priorj',
                   'init.q','init.r','init.k','pen.bk','pen.F','b.yrs','bk.beta','CV.C','CV.cpue','nbks','rk.cor')
  # Parameters to be returned by JAGS #><> HW add key quantaties
  jags.save.params <- c('r','k','q', 'P','ct.jags','cpuem','proc.logB','B','F','BBmsy','FFmsy','ppd.logrk')

  # JAGS model ----
  Model = "model{
   # to reduce chance of non-convergence, Pmean[t] values are forced >= eps
   eps<-0.01
   #><> Add Catch.CV
   for(t in 1:nyr){
     ct.jags[t] ~ dlnorm(log(ct[t]),pow(CV.C,-2))
   }

   penm[1]  <- 0 # no penalty for first biomass
   Pmean[1] <- log(alpha)
   P[1]     ~ dlnorm(Pmean[1],itau2)

   for (t in 2:nyr) {
     Pmean[t] <- ifelse(P[t-1] > 0.25,
       log(max(P[t-1] + r*P[t-1]*(1-P[t-1]) - ct.jags[t-1]/k,eps)),  # Process equation
       log(max(P[t-1] + 4*P[t-1]*r*P[t-1]*(1-P[t-1]) - ct.jags[t-1]/k,eps))) # linear decline of r at B/k < 0.25
     P[t]     ~ dlnorm(Pmean[t],itau2) # Introduce process error
     penm[t]  <- ifelse(P[t]<(eps+0.001),log(q*k*P[t])-log(q*k*(eps+0.001)),
               # ifelse(P[t]>1,ifelse((ct[t]/max(ct))>0.2,log(q*k*P[t])-log(q*k*(0.99)),0),0)) # penalty if
Pmean is outside viable biomass
                ifelse(P[t]>1.1,log(q*k*P[t])-log(q*k*(0.99)),0))
   }

   # Get Process error deviation
   for(t in 1:nyr){
     proc.logB[t] <- log(P[t]*k)-log(exp(Pmean[t])*k)}

   # ><> b.priors with penalties
   # Biomass priors/penalties are enforced as follows
   for(i in 1:nbks){
   bk.mu[i] ~ dbeta(bk.beta[1,i],bk.beta[2,i])
   bk.beta[3,i] ~ dnorm(bk.mu[i]-P[b.yrs[i]],10000)
   }

   for (t in 1:nyr){
     Fpen[t]   <- ifelse(ct[t]>(0.9*k*P[t]),ct[t]-(0.9*k*P[t]),0) # Penalty term on F > 1, i.e. ct>B
     pen.F[t]  ~ dnorm(Fpen[t],1000)
     pen.bk[t] ~ dnorm(penm[t],10000)
```

```
   cpuem[t]  <- log(q*P[t]*k);
   btj[t]     ~ dlnorm(cpuem[t],pow(sigma2,-1));
  }

# priors
log.alpha              <- log((startbio[1]+startbio[2])/2) # needed for fit of first biomass
sd.log.alpha            <- (log.alpha-log(startbio[1]))/4
tau.log.alpha           <- pow(sd.log.alpha,-2)
alpha                  ~  dlnorm(log.alpha,tau.log.alpha)

# set realistic prior for q
log.qm             <- mean(log(q.priorj))
sd.log.q           <- (log.qm-log(q.priorj[1]))/2
tau.log.q          <- pow(sd.log.q,-2)
q                  ~  dlnorm(log.qm,tau.log.q)

# define process (tau) and observation (sigma) variances as inversegamma priors
itau2 ~ dgamma(4,0.01)
tau2  <- 1/itau2
tau   <- pow(tau2,0.5)

isigma2 ~ dgamma(2,0.01)
sigma2 <- 1/isigma2+pow(CV.cpue,2) # Add minimum realistic CPUE CV
sigma  <- pow(sigma2,0.5)

log.rm             <- mean(log(prior.r))
sd.log.r           <- abs(log.rm - log(prior.r[1]))/2
tau.log.r          <- pow(sd.log.r,-2)

# bias-correct lognormal for k
log.km             <- mean(log(prior.k))
sd.log.k           <- abs(log.km-log(prior.k[1]))/2
tau.log.k          <- pow(sd.log.k,-2)

# Construct Multivariate lognormal (MVLN) prior
mu.rk[1] <- log.rm
mu.rk[2] <- log.km

# Prior for correlation log(r) vs log(k)
#><>MSY: now directly taken from mvn of ki = 4*msyi/ri
rho <- rk.cor

# Construct Covariance matrix
cov.rk[1,1] <- sd.log.r * sd.log.r
cov.rk[1,2] <- rho
cov.rk[2,1] <- rho
cov.rk[2,2] <- sd.log.k * sd.log.k

# MVLN prior for r-k
log.rk[1:2] ~ dmnorm(mu.rk[],inverse(cov.rk[,]))
r <- exp(log.rk[1])
```

```
  k <- exp(log.rk[2])

  #><>MSY get posterior predictive distribution for rk
  ppd.logrk[1:2] ~ dmnorm(mu.rk[],inverse(cov.rk[,]))

  # ><>HW: Get B/Bmsy and F/Fmsy directly from JAGS
  Bmsy <- k/2
  Fmsy <- r/2
  for (t in 1:nyr){
  B[t] <- P[t]*k # biomass
  F[t] <- ct.jags[t]/B[t]
  BBmsy[t] <- P[t]*2 #true for Schaefer
  FFmsy[t] <- ifelse(BBmsy[t]<0.5,F[t]/(Fmsy*2*BBmsy[t]),F[t]/Fmsy)
  }
} "    # end of JAGS model

  # Write JAGS model to file ----
  cat(Model, file="r2jags.bug")

  #><>MSY: change to lognormal inits (better)
  j.inits <- function(){list("log.rk"=c(rnorm(1,mean=log(init.r),sd=0.2),rnorm(1,mean=log(init.k),sd=0.1)),
                         "q"=rlnorm(1,mean=log(init.q),sd=0.2),"itau2"=1000,"isigma2"=1000)}
  # run model ----
  jags_outputs <- jags.parallel(data=jags.data,
                             working.directory=NULL, inits=j.inits,
                             parameters.to.save=jags.save.params,
                             model.file="r2jags.bug", n.chains = n.chains,
                             n.burnin = 30000, n.thin = 10,
                             n.iter = 60000)
  return(jags_outputs)
}

#><> beta.prior function
get_beta <- function(mu,CV,Min=0,Prior="x",Plot=FALSE){
  a = seq(0.0001,1000,0.001)
  b= (a-mu*a)/mu
  s2 = a*b/((a+b)^2*(a+b+1))
  sdev = sqrt(s2)
  # find beta parameter a
  CV.check = (sdev/mu-CV)^2
  a = a[CV.check==min(CV.check)]
  # find beta parameter b
  b = (a-mu*a)/mu
  x = seq(Min,1,0.001)
  pdf = dbeta(x,a,b)
  if(Plot==TRUE){
    plot(x,pdf,type="l",xlim=range(x[pdf>0.01]),xlab=paste(Prior),ylab="",yaxt="n")
    polygon(c(x,rev(x)),c(rep(0,length(x)),rev(ifelse(pdf==Inf,100000,pdf))),col="grey")
  }
  return(c(a,b))
}
```

```
#><> convert b.prior ranges into beta priors
beta.prior = function(b.prior){
  bk.beta = matrix(0,nrow = 3,ncol=3)
  for(i in 1:3){
    sd.bk = (b.prior[2,i]-b.prior[1,i])/(4*0.98)
    mu.bk = mean(b.prior[1:2,i])
    cv.bk = sd.bk/mu.bk
    bk.beta[1:2,i] = get_beta(mu.bk,cv.bk)
  }
  return(bk.beta)
}

#Fits an ellipse around the CMSY r-k cloud and estimates the rightmost focus
traceEllipse<-function(rs,ks,prior.r,prior.k){
  log.rs<-log(rs)
  log.ks<-log(ks)

#  #select data within the bounding box
#  log.rs<-log.rs[which(rs>prior.r[1] & rs<prior.r[2] &
#                        ks>prior.k[1] & ks<prior.k[2]
#  )]
#  log.ks<-log.ks[which(rs>prior.r[1] & rs<prior.r[2] &
#                        ks>prior.k[1] & ks<prior.k[2]
#  )]

  #prepare data for ellipse fitting
  cloud.data <- as.matrix(data.frame(x = log.rs, y = log.ks))
  ellip <- EllipseDirectFit(cloud.data)
  #estimate ellipse characteristics
  atog<-AtoG(ellip)
  ellipG <- atog$ParG
  ell.center.x<-ellipG[1]
  ell.center.y<-ellipG[2]
  ell.axis.a<-ellipG[3]
  ell.axis.b<-ellipG[4]
  ell.tilt.angle.deg<-180/pi*ellipG[5]
  ell.slope<-tan(ellipG[5])
  xy.ell<-calculateEllipse(ell.center.x,
                        ell.center.y,
                        ell.axis.a,
                        ell.axis.b,
                        ell.tilt.angle.deg)
  #draw ellipse
  #points(x=xy.ell[,1],y=xy.ell[,2],col='red',type='l')
  ell.intercept.1 = ell.center.y-ell.center.x*ell.slope
  #draw ellipse main axis
  #abline(a =ell.intercept.1, b=ell.slope,col='red')
  #calculate focus from demi-axes
  ell.demiaxis.c.sqr<-(0.25*ell.axis.a*ell.axis.a)-(0.25*ell.axis.b*ell.axis.b)
  if (ell.demiaxis.c.sqr<0)
```

```
    ell.demiaxis.c.sqr<-ell.axis.a/2
  else
    ell.demiaxis.c<-sqrt(ell.demiaxis.c.sqr)
  sin.c<-ell.demiaxis.c*sin(ellipG[5])
  cos.c<-ell.demiaxis.c*cos(ellipG[5])
  ell.foc.y<-ell.center.y-sin.c
  ell.foc.x<-ell.center.x-cos.c
  #draw focus
  #points(x=ell.foc.x,y=ell.foc.y,
  #       pch = 16, cex = 1.2,
  #      col='green',bty='l')

  return (c(exp(ell.foc.x),exp(ell.foc.y)))
}
#---------------------------------------------
# END OF FUNCTIONS
#---------------------------------------------

#------------------------------------------
# Start output to screen
#------------------------------------------
cat("-------------------------------------------\n")
cat("CMSY++ Analysis,", date(),"\n")
cat("-------------------------------------------\n")

#------------------------------------------
# Read data and assign to vectors
#------------------------------------------
# create headers for data table file
if(write.output==T){
  outheaders = data.frame("Group","Region", "Subregion","Name","SciName","Stock",
                          "start.yr","end.yr","start.yr.new","btype",
                          "N
bt","start.yr.cpue","end.yr.cpue","min.cpue","max.cpue","min.yr.cpue","max.yr.cpue",
                          "endbio.low","endbio.hi","q.prior.low","q.prior.hi",
                          "MaxCatch","MSY_prior","MeanLast5RawCatch","SDLast5RawCatch","LastCatch",
                          "MinSmoothCatch","MaxSmoothCatch","MeanSmoothCatch","gMeanPrior_r",

"MSY_BSM","lcl.MSY_BSM","ucl.MSY_BSM","r_BSM","lcl.r_BSM","ucl.r_BSM","log.r_var",

"k_BSM","lcl.k_BSM","ucl.k_BSM","log.k_var","log.kr_cor","log.kr_cov","q_BSM","lcl.q_BSM","ucl.
q_BSM",

"rel_B_BSM","lcl.rel_B_BSM","ucl.rel_B_BSM","rel_start_B_BSM","lcl.rel_start_B_BSM","ucl.rel_sta
rt_B_BSM",
                          "rel_int_B_BSM","lcl.rel_int_B_BSM","ucl.rel_int_B_BSM","int.yr","rel_F_BSM",

"r_CMSY","lcl.r_CMSY","ucl.r_CMSY","k_CMSY","lcl.k_CMSY","ucl.k_CMSY","MSY_CMSY","lcl
.MSY_CMSY","ucl.MSY_CMSY",
```

```
"rel_B_CMSY","2.5th.rel_B_CMSY","97.5th.rel_B_CMSY","rel_start_B_CMSY","2.5th.rel_start_B_C
MSY","97.5th.rel_start_B_CMSY",
            "rel_int_B_CMSY","2.5th.rel_int_B_CMSY","97.5th.rel_int_B_CMSY",
            "rel_F_CMSY","2.5th.rel_F_CMSY","97.5th.rel_F_CMSY",
            "F_msy","lcl.F_msy","ucl.F_msy","curF_msy","lcl.curF_msy","ucl.curF_msy",
            "MSY","lcl.MSY","ucl.MSY","Bmsy","lcl.Bmsy","ucl.Bmsy",
            "last.B","lcl.last.B","ucl.last.B","last.B_Bmsy","lcl.last.B_Bmsy","ucl.last.B_Bmsy",
            "last.F","lcl.last.F","ucl.last.F","last.F_Fmsy","lcl.last.F_Fmsy","ucl.last.F_Fmsy",
            "sel_B","sel_B_Bmsy","sel_F","sel_F_Fmsy",
            # create columns for catch, F/Fmsy and Biomass for 1950 to 2020
            "c50","c51","c52","c53","c54","c55","c56","c57","c58","c59",
            "c60","c61","c62","c63","c64","c65","c66","c67","c68","c69",
            "c70","c71","c72","c73","c74","c75","c76","c77","c78","c79",
            "c80","c81","c82","c83","c84","c85","c86","c87","c88","c89",
            "c90","c91","c92","c93","c94","c95","c96","c97","c98","c99",
            "c00","c01","c02","c03","c04","c05","c06","c07","c08","c09",
            "c10","c11","c12","c13","c14","c15","c16","c17","c18","c19",
            "c20","c21","c22","c23","c24","c25","c26","c27","c28","c29","c30",

"F.Fmsy50","F.Fmsy51","F.Fmsy52","F.Fmsy53","F.Fmsy54","F.Fmsy55","F.Fmsy56","F.Fmsy57","F.F
msy58","F.Fmsy59",

"F.Fmsy60","F.Fmsy61","F.Fmsy62","F.Fmsy63","F.Fmsy64","F.Fmsy65","F.Fmsy66","F.Fmsy67","F.F
msy68","F.Fmsy69",

"F.Fmsy70","F.Fmsy71","F.Fmsy72","F.Fmsy73","F.Fmsy74","F.Fmsy75","F.Fmsy76","F.Fmsy77","F.F
msy78","F.Fmsy79",

"F.Fmsy80","F.Fmsy81","F.Fmsy82","F.Fmsy83","F.Fmsy84","F.Fmsy85","F.Fmsy86","F.Fmsy87","F.F
msy88","F.Fmsy89",

"F.Fmsy90","F.Fmsy91","F.Fmsy92","F.Fmsy93","F.Fmsy94","F.Fmsy95","F.Fmsy96","F.Fmsy97","F.F
msy98","F.Fmsy99",

"F.Fmsy00","F.Fmsy01","F.Fmsy02","F.Fmsy03","F.Fmsy04","F.Fmsy05","F.Fmsy06","F.Fmsy07","F.F
msy08","F.Fmsy09",

"F.Fmsy10","F.Fmsy11","F.Fmsy12","F.Fmsy13","F.Fmsy14","F.Fmsy15","F.Fmsy16","F.Fmsy17","F.F
msy18","F.Fmsy19",

"F.Fmsy20","F.Fmsy21","F.Fmsy22","F.Fmsy23","F.Fmsy24","F.Fmsy25","F.Fmsy26","F.Fmsy27","F.F
msy28","F.Fmsy29","F.Fmsy30",
            "B50","B51","B52","B53","B54","B55","B56","B57","B58","B59",
            "B60","B61","B62","B63","B64","B65","B66","B67","B68","B69",
            "B70","B71","B72","B73","B74","B75","B76","B77","B78","B79",
            "B80","B81","B82","B83","B84","B85","B86","B87","B88","B89",
            "B90","B91","B92","B93","B94","B95","B96","B97","B98","B99",
            "B00","B01","B02","B03","B04","B05","B06","B07","B08","B09",
            "B10","B11","B12","B13","B14","B15","B16","B17","B18","B19",
            "B20","B21","B22","B23","B24","B25","B26","B27","B28","B29","B30")
```

```
  write.table(outheaders,file=outfile, append = T, sep=",",row.names=F,col.names=F)
}

# Read data
cdat         <- read.csv(catch_file, header=T, dec=".", stringsAsFactors = FALSE)
cinfo        <- read.csv(id_file, header=T, dec=".", stringsAsFactors = FALSE)
load(file = nn_file) # load neural network file
cat("Files", catch_file, ",", id_file,",",nn_file,"read successfully","\n")

#---------------------------------
# Analyze stock(s)
#---------------------------------
if(is.na(stocks[1])==TRUE){
  # stocks         <- as.character(cinfo$Stock) # Analyze stocks in sequence of ID file
  # stocks         <- sort(as.character(cinfo$Stock[cinfo$Stock>="Cras_vir_Virginian"])) # Analyze in
alphabetic order after a certain stock
   stocks        <- sort(as.character(cinfo$Stock)) # Analyze stocks in alphabetic order
  # stocks         <- as.character(cinfo$Stock[cinfo$btype!="None" & cinfo$Stock>"Squa_aca_BlackSea"])
# Analyze stocks by criteria in ID file
}

# analyze one stock after the other...
for(stock in stocks) {

  cat("Processing",stock,",", as.character(cinfo$ScientificName[cinfo$Stock==stock]),"\n")

  #retrospective analysis
  retros.nyears<-ifelse(retros==T,3,0) #retrospective analysis
  FFmsy.retrospective<-list() #retrospective analysis
  BBmsy.retrospective<-list() #retrospective analysis
  years.retrospective<-list() #retrospective analysis

  retrosp.step =0
  for (retrosp.step in 0:retros.nyears){ #retrospective analysis loop

  # Declare conditional Objects that feature with ifelse clauses
    B.sel        <- NULL
    B.Bmsy.sel   <- NULL
    F.sel        <- NULL
    F.Fmsy.sel   <- NULL
    true.MSY     <- NULL
    true.r       <- NULL
    true.k       <- NULL
    true.Bk      <- NULL
    true.F_Fmsy  <- NULL
    true.q       <- NULL

  # assign data from cinfo to vectors
    btype        <- as.character(cinfo$btype[cinfo$Stock==stock])
    res          <- as.character(cinfo$Resilience[cinfo$Stock==stock])
    start.yr     <- as.numeric(cinfo$StartYear[cinfo$Stock==stock])
```

```
    end.yr       <- as.numeric(cinfo$EndYear[cinfo$Stock==stock])
    end.yr.orig  <- end.yr
    end.yr                  <- end.yr-retrosp.step #retrospective analysis
    yr           <- as.numeric(cdat$yr[cdat$Stock==stock & cdat$yr >= start.yr & cdat$yr <= end.yr])
    if(length(yr)==0){
      cat("ERROR: Could not find the stock in the Catch file -
      check that the stock names match in ID and Catch files and that commas are used (not semi-colon)")
      return (NA) }

    # code to change start year to avoid ambiguity in biomass prior ----------------------------------------
    ct.raw       <- as.numeric(cdat$ct[cdat$Stock==stock & cdat$yr >= start.yr & cdat$yr <= end.yr])/1000
## assumes that catch is given in tonnes, transforms to '000 tonnes
    ct           <- ksmooth(x=yr,y=ct.raw,kernel="normal",n.points=length(yr),bandwidth=bw)$y
    ct.3         <- mean(ct[1:3])
    max.ct       <- max(ct)

    if(btype=="biomass" | btype=="CPUE" ) {
      bt.raw1 <- as.numeric(cdat$bt[cdat$Stock==stock & cdat$yr >= start.yr & cdat$yr <= end.yr])
      # if bt.raw is zero, change to NA
      bt.raw1[bt.raw1==0] <- NA
      if(btype=="biomass") { # make sure both catch and biomass are divided by 1000
        bt <- bt.raw1/1000 } else { # get number of integer digits for bt.raw (because sometimes they give
numbers of eggs!)
          bt.digits <- floor(log10(mean(bt.raw1,na.rm=T)))+1
          if(bt.digits>3) {bt.raw <- bt.raw1/10^(bt.digits-1)} else {bt.raw <- bt.raw1}
          bt     <- bt.raw #ksmooth(x=yr,y=bt.raw,kernel="normal",n.points=length(yr),bandwidth=3)$y
        } # end of bt==CPUE loop
      if(length(bt[is.na(bt)==F])==0) {
        cat("ERROR: No CPUE or biomass data in the Catch input file")
        return (NA) }
    } else {bt <- NA; bt.raw <- NA} # if there is no biomass or CPUE, set bt to NA


    # code to change start year to avoid ambiguity in biomass prior ----------------------------------------
    start.yr.new <- NA # initialize / reset start.yr.new with NA
    if(is.na(cinfo$stb.low[cinfo$Stock==stock]) & ct.3 < (0.33*max.ct) & start.yr < 2000 &
(btype=="None" || yr[is.na(bt)==F][1]>yr[3])) { # it is unlikely that a fishery started on an unexploited
stock after 2000
      start.yr.new <- yr[which(ct >= (0.4*max.ct))][1]
      cat("\n
*************************************************************************************
****
          Attention: Low catch in",start.yr,"may indicate either depleted or unexploited biomass.
          Set startbio in ID file to 0.01-0.2 or 0.8-1.0 to indicate depleted or unexploited biomass.\n")
      if(auto.start==T) { # change start year automatically if auto.start is TRUE
        start.yr  <- start.yr.new
        cat("         Meanwhile start year was set to",start.yr,"to avoid ambiguity.\n")
      } else {
        cat("         Else, set start year in ID file to",start.yr.new,"to avoid uncertainty\n")
      }
```

```
    cat("
*************************************************************************************
*****\n\n") }
  # end of code for start biomass prior ambiguity

  ename        <- cinfo$Name[cinfo$Stock==stock]
  r.low        <- as.numeric(cinfo$r.low[cinfo$Stock==stock])
  r.hi         <- as.numeric(cinfo$r.hi[cinfo$Stock==stock])
  stb.low      <- as.numeric(cinfo$stb.low[cinfo$Stock==stock])
  stb.hi       <- as.numeric(cinfo$stb.hi[cinfo$Stock==stock])
  int.yr       <- as.numeric(cinfo$int.yr[cinfo$Stock==stock])
  intb.low     <- as.numeric(cinfo$intb.low[cinfo$Stock==stock])
  intb.hi      <- as.numeric(cinfo$intb.hi[cinfo$Stock==stock])
  endb.low     <- as.numeric(cinfo$endb.low[cinfo$Stock==stock])
  endb.hi      <- as.numeric(cinfo$endb.hi[cinfo$Stock==stock])
  e.creep      <- as.numeric(cinfo$e.creep[cinfo$Stock==stock])
  force.cmsy   <- cinfo$force.cmsy[cinfo$Stock==stock]
  comment      <- as.character(cinfo$Comment[cinfo$Stock==stock])
  source       <- as.character(cinfo$Source[cinfo$Stock==stock])
  # set global defaults for uncertainty
  sigR         <- sigmaR
  # for simulated data only
  if(substr(id_file,1,3)=="Sim") {
    true.MSY     <- cinfo$true.MSY[cinfo$Stock==stock]/1000
    true.r       <- cinfo$true.r[cinfo$Stock==stock]
    true.k       <- cinfo$true.k[cinfo$Stock==stock]/1000
    true.Bk      <- (cinfo$last.TB[cinfo$Stock==stock]/1000)/true.k
    true.F_Fmsy  <- cinfo$last.F_Fmsy[cinfo$Stock==stock]
    true.q       <- cinfo$last.cpue[cinfo$Stock==stock]/cinfo$last.TB[cinfo$Stock==stock]
  }
  # do retrospective analysis
  if (retros==T && retrosp.step==0){
    cat("* ",ifelse(btype!="None","BSM","CMSY")," retrospective analysis for ",
        stock," has been enabled\n",sep="") #retrospective analysis
  }
  if (retros==T){
    cat("* Retrospective analysis: step n. ",(retrosp.step+1),"/",(retros.nyears+1),
        ". Range of years: [",start.yr ," - ",end.yr,"]\n",sep="") #retrospective analysis
  }

  # ------------------------------------------------------------
  # check for common errors
  #-------------------------------------------------------------
  if(length(btype)==0){
    cat("ERROR: Could not find the stock in the ID input file - check that the stock names match in ID
and Catch files and that commas are used (not semi-colon)")
    return (NA) }
  if(start.yr < cdat$yr[cdat$Stock==stock][1]){
    cat("ERROR: start year in ID file before first year in catch file\n")
    return (NA)
    break}
```

```
    if(length(yr)==0){
      cat("ERROR: Could not find the stock in the Catch input files - Please check that the code is written
correctly")
      return (NA) }
    if(btype %in% c("None","CPUE","biomass")==FALSE){
      cat("ERROR: In ID file, btype must be None, CPUE, or biomass.")
      return (NA) }
    if(retros==F & length(yr) != (end.yr-start.yr+1)) {
      cat("ERROR: indicated year range is of different length than years in catch file\n")
      return (NA)}
    if(length(ct.raw[ct.raw>0])==0) {
      cat("ERROR: No catch data in the Catch input file")
      #return (NA)
      next }
    if(is.na(int.yr)==F & (int.yr < start.yr | int.yr > end.yr)) {
      cat("ERROR: year for intermediate B/k prior outside range of years")
      return (NA)}
    if(is.na(int.yr)==T & (is.na(intb.low)==F | is.na(intb.hi)==F)) {
        cat("ERROR: intermediate B/k prior given without year")
        return (NA)}

    # apply correction for effort-creep to commercial(!) CPUE
    if(btype=="CPUE" && is.na(e.creep)==FALSE) {
      cpue.first  <- min(which(is.na(bt)==F))
      cpue.last   <- max(which(is.na(bt)==F))
      cpue.length <- cpue.last - cpue.first
      bt.cor      <- bt
      for(i in 1:(cpue.length)) {
        bt.cor[cpue.first+i]  <- bt[cpue.first+i]*(1-e.creep/100)^i # equation for decay in %
      }
      bt <- bt.cor
    }

    if(retros==T && force.cmsy == F && (btype !="None" & length(bt[is.na(bt)==F])<nab) ) { #stop
retrospective analysis if cpue is < nab
      cat("Warning: Cannot run retrospective analysis for ",end.yr,", number of remaining ",btype," values
is too low (<",nab,")\n",sep="")
      #retrosp.step<-retros.nyears
      break }

    if(is.na(mean(ct.raw))){
      cat("ERROR: Missing value in Catch data; fill or interpolate\n")
    }
    nyr          <- length(yr) # number of years in the time series


    # initialize vectors for viable r, k, bt, and all in a matrix
    mdat.all    <- matrix(data=vector(),ncol=2+nyr+1)

    # initialize other vectors anew for each stock
    current.attempts <- NA
```

```
  # use start.yr if larger than select year
  if(is.na(select.yr)==F) {
    sel.yr <- ifelse(start.yr > select.yr,start.yr,select.yr)
  } else sel.yr <- NA

  #----------------------------------------------------
  # Determine initial ranges for parameters and biomass
  #----------------------------------------------------
  if(!(res %in% c("High","Medium","Low","Very low"))) {
    cat("ERROR: Resilience not High, Medium, Low, or Very low in ID input file")
    return (NA)} else {
  # initial range of r from input file
  if(is.na(r.low)==F & is.na(r.hi)==F) {
    prior.r <- c(r.low,r.hi)
  } else
    # initial range of r based on resilience
    if(res == "High") {
      prior.r <- c(0.6,1.5)} else if(res == "Medium") {
        prior.r <- c(0.2,0.8)}    else if(res == "Low") {
          prior.r <- c(0.05,0.5)}  else { # i.e. res== "Very low"
            prior.r <- c(0.015,0.1)}
  }
  gm.prior.r      <- exp(mean(log(prior.r))) # get geometric mean of prior r range

  #----------------------------------------
  # determine MSY prior
  #----------------------------------------
  # get index of years with lowest and highest catch
  min.yr.i     <- which.min(ct)
  max.yr.i     <- which.max(ct)
  yr.min.ct    <- yr[min.yr.i]
  yr.max.ct    <- yr[max.yr.i]
  min.ct       <- ct[min.yr.i]
  max.ct       <- ct[max.yr.i]
  min_max      <- min.ct/max.ct
  mean.ct      <- mean(ct)
  sd.ct        <- sd(ct)

  ct.sort     <- sort(ct.raw)
  # if max catch is reached in last 5 years or catch is flat, assume MSY=max catch
  if(max.yr.i>(nyr-4) || ((sd.ct/mean.ct) < 0.1 && min_max > 0.66)) {
      MSY.pr <- mean(ct.sort[(nyr-2):nyr]) } else {
        MSY.pr <- 0.75*mean(ct.sort[(nyr-4):nyr]) } # else, use fraction of mean of 5 highest catches as
MSY prior

  #><>MSY: MSY prior
  sd.log.msy.pr <- 0.3 # rounded upward to account for reduced variability in selected stocks
  log.msy.pr    <- log(MSY.pr)
  prior.msy     <- c(exp(log.msy.pr-1.96*sd.log.msy.pr),exp(log.msy.pr+1.96*sd.log.msy.pr))
  init.msy      <- MSY.pr
```

```
#---------------------------------------------------------------
# Multivariate normal sampling of r-k log space
#---------------------------------------------------------------
# turn numerical ranges into log-normal distributions
mean.log.r=mean(log(prior.r))
sd.log.r=(log(prior.r[2])-log(prior.r[1]))/(2*1.96)  # assume range covers 4 SD

#><>MSY: new k = r-msy space
# generate msy and r independently
ri1     <- rlnorm(n,mean.log.r,sd.log.r)
msyi1  <- rlnorm(n,log.msy.pr,sd.log.msy.pr)
ki1     <- msyi1*4/ri1
#><>MSY: get log median and covariance
cov_rk <- cov(cbind(log(ri1),log(ki1)))
mu_rk <-  apply(cbind(log(ri1),log(ki1)),2,median)
rk.cor <- cov_rk[2,1] #MSY: correlation rho input to JAGS
#><>MSY: mvn prior for k = 4*msy/r
mvn.log.rk <- rmvnorm(n,mean=mu_rk,cov_rk)

ri2    <- exp(mvn.log.rk[,1])
ki2    <- exp(mvn.log.rk[,2])

mean.log.k <- median(log(ki1))
sd.log.k.pr <- sd(log(ki1))
# quick check must be the same
sd.log.k = sqrt(cov_rk[2,2])
sd.log.k.pr
sd.log.k
#><>MSY: k.prior
prior.k     <- exp(mean.log.k-1.96*sd.log.k.pr) # declare variable and set prior.k[1] in one step
prior.k[2]  <- exp(mean.log.k+1.96*sd.log.k.pr)
msy.init <- exp(mean.log.k)

#-----------------------------------------
# determine prior B/k ranges
#-------------------------------------------------
# determine intermediate year int.yr for prior B/k
if(is.na(cinfo$int.yr[cinfo$Stock==stock])==F) {
  int.yr <- cinfo$int.yr[cinfo$Stock==stock]     # use int.yr give by user
} else {if(min_max > 0.7) { # if catch is about flat, use middle year as int.yr
  int.yr    <- as.integer(mean(c(start.yr, end.yr)))
  } else { # only consider catch 5 years away from end points and within last 30 years # 50
  yrs.int       <- yr[yr>(yr[nyr]-30) & yr>yr[4] & yr<yr[nyr-4]]
  ct.int        <- ct[yr>(yr[nyr]-30) & yr>yr[4] & yr<yr[nyr-4]]
  min.ct.int    <- min(ct.int)
  min.ct.int.yr <- yrs.int[which.min(ct.int)]
  max.ct.int    <- max(ct.int)
  max.ct.int.yr <- yrs.int[which.max(ct.int)]
  #if min year is after max year, use min year for int year
  if(min.ct.int.yr > max.ct.int.yr) { int.yr <- min.ct.int.yr } else {
```

```
      # if min.ct/max.ct after max.ct < 0.7, use that year for int.yr
      min.ct.after.max <- min(ct.int[yrs.int >= max.ct.int.yr])
      if((min.ct.after.max/max.ct.int) < 0.75) {
        int.yr <- yrs.int[yrs.int > max.ct.int.yr & ct.int==min.ct.after.max]
      } else {int.yr <- min.ct.int.yr}
    }
    # get latest year where ct < 1.2 min ct
    # int.yr        <- max(yrs.int[ct.int<=(1.2*min.ct.int)])
   }
  }# end of int.yr loop

  # get additional properties of catch time series
  mean.ct.end       <- mean(ct.raw[(nyr-4):nyr]) # mean of catch in last 5 years
  mean.ct_MSY.end   <- mean.ct.end/MSY.pr
  # Get slope of catch in last 10 years
  ct.last           <- ct[(nyr-9):nyr]/mean(ct) # last catch standardized by mean catch
  yrs.last          <- seq(1:10)
  fit.last          <- lm(ct.last ~ yrs.last)
  slope.last        <- as.numeric(coefficients(fit.last)[2])
  slope.last.nrm    <- (slope.last - slope.last.min)/(slope.last.max - slope.last.min) # normalized slope 0-1
  # Get slope of catch in first 10 years
  ct.first          <- ct[1:10]/mean.ct # catch standardized by mean catch
  yrs.first         <- seq(1:10)
  fit.first         <- lm(ct.first ~ yrs.first)
  slope.first       <- as.numeric(coefficients(fit.first)[2])
  slope.first.nrm   <- (slope.first - slope.first.min)/(slope.first.max - slope.first.min) # normalized slope 0-
1

  ct_max.1          <- ct[1]/max.ct
  ct_MSY.1          <- ct[1]/MSY.pr
  mean.ct_MSY.start <- mean(ct.raw[1:5])/MSY.pr
  ct_MSY.int        <- ct[which(yr==int.yr)]/MSY.pr
  ct_max.end        <- ct[nyr]/max.ct
  ct_MSY.end        <- ct[nyr]/MSY.pr
  max.ct.i          <- which.max(ct)/nyr
  int.ct.i          <- which(yr==int.yr)/nyr
  min.ct.i          <- which.min(ct)/nyr
  yr.norm           <- (nyr - yr.norm.min)/(yr.norm.max - yr.norm.min) # normalize nyr 0-1

  # classify catch patterns as Flat, LH, LHL, HL, HLH or OTH
  if(min_max >=0.45 & ct_max.1 >= 0.45 & ct_max.end >= 0.45) { Flat <- 1 } else Flat <- 0
  if(min_max<0.25 & ct_max.1<0.45 & ct_max.end>0.45) { LH <- 1 } else LH <- 0
  if(min_max<0.25 & ct_max.1 < 0.45 & ct_max.end < 0.25) { LHL <- 1 } else LHL <- 0
  if(min_max<0.25 & ct_max.1 > 0.5 & ct_max.end < 0.25) { HL <- 1 } else HL <- 0
  if(min_max<0.25 & ct_max.1 >= 0.45 & ct_max.end >= 0.45) { HLH <- 1 } else HLH <- 0
  if(sum(c(Flat,LHL,LH,HL,HLH))<1) { OTH <- 1 } else OTH <- 0

  # Compute predictions for start, end, and int Bk with trained neural networks
  # B/k range that contains 90% of the data points if ct/MSY.pr >= 1
  bk.MSY <- c(0.256 , 0.721 ) # based on all ct/MSY.pr data for 400 stocks # data copied from
Plot_ct_MSY_13.R output
```

```
    CL.1   <- c( 0.01 , 0.203 )
    CL.2   <- c( 0.2 , 0.431 )
    CL.3   <- c( 0.8 , -0.45 )
    CL.4   <- c( 1.02 , -0.247 )

    # estimate startbio
    # if ct/MSY.pr >= ct_MSY.lim use bk.MSY range
    if(mean.ct_MSY.start >= ct_MSY.lim) {
      startbio    <- bk.MSY
    } else { # else run neural network to determine whether B/k is above or below 0.5
        nninput.start  <-
as.data.frame(cbind(Flat,LH,LHL,HL,HLH,OTH,min_max,max.ct.i,min.ct.i,yr.norm, #ct_MSY.1,
                                  mean.ct_MSY.start,slope.first.nrm,mean.ct_MSY.end,slope.last.nrm))
#gm.prior.r
        pr.nn.startbio <- compute(nn.startbio, nninput.start)
        pr.nn_indices.startbio <- max.col(pr.nn.startbio$net.result)
        ct_MSY.use     <- ifelse(ct_MSY.1 < mean.ct_MSY.start,ct_MSY.1,mean.ct_MSY.start)
        if(pr.nn_indices.startbio==1) { # if nn predicts B/k below 0.5
          startbio      <- c(CL.1[1]+CL.1[2]*mean.ct_MSY.start,CL.2[1]+CL.2[2]*mean.ct_MSY.start) } else
{
            startbio      <- c(CL.3[1]+CL.3[2]*mean.ct_MSY.start,CL.4[1]+CL.4[2]*mean.ct_MSY.start) }
    } # end of neural network loop

    # estimate intbio
    if(ct_MSY.int >= ct_MSY.lim) {
      intbio    <- bk.MSY
    } else { # else run neural network to determine whether B/k is above or below 0.5
    nninput.int    <- as.data.frame(cbind(Flat,LH,LHL,HL,HLH,OTH, # shapes
                                  min_max,max.ct.i,min.ct.i,yr.norm, # general
                                  int.ct.i,ct_MSY.int,                  # int
                                  mean.ct_MSY.end,slope.last.nrm,        # end
                                  mean.ct_MSY.start,slope.first.nrm))     # start

    pr.nn.intbio   <- compute(nn.intbio, nninput.int)
    pr.nn_indices.intbio <- max.col(pr.nn.intbio$net.result)
    if(pr.nn_indices.intbio==1){ # if nn predicts B/k below 0.5
      intbio      <- c(CL.1[1]+CL.1[2]*ct_MSY.int,CL.2[1]+CL.2[2]*ct_MSY.int) } else {
          intbio    <- c(CL.3[1]+CL.3[2]*ct_MSY.int,CL.4[1]+CL.4[2]*ct_MSY.int)}
    } # end of nn loop

    # estimate endbio
      # if ct/MSY.pr >= ct_MSY.lim use bk.MSY range
      if(mean.ct_MSY.end >= ct_MSY.lim) {
        endbio    <- bk.MSY
      } else { # else run neural network to determine whether B/k is above or below 0.5
         nninput.end    <- as.data.frame(cbind(Flat,LH,LHL,HL,HLH,OTH,ct_MSY.int,min_max,max.ct.i,
# arbitrary best sequence
                                     int.ct.i,min.ct.i,yr.norm,
                                     mean.ct_MSY.start,slope.first.nrm,mean.ct_MSY.end,slope.last.nrm))
         pr.nn.endbio   <- compute(nn.endbio, nninput.end)
         pr.nn_indices.endbio <- max.col(pr.nn.endbio$net.result)
```

```
      ct_MSY.use    <- ifelse(ct_MSY.end < mean.ct_MSY.end,ct_MSY.end,mean.ct_MSY.end)
      if(pr.nn_indices.endbio==1){ # if nn predicts B/k below 0.5
       endbio      <- c(CL.1[1]+CL.1[2]*ct_MSY.use,CL.2[1]+CL.2[2]*ct_MSY.use) } else {
         endbio      <- c(CL.3[1]+CL.3[2]*ct_MSY.use,CL.4[1]+CL.4[2]*ct_MSY.use)}

  } # end of nn loop

   # ------------------------------------------------------
   # if abundance data are available, use to set B/k priors
   #-------------------------------------------------------
   # The following assumes that max smoothed cpue will not exceed carrying capacity and will
   # not be less than a quarter of carrying capacity

   if(btype != "None") {
     # get length, min, max, min/max ratio of smoothed bt data
     start.bt      <- yr[which(bt>0)[1]]
     end.bt        <- yr[max(which(bt>0))]
     yr.bt         <- seq(from=start.bt,to=end.bt,by=1) #range of years with bt data
     bt.no.na      <- approx(bt[yr>=start.bt & yr<=end.bt],n=length(yr.bt))$y
     bt.sm         <- ksmooth(x=yr.bt,y=bt.no.na,kernel="normal",n.points=length(yr.bt),bandwidth=bw)$y
     min.bt.sm     <- min(bt.sm,na.rm=T)
     max.bt.sm     <- max(bt.sm,na.rm=T)
     yr.min.bt.sm  <- yr.bt[which.min(bt.sm)]
     yr.max.bt.sm  <- yr.bt[bt.sm==max.bt.sm]

   # The prior B/k bounds derived from cpue are Bk.cpue.pr.low = 0.25 * cpue/max.cpue
   # and Bk.cpue.pr.hi = 1.0 * cpue/max.cpue
     if(bt4pr == T) { # if B/k priors shall be estimated from CPUE...
     # if cpue is available in first 3 years, use to set startbio
     if(is.na(stb.low)==T & is.na(stb.hi)==T & start.bt <= yr[3]) {
         startbio.bt <- c(0.25*bt.sm[1]/max.bt.sm,bt.sm[1]/max.bt.sm)
         # if first catch is low and cpue close to max, assume unexploited stock
         if(ct[1]/max.ct < 0.2 & bt.sm[1]/max.bt.sm > 0.8) {startbio.bt <- c(0.8,1)}

       # use startbio estimated from bt only if it is narrower or similar to startbio estimated by the neural
network
       if((1.25*(startbio[2]-startbio[1])) >  (startbio.bt[2]-startbio.bt[1])) {
         startbio <- startbio.bt }

     } # end of startbio loop

     # use min cpue to set intbio (ignore years close to start or end)
     if(is.na(intb.low)==T & is.na(intb.hi)==T) {
       st.33     <- ifelse(start.bt<(start.yr+3),start.yr+3,start.bt) # first year eligible for intbio
       end.33    <- ifelse(end.bt>(end.yr-3),end.yr-3,end.bt) # last year eligible for intbio
       bt.33     <- bt.sm[yr.bt>=st.33 & yr.bt<=end.33] # CPUE values relevant for intbio
       yr.bt.33  <- seq(from=st.33,to=end.33,by=1) # range of years with relevant bt data
       min.bt.33 <- min(bt.33,na.rm=T) # mimimum of relevant bt
       int.yr.bt <- yr.bt.33[bt.33==min.bt.33] # year with min bt
       intbio.bt <- c(0.25*min.bt.33/max.bt.sm,min.bt.33/max.bt.sm) # intbio prior predicted for int.yr.bt
```

```
        # if mean catch/MSY before int.yr is high (> 0.8), use narrower range
        ct.MSY.prev  <- mean(ct[yr>=(int.yr-4) & yr<=int.yr])/MSY.pr
        if(ct.MSY.prev > 0.8) { intbio.bt <- c(1.2*intbio.bt[1],0.8*intbio.bt[2]) }
        # if cpue range is narrow, use lower intbio
        if(min.bt.sm/max.bt.sm>0.3) {intbio.bt <- c(0.8*intbio.bt[1],0.8*intbio.bt[2]) }

        # use intbio estimated from bt only if it is narrower or similar to intbio estimated by the neural
network
        if((1.25*(intbio[2]-intbio[1])) >=  (intbio.bt[2]-intbio.bt[1])) {
          int.yr   <- int.yr.bt
          intbio   <- intbio.bt }

      } # end of intbio loop

      # if cpue is within last 3 years of time series, use to set endbio
      if(is.na(endb.low)==T & is.na(endb.hi)==T) {
        if(end.bt >= yr[nyr-2]) {
          endbio.bt  <- c(0.25*bt.sm[yr.bt==end.bt]/max.bt.sm,bt.sm[yr.bt==end.bt]/max.bt.sm)
          # if mean catch/MSY before end.yr is high (> 0.8), use narrower range,
          # because with high previous catch, biomass can neither be very low nor near k
          ct.MSY.prev  <- mean(ct[yr>=(end.yr-4) & yr<=end.yr])/MSY.pr
          if(ct.MSY.prev > 0.8) { endbio.bt <- c(1.2*endbio.bt[1],0.8*endbio.bt[2]) }
          # if endbio estimated by neural network is low and cpue is well below max, use endbio
          if(mean(endbio.bt)>mean(endbio) & mean(endbio)<0.3 & bt.sm[yr.bt==end.bt]/max.bt.sm < 0.7)
{endbio.bt <- endbio}
          # if cpue range is narrow, use lower endbio
          if(min.bt.sm/max.bt.sm>0.3) {endbio.bt <- c(0.8*endbio.bt[1],0.8*endbio.bt[2]) }

        # use endbio estimated from bt only if it is narrower or similar to endbio estimated by the neural
network
          if((1.25*(endbio[2]-endbio[1])) >  (endbio.bt[2]-endbio.bt[1])) {
            endbio   <- endbio.bt }
        }
      } # end of endbio loop
     } # end of b/k prior loop
    } # end of bt priors loop

  # if user defined B/k priors in the ID file, use those
    if(is.na(stb.low)==F & is.na(stb.hi)==F) {startbio <- c(stb.low,stb.hi)}
    if(is.na(intb.low)==F & is.na(intb.hi)==F) {
      int.yr   <- cinfo$int.yr[cinfo$Stock==stock]
      intbio   <- c(intb.low,intb.hi)}
    if(is.na(endb.low)==F & is.na(endb.hi)==F) {endbio   <- c(endb.low,endb.hi)}

  cat("startbio=",startbio,ifelse(is.na(stb.low)==T,"default","expert"),
      ", intbio=",int.yr,intbio,ifelse(is.na(intb.low)==T,"default","expert"),
      ", endbio=",endbio,ifelse(is.na(endb.low)==T,"default","expert"),"\n")

  #----------------------------------------------------------------
  # Multivariate normal sampling of r-k log space
  #----------------------------------------------------------------
```

```
# turn numerical ranges into log-normal distributions

mean.log.r=mean(log(prior.r))
sd.log.r=(log(prior.r[2])-log(prior.r[1]))/4  # assume range covers 4 SD

mean.log.k <- mean(log(prior.k))
sd.log.k   <- (log(prior.k[2])-log(prior.k[1]))/4 # assume range covers 4 SD

mvn.log.rk <-
mvn(n=n,mean.log.r=mean.log.r,sd.log.r=sd.log.r,mean.log.k=mean.log.k,sd.log.k=sd.log.k)
#><>MSY rk based on empirical mvn
ri.emp     <- exp(mvn.log.rk[,1])
ki1.emp    <- exp(mvn.log.rk[,2])

#----------------------------------------------------------------
#Plot data and progress -----
#----------------------------------------------------------------
# check for operating system, open separate window for graphs if Windows
if(grepl("win",tolower(Sys.info()['sysname']))) {windows(14,9)}
par(mfrow=c(2,3),mar=c(5.1,4.5,4.1,2.1))
# (a): plot catch ----
plot(x=yr, y=ct.raw,
     ylim=c(0,max(ifelse(substr(id_file,1,3)=="Sim",
                  1.1*true.MSY,0),1.2*max(ct.raw))),
     type ="l", bty="l", main=paste("A:",gsub(":","",gsub("/","-",stock))), xlab="", ylab="Catch (1000
tonnes/year)", lwd=2, cex.main = 1.5, cex.lab = 1.55, cex.axis = 1.5)
lines(x=yr,y=ct,col="blue", lwd=1)
points(x=yr[max.yr.i], y=max.ct, col="red", lwd=2)
points(x=yr[min.yr.i], y=min.ct, col="red", lwd=2)
lines(x=yr,y=rep(MSY.pr,length(yr)),lty="dotted",col="purple")
if(substr(id_file,1,3)=="Sim") lines(x=yr,y=rep(true.MSY,length(yr)),lty="dashed",col="green")

# (b): plot r-k graph
plot(x=ri1, y=ki1, xlim = c(0.95*quantile(ri1,0.001),1.2*quantile(ri1,0.999)),
     ylim = c(0.95*quantile(ki1,0.001),1.2*quantile(ki1,0.999)),
     log="xy", xlab="r", ylab="k (1000 tonnes)", main="B: Finding viable r-k", pch=".", cex=2, bty="l",
     col=grey(0.7,0.4), cex.main = 1.5, cex.lab = 1.55, cex.axis = 1.5)
lines(x=c(prior.r[1],prior.r[2],prior.r[2],prior.r[1],prior.r[1]), # plot original prior range
      y=c(prior.k[1],prior.k[1],prior.k[2],prior.k[2],prior.k[1]),
      lty="dotted")

#--------------------------------------------------------------------
# Prepare MCMC analyses
#--------------------------------------------------------------------
# set inits for r-k in lower right corner of log r-k space to avoid intermediate maxima
init.r      <- prior.r[1]+0.8*(prior.r[2]-prior.r[1])
init.k      <- prior.k[1]+0.1*(prior.k[2]-prior.k[1])

# vector with no penalty (=0) if predicted biomass is within viable range, else a penalty of 10 is set
pen.bk = pen.F = rep(0,length(ct))
```

```
  # Add biomass priors
  b.yrs = c(1,length(start.yr:int.yr),length(start.yr:end.yr))
  b.prior = rbind(matrix(c(startbio[1],startbio[2],intbio[1],intbio[2],endbio[1],endbio[2]),2,3),rep(0,3)) # 
last row includes the 0 penalty

  #-----------------------------------------------------------------
  # First run of BSM with only catch data = CMSY++
  #-----------------------------------------------------------------
    # changes by RF to account for asymmetric distributions
    bt.start  <- mean(c(prior.k[1]*startbio[1],prior.k[2]*startbio[2])) # derive proxy for first bt value
    bt.cmsy   <- c(bt.start,rep(NA,length(ct)-1)) # create proxy abundance with one start value and rest = 
NA
    bt.int    <- mean(c(prior.k[1]*intbio[1],prior.k[2]*intbio[2]))
    bt.last  <- mean(c(prior.k[1]*endbio[1],prior.k[2]*endbio[2]))

    mean.cmsy.ct   <- mean(c(ct[1],ct[yr==int.yr],ct[nyr]),na.rm=T) # get mean catch of years with prior bt
    mean.cmsy.cpue <- mean(c(bt.start,bt.int,bt.last),na.rm=T) # get mean of prior bt

    q.prior.cmsy    <- c(0.99,1.01) # since no abundance data are available in this run,
    init.q.cmsy     <- 1            # q could be omitted and is set here to (practically) 1

  cat("Running MCMC analysis with only catch data....\n")

  # call Schaefer model function
  jags_cmsy <- 
bsm(ct=ct,btj=bt.cmsy,nyr=nyr,prior.r=prior.r,prior.k=prior.k,startbio=startbio,q.priorj=q.prior.cmsy,
                  init.q=init.q.cmsy,init.r=init.r,init.k=init.k,pen.bk=pen.bk,pen.F=pen.F,b.yrs=b.yrs,

b.prior=b.prior,CV.C=CV.C,CV.cpue=CV.cpue,nbk=nbk,rk.cor.beta=rk.cor.beta,cmsyjags=TRUE)

  #-----------------------------------------------
  # Get CMSY++ results
  #-----------------------------------------------
  rs               <- as.numeric(mcmc(jags_cmsy$BUGSoutput$sims.list$r))   # unique.rk[,1]
  ks               <- as.numeric(mcmc(jags_cmsy$BUGSoutput$sims.list$k))  # unique.rk[,2]
  ellipse.cmsy       <- traceEllipse(rs,ks,prior.r,prior.k) # GP
  r.cmsy            <- ellipse.cmsy[1] # GP
  k.cmsy            <- ellipse.cmsy[2] # GP
  # restrict CI quantiles to above 25th percentile of rs
  rs.025            <- as.numeric(quantile(rs,0.025))
  r.quant.cmsy       <- as.numeric(quantile(rs[rs>rs.025],c(0.5,0.025,0.975))) # median, 95% CIs in range 
around
  k.quant.cmsy       <- as.numeric(quantile(ks[rs>rs.025],c(0.5,0.025,0.975)))
  lcl.r.cmsy        <- r.quant.cmsy[2]
  ucl.r.cmsy        <- r.quant.cmsy[3]
  lcl.k.cmsy        <- k.quant.cmsy[2]
  ucl.k.cmsy        <- k.quant.cmsy[3]
  MSY.quant.cmsy     <- quantile(rs[rs>rs.025]*ks[rs>rs.025]/4,c(0.5,0.025,0.975))
  MSY.cmsy          <- r.cmsy*k.cmsy/4
  lcl.MSY.cmsy       <- MSY.quant.cmsy[2]
  ucl.MSY.cmsy       <- MSY.quant.cmsy[3]
```

```
qs                <- as.numeric(mcmc(jags_cmsy$BUGSoutput$sims.list$q))
q.quant.cmsy      <- quantile(qs,c(0.5,0.025,0.975))
q.cmsy            <- q.quant.cmsy[1]
lcl.q.cmsy        <- q.quant.cmsy[2]
ucl.q.cmsy        <- q.quant.cmsy[3]

Fmsy.quant.cmsy    <- as.numeric(quantile(rs[rs>rs.025]/2,c(0.5,0.025,0.975)))
Fmsy.cmsy          <- r.cmsy/2 # HW checked
lcl.Fmsy.cmsy      <- Fmsy.quant.cmsy[2] #><>HW to be added to report output
ucl.Fmsy.cmsy      <- Fmsy.quant.cmsy[3] #><>HW to be added to report output
Bmsy.quant.cmsy    <- as.numeric(quantile(ks[rs>rs.025]/2,c(0.5,0.025,0.975)))
Bmsy.cmsy          <- k.cmsy/2 # HW checked
lcl.Bmsy.cmsy      <- Bmsy.quant.cmsy[2] #><>HW to be added to report output
ucl.Bmsy.cmsy      <- Bmsy.quant.cmsy[3] #><>HW to be added to report output
# HW posterior predictives can stay unchanged
ppd.r             <- exp(as.numeric(mcmc(jags_cmsy$BUGSoutput$sims.list$ppd.logrk[,1])))
ppd.k             <- exp(as.numeric(mcmc(jags_cmsy$BUGSoutput$sims.list$ppd.logrk[,2])))

#><>HW get FFmsy directly from JAGS
all.FFmsy.cmsy  = jags_cmsy$BUGSoutput$sims.list$FFmsy
FFmsy.quant.cmsy = apply(all.FFmsy.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
FFmsy.cmsy = FFmsy.quant.cmsy[1,]
lcl.FFmsy.cmsy = FFmsy.quant.cmsy[2,]
ucl.FFmsy.cmsy = FFmsy.quant.cmsy[3,]
#><>HW get BBmsy directly from JAGS
all.BBmsy.cmsy  = jags_cmsy$BUGSoutput$sims.list$BBmsy
BBmsy.quant.cmsy = apply(all.BBmsy.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
BBmsy.cmsy = BBmsy.quant.cmsy[1,]
lcl.BBmsy.cmsy = BBmsy.quant.cmsy[2,]
ucl.BBmsy.cmsy = BBmsy.quant.cmsy[3,]
# get relative biomass P=B/k as predicted by BSM, including predictions for years with NA abundance
all.bk.cmsy  = jags_cmsy$BUGSoutput$sims.list$P
bk.quant.cmsy = apply(all.bk.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
bk.cmsy = bk.quant.cmsy[1,]
lcl.bk.cmsy = bk.quant.cmsy[2,]
ucl.bk.cmsy = bk.quant.cmsy[3,]
#><> NEW get biomass from JAGS posterior
all.B.cmsy  = jags_cmsy$BUGSoutput$sims.list$B
B.quant.cmsy = apply(all.B.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
B.cmsy = B.quant.cmsy[1,]
lcl.B.cmsy = B.quant.cmsy[2,]
ucl.B.cmsy = B.quant.cmsy[3,]
#><> NEW get F from JAGS posterior
all.Ft.cmsy  = jags_cmsy$BUGSoutput$sims.list$F
Ft.quant.cmsy = apply(all.Ft.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
Ft.cmsy = Ft.quant.cmsy[1,]
lcl.Ft.cmsy = Ft.quant.cmsy[2,]
ucl.Ft.cmsy = Ft.quant.cmsy[3,]

# get catch estimates given catch CV
all.ct.cmsy  = jags_cmsy$BUGSoutput$sims.list$ct.jags
```

```
ct.quants.cmsy = apply(all.ct.cmsy,2,quantile,c(0.5,0.025,0.975),na.rm=T)
ct.cmsy        <- ct.quants.cmsy[1,]
lcl.ct.cmsy    <- ct.quants.cmsy[2,]
ucl.ct.cmsy    <- ct.quants.cmsy[3,]

#-----------------------------------------------------------------
# Plot results
#-----------------------------------------------------------------
# (b) continued
# plot viable r-k pairs from catch-only BSM run
points(x=rs,y=ks,pch=".",cex=1,col="gray55")

# show CMSY++ estimate in prior space of graph B
points(x=r.cmsy, y=k.cmsy, pch=19, col="blue")
lines(x=c(lcl.r.cmsy, ucl.r.cmsy),y=c(k.cmsy,k.cmsy), col="blue")
lines(x=c(r.cmsy,r.cmsy),y=c(lcl.k.cmsy, ucl.k.cmsy), col="blue")

lines(x=c(prior.r[1],prior.r[2],prior.r[2],prior.r[1],prior.r[1]), # re-plot original prior range
      y=c(prior.k[1],prior.k[1],prior.k[2],prior.k[2],prior.k[1]),lty="dotted")

# -----------------------------------------------------------------
# Second run with Bayesian analysis of catch & biomass (or CPUE) with Schaefer model ----
# -----------------------------------------------------------------
  FullSchaefer <- F
#   bt         <- bt.raw
  if(btype != "None" & length(bt[is.na(bt)==F])>=nab) {
  FullSchaefer <- T
  cat("Running MCMC analysis with catch and CPUE.... \n")

  if(btype=="biomass") {
     q.prior <- q.biomass.pr
     init.q  <- mean(q.prior)
  } else { # if btype is CPUE
    # get mean of 3 highest bt values
    bt.sort <- sort(bt)
    mean.max.bt <- mean(bt.sort[(length(bt.sort)-2):length(bt.sort)],na.rm = T)
    # Estimate q.prior[2] from max cpue = q * k, q.prior[1] from max cpue = q * 0.25 * k
    q.1        <- mean.max.bt/prior.k[2]
    q.2        <- mean.max.bt/(0.25*prior.k[1])
    q.prior     <- c(q.1,q.2)
    q.init      <- mean(q.prior) }

  # call Schaefer model function
  jags_bsm <- bsm(ct=ct,btj=bt,nyr=nyr,prior.r=prior.r,prior.k=prior.k,startbio=startbio,q.priorj=q.prior,
                  init.q=init.q,init.r=init.r,init.k=init.k,pen.bk=pen.bk,pen.F=pen.F,b.yrs=b.yrs,

b.prior=b.prior,CV.C=CV.C,CV.cpue=CV.cpue,nbk=nbk,rk.cor.beta=rk.cor.beta,cmsyjags=FALSE)

  # ------------------------------------------------------------
  # Results from BSM Schaefer - ><>HW now consistent with CMSY++
  # ------------------------------------------------------------
```

```
rs.bsm            <- as.numeric(mcmc(jags_bsm$BUGSoutput$sims.list$r))   # unique.rk[,1]
ks.bsm            <- as.numeric(mcmc(jags_bsm$BUGSoutput$sims.list$k))  # unique.rk[,2]
#><> HW: Go directly with posterior median and CIs (non-parametric)
r.quant.bsm       <- as.numeric(quantile(rs.bsm,c(0.5,0.025,0.975))) #median, 95% CIs
r.bsm             <- r.quant.bsm[1]
lcl.r.bsm         <- r.quant.bsm[2]
ucl.r.bsm         <- r.quant.bsm[3]
k.quant.bsm          <- as.numeric(quantile(ks.bsm,c(0.5,0.025,0.975)))
k.bsm             <- k.quant.bsm[1]
lcl.k.bsm         <- k.quant.bsm[2]
ucl.k.bsm         <- k.quant.bsm[3]
MSY.quant.bsm     <- quantile(rs.bsm*ks.bsm/4,c(0.5,0.025,0.975))
MSY.bsm           <- MSY.quant.bsm[1]
lcl.MSY.bsm       <- MSY.quant.bsm[2]
ucl.MSY.bsm       <- MSY.quant.bsm[3]
qs.bsm            <- as.numeric(mcmc(jags_bsm$BUGSoutput$sims.list$q))
q.quant.bsm       <- as.numeric(quantile(qs.bsm,c(0.5,0.025,0.975)))
q.bsm             <- q.quant.bsm[1]
lcl.q.bsm         <- q.quant.bsm[2]
ucl.q.bsm         <- q.quant.bsm[3]

Fmsy.quant.bsm      <- as.numeric(quantile(rs.bsm/2,c(0.5,0.025,0.975)))
Fmsy.bsm           <- Fmsy.quant.bsm[1]
lcl.Fmsy.bsm        <- Fmsy.quant.bsm[2] #><>HW to be added to report output
ucl.Fmsy.bsm        <- Fmsy.quant.bsm[3] #><>HW to be added to report output
Bmsy.quant.bsm      <- as.numeric(quantile(ks.bsm/2,c(0.5,0.025,0.975)))
Bmsy.bsm           <- Bmsy.quant.bsm[1]
lcl.Bmsy.bsm        <- Bmsy.quant.bsm[2] #><>HW to be added to report output
ucl.Bmsy.bsm        <- Bmsy.quant.bsm[3] #><>HW to be added to report output

#><>HW get FFmsy directly from JAGS
all.FFmsy.bsm  = jags_bsm$BUGSoutput$sims.list$FFmsy
FFmsy.quant.bsm = apply(all.FFmsy.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
FFmsy.bsm = FFmsy.quant.bsm[1,]
lcl.FFmsy.bsm = FFmsy.quant.bsm[2,]
ucl.FFmsy.bsm = FFmsy.quant.bsm[3,]
#><>HW get BBmsy directly from JAGS
all.BBmsy.bsm  = jags_bsm$BUGSoutput$sims.list$BBmsy
BBmsy.quant.bsm = apply(all.BBmsy.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
BBmsy.bsm = BBmsy.quant.bsm[1,]
lcl.BBmsy.bsm = BBmsy.quant.bsm[2,]
ucl.BBmsy.bsm = BBmsy.quant.bsm[3,]
# get relative biomass P=B/k as predicted by BSM, including predictions for years with NA abundance
all.bk.bsm  = jags_bsm$BUGSoutput$sims.list$P
bk.quant.bsm = apply(all.bk.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
bk.bsm = bk.quant.bsm[1,]
lcl.bk.bsm = bk.quant.bsm[2,]
ucl.bk.bsm = bk.quant.bsm[3,]
#><> NEW get biomass from JAGS posterior
all.B.bsm  = jags_bsm$BUGSoutput$sims.list$B
B.quant.bsm = apply(all.B.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
```

```
  B.bsm = B.quant.bsm[1,]
  lcl.B.bsm = B.quant.bsm[2,]
  ucl.B.bsm = B.quant.bsm[3,]
  #><> NEW get F from JAGS posterior
  all.Ft.bsm  = jags_bsm$BUGSoutput$sims.list$F
  Ft.quant.bsm = apply(all.Ft.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
  Ft.bsm = Ft.quant.bsm[1,]
  lcl.Ft.bsm = Ft.quant.bsm[2,]
  ucl.Ft.bsm = Ft.quant.bsm[3,]

  # get catch estimates given catch CV
  all.ct.bsm  = jags_bsm$BUGSoutput$sims.list$ct.jags
  ct.quants.bsm = apply(all.ct.bsm,2,quantile,c(0.5,0.025,0.975),na.rm=T)
  ct.bsm         <- ct.quants.bsm[1,]
  lcl.ct.bsm     <- ct.quants.bsm[2,]
  ucl.ct.bsm     <- ct.quants.bsm[3,]

  #-------------------------------------------
  # BSM fits
  #-------------------------------------------
  #><> HW PLOT E (observations)
  F.bt.jags       <- q.bsm*ct.raw/bt # F from raw data
  F.bt_Fmsy.jags  <- vector() # initialize vector
  for(z in 1: length(F.bt.jags)) {
    F.bt_Fmsy.jags[z] <- ifelse(is.na(bt[z])==T,NA,F.bt.jags[z]/
                              ifelse(((bt[z]/q.bsm)/k.bsm)<0.25,Fmsy.bsm*4*(bt[z]/q.bsm)/k.bsm,Fmsy.bsm))}

  #><> get cpue fits from BSM
  cpue.bsm       <- exp(jags_bsm$BUGSoutput$sims.list$cpuem)
  pe.logbt.bsm   <- (jags_bsm$BUGSoutput$sims.list$proc.logB)
  # get cpue predicted
  pred.cpue          <- apply(cpue.bsm,2,quantile,c(0.5,0.025,0.975))
  cpue.bsm         <- pred.cpue[1,]
  lcl.cpue.bsm     <- pred.cpue[2,]
  ucl.cpue.bsm     <- pred.cpue[3,]
  # get process error on log(biomass)   pred.cpue          <- apply(cpue.jags,2,quantile,c(0.5,0.025,0.975))
  pred.pe        <- apply(pe.logbt.bsm,2,quantile,c(0.5,0.025,0.975))
  pe.bsm        <- pred.pe[1,]
  lcl.pe.bsm     <- pred.pe[2,]
  ucl.pe.bsm     <- pred.pe[3,]


  # get variance and correlation between log(r) and log(k)
  log.r.var    <- var(x=log(rs.bsm))
  log.k.var    <- var(x=log(ks.bsm))
  log.kr.cor   <- cor(x=log(rs.bsm),y=log(ks.bsm))
  log.kr.cov   <- cov(x=log(rs.bsm),y=log(ks.bsm))

} # end of MCMC BSM Schaefer loop

# -------------------------------------------
```

```
  # Get results for management ----
  # --------------------------------------------
  if(FullSchaefer==F | force.cmsy==T) { # if only CMSY is available or shall be used
    MSY   <-MSY.cmsy; lcl.MSY<-lcl.MSY.cmsy; ucl.MSY<-ucl.MSY.cmsy
    Bmsy  <-Bmsy.cmsy; lcl.Bmsy<-lcl.Bmsy.cmsy; ucl.Bmsy<-ucl.Bmsy.cmsy
    Fmsy  <-Fmsy.cmsy; lcl.Fmsy<-lcl.Fmsy.cmsy; ucl.Fmsy<-ucl.Fmsy.cmsy
    F.Fmsy<-FFmsy.cmsy;lcl.F.Fmsy<-lcl.FFmsy.cmsy; ucl.F.Fmsy<-ucl.FFmsy.cmsy
    B.Bmsy<-BBmsy.cmsy[1:nyr];lcl.B.Bmsy<-lcl.BBmsy.cmsy[1:nyr][1:nyr];ucl.B.Bmsy<-
ucl.BBmsy.cmsy[1:nyr]
    B <- B.cmsy[1:nyr];lcl.B<-lcl.B.cmsy[1:nyr][1:nyr];ucl.B<-ucl.B.cmsy[1:nyr]
    Ft <- Ft.cmsy[1:nyr];lcl.Ft<-lcl.Ft.cmsy[1:nyr][1:nyr];ucl.Ft<-ucl.Ft.cmsy[1:nyr]
    bk <- bk.cmsy[1:nyr];lcl.bk<-lcl.bk.cmsy[1:nyr][1:nyr];ucl.bk<-ucl.bk.cmsy[1:nyr]

    ct.jags <- ct.cmsy; lcl.ct.jags = lcl.ct.cmsy; ucl.ct.jags=ucl.ct.cmsy #catch estimate given catch error

  } else { # if FullSchaefer is TRUE
    MSY   <-MSY.bsm; lcl.MSY<-lcl.MSY.bsm; ucl.MSY<-ucl.MSY.bsm
    Bmsy  <-Bmsy.bsm; lcl.Bmsy<-lcl.Bmsy.bsm; ucl.Bmsy<-ucl.Bmsy.bsm
    Fmsy  <-Fmsy.bsm; lcl.Fmsy<-lcl.Fmsy.bsm; ucl.Fmsy<-ucl.Fmsy.bsm
    F.Fmsy<-FFmsy.bsm;lcl.F.Fmsy<-lcl.FFmsy.bsm; ucl.F.Fmsy<-ucl.FFmsy.bsm
    B.Bmsy<-BBmsy.bsm[1:nyr];lcl.B.Bmsy<-lcl.BBmsy.bsm[1:nyr][1:nyr];ucl.B.Bmsy<-
ucl.BBmsy.bsm[1:nyr]
    B <- B.bsm[1:nyr];lcl.B<-lcl.B.bsm[1:nyr][1:nyr];ucl.B<-ucl.B.bsm[1:nyr]
    Ft <- Ft.bsm[1:nyr];lcl.Ft<-lcl.Ft.bsm[1:nyr][1:nyr];ucl.Ft<-ucl.Ft.bsm[1:nyr]
    bk <- bk.bsm[1:nyr];lcl.bk<-lcl.bk.bsm[1:nyr][1:nyr];ucl.bk<-ucl.bk.bsm[1:nyr]
    ct.jags <- ct.bsm; lcl.ct.jags = lcl.ct.bsm; ucl.ct.jags=ucl.ct.bsm #catch estimate given catch error

  }

  #><> New section simplified for CMSY++ and BSM
    Fmsy.adj     <- ifelse(B.Bmsy>0.5,Fmsy,Fmsy*2*B.Bmsy)
    lcl.Fmsy.adj <- ifelse(B.Bmsy>0.5,lcl.Fmsy,lcl.Fmsy*2*B.Bmsy)
    ucl.Fmsy.adj <- ifelse(B.Bmsy>0.5,ucl.Fmsy,ucl.Fmsy*2*B.Bmsy)

    if(is.na(sel.yr)==F){
      B.Bmsy.sel<-B.Bmsy[yr==sel.yr]
      B.sel<-B.Bmsy.sel*Bmsy
      F.sel<-ct.raw[yr==sel.yr]/B.sel
      F.Fmsy.sel<-F.sel/Fmsy.adj[yr==sel.yr]
    }

  # ------------------------------------------
  # print input and results to screen ----
  #-------------------------------------------
  cat("---------------------------------------\n")
  cat("Species:", cinfo$ScientificName[cinfo$Stock==stock], ", stock:",stock,", ",ename,"\n")
  cat(cinfo$Name[cinfo$Stock==stock], "\n")
  cat("Region:",cinfo$Region[cinfo$Stock==stock],",",cinfo$Subregion[cinfo$Stock==stock],"\n")
  cat("Catch data used from years", min(yr),"-", max(yr),", abundance =", btype, "\n")
  cat("Prior initial relative biomass =", startbio[1], "-",
startbio[2],ifelse(is.na(stb.low)==T,"default","expert"), "\n")
```

```
  cat("Prior intermediate rel. biomass=", intbio[1], "-", intbio[2], "in year",
int.yr,ifelse(is.na(intb.low)==T,"default","expert"), "\n")
  cat("Prior final relative biomass   =", endbio[1], "-",
endbio[2],ifelse(is.na(endb.low)==T,"default","expert"), "\n")
  cat("Prior range for r =", format(prior.r[1],digits=2), "-",
format(prior.r[2],digits=2),ifelse(is.na(r.low)==T,"default","expert"),
      ", prior range for k =", prior.k[1], "-", prior.k[2],", MSY prior =",MSY.pr,"\n")
  # if Schaefer and CPUE, print prior range of q
  if(FullSchaefer==T) {
    cat("B/k prior used for first year in BSM",ifelse(nbk>1,"and intermediate year",""),ifelse(nbk==3,"and
last year",""),"\n")
    cat("Prior range of q =",q.prior[1],"-",q.prior[2],", assumed effort creep",e.creep,"%\n") }
  if(substr(id_file,1,3)=="Sim") { # if data are simulated, print true values
    cat("True values: r =",true.r,", k = 1000, MSY =", true.MSY,", last B/k =", true.Bk,
        ", last F/Fmsy =",true.F_Fmsy,", q = 0.01\n") }

  # results of CMSY analysis
  cat("\nResults of CMSY analysis \n")
  cat("-------------------------\n")
  cat("r   =", r.cmsy,", 95% CL =", lcl.r.cmsy, "-", ucl.r.cmsy,", k =", k.cmsy,", 95% CL =", lcl.k.cmsy, "-
", ucl.k.cmsy,"\n")
  cat("MSY =", MSY.cmsy,", 95% CL =", lcl.MSY.cmsy, "-", ucl.MSY.cmsy,"\n")
  cat("Relative biomass in last year =", bk.cmsy[nyr], "k, 2.5th perc =", lcl.bk.cmsy[nyr],
      ", 97.5th perc =", ucl.bk.cmsy[nyr],"\n")
  cat("Exploitation F/(r/2) in last year =", FFmsy.cmsy[nyr],", 2.5th perc =",lcl.FFmsy.cmsy[nyr],
      ", 97.5th perc =",ucl.FFmsy.cmsy[nyr],"\n\n")


  # print results from full Schaefer if available
  if(FullSchaefer==T) {
    cat("Results from Bayesian Schaefer model (BSM) using catch &",btype,"\n")
    cat("------------------------------------------------------------\n")
    cat("q   =", q.bsm,", lcl =", lcl.q.bsm, ", ucl =", ucl.q.bsm,"(derived from catch and CPUE) \n")
    cat("r   =", r.bsm,", 95% CL =", lcl.r.bsm, "-", ucl.r.bsm,", k =", k.bsm,", 95% CL =", lcl.k.bsm, "-",
ucl.k.bsm,", r-k log correlation =", log.kr.cor,"\n")
    cat("MSY =", MSY.bsm,", 95% CL =", lcl.MSY.bsm, "-", ucl.MSY.bsm,"\n")
    cat("Relative biomass in last year =", bk.bsm[nyr], "k, 2.5th perc =",lcl.bk.bsm[nyr],
        ", 97.5th perc =", ucl.bk.bsm[nyr],"\n")
    cat("Exploitation F/(r/2) in last year =", FFmsy.bsm[nyr],", 2.5th perc =",lcl.FFmsy.bsm[nyr],
        ", 97.5th perc =",ucl.FFmsy.bsm[nyr],"\n\n")
  }

  # print results to be used in management
  cat("Results for Management (based on",ifelse(FullSchaefer==F |
force.cmsy==T,"CMSY","BSM"),"analysis) \n")
  cat("-------------------------------------------------------------\n")
  if(force.cmsy==T) cat("Mangement results based on CMSY because abundance data seem
unrealistic\n")
  cat("Fmsy =",Fmsy,", 95% CL =",lcl.Fmsy,"-",ucl.Fmsy,"(if B > 1/2 Bmsy then Fmsy = 0.5 r)\n")
  cat("Fmsy =",Fmsy.adj[nyr],", 95% CL =",lcl.Fmsy.adj[nyr],"-",ucl.Fmsy.adj[nyr],"(r and Fmsy are
linearly reduced if B < 1/2 Bmsy)\n")
```

```
  cat("MSY  =",MSY,", 95% CL =",lcl.MSY,"-",ucl.MSY,"\n")
  cat("Bmsy =",Bmsy,", 95% CL =",lcl.Bmsy,"-",ucl.Bmsy,"\n")
  cat("Biomass in last year =",B[nyr],", 2.5th perc =", lcl.B[nyr], ", 97.5 perc =",ucl.B[nyr],"\n")
  cat("B/Bmsy in last year  =",B.Bmsy[nyr],", 2.5th perc =", lcl.B.Bmsy[nyr], ", 97.5 perc
=",ucl.B.Bmsy[nyr],"\n")
  cat("Fishing mortality in last year =",Ft[nyr],", 2.5th perc =", lcl.Ft[nyr], ", 97.5 perc =",ucl.Ft[nyr],"\n")
  cat("Exploitation F/Fmsy  =",F.Fmsy[nyr],", 2.5th perc =", lcl.F.Fmsy[nyr], ", 97.5 perc
=",ucl.F.Fmsy[nyr],"\n")

  # show stock status and exploitation for optional selected year
  if(is.na(sel.yr)==F) {
    cat("\nStock status and exploitation in",sel.yr,"\n")
    cat("Biomass =",B.sel, ", B/Bmsy =",B.Bmsy.sel,", F =",F.sel,", F/Fmsy =",F.Fmsy.sel,"\n") }

  cat("Comment:", comment,"\n")
  cat("----------------------------------------------------------\n")

  # -----------------------------------------
  # Plot results ----
  # -----------------------------------------
  # (b) continued
  # plot best r-k from full Schaefer analysis in prior space of graph B
  if(FullSchaefer==T) {
    points(x=r.bsm, y=k.bsm, pch=19, col="red")
    lines(x=c(lcl.r.bsm, ucl.r.bsm),y=c(k.bsm,k.bsm), col="red")
    lines(x=c(r.bsm,r.bsm),y=c(lcl.k.bsm, ucl.k.bsm), col="red")
  }
  if(substr(id_file,1,3)=="Sim") points(x=true.r,y=true.k,col="green", cex=3, lwd=2)


  # (c) Analysis of viable r-k plot -----
  # ----------------------------
  max.y    <- max(c(ifelse(FullSchaefer==T,max(ks.bsm,ucl.k.bsm),NA),
                ifelse(substr(id_file,1,3)=="Sim",1.2*true.k,NA),ks),na.rm=T)
  min.y    <- min(c(ifelse(FullSchaefer==T,min(ks.bsm),NA),ks,
                ifelse(substr(id_file,1,3)=="Sim",0.8*true.k,NA)),na.rm=T)
  max.x    <- max(c(ifelse(FullSchaefer==T,max(rs.bsm),NA),rs),na.rm=T)
  min.x    <- min(c(ifelse(FullSchaefer==T,min(rs.bsm),NA),0.9*lcl.r.cmsy,prior.r[1],rs),na.rm=T)

  plot(x=rs, y=ks, xlim=c(min.x,max.x),
       ylim=c(min.y,max.y),
       pch=16, col="gray",log="xy", bty="l",
       xlab="", ylab="k (1000 tonnes)", main="C: Analysis of viable r-k",  cex.main = 1.5, cex.lab = 1.55,
cex.axis = 1.5)
  title(xlab = "r", line = 2.25, cex.lab = 1.55)

  # plot r-k pairs from MCMC
  if(FullSchaefer==T) {points(x=rs.bsm, y=ks.bsm, pch=16,cex=0.5)}

  # plot best r-k from full Schaefer analysis
  if(FullSchaefer==T) {
```

```
    points(x=r.bsm, y=k.bsm, pch=19, col="red")
    lines(x=c(lcl.r.bsm, ucl.r.bsm),y=c(k.bsm,k.bsm), col="red")
    lines(x=c(r.bsm,r.bsm),y=c(lcl.k.bsm, ucl.k.bsm), col="red")
  }

  # plot blue dot for CMSY r-k, with 95% CL lines
  points(x=r.cmsy, y=k.cmsy, pch=19, col="blue")
  lines(x=c(lcl.r.cmsy, ucl.r.cmsy),y=c(k.cmsy,k.cmsy), col="blue")
  lines(x=c(r.cmsy,r.cmsy),y=c(lcl.k.cmsy, ucl.k.cmsy), col="blue")

  if(substr(id_file,1,3)=="Sim") points(x=true.r,y=true.k,col="green", cex=3, lwd=2)

  # (d) Pred. biomass plot ----
  #--------------------
  # determine k to use for red line in b/k plot
  if(FullSchaefer==T)  {k2use <- k.bsm} else {k2use <- k.cmsy}
  # determine hight of y-axis in plot
  max.y  <- max(c(ucl.bk.cmsy,ifelse(FullSchaefer==T,max(ucl.bk.bsm[1:nyr]),NA),
                ifelse(FullSchaefer==T,max(bt/(q.bsm*k.bsm),na.rm=T),NA),
                0.6,startbio[2],endbio[2],intbio[2]),na.rm=T)
  max.y  <- ifelse(max.y>4,4,max.y)
  # Main plot of relative CMSY biomass
  plot(x=yr,y=bk.cmsy[1:nyr], lwd=1.5, xlab="", ylab="Relative biomass B/k", type="l",
       ylim=c(0,max.y), bty="l", main="D: Stock size",col="blue",  cex.main = 1.5, cex.lab = 1.55, cex.axis
= 1.5)
  lines(x=yr, y=lcl.bk.cmsy[1:nyr],type="l",lty="dotted",col="blue")
  lines(x=yr, y=ucl.bk.cmsy[1:nyr],type="l",lty="dotted",col="blue")
  # plot lines for 0.5 and 0.25 biomass
  abline(h=0.5, lty="dashed")
  abline(h=0.25, lty="dotted")
  # Add BSM
  if(FullSchaefer==T){
   lines(x=yr, y=bk.bsm[1:nyr],type="l",col="red")
   lines(x=yr, y=lcl.bk.bsm[1:nyr],type="l",lty="dotted",col="red")
   lines(x=yr, y=ucl.bk.bsm[1:nyr],type="l",lty="dotted",col="red")
   # Add CPUE points
   points(x=yr,y=bt/(q.bsm*k.bsm),pch=21,bg="grey")
  }
  # plot biomass windows
  lines(x=c(yr[1],yr[1]), y=startbio, col="purple",lty=ifelse(is.na(stb.low)==T,"dotted","solid"))
  lines(x=c(int.yr,int.yr), y=intbio, col="purple",lty=ifelse(is.na(intb.low)==T,"dotted","solid"))
  lines(x=c(max(yr),max(yr)), y=endbio, col="purple",lty=ifelse(is.na(endb.low)==T,"dotted","solid"))

  # if CPUE has been corrected for effort creep, display uncorrected CPUE
  if(btype=="CPUE" & FullSchaefer==T & e.creep.line==T & is.na(e.creep)==FALSE) {
    lines(x=yr,y=bt.raw/(q.bsm*k.bsm),type="l", col="green", lwd=1)
  }
  if(substr(id_file,1,3)=="Sim") points(x=yr[nyr],y=true.Bk,col="green", cex=3, lwd=2)

  # (e) Exploitation rate plot ----
  # -------------------------
```

```
  # if CPUE data are available but fewer than nab years, plot on second axis
  if(btype == "CPUE" | btype=="biomass") {
    q=1/(max(bk.cmsy[1:nyr][is.na(bt)==F],na.rm=T)*k.cmsy/max(bt,na.rm=T))
    u.cpue      <- q.bsm*ct/bt
  }
  # determine upper bound of Y-axis
  max.y <-
max(c(1.5,ucl.FFmsy.cmsy,ifelse(FullSchaefer==T,max(c(ucl.FFmsy.bsm),na.rm=T),NA),na.rm=T),na.r
m=T)
  max.y <- ifelse(max.y>10,10,max.y)
  # plot F from CMSY
  plot(x=yr,y=FFmsy.cmsy, type="l", bty="l", lwd=1.5, ylim=c(0,max.y), xlab="",
       ylab=expression(F/F[MSY]), main="E: Exploitation rate", col="blue",  cex.main = 1.5, cex.lab =
1.55, cex.axis = 1.5)
  lines(x=yr,y=lcl.FFmsy.cmsy,lty="dotted",col="blue")
  lines(x=yr,y=ucl.FFmsy.cmsy,lty="dotted",col="blue")
  abline(h=1, lty="dashed")

  # plot F/Fmsy as points from observed catch and CPUE and as red curves from BSM predicted catch
and biomass
  if(FullSchaefer==T){
    points(x=yr, y=F.bt_Fmsy.jags, pch=21,bg="grey")
    lines(x=yr,y=FFmsy.bsm, col="red")
    lines(x=yr,y=lcl.FFmsy.bsm, col="red",lty="dotted")
    lines(x=yr,y=ucl.FFmsy.bsm, col="red",lty="dotted")
  }
  if(substr(id_file,1,3)=="Sim") points(x=yr[nyr],y=true.F_Fmsy,col="green", cex=3, lwd=2)

  # (f) Parabola plot ----
  #-------------------------
  max.y <- max(c(ct/MSY.cmsy,ifelse(FullSchaefer==T,max(ct/MSY.bsm),NA),1.2),na.rm=T)
  # plot parabola
  x=seq(from=0,to=2,by=0.001)
  y.c  <- ifelse(x>0.25,1,ifelse(x>0.125,4*x,exp(-10*(0.125-x))*4*x)) # correction for low recruitment
below half and below quarter of Bmsy
  y=(4*x-(2*x)^2)*y.c
  plot(x=x, y=y, xlim=c(0,1), ylim=c(0,max.y), type="l", bty="l",xlab="",
       ylab="Catch / MSY", main="F: Equilibrium curve",  cex.main = 1.5, cex.lab = 1.55, cex.axis = 1.5)
  title(xlab= "Relative biomass B/k", line = 2.25, cex.lab = 1.55)

  # plot catch against CMSY estimates of relative biomass
  #><> HW add catch with error from JAGS
  lines(x=bk.cmsy[1:nyr], y=ct.cmsy/MSY.cmsy, pch=16, col="blue", lwd=1)
  points(x=bk.cmsy[1], y=ct.cmsy[1]/MSY.cmsy[1], pch=0, cex=2, col="blue")
  points(x=bk.cmsy[nyr], y=ct.cmsy[length(ct)]/MSY.cmsy[length(MSY.cmsy)],cex=2,pch=2,col="blue")

  # for CPUE, plot catch scaled by BSM MSY against observed biomass derived as q * CPUE scaled by
BSM k
  if(FullSchaefer==T) {
    points(x=bt/(q.bsm*k.bsm), y=ct/MSY.bsm, pch=21,bg="grey")
    lines(x=bk.bsm[1:nyr], y=ct.bsm/MSY.bsm, pch=16, col="red",lwd=1)
```

```
    points(x=bk.bsm[1], y=ct.bsm[1]/MSY.bsm, pch=0, cex=2, col="red")
    points(x=bk.bsm[nyr], y=ct.bsm[length(ct)]/MSY.bsm[length(MSY.bsm)], pch=2, cex=2,col="red")
  }
  if(substr(id_file,1,3)=="Sim") points(x=true.Bk,y=ct[nyr]/true.MSY,col="green", cex=3, lwd=2)
  #analysis.plot <- recordPlot()

  #save analytic chart to JPEG file
  if (save.plots==TRUE) {
    jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_AN.jpg",sep="")
          if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
            dev.copy(jpeg,jpgfile,
          width = 1024,
          height = 768,
          units = "px",
          pointsize = 18,
          quality = 95,
          res=80,
          antialias="cleartype")
    dev.off()
  }

  #---------------------------------------------
  # Plot Management-Graphs if desired ----
  #---------------------------------------------
  if(mgraphs==T) {
    # open window for plot of four panels
    if(grepl("win",tolower(Sys.info()['sysname']))) {windows(14,12)}
    par(mfrow=c(2,2))
    # make margins narrower
    par(mar=c(3.1,4.2,2.1,2.1))

    #---------------------
    # plot catch with MSY ----
    #---------------------
    max.y <- max(c(1.1*max(ct.jags),ucl.MSY),na.rm=T)
    plot(x=yr,rep(0,nyr),type="n",ylim=c(0,max.y), bty="l", main=paste("Catch",gsub(":","",gsub("/","-
",stock))),
        xlab="",ylab="Catch (1000 tonnes/year)",  cex.main = 1.6, cex.lab = 1.35, cex.axis = 1.35)
    rect(yr[1],lcl.MSY,yr[nyr],ucl.MSY,col="lightgray", border=NA)
    lines(x=c(yr[1],yr[nyr]),y=c(MSY,MSY),lty="dashed", col="black", lwd=2)
    lines(x=yr, y=ct.jags, lwd=2) #
    text("MSY",x=end.yr-1.5, y=MSY+MSY*0.1, cex = .75)

    #----------------------------------------
    # Plot of estimated biomass relative to Bmsy
    #----------------------------------------
    # plot empty frame
    plot(yr, rep(0,nyr),type="n", ylim=c(0,max(c(2, max(ucl.B.Bmsy)))),
ylab=expression(B/B[MSY]),xlab="", main="Stock size", bty="l",  cex.main = 1.6, cex.lab = 1.35,
cex.axis = 1.35)
```

```
    # plot gray area of uncertainty in predicted biomass
    polygon(c(yr,rev(yr)), c(lcl.B.Bmsy,rev(ucl.B.Bmsy)),col="lightgray", border=NA)
    # plot median biomass
    lines(yr,B.Bmsy,lwd=2)
    # plot lines for Bmsy and 0.5 Bmsy
    lines(x=c(yr[1],yr[nyr]),y=c(1,1), lty="dashed", lwd=1.5)
    lines(x=c(yr[1],yr[nyr]),y=c(0.5,0.5), lty="dotted", lwd=1.5)

    # -------------------------------------
    ## Plot of exploitation rate
    # -------------------------------------
    # plot empty frame
    plot(yr, rep(0,nyr),type="n", ylim=c(0,max(c(2,ucl.F.Fmsy))),
         ylab=expression(F/F[MSY]),xlab="", main="Exploitation", bty="l",  cex.main = 1.6, cex.lab = 1.35,
cex.axis = 1.35)
    # plot gray area of uncertainty in predicted exploitation
    polygon(c(yr,rev(yr)), c(lcl.F.Fmsy,rev(ucl.F.Fmsy)),col="lightgray", border=NA)
    # plot median exploitation rate
    lines(x=yr,y=F.Fmsy,lwd=2)
    # plot line for u.msy
    lines(x=c(yr[1],yr[nyr]),y=c(1,1), lty="dashed", lwd=1.5)

    # -------------------------------------
    ## plot stock-status graph
    # -------------------------------------

    if(FullSchaefer==T & force.cmsy==F) {
    x.F_Fmsy = all.FFmsy.bsm[,nyr]
    y.b_bmsy = all.BBmsy.bsm[,nyr]} else { # use CMSY data
    x.F_Fmsy = all.FFmsy.cmsy[,nyr]
    y.b_bmsy = all.BBmsy.cmsy[,nyr]
    }

    kernelF <-
ci2d(x.F_Fmsy,y.b_bmsy,nbins=201,factor=2.2,ci.levels=c(0.50,0.80,0.75,0.90,0.95),show="none")
    c1 <- c(-1,100)
    c2 <- c(1,1)

    max.x1   <- max(c(2, max(kernelF$contours$"0.95"$x,F.Fmsy),na.rm =T))
    max.x    <- ifelse(max.x1 > 5,min(max(5,F.Fmsy*2),8),max.x1)
    max.y    <- max(max(2,quantile(y.b_bmsy,0.96)))

    plot(1000,1000,type="b", xlim=c(0,max.x),
ylim=c(0,max.y),lty=3,xlab="",ylab=expression(B/B[MSY]), bty="l",  cex.main = 1.6, cex.lab = 1.35,
cex.axis = 1.35)
    mtext(expression(F/F[MSY]),side=1, line=2.3, cex=1,adj=0.55)

    # extract interval information from ci2d object
    # and fill areas using the polygon function
    polygon(kernelF$contours$"0.95",lty=2,border=NA,col="cornsilk4")
    polygon(kernelF$contours$"0.8",border=NA,lty=2,col="grey")
```

```
    polygon(kernelF$contours$"0.5",border=NA,lty=2,col="cornsilk2")

    ## Add points and trajectory lines
    lines(c1,c2,lty=3,lwd=0.7)
    lines(c2,c1,lty=3,lwd=0.7)
    lines(F.Fmsy,B.Bmsy, lty=1,lwd=1.)

    # points(F.Fmsy,B.Bmsy,cex=0.8,pch=4)
    points(F.Fmsy[1],B.Bmsy[1],col=1,pch=22,bg="white",cex=1.5)
    points(F.Fmsy[which(yr==int.yr)],B.Bmsy[which(yr==int.yr)],col=1,pch=21,bg="white",cex=1.5)
    points(F.Fmsy[nyr],B.Bmsy[nyr],col=1,pch=24,bg="white",cex=1.5)

    ## Add legend
    legend('topright', inset = .03, c(paste(start.yr),paste(int.yr),paste(end.yr),"50% C.I.","80% C.I.","95%
C.I."),
           lty=c(1,1,1,-1,-1,-
1),pch=c(22,21,24,22,22,22),pt.bg=c(rep("white",3),"cornsilk2","grey","cornsilk4"),
           col=1,lwd=.8,cex=0.85,pt.cex=c(rep(1.1,3),1.5,1.5,1.5),bty="n",y.intersp = 1.1)
    #End of Biplot

  } # end of management graphs

  #management.plot <- recordPlot()

  # save management chart to JPEG file
  if (save.plots==TRUE & mgraphs==TRUE)  {
    jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_MAN.jpg",sep="")
              if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
    dev.copy(jpeg,jpgfile,
             width = 1024,
             height = 768,
             units = "px",
             pointsize = 18,
             quality = 95,
             res=80,
             antialias="cleartype")
    dev.off()
  }

  #---------------------------------------------------------
  #><>MSY: rk.diags plot
  #---------------------------------------------------------
  if(rk.diags==T) {
    # open window for plot of four panels
    if(grepl("win",tolower(Sys.info()['sysname']))) {windows(9,9)}
    # make margins narrower
    par(mfrow=c(1,1),mar=c(4.5,4.5,2,0.5))
    plot(x=ri1, y=ki1, xlim = c(0.95*quantile(ri1,0.001),1.2*quantile(ri1,0.999)),
         ylim = c(0.95*quantile(ki1,0.001),1.2*quantile(ki1,0.999)),
         log="xy", xlab="r", ylab="k (1000 tonnes)", main="r-k diagnostic", pch=".", cex=3, bty="l",
```

```
      col=rgb(0,0,1,0.5), cex.main = 1.5, cex.lab = 1.55, cex.axis = 1.5)
   points(ppd.r,ppd.k,pch=16,col=rgb(1,0,0,0.5),cex=0.5)
   points(ri.emp,ki1.emp,pch=16,col=rgb(1,0,1,0.5),cex=0.5)
   points(rs,ks,pch=16,col=rgb(0,1,0,0.9),cex=0.5)
   lines(x=c(prior.r[1],prior.r[2],prior.r[2],prior.r[1],prior.r[1]), # plot original prior range
        y=c(prior.k[1],prior.k[1],prior.k[2],prior.k[2],prior.k[1]),
        lty="dotted")
   legend("topright",c("Logistic r-k","Empirical r-k","JAGS r-k","Posterior r-k"),pt.cex = 1.2,pch=15,
         col=c(rgb(0,0,1,0.7),rgb(1,0,1,0.7),rgb(1,0,0,0.7),rgb(0,1,0,1)),bty="n")

   if (save.plots==TRUE) {
     jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_rk_Diags.jpg",sep="")
     if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
     dev.copy(jpeg,jpgfile,
              width = 768,
              height = 768,
              units = "px",
              pointsize = 18,
              quality = 95,
              res=80,
              antialias="cleartype")
     dev.off()
   }
  }
  #-----------------------------------------------------------
  #><> Optional prior - posterior plots
  #---------------------------------------------------------
  if(pp.plot==T) {
   # open window for plot of four panels
   if(grepl("win",tolower(Sys.info()['sysname']))) {windows(17,12)}
   # make margins narrower
   par(mfrow=c(2,3),mar=c(4.5,4.5,2,0.5))
   greycol = c(grey(0.7,0.5),grey(0.3,0.5)) # changed 0.6 to 0.7

   # plot PP-diagnostics for CMSY
   # r
   rk <-
exp(mvn(n=5000,mean.log.r=mean.log.r,sd.log.r=sd.log.r,mean.log.k=mean.log.k,sd.log.k=sd.log.k))
   pp.lab = "r"
   rpr = sort(rk[,1])
   post = rs
   prior <-dlnorm(sort(rpr),meanlog = mean.log.r, sdlog = sd.log.r) #><>HW now pdf

   # generic ><>HW streamlined GP to check
   nmc = length(post)
   pdf = stats::density(post,adjust=2)
   plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
      yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
   polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
   polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
```

```
PPVR = round((sd(post)/mean(post))^2/(sd(prior)/mean(prior))^2,2)
PPVM = round(mean(post)/mean(prior),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

# k
pp.lab = "k (1000 tonnes)"
rpr = sort(rk[,2])
post = ks
prior <-dlnorm(sort(rpr),meanlog = mean.log.k, sdlog = sd.log.k) #><>HW now pdf
# generic ><>HW streamlined GP to check
nmc = length(post)
pdf = stats::density(post,adjust=2)
plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
    yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
PPVR = round((sd(post)/mean(post))^2/(sd(prior)/mean(prior))^2,2)
PPVM = round(mean(post)/mean(prior),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

# Header
mtext(paste0("CMSY prior & posterior distributions for ",stock),  side=3,cex=1.5)

# MSY
pp.lab = "MSY (1000 tonnes/year)"
rpr = sort(rk[,1]*rk[,2]/4)
post = rs*ks/4
prior <-dlnorm(sort(rpr),meanlog = mean(log(rpr)), sdlog = sd(log(rpr))) #><>HW now pdf
prand <- rlnorm(2000,meanlog = mean(log(rpr)), sdlog = sd(log(rpr)))
# generic ><>HW streamlined GP to check
nmc = length(post)
pdf = stats::density(post,adjust=2)
plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
    yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
PPVM = round(mean(post)/mean(prand),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

#><> bk beta priors
bk.beta = (beta.prior(b.prior))

# bk1
pp.lab=paste0("B/k ",yr[1])
```

```
    post = all.bk.cmsy[,1]
    nmc = length(post)
    rpr = seq(0.5*startbio[1],startbio[2]*1.5,0.005)
    pdf = stats::density(post,adjust=2)
    prand <- sort(rbeta(2000,bk.beta[1,1], bk.beta[2,1]))
    prior <-dbeta(sort(prand),bk.beta[1,1], bk.beta[2,1]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019

plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,0.3*rpr,min(1.7*rpr[2],1.05),max(pdf
$x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
    #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
    polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
    polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
    PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
    PPVM = round(mean(post)/mean(prior),2)
    pp = c(paste("PPVR =",PPVR))
    legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
    legend("topright",pp,cex=1.4,bty="n")

    # bk2
    pp.lab=paste0("B/k ", int.yr)
    post = all.bk.cmsy[,which(int.yr==yr)]
    rpr = seq(0.5*intbio[1],intbio[2]*1.5,0.005)
    pdf = stats::density(post,adjust=2)
    prand <- sort(rbeta(2000,bk.beta[1,2], bk.beta[2,2]))
    prior <-dbeta(sort(prand),bk.beta[1,2], bk.beta[2,2]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019

plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,0.3*rpr,min(1.7*rpr[2],1.05),max(pdf
$x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
    #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
    polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
    polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
    PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
    PPVM = round(mean(post)/mean(prior),2)
    pp = c(paste("PPVR =",PPVR))
    legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
    legend("topright",pp,cex=1.4,bty="n")

    # bk3
    pp.lab=paste0("B/k ",yr[length(yr)])
    post = all.bk.cmsy[,length(yr)]
    rpr = seq(0.5*endbio[1],endbio[2]*1.5,0.005)
    pdf = stats::density(post,adjust=2)
    prand <- sort(rbeta(2000,bk.beta[1,3], bk.beta[2,3]))
    prior <-dbeta(sort(prand),bk.beta[1,3], bk.beta[2,3]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019

plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,prand,min(1.7*rpr[2],1.05),max(pdf$
```

```
x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
   #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
   polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
   polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
   PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
   PPVM = round(mean(post)/mean(prior),2)
   pp = c(paste("PPVR =",PPVR))
   legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
   legend("topright",pp,cex=1.4,bty="n")

    #save analytic chart to JPEG file
   if (save.plots==TRUE) {
    jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_PP_CMSY.jpg",sep="")
            if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
     dev.copy(jpeg,jpgfile,
          width = 1024,
          height = 768,
          units = "px",
          pointsize = 18,
          quality = 95,
          res=80,
          antialias="cleartype")
     dev.off()
   }

   # plot PP diagnostics for BSM if available
   if(FullSchaefer==T & force.cmsy==F){ # BSM PLOT
   # open window for plot of four panels
   if(grepl("win",tolower(Sys.info()['sysname']))) {windows(17,12)}
   # make margins narrower
   par(mfrow=c(2,3),mar=c(4.5,4.5,2,0.5))
   greycol = c(grey(0.7,0.5),grey(0.3,0.5))

   # r
   rk <-
exp(mvn(n=5000,mean.log.r=mean.log.r,sd.log.r=sd.log.r,mean.log.k=mean.log.k,sd.log.k=sd.log.k))
   pp.lab = "r"
   rpr = sort(rk[,1])
   post = rs.bsm
   prior <-dlnorm(sort(rpr),meanlog = mean.log.r, sdlog = sd.log.r) #><>HW now pdf

   # generic ><>HW streamlined GP to check
   nmc = length(post)
   pdf = stats::density(post,adjust=2)
   plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
      yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
   polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
   polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
   PPVR = round((sd(post)/mean(post))^2/(sd(prior)/mean(prior))^2,2)
```

```
PPVM = round(mean(post)/mean(prior),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

# k
pp.lab = "k (1000 tonnes)"
rpr = sort(rk[,2])
post = ks.bsm
prior <-dlnorm(sort(rpr),meanlog = mean.log.k, sdlog = sd.log.k) #><>HW now pdf
# generic ><>HW streamlined GP to check
nmc = length(post)
pdf = stats::density(post,adjust=2)
plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
    yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
PPVR = round((sd(post)/mean(post))^2/(sd(prior)/mean(prior))^2,2)
PPVM = round(mean(post)/mean(prior),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

# Header
mtext(paste0("BSM prior & posterior distributions for ",stock),  side=3,cex=1.5)

# MSY
pp.lab = "MSY (1000 tonnes/year)"
rpr = sort(rk[,1]*rk[,2]/4)
post = rs.bsm*ks.bsm/4
prior <-dlnorm(sort(rpr),meanlog = mean(log(rpr)), sdlog = sd(log(rpr))) #><>HW now pdf
# generic ><>HW streamlined GP to check
nmc = length(post)
pdf = stats::density(post,adjust=2)
plot(pdf,type="l",ylim=range(prior,pdf$y*1.1),xlim=range(c(pdf$x,rpr,max(pdf$x,rpr)*1.1)),
    yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis = 1.5)
polygon(c((rpr),rev(prior)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
PPVR = round((sd(post)/mean(post))^2/(sd(prior)/mean(prior))^2,2)
PPVM = round(mean(post)/mean(prior),2)
pp = c(paste("PPVR =",PPVR))
legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
legend("topright",pp,cex=1.4,bty="n")

# bk1
pp.lab=paste0("B/k ",yr[1])
post = all.bk.bsm[,1]
nmc = length(post)
rpr = seq(0.5*startbio[1],startbio[2]*1.5,0.005)
pdf = stats::density(post,adjust=2)
prand <- sort(rbeta(2000,bk.beta[1,1], bk.beta[2,1]))
```

```
    prior <-dbeta(sort(prand),bk.beta[1,1], bk.beta[2,1]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019

plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,0.3*rpr,min(1.7*rpr[2],1.05),max(pdf
$x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
    #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
    polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
    polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
    PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
    PPVM = round(mean(post)/mean(prior),2)
    pp = c(paste("PPVR =",PPVR))
    legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
    legend("topright",pp,cex=1.4,bty="n")

    # bk2
    pp.lab=paste0("B/k ", int.yr)
    post = all.bk.bsm[,which(int.yr==yr)]
    rpr = seq(0.5*intbio[1],intbio[2]*1.5,0.005)
    pdf = stats::density(post,adjust=2)
    prand <- sort(rbeta(2000,bk.beta[1,2], bk.beta[2,2]))
    prior <-dbeta(sort(prand),bk.beta[1,2], bk.beta[2,2]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019

plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,0.3*rpr,min(1.7*rpr[2],1.05),max(pdf
$x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
    #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
    if(nbk>1) polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
    if(nbk==1) polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),lty=2)
    polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
    PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
    PPVM = round(mean(post)/mean(prior),2)
    pp = c(paste("PPVR =",PPVR))
    if(nbk>1){
    legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
    legend("topright",pp,cex=1.4,bty="n")
    } else {
      legend('right',c("Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol[2],bty="n",cex=1.5)
    }

    # bk3
    pp.lab=paste0("B/k ",yr[length(yr)])
    post = all.bk.bsm[,length(yr)]
    nmc = length(post)
    rpr = seq(0.5*endbio[1],endbio[2]*1.5,0.005)
    pdf = stats::density(post,adjust=2)
    prand <- sort(rbeta(2000,bk.beta[1,3], bk.beta[2,3]))
    prior <-dbeta(sort(prand),bk.beta[1,3], bk.beta[2,3]) #><>HW now pdf
    #prior.height<-1/(prior[2]-prior[1])     # modification by GP 03/12/2019
```

```
plot(pdf,type="l",ylim=range(c(pdf$y,0,prior)),xlim=range(c(pdf$x,prand,min(1.7*rpr[2],1.05),max(pdf$
x,rpr)*1.1)),yaxt="n",xlab=pp.lab,ylab="",xaxs="i",yaxs="i",main="",bty="l",cex.lab = 1.55, cex.axis =
1.5)
    #rect(prior[1],0,prior[2],prior.height,col=greycol[1])
    if(nbk>2) polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),col=greycol[1])
    if(nbk<3) polygon(c(prand,rev(prand)),c(prior,rep(0,length(sort(prior)))),lty=2)
    polygon(c(pdf$x,rev(pdf$x)),c(pdf$y,rep(0,length(pdf$y))),col=greycol[2])
    PPVR = round((sd(post)/mean(post))^2/(sd(prand)/mean(prand))^2,2)
    PPVM = round(mean(post)/mean(prior),2)
    pp = c(paste("PPVR =",PPVR))
    if(nbk>2){
      legend('right',c("Prior","Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol,bty="n",cex=1.5)
      legend("topright",pp,cex=1.4,bty="n")
    } else {
      legend('right',c("Posterior"),pch=22,pt.cex=1.5,pt.bg = greycol[2],bty="n",cex=1.5)
    }

     #save analytic chart to JPEG file
     if (save.plots==TRUE) {
       jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_PP_BSM.jpg",sep="")
              if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
       dev.copy(jpeg,jpgfile,
              width = 1024,
              height = 768,
              units = "px",
              pointsize = 18,
              quality = 95,
              res=80,
              antialias="cleartype")
       dev.off()
     }
    } # end of BSM plot
  } # End of posterior/prior plot

  #-----------------------------------------------------------
  #>< Optional BSM diagnostic plot
  #---------------------------------------------------------
  if(BSMfits.plot==T & FullSchaefer==T & force.cmsy==F){
    #---------------------------------------------
    # open window for plot of four panels
    if(grepl("win",tolower(Sys.info()['sysname']))) {windows(9,6)}
    # make margins narrower
    par(mfrow=c(2,2),mar=c(3.1,4.1,2.1,2.1),cex=1)
    cord.x <- c(yr,rev(yr))
    # Observed vs Predicted Catch
    cord.y<-c(lcl.ct.jags,rev(ucl.ct.jags))
    plot(yr,ct,type="n",ylim=c(0,max(ct.jags,na.rm=T)),lty=1,lwd=1.3,xlab="Year",
        ylab=paste0("Catch (1000 tonnes)"),main=paste("Catch fit",stock),bty="l")
    polygon(cord.x,cord.y,col="gray",border=0,lty=1)
```

```
    lines(yr,ct.jags,lwd=2,col=1)
    points(yr,(ct),pch=21,bg="white",cex=1.)
    legend("topright",c("Observed","Predicted","95%CIs"),pch=c(21,-1,22),pt.cex = c(1,1,1.5),
           pt.bg=c("white",-1,"grey"),lwd=c(-1,2,-1),col=c(1,1,"grey"),bty="n",y.intersp = 0.9)

    # Observed vs Predicted CPUE
    cord.y<-c(lcl.cpue.bsm,rev(ucl.cpue.bsm))

plot(yr,bt,type="n",ylim=c(0,max(c(pred.cpue,bt),na.rm=T)),lty=1,lwd=1.3,xlab="Year",ylab=paste0("cp
ue"),
         main="cpue fit",bty="l")
    polygon(cord.x,cord.y,col="gray",border=0,lty=1)
    lines(yr,cpue.bsm,lwd=2,col=1)
    points(yr,(bt),pch=21,bg="white",cex=1.)
    legend("topright",c("Observed","Predicted","95%CIs"),pch=c(21,-1,22),pt.cex =
c(1,1,1.5),pt.bg=c("white",-1,"grey"),lwd=c(-1,2,-1),col=c(1,1,"grey"),bty="n",y.intersp = 0.9)

    # Process error log-biomass
    cord.y<-c(lcl.pe.bsm,rev(ucl.pe.bsm))
    plot(yr,rep(0,length(yr)),type="n",ylim=c(-
max(c(abs(pred.pe),0.2),na.rm=T),max(c(abs(pred.pe),0.2),na.rm=T)),lty=1,lwd=1.3,xlab="Year",ylab=p
aste0("Deviation log(B)"),main="Process variation",bty="l")
    polygon(cord.x,cord.y,col="gray",border=0,lty=1)
    abline(h=0,lty=2)
    lines(yr,pe.bsm,lwd=2)


    #---------------------------------------------------
    # Function to do runs.test and 3 x sigma limits
    #--------------------------------------------------
    runs.sig3 <- function(x,type="resid") {
      if(type=="resid"){mu = 0}else{mu = mean(x, na.rm = TRUE)}
      # Average moving range
      mr  <- abs(diff(x - mu))
      amr <- mean(mr, na.rm = TRUE)
      # Upper limit for moving ranges
      ulmr <- 3.267 * amr
      # Remove moving ranges greater than ulmr and recalculate amr, Nelson 1982
      mr  <- mr[mr < ulmr]
      amr <- mean(mr, na.rm = TRUE)
      # Calculate standard deviation, Montgomery, 6.33
      stdev <- amr / 1.128
      # Calculate control limits
      lcl <- mu - 3 * stdev
      ucl <- mu + 3 * stdev
      if(nlevels(factor(sign(x)))>1){
        runstest = snpar::runs.test(resid)
        pvalue = round(runstest$p.value,3)} else {
        pvalue = 0.001
      }
```

```
      return(list(sig3lim=c(lcl,ucl),p.runs= pvalue))
    }

    # get residuals
    resid = (log(bt)-log(cpue.bsm))[is.na(bt)==F]
    res.yr = yr[is.na(bt)==F]
    runstest = runs.sig3(resid)

    # CPUE Residuals with runs test
    plot(yr,rep(0,length(yr)),type="n",ylim=c(min(-
0.25,runstest$sig3lim[1]*1.1),max(0.25,runstest$sig3lim[2]*1.1)),lty=1,lwd=1.3,xlab="Year",ylab=expre
ssion(log(cpue[obs])-log(cpue[pred])),main="Residual diagnostics",bty="l")
    abline(h=0,lty=2)
    RMSE = sqrt(mean(resid^2)) # Residual mean sqrt error
    if(RMSE>0.1){lims = runstest$sig3lim} else {lims=c(-1,1)}
    cols = c(rgb(1,0,0,0.5),rgb(0,1,0,0.5))[ifelse(runstest$p.runs<0.05,1,2)]
    if(RMSE>=0.1) rect(min(yr),lims[1],max(yr),lims[2],col=cols,border=cols) # only show runs if RMSE
>= 0.1
    for(i in 1:length(resid)){
      lines(c(res.yr[i],res.yr[i]),c(0,resid[i]))
    }
    points(res.yr,resid,pch=21,bg=ifelse(resid < lims[1] | resid > lims[2],2,"white"),cex=1)

    # save management chart to JPEG file
    if (save.plots==TRUE & FullSchaefer == T & BSMfits.plot==TRUE) {
      jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_bsmfits.jpg",sep="")
            if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
      dev.copy(jpeg,jpgfile,
            width = 1024,
            height = 768,
            units = "px",
            pointsize = 18,
            quality = 95,
            res=80,
            antialias="cleartype")
      dev.off()
    }
  }


  #-------------------------------------
  # HW Produce optional kobe plot
  #-------------------------------------

  if(kobe.plot==T){
    # open window for plot of four panels
    if(grepl("win",tolower(Sys.info()['sysname']))) {windows(7,7)}
    par(mfrow=c(1,1))
    # make margins narrower
    par(mar=c(5.1,5.1,2.1,2.1))
```

```
  if(FullSchaefer==T & force.cmsy==F) {
    x.F_Fmsy = all.FFmsy.bsm[,nyr]
    y.b_bmsy = all.BBmsy.bsm[,nyr]} else { # use CMSY data
      x.F_Fmsy = all.FFmsy.cmsy[,nyr]
      y.b_bmsy = all.BBmsy.cmsy[,nyr]
    }
  #><>HW better performance if FFmsy = x for larger values
  kernel.temp <-
ci2d(x.F_Fmsy,y.b_bmsy,nbins=201,factor=2.2,ci.levels=c(0.50,0.80,0.75,0.90,0.95),show="none")
  kernelF = kernel.temp

  max.x1=max.y1   <- max(c(2, max(kernelF$contours$"0.95"$x,F.Fmsy),na.rm =T))
  max.y    <- ifelse(max.x1 > 5,min(max(5,F.Fmsy*2),8),max.x1)
  max.x    <- max(max(2,quantile(y.b_bmsy,0.96)))

  # -------------------------------------
  ## KOBE plot building
  # -------------------------------------
  #Create plot
  plot(1000,1000,type="b", xlim=c(0,max.x),
ylim=c(0,max.y),lty=3,xlab="",ylab=expression(F/F[MSY]), bty="l",  cex.main = 2, cex.lab = 1.35,
cex.axis = 1.35,xaxs = "i",yaxs="i")
  mtext(expression(B/B[MSY]),side=1, line=3, cex=1.3)
  c1 <- c(-1,100)
  c2 <- c(1,1)

  # extract interval information from ci2d object
  # and fill areas using the polygon function
  zb2 = c(0,1)
  zf2  = c(1,100)
  zb1 = c(1,100)
  zf1  = c(0,1)
  polygon(c(zb1,rev(zb1)),c(0,0,1,1),col="green",border=0)
  polygon(c(zb2,rev(zb2)),c(0,0,1,1),col="yellow",border=0)
  polygon(c(1,100,100,1),c(1,1,100,100),col="orange",border=0)
  polygon(c(0,1,1,0),c(1,1,100,100),col="red",border=0)

  polygon(kernelF$contours$"0.95"[,2:1],lty=2,border=NA,col="cornsilk4")
  polygon(kernelF$contours$"0.8"[,2:1],border=NA,lty=2,col="grey")
  polygon(kernelF$contours$"0.5"[,2:1],border=NA,lty=2,col="cornsilk2")
  points(B.Bmsy,F.Fmsy,pch=16,cex=1)
  lines(c1,c2,lty=3,lwd=0.7)
  lines(c2,c1,lty=3,lwd=0.7)
  lines(B.Bmsy,F.Fmsy, lty=1,lwd=1.)
  points(B.Bmsy[1],F.Fmsy[1],col=1,pch=22,bg="white",cex=1.5)
  points(B.Bmsy[which(yr==int.yr)],F.Fmsy[which(yr==int.yr)],col=1,pch=21,bg="white",cex=1.5)
  points(B.Bmsy[nyr],F.Fmsy[nyr],col=1,pch=24,bg="white",cex=1.5)
  # Get Propability
  Pr.green = sum(ifelse(y.b_bmsy>1 & x.F_Fmsy<1,1,0))/length(y.b_bmsy)*100
  Pr.red = sum(ifelse(y.b_bmsy<1 & x.F_Fmsy>1,1,0))/length(y.b_bmsy)*100
```

```
   Pr.yellow = sum(ifelse(y.b_bmsy<1 & x.F_Fmsy<1,1,0))/length(y.b_bmsy)*100
   Pr.orange = sum(ifelse(y.b_bmsy>1 & x.F_Fmsy>1,1,0))/length(y.b_bmsy)*100

   sel.years = c(yr[sel.yr])

   legend('topright',
          c(paste(start.yr),paste(int.yr),paste(end.yr),"50% C.I.","80% C.I.","95%
C.I.",paste0(round(c(Pr.red,Pr.yellow,Pr.orange,Pr.green),1),"%")),
          lty=c(1,1,1,rep(-
1,8)),pch=c(22,21,24,rep(22,8)),pt.bg=c(rep("white",3),"cornsilk2","grey","cornsilk4","red","yellow","or
ange","green"),
          col=1,lwd=1.1,cex=1.1,pt.cex=c(rep(1.3,3),rep(1.7,3),rep(2.2,4)),bty="n",y.intersp = 1.)

   if (save.plots==TRUE & kobe.plot==TRUE) {
     jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_KOBE.jpg",sep="")
            if (retrosp.step>0) jpgfile<-gsub(".jpg", paste0("_retrostep_",retrosp.step,".jpg"), jpgfile)
#modification added to save all steps in retrospective analysis
     dev.copy(jpeg,jpgfile,
            width = 1024*0.7,
            height = 1024*0.7,
            units = "px",
            pointsize = 18,
            quality = 95,
            res=80,
            antialias="cleartype")
     dev.off()
   }
  }

  #HW Kobe plot end
  #-------------------------------------------------------
  # Write cmsy rdata oject (new ><>HW July 2021)
  #-------------------------------------------------------
  if(write.rdata==TRUE){
   cmsy = list()
   cmsy$stock = stock
   cmsy$yr = yr
   cmsy$catch = ct
   cmsy$cmsy = list()
   cmsy$cmsy$timeseries = array(data=NA,dim=c(length(yr),3,2),dimnames =
list(yr,c("mu","lci","uci"),c("BBmsy","FFmsy")))
   cmsy$cmsy$timeseries[,1,"BBmsy"] =  BBmsy.cmsy
   cmsy$cmsy$timeseries[,2,"BBmsy"] =  lcl.BBmsy.cmsy
   cmsy$cmsy$timeseries[,3,"BBmsy"] =  ucl.BBmsy.cmsy
   cmsy$cmsy$timeseries[,1,"FFmsy"] =  FFmsy.cmsy
   cmsy$cmsy$timeseries[,2,"FFmsy"] =  lcl.FFmsy.cmsy
   cmsy$cmsy$timeseries[,3,"FFmsy"] =  ucl.FFmsy.cmsy
   cmsy$cmsy$brp =
t(data.frame(mu=c(r.cmsy,k.cmsy,MSY.cmsy,Bmsy.cmsy,Fmsy.cmsy),lci=c(lcl.r.cmsy,lcl.k.cmsy,lcl.MS
Y.cmsy,lcl.Bmsy.cmsy,lcl.Fmsy.cmsy),uci=c(ucl.r.cmsy,ucl.k.cmsy,ucl.MSY.cmsy,ucl.Bmsy.cmsy,ucl.F
msy.cmsy)))
```

```
    colnames(cmsy$cmsy$brp) = c("r","k","MSY","Bmsy","Fmsy")
    cmsy$cmsy$rk = data.frame(r=rs,k=ks)
    cmsy$cmsy$kobe = data.frame(BBmsy=all.BBmsy.cmsy[,nyr],FFmsy=all.FFmsy.cmsy[,nyr])


    if(FullSchaefer==F){
      cmsy$bsm = NULL
    } else {
      cmsy$bsm = list()
      cmsy$bsm$timeseries = array(data=NA,dim=c(length(yr),3,2),dimnames =
list(yr,c("mu","lci","uci"),c("BBmsy","FFmsy")))
      cmsy$bsm$timeseries[,1,"BBmsy"] =  BBmsy.bsm
      cmsy$bsm$timeseries[,2,"BBmsy"] =  lcl.BBmsy.bsm
      cmsy$bsm$timeseries[,3,"BBmsy"] =  ucl.BBmsy.bsm
      cmsy$bsm$timeseries[,1,"FFmsy"] =  FFmsy.bsm
      cmsy$bsm$timeseries[,2,"FFmsy"] =  lcl.FFmsy.bsm
      cmsy$bsm$timeseries[,3,"FFmsy"] =  ucl.FFmsy.bsm
      cmsy$bsm$brp =
t(data.frame(mu=c(r.bsm,k.bsm,MSY.bsm,Bmsy.bsm,Fmsy.bsm),lci=c(lcl.r.bsm,lcl.k.bsm,lcl.MSY.bsm,l
cl.Bmsy.bsm,lcl.Fmsy.bsm),uci=c(ucl.r.bsm,ucl.k.bsm,ucl.MSY.bsm,ucl.Bmsy.bsm,ucl.Fmsy.bsm)))
      colnames(cmsy$bsm$brp) = c("r","k","MSY","Bmsy","Fmsy")
      cmsy$bsm$rk = data.frame(r=rs.bsm,k=ks.bsm)
      cmsy$bsm$kobe = data.frame(BBmsy=all.BBmsy.bsm[,nyr],FFmsy=all.FFmsy.bsm[,nyr])
    } # end of Full Schaefer condition

    # save
    save(cmsy,file=paste0("cmsy_",stock,".rdata"))

  } #Write Rdata


  # -------------------------------------
  ## Write results into csv outfile
  # -------------------------------------
  if(write.output == TRUE && retrosp.step==0) { #account for retrospective analysis - write only the last
result

    # fill catches from 1970 to 2020
    # if leading catches are missing, set them to zero; if trailing catches are missing, set them to NA
    ct.out     <- vector()
    F.Fmsy.out <- vector()
    bt.out     <- vector()

    j <- 1
    for(i in 1950 : 2030) {
      if(yr[1]>i) {
        ct.out[j]     <-0
        F.Fmsy.out[j] <-0
        bt.out[j]     <-2*Bmsy
      } else {
        if(i>yr[length(yr)]) {
```

```
   ct.out[j]     <-NA
   F.Fmsy.out[j] <-NA
   bt.out[j]     <-NA } else {
    ct.out[j]     <- ct.raw[yr==i]
    F.Fmsy.out[j] <- F.Fmsy[yr==i]
    bt.out[j]     <- B[yr==i]}
 }
 j=j+1
}

# write data into csv file
output = data.frame(as.character(cinfo$Group[cinfo$Stock==stock]),
          as.character(cinfo$Region[cinfo$Stock==stock]),
          as.character(cinfo$Subregion[cinfo$Stock==stock]),
          as.character(cinfo$Name[cinfo$Stock==stock]),
          cinfo$ScientificName[cinfo$Stock==stock],
          stock, start.yr, end.yr, start.yr.new, btype,length(bt[is.na(bt)==F]),
          ifelse(FullSchaefer==T,yr[which(bt>0)[1]],NA),
          ifelse(FullSchaefer==T,yr[max(which(bt>0))],NA),
          ifelse(FullSchaefer==T,min(bt[is.na(bt)==F],na.rm=T),NA),
          ifelse(FullSchaefer==T,max(bt[is.na(bt)==F],na.rm=T),NA),
          ifelse(FullSchaefer==T,yr[which.min(bt)],NA),
          ifelse(FullSchaefer==T,yr[which.max(bt)],NA),
          endbio[1],endbio[2],
          ifelse(FullSchaefer==T,q.prior[1],NA),
          ifelse(FullSchaefer==T,q.prior[2],NA),
          max(ct.raw),MSY.pr,mean(ct.raw[(nyr-4):nyr]),sd(ct.raw[(nyr-4):nyr]),ct.raw[nyr],
          min(ct),max(ct),mean(ct),gm.prior.r,
          ifelse(FullSchaefer==T,MSY.bsm,NA), # full Schaefer
          ifelse(FullSchaefer==T,lcl.MSY.bsm,NA),
          ifelse(FullSchaefer==T,ucl.MSY.bsm,NA),
          ifelse(FullSchaefer==T,r.bsm,NA),
          ifelse(FullSchaefer==T,lcl.r.bsm,NA),
          ifelse(FullSchaefer==T,ucl.r.bsm,NA),
          ifelse(FullSchaefer==T,log.r.var,NA),
          ifelse(FullSchaefer==T,k.bsm,NA),
          ifelse(FullSchaefer==T,lcl.k.bsm,NA),
          ifelse(FullSchaefer==T,ucl.k.bsm,NA),
          ifelse(FullSchaefer==T,log.k.var,NA),
          ifelse(FullSchaefer==T,log.kr.cor,NA),
          ifelse(FullSchaefer==T,log.kr.cov,NA),
          ifelse(FullSchaefer==T, q.bsm,NA),
          ifelse(FullSchaefer==T,lcl.q.bsm,NA),
          ifelse(FullSchaefer==T,ucl.q.bsm,NA),
          ifelse(FullSchaefer==T,bk.bsm[nyr],B.Bmsy[nyr]/2), # last B/k JAGS
          ifelse(FullSchaefer==T,lcl.bk.bsm[nyr],NA),
          ifelse(FullSchaefer==T,ucl.bk.bsm[nyr],NA),
          ifelse(FullSchaefer==T,bk.bsm[1],B.Bmsy[1]/2), # first B/k JAGS
          ifelse(FullSchaefer==T,lcl.bk.bsm[1],NA),
          ifelse(FullSchaefer==T,ucl.bk.bsm[1],NA),
          ifelse(FullSchaefer==T,bk.bsm[yr==int.yr],B.Bmsy[yr==int.yr]/2), # int year B/k JAGS
```

```
            ifelse(FullSchaefer==T,lcl.bk.bsm[yr==int.yr],NA),
            ifelse(FullSchaefer==T,ucl.bk.bsm[yr==int.yr],NA),
            int.yr, # int year
            ifelse(FullSchaefer==T,FFmsy.bsm[nyr],NA), # last F/Fmsy JAGS
            r.cmsy, lcl.r.cmsy, ucl.r.cmsy, # CMSY r
            k.cmsy, lcl.k.cmsy, ucl.k.cmsy, # CMSY k
            MSY.cmsy, lcl.MSY.cmsy, ucl.MSY.cmsy, # CMSY MSY
            bk.cmsy[nyr],lcl.bk.cmsy[nyr],ucl.bk.cmsy[nyr], # CMSY B/k in last year with catch data
            bk.cmsy[1],lcl.bk.cmsy[1],ucl.bk.cmsy[1], # CMSY B/k in first year
            bk.cmsy[yr==int.yr],lcl.bk.cmsy[yr==int.yr],ucl.bk.cmsy[yr==int.yr], # CMSY B/k in
intermediate year
            FFmsy.cmsy[nyr],lcl.FFmsy.cmsy[nyr],ucl.FFmsy.cmsy[nyr],
            Fmsy,lcl.Fmsy,ucl.Fmsy,Fmsy.adj[nyr],lcl.Fmsy.adj[nyr],ucl.Fmsy.adj[nyr],
            MSY,lcl.MSY,ucl.MSY,Bmsy,lcl.Bmsy,ucl.Bmsy,
            B[nyr], lcl.B[nyr], ucl.B[nyr], B.Bmsy[nyr], lcl.B.Bmsy[nyr], ucl.B.Bmsy[nyr],
            Ft[nyr], lcl.Ft[nyr], ucl.Ft[nyr], F.Fmsy[nyr], lcl.F.Fmsy[nyr], ucl.F.Fmsy[nyr],
            ifelse(is.na(sel.yr)==F,B.sel,NA),
            ifelse(is.na(sel.yr)==F,B.Bmsy.sel,NA),
            ifelse(is.na(sel.yr)==F,F.sel,NA),
            ifelse(is.na(sel.yr)==F,F.Fmsy.sel,NA),

ct.out[1],ct.out[2],ct.out[3],ct.out[4],ct.out[5],ct.out[6],ct.out[7],ct.out[8],ct.out[9],ct.out[10],        #
1950-1959

ct.out[11],ct.out[12],ct.out[13],ct.out[14],ct.out[15],ct.out[16],ct.out[17],ct.out[18],ct.out[19],ct.out[20], #
1960-1969

ct.out[21],ct.out[22],ct.out[23],ct.out[24],ct.out[25],ct.out[26],ct.out[27],ct.out[28],ct.out[29],ct.out[30], #
1970-1979

ct.out[31],ct.out[32],ct.out[33],ct.out[34],ct.out[35],ct.out[36],ct.out[37],ct.out[38],ct.out[39],ct.out[40], #
1980-1989

ct.out[41],ct.out[42],ct.out[43],ct.out[44],ct.out[45],ct.out[46],ct.out[47],ct.out[48],ct.out[49],ct.out[50], #
1990-1999

ct.out[51],ct.out[52],ct.out[53],ct.out[54],ct.out[55],ct.out[56],ct.out[57],ct.out[58],ct.out[59],ct.out[60], #
2000-2009

ct.out[61],ct.out[62],ct.out[63],ct.out[64],ct.out[65],ct.out[66],ct.out[67],ct.out[68],ct.out[69],ct.out[70], #
2010-2019

ct.out[71],ct.out[72],ct.out[73],ct.out[74],ct.out[75],ct.out[76],ct.out[77],ct.out[78],ct.out[79],ct.out[80],ct
.out[81], # 2020-2030

F.Fmsy.out[1],F.Fmsy.out[2],F.Fmsy.out[3],F.Fmsy.out[4],F.Fmsy.out[5],F.Fmsy.out[6],F.Fmsy.out[7],F
.Fmsy.out[8],F.Fmsy.out[9],F.Fmsy.out[10], # 1950-1959

F.Fmsy.out[11],F.Fmsy.out[12],F.Fmsy.out[13],F.Fmsy.out[14],F.Fmsy.out[15],F.Fmsy.out[16],F.Fmsy.
out[17],F.Fmsy.out[18],F.Fmsy.out[19],F.Fmsy.out[20], # 1960-1969
```

```
F.Fmsy.out[21],F.Fmsy.out[22],F.Fmsy.out[23],F.Fmsy.out[24],F.Fmsy.out[25],F.Fmsy.out[26],F.Fmsy.
out[27],F.Fmsy.out[28],F.Fmsy.out[29],F.Fmsy.out[30], # 1970-1979

F.Fmsy.out[31],F.Fmsy.out[32],F.Fmsy.out[33],F.Fmsy.out[34],F.Fmsy.out[35],F.Fmsy.out[36],F.Fmsy.
out[37],F.Fmsy.out[38],F.Fmsy.out[39],F.Fmsy.out[40], # 1980-1989

F.Fmsy.out[41],F.Fmsy.out[42],F.Fmsy.out[43],F.Fmsy.out[44],F.Fmsy.out[45],F.Fmsy.out[46],F.Fmsy.
out[47],F.Fmsy.out[48],F.Fmsy.out[49],F.Fmsy.out[50], # 1990-1999

F.Fmsy.out[51],F.Fmsy.out[52],F.Fmsy.out[53],F.Fmsy.out[54],F.Fmsy.out[55],F.Fmsy.out[56],F.Fmsy.
out[57],F.Fmsy.out[58],F.Fmsy.out[59],F.Fmsy.out[60], # 2000-2009

F.Fmsy.out[61],F.Fmsy.out[62],F.Fmsy.out[63],F.Fmsy.out[64],F.Fmsy.out[65],F.Fmsy.out[66],F.Fmsy.
out[67],F.Fmsy.out[68],F.Fmsy.out[69],F.Fmsy.out[70], # 2010-2019

F.Fmsy.out[71],F.Fmsy.out[72],F.Fmsy.out[73],F.Fmsy.out[74],F.Fmsy.out[75],F.Fmsy.out[76],F.Fmsy.
out[77],F.Fmsy.out[78],F.Fmsy.out[79],F.Fmsy.out[80],F.Fmsy.out[81], # 2020-2030

bt.out[1],bt.out[2],bt.out[3],bt.out[4],bt.out[5],bt.out[6],bt.out[7],bt.out[8],bt.out[9],bt.out[10],          #
1950-1959

bt.out[11],bt.out[12],bt.out[13],bt.out[14],bt.out[15],bt.out[16],bt.out[17],bt.out[18],bt.out[19],bt.out[20],
# 1960-1969

bt.out[21],bt.out[22],bt.out[23],bt.out[24],bt.out[25],bt.out[26],bt.out[27],bt.out[28],bt.out[29],bt.out[30],
# 1970-1979

bt.out[31],bt.out[32],bt.out[33],bt.out[34],bt.out[35],bt.out[36],bt.out[37],bt.out[38],bt.out[39],bt.out[40],
# 1980-1989

bt.out[41],bt.out[42],bt.out[43],bt.out[44],bt.out[45],bt.out[46],bt.out[47],bt.out[48],bt.out[49],bt.out[50],
# 1990-1999

bt.out[51],bt.out[52],bt.out[53],bt.out[54],bt.out[55],bt.out[56],bt.out[57],bt.out[58],bt.out[59],bt.out[60],
# 2000-2009

bt.out[61],bt.out[62],bt.out[63],bt.out[64],bt.out[65],bt.out[66],bt.out[67],bt.out[68],bt.out[69],bt.out[70],
# 2010-2019

bt.out[71],bt.out[72],bt.out[73],bt.out[74],bt.out[75],bt.out[76],bt.out[77],bt.out[78],bt.out[79],bt.out[80],
bt.out[81]) # 2020-2030

   write.table(output, file=outfile, append = T, sep = ",",
             dec = ".", row.names = FALSE, col.names = FALSE)
 }

 #--------------------------------------------------------------------------------
 # The code below creates a report in PDF format if write.pdf is TRUE ----
 #--------------------------------------------------------------------------------
```

```
  ## To generate reports in PDF format, install a LaTeX program. For Windows, you can use
https://miktex.org/howto/install-miktex (restart after installation)
  ## Set write.pdf to 'TRUE' if you want pdf output.

  options(tinytex.verbose = TRUE)

  # Using MarkdownReports, this creates a markdown file for each stock then using rmarkdown to render
each markdown file into a pdf file.
  if(write.pdf == TRUE) {
    library(knitr)
    library(tinytex)

    docTemplate <- "\\documentclass[12pt,a4paper]{article}
    \\setlength\\parindent{0pt}
    \\usepackage{geometry}
    \\usepackage{graphicx}
    \\usepackage{grffile}
    \\geometry{margin=0.5in}
    \\begin{document}

    \\section*{#TITLE#}


    #INTRO#

    \\begin{figure}[ht]
    \\centering
    \\includegraphics[width=1.00\\textwidth ext=.jpg type=jpg]{#IMAGE1#}
    \\end{figure}

    #MANAGEMENT#

    \\pagebreak

    \\begin{figure}[ht]
    \\centering
    \\includegraphics[width=1.00\\textwidth ext=.jpg type=jpg]{#IMAGE2#}
    \\end{figure}

    #ANALYSIS#

    \\end{document}"

    title = gsub(":","",gsub("/","-",cinfo$Name[cinfo$Stock==stock]))

    intro = (paste("Species: \\\\emph{",cinfo$ScientificName[cinfo$Stock==stock],"}, Stock code: ",
                gsub(":","",gsub("/","-",stock)), sep=""))
    intro = (paste(intro,"\n\n","Region: ",gsub(":","",gsub("/","-",cinfo$Region[cinfo$Stock==stock])),
sep=""))
    intro = (paste(intro,"\n\n","Marine Ecoregion: ",gsub(":","",gsub("/","-
",cinfo$Subregion[cinfo$Stock==stock])), sep="" ))
```

```
  intro = (paste(intro,"\n\n","Reconstructed catch data used from years ", min(yr)," - ", max(yr),sep=""))
  intro = (paste(intro,"\n\n","For figure captions and method see http://www.seaaroundus.org/cmsy-
method"))


  docTemplate<-gsub("#TITLE#", title, docTemplate)
  docTemplate<-gsub("#INTRO#", intro, docTemplate)



  management_text<-paste("\\\\textbf{Results for management (based on",ifelse(FullSchaefer==F |
force.cmsy==T,"CMSY","BSM"),"analysis)}\\\\\\\\")
  management_text<-(paste(management_text,"\n\n","Fmsy = ",format(Fmsy, digits =3),", 95% CL =
",format(lcl.Fmsy, digits =3)," - ",format(ucl.Fmsy, digits =3)," (if B $>$ 1/2 Bmsy then Fmsy = 0.5 r)",
sep=""))
  management_text<-(paste(management_text,"\n\n","Fmsy = ",format(Fmsy.adj[nyr], digits =3),", 95%
CL = ",format(lcl.Fmsy.adj[nyr], digits =3)," - ",format(ucl.Fmsy.adj[nyr], digits =3)," (r and Fmsy are
linearly reduced if B $<$ 1/2 Bmsy)",sep=""))
  management_text<-(paste(management_text,"\n\n","MSY = ",format(MSY, digits =3),",  95% CL =
",format(lcl.MSY, digits =3)," - ",format(ucl.MSY, digits =3),'; Bmsy = ',format(Bmsy, digits =3),",  95%
CL = ",format(lcl.Bmsy, digits =3)," - ",format(ucl.Bmsy, digits =3)," (1000 tonnes)",sep=""))
  management_text<-(paste(management_text,"\n\n","Biomass in last year = ",format(B[nyr], digits
=3),", 95% CL = ", format(lcl.B[nyr], digits =3), " - ",format(ucl.B[nyr], digits =3)," (1000
tonnes)",sep=""))
  management_text<-(paste(management_text,"\n\n","B/Bmsy in last year = " ,format(B.Bmsy[nyr],
digits =3),", 95% CL = ", format(lcl.B.Bmsy[nyr], digits =3), " - ",format(ucl.B.Bmsy[nyr], digits
=3),sep=""))
  management_text<-(paste(management_text,"\n\n","Fishing mortality in last year = ",format(Ft[nyr],
digits =3),", 95% CL =", format(lcl.Ft[nyr], digits =3), " - ",format(ucl.Ft[nyr], digits =3),sep=""))
  management_text<-(paste(management_text,"\n\n","F/Fmsy  = ",format(F.Fmsy[nyr], digits =3),", 95%
CL = ", format(lcl.F.Fmsy[nyr], digits =3), " - ",format(ucl.F.Fmsy[nyr], digits =3),sep=""))
  management_text<-(paste(management_text,"\n\n","Comment:", gsub(":","",gsub("/","",comment)),
""))
  docTemplate<-gsub("#MANAGEMENT#", management_text, docTemplate)

  analysis_text<-(paste("\\\\textbf{Results of CMSY analysis conducted in JAGS}\\\\\\\\",sep=""))
  analysis_text<-(paste(analysis_text,"\n\n","r = ", format(r.cmsy, digits =3),", 95% CL = ",
format(lcl.r.cmsy, digits =3), " - ", format(ucl.r.cmsy, digits =3),"; k = ", format(k.cmsy, digits =3),", 95%
CL = ", format(lcl.k.cmsy, digits =3), " - ", format(ucl.k.cmsy, digits =3)," (1000 tonnes)",sep=""))
  analysis_text<-(paste(analysis_text,"\n\n","MSY = ", format(MSY.cmsy, digits =3),", 95% CL = ",
format(lcl.MSY.cmsy, digits =3), " - ", format(ucl.MSY.cmsy, digits =3)," (1000 tonnes/year)",sep=""))
  analysis_text<-(paste(analysis_text,"\n\n","Relative biomass last year = ", format(bk.cmsy[nyr], digits
=3), " k, 95% CL = ", format(lcl.bk.cmsy[nyr], digits =3), " - ", format(ucl.bk.cmsy[nyr], digits
=3),sep=""))
  analysis_text<-(paste(analysis_text,"\n\n","Exploitation F/(r/2) in last year = ",
format((FFmsy.cmsy)[length(bk.cmsy)-1], digits =3),sep=""))

  if(FullSchaefer==T) {
    analysis_text <- paste(analysis_text,"\\\\\\\\")
    analysis_text<-(paste(analysis_text,"\n\n", "\\\\textbf{Results from Bayesian Schaefer model using
catch and ",btype,"}\\\\\\\\",sep=""))
```

```
      analysis_text<-(paste(analysis_text,"\n\n","r = ", format(r.bsm, digits =3),", 95% CL = ",
format(lcl.r.bsm, digits =3), " - ", format(ucl.r.bsm, digits =3),"; k = ", format(k.bsm, digits =3),", 95%
CL = ", format(lcl.k.bsm, digits =3), " - ", format(ucl.k.bsm, digits =3),sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","r-k log correlation = ", format(log.kr.cor, digits
=3),sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","MSY = ", format(MSY.bsm, digits =3),", 95% CL = ",
format(lcl.MSY.bsm, digits =3), " - ", format(ucl.MSY.bsm, digits =3)," (1000 tonnes/year)",sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","Relative biomass in last year = ", format(bk.cmsy[nyr],
digits =3), " k, 95% CL = ",format(lcl.bk.cmsy[nyr], digits =3)," - ", format(ucl.bk.cmsy[nyr], digits
=3),sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","Exploitation F/(r/2) in last year = ",
format((ct.raw[nyr]/(bk.cmsy[nyr]*k.bsm))/(r.bsm/2), digits =3),sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","q = ", format(q.bsm, digits =3),", 95% CL = ",
format(lcl.q.bsm, digits =3), " - ", format(ucl.q.bsm, digits =3),sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","Prior range of q = ",format(q.prior[1], digits =3)," -
",format(q.prior[2], digits =3),sep=""))
    }
    # show stock status and exploitation for optional selected year
    if(is.na(sel.yr)==F) {
      analysis_text<-(paste(analysis_text,"\n\n","Stock status and exploitation in ",sel.yr,sep=""))
      analysis_text<-(paste(analysis_text,"\n\n","Biomass = ",format(B.sel, digits =3), ", B/Bmsy =
",format(B.Bmsy.sel, digits =3),", fishing mortality F = ",format(F.sel, digits =3),", F/Fmsy =
",format(F.Fmsy.sel, digits =3),sep=""))
    }

    if(btype !="None" & length(bt[is.na(bt)==F])<nab) {
      analysis_text<-(paste(analysis_text,"\n\n","Less than ",nab," years with abundance data available,
shown on second axis",sep="")) }


    analysis_text<-(paste(analysis_text,"\n\n","Relative abundance data type = ", format(btype, digits
=3),sep=""))
    analysis_text<-(paste(analysis_text,"\n\n","Prior initial relative biomass = ", format(startbio[1], digits
=3) , " - ", format(startbio[2], digits =3),ifelse(is.na(stb.low)==T," default"," expert"),sep=""))
    analysis_text<-(paste(analysis_text,"\n\n","Prior intermediate relative biomass = ", format(intbio[1],
digits =3), " - ", format(intbio[2], digits =3), " in year ", int.yr,ifelse(is.na(intb.low)==T," default","
expert"),sep=""))
    analysis_text<-(paste(analysis_text,"\n\n","Prior final relative biomass = ", format(endbio[1], digits
=3), " - ", format(endbio[2], digits =3),ifelse(is.na(endb.low)==T,", default"," expert"),sep=""))
    analysis_text<-(paste(analysis_text,"\n\n","Prior range for r = ", format(prior.r[1],digits=2), " - ",
format(prior.r[2],digits=2),ifelse(is.na(r.low)==T," default"," expert"),", prior range for k = " ,
format(prior.k[1], digits =3), " - ", format(prior.k[2], digits =3)," (1000 tonnes) default",sep=""))
    analysis_text<-(paste(analysis_text,"\n\n","Source for relative biomass: \n\n",source,"",sep=""))

    docTemplate<-gsub("#ANALYSIS#", analysis_text, docTemplate)

    docTemplate<-gsub("_", "\\\\_", docTemplate)
    docTemplate<-gsub("%", "\\\\%", docTemplate)


    analysischartfile<-paste(gsub(":","",gsub("/","-",stock)),"_AN.jpg",sep="")
```

```
   managementchartfile<-paste(gsub(":","",gsub("/","-",stock)),"_MAN.jpg",sep="")
   docTemplate<-gsub("#IMAGE1#", managementchartfile, docTemplate)
   docTemplate<-gsub("#IMAGE2#", analysischartfile, docTemplate)

   # unique filenames to prevent error if files exists from previous run
   documentfile<-paste(gsub(":","",gsub("/","-",stock)),substr(as.character(Sys.time()),1,10),"-
",sub(":","",substr(as.character(Sys.time()),12,16)),".RnW",sep="") # concatenated hours and minutes
added to file name
   cat(docTemplate,file=documentfile,append=F)

   knit(documentfile)
   knitr::knit2pdf(documentfile)

   cat("PDF document is ",gsub(".RnW",".pdf",documentfile))

  }
  # end of loop to write text to file


  if(close.plots==T) graphics.off() # close on-screen graphics windows after files are saved

  FFmsy.retrospective[[retrosp.step+1]]<-F.Fmsy #retrospective analysis
  BBmsy.retrospective[[retrosp.step+1]]<-B.Bmsy #retrospective analysis
  years.retrospective[[retrosp.step+1]]<-yr #retrospective analysis

  } #retrospective analysis - end loop

        #retrospective analysis plots
        if (retros == T){

          if(grepl("win",tolower(Sys.info()['sysname']))) {windows(14,7)}
                par(mfrow=c(1,2), mar=c(4,5,4,5),  oma=c(2,2,2,2))

         allyears<-years.retrospective[[1]]
         nyrtotal<-length(allyears)
         legendyears<-c("All years")
         #CHECK IF ALL YEARS HAVE BEEN COMPUTED
         for (ll in 1:4){
           if (ll>length(FFmsy.retrospective)){
             FFmsy.retrospective[[ll]]<-c(0)
             BBmsy.retrospective[[ll]]<-c(0)
           }
           else {
             if(ll>1)
               legendyears<-c(legendyears,allyears[nyrtotal-ll+1])
           }
         }

         #PLOT FFMSY RETROSPECTIVE ANALYSIS
         plot(x=allyears[1:nyrtotal],y=FFmsy.retrospective[[1]], main="",
              ylim=c(0,max(max(FFmsy.retrospective[[1]],na.rm=T),
```

```
                    max(FFmsy.retrospective[[2]],na.rm=T),
                    max(FFmsy.retrospective[[3]],na.rm=T),
                    max(FFmsy.retrospective[[4]],na.rm=T))),
                lwd=2, xlab="Year", ylab="F/Fmsy", type="l", bty="l",
                cex.main = 1.5, cex.lab = 1.5, cex.axis = 1.5) #, xaxs="i",yaxs="i",xaxt="n",yaxt="n")
            #PLOT ONLY THE TIME SERIES THAT ARE COMPLETE
            if (length(FFmsy.retrospective[[2]])>1 || FFmsy.retrospective[[2]]!=0)
              lines(x=allyears[1:(nyrtotal-1)],y=FFmsy.retrospective[[2]], type = "o", pch=15, col="red")
            if (length(FFmsy.retrospective[[3]])>1 || FFmsy.retrospective[[3]]!=0)
              lines(x=allyears[1:(nyrtotal-2)],y=FFmsy.retrospective[[3]], type = "o", pch=16, col="green")
            if (length(FFmsy.retrospective[[4]])>1 || FFmsy.retrospective[[4]]!=0)
              lines(x=allyears[1:(nyrtotal-3)],y=FFmsy.retrospective[[4]], type = "o", pch=17, col="blue")
            legend("bottomleft", legend = legendyears,
                  col=c("black","red", "green", "blue"), lty=1, pch=c(-1,15,16,17))
            #PLOT BBMSY RETROSPECTIVE ANALYSIS
            plot(x=allyears[1:(nyrtotal)],y=BBmsy.retrospective[[1]],main="",
ylim=c(0,max(max(BBmsy.retrospective[[1]],na.rm=T),
                                                    max(BBmsy.retrospective[[2]],na.rm=T),
                                                    max(BBmsy.retrospective[[3]],na.rm=T),
                                                    max(BBmsy.retrospective[[4]],na.rm=T))),
                lwd=2, xlab="Year", ylab="B/Bmsy", type="l", bty="l",cex.main = 1.5, cex.lab = 1.5,
cex.axis = 1.5) #, xaxs="i",yaxs="i",xaxt="n",yaxt="n")
            if (length(BBmsy.retrospective[[2]])>1 || BBmsy.retrospective[[2]]!=0)
              lines(x=allyears[1:(nyrtotal-1)],y=BBmsy.retrospective[[2]], type = "o", pch=15, col="red")
            if (length(BBmsy.retrospective[[3]])>1 || BBmsy.retrospective[[3]]!=0)
              lines(x=allyears[1:(nyrtotal-2)],y=BBmsy.retrospective[[3]], type = "o", pch=16, col="green")
            if (length(BBmsy.retrospective[[4]])>1 || BBmsy.retrospective[[4]]!=0)
              lines(x=allyears[1:(nyrtotal-3)],y=BBmsy.retrospective[[4]], type = "o", pch=17, col="blue")
            legend("bottomleft", legend = legendyears,
                  col=c("black","red", "green", "blue"), lty=1, pch=c(-1,15,16,17))

            mtext(paste0("Retrospective analysis for ",stock),  outer = T , cex=1.5)

            #save analytic chart to JPEG file
   if (save.plots==TRUE) {
     jpgfile<-paste(gsub(":","",gsub("/","-",stock)),"_RetrospectiveAnalysis.jpg",sep="")
     dev.copy(jpeg,jpgfile,
            width = 1024,
            height = 576,
            units = "px",
            pointsize = 10,
            quality = 95,
            res=80,
            antialias="default")
     dev.off()
   }

            if(close.plots==T) graphics.off() # close on-screen graphics windows after files are saved
          } #retrospective analysis plots - end

} # end of stocks loop
```