ADVANCES IN THE ASSESSMENT OF THE SAGINAW BAY STOCK OF WALLEYES, LAKE HURON AND EVALUATION OF MANAGEMENT OPTIONS

By

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ABSTRACT

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Fundamental to the careful management of fish stocks is information on mortality rates and other dynamic functions that characterize that stock. Prior to this work, such efforts for walleyes from the Saginaw Bay stock were conducted with a Brownie style analysis of jaw tag reports. Unlikely assumptions and limited participation by all fisheries in their report of tags, necessitated the elevation of stock assessment methods to state of the art methods. I developed a statistical catch-at-age model to accomplish this and evaluated four versions including three different treatments of natural mortality (M): a constant value, age-based M values, and time-varying M values. Deviance information criterion model selection procedures indicated that an age-based M model version was the optimal fit of the data. I also evaluated an integrated version that incorporated tag returns as auxiliary information for the recreational component. In this case, model selection was based on conformity between observed and predicted data and model convergence. The integrated version was ruled out due to poor agreement of the observed and predicted values, and predictions of abundance that were not reflected by the fisheries. It was concluded that the component of the population used for tagging may exhibit dynamics that differ from the rest of the stock. Total annual mortality of walleyes was greatest for older ages in all fisheries and ranged from 32% for age-2 fish to 39% for fish ages-10 and older. The recreational fishery accounted for the majority of fishing mortality but the commercial trapnet

fishery in the main basin of Lake Huron and by-kill from other trapnets in the bay accounted for proportionally greater fishing mortality of younger ages of fish. Abundance peaked in 2007 at 4 million walleyes age 2 and older but estimates indicated a previous period of high abundance in the late 1980s, forcing the reconsideration of the past stock as depressed and dependent on stocking. Statistical catch-at-age methods characterize the dynamics of a stock from the past up to the present but do not project forward what the fish stock is likely to do in the future under various management scenarios. After consulting with fishery managers, I developed a stochastic simulation model and used it to evaluate management options for the recreational fishery in the form of a decision analysis and a value-of-information analysis for improved estimates of by-kill magnitude. This analysis was in light of two critical uncertain states of nature concerning the true magnitude (catchability) of the by-kill and the future of alewives in Lake Huron, the latter being a strong determinant of walleye recruitment. Management option evaluation indicated a greater harvestable surplus that could be allocated. Sustainable harvest was calculated as average harvest treating harvest in years when sustainability criteria were not met as zero. Sustainable harvest would be maximized if recreational fishing mortality were increased 50% from recent levels. Realizing this potential, however, would require more intensive management to ensure that desired levels of *F* occurred. Choices by managers as to how to allocate surplus harvest are a matter of policy, but concerns over maintaining predation pressure on alewives so as to suppress any resurgence may be reasons to manage conservatively by electing to instead maintain a higher predator abundance. The value of information analysis suggests that further research investment in the uncertainty over by-kill catchability might be justified on the basis of producing net-benefits from the recreational fishery.

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PREFACE

The materials in chapters two and three are intended for publication in peer-reviewed journals. I therefore would like to acknowledge my coauthors; Dr. Jim Bence for chapter 2 and Drs. Mike Jones and Jim Bence for chapter 3. For the purpose of this dissertation, I have generally used first person in the singular but it is understood that any publication that results from this work may differ slightly and include plurality in language.

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CHAPTER 1

DISSERTATION INTRODUCTION

Of the Laurentian Great Lakes, Lake Huron is the second largest and regarded as oligotrophic (Beeton et al. 1999). There are eutrophic regions of the lake, chief among them being Saginaw Bay at 2,947 km^2, lying entirely in the Michigan waters of the lake (Figure 1.1). Saginaw Bay historically was the site of the second largest walleye (*Sander vitreus*) fishery and population in the Great Lakes, behind only that of Lake Erie (Baldwin and Saafeld 1962; Schneider and Leach 1979).

The history of the Saginaw Bay walleye population and its fisheries have been characterized by three periods (Fielder and Thomas 2006). During the first period (late 1800s ~1970) there was unregulated commercial exploitation, habitat degradation, declining water quality, and effects of invasive species. The commercial walleye fishery collapsed in the mid-1940s due to recruitment failures attributed to these reasons (Schneider and Leach 1979; Keller et al. 1987). The second period (1971 – 2002) began with the passage of water quality legislation and the formal closure of commercial fishing for walleye in the bay. The Michigan Department of Natural Resources (DNR) implemented a walleye fingerling stocking program in the early 1980s and a sport fishery soon emerged (Mrozinski et al. 1991; Fielder 2002, Fielder et al. 2014). The population and fishery, however was still largely dependent on stocking and short of recovery targets (Fielder and Baker 2004).

The most recent period in Saginaw Bay's walleye history (2003 to present) has been the remarkable recovery of natural reproduction and the achievement of recovery goals (Fielder and Baker 2004; Fielder and Thomas 2014). This was brought about due to improved reproductive success which in turn was attributed to the decline of alewives (*Alosa pseudoharengus*) in Lake Huron (Fielder et al. 2007). Alewives are predators and competitors on newly hatched Percid fry (Kohler and Ney 1980; Brandt et al. 1987; Brooking et al. 1998) and use Saginaw Bay as spawning and nursery grounds (Organ et al. 1979). Walleye recovery targets were formally met in 2009.

Food web changes and trophic interactions are believed to have precipitated the near extirpation of alewives and decline in rainbow smelt (*Osmerus mordax*) in Lake Huron in the early 2000s (Riley et al. 2008; Riley and Roseman 2013). This is hypothesized to have been due to a combination of sequestering of productivity into the nearshore zone of the lake (Hecky et al. 2004; Cha et al. 2011), a decline in offshore productivity affecting phytoplankton and zooplankton as well as macroinvertebrates (Nalepa et al. 2007, 2009; Barbiero et al. 2009, 2011), and heavy predation from the lake's predators (Bence 2008, He et al. in press). The decline of alewives led to a severe contraction of the popular Chinook salmon (*Oncorhynchus tshawytscha*) fishery which drove a corresponding decline in recreational fishing effort in the Michigan waters of the lake (Michigan DNR, unpublished data). Walleye have emerged as an integral component in the remaining recreational fishery in Lake Huron (Fielder et al. 2014).

Saginaw Bay walleye have long been hypothesized to contribute to the main basin walleye population by some degree of migration (Hile 1954). A study of Saginaw Bay mortality and exploitation via jaw tagging further confirmed that at least some walleyes migrate throughout the Michigan waters of the lake (Fielder 2014). Genetic studies indicated that the Tittabawassee River (a tributary to the Saginaw River; Figure 1.1) spawning genotype was a substantial component of the commercial walleye fishery operating in Ontario's southern main basin waters (McParland et al. 1996). More recently, a telemetry study of Saginaw Bay walleye movement has confirmed that not only are walleyes making such a migration, but as many as half the adult fish emigrate as early as June after spawning in the bay's tributaries (T. Hayden, U.S. Geological Survey, Great Lakes Science Center, personal communication).

Large-scale emigration of walleye from Saginaw Bay to the main basin of the lake underscores the relevance of this species in understanding the whole lake fish community, including efforts to manage for a balance between predators and prey (He et al. in press). Such movement also contributes to spatial complexity of walleye exploitation across fishery types and jurisdictions. These revelations in combination with the recovery of the stock herald an elevated need for improved understanding of stock dynamics, exploitation, and sustainability. This information is needed to inform management for the future as a now recovered walleye stock will play an increasing important role in Lake Huron.

At the outset of this research, there were several unknowns and misconceptions. The awareness around the full extent of the movement made by Saginaw Bay walleyes was only revealed concurrently with this analysis. One of the benefits of stock assessment modeling is that it forces one to think explicitly about what processes shape the stock including the sources of mortality (Hilborn and Mangel 1997). Previously little regard was given to how Saginaw Bay walleyes might be exploited outside of the bay or how other fisheries may act in concert to constitute a collective source of mortality. These included recreational harvest outside of the bay, commercial harvest by Ontario fisheries and tribal commercial harvest (permitted as a by-catch) in the 1836 Treaty Waters of northern Lake Huron (Figure 1.1). An additional source of mortality not previously considered was that of by-kill (mortality of by-catch) by state of Michigan licensed commercial fisheries still operating in inner Saginaw Bay (permitted for other species aside from walleye). That assessment, performed by MacMillan and Roth (2012), added to the scope of Saginaw Bay walleye exploitation.

The stock assessment work undertaken in this research was not the first for Saginaw Bay walleyes. The Michigan DNR had sought to characterize the dynamics of mortality and exploitation for more than three decades using a Brownie-style analysis of tag recoveries (Fielder 2014). That work provided estimates of exploitation rate, total mortality rate, fishing mortality rate, and natural mortality rate. These metrics served as the basis for evaluating the status and sustainability of the walleye fishery for the Michigan DNR. That study, however, was almost exclusively limited to the recreational fishery as the other fisheries typically would not report the jaw tags. Consequently, the rates estimated were specific to only one component of several shaping that stock. This limitation was not fully apparent until those findings could be contrasted with the statistical catch-at-age (SCA) stock assessment performed in Chapter 2.

The motivation for developing a SCA model for Saginaw Bay walleye was driven by another study entitled "Quantifying new top-down influences on the rapidly changing food web in the main basin of Lake Huron." This work sought to evaluate certain predator/prey questions for the lake via a bioenergetics approach, which necessitated estimates of predator populations by age (He et al. in press). The Brownie-style analysis employed by the Michigan DNR could generate estimates of abundance but was not age structured. Aside from accommodating the bioenergetics model, I wished to elevate the stock assessment for Saginaw Bay walleyes to state of the art methods, so as to provide a stronger basis for management. SCA methods more thoroughly accommodate multiple fisheries than the earlier Brownie-style tag recovery analysis. SCA analysis posed its own unique challenges, however, in that estimates of natural mortality are not typically generated as a product of the analysis (Quinn and Deriso 1999) in contrast to tagging studies. A goal of my SCA analysis was to evaluate alternative estimates and sources of natural mortality information.

A further element of SCA modeling is the ability to integrate a greater variety of information (Punt et al. 2001) to improve model fit, resulting in more realistic parameter estimates. The ability to potentially combine the walleye tag returns as auxiliary information to help inform the SCA model fitting process could result in a hybrid model. The intent of this analysis was not just improved estimates but a strategy to guide stock assessment and inform management in the future.

An additional challenging aspect of this work was a need to account for the role of walleyes that immigrate to Lake Huron from Lake Erie on the Saginaw Bay population assessment. Because I derive the model based on the concepts of maximum penalized likelihood estimation by parameter fitting to match observed and predicted values such as harvest, I also had to account for harvest of Lake Erie stock fish in Lake Huron, so to be able to predict the harvest correctly without overestimating harvest from the Saginaw Bay stock.. This meant developing a means to predict the number of Lake Erie immigrants, so their contribution to the Lake Huron harvest could be accounted for. Lake Erie immigrants were initially believed to account for overall greater walleye abundances in the 1980s (i.e. more Lake Erie walleyes in Lake Huron than Saginaw Bay walleyes). This analysis provides the ability to evaluate that hypothesis.

In spite of the insights gained from the SCA analysis reported in Chapter 2, key uncertainties persist. The original estimate of by-kill reported by MacMillan and Roth (2012) was based on an observed period of May – August and a much larger extrapolated year-round value was also reported. Abundance estimates from the SCA model proved sensitive to which estimate was used. This uncertainty in the stock assessment model could translate into important uncertainty about the performance of future management strategies. Another key uncertainty governing the future of the stock is how alewives will trend. Because the food web changes in Lake Huron since the early 2000s were so unprecedented, it is uncertain whether alewives will remain scarce or will recover to previous levels of abundance. Alewife population recovery in Saginaw Bay may be tied to maintenance of predation pressure by walleyes. The future of alewives will likely be a critical determinant of future walleye recruitment and the whether the stock will sustain its recovery (Fielder et al. 2007).

The SCA model seeks to describe the status of the stock “today” based on how it performed in the past. Projecting the status of the stock out into the future is an entirely different matter but one closely tied to the stock assessment work. Ultimately fishery managers want to be able to design management strategies to sustain and optimally utilize the resource in the future. Because there are a number of uncertainties, I could not predict a single outcome for any given management strategy. Instead I sought to embrace uncertainty through use of decision analysis (Peterman and Anderson 1999) and a value of information analysis (Clemen and Reilly 2001). In Chapter 3 I describe the development of a stochastic simulation model based on the parameters developed in the SCA model. This is the basis to then conduct a decision analysis on management options for the future of the recreational fishery; asking the question; given the probability of the various combinations of potential states of nature represented by the uncertainties, which management option maximizes our goal while minimizing any exceedance of our limits of sustainability? A form of this decision analysis is an examination of the value of information. This analysis asks the question; is further investment in research justified to reduced or eliminate an uncertainty? That is the question asked about if improved understanding of the by-kill magnitude was warranted. These are the sort of practical management questions that can be tackled by the process of decision analysis accomplished through simulation modeling.

Management of the Saginaw Bay stock of walleye is transitioning from a recovery effort to one of maintenance and possibly allocation. The cessation of stocking in 2006 means that the principal future role of fishery managers will be to choose harvest policies and regulations as the primary means to meet future management objectives, balancing between meeting the harvest goals of the fisheries yet ensuring sustainability. The question of sustainability is elusive, however. Thresholds can be defined and strategies evaluated within the simulation model, however, the exact role of walleye as a predator on alewives in the lake is a harder question to isolate. Harvest reduces the walleye stock predictably but what is the threshold needed to ensure sufficient predation pressure on alewives to minimize the risk of a recovery? These questions are also explored but prove difficult since the full answer lies in the combined suite of predators in the lake, something beyond the scope of this work.

As is often the case with these types of analyses, as our understanding grows and questions are answered, new questions emerge exposing additional uncertainties. This becomes the context for further research and adaptive management options. The context for this research needs to be contemplated based partly on what the understanding of the stock was at the outset of the work. This work advances our understanding by more explicitly characterizing the status of the Saginaw Bay walleye stock and providing tools for crafting future management direction. Considerable discoveries have been made, and misconceptions revealed if not answered. Equally important is the recognition of new critical uncertainties that will confront future management and research. The ultimate utility of this work will depend on fishery managers and their willingness to advance management of this resource based on these findings.

APPENDIX

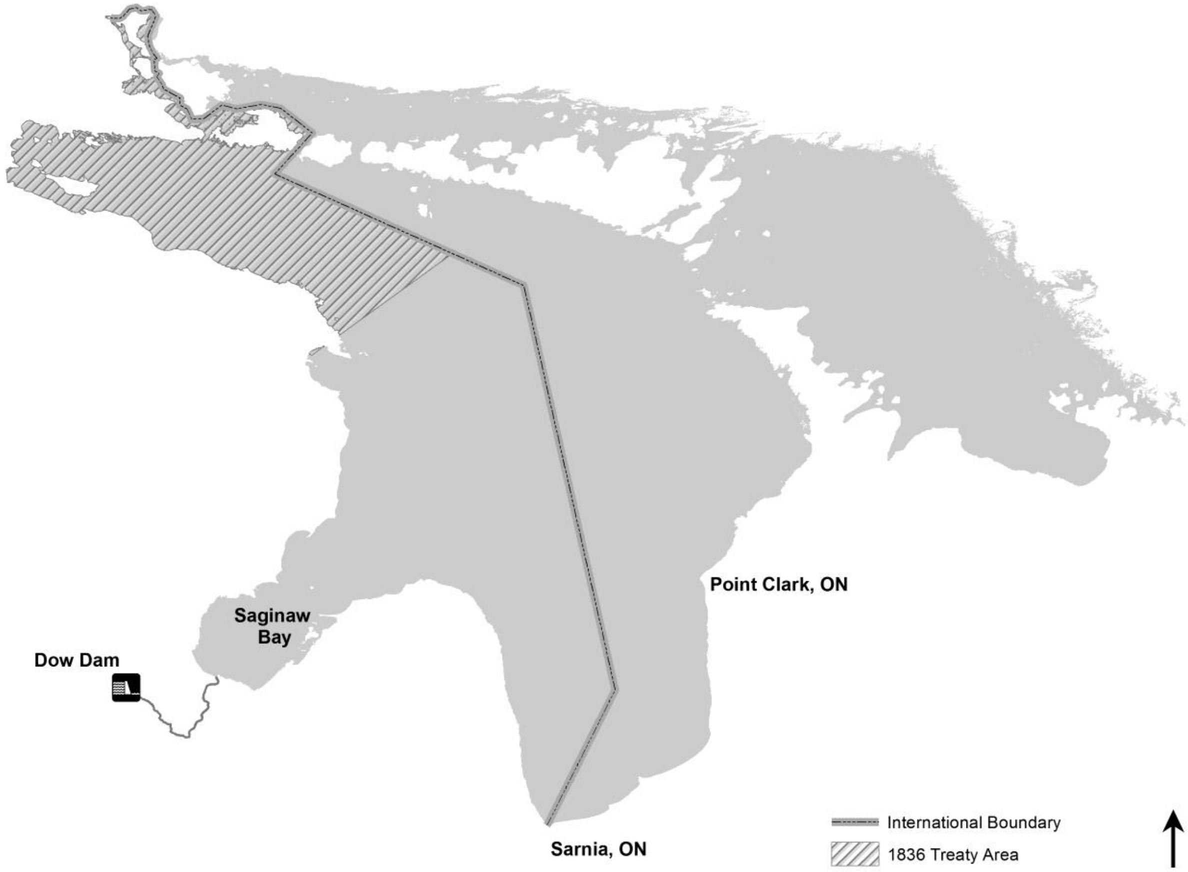

Figure 1.1 Saginaw Bay and Lake Huron.

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CHAPTER 2

INTEGRATION OF AUXILIARY INFORMATION IN STATISTICAL CATCH-AT-AGE ANALYSIS OF THE SAGINAW BAY STOCK OF WALLEYES IN LAKE HURON

Abstract

Estimates of mortality rates and abundance for the Saginaw Bay stock of walleye *Sander vitreus* has traditionally been performed with an analysis of tag returns using a Brownie style analysis. An estimation approach that more fully accounted for sources of exploitation in addition to the recreational fishery in Saginaw Bay and inclusive of the rest of Lake Huron was needed. I developed a statistical catch-at-age model to accomplish this and evaluated four versions including three different treatments of natural mortality (*M*): a constant value, age-based *M* values, and time-varying *M* values. Deviance information criterion model selection procedures indicated that an age-based *M* model version was optimal. I also evaluated an integrated version that incorporated tag returns as auxiliary information for the recreational component. In this case, model selection was based on conformity between observed and predicted data and model convergence. The integrated version was ruled out due to poor agreement of the observed and predicted values, and predictions of abundance that were not reflected by the fisheries. It was concluded that the component of the population used for tagging may exhibit dynamics that differ from the rest of the stock. Total annual mortality of walleyes was greatest for older ages in all fisheries and ranged from 32% for age-2 fish to 39% for fish ages-10 and older. The recreational fishery accounted for the majority of fishing mortality but the commercial trapnet fishery in the main basin of Lake Huron and by-kill from other trapnets in the bay accounted for proportionally greater fishing mortality of younger ages of fish. Abundance peaked in 2007 at 4 million walleyes age 2 and older but estimates indicated a previous period of high abundance in the late 1980s, forcing the reconsideration of the past stock as depressed and dependent on stocking.

Introduction

Statistical catch-at-age (SCA) methods are widely regarded as the state of the art approach to stock assessment (NRC 1998; Quinn and Deriso 1999; Maunder 2003; Hilborn 2012) and are a form of "integrated analysis" (Quinn and Deriso 1999; Punt et al. 2001). Statistical catch-at-age models are age-structured and describe changes in abundance of individual cohorts over time (Megrey 1989). Such models include a population submodel from which estimates of abundance and mortality rates are derived. In addition, observation submodels describe the fisheries and fishery-independent assessment (Fournier and Archibald 1982; Methot 1990, 2000). The modern day approach to model fitting is a likelihood based approach (Methot 1990, 2000), sometimes in a Bayesian context (Maunder 2003), from which the model parameters are adjusted so that a match to observed data (and prior information) is achieved as measured by an objective function. Statistical catch-at-age methods in combination with the likelihood approach to model fitting are hailed for their flexibility in utilizing a variety of data to characterize complex dynamics of fish stocks and their fisheries (Magnusson and Hilborn 2007; Butterworth and Rademeyer 2008; Methot 2009; Hilborn 2012).

Walleye *Sander vitreus* from Saginaw Bay in Lake Huron is a stock with complex dynamics that requires a flexible approach to assessment. Walleyes are an important native predator in Lake Huron (Roth et al. 2013) and the Saginaw Bay stock is the largest source of recruits (Schneider and Leach 1979). Saginaw Bay is a relatively shallow, coolwater embayment of about 2,947 km^2, that lies entirely in the Michigan waters of Lake Huron (Figure 2.1). The Saginaw Bay walleye fishery dates to the late 1800s and historically was the second largest in the Great Lakes, behind that of Lake Erie (Baldwin and Saalfeld 1962; Schneider 1977). Fielder and

Thomas (2006) characterized the history of walleye in Saginaw Bay as having three phases. The first period, characterized by unbridled commercial exploitation, severe habitat degradation, and effects of invasive species, ended with collapse of the fishery in the mid-1940s (Schneider 1977; Schneider and Leach 1977, 1979). After the passage of water quality legislation in the 1970s, closure of the commercial fishery, and the initiation of a fingerling stocking program, a recreational fishery emerged (Fielder et al. 2014) but it was believed to have remained dependent on stocking (Fielder 2002; Fielder and Thomas 2006). Most recently a period of recovery has occurred and is attributed to the disappearance of the invasive alewife *Alosa pseudoharengus* and substantial decline in rainbow smelt *Osmerus mordax* (Riley and Roseman 2013), which were predators on newly hatched percids (Fielder et al. 2007).

Since the early 1970s, the Michigan Department of Natural Resources (DNR) has recognized the importance of stock assessment information for Saginaw Bay walleye. Investments in assessment included analysis of trends in abundance, recruitment, and growth rates since 1971 (Fielder and Thomas 2014), creel surveys to document extraction since 1986 (Fielder et al. 2014) and an analysis of mortality and exploitation rates based on a tagging program conducted since 1981 (Fielder 2014).

The spatial extent of the Saginaw Bay stock of walleye, however, reaches beyond the confines of the bay (Hile 1954). Return of jaw tags has been limited to the recreational fishery (Fielder 2014) but has indicated considerable out-migration from Saginaw Bay proper to much of the rest of Lake Huron. Genetic studies have also documented that Tittabawassee River genotypes of walleye (a spawning tributary within Saginaw Bay) have been found to comprise as much as 9% of the harvest of walleyes in commercial fisheries operating in the southern Ontario waters of the lake even before the recovery (McParland et al. 1996). More recently, an acoustic telemetry study has indicated that as many as half of the adult walleyes are emigrating from Saginaw Bay during the open water months (T. Hayden, U.S. Geological Survey, personal communication). Other fisheries thought to be likely exploiting Saginaw Bay walleyes outside the bay includes the recreational fishery in the nearshore waters of Lake Huron and a tribal gillnet fishery in the area of northern Lake Huron defined by the 1836 Treaty (Figure 2.1) where walleyes are retained as by-catch. By-kill of walleyes also occurs in the state-licensed commercial fishery that operates in the bay and constitutes another source of mortality (MacMillan and Roth 2012).

Compounding the challenges of stock assessment for Saginaw Bay walleye is the effect of immigration of walleyes from Lake Erie. Some walleyes from the central and western basins of Lake Erie are documented to inhabit portions of Lake Huron seasonally (Wolfert 1963; Ferguson and Derksen 1971; Thomas and Haas 2005; Wang et al. 2007). A mixed-stock analysis of walleye from commercial fisheries on the Ontario portion of southern Lake Huron indicated that walleyes from western Lake Erie contributed as much as 67-72% of the total commercial catch in 1994 and 1995 (McParland et al. 1996). Tag returns from Lake Huron of walleyes tagged in Lake Erie average about 1% but have been as great as 2.6% in some years (Lake Erie Walleye Task Group, Great Lakes Fishery Commission, unpublished data). These are proportions of the entire exploitable walleye population in central and western Lake Erie, which regularly number in the tens of millions. This outside source of walleyes must also be accounted for in a comprehensive stock assessment for Saginaw Bay walleye.

The objective of this study was to use SCA methods to more fully characterize population dynamics of the Saginaw Bay stock of walleye. I sought to develop a model that accounted for four fisheries (Michigan recreational fishery, Ontario trapnet fishery, Ontario and tribal gillnet fisheries, and the effects of commercial by-kill within the bay) and adjusted for immigration of Lake Erie walleyes and their contribution to each of the fisheries. I also evaluated whether existing tag return data could be incorporated as auxiliary information to yield a superior integrated model.

Methods

The analytical approach to this analysis was to (1) develop an SCA model for the Saginaw Bay stock of walleye in Lake Huron, including adjustments for migrants from Lake Erie, (2) evaluate three options of natural mortality and settle on a final "baseline" model version, and lastly (3) develop an integrated model version incorporating tag returns as auxiliary information and determine the optimal model (baseline versus the integrated version).

Statistical catch-at-age model. -- The SCA analysis was conducted on annual time steps from 1986 through 2011. The modeling began with 1986 because recreational harvest estimates were not consistently available before that year. Ages of walleye modeled were 2 through 13, and age 13 fish included an aggregate of all walleyes age 13 and over. These ages were selected because younger walleyes (< age 2) are not typically recruited to most of the fisheries. I chose age 13 to aggregate because the Saginaw Bay stock of walleye has exhibited considerable longevity at certain points in its history. There was no attempt to quantify aging error from any of the fisheries or survey.

Population submodel.-- Predicted walleye numbers (*N*) at age *a*+1 at the start of year *y*+1 were derived by the population equation:

$$N_{a+1,y+1} = N_{a,y}e^{-Z_{a,y}} = N_{a,y}e^{-(M_{a,y}+F_{a,y})} \qquad [1]$$

where Z is the total instantaneous mortality rate for the corresponding age and year; Z is the sum of instantaneous natural mortality, M, and the total instantaneous fishing mortality, F, for age a and year y.

Natural mortality options.-- Instantaneous natural mortality is not typically estimable from within a SCA model and instead is supplied (Quinn and Deriso 1999). Three alternative assumptions regarding natural mortality were used in alternative assessment models compared in this analysis, and in each case treating values for M as known. First, I used time-varying (annual) estimates (M_y) derived from the analysis of the tagging operation conducted annually by the Michigan DNR (Fielder 2014). Second, I used age-based estimates of M_a borrowed from the walleye tagging assessment in the neighboring western basin Lake Erie (Vandergoot and Brendon 2014). Those values were 0.335 for ages 2-4 and 0.152 for ages 5+. Lastly I used a value for M=0.23 that was constant over years and ages derived from the Pauly (1980) equation, taking into account Von Bertlanaffy growth parameters and temperature data. Growth parameters of L_∞ and K were obtained from survey data for Saginaw Bay walleye (Fielder et al. 2000; Fielder and Thomas 2006, 2014) based on all available data from the initiation of the survey in 1989 through 2011, and temperature was derived from mean annual air temperature data obtained from Midland-Bay City-Saginaw (MBS) airport.

Fishing mortality.—All model variations evaluated included the same treatment of fishing mortality. For the recreational, commercial trapnet, and commercial gillnet fisheries, instantaneous fishing mortality was treated as separable by age and year such that

$$F_{a,y} = s_a q E_y \varepsilon_y \qquad [2]$$

where s_a is the age-specific selectivity of the fishery, q is the catchability of the fishery, E_y is the year specific fishing effort, and ε_y represents the catchability deviations (process error). These elements, aside from the effort, are estimated as parameters (or calculated from estimated parameters) in the model. Selectivity for each fishery was freely estimated out to age 10, and fish older than age 10 were assumed to have the same selectivity as age-10 fish. Depending on the fishery, the catchability deviations were either based on a white-noise (trapnet and gillnet commercial fisheries) or a random walk (recreational fishery) model. In the case of white noise, ε_y are assumed to come from a lognormal distribution. For the random walk, ε_y are modeled as

$$\begin{aligned} &\varepsilon_y = \varepsilon_{y-1}\delta_{y-1} \quad y > 1986 \\ &\varepsilon_y = 1 \quad y = 1986 \end{aligned} \qquad [3]$$

and δ_y (random walk deviations) are lognormal. In the case of white noise, the catchability deviations allow for variation around a mean catchability but the model fit is penalized when ε_y deviates from that mean. In this case the ε_y are estimated parameters. In the case of the random walk, the random walk deviations, δ_y, are what is penalized in the model fit for changes in catchability from one year to the next, and these rather than the ε_y are the estimated parameters . I used a random walk to model ε_y for the recreational fishery because of the colonization of Saginaw Bay by dreissenid mussels in 1992 – 1993 midway through the time series (Nalepa et al. 1995). Dreissenid mussels were documented to increase water clarity and are theorized to have affected catchability in some fisheries including that in Saginaw Bay (Fielder et al. 2000). The use of random walks is an omnibus approach to estimating time-varying parameters when they may not come from a distribution with a consistent mean (Wilberg and Bence 2006; Wilberg et al. 2010). I presumed that catchability would be more stable for the commercial trapnet and gillnet fisheries, which are prosecuted outside Saginaw Bay, and hence used the white noise model in those cases.

Instantaneous fishing mortality stemming from the commercial by-catch (constituting by-kill) in Saginaw Bay could not be derived as it was for the other fisheries because only one estimate of by-kill was available (for 2010). However, this source of extraction is believed to be large (MacMillan and Roth 2012) and could not be ignored. To calculate F for this source of extraction, the Newton-Raphson method (Quinn and Deriso 1999; Haddon 2001) was employed to find a catchability value so that the 2010 by-kill was matched. Year-specific F values were then determined as the product of catchability and annual commercial effort in the bay (Michigan DNR, unpublished data), which is functionally equivalent to equation 2 with an assumption of constant selectivity (1.0) across ages. The resulting annual values for F derived for the commercial by-kill in Saginaw Bay were then included in population calculations (as a component of the total instantaneous F value). While the inclusion of by-kill influences fit to the data, it was not directly part of the objective function given that there was only one by-kill observation that was exactly matched. MacMillan and Roth (2012) offered two estimates of by-kill for Saginaw Bay commercial fisheries: a lesser value of 23,500 walleyes represented their observed period of May-August and an extrapolated larger value of 102,000 walleyes was given for the entire year. The larger expanded value represented a set of assumptions that were regarded as tenuous so I used the lower value from the observed period in my model fitting. Using my final model (after model selection), I evaluated sensitivity to the by-kill by refitting the model with the larger expanded value. I did not directly incorporate other sources of discard mortality. However, as part of my sensitivity analysis I did evaluate how estimates were influenced when a higher than reported recreational harvest occurred.

Observation submodels.-- Predicted catch from each of the four fishery components was treated the same across the model variations and was derived from the Baranov Catch equation (Quinn and Deriso 1999):

$$\hat{C}_{a,y} = \frac{F_{a,y}}{Z_{a,y}} N_{a,y} \left(1 - e^{-Z_{a,y}}\right) \quad [4]$$

where the predicted catch at age '*a*' in year '*y*' is the product of the ratio of fishing mortality to total mortality and the numbers dying each year.

The predicted survey catch-per-unit-of-effort (CPUE) ($\hat{I}$) was derived as:

$$\hat{I}_{a,y} = q_y^{surv} s_a^{surv} N_{a,y} e^{-\frac{8.5}{12} Z_{a,y}} \quad [5]$$

where q_y^{surv} is survey catchability and s_a^{surv} is age specific survey selectivity. The term $e^{-\frac{8.5}{12} Z_{a,y}}$ sets the corresponding population size for that age and year to the time of year the survey is conducted. As with the fisheries, the survey selectivity was fixed for ages 11-13 to that estimated for age 10. The q_y^{surv} was modeled as a random walk, similarly to the catchability deviations for the recreational fishery (equation 3), for the same reasons (as this survey is conducted in Saginaw Bay) but starting in 1989 rather than 1986 when this survey was initiated. The treatment of survey CPUE was the same across the model variations.

Other parameters include initial abundance at age of walleyes (N_2 to N_{13}) in 1986 (first year of modeling) and initial numbers at age 2 for each year of the model (recruitment) (Table 2.1). Because of the use of random walk and white noise penalties in the objective function, however, fewer than the total 181 parameters represented in Table 2.1 were freely estimated.

Auxiliary information.-- Each year during the time series, about 3,000 walleyes were jaw-tagged and released during the annual spawning run (late March or early April) at Dow Dam on the Tittabawassee River (Figure 2.1). Tag returns came from the recreational fishery, and tags were rarely or never reported from the other fisheries even when encountered. I developed a version of SCA that included the fit to the recreational tag return data as a component in the objective function, and I evaluated this integrated model version. The number reported by anglers in any given year '*j*' after initial release year '*r*' is a function of annual survivals S_i, for *i* in years *r* to *j*-1, and the recovery rate in the recreational fishery f_j. Thus, the probability of a tag return being observed in year *j* in the recreational fishery given the fish was tagged in year *r* is

$$p_{r,j} = \left(\prod_{i=r}^{j-1} S_i \theta \right) f_j \qquad [6]$$

where θ is a tag retention rate described by Fielder (2014) and originally obtained from Vandergoot et al. (2012). In conventional Brownie et al. (1985) tag-return analysis, the values of S_i and f_j are parameters estimated solely based on the tagging data, but in my integrated model their values are obtained as functions of parameters that are already estimated as part of the population model. I assumed that equation 6 applied only to walleyes ages 4 and above, given that fish younger than that age are not typically tagged as part of that survey (Fielder 2014). During model fitting, estimates of S_i were calculated as the ratio of modeled numbers of age-5+ fish alive in year *i*+1 to the number of age-4+ fish alive in year *i*. The f_j values were calculated as the exploitation rate for year *j* (estimate of harvest of fish age 4 and older based on equation 4 divided by estimate of *N* for fish age 4 and older at start of year *j*). Equation 6 is not age structured. While methods exist for age structuring Brownie style analyses, that has not been the approach by Michigan DNR, as often the number of aged specimens was insufficient to organize an age-based tag-return analysis.

Model fitting.-- I used highest posterior density (HPD) estimation to obtain point estimates of parameters and quantities estimated from parameters. This Bayesian approach and its application in fisheries have evolved from a maximum likelihood approach (Fournier and Archibald 1982; Methot 1990; Aldrich 1997) to account for process errors (Schnute 1994; Linton and Bence 2008). Using this approach, parameters are estimated based on the minimization of an objective function, which is the sum of the negative log likelihood for the data and the negative log prior densities for the parameters. The separate negative log-likelihood components for each type of data predicted by each of the submodels were summed, yielding the joint negative log likelihood term. In addition, for parameters allowing for catchability variations, there was a negative log prior term associated with each fishery or the survey based on the assumed prior distribution for either the ε_y (white noise) or δ_y (random walk) deviation for that fishery or survey. These prior terms were summed to obtain the joint negative log prior density. I assumed bounded uniform priors for other parameters, and thus prior densities were constant within the bounds so were not included in the objective function. The objective function was minimized using AD Model Builder version 10.0 (AD Model Builder Project 2011; Fournier et al. 2012). The prior components can be viewed as penalties for deviations from the values deemed most likely *a priori*, and HPD estimation is also referred to as penalized likelihood estimation.

For each of the observed fishery catches (recreational, Ontario trapnet, lake-wide gillnet), each of the four sets of fishery or survey catchability deviations (ε_y for white noise or δ_y random walks), and for the survey CPUE, a lognormal distribution was assumed

$$L_i = IC + n \ln \widehat{\sigma}_i + \frac{1}{2} \sum_y \left[\frac{\ln X_{i,y} - \ln \hat{X}_{i,y}}{\widehat{\sigma}_i} \right]^2 \qquad [7]$$

where IC is an ignorable constant that was not included in my calculations. Each data source is designated by *i*, sample size is denoted by *n*, and $\widehat{\sigma}_i$ is the standard deviation that applies to each quantity $X_{i,y}$. In the case of fishery catch and survey CPUE, $\hat{X}_{i,y}$ represents a model prediction of observed catch or CPUE and $X_{i,y}$ represents the observed number of fish caught. In the cases of the components for white noise catchability, $X_{i,y}$ represents the catchability deviations (ε_y), and for the random walk components, $X_{i,y}$ represents random-walk deviations (δ_y). In both of these cases $\hat{X}_{i,y}$ has an assumed value of 1. Thus there are 8 lognormal components (L_i): three for the different fitted fishery catches (all fisheries except the by-kill from state-licensed trapnets), one for the CPUE from the survey, two for random-walk deviations (for the survey and recreational fishery), and two for white-noise catchability deviations (Ontario trapnet fishery and lake-wide gillnet fishery).

The values of $\widehat{\sigma}_i$ play a role in all eight lognormal components. Unfortunately, we know from the theory of penalized likelihood that not all of these $\widehat{\sigma}_i$ can be estimated during model fitting (Linton and Bence 2008). My approach was to estimate the $\widehat{\sigma}_i$ associated with the observed data (fishery catch or CPUE), so four of these were estimated. The $\hat{\sigma}_i$ for the white noise or random-walk deviations were then calculated based on an assumed ratio of their variance ($\hat{\sigma}_i^2$) relative to the variance for catch or CPUE from the same fishery or survey.

We set the ratios for both the survey and recreational fishery catchability random walk variance to 0.85, hypothesizing that the interannual changes in catchability, as a proportion of the current value, would be of lesser magnitude than the observation error associated with catch (as a proportion of the true or expected value), but nearly as large. I set the ratios for the commercial fishery effort deviation variances to 1.0 for the lake-wide gillnet fishery and to 0.25 for the Ontario trapnet fishery. For the gillnet fishery I had no specific reason to expect actual changes in catchability, but I assumed that estimation error variance for effort would be at least as large as for the actual landings, as effort reporting is not a focus. For the Ontario trapnet fishery I hypothesized that variance in effort estimates would be substantially less than those of harvest, as they are not subject to all of the errors that beset harvest (e.g., weighing, converting from weight to numbers), and the Ontario effort reporting system is well developed. I acknowledge that these ratios, while based on my best judgment are somewhat arbitrary. Consequently I explore the influence of the ratios in the sensitivity analysis.

The age-composition data (proportions at age) from each fishery and the survey were based on age samples assumed to arise from a multinomial distribution, leading to the likelihood equation

$$L_i = -\sum_y N_{i,y} \sum_a p_{i,y,a} \ln \hat{p}_{i,y,a} \qquad [8]$$

where $N_{i,y}$ is the sample size for the number of specimens aged but was capped at an effective sample size of 200. This cap limited the influence of the component in the objective function and prevented this likelihood component from being over weighted for a specific year and data source (Fournier and Archibald 1982). The cap of 200 is consistent with the examination of residuals, which suggested markedly better fits were not obtained for year and data sources when age-composition sample size exceeded the cap. The observed proportion of age '*a*' in year '*y*' for each source of age composition data was denoted as $p_{i,y,a}$ and the corresponding predicted value as $\widehat{p}_{i,y,a}$ is the predicted proportion.

The likelihood component for the auxiliary information (tag return comparison) was based on the multinomial distribution as

$$L_{13} = -\sum_{r}\left[\left(\sum_{j} R_{r,j} \ln p_{r,j}\right) + UR_r \ln\left(1 - \sum_{j} p_{r,j}\right)\right] \qquad [9]$$

where $p_{r,j}$ is the probability of the tag recovery from the r^{th} tagging year in the j^{th} recovery year, UR_r is the number of tags not recovered from the original lot tagged in year *r*, and $R_{r,j}$ is the number of tags recovered from tagging year *r* in recovery year '*j*'; $R_{r,j}$ was the adjusted value of the actual number of tags reported expanded by the year–specific correction factor for nonreporting (Fielder 2014).

Two model versions were developed. The *baseline* version omitted the tag return component from the objective function, and the *integrated* version included the tag return evaluation in the objective function. The baseline version was the SCA model chosen from the three candidate models (based on the natural mortality options) as a result of the model selection criteria. Because the predicted tag returns were generated with existing parameters, the total parameter set (181) is the same for the baseline and integrated model versions. Comparison of the two versions is addressed in following sections on sensitivity analysis and model selection.

Fisheries and fishery-independent data.-- Estimates of recreational harvest and effort were available for most of the Michigan waters of Lake Huron since 1986. In this context, harvest refers to actual number retained and does not account for any discarded that die due to hooking mortality. While I do not adjust for such mortality, I do evaluate the consequences of underreported recreational harvest in the sensitivity analyses. Because the Saginaw Bay stock of walleye is the subject population, decisions had to be made as to what estimates of harvest to include. Although there is undoubtedly some local natural reproduction outside the bay, the decision was made to assume that it was negligible and the majority of Michigan's main-basin walleye harvest could be credited to the Saginaw Bay stock because of the seasonal movement from the bay.

While walleyes are sought by recreational anglers in Ontario, recreational harvest is not regularly estimated there. Based on the bathymetry of Lake Huron, it was rationalized that Saginaw Bay walleye would not likely reach Ontario waters past the abyssal area of Lake Huron north of the Sixth Fathom Scarp, effectively limiting them to the Ontario waters in the southernmost portion of the main basin from Pt. Clark, to Sarnia, Ontario. For the purpose of this SCA analysis, the recreational fishery there was regarded as negligible, but as indicated above the influence of higher-than-reported recreational harvest is evaluated as an assumption in the sensitivity analysis.

Recreational walleye fishery harvest estimates were obtained from the Michigan DNR's statewide annual creel survey study and direct reporting for charter boat operations. The creel survey follows the methods of Schneider (2000). Michigan DNR creel survey estimates were obtained from Fielder et al. (2014) and as unpublished data. Ages of walleyes were obtained from annual biological samples of the recreational fishery throughout the survey season. Ages were estimated from hard structures: scales for early years and spines since 2009. Numbers of fish aged each year averaged 521. Proportions at age for the recreational fishery were derived from those annual biological samples.

Commercial harvest numbers are calculated based on yield-reporting programs and the average weight of harvested fish each year for each fishery, based on biological sampling. Walleye is a highly valued species and I assumed that commercial discard was negligible. The provincially licensed commercial trapnet fishery occurs in the Ontario southern basin waters of Lake Huron from Pt. Clark to Sarnia. Most of the effort is reported to occur in the most south-westerly area around Sarnia. While all reported harvest was included as the observed harvest for this fishery, I only used effort targeted on walleyes (number of trapnet lifts). Ages of walleyes were obtained from samples of the trapnet harvest and estimated from hard structures (scales or spines), and numbers averaged 527 per year. Proportions at age for the trapnet fishery were derived from the sample.

The commercial gillnet fishery exists in two regions of Lake Huron thought to include Saginaw Bay stock of walleye. There is a Provincially licensed gillnet fishery targeting walleye and other species in the southern main basin of the Ontario waters of the lake from Pt. Clark to Sarnia concurrent with the trapnet fishery. The second portion of the gillnet fishery is a tribal fishery authorized under the 1836 Treaty and 2000 Consent Decree (USA v. State of Michigan

2000). That fishery exists from the Straits of Mackinaw east to De Tour Passage (Figure 2.1) excluding the embayments of the Les Cheneaux Islands. That fishery is similar to the Ontario gillnet fishery and nets comprise mesh sizes from 114 to 140 mm stretch measure. Tribal harvest is permitted as a retention of the by-caught walleyes. Annual effort was recorded as the cumulative km of nets fished. These data were obtained from the Chippewa-Ottawa Resource Authority and Ontario Ministry of Natural Resources. Age distributions were also similar allowing them to be combined with sample sizes of around 100 per year. All SCA model variations combined the two gillnet fisheries as a single fishery in the estimation.

The fishery independent survey is a gillnet-based assessment operation, using variable-mesh gear, conducted annually each September by the Michigan DNR since 1989 (Fielder et al. 2000; Fielder and Thomas 2006, 2014). Walleyes as young as age 1 were vulnerable to this gear in all years (Fielder and Thomas 2006). Age distributions were obtained from ages of hard structures (scales in early years, spines since about 1997) numbering about 500 each year. All the walleyes in the catch were aged.

Immigrants from Lake Erie.-- Each fishery and survey component had the potential for augmentation by migratory Lake Erie walleyes and needed some level of adjustment. In each case, the predicted fishery catch or survey CPUE compared with the observed value in the objective function was the sum of Saginaw Bay stock of walleye and Lake Erie walleye. Immigrant walleyes from Lake Erie were given by

$$n_y^E = N_y^E P_{y,a} T_y \omega_y C_a \qquad [10]$$

where n_y^E is the number of walleyes at age *a* in year *y* in Lake Huron that results from Lake Erie migrants, N_y^E is the total walleye population in the central and western basins of Lake Erie in a given year, $P_{y,a}$ is the year-specific age distribution of the Lake Erie walleye population, T_y is the year-specific proportion of walleyes migrating to Lake Huron as based on the jaw tag returns. Those values are reported by the Lake Erie Walleye Task Group (LEWTG) of the Great Lakes Fishery Commission (Thomas et al. 2011). The proportion of Lake Erie walleyes migrating to Lake Huron based on jaw tags reported from Lake Erie fish (T_y) was further adjusted based on a running 3-year average (the average of the previous two years and the reported value for the current year became the new value for the "current" year). A year-specific correction factor for nonreporting of tags from the recreational fishery in Lake Huron was incorporated as ω_y (Fielder 2014). The contribution (expressed as a proportion) of each age that is thought to make the migration from Lake Erie is denoted as C_a. This value is 1.0 for ages 5 and older but is reduced to 0.5 for age 4 and 0.0 for ages 2-3. The reduction for younger fish is based on information reported by Wolfert (1963), Ferguson and Derksen (1971), and Wang et al. (2007), who observed that younger Lake Erie walleyes were less prone to large migrations.

The estimates generated by the Lake Erie SCA model are specific to the western- and central-basin stocks in that lake (Thomas et al. 2011). The same model also estimates proportions at age, however those are aggregated at age 7+. To adjust the Lake Erie estimated age; distribution out to age 13 to conform to that used in this (Saginaw Bay) model, the aggregated age-7+ fraction was distributed across ages out to age 13 based on assuming a 50% survival rate of walleyes for each subsequent age beginning with age 6.

Unlike the estimation process for the catch of the Saginaw Bay stock of walleye, fishing mortality *F* was not estimated directly for Lake Erie walleye but rather as a fraction of the *F* for Saginaw Bay fish for each of the fisheries. The Lake Erie *F* within Lake Huron was set at half (0.5) of the corresponding fishery *F* for each of the fisheries operating in Lake Huron including the by-kill in the Saginaw Bay commercial fishery. This was based on the belief that once in Lake Huron, Lake Erie walleyes would be subject to the same fishing mortality rate as the Saginaw Bay stock but for approximately half the year. The one exception is for the gillnet fishery, which was spatially split between southern Lake Huron and northern Lake Huron. Rationalizing that Lake Erie walleyes will not substantially migrate as far north as northern Lake Huron, only half of the gillnet fishery was set to exploit fish from Lake Erie, and thus the multiplier for the gillnet *F* was 0.25. Values for natural mortality of Lake Erie immigrants were similarly adjusted by these fractions. The catch attributable to Lake Erie fish was derived from the Baranov Catch Equation (equation 4) applying the fishing mortality rates described above, and n_y^E.

The survey CPUE was adjusted for Lake Erie contributions by using equation 5 (for the predicted survey CPUE) but applying the formulation to numbers and total mortality rate specific to Lake Erie fish. This approach used the same estimated survey selectivity and catchability as estimated by the model for Saginaw Bay fish. As with the fisheries, the predicted values used in the calculation of the likelihood component was the sum of the two predicted CPUE values.

Spawning stock biomass.-- The mean weight at age and by sex was available for the time series from the walleyes caught in the Michigan DNR survey (Fielder and Thomas 2014). Similarly the survey provided a matrix of maturity (expressed as proportions) of females by year and age. Spawning stock biomass at age and year was derived as half the total biomass (to reflect females only) and the product of the maturity matrix.

Model selection.-- Deviance information criterion (DIC) was used to select among the models of the three candidate treatments of natural mortality *M*. Deviance information criterion is a Bayesian approach to selecting among models, analogous to Akaike's Information Criterion used when fitting models by maximum likelihood (Spiegelhalter et al. 2002). Because DIC is limited to models involving the same data, this technique could not be used to select between models including or excluding the tag return data. The "best" model is the one with the lowest DIC value. Wilberg and Bence (2008) found DIC to work well as a model selection technique for SCA analysis.

Deviance information criterion model selection is based on Markov Chain Monte Carlo (MCMC) analysis which is implemented in AD Model Builder based on the Metropolis-Hastings algorithm and begins by first obtaining the parameter values based on the HPD and the associated asymptotic variance-covariance matrix (Wilberg and Bence 2008; AD Model Builder Project 2011). When calculating DIC, I used half of the variance of the individual deviance values method for estimating the effective number of parameters (Spiegelhalter et al. 1998; Gelman et al. 2004) and HPD point estimates.

In my MCMC chain I implemented 1,000,000 steps and saved every 200th step to thin the chain and save on computing time, which resulted in 5,000 values. The first 1,000 were discarded as a burn-in period and DIC analysis was based on the remaining 4,000 values. To determine whether the length of the burn-in period was long enough to ensure convergence, I visually inspected trace plots the MCMC chains (of the objective function) and evaluated the burn-in point with stabilization in the plot (Gelman et al. 2004).

The model that I selected using DIC was then deemed the “baseline” model and contrasted with the model integrated with tag returns as auxiliary information. The question was whether the added influence of tag returns in the evaluation of the model objective function would result in an overall improved estimation. Selection between these two candidate models (with and without tag returns) was based on model fit between observed and predicted values, and particularly evaluation of whether there were systematic patterns to residuals.

Uncertainty and sensitivity analysis.-- Sensitivity analysis was only applied to the baseline model selected by DIC. Analysis of the sensitivity of the model to the various likelihood components was based on performance metrics of management interest. Performance metrics included spawning stock biomass of females (SSB) and total annual mortality (*A*). Further performance metrics included the exploitation rates of each of the four fisheries modeled but limited to age-4 and older walleyes to limit comparison to age-groups fully selected in each fishery type. Lastly the annual population sizes were compared as a measure of sensitivity to each model component. All metrics were evaluated on time series means as percent of the optimal model. Minimum estimates of 95% confidence intervals were based on $\pm$1.96 of the asymptotic posterior standard deviation.

Analysis of sensitivity was conducted by applying a weighting factor lambda (λ) of either 0.5 or 2.0 to each of the likelihood and prior components. This served to either deemphasize or over emphasize the effect of that component in order to examine the effect on the aforementioned performance metrics. Lambda was left at 1.0 for all other likelihood components so as to evaluate each component’s sensitivity singularly. In some cases, the model would not converge.

Starting values for parameters were varied typically as half and twice the selected values to test for robustness of model convergence. Failure to converge or large departures of model predictions from observed values would increase concerns that the final "converged" estimates obtained from the starting values might not be at the global minimum for the objective function. Starting values were adjusted until values that met this criterion were identified.

The SCA model was structured by having to make certain assumptions about walleye stock structure and fishery dynamics. These assumptions constitute a source of uncertainty. To evaluate the significance of these assumptions, performance metrics were also examined by increasing and decreasing assumed values. These assumptions included the following: (1) The duration of Lake Erie walleyes inhabiting Lake Huron. This was set in the model by assigning mortality rates that were one-half of those of the Saginaw Bay fish, but was trialed here at +/- 20% implying 7.2-month and 4.8-month durations as opposed to a six-month duration. (2) The proportion of fish of each age of Lake Erie walleyes migrating to Lake Huron. Fish of ages 2, 3, and 4 were trialed at 50, 100, and 100%, respectively, in their propensity to migrate to Lake Huron instead of none for ages 2 and 3 and 50% for age 4. (3) The assumption of Ontario's recreational fishery harvest being nil is improbable as is the assumption of no catch-and-release mortality, so elevating the recreational catch by an additional 10% of the present observed values was evaluated for effect on the performance metrics. (4) The larger expanded value of by-kill reported by MacMillan and Roth (2012) was evaluated. (5) I evaluated the sensitivity to variance ratios by choosing alternative values. Recognizing that a variance ratio of 1.0 implied the same variance for the effort deviations or catchability random walk as the catch or CPUE, I chose alternative values to test for sensitivity by selecting values of similar proportions above or below 1.0. (6) I evaluated the sensitivity of model predictions to the assumption of time-varying catchability for the recreational fishery. Preliminary analysis suggested that catchability did vary but not in anticipated patterns. To explore the influence of allowing expected catchability to drift over time for the recreational fishery, I refit the model with a white-noise treatment of the variability of recreational catchability, which assumes catchability varies about a constant mean. (7) Lastly, I evaluated the treatment of the age-based *M* as fully known. This was done two ways: first I treated M_{age} as a prior of its own and incorporated in the objective function based on a lognormal distribution using equation 7. For that purpose σ was approximated at one-quarter of the maximum range of the confidence intervals for the age-based *M* values from Vandergoot and Brenden (2014). Secondly I evaluated model sensitivity to alternative set values of M_{age} using the upper and lower 95% confidence intervals.

Standardized residual values between observed and predicted for the baseline model were examined. Residuals were based on the proportions at age for the survey CPUE and each fishery catch with the residuals computed as the observed minus predicted and standardized as the quotient of the difference and the predicted standard deviation. A uniform scatter for each about zero was interpreted to mean that no systematic pattern existed.

Results

Model selection-- Application of the DIC model selection procedures indicated that the age-varying natural mortality best reflected the observed data. In spite of this candidate model having the greatest effective number of parameters, analysis indicated it had the lowest overall DIC value (Table 2.2). Consequently, it was the age-varying natural mortality model version that then constituted the baseline model version for integration with tag returns as an alternative model version for further evaluation. The integrated model resulted in a fit of predicted and observed values that compared favorably with the baseline model except that the predicted recreational catch was over estimated relative to the observed (Figure 2.2A). The mean (over years) recreational catch predicted by the integrated model was more than twice the mean catch predicted by the baseline model. In contrast the baseline model predictions of recreational catch were within 1% of the observed values.

The integrated version of the model generated predicted tag returns by utilizing the annual recreational exploitation and survival rates to generate the tag return probabilities. Exploitation rates differed between the Brownie model and the baseline model since 2004 (Figure 2.2B). The elevated exploitation rate depicted by the observed tag returns probably resulted in an inflation of the recreational catch causing the departure from the observed. The result was an elevated (72% greater) population estimate. The integrated version also estimated that the population had declined in the last two years of the time series (2010 and 2011) to record lows, which were not consistent with the observed fishery trends. From this, and the systematic overestimation of observed recreational harvest by the integrated model, I concluded that the inclusion of the tag return auxiliary information did not result in a superior model and I retained the baseline version as my selected model.

Baseline model-- The baseline model achieved an overall good fit of the observed data sets (fishery extractions and fishery-independent survey; Figure 2.3). An examination of standardized residual proportions at age for the survey and each fishery generally revealed no consistent pattern. There was a slight preponderance of positive residuals over negative values, especially for older ages across fisheries. This may have been a result of aging error or over estimation of certain terminal age-groups.

Abundance of the walleye stock was estimated by the baseline SCA model to have declined steadily since 1988 and then increased beginning in 2005. The stock peaked at about 4 million walleyes (age 2 and older) in 2007 before declining again and leveling off at about 2.4 million by the end of the time series (Figure 2.4). Uncertainty in the abundance was greatest in recent years likely reflecting the model's estimation uncertainty over year-classes not yet depleted, a characteristic common to SCA fits (Figure 2.4).

Selectivities steadily increased for older ages of walleyes through age 10 in the lake-wide gillnet and recreational fisheries (at which point selectivities were assumed to remain at the age-10 value and were not estimated; Figure 2.5). In contrast, the highest selectivity for the trapnet fishery was ages 3 and 4. Minimum mesh sizes in the gillnet fishery and minimum length limits in the recreational fishery may have contributed to the low selectivity of age-2 and age-3 in those fisheries.

Estimated catchability of the recreational fishery and survey varied considerably over the series (Figure 2.6). The survey catchability reflected a greater catchability before dreissenid mussel colonization (about 1993), as I hypothesized would occur due to changes in water clarity. However, catchability of walleyes in the recreational fishery reflected a pattern that was more characteristic of recent population trends or perhaps the disappearance of alewives.

Total annual mortality ranged from a low of 32% in 1991 to a high of 53% in 1986 (Figure 2.7). Uncertainty about total mortality was greatest for 1986 and was likely associated with the need to estimate an initial population consisting of some cohorts that were reflected in only a few years of data. Uncertainty in estimates of total mortality increased slightly beginning in 2001. Total annual mortality rates generally followed a pattern that suggested, to some degree, mortality was an inverse function of abundance of fish (Figures 2.4, 2.7).

Estimated age-specific total annual mortality of walleyes showed a consistent qualitative pattern over time, in which a peak occurred at age 4 and a decline to a substantially lower value for age 5, followed by a gradual increase to the levels experienced by age-10 and older fish (Figure 2.8). The total annual mortality reached for fish of ages 10 and older, however, decreased over the time series. The age specific patterns reflect selectivity and natural mortality rates, and the sharp decrease from age 4 to age 5 corresponds to the lower M for age-5 and older walleyes and a decrease in selectivity for the trapnet fishery.

Recreational fishing mortality (F_{mrc}) of walleyes was greatest in proportion of all sources of combined fishing mortality for all ages and was nearly 80% of the total by age 7 and older (Figure 2.9). Fishing mortality increased with walleye age for the recreational and gillnet fisheries, likely reflecting increasing selectivity as a function of length limits and mesh sizes. This was in contrast with the Ontario trapnet fishery, where fishing mortality was highest on the younger age groups and then declined with age. Recreational fishing mortality increased over the time series, especially after 2000, where age 5 was used as an indicator (Figure 2.10). Fishing mortality declined or was steady for the other fisheries over the same time series.

Estimated recruitment of walleyes at age 2 clearly indicates the resurgence in reproductive success beginning with the 2003 year class (Figure 2.11). Total biomass and spawning-stock biomass of the Saginaw Bay stock followed a similar trajectory (Figure 2.12). Biomass metrics were much higher earlier in the time series, peaking in 1989, and then exhibited a decline until the recent resurgence beginning in 2006. Uncertainty for the estimates was generally less for this time series relative to other estimated metrics but also increased for the three most recent years.

The baseline SCA model exhibited high sensitivity to weighting for the CPUE of the survey and gillnet harvest, but not the recreational fishery harvest (Table 2.3). The baseline model was somewhat sensitive to weighting of the age structure of the trapnet and gillnet fisheries. Aside from those cases, there was generally little departure on a percentage basis from the baseline version for most metrics as component weightings were changed. Collectively, altering weighting factors resulted in the model failing to converge just three times.

Although by-kill estimation was not directly part of the objective function, the value used to derive the catchability for application to commercial effort of past years did result in estimation differences from the baseline model (Table 2.4). The higher extrapolated (year-round) estimate of by-kill in 2010 (102,000 walleyes) increased the population estimate by 36% and SSB by 26% (Table 2.4). Total annual mortality was not affected on average, but corresponding exploitation rates in the fisheries were reduced by about 20% each except for the by-kill exploitation rate, which increased 202%. Increasing recreational fishery harvest from the baseline model by 10% resulted in a 5-6% increase in population and SSB estimates and a similar magnitude decline in exploitation rates except for the recreational fishery (Table 2.4).

The influence of the duration of Lake Erie walleye habitation in Lake Huron had only minor effects on model estimates when increased from 6 months to 7.2 months (Table 2.4). A lack of convergence prevented evaluation of a shorter duration. Similarly, the full inclusion of age-3 and one-half of the age-2 walleyes in the immigration had only a minor effect on the estimates of the baseline model (Table 2.4).

The baseline (age-based *M*) model proved reasonably robust to the assumptions of variance ratios as shifting the weight of the variance had only minor effects on the metrics of management interest (Table 2.4). This suggests that, while somewhat arbitrary, the choice of variance ratios did not have a profound effect on the overall estimation.

Model estimates were sensitive to the assumption of time-varying catchability in the recreational fishery (Table 2.4). Application of an alternative white noise treatment of *q* resulted in a 22% increase in total population size on average with most of the departure occurring in the last seven years of the time series. In order to fit the model with a white noise treatment of *q* deviations, the recreational fishery variance ratio had to be increased to 1.10.

Treating the age based *M* value as a prior in the estimation process had little effect on model performance in which there was a <1% departure from the baseline for all metrics and an increase in the standard deviation by just 0.1% over the baseline. It did increase uncertainty slightly for some other metrics and added to the parameter load. Trialing age based *M* at the upper and lower 95% confidence limits did result in a modest effect on model metrics (Table 2.4): generally a 10-20% effect with greater population estimate resulting from the upper limit value, and a lower population from the lower limit value.

Discussion

The SCA model presented in this study allows the explicit incorporation of multiple fisheries in the stock assessment and overcomes a weakness of the tag-recapture assessment methods that have been used in the past. By incorporating all the fisheries exploiting this stock, more plausible estimates of overall mortality, and consequently fishing mortality were obtained. Although the recreational fishery accounted for the majority of the total fishing mortality (Figure 2.9), the omission of the other fisheries clearly underestimated overall fishing mortality, especially for younger ages of walleyes. This was most apparent in the annual estimates of natural mortality derived from the Brownie data (as the difference between Z and F). This method of M estimation passes any bias in F to M and in the instance of the Brownie model resulted in an over estimation of M. That greater value almost certainly reflected the fishing mortality of the trapnet, lake-wide gillnet, and commercial by-kill fisheries. The difficulty in obtaining tag returns from commercial fisheries is widespread and methodologies for addressing this have had only limited success especially in improved estimates of M (Eveson et al. 2007). The elevated M values of the time-varying M model version resulted in the over estimation of the population. That version of the SCA model likely estimated the greater abundance so as to fulfill the observed fisheries and the supplied high annual M values. While an annual estimate of M might be desirable for use in a SCA model, in this case model selection procedures favored the age-based natural mortality expression.

Natural mortality rates are generally difficult to assess in a fish population and are often assigned an assumed set value for population modeling (Quinn and Deriso 1999; Nate et al. 2011). I treated M as known and assumed age-specific natural mortality borrowed from Lake Erie because this proved to fit the data better than other expressions of M (constant and time-varying), but I was unable to fully evaluate the accuracy of these values. The DIC selection of the age-varying natural mortality model version may be a reflection that natural mortality of the Saginaw Bay stock does vary by age. It doesn't necessarily mean that those are the most correct values. Misspecification of M can have considerable influence over model estimates (Clark 1999; Deroba and Schueller 2013). Deroba and Schueller (2013) evaluated reliance of a constant M value on stock assessments through simulations and found it to bias estimates of SSB and F by as much as +/-100% of the estimate for both long- and short-lived species. The degree of bias of a misspecified natural mortality may depend on how M was treated in the model and what the true values were. Deroba and Schueller (2013) reported that parameter bias was generally less when time-varying *M* values are misapplied than when misspecified as age varying or as a constant, and as such, bias affected estimates of SSB and recruitment.

The difficultly remains in obtaining reliable estimates of time- or age-varying *M*. Quinn and Deriso (1999) favored using tag-based studies to derive *M*, but in this instance, it failed to result in an accurate estimate of *M* because of the lack of representation of the competing fisheries. More stock assessment efforts are turning to estimating *M* within a SCA analysis, although typically this requires an informative prior value (Wang and Liu 2006; Lee et al. 2011; Maunder and Wong 2011; Vincent 2013). I evaluated this in the sensitivity analysis and found that when the specified values for *M* were treated as medians of a prior lognormal distribution, this did not materially affect the model point estimates. There was some increase in uncertainty but this was modest. In this instance, I concluded that this does not strengthen the model. I believe that there is more uncertainty associated with transferring estimates of *M* from Lake Erie to Lake Huron than was captured as estimation error for the Lake Erie estimates. I tested the impact of specifying *M* at the upper and lower bounds of the Lake Erie estimates and this did have a moderate effect on the abundance and exploitation estimates, suggesting that this is a consequential model term, especially if it were to turn out that natural mortality of walleyes in Lake Huron was substantially different than in Lake Erie. Future improvements to the model may be better realized by development of stock-specific, age-based *M* values for Saginaw Bay walleyes based on a tagging study following the methods of Vandergoot and Brenden (2014).

The time series mean estimate of total annual mortality for Saginaw Bay walleye was 37%, which was the same as that from the Brownie model (Fielder 2014) for the same years suggesting that both models are in agreement for total mortality. Brownie model-based estimates of total annual mortality ranged more over time than those generated by SCA, but on average both estimates agree suggesting Brownie estimation (from tagging analysis) could accurately estimate total mortality, but it overestimated *M* because of the lack of representation from fisheries other than the recreational.

The trapnet by-kill decrease over time resulted from the large decreases in inner Saginaw Bay trapnet fishing effort (Fielder et al. 2014) and the assumption that this source of mortality was directly proportional to the inner Saginaw Bay trapnet fishing effort. Only the recreational fishing mortality increased substantially in recent years, a response to the stock recovery and increases in vulnerability as confirmed by trends in catchability (Figure 2.6). Generally recreational fishing effort has declined or been stable in recent years (Fielder et al. 2014) so the increasing recreational *F* must be a function of the time-varying catchability.

The initial peak abundance of Saginaw Bay walleyes in 1988 is evident in the population estimate (Figure 2.4) as well as the biomass trends (Figure 2.12). Previously, when indices of abundance were noted to be high for those early years it was dismissed as an artifact of Lake Erie immigration and or increased catchability due to changes in water clarity stemming from dreissenid mussel colonization in 1993 (Fielder et al. 2000; Fielder and Thomas 2006). My version of the SCA model generated these estimates of abundance and biomass specific to the Saginaw Bay stock, effectively factoring out any effect of Lake Erie fish. Similarly, the utilization of a random-walk procedure for application of changing catchability was intended to allow for any change in catchability stemming from dreissenid colonization and appears to have achieved that for the survey CPUE (Figure 2.6). In spite of these efforts, the model is still projecting high abundance at a time when generally the walleye population was still regarded as unrecovered. Alternatively, if my assumption of time-varying catchability in the recreational fishery is mistaken and the white-noise depiction is more accurate, then the abundance in recent years is greater, suggesting that abundance in the early years was not similar to the more recent recovery.

Operating on the premise that recreational fishery catchability was in fact time varying, then this analysis forces one to consider that abundance of the Saginaw Bay walleye stock most likely was genuinely substantial in those early years of the time series. While it was believed that the fishery was dependent on stocking until 2003 (Fielder 2002; Fielder and Thomas 2014), the use of oxytetracycline marking to identify hatchery fish in stocking evaluations was not available until 1997 (Fielder 2002). Consequently it is difficult to rule out a surge in reproductive success early in the time series. While the abundance estimate in 1988 rivaled the peak of the more recent recovery (2007), earlier biomass was much greater in both total and spawning stock than during the more recent resurgence (Figure 2.12). This suggests that the high abundance in 1988 was not merely due to large numbers of young fish but was comprised of mature fish and older or fast growing fish. Recruitment estimated by the SCA model at age 2 indicated year-class strength in 1984-1986 that was on the same magnitude of some recent years (Figure 2.11). The downward decline of abundance in the interceding years is consistent with the lower recruitment of the same years. Overall, the phenomenon illustrates that gains in abundance can be lost if recruitment fails to remain strong, at least periodically. The more recent decline in recruitment does not bode well for the on-going recovery of the Saginaw Bay walleye stock. Fielder et al. (2007) forecasted that recruitment should remain strong as long as alewives remain scarce, but Fielder and Thomas (2014) suggested that recent lower recruitment may be reflecting density dependence in the stock/recruitment relationship.

Failure of the attempt to strengthen the baseline SCA model by integrating auxiliary information in the form of tag returns raises the question as to why these data did not have the intended benefit. I followed the recommendations of Maunder (1998) and Maunder and Punt (2013) for the optimal methods of incorporating tag return as estimating the probabilities within an SCA model for the corresponding likelihood component, but this still resulted in a poor fit. Customarily if the addition of information reduces the fit of the model, it suggests conflicting or contradictory dynamics (Richards 1991; Schnute and Hilborn 1993; Haddon 2001). Homogeneity of capture probability is a fundamental assumption in tag return analysis (Brownie et al. 1985) and the tag-based method equivalent to the assumption of single-stock estimation within SCA. This raises the question of how representative the Tittabawassee River spawning run of walleyes (used as the tagging source) is of the rest of the bay's population. There are other reproductive sources of walleye within the bay (Fielder 2002). The operational premise in the management of the bay's walleye fishery to date is: (1) That the combined reproductive sources operate with a single dynamic (i.e. as a single population). (2) That the Tittabawassee River is the single largest source and would be most reflective of the bay's walleye population. Recent attempts to better understand the mix of reproductive sources within Saginaw Bay, based on otolith microchemistry methods, have suggested that the Tittabawassee River may, in fact, not be the single greatest reproductive source (B. Murry, Central Michigan University, personal communication).

New information on movement dynamics of Tittabawassee River walleye from a telemetry study has suggested that fish are exposing themselves to certain fisheries and not others, by virtue of movement choices each year (T. Hayden, USGS, personal communication). Variable spatial structure of fish stocks complicates stock assessment and can be difficult to account for (Goethel et al. 2011). Accounting for movement of fish, usually from source locations to harvest or ‘sink’ localities in stock assessment typically involves the incorporation of a movement matrix (Quinn et al. 1990; Quinn and Deriso 1999; Bence et al. 2011) and is regarded to be among some of the challenges of the future of stock assessment modeling in fisheries (Quinn 2003). Such movement can have implications for management of the stocks (Wilberg et al. 2008), and is a challenge to the assessment of other species in the Great Lakes as well (Nalepa et al. 2005), and for walleye in other locations (Thomas et al. 2011). Some investigators have resorted to entirely different modeling approaches to compensate for the mixing of stocks (Michielsens et al. 2006; Molton et al. 2012). In this instance I concluded that attempting to use auxiliary information from one specific breeding source in the SCA objective function exposed the differences in dynamics and confounded the model’s estimation. Fielder (2014) has recognized this limitation and has recommended a diversification of source spawning runs for the future continuation of that tagging study. Better stock definition for walleye is needed in Lake Huron, with the definition not only determined by genetic or microchemistry type analyses but by differences in population metrics such as mortality, exploitation patterns, and movement.

Structure of the Saginaw Bay baseline SCA model exhibited sensitivity to only certain components of the joint likelihood function (among data sources). The failure to result in an iterative convergence in just three sensitivity trials suggests that the model structure is reasonably robust. The baseline SCA model is complex, however, given the four fisheries. It is difficult to say how the 181 parameters are interrelated during the model fitting process. Detailed analysis of parameter correlation may disentangle those relationships, but it is apparent from the sensitivity analysis that the model is generally consistent with its convergence. Future work on this model might explore whether similar estimates and confidence could be obtained with a simpler model or achieve greater resiliency. Key assumptions in this baseline model appear to include the by-kill values used with the larger extrapolated year-round values that resulted in a larger Saginaw Bay walleye population estimate. From this, it might be concluded that the estimates of the baseline are conservative in that relaxed assumptions would tend to lead to a larger estimated population.

The development of an SCA model to describe the Saginaw Bay stock of walleye in Lake Huron is a significant advancement in the assessment of this population. Not only has it offered age-based estimates of mortality rates and abundance, but it has also helped shed light on deficiencies of the Brownie model and biases that affect those estimates. The integrated version did not result in an improved model in this instance, but if the improvements in the Brownie model suggested by Fielder (2014) are achieved, future integration may still be possible. Statistical catch-at-age models are often used as the basis for forecasting models that allow evaluation of alternative fishery management strategies. Estimates like those generated from this SCA analysis would be essential in developing such a model. Management choices for walleye in most of the Michigan waters of Lake Huron has been, to date, primarily as a fixed rule (e.g., length limit, bag limit, and season closure in the spawning rivers) for the recreational fishery, and a yield allowance for by-catch in the tribal gillnet fishery in the northern portion of the lake. A simulation model based on the availability of estimated dynamics including recruitment, abundance and mortality rates would assist managers to design harvest regulations that are more state-based, and even address allocation if different jurisdictions ever feel that is necessary. Ultimately, the utility of this assessment model and its estimates will depend on fishery manager's willingness to advance management to keep pace with the information stemming from the assessment of this stock.

APPENDIX

Table 2.1. Estimated parameters of the catch-at-age model of the Saginaw Bay stock of walleye in Lake Huron.

Parameter	Description
S_a	Age-specific selectivity for each of the fisheries
s_a^{surv}	Age specific selectivity for the survey
q	Catchability coefficient for each of the fisheries (or starting value for recreational fishery random walk)
q^{surv}	Random walk time varying catchability for the survey
ε	Catchability deviations (white noise process error term) for the trapnet and gillnet fisheries or random walk deviations for recreational fishery and survey
$N_{a,1986}$	Initial numbers for the beginning year of 1986
$N_{2,y}$	Initial numbers of age-2 walleye for each modeled year (recruitment)
σ	Observation standard deviations for each fishery & survey except the state-licensed by-kill.

Table 2.2. Deviance information criterion (DIC) model selection of three candidate statistical catch-at-age models for the Saginaw Bay stock of walleye in Lake Huron based on different treatment of natural mortality (*M*): constant, age varying, and time varying. Included is the effective number of parameters (pD).

Model	DIC value	Delta from min	'Best' model	pD
Constant M	60208.4	66.2	No	160
Age-varying M	60142.2	0.0	Yes	180
Time-varying M	60340.8	198.7	no	149

Table 2.3. Sensitivity of penalized likelihood component analysis of the Saginaw Bay stock of walleye in Lake Huron statistical-catch-at-age model as percent change from the aged-based natural mortality model (baseline) version. Sensitivity was tested by applying a weighting factor lambda (λ) of either 0.5 or 2.0 to each of the 12 likelihood components in the baseline version of the model and assessing percent change from the time series mean for four metrics of management interest: population size (*N*), total annual mortality (*A*), spawning-stock biomass of females (SSB), and the exploitation rate (μ) of the four fisheries. Weighting factors that resulted in a lack of convergence are denoted by DNC (did not converge).

Weighting factor	N	A	SSB	Recreational μ	Trapnet μ	Gillnet μ	By-kill μ
Recreational harvest							
λ_1 =0.5	0.02	0.42	-0.50	2.66	0.63	0.23	1.99
λ_1 =2.0	0.51	-0.32	0.75	-1.77	-0.94	-0.73	-1.34
Recreational random walk							
λ_2 =0.5	0.12	0.28	0.22	0.29	-0.16	-0.22	1.84
λ_2 =2.0	0.68	-1.01	0.24	-1.75	-0.64	-0.61	-5.78
Recreational age structure							
λ_3 =0.5	-0.28	-0.06	-0.85	1.55	2.63	1.43	-3.73
λ_3 =2.0	-0.89	1.93	0.34	2.22	-1.00	1.36	14.23
Survey catch-per-unit-of-effort							
λ_4 =0.5	289.27	39.29	251.98	-57.56	240.57	128.19	43.02
λ_4 =2.0	0.09	-0.04	0.09	-0.16	-0.13	-0.14	-0.19
Survey random walk							
λ_5 =0.5	-0.18	0.17	-0.09	0.36	0.15	0.18	1.09
λ_5 =2.0	DNC	DNC	DNC	DNC	DNC	DNC	DNC
Survey age structure							
λ_6 =0.5	1.47	-1.01	2.26	-4.74	-3.55	-6.73	0.35
λ_6 =2.0	4.53	6.47	-0.72	26.18	4.79	6.77	17.84
Trapnet harvest							
λ_7 =0.5	-0.23	0.33	-0.01	0.23	-0.05	0.54	1.39
λ_7 =2.0	11.80	5.63	8.54	-9.97	-5.68	95.48	11.29
Trapnet effort							
λ_8 =0.5	DNC	DNC	DNC	DNC	DNC	DNC	DNC
λ_8 =2.0	0.53	-0.32	0.25	-0.13	-0.46	-0.94	-1.17
Trapnet age structure							
λ_9 =0.5	0.94	-1.15	-0.53	0.48	-0.13	3.89	-6.87
λ_9 =2.0	625.12	11.49	567.72	-85.23	-85.23	693.50	-73.49
Gillnet harvest							
λ_{10} =0.5	417.59	44.18	361.30	-68.16	234.87	216.26	-57.33
λ_{10} =2.0	DNC	DNC	DNC	DNC	DNC	DNC	DNC
Gillnet effort							
λ_{11}=0.5	-0.81	1.03	-0.12	0.81	0.50	3.27	5.69
λ_{11}=2.0	1.50	-1.42	0.40	-1.38	-0.99	-2.99	-7.58
Gillnet age structure							
λ_{12} =0.5	-0.02	-0.01	-0.19	0.01	-0.11	0.05	-2.46
λ_{12} =2.0	411.51	628.02	375.61	-12.94	283.44	-50.40	411.51

Table 2.4. Sensitivity of assumptions analysis of the Saginaw Bay stock of walleye in Lake Huron statistical-catch-at-age model from the age-based natural mortality model (baseline) version for key assumptions: (1) An expanded (extrapolated) estimate of the magnitude of commercial by-kill in the bay from MacMillan and Roth (2012). (2) An expanded recreational observed catch to simulate an Ontario component. (3) Two alternative durations of residency time for the habitation of Lake Erie (LE) walleyes in Lake Huron. (4) The ages at which Lake Erie walleye are hypothesized to immigrate was adjusted to fully include age-3 and one-half of age-2 fish. (5) Alternative variance ratios used in the likelihood functions for relating white-noise or random-walk deviations of catchability to catch. (6) Treatment of recreational catchability as a white-noise process instead of random walk. (7) Treatment of age-based natural mortality *M* as a prior in the model estimation and then alternative values based on 95% confidence intervals. Sensitivity was assessed as percent change from the time series mean for four metrics of management interest: population size (*N*), total annual mortality (*A*), spawning stock biomass of females (SSB), and the exploitation rate (μ) of the four fisheries. A lack of model convergence is denoted by DNC (did not converge).

Model version	N	A	SSB	Recreational μ	Trapnet μ	Gillnet μ	By-kill μ
By-kill magnitude							
Extrapolated value	36.18	-0.03	26.34	-19.36	-20.14	-19.68	201.83
Expanded recreational fishery							
10% increase	5.75	-0.05	5.15	3.63	-5.63	-5.86	-4.27
Duration of LE habitation							
0.60 year	-0.75	-0.19	-0.80	-0.34	0.01	0.02	0.11
0.40 year	DNC	DNC	DNC	DNC	DNC	DNC	DNC
LE immigration							
Includes ages 2 and 3	-2.89	-1.68	6.10	-1.90	-4.50	1.26	-3.15
Variance ratios							
Recreational							
1.15	-0.08	-0.02	-0.18	0.31	0.19	0.15	-0.24
Trapnet							
1.25	0.16	0.15	0.19	0.10	-1.23	0.03	0.72
Gillnet							
1.25	0.04	-0.06	0.00	-0.01	0.00	-0.69	-0.36
0.75	-0.06	0.08	-0.02	0.03	0.02	0.84	0.56
Survey							
1.15	0.04	-0.05	0.01	-0.09	-0.02	-0.02	-0.28
Catchability deviations							
Recreational white noise	22.22	-10.07	12.21	-19.34	-15.91	-17.95	-47.00

Table 2.4 (cont'd)

Age-based *M* values							
M_{age} as a prior	0.45	-0.03	0.01	-0.16	-0.40	-0.04	0.05
M_{age} 95% upper limit	21.93	3.22	12.83	-8.76	-9.81	-9.19	-15.74
M_{age} 95% lower limit	-15.51	-3.17	-9.94	7.93	8.77	8.01	15.99

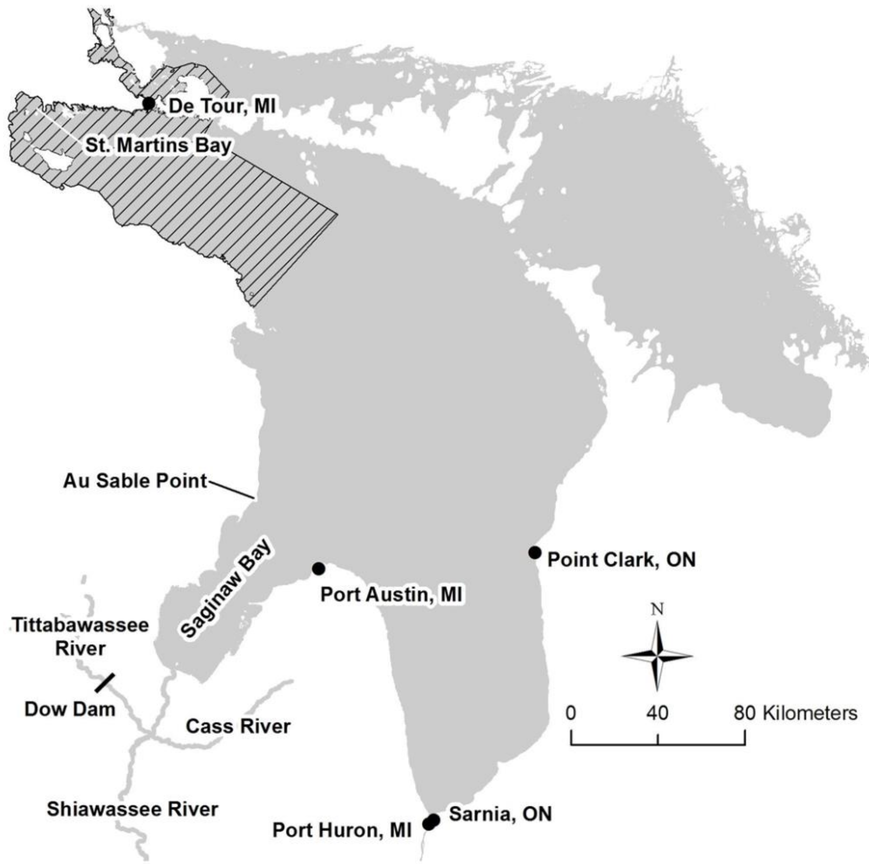

Figure 2.1. Saginaw Bay and Lake Huron showing geographic features of importance to the model components. The vicinity indicated by hash marks represents the 1836 Treaty area of Lake Huron.

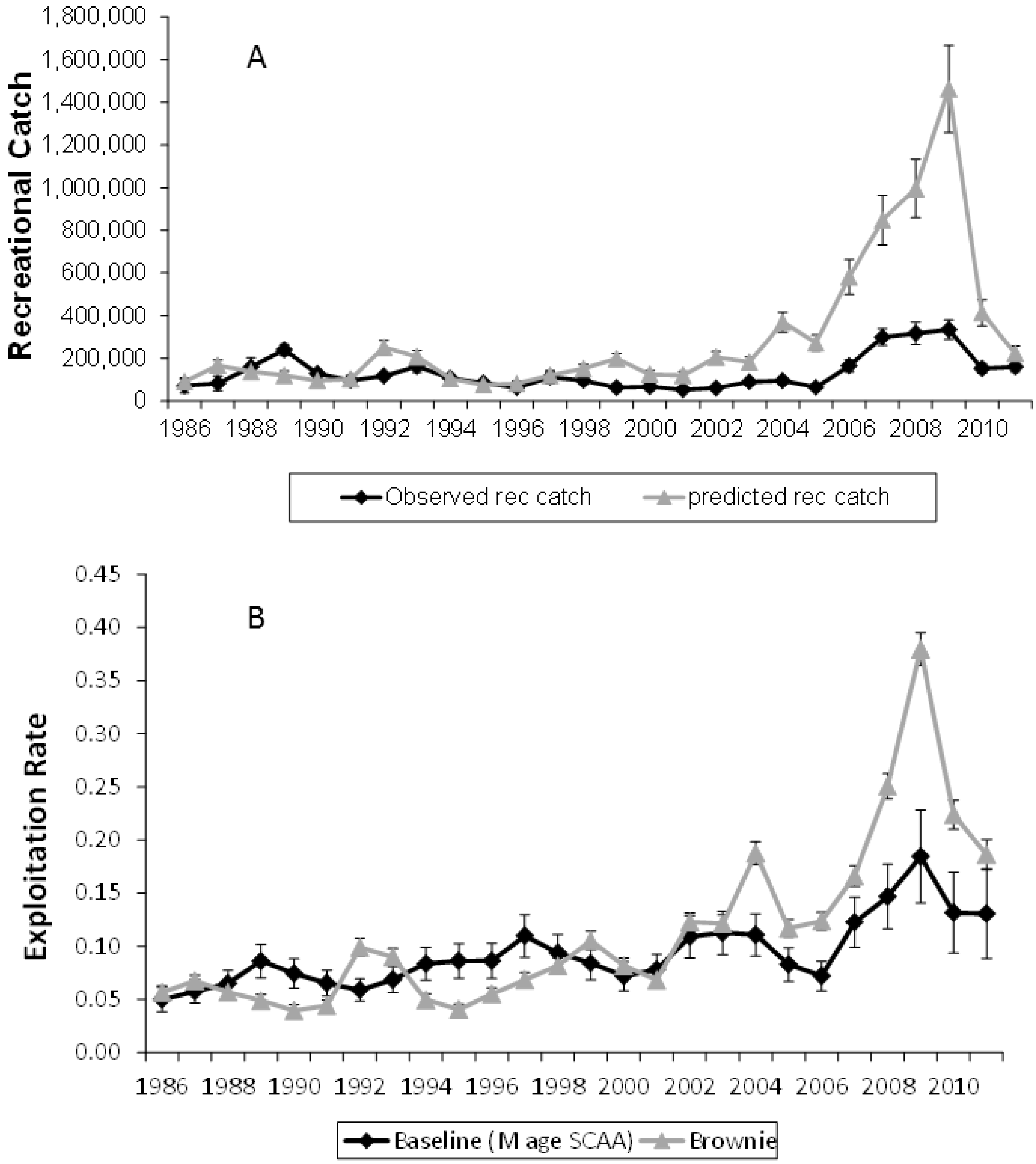

Figure 2.2. (A) Comparison of observed and predicted recreational walleye catch based on the integrated model version. (B) Recreational exploitation rates between that estimated by the age based natural mortality (baseline) version of the Saginaw Bay statistical-catch-at-age model version and that from the Brownie model (from Fielder 2014). Error bars are ±1.96 standard errors.

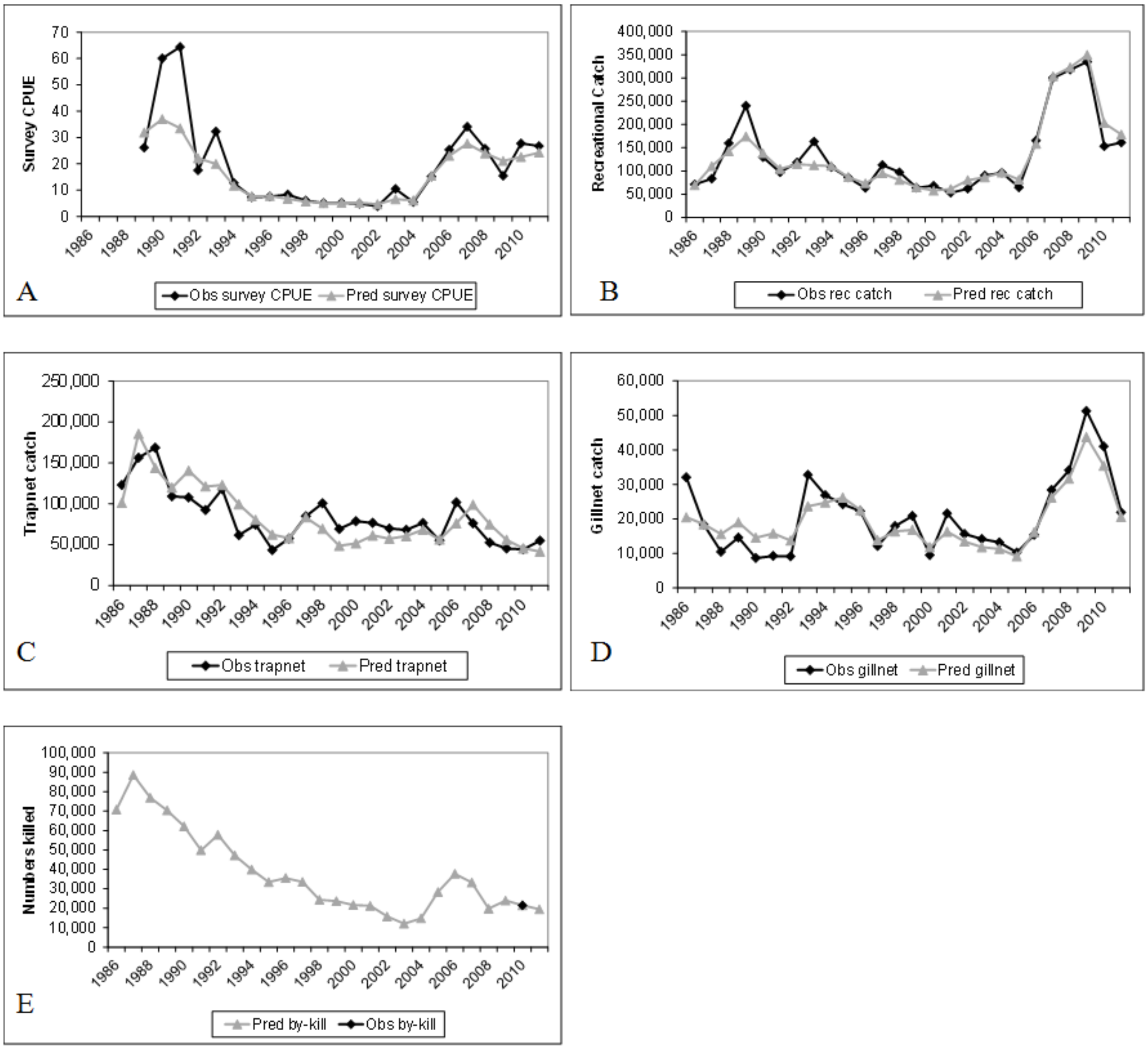

Figure 2.3. Observed and predicted values 1986 – 2011, from the *M*-age based (baseline) version of the Lake Huron walleye statistical-catch-at-age model for the (A) fishery-independent survey, (B) recreational fishery catch, (C) trapnet fishery catch, (D) lake-wide (combined Ontario and tribal) gillnet fishery catch, and (E) the commercial by-kill.

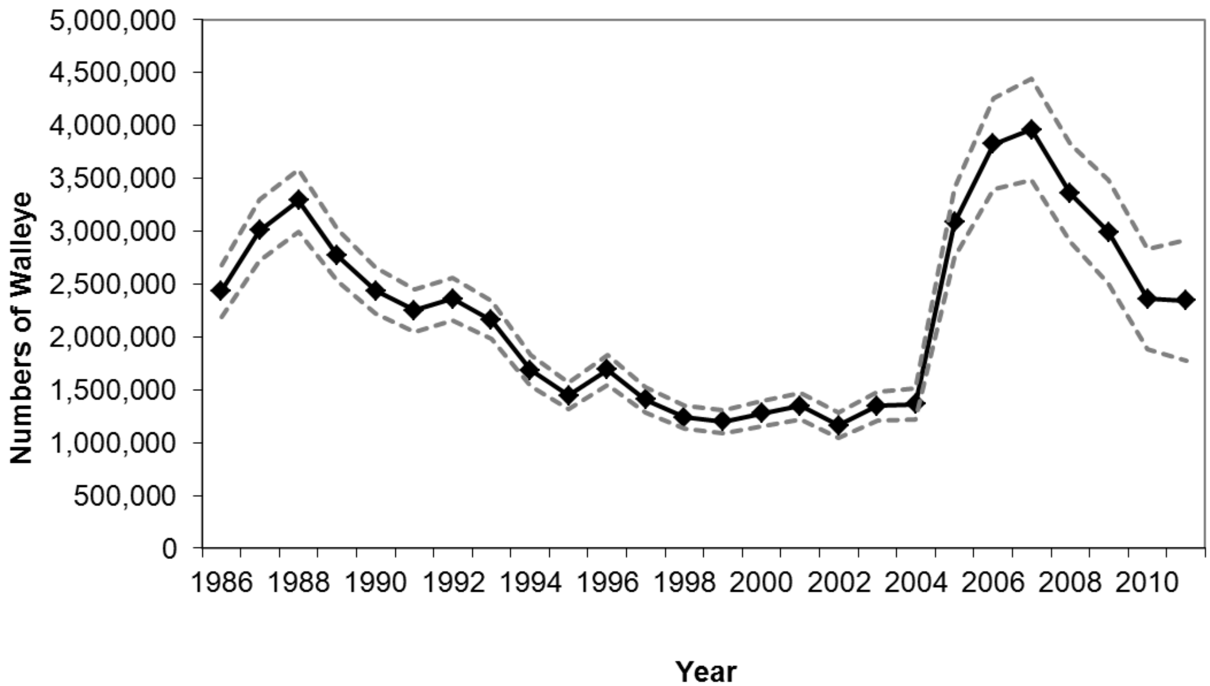

Figure 2.4. Numbers of the Saginaw Bay stock of walleye in Lake Huron 1986 – 2011 age 2 and older and the +1.96 standard errors (dashed lines) confidence interval, as predicted by the age-based natural mortality (baseline) version of the statistical-catch-at-age model.

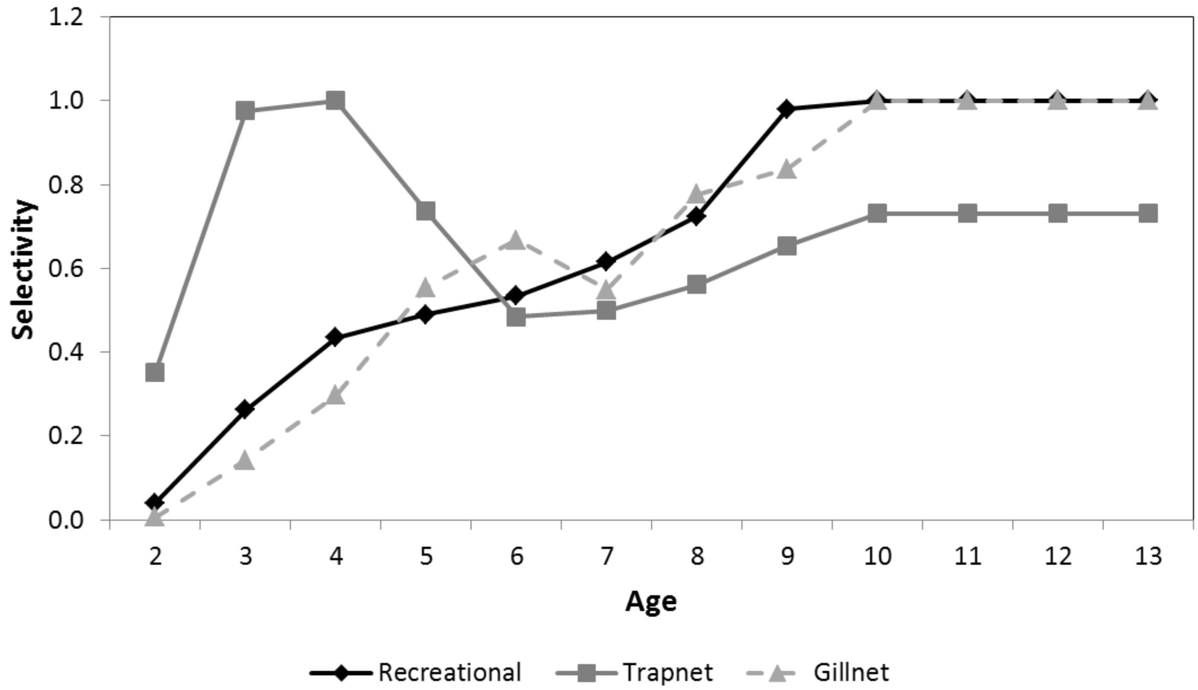

Figure 2.5. Selectivity of the three estimated fisheries scaled to 1.0 based on maximum value by age for the age-based natural mortality (baseline) version of the Saginaw Bay stock, statistical-catch-at-age model for Lake Huron, 1986-2011 data.

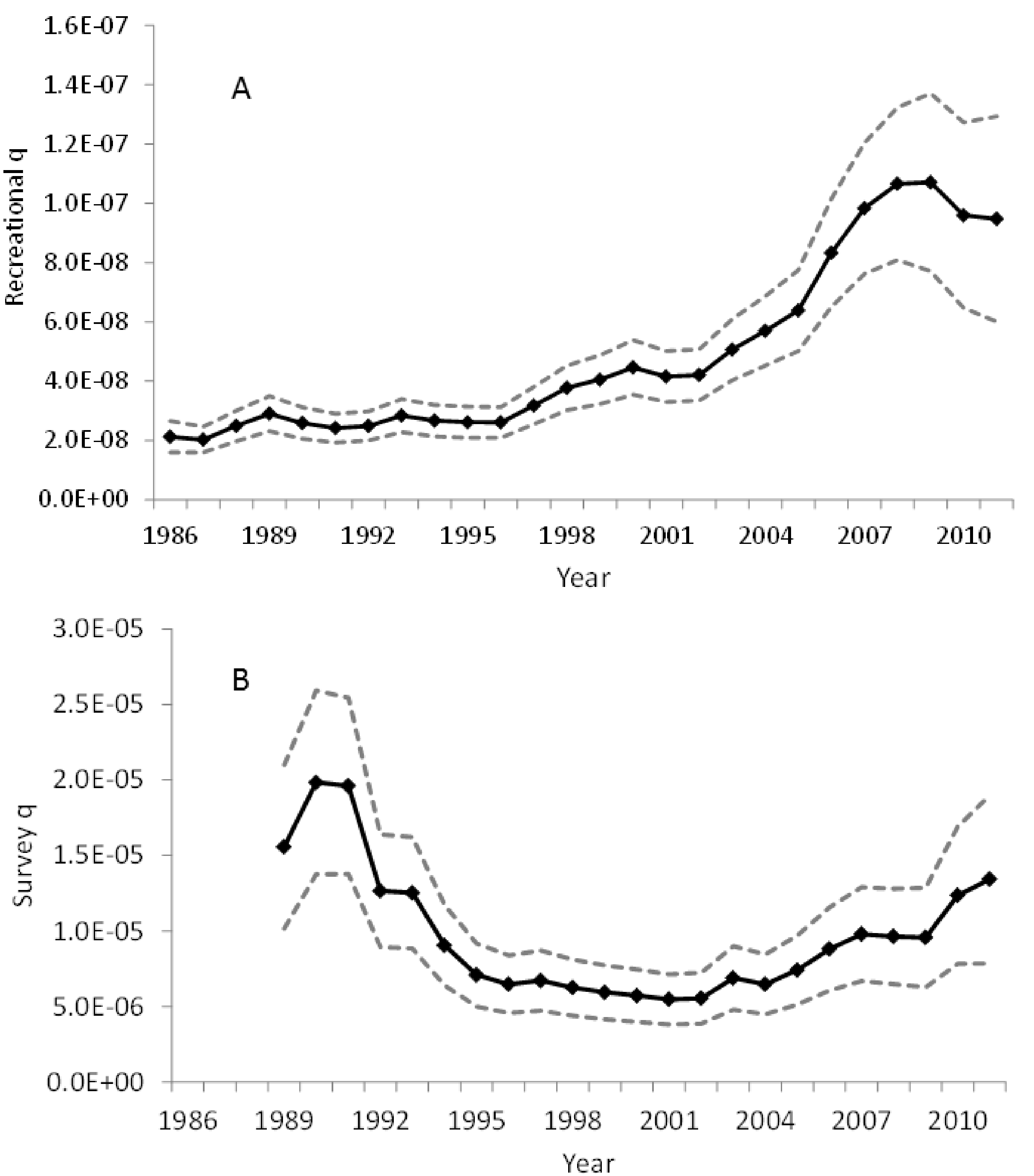

Figure 2.6. Time-varying catchability (*q*) and the $\pm$1.96 standard errors (dashed lines) confidence interval of the (A) recreational fishery and (B) survey of the Saginaw Bay stock of walleye in Lake Huron from the age-based natural mortality (baseline) version of statistical-catch-at-age model 1986-2011.

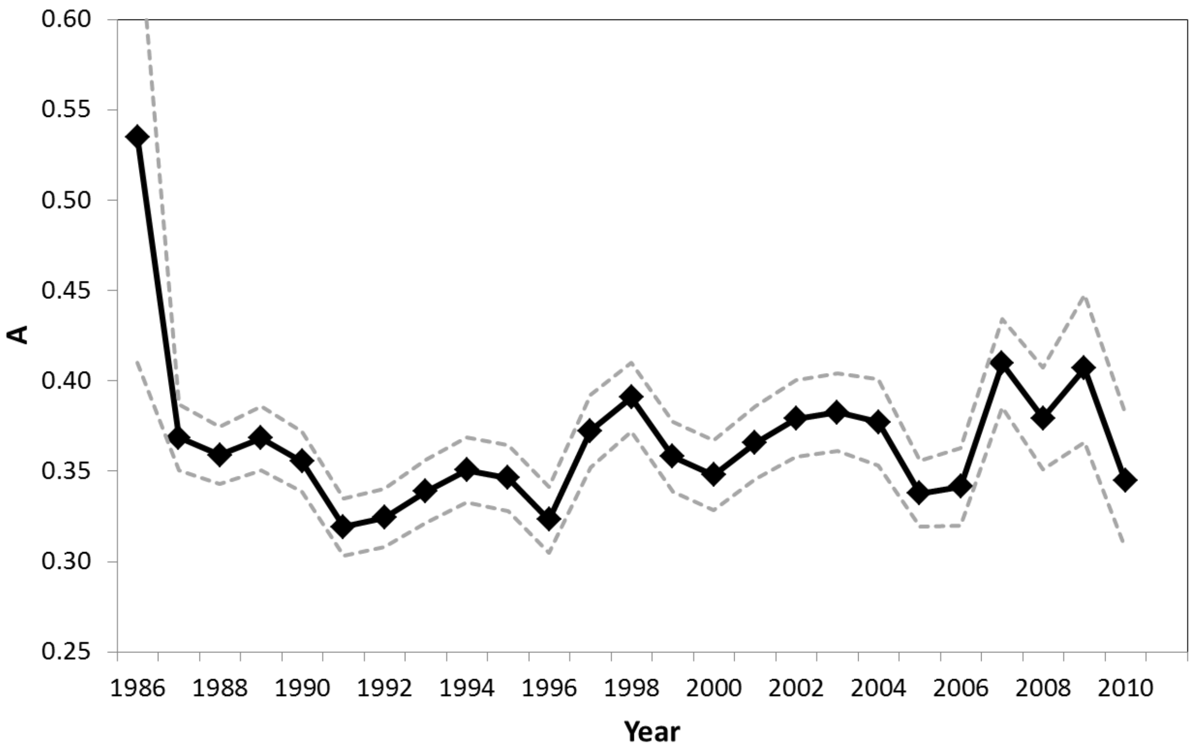

Figure 2.7. Total annual mortality rate (limited to age-4 and older fish), *A* for the Saginaw Bay stock of walleye in Lake Huron 1986-2010 and $\pm$1.96 standard errors (dashed lines) confidence interval, as predicted by the age-based natural mortality (baseline) version of the statistical-catch-at-age model.

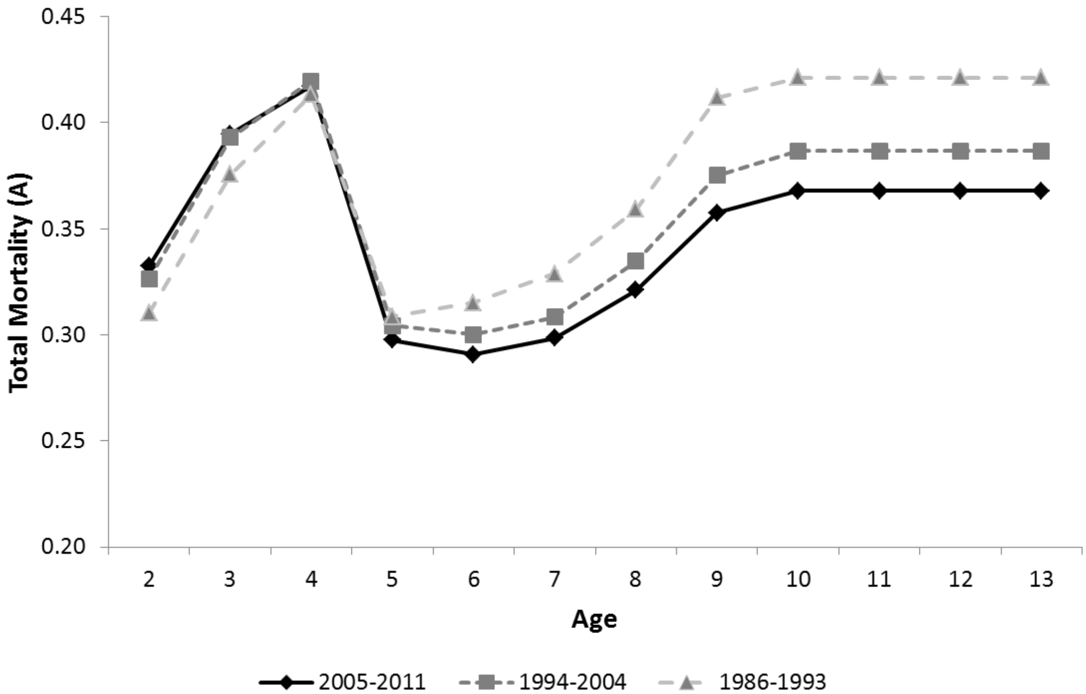

Figure 2.8. Total annual mortality (*A*) of the Saginaw Bay stock of walleye by age (years) for three time periods as estimated by the age based natural mortality statistical-catch-at-age model (baseline) version.

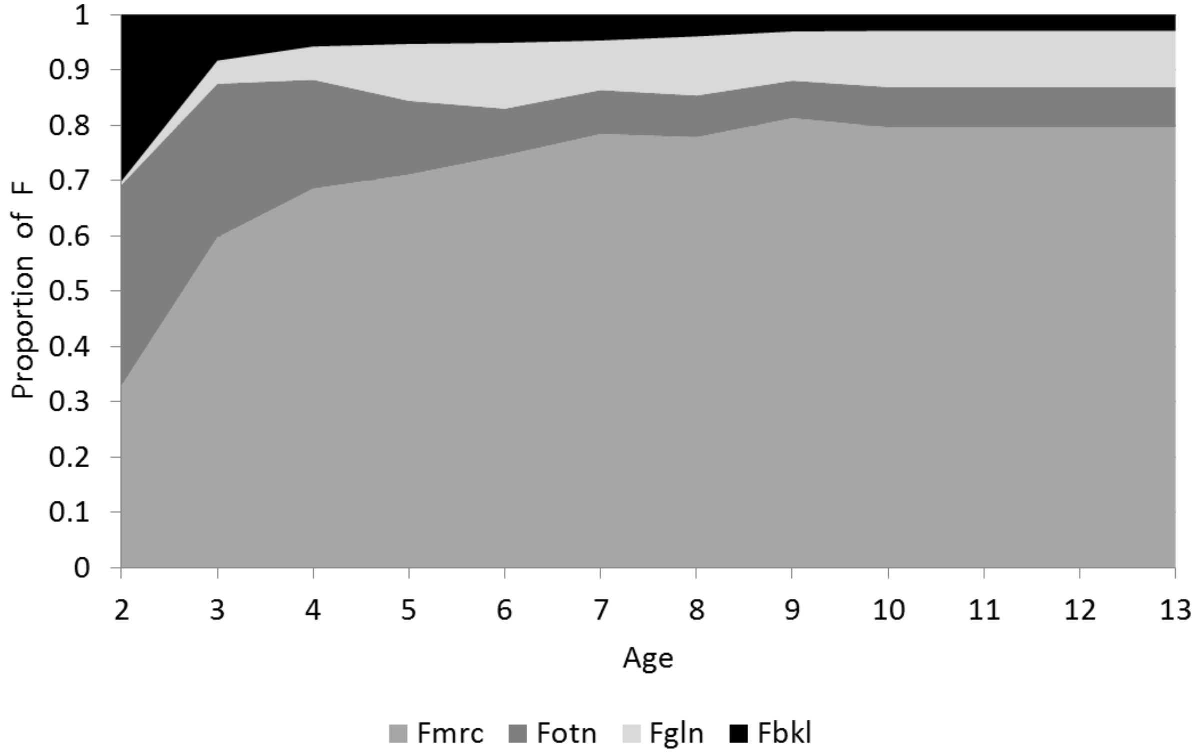

Figure 2.9. Proportion of fishing mortality (*F*) by age for 2011 from the age-based natural mortality (baseline) version of the Saginaw Bay stock of walleye statistical-catch-at-age model for walleye from the Michigan recreational fishery (*F*mrc), Ontario trapnet fishery (*F*otn), the lake-wide (combined Ontario and tribal) gillnet fishery (*F*gln) and the by-kill stemming from the state licensed trapnet fishery in Saginaw Bay (*F*bkl).

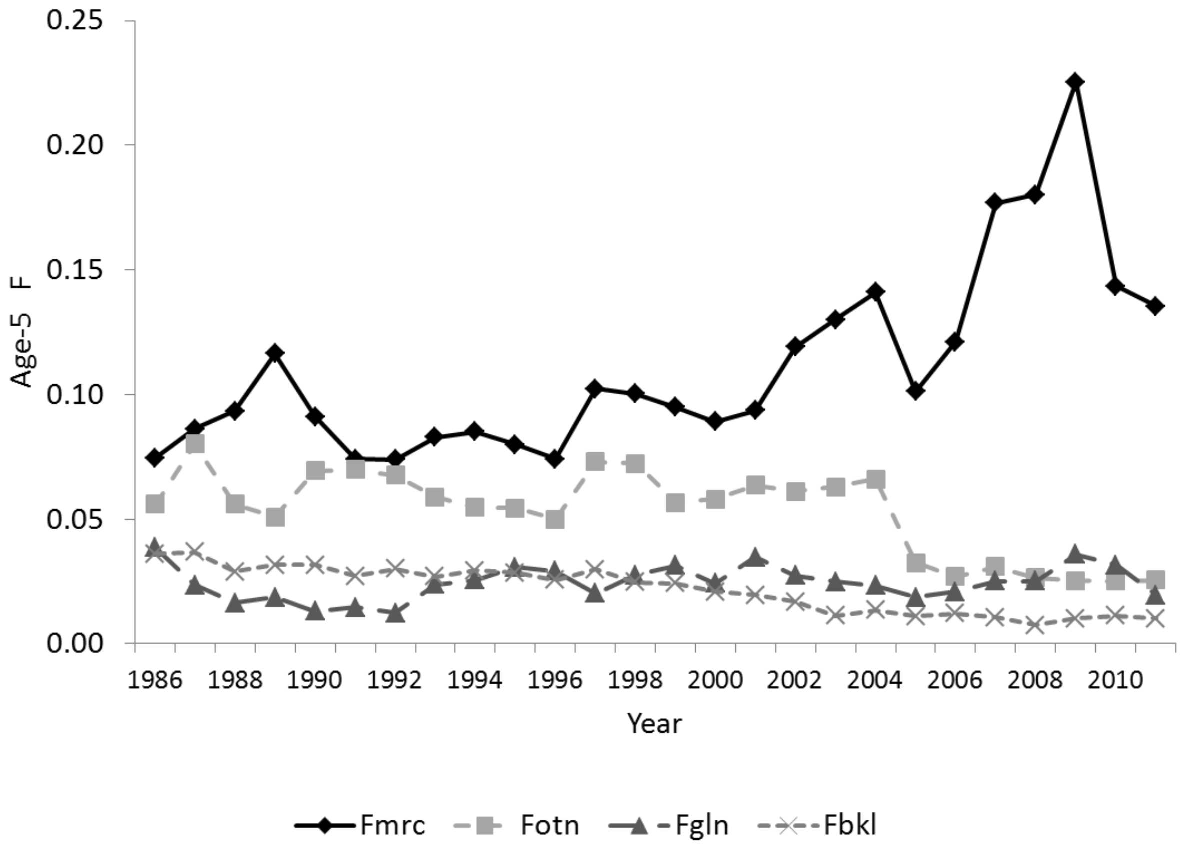

Figure 2.10. Fishing mortality (F) of age-5 walleye over time from the four fisheries represented by the age-based natural mortality (baseline) version of the Saginaw Bay stock of walleye statistical-catch-at-age model. Michigan recreational fishery (*F*mrc), Ontario trapnet fishery (*F*otn), the lake-wide (combined Ontario and tribal) gillnet fishery (*F*gln) and the by-kill stemming from the state licensed trapnet fishery in Saginaw Bay (*F*bkl).

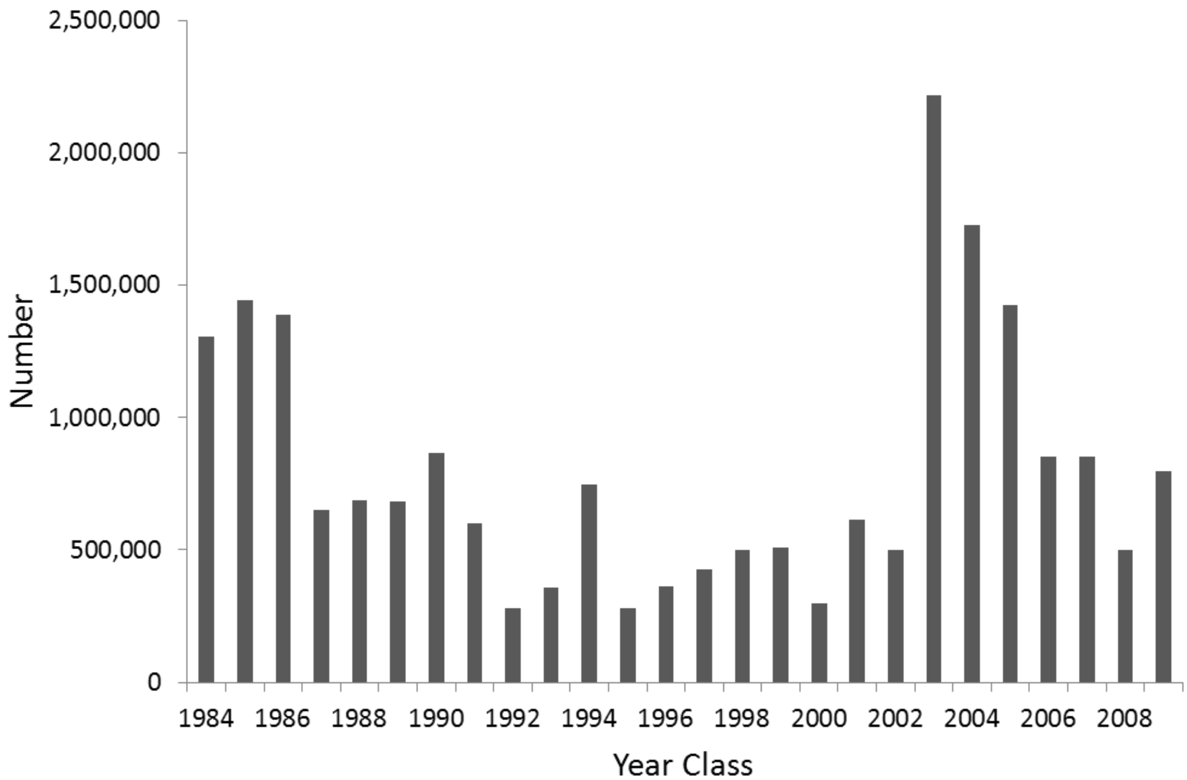

Figure 2.11. Recruitment of walleye to the Saginaw Bay stock as estimated by the age-based natural mortality statistical-catch-at-age model (baseline) version based on age-2 numbers attributed to their originating year class.

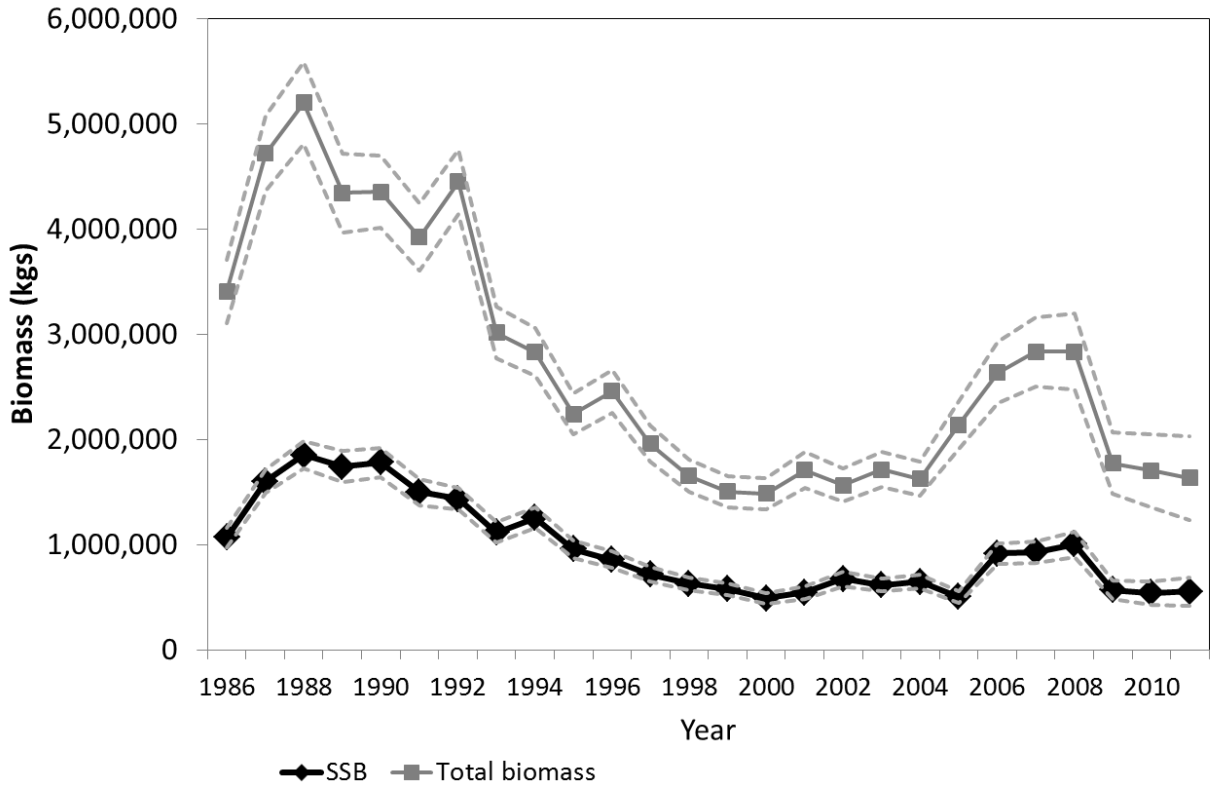

Figure 2.12. Total biomass (all ages and both sexes) and spawning-stock biomass (SSB) of mature female walleye (in kilograms) for the Saginaw Bay stock of walleye in Lake Huron, 1986-2011 and ±1.96 standard errors (dashed lines) confidence interval, as predicted by the age based natural mortality version of the statistical-catch-at-age model.

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CHAPTER 3

ANALYSIS OF MANAGEMENT OPTIONS AND VALUE OF INFORMATION FOR THE SAGINAW BAY STOCK OF WALLEYES BASED ON STOCHASTIC SIMULATIONS

Abstract

Saginaw Bay walleyes contribute to fisheries throughout Lake Huron, including a recreational fishery and by-kill stemming from the state-licensed commercial fishery in the bay. Two critical uncertain states of nature exist concerning the true magnitude (catchability) of the by-kill and the future of alewives in Lake Huron, the latter being a strong determinant of walleye recruitment. After consulting with fishery managers, a stochastic simulation model was developed and used to evaluate management options for the recreational fishery in the form of a decision analysis and the value of information for improved estimates of by-kill magnitude. Management option evaluation indicated a greater harvestable surplus that could be allocated. Sustainable harvest was average harvest treating harvest in years when sustainability criteria were not met as zero. Sustainable harvest would be maximized if recreational fishing mortality were increased 50% from recent levels. Realizing this potential, however, would require more intensive management to ensure that desired levels of *F* occurred. Choices by managers as to how to allocate surplus harvest are a matter of policy, but concerns over maintaining predation pressure on alewives so as to suppress any resurgence may be reasons to manage conservatively by electing to instead maintain a higher predator abundance. The value of information analysis revealed that further research investment in the uncertainty over by-kill catchability could provide net benefits from the recreational fishery.

Introduction

The Saginaw Bay (Figure 3.1) stock of walleye is the single largest source of walleye in Lake Huron (Schneider and Leach 1977; 1979) and historically sustained the largest walleye fishery in the Great Lakes outside of Lake Erie (Baldwin and Saalfeld 1962). The stock declined and its fisheries collapsed in the mid-20th century due to a series of year class failures, which were attributed to habitat destruction, poor water quality, and effects of invasive species (Schneider 1977; Schneider and Leach 1977; 1979). After improving conditions and initiation of a fingerling stocking program in the early 1980s (Fielder 2002), a recreational fishery emerged (Fielder et al. 2014). Full recovery and the discontinuation of stocking came in 2006 (Fielder and Thomas 2006; 2014); the recovery was attributed to the decline of alewives in Lake Huron which were predators and competitors on newly hatched walleye fry (Fielder at al. 2007; Riley et al. 2008; Dunlop et al. 2010).

Early walleye fisheries in Saginaw Bay were almost exclusively commercial (Baldwin and Saalfeld 1962; Schneider 1977). The recreational fishery that emerged in the 1980s was all that remained in the bay after formal closure of commercial walleye fisheries in the early 1970s (Schneider 1977; Fielder et al. 2014). Commercial fishing continued in Saginaw Bay for other species. Modern day management efforts such as habitat improvement and stocking focused on promoting the recovery of the walleye population (Fielder and Baker 2004). Aside from those efforts, management of the stock was based principally on statewide harvest regulations on the recreational fishery including a five fish per day bag limit, a 381 mm minimum length limit, and a spring spawning closure in tributaries to the open water.

Today, several fisheries, both in and outside Saginaw Bay are believed to exploit this stock of walleye including commercial trapnet and gillnet extractions in Ontario's southern Lake Huron waters, a tribal gillnet fishery in northern Lake Huron permitted as a by-catch under the 1836 Treaty 2000 consent decree, recreational fisheries both in and outside the bay, and lastly a by-kill (by-catch mortality) of walleyes in Saginaw Bay from the remaining commercial fishery. The exploitation outside the bay stems from migration of some walleyes, initially confirmed by a tagging program that began in 1981(Fielder 2014). Those angler-reported tag returns amounted to 9% being reported from outside the bay over the years. More recently, a telemetry study of walleye movement indicated that about half of the adults make a seasonal emigration from the bay to points throughout Lake Huron (T. Hayden USGS, Personal communication). Fielder and Bence (2014) assessed the Saginaw Bay stock of walleyes through the use of statistical-catch-at-age (SCA) analysis. That analysis concluded that the dynamics of the stock were affected by each of these fisheries.

The commercial by-kill of walleyes in Saginaw Bay was quantified by MacMillan and Roth (2012) who generated two estimates; a lesser value of 21,500 for their observation period of May through August 2010, and a larger estimate of 102,000 extrapolated to the entire year. Analysis by Fielder and Bence (2014) found the estimates generated by their SCA model to be sensitive to the choice of the by-kill estimate (observed seasonal or extrapolated year-round) used to parameterize the model. Additional research has been proposed to refine the estimates of commercial walleye by-kill in Saginaw Bay (B. Roth Michigan State University, personal communication).

With the transition from an emphasis on stock recovery to the next stage of management, fishery managers today on Lake Huron are seeking to define new management goals and objectives for the Saginaw Bay walleye population and fisheries. The walleye fishery in Lake Erie is managed through a combined assessment and allocation process under the guidance of the Great Lakes Fishery Commission. Goals there have been to fairly allocate resources, and fully utilize the resource but within the boundaries of sustainability (GLFC 2005). Part of the motivation to update management practices on Saginaw Bay is to reflect new information about the extent and complexity of exploitation of the stock. In spite of this new information, considerable uncertainty remains making management decision making and research planning difficult.

Several sources of uncertainty about the dynamics of this stock persist. In this analysis we concern ourselves principally with two; what is the true amount of walleye by-kill occurring in Saginaw Bay's state-licensed commercial fishery and what will alewives do in the future? If alewives remain scarce, walleye are expected to continue to sustain strong year classes but should alewives recover, walleye year classes are expected to become weak and reduced again (Fielder et al. 2007; 2010). There is a lack of consensus on the future of alewives in the lake (Riley et al. 2008). Accounting for uncertainty in fishery management does not necessarily result unless specifically sought. Williams (1997) describes natural resource management in the face of uncertainty and argues that too often, decision makers ignore uncertainty. Wise fishery management will seek to consider uncertainty for making decisions (Walters 1986; Lane and Stephenson 1998; Jones and Bence 2009) and, where appropriate, seek opportunities to reduce critical uncertainties.

Not all uncertainties, however, are of sufficient magnitude or significance to warrant investment in their elimination (Hansen and Jones 2008). Analysis of the value of information is one form of decision analysis. The expected value of perfect information (EVPI) is an estimate of the expected increases in benefits or decrease in expected losses, if we could eliminate a source of uncertainty (Peterman and Peters 1998). The concept of EVPI is closely tied to those of adaptive management where one seeks to reduce uncertainty so as to further management of a resource (Walters 1986). Simply put, analysis of EVPI can be thought to answer the question "does the elimination of uncertainty justify the cost of doing an experiment or paying for new information?" (Clemen and Reilly 2001).

My objective with this analysis was to offer insights to managers on the development of new management goals and objectives for this stock, specifically with regards to the extent to which the recreational fishery may exploit walleyes within limits of sustainability. Secondly, I address whether management would benefit from refined estimates of state-licensed commercial by-kill in Saginaw Bay by conducting a value of information analysis, thereby determining the utility of reducing one element of uncertainty about Saginaw Bay walleye management. To accomplish the examination of management options, and to enable the EVPI analysis, I develop a stochastic (system) model and use it to simulate the dynamics of the stock, its exploitation and test the population and fishery response across the range of uncertainties and management scenarios. My intent is to better frame the range of management options available and the tradeoffs that will face future management.

Methods

Management input.--I framed the decision analysis by first meeting with State of Michigan fishery managers from the Department of Natural Resources (DNR) whose jurisdiction included the recreational fisheries within Michigan waters of Lake Huron and the by-kill within the state-licensed commercial fishery. Fielder and Bence (2014) found these sources to collectively constitute the majority of total fishing mortality exerted on the stock. Interaction with fishery managers was based on one meeting devoted to discussing management objectives and the current state of knowledge, and uncertainty, concerning Saginaw Bay walleye stocks and fisheries, and also periodic participation in the Michigan DNR's Lake Huron Basin Team meetings, which included ongoing discussions of walleye management and information needs. Between February 2013 and February 2014, researchers and managers met three times to explore these issues.

Among the topics discussed was the existing state of management. Participants were in agreement that emphasis over the previous three decades was on stock recovery and that management has relied on statewide recreational harvest regulations. Considerable investment had been made in research and assessment, and while substantial knowledge had been amassed, many uncertainties remained, especially in light of the growing awareness of the complexity of the lake wide nature of the stock, its movement, and exploitation. Additional discussions were focused on identifying uncertainties that managers felt were necessary to reduce, to make management decisions. Performance measures and critical thresholds were discussed that helped frame a basis for simulation modeling. As development of the simulation model progressed, discussions included feedback on the model structure and performance as a basis to reflect the primary considerations of walleye management.

Aside from the state-wide recreational fishery regulations, the only state-based management rule that existed was a pledge that managers would annually revisit the decision to suspend walleye stocking and may reinstate it if alewives ever became abundant again. Alewife abundance was annually estimated by the U.S. Geological Survey's (USGS) Great Lakes Science Center (GLSC)'s bottom trawling and hydroacoustic survey. Analyses have suggested that a threshold of alewife density existed at 20 age-1 and older alewife/ha such that densities less than that allowed for recruitment of walleye (Fielder et al. 2007; Fielder and Thomas 2014). Managers maintained that walleye fingerling stocking likely would be resumed if and when alewife density ever increased above this threshold in the future. This suggested one obvious management option to include in the simulation model.

Objectives and performance measures.-- Managers were in agreement that stock sustainability was a primary objective, as was the desire to manage for the greatest recreational harvest (in numbers) possible. Knowing that walleye management in Lake Erie has led to a liberalization of recreational harvest regulations over state-wide rules in many years, managers wanted to determine the greatest recreational harvest that could be sustained with an expectation that harvest regulations could then be crafted to achieve or allow for that.

On the other hand, managers were also concerned that a liberal harvest policies or allocation of walleye may lead to a reduced stock. To capture the idea of sustainability being a function of spawning stock, we identified the ratio of mature female spawning stock biomass (SSB) of walleyes relative to the unfished SSB (β_0) as a metric representing a threshold of management concern. Specifically the proportion of years across multiple simulations for any given management scenario that dropped below 20% β_0 was designated as a performance measure to address sustainability with respect to the risk of recruitment overfishing. The 20% β_0 threshold was chosen because it was consistent with the inflection point in the stock-recruitment relationship such that stock sizes less than that risked recruitment-overfishing.

Criteria for detection of walleye recovery from the degraded state was defined by Fielder and Baker (2004) and offered some additional basis for defining performance measures for future management. The principal benchmark for defining recovery was a mean total length (TL) of age-3 walleye (sexes combined) at or below 110% the state average rate at the time of survey capture which was 425mm (for a September collection). The benchmark was based on the belief that mean TL at age could serve as a surrogate for growth rate, which is affected by density. When size at age is above this threshold (i.e., relative high growth rates), the system should be able to support higher densities of walleye. Walleye mean TL at age 3 slowed, falling below this threshold for the third consecutive year in 2009 (Fielder and Thomas 2014) and was the primary basis for declaring the stock recovered.

With the above objectives and considerations in mind, specific performance measures were identified. Mean TL at age-3, SSB ratio (the proportion of years SSB fell below 20% of β_0), and recreational harvest were therefor selected as the performance measures (Table 3.1). The decision analysis and value of information analysis required the combination of these measures into one overall objective function. For this purpose we used the average recreational harvest (over years for a simulation). Harvest in years when one or both thresholds of sustainability (TL of walleye >425mm, SSB below 20% β_0) were violated was set to zero in the calculation of the average. From here on I refer to this function as "sustainable harvest".

Critical uncertainties.-- Managers emphasized that they remain uncertain about future trends of alewives in Lake Huron (Table 3.1). Although alewives have not recovered after 10 years post collapse, it remained unclear whether their continuing scarcity was due to lower productivity (bottom up) or suppression via predation (top down). Recognizing that alewives were a strong determinant of walleye recruitment (Fielder et al. 2007), their future was included as a critical uncertainty. After reflection, the managers and researchers concluded that a reasonable characterization of expert opinion would be that on-going suppression of alewives was three times more likely than their resurgence. I examined the sensitivity of my conclusions to this choice of probabilities by repeating the analysis at a lesser 10% likelihood of alewife recovery.

The second critical uncertainty was whether the true value of commercial by-kill was best reflected by the lower value estimated for the period when by-kill was directly observed by MacMillan and Roth (2012) or the larger value that reflects an extrapolation to the remainder of the year (Table 3.1). Most managers were skeptical that the true value was as great as the extrapolated value because the measurements were limited primarily to one fisher and because of the potential for seasonal differences outside the warmer months. However, they also conceded that the true value had to be greater than that which was reported for the observation period alone. Not having any clear basis for assigning probabilities beyond that rationale, it was agreed to treat the two as equally likely. The assumed magnitude of by-kill directly affected the estimate of by-kill catchability from Fielder and Bence (2014). In turn, the differing estimates of by-kill catchability affected most other population metrics and parameters estimated by the SCA model. Thus, when evaluating the effect of the two alternative by-kill hypotheses, the simulation model had to be reparameterized with values from the SCA model fit to the appropriate by-kill value.

We developed a decision tree to graphically depict the potential decision framework (Figure 3.2). Other uncertainties also existed such as the future of recruitment, fishing effort, natural mortality, and catchability in the other fisheries aside from the by-kill. These uncertainties, however, were either accounted for by incorporating stochasticity about their relationships in the simulation model (e.g. stock/recruitment function and fishery catchability) or were treated as constants (effort and natural mortality).

Candidate recreational harvest policies and decision analysis.-- Recognizing that the management agency principally had the most influence over the recreational fishery, analysis was limited to those extractions. In the simulations I evaluated a range of recreational fishing mortality rates. In particular, I varied recreational fishing mortality from 10% to 400% of recent levels here after referred to as fishing intensity and applied as scalars (multipliers) to the current fishing mortality rate (Table 3.1) and represented by the notation *F*value such that *F*1.5 means 1.5 times the current fishing mortality. Managers were not ready to identify any new state-based management options for the recreational fishery but did want to answer the objective of learning the range of population response to varying amounts of recreational harvest with an emphasis on the upper limit to exploitation that would still keep the frequency of SSB falling below 20% of β_0 rare, and a mean TL of age-3 walleyes $\leq$ 425 mm.

The sustainable harvest for each level of fishing intensity was analyzed as a decision analysis according to Figure 3.2. Decision analysis principally followed the methods of Peterman and Anderson (1999). This decision analysis was premised on the uncertain states of nature regarding by-kill catchability and future alewife trends and their probabilities described in Table 3.1. The combined probability of occurrence of these alternative states of nature was the product of their individual probabilities (Table 3.1). Thus to calculate the average sustainable harvest for a given level of fishing intensity, a weighted average was calculated based on the simulation results for each of the four uncertain states of nature and using the probabilities of those states as weights.

Value of by-kill information.-- The calculation of EVPI followed the methods of Clemen and Reilly (2001) and also used sustainable harvest as the objective function. The management options evaluated were the same as previously described for the recreational fishing mortality intensities (Table 3.1). The expected value after knowing the true model (elimination of uncertainty) was the average of the maximum performance (maximum recreational harvest) obtained under conditions of either high or low by-kill. Maximizing separately for each by-kill condition was premised on the idea that recreational F could be optimized for the given by-kill level if this were known. The EVPI was the difference between that value, and maximum value of the "best" management option when the same recreational F had to be applied regardless of by-kill because the level of by-kill was unknown. In this case, that was the greatest sustainable recreational harvest across management options (the ranges of fishing intensities simulated) within the four uncertain states of nature.

The expected value of imperfect information (EVII) is an extension that attempts to further account for the uncertainty in the ability of experiments to successfully reduce or eliminate the uncertainty about the states of nature. We regarded the probability of a new study of walleye by-kill to successfully achieve its objectives as 95% likely based on the standard usage of a significance level of 0.05 for a type-I error in any statistical tests stemming from further by-kill research.

This approach to value of information is premised on the two estimates of by-kill. In reality the true value may be an intermediate level and as such the dichotomous choice is really a simplification. Thus my two estimates of EVPI and EVII may be optimistic, recognizing that an intermediate value would likely yield intermediate outcomes.

Simulation model and time frame.-- For each of the four uncertain states of nature, 250 simulations were conducted for each fishing intensity scenario (including the by-kill scenarios needed for the value of information analysis). Thus there were 1,000 simulations for each fishing scenario. Each simulation was done over a 50 year time-horizon, reflecting a desire that outcomes not be dominated by initial conditions. I chose to base decision analysis as well as scenario performance on the entire 50 year time span recognizing that the result would then be a reflection of both transient dynamics as the system moved toward a stationary set of results and long term performance. When calculating the average sustainable harvest, the results for each uncertain state of nature were weighted by the assumed probability for that state. All model coding was performed in AD Model Builder (Fournier et al. 2012; ADMB 2013).

The principal state variable modeled was number of walleyes by year at age represented by the exponential population equation (equation 2.1 in Table 3.2). The model was formulated and parameterized based on the fitted SCA model from Fielder and Bence (2014) and represented ages 2 – 13+. The gillnet fisheries were estimated as a single fishery in that original analysis, and continue to share the same catchability and selectivity here in the simulation model but their effort is broken out. Scenarios held effort constant at the average value observed in the various fisheries since walleye recovery was achieved (based on values from 2004 – 2011).

Stochasticity was incorporated in each of the fisheries as an error term about catchability '*q*' either as a white noise process error variation or random walk deviations (for the recreational fishery) for log-scale *q*. To ensure, however, that recreational catchability did not trend to extremes from the random walk process over long scenario durations, I limited the product of the recreational q and ε_y from equation T2.3 to no more than twice or no less than ½ the starting q value. I did not have an estimate of the variance for the by-kill catchability, so I applied the estimated variance from the Ontario trapnet fishery to this quantity, because these two fisheries use similar gear types.

Recruitment was incorporated two ways, from natural reproduction and from stocking. The stock-recruitment (S/R) relationship was based on a Ricker model (Ricker 1975) and followed the methods of Fielder et al. (2007), which previously analyzed the S/R relationship of Saginaw Bay walleyes. That work concluded that the abundance of alewives was the single best determinant of walleye recruitment for this stock as alewives have been demonstrated to be a formidable predator and competitor on newly hatched percid larvae.

I wanted a S/R function that reflected the sensitivity to alewife abundance as demonstrated by Fielder et al. (2007), but one that also was responsive to changes in stock density in simulations. Therefore, I developed a new S/R function for wild recruits that used both stock (represented as number of eggs produced in 100,000 increments) and density of alewives in Lake Huron following a multivariate Ricker S/R function as described by Chen and Irvine (2001) and Haddon (2001).

To accommodate scenarios where stocking would resume because alewives again became abundant, a separate recruitment function for stocked fish was needed. The stocked fish recruitment model predicted age-2 stocked recruits from spring fingerling stocking numbers two years earlier, following a Ricker model. The model was estimated using data from 1997 – 2005 although 2003 was omitted as an outlier. That year was a transitional year in recovery with unusual dynamics (Fielder and Thomas 2006). The model also included a coefficient for the effect of the abundance of wild recruits (equation T2.6) due to observations of a negative relationship between survival of stocked fish and wild fish recruitment from the same year (R^2 =0.48), consistent with the general concept of stocking success being inversely related to natural reproduction (Laarman 1978; Li et al. 1996).

Total recruitment in any given year in the simulation model was then the sum of wild recruitment R_y^W and hatchery recruitment R_y^H , if any. Total recruitment was then incorporated in the population equation (equation T2.1) as the starting numbers of walleyes (age-2) for each cohort. The simulated recruitment for both wild and hatchery recruitment included a stochastic component based on the observed process error in the S/R models.

Because alewife density was an important determinant of wild recruitment, and because some management rules about walleye stocking were defined on alewife abundance, alewife trends had to be part of the simulation model. I developed a separate alewife population surplus production sub-model (Hilborn and Walters 1992) based on a logistic function requiring two parameters; the finite rate of increase or *R* (based on the intrinsic rate of increase) and the carrying capacity *k* (Table 3.2, equation T2.7).

To accommodate alewife trends as a critical uncertainty, I incorporated two alternatives futures for alewives in Lake Huron: (1) alewives return to high levels of the 1970s and 1980s over a 25 year period, providing that predation is not inhibitory; and (2) alewives remain scarce at the levels observed between 2004 – 2011. Both alternatives used the aforementioned logistic function, both with different finite rates of increase (*R*); for alternative 2, *R* was simply set to zero. I estimated *k* from the USGS GLSC alewife bottom trawl data, using the highest value observed over the time series (600/ha). I then estimated a value of *R* (for alternative 1) that would result in the alewife population increasing to *k* over 25 years.

Walleyes regularly prey on alewives when present (Fielder and Thomas 2006; Schaeffer 1994) so alewife numbers were further adjusted based on walleye consumption. Walleye consumption was modeled based on a Type II functional response of prey to predation (equation T2.8, Holling 1959). Parameters include the number of days per year that alewives are exposed to walleye predation (270), the area of available alewife habitat in Lake Huron (1,522,618 ha), which is necessary to convert alewife abundance to density, the handling time (one alewife per day), and the attack rate. I estimated the attack rate parameter by comparing stomach contents (consumption) to estimated alewife density, and assuming the other functional response parameters were known. Total walleye consumption of alewives was subtracted from the population predicted from the logistic population equation (T2.7) for the same year and the resulting number of alewives was used for alewife abundance in the walleye S/R function for wild recruits (equation T2.5). Although alewives are treated as an uncertainty in this analysis, the feedback of walleye consumption also afforded some degree of performance measure in that walleye abundance, as a function of management, had some degree of influence over alewife trends.

A pivotal value in the calculation of alewife abundance was the area of alewife habitat in Lake Huron used to return numbers of alewives consumed to a density basis. My value of habitat area was derived by first limiting alewife habitat to the main basin of the lake and then subtracting the near shore area based on the belief that warmer near shores waters would not constitute age-1 and older alewife habitat and also subtracted the mid lake area (about 1.4 million ha) based on the description of Eshenroder and Burnham-Curtis (1999) that the mid-lake main basin is likely largely devoid of pelagic fishes. This process left us with the conservative estimate of 1,522,618 ha of adult alewife habitat in the main basin of Lake Huron. I note that these calculations treat the trawl swept area values for alewife as reflective of actual alewife densities (see He et al. in press, for further discussion of this assumption).

To predict fall mean walleye TL at age-3 in the simulations, I quantified the relationship between walleye abundance (all ages combined) and observed September mean TL for age-3 following the methods of Shuter and Koonce (1977). I regressed the log of the difference between the mean TL at age 3 and the largest observed length for that age, against the log of the 3-year running average of estimated population abundance (age-2+) for the first three years of the cohort. Length data were taken from the annual Saginaw Bay Fish Community Survey (Fielder and Thomas 2014) for 2003-2011 and the population values were from the SCA model projection (ages combined) from Fielder and Bence (2014) for the same years. Data were also available for years 1989-2002, but were not included in the analysis because they did not represent the growth dynamics of the recovered walleye population. The resulting relationship exhibited an R^2 of 0.70 and was significant at (F test) P=0.005. The predicted mean TL at age-3 was the observed maximum less the predicted value according to equation T2.10.

Results

Recreational fishery performance.-- The greatest sustainable harvest was achieved at recreational *F*1.5 (approximately 50% increase in the recreational fishing mortality) (Table 3.3). Although sustainability was taken into account, this level of fishery expansion (*F*1.5), still exceeded the sustainability thresholds in some years. The proportion of years (with alewives remaining scarce), for example, that SSB fell below 20% β_0 was 8% for *F*1.5, while only 1% at *F*1.0 (Figure 3.3E). Similarly, the proportion of years that the mean TL of age-3 walleyes exceeded the 425mm threshold rose from 21% (*F*1.0) to 26% (*F*1.5) (Figure 3.3D). Proportional increases were even greater for scenarios that accounted for the recovery of alewives (Figure 3.3). By defining a composite performance metric, the decision analysis accounted for these trade-offs to yield an overall preferred option in light of the uncertainty and stochasticity, suggesting that these slight increases in risk were an acceptable trade off up to *F*1.5.

When alewives remained scarce, the mean SSB and mean TL of age-3 walleyes (averaged within years across the 250 simulations) fell within their thresholds of sustainability up to a fishing intensity as great as *F*3.0 for SSB and *F* 2.0 for mean TL of age-3 walleyes (Figures 3.4A and B). These means, however, conceal the range of performance, and exceedance of the sustainability criteria in some years even at lower fishing intensities and thus the lesser value of just F1.5 indicated by the decision analysis as the preferred option. The performance of the recreational fishery, however, varied considerably with the uncertainty of future alewife trends (Figures 3.3 and 3.4). In every instance, the hypothetical recovery and presence of alewives reduced the sustainable intensity of the recreational fishery. To maintain the mean SSB above 20% β_0, fishing intensity would have to be reduced to at least F0.5 (Figure 3.4C) and no degree of reduction in fishing intensity would prevent the mean TL age-3 from exceeding the target (Figure 3.4D). In spite of this, repeating the decision analysis at a lower probability of alewife recovery (10% likelihood instead of 25% likelihood) did not substantively change the outcome.

Predictably, the walleye population size decreased with increasing fishing intensity across both possible alewife futures (Figure 3.3C). Average recreational harvest itself continued to increase up to F3.0 but gains in harvest beyond F1.5 were marginal, with F1.5 as 86% of the maximum. The corresponding upper limit of total annual mortality (*A*) for an F1.5 was 0.41 (Figure 3.3F). By contrast, in the presence of alewives, average SSB fell below 20% β_0 for F1.0 (Figure 3.4C) corresponding to a total annual mortality of about 0.35 (Figure 3.3F). Of the two performance measures of sustainability, the ratio of SSB to unfished SSB appears to be somewhat more forgiving to the effect of harvest than the mean TL at age-3 threshold. The growth rate-based criterion reaches its threshold slightly before the SSB-based criteria does. For example, average SSB was at 20% β_0 at F3.0 (Figure 3.4A), but mean TL at age-3 exceeded its threshold value at this F (Figure 3.4B). Generally the two metrics agree, however. The sustainable maximum fishing intensity of F1.5 from the decision analysis approximately corresponds to an instantaneous recreational fishing mortality F of about 0.13 of the fully selected ages.

Value of by-kill information.-- The analysis of perfect information indicated a positive gain to the fishery in terms of sustainable harvest from knowing the true by-kill magnitude (Table 4). Because the units for these values was the sustainable recreational harvest, derived by assigning zero to years when the sustainability criteria was exceeded, the magnitude of the value of the perfect information is not a representation of the actual gains in the numbers of walleyes that would be harvested as a result from eliminating this uncertainty. As a proportion of the total expected value of the best decision, however, we see that the EVPI amounts to about 5.5% as much. One might conclude then that the value of information is equivalent to about 5.5% of value of the recreational fishery. Analysis of imperfect information is intended to provide a similar valuation but incorporating a degree of uncertainty over the study's ability to fully deliver on the necessary findings. There is no particular reason to hypothesize that an expanded study of by-kill in Lake Huron would not fulfill its objectives but hypothesizing a potential 5% error rate in any statistical analysis, the EVII reduces the benefit to 0.3% of the recreational fishery value (Table 4). Testing sensitivity of the value of information to a lesser probability of alewife recovery (10% likelihood verses 25% likelihood of recovery) did reduce the EVPI from 5.5% of the fishery value to 4.2%.

Discussion

Nearly all metrics and performance measures, (validated by the outcome of the decision analysis), indicated that the Saginaw Bay walleye population is capable of sustaining greater recreational harvest. The choice of whether to adopt management options that allow for increased harvest within limits of sustainability is partly a consideration of how conservative managers want to be. Walleye recovery on Lake Erie led to a management practice of annually determining the harvestable surplus and making allocation choices amongst the various fisheries and jurisdictions (GLFC 2005). In many years, this constituted more liberal recreational harvest regulations than the customary statewide regulations enforced by Michigan DNR. The importance of the Lake Erie approach is that the regulations were regularly revisited and adjusted based on updated management information and model projections. A decision to manage for a Saginaw Bay walleye fishery closer to the limits of sustainability would necessitate regular stock assessments and the willingness to modify harvest regulations as needed to stay within the limits of sustainability.

Michigan DNR law enforcement officers report that harvest beyond the daily bag limit of five walleyes per angler is a common violation. “Over bagging” or double bagging (making two fishing trips in one day) is an enforcement problem when angler catch rates are high as in Saginaw Bay at certain times of the year. This suggests that increased recreational allocation in the form of an increased daily bag limit may result in greater utilization of the walleye population and help alleviate the temptation to violate daily bag limits. This has been Michigan DNR’s management tool of choice for increased harvest of walleyes in Lake Erie’s recreational fishery. In 2013, 32% of open water (April – October) angler parties of four or less anglers on Saginaw Bay reached their collective party limit (Michigan DNR unpublished data).

While not detailed in this analysis, it was clear from the simulations that population effects from one fishery in turn affected the other walleye fisheries around the lake. The impacts of increased allocation to recreational fisheries in Michigan on the other walleye fisheries was not part of the decision analysis. Certainly, however, any increased mortality of walleyes (via increased recreational exploitation) will reduce the overall population and cause some degree of contraction in the other fisheries unless their fishing effort increased. Similarly, increased harvest from those fisheries would also have impacts on the Michigan fisheries. This underscores the need to begin to coordinate management of all the fisheries that exploit the Saginaw Bay stock of walleyes in Lake Huron, if necessary by working under the aegis of the Great Lakes Fishery Commission as is done in Lake Erie (GLFC 2005).

Increased exploitation of walleye as a management option has consequences beyond sustainability questions that need to be considered. The management implications of the on-going uncertainty regarding alewife futures means that managers may be wise to go slow in their allocation of additional surplus walleye as their role as a predator is still not fully understood. Similarly, if increased harvest is opted for by fishery managers, how to allocate that across fisheries is largely a matter of policy. In spite of the recovery of the walleye population, recreational fishing effort in Saginaw Bay has been steadily declining (Fielder et al. 2014). Fielder et al. (2014) offers two hypotheses for this, first that fishing effort in the bay is driven more by availability of yellow perch (*Perca flavescens*) than by walleye, and yellow perch are in severe decline. Secondly, as walleye angler catch rates increase, trip length declines as anglers reach either their daily bag limits or a satisfactory catch sooner.

The true magnitude of the commercial by-kill was one critical uncertainty identified at the outset of this analysis. Fielder et al. (2014) estimated that the value of the recreational fishery in terms of economic activity generated was $33 million per year between 2008 and 2010. As a follow up to MacMillan and Roth (2012), an expanded study of walleye commercial by-kill in Lake Huron was proposed, estimated to cost $496,000 (B. Roth, Michigan State University, personal communication). Amortized over the 50-year simulation period, the study cost would be $9,920/year, This is well below EVPI of 5.5% ($1,815,000) of the annual recreational fishery value, of $33 million total (Fielder et al. 2014). The lesser utility based on the EVII still constitutes a $99,000/year value easily exceeding the expected cost of the study. However trialing probabilities of a successful study of by-kill at less than 95% results in a loss of positive value to the reduction of this uncertainty. This suggests that the benefit of further by-kill research is at its margins of justification should the study's probability of success be questionable in anyway. One possibility is that the actual by-kill is not close to the two alternatives we considered, but rather at a more intermediate level. This would reduce the benefits associated with improving the estimated level of by-kill. Nevertheless, from the value of information analysis, I conclude that further research to eliminate the uncertainty over the by-kill catchability magnitude is justified. In addition to potential fishery gains from optimizing management in light of this added information, the Saginaw Bay walleye SCA model would also be improved by better by-kill information, and this would benefit all other uses of those estimates.

The uncertainty over alewife futures is another matter. While not the subject of its own value of information analysis, due to the complexity or inability to reduce that uncertainty, it unquestionably is a profound driver of all the simulations. Fielder et al. (2007) aptly concluded that alewife effects dwarfs all other determinants of walleye recruitment in Saginaw Bay. For the wild walleye S/R function, I included stock size as I wanted that feedback from population trends but any stock size effect seems to be vastly overshadowed by trends with alewives. Of the two sustainability based performance measures, the maintenance of the SSB at or above 20% β_0 might be less consequential.

The decision and value of information analysis was not substantially sensitive to the probability of alewife recovery. The lower tested probability of 10% likelihood (versus 25% likelihood of alewife recovery) did not alter the optimal management option choice. In fact, it appears from Table 3.3 that if the true probability of alewife recovery was nil, the optimal management option would remain unchanged from the 1.5 recreational fishing intensity. Thus lingering uncertainty over the future of alewives does not greatly affect the benefits from management options I explored. The lower, 10% probability of alewife recovery did, reduce the EVPI over by-kill catchability from 5.5% of the fishery value to 4.2%. This suggests that as alewife recovery likelihood decreases, the benefit of further by-kill research becomes less. The low sensitivity of the probability of alewife recovery and the profound effects if alewives do recover as indicated in Figures 3.3 and 3.4, are not contradictory. The probability of recovery is a variable in testing management options and a reduction to 10% probability or less was not consequential, but the effects of alewives, if they in fact do recovery, is a function of their influence on recruitment of walleye, which is profound.

Herein I explored options where recreational fishing mortality rates were fixed over time, based on the assumed level of knowledge regarding an alewife recovery. In reality a recovery of alewife would probably not take managers by surprise, given that alewives would likely need to build at least two year classes (thus giving two years advanced notice) before having deleterious effects on walleye recruitment. Results presented here suggests that under conditions when a recovery does occur, substantially lower fishing mortality rates are necessitated to maximize benefits. It is possible that an adaptive policy where harvest rates are reduced (and stocking of walleye is initiated) when a recovery of alewife begins would provide benefits and be more practical than determining in advance whether alewife will recover or not.

Managers wanted to be able to evaluate the tradeoffs between management options based partly on the effects of walleye predation on alewives, and how that in turn modulated the effect of alewife on walleye recruitment. While these interactions were incorporated in the model and consequently the decision and value of information analysis, I do not feel as if I fully captured that complex dynamic. The abundance of alewives in the model was a function of the expansion of alewife densities across the total alewife habitat of the lake. I rationalized a minimal value (1.5 million ha) in an attempt to maximize The model's sensitivity to this dynamic while others (He et al. in press) have used a much greater estimate of alewife habitat area of 3.2 million ha. I recognize that the ability of alewives to be suppressed by predation is a function of the suite of all predators in Lake Huron. He et al. (in press) estimated that walleyes in Lake Huron constituted about 10% of the collective consumption demand on available prey forms in the main basin since 2003. Very possibly alewives cannot recover in the face of predation across all predators but such an analysis was beyond the scope of this study.

Fielder and Bence (2014) in their analysis of walleye stock dynamics in Lake Huron, included the effects of walleye immigration from Lake Erie and their contribution to the overall fisheries in Lake Huron. Some proportion of adult walleyes has been documented to make such a migration (Thomas and Haas 2005, Wang et al. 2007). As part of their analysis, Fielder and Bence (2014) estimated that from 1986-2011 Lake Erie walleyes averaged 8% as much as Saginaw Bay fish but only 2.8% since 2004. While at times these numbers were considerable, in recent years jaw tag returns from Lake Erie tagged fish have trailed off to zero (Lake Erie Walleye Task Group of the Great Lakes Fishery Commission, unpublished data; Thomas et al. 2011). The simulation analysis was limited to the scope of the Saginaw Bay walleye stock. I elected not to attempt to additionally account for the effects of Lake Erie walleyes. If there were to be greater future contributions by Lake Erie fish, likely the realized fishery response would be slightly greater than the predictions in the analysis reflecting the supplementary catch. Predatory effects of Lake Erie walleyes on alewives might be another effect but given the difficultly of documenting any limiting effect on alewives by Saginaw Bay fish alone, I hypothesize that Lake Erie predation effects would be negligible.

While this analysis may be a step forward in the evolution of management tools for the Saginaw Bay stock of walleyes in Lake Huron, further advancement will necessitate more deliberate objective setting by fishery managers. An essential element to making decisions is the formulation of management objectives (Peterman and Peters 1998). Without defined management objectives, it is difficult or impossible for management strategy evaluations or decision analysis to effectively proceed. Collaborations for this analysis were merely a first step of the sort of efforts required. Further deliberation, and clear declarations of goals and objectives in consultation with stakeholders, will be needed before further evaluation of options can be generated. Quantitative stock assessment, management option evaluation, and decision analysis can only proceed so far in the absence of these goals and objectives.

APPENDIX

Table 3.1. Description of critical uncertainties (uncertain states of nature), management scenarios, and performance measures.

Component	Description
<u>Uncertainties</u>	
By-kill low	State-licensed by-kill catchability is correctly depicted by 21,500 value for May-August observed period. Assigned probability of 0.5
By-kill high	State-licensed by-kill catchability is correctly depicted by 102,000 extrapolated value for entire year. Assigned probability of 0.5
Alewives recover	Alewives in Lake Huron follow a logistic population trend with a finite rate of increase ‘*R*’ of 1.5. Assigned probability of 0.25
Alewives remain scarce	Alewives in Lake Huron don’t recovery (follow a logistic population trend with a finite rate of increase ‘*R*’ of 0). Assigned probability of 0.75
<u>Harvest policies</u>	
Scalars (multipliers) of $F_{\text{recreational}}$ intensity	0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 x the current F
<u>Performance measures</u>	
Sustainable harvest	Average recreational harvest with zeros applied for years when other performance measure thresholds are exceeded. This measure to be maximized.
% years SSB < 20% β_0	Percentage of years with SSB below 20% unfished level (β_0)
% years mean TL (age-3) > 425mm	Percentage of years that mean total length of age 3 walleyes exceeds 110% state average growth rate (recovery index)

Table 3.2. Equations, symbols and descriptions of variables used in the stochastic simulation model.

Equation	Number	Symbol	Description
		Index variables	
$N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}} = N_{a,y} e^{-(M_a + F_{a,y})}$	T2.1	y	Year
		a	Age
$F(f)_{a,y} = s_a q E_y \varepsilon_y$	T2.2	State and control variables	
		N	Number of walleye
$\varepsilon_y = \varepsilon_{y-1}\delta_{y-1}$ for recreational fishery only	T2.3	Z	Instantaneous total mortality
		M	Instantaneous natural mortality
$F_{a,y} = \sum F(f)_{a,y}$	T2.4	$F(f)$	Instantaneous fishing mortality for each individual fishery
		F	Instantaneous total fishing mortality
$\ln\left(\frac{R_y^W}{S_y}\right) = \ln(\alpha^W) - \beta_s S_y - \beta_A A_y + \ln(\varepsilon_y^W)$	T2.5	R_y^W	Yearly wild recruitment
		R_y^H	Yearly hatchery recruitment
$\ln\left(\frac{R_y^H}{S_y}\right) = \ln(\alpha^H) - \beta_P P_y - \beta_W R_y^W + \ln(\varepsilon_y^H)$	T2.6	S_y	Yearly stock size (100K egg increments)
		A_y	Yearly density of alewives
$A_{y+1} = A_y + RA_y\left(1 - \frac{A_y}{k}\right)$	T2.7	P_y	Yearly number of fingerlings planted
		Con_y	Yearly consumption of alewives by walleyes, expressed on a density unit
$Con_y = \frac{\left(\frac{\mathring{a}A_y}{1+\mathring{a}hA_y}\right) N_y (270)}{1522618}$	T2.8	$C_{a,y}$	Catch (harvest) from each of the fisheries
		$L_{3,y}$	Yearly mean total length age-3 walleyes
$C_{a,y} = \frac{F_{a,y}}{Z_{a,y}} N_{a,y}\left(1 - e^{-Z_{a,y}}\right)$	T2.9	$\overline{N}_{y-y-2}$	Three prior year running-average number of walleye
		Structural parameters	
$L_{3,y} = 505 - 2.7824786610^{-9} e^{1.62134774\overline{N}_{y-y-2}}$	T2.10	s_a	Age specific selectivity for each fishery
		q	Catchability of each fishery
		E_y	Year specific fishing effort for each fishery

Table 3.2 (cont'd)

$SSB_y = \sum_{a=2}^{13+} Mat_a W_a N_{a,y} \frac{1}{2}$	T2.11	Mat_a	Maturity by age
		W_a	Weight at age
		β_s	Ricker stock-wild recruitment parameter for stock size
		β_A	Ricker stock-wild recruitment parameter for alewife density
		β_P	Ricker stock-hatchery recruitment parameter for number planted
		β_W	Ricker stock-hatchery recruitment parameter for wild recruitment
		α^W	Ricker stock-wild recruitment parameter
		α^H	Ricker-hatchery recruitment parameter
		R	Finite rate of increase for alewives
		k	Carrying capacity for alewives
		$\mathring{a}$	Attack rate by walleyes on alewives
		h	Alewife handling time by walleyes
		Distributional parameters and associated stochastic errors	
		ε_y^W	Yearly wild recruitment deviation
		ε_y^H	Yearly hatchery recruitment deviation
		ε_y	Catchability deviation for each value of q (from a random walk process for the recreational fishery or as white noise drawn from a normal distribution for all others)
		δ_y	Yearly deviation from random-walk process for recreational fishery catchability

Table 3.3. Decision analysis of eight varying degrees of fishing intensity (applied as a multiplier to the recreational fishing mortality *F*) across two critical uncertainties regarding alewife futures and true levels of commercial by-kill of walleyes resulting in a total of four combinations. Values are sustainable recreational harvest of walleyes in Saginaw Bay; mean recreational harvest with zeros assigned to years exceeding sustainability thresholds. Maximum value is indicated with box.

Recreational *F* multiplier	Low by-kill rate & alewives scarce	Low by-kill rate & alewives recover	High by-kill rate & alewives scarce	High by-kill rate & alewives recover	Expected value
Probability→	0.375	0.125	0.375	0.125	
0.1	4896	18335	3120	12817	6900
0.5	23253	53722	15420	46192	26992
1.0	45173	50609	30317	43422	40063
1.5	52922	46431	43355	41435	$\boxed{47087}$
2.0	49799	35397	45952	36124	44847
2.5	45056	28858	41847	27480	39631
3.0	40763	23755	38144	21324	35225
4.0	31487	16601	29737	12728	26625

Table 3.4. Analysis of the expected value of perfect by-kill information (EVPI) and expected value of imperfect by-kill information (EVII). High and low by-kill reference two alternative states of nature based on the magnitude of inner Saginaw Bay state-licensed commercial by-kill stemming from two estimates (a lower value based on an observed period and a higher value based on an extrapolated annual basis).

Metric			Value
Expected value of "best" decision (maximum value from Table 3.3)			47087
EVPI Calculation			
Value if we know high by-kill model was true			46072
Value if we know low by-kill model was true			53322
Expected value after knowing true by-kill model			49697
EVPI	49697-	47087	2610
% EVPI of total fishery			5.5%
EVII Calculation			
Value if we know high by-kill model was true			43768
Value if we know low by-kill model was true			50656
Expected value after knowing true by-kill model			47212
EVII	47212-	47087	125
% EVII of total fishery			0.3%

Figure 3.1. Saginaw Bay and Lake Huron.

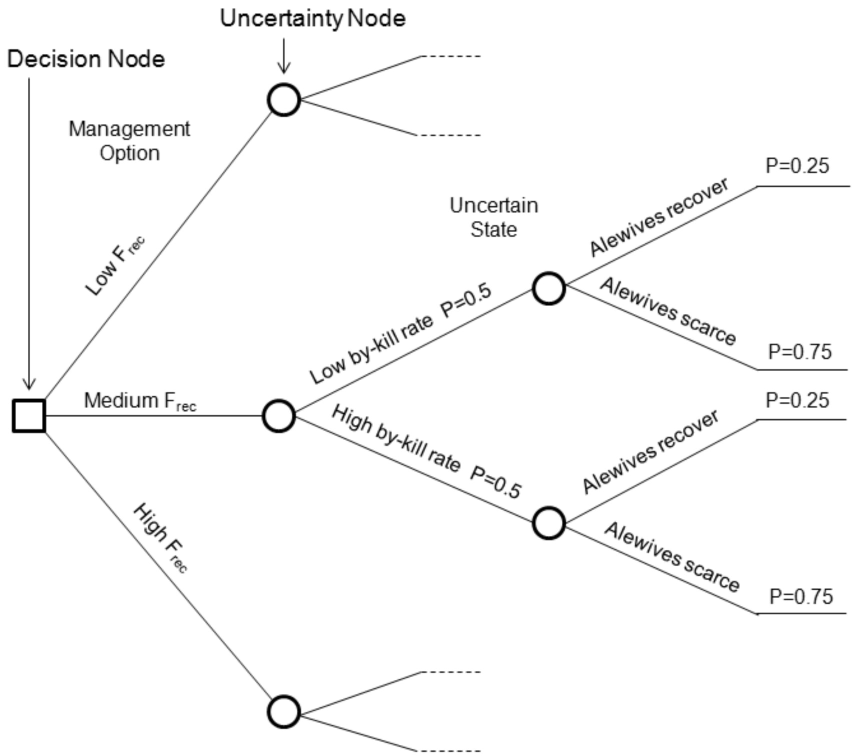

Figure 3.2. Decision tree reflecting alternative harvest policies for varying levels of recreational fishing mortality (F_{rec} depicted as low, medium, and high). In actuality, eight different levels were evaluated.

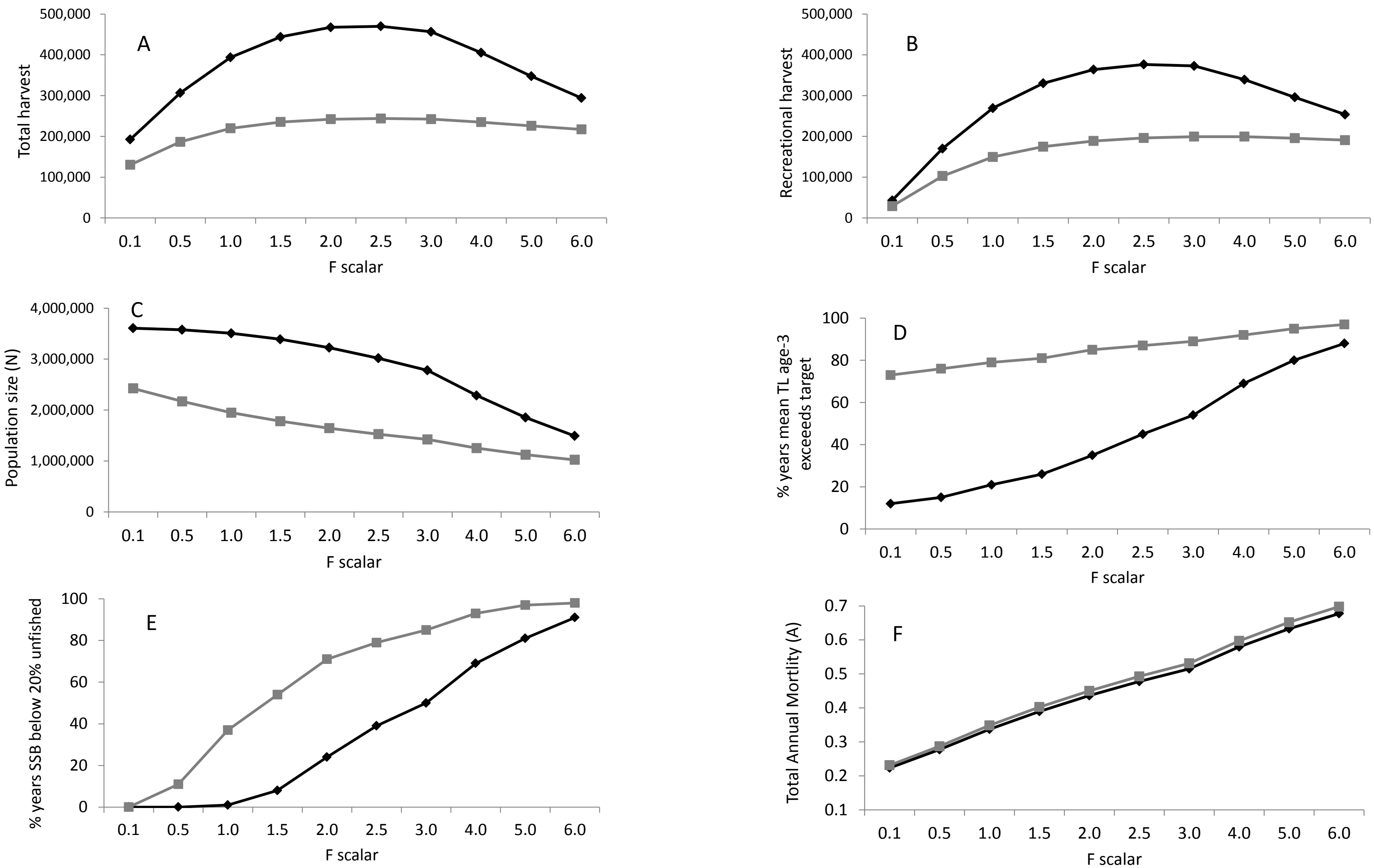

Figure 3.3. Forecasts for different levels of recreational fishing intensity (applied as a scalar to fishing mortality) across uncertain states of future alewife trends: Alewives scarce Alewives recover , based on means of 50 year forecasts of: total catch (all fisheries), recreational harvest, population size, percent of years that age-3 walleye total length exceeds management target, percent of years spawning stock biomass (SSB) drops below the 20% of unfished threshold, and total annual mortality (A).

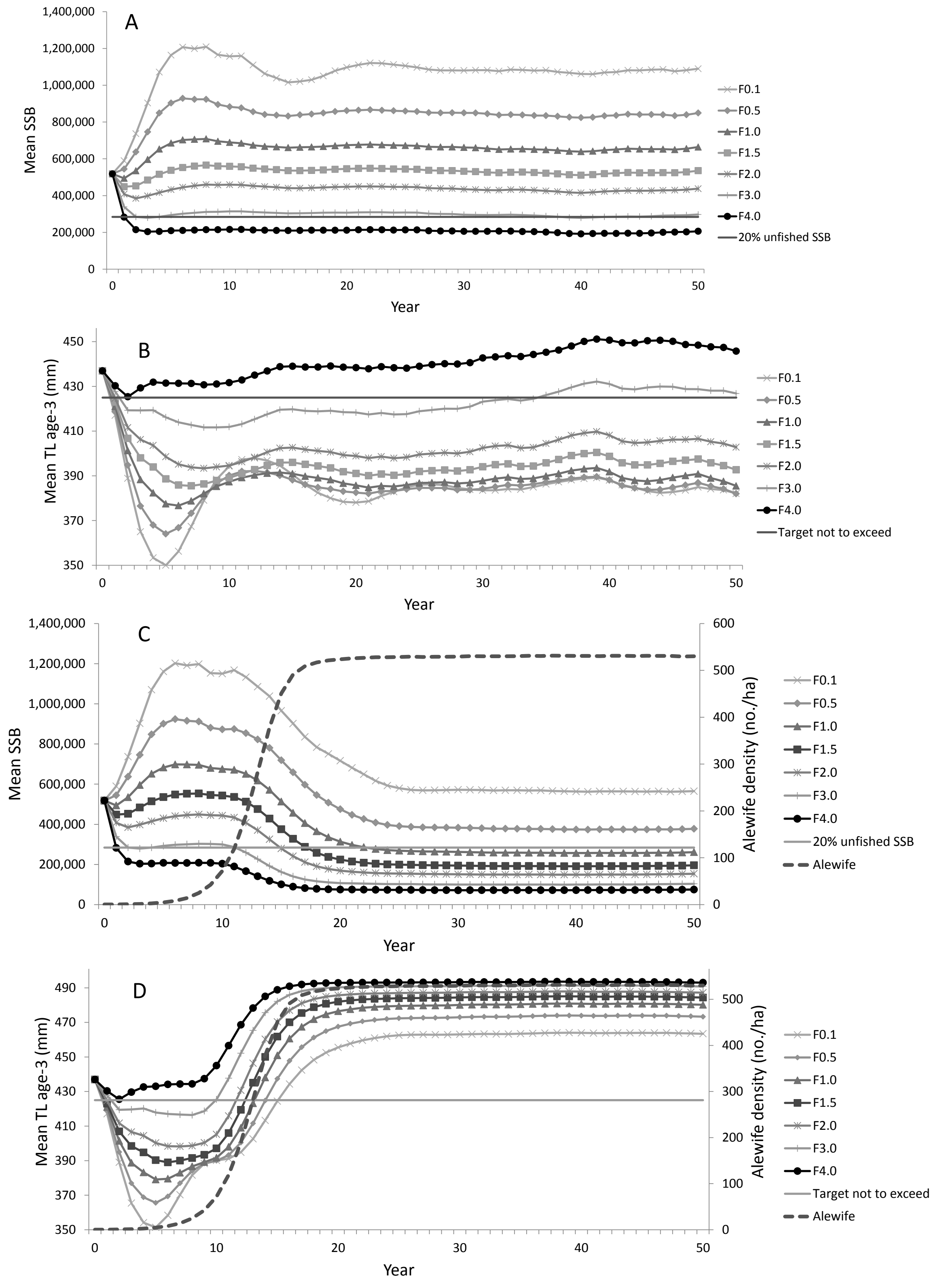

Figure 3.4. Mean spawning stock biomass (SSB) and mean total length (TL) of age-3 walleyes and critical thresholds of management importance across 50 year forecasts of six recreational fishing intensity management options, across two versions of future alewife trends (without alewife recovery; graphics A and B, and with alewife recovery; graphics C and D).

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