Assessment of population dynamics and fishery status for Lake Winnipeg Walleye (*Sander vitreus*), Sauger (*S. canadensis*) and Lake Whitefish (*Coregonus clupeaformis*)

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EXECUTIVE SUMMARY

The Pioneer Commercial Fishers of Manitoba (PCFM) provided an “arm’s length” grant in aid of research to the Anishinabek/Ontario Fisheries Resource Centre (A/OFRC) to conduct analyses required to assess the population dynamics of walleye, sauger and lake whitefish in Lake Winnipeg and the status of the fishery.

The fundamental objective was to use state of the art methods to conduct quantitative fishery assessments to be constrained only by the quality and quantity of available data. The deliverable is this comprehensive report on the study methods and the results of the analyses, including graphical communication of the status of the three fisheries that is easy to understand, as well as a discussion of the strengths and weaknesses of the analyses.

Main data solicitation and synthesis

The A/OFRC project team organized phone calls, and/or emails, teleconferences and face to face meetings with Manitoba Agriculture and Resource Development (ARD) staff to obtain historical and ongoing surveys on Lake Winnipeg as well as fishery-dependent databases, and PCFM members to elicit background information about the fishery and the fishing industry.

The following fishery-dependent (i.e., commercial fishing) data sets were made available to the study team: 1. Annual commercial catch 1973-2019; annual commercial gill net catch per unit effort (CUE) 1973-2019. The following fishery-independent (i.e., ARD) data sets were also made available: 1. Index survey netting data 1979-2003, 2. Index survey netting data 2009-2019, and 3. Lake Winnipeg small mesh index survey data 2012-2019. Given the data available and their demonstrated patterns and correlations, we developed several alternative analytical approaches to understanding the population dynamics of walleye, sauger and lake whitefish in Lake Winnipeg and the status of the fishery.

Data about prices and landings of walleye, sauger and lake whitefish per delivery were obtained from the Freshwater Fish Marketing Corporation (FFMC) and used to develop a fourth fishery-dependent CUE data time series spanning 1973-2019.

Main analytical approaches

The assessment of the population dynamics of walleye, sauger and lake whitefish and the status of each fishery began with a review of the available information about changes in the lake ecosystem and fishery over the years, e.g., evidence for or against subpopulation (stock) structure, the timing and degree of eutrophication, floods, changes in rainbow smelt biomass, altered fish community structure and potential species interactions.

We sought to understand whether the dynamics of the walleye, sauger and whitefish populations were stationary, or if key population processes fundamentally changed over time, i.e., exhibit nonstationary dynamics. Nonstationary fish population dynamics are increasingly reported and can lead to unreliable fishery assessments if not recognized in the analysis. Examination of trends in data indicated a strong possibility of nonstationary population dynamics. There was considerable uncertainty about population productivity (growth rate), r, and how it may have changed over time, so we developed models to account for nonstationarity on the expectation that they would provide better model fits to data than models that did not. In this way, the outputs of a range of combinations of assessment model and data sources, each conditioned on alternate hypotheses about nonstationarity, were used to infer population status and size (biomass in this case), as well as fishery status over time, in terms of widely used biological and management reference points.

Biomass dynamic models (SSBDMs) are used for fishery assessment when data about catch at age, or length, are not available. Available data were inspected to assess their suitability for use with models more complex than SSBDMs and found to be unsuitable for a variety of reasons. SSBDMs, however, do provide better insights to fishery status than those that can be used for assessment of data-poor fisheries.

We used a SSBDM to assess the population size (biomass) and the status of each of the walleye, sauger and lake whitefish fisheries. We developed seven model/data scenarios (Table ES1), some of which could also be selectively combined with each of four alternate hypotheses regarding how population productivity may have changed to diagnose whether the dynamics of each species were nonstationary, and if so, when any significant changes in productivity may have happened.

Table ES1: SSBDM model/data scenarios and hypotheses about how productivity (*r* in the model) might have changed on Lake Winnipeg

Data/model Scenarios:	Walleye	Sauger	Lake whitefish
1. Commercial catch 1973-2019; CUEs 1973-2019 (commercial 1973-2018, ARD index netting 1979-2003, 2009-2019, ARD small mesh 2012-2019)	√	√	√
2. S1 but with south basin commercial walleye and sauger catches adjusted based on assumed 25% of sauger reported as walleye from 1997-2019	√		
3. S1 but with south basin commercial walleye and sauger catches adjusted based on annual variation in price ratio of walleye to sauger	√	√	
4. Basin specific walleye dynamics with commercial walleye catch 1997-2019, walleye CUEs 1997-2019 (commercial 1997-2018, ARD index netting 1997-2003, 2009-2019, ARD small mesh 2012-2019)	√		
5. Basin specific walleye dynamics with commercial walleye catch 1997-2019 adjusted to correct for misreporting, walleye CUEs 1997-2019 (commercial 1997-2018, ARD index netting 1997-2003, 2009-2019, ARD small mesh 2012-2019)	√		
6. Catch 1973-2019; CUE 1973-2019 (ARD index netting 1979-2003, 2009-2019, ARD small mesh 2012-2019)	√	√	√
Scenarios were selectively combined, where possible, with the following hypotheses on walleye population productivity (*r*): H1. *r* followed a random walk process H2. three *r* periods (two-step) H3. two *r* periods (one-step) H4. constant *r* (no step)			

Major findings

Walleye

The trends in all three of the index (ARD) CUE time series matched the commercial CUE time series. Statistically, the estimated correlations among the commercial CUEs and index

CUEs, particularly 1979-2003 and 2009-2019, were highly significant. Despite the limited sample sizes of the three discontinuous index CUEs, and potential limitations of the commercial CUEs, the consistent trends across multiple sources confirmed their utility for the purpose of quantitative fishery assessment.

The top-performing model/data/*r* combination indicated that the walleye fishery was strong in 2019 (Table ES2). Biomass was ~69% of the carrying capacity, the risk that overfishing occurred was 1%, and the risk that the population was overfished was 6%. These strong signals were the result of stable biomass in the north basin and recent increases in channel and south basin biomass, combined with reduced commercial catch. The fishing mortality rate in 2019 was the lowest since the early 1970s.

Table ES2. Summary of the status of the walleye, sauger and lake whitefish populations and fisheries in 2019 based on the best model/data scenario and hypothesis about population productivity (*r*).

Depletion (B_{2019}/K) (higher is better)			Risk of overfishing the population in 2019 $P(F_{2019}>F_{msy})$ (lower is better)			Risk of the population being overfished in 2019 $P(B_{2019}<B_{msy})$ (lower is better)		
Walleye	Sauger	Lake Whitefish	Walleye	Sauger	Lake Whitefish	Walleye	Sauger	Lake Whitefish
0.69	0.07	0.67	0.01	0.39	0.13	0.06	1.00	0.10

On the other hand, in 2019, population and fishery statuses were less optimistic when the commercial CUE data were excluded and only the three index CUE series were used in the analysis. Nevertheless, that model/data/*r* combination indicated that the status of the population was good to the extent that, in our experience, it could be expected to gain a passing stock status score under the MSC certification scheme, despite a recent decline in the productivity of the walleye population. If biologically real, however, this apparent decrease in productivity should not be ignored because it could affect the management of the fishery. Such changes are difficult to detect and need to be further monitored and investigated.

We recommend that model/data/*r* combinations that include all the available time series, including the commercial CUE series, be considered for assessment and management purposes. We expect that low demand for walleye and ensuing low fishing effort and catches

anticipated in 2020 due to the COVID-19 pandemic should mean that the already strong status of the walleye population and fishery will continue to improve in 2020.

Sauger

Sauger population and fishery statuses were far less robust to alternative model/data/*r* combinations than was the case with walleye, i.e., uncertainty about the best combination remained high despite best efforts to reduce it. This uncertainty was largely attributable to weak correlations among the various CUE data series; the commercial and index CUE data series indicated alternative narratives about sauger population dynamics.

Sauger population productivity was nonstationary; most probably it decreased in 1994-1997 and again in 2013-2015. Sauger productivity was relatively greater in the 1970s and 1980s and MSY was correspondingly greater. Commercial catches during those periods were close to MSY, but lower still than catch at the fishing mortality rate consistent with MSY. This situation changed during the mid-late 1990s, concurrent with the decreased sauger population productivity which may have triggered the lower catches of the 2000s.

The degree of change in population productivity, the carrying capacity, biomass dynamics and fishing mortality rate over time were largely influenced by whether the commercial CUE data were used in the analysis. The biomass estimates were much higher, and fishing mortality estimates much lower, when the commercial CUE data were excluded than when they were included. The top-performing model/data/*r* combination indicated that 2019 sauger biomass was ~7-8% of the carrying capacity when commercial CUEs were included (Table ES2), but 47% when the commercial CUEs were excluded. The risk that overfishing occurred was 39% with commercial CUEs included (Table ES2) and 19% without, but the risk that the population was overfished was 1 when commercial CUE data were included (Table ES2) and 54% when excluded.

The differing effects of the commercial versus index CUE data on the results should not be ignored. The weak correlations among the commercial and various index CUEs indicated that the commercial CUEs may not be as accurate an index of abundance, as they seemed to be for walleye (and, to a lesser extent, lake whitefish; see below), and/or that the index CUEs may not be as accurate an index of abundance as they seemed to be for walleye. The commercial CUE data may be unreliable because of putative spatial and temporal changes in targeted commercial sauger fishing effort since the late 2000s, avoidance of sauger as

walleye and lake whitefish abundance and relative price surged, and/or ecosystem-related changes that changed the catchability of sauger in the commercial gear (E. Sveinson and R. Smith, pers. com). The index CUE data may be unreliable because of temporal discontinuities and spatial limitations in the index netting surveys, missing and/or spurious catch and effort data from some areas in some years, and a lack of sufficient environmental information to allow for survey CUE standardization.

The quantity and quality of the available sauger data are such that model/data selection uncertainty was high enough that none we explored are sufficiently robust and reliable for credible assessments of neither population nor fishery status. A sauger management plan is urgently needed, and any such plan should include initiatives such as enhanced monitoring, including index survey improvements, commercial sauger catch sampling, a commercial fishers' log book program and a commercial fish harvest database designed to improve the quantity and quality of commercial sauger CUE data. A sauger management plan should also include a stakeholder-engaged, structured decision making process to develop a harvest control rule that could be used to set annual limits to commercial and recreational sauger catches until the available data indicate the sauger population size is at or close to the biomass at MSY.

Lake whitefish

Visual inspection revealed some discrepancies between the trend in commercial whitefish CUE time series and trends in the CUE time series calculated from the fishery-independent gillnet index survey data. The commercial CUE time series did not show any clear trend between the 1970s and early 2010s but a positive trend occurred after the mid-2010s. Statistically, the estimated correlations among the commercial CUE time series and CUEs from the ARD index surveys, particularly 1979-2003 and 2009-2019, were not significant.

The lake whitefish stock assessment was done under just two model/data/*r* combinations, i.e., with and without commercial CUE data, that allowed us to investigate the relative effects of the commercial versus index survey CUE data on the analysis and inferences about the whitefish population and fishery statuses. Results from both scenarios indicated strongly nonstationary productivity in the lake whitefish population. Productivity tended to be lower in the late 1980s and early 1990s than earlier; it increased to greater than historical values after 2010. Overfishing had happened, and the lake whitefish population was overfished, regularly between the late 1980s and around 2010. The risk of both overfishing

and being overfished dropped to very low levels after 2010, then increased slightly in recent years.

The lake whitefish population and fishery statuses in 2019 were strong. The whitefish population biomass was well above that sustainable at MSY at 67% of carrying capacity. The risk that overfishing had happened was 13% and that the population was overfished, 10% (Table ES2). Excluding the commercial CUE data, these risks were 13% and 23% respectively. These indicators suggest that the status of the 2019 lake whitefish population was good to the extent that, in our experience, it could be expected to gain a passing stock status score under the MSC certification scheme.

The differences between the results of the best two combinations were small; both painted a positive picture of the status of the lake whitefish population and fishery. Until there are better data available to support more complex assessment models, we suggest that the top-performing combination, which included commercial CUEs, be considered for assessment and management of the lake whitefish fishery.

Major recommendations for future data collection and fishery management

- The current assessments rely heavily on the commercial (fishery-dependent) CUEs. Neither fishery-dependent nor -independent data could be standardized for any species because of the lack of related information about environmental factors or, in the case of the 1979-2003 ARD index survey, space and time information. Fishery-dependent data should be collected, by way of a fishers' logbook program and database, to allow reliable, and standardized, estimates of targeted effort, catch, discards and releases.

- Recreational fishery catch and effort (the other critical component of fishery-dependent data to include in stock assessments) should be collected, by way of creel censuses and/or an angler diary program, and database, to allow reliable estimates of targeted recreational effort, catch, discards and releases.

- Commercial stakeholders' knowledge about prices and their opinions about reasons for changes in historical harvest and effort were synthesized and partly included in our assessment (e.g., price ratio and its influence on walleye-sauger misreporting).

Such information and approaches may be better considered using surveys and workshops with fishers' representatives.

- The PCFM should consider working with other stakeholders to initiate a third-party review of the current assessment and management system. The review should also include specific recommendations to improve the fisheries assessment and management system on Lake Winnipeg.

- ARD and stakeholders should take the findings here, as well as the extra data sensitivity analyses in the appendices, into account when considering management decisions including mesh size restrictions and the seasonal openings and closings of the commercial and recreational fisheries.

- The role of rainbow smelt in the Lake Winnipeg ecosystem, the interrelationships between smelt and commercially and recreationally important species, and effects on the stakeholders are poorly understood. The PCFM should cooperate with other stakeholders to support monitoring and research to improve understanding of the effects of smelt on the commercial and recreational fisheries.

- The process for developing an urgently needed management plan for sauger should include all affected parties in a structured decision-making process facilitated by an independent third party.

1. BACKGROUND

Decisions about fisheries assessment and management tend to be exercised in the context of considerable ecological and social complexity and uncertainty (e.g., Berkes 2003). Most often, decisions are characterized by difficult judgments, high stakes, limited resources, misunderstandings and conflict; yet fisheries stakeholders are increasing demanding quality, consistency and transparency in decision making (e.g., Pita et al. 2010; Röckmann et al. 2012). The various elements of the Lake Winnipeg fishery system, including assessment, management and governance, are not immune.

The Lake Winnipeg Quota Review Task Force (LWTF 2011) was formed by the Department of Water Stewardship to help mitigate this 'wicked problem' (see: Churchman 1967, Rittel and Webber 1973, Khan and Neis 2010) by evaluating "the biological sustainability of the fishery and … help inform decisions about quota adjustments". It reached three major conclusions:

"1. The available fisheries information and analysis from sources consulted are inadequate to determine absolute estimates of current or past biological productivity for Lake Winnipeg, and the proper application of standard stock assessment methods based on biomass or indices is not possible with the data at hand.

2. Because of the lack of data, the Task Force is unable to recommend either increases or decreases in a total Recommended Allowable Harvest (RAH) of 6.52 million kg for the Lake.

3. The uncertainty and lack of adequate information needed to make informed decisions about possible changes in RAHs will continue unless there are changes made to data collection by the MFB, FFMC, and fishers, and additional research is done to enhance our understanding of the fishery, the fish and the broader ecosystem." (LWTF 2011)

In November 2019, the Pioneer Commercial Fishers of Manitoba (PCFM) provided an "arm's length" grant in aid of research to the Anishinabek/Ontario Fisheries Resource Centre (A/OFRC)[1] to conduct analyses required to address the Task Force conclusions,

[1] The A/OFRC was established in 1995 to serve as an independent source of information on fisheries assessment, conservation and management, promoting the value of both western science and traditional

particularly the contention that "the proper application of standard stock assessment methods based on biomass or indices [was] not possible with the data at hand."

The first index fishing survey program on Lake Winnipeg ran from 1979-2003 and the most recent index fishing survey program began in 2009 (Manitoba Agriculture and Resource Development (ARD) website). By 2019, the time series for these two surveys included 30 years of fishery-independent data. Nine years after the LWTF report, we find what may have been sufficient data to assess the fishery using quantitative fishery assessment methods, though we are aware of none having been performed and, in any case, did not assess whether our analysis could have been done with the data available to the Task Force.

Project Objectives

The primary objective was to use state of the art methods to conduct quantitative population and fishery status assessments for Lake Winnipeg walleye, sauger and lake whitefish constrained only by the quality and quantity of available data. To some extent, we improved the quantity and quality of data by correcting for bias we detected or that was suspected by ARD staff and fishers. Specifically, the grant stipulated we

- compile all available pertinent data, discuss the data, and its caveats, with fisheries staff at ARD, and conduct preliminary analyses;
- conduct a thorough review of all available documentation regarding the approaches used by Manitoba Sustainable Development (SD) and ADR for conducting fishery assessments for these fisheries;
- determine which types of fishery assessment methods are most likely to be compatible with the various data sources for each fishery;

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ecological knowledge. The A/OFRC is a not-for-profit corporation controlled by a Board with equal numbers of Directors nominated by the Province of Ontario and the Anishinabek Nation. The roles of the Centre are to report on stock status, evaluate stresses on fish populations and habitats, promote the use of state-of-the-art science and technology, and to provide a forum for information sharing and participation with stakeholders. The Centre also plays an important role in offering management recommendations to promote sustainable fisheries and resolve conflict. The Grant in Aid of Research (GIAR) provided to the A/OFRC by the PCFM clearly stipulates that the PCFM will provide the research grant funds "up front" and will have no control over the publication of any of the A/OFRC team's findings. The A/OFRC study team consisted of Kevin Reid, Ph.D. (Project lead and analyst), Prof. Yan Jiao, Ph.D. (Lead analyst), Prof. Thomas D. Nudds, Ph.D. (Senior advisor/facilitator) and Peter Meisenheimer, M.Sc. (Project administrator and communications).

- incorporate fishers' knowledge into the research priorities of the study team;
- construct the respective models, interpret the results including the performance of the various models, validate the models, data inputs and re-run the analyses as required; and
- produce a comprehensive report on the study methods, and the results of the analyses including graphical communication of the status of the three fisheries that is easy to understand, and a discussion of the strengths and weaknesses of the analyses.

Consequently, this report describes the analysis, results and conclusions of A/OFRC's development of fishery assessment tools and techniques for determining the population dynamics and fishery status for Lake Winnipeg walleye, sauger and lake whitefish

The A/OFRC team used a variety of methods to improve our understanding of the fishery, the assessment and management systems, the availability of fishery-dependent and -independent data for analyses, and the quantity and quality of those data. These included teleconferences, in-person meetings, stakeholder surveys and email exchanges among the A/OFRC team and fisheries staff at ARD.

Study Approach

We first reviewed available information about historical changes in the walleye, sauger and lake whitefish fishery and the Lake Winnipeg ecosystem, e.g., timing and degree of eutrophication, changes in rainbow smelt biomass, altered fish community structure and potential species interactions, to indicate the potential for nonstationarity in the system that would determine suitability of assessment models from the suite available.

Nonstationary population dynamics are increasingly recognized in such populations and ecosystems (Turchin, 2003, Jiao et al 2008, 2009, 2012), and can cause fishery assessments to be erroneous if not recognized in the analysis (Jiao et al 2012). We sought to understand whether the dynamics of the walleye, sauger and whitefish populations were stationary, or if key processes driving population dynamics fundamentally changed over time, i.e., nonstationary dynamics. If stationary dynamics were detected, then each population's productivity, or growth rate (r), as well as other population metrics, would be analysed via a white noise process, i.e., no productivity changes over time (Jiao et al. 2008). If not, we expected that models that accounted for nonstationary dynamics would provide better

model fits than models that did not. In this way, the outputs of a range of models and data sources, each conditioned on alternate hypotheses about stationarity could be used to infer population size (biomass in this case) and fishery statuses over time in terms of widely used biological reference points (defined in Table ES2), and to make management recommendations.

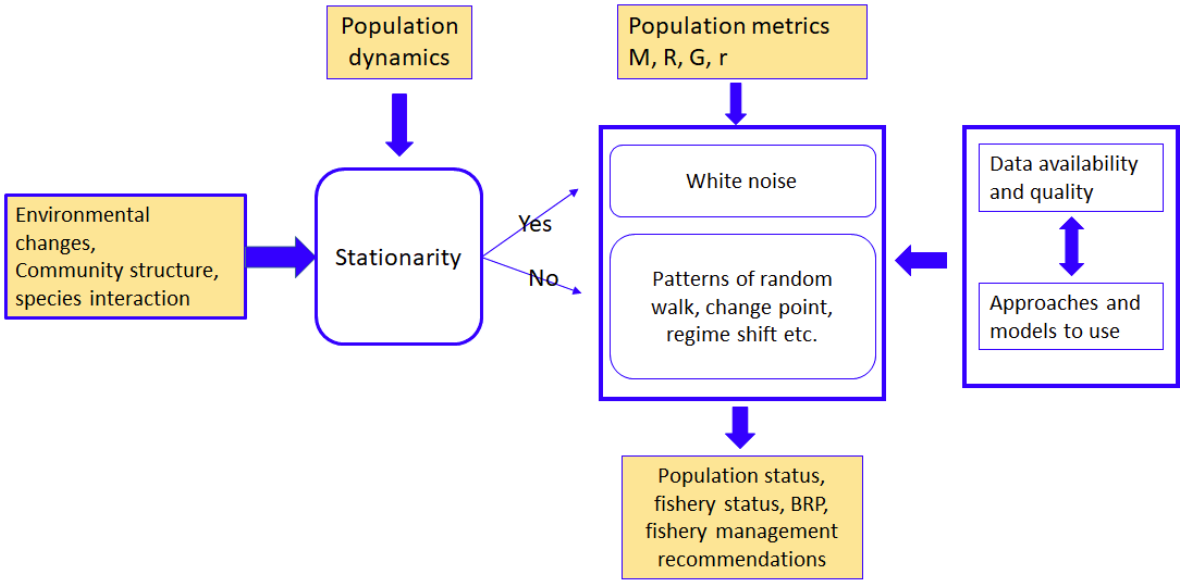

Figure 1. General approach to fishery assessment for the Lake Winnipeg walleye, sauger and lake whitefish fisheries

2. DATA AVAILABILITY AND SYNTHESIS

Raw commercial catch and effort (# of deliveries) data for walleye, sauger and lake whitefish from 1997 to 2019 were provided by ARD and compiled by A/OFRC. Commercial catch data pre-1997 were taken from the Lake Winnipeg Task Force Report (LWTF 2011). The complete compiled commercial catch data (Figures 2a and 2b) are one of the most critical sources of information used in the fishery assessment. Commercial catches were represented by reported landings and excluded fish that were released, discarded and/or misreported.

Discussions with south basin commercial fishers suggested that, due to low price difference offered by the Freshwater Fisheries Marketing Corporation (FFMC) for walleye and round sauger, together with the system of combined, multi-species quotas on Lake Winnipeg,

sauger was sometimes landed, reported, processed (cut) and locally marketed, as “baby” walleye. Fishers’ suggested misreporting in the range of 25-35% in recent times.

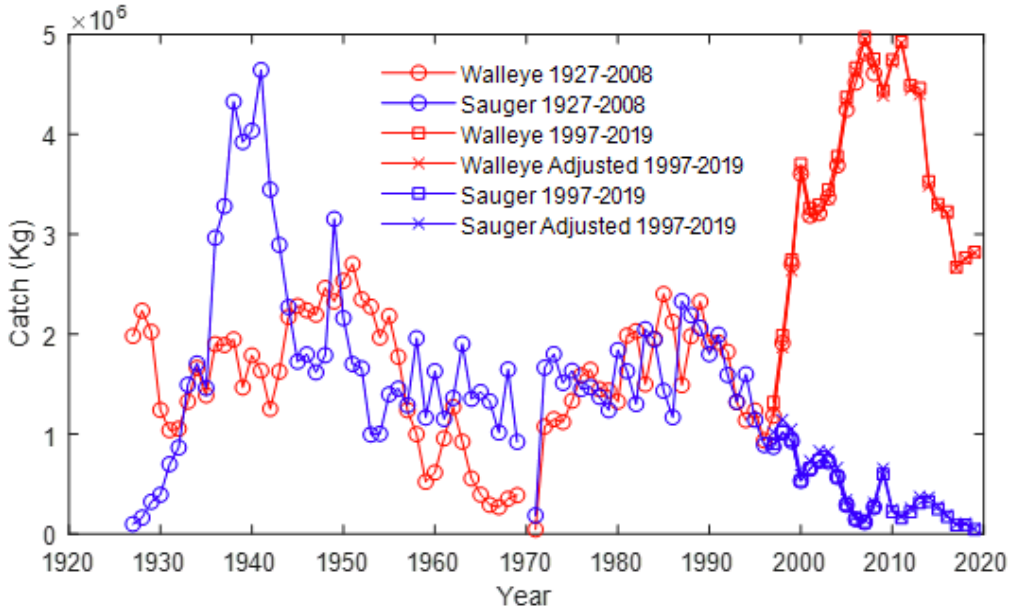

Figure 2a: Walleye and sauger catches from the Lake Winnipeg commercial fishery excluding releases and discards. WalleyeAdjusted and SaugerAdjusted are the gillnet fishery landings adjusted for misreporting based on price ratios between the species.

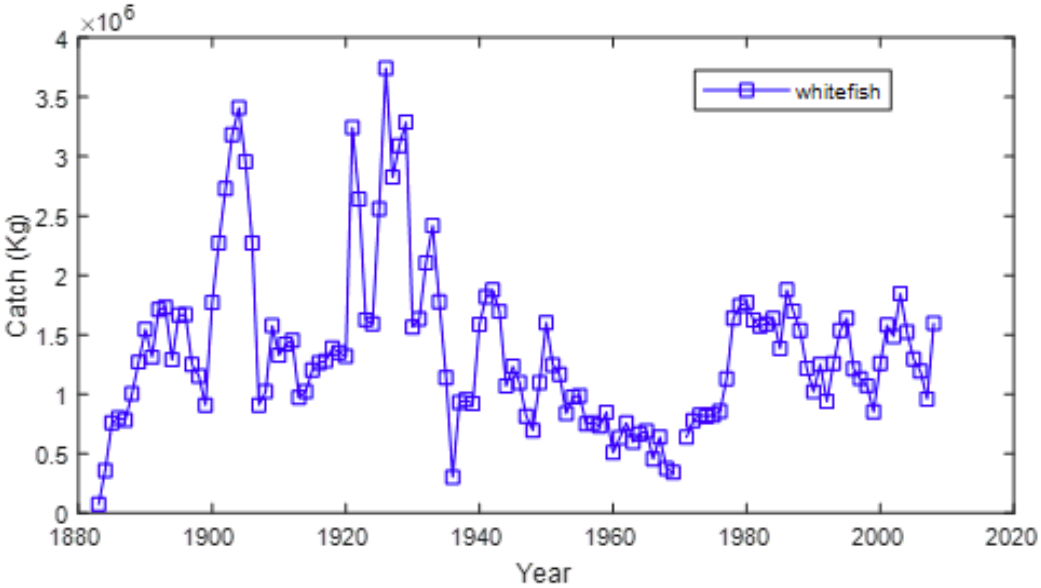

Figure2b: Whitefish catches from the Lake Winnipeg commercial fishery.

FFMC prices (1997-2020) from both the winter and summer seasons, if not reported or synthesized annually, were averaged to generate price ratios to describe the relationship between the ratios and misreporting rates (Figures 3, 4), ultimately to adjust the commercial catch of walleye (and sauger) in the southern basin and lake wide (Figure 2a). No information was available about commercial catch discards and releases, nor recreational harvest or effort.

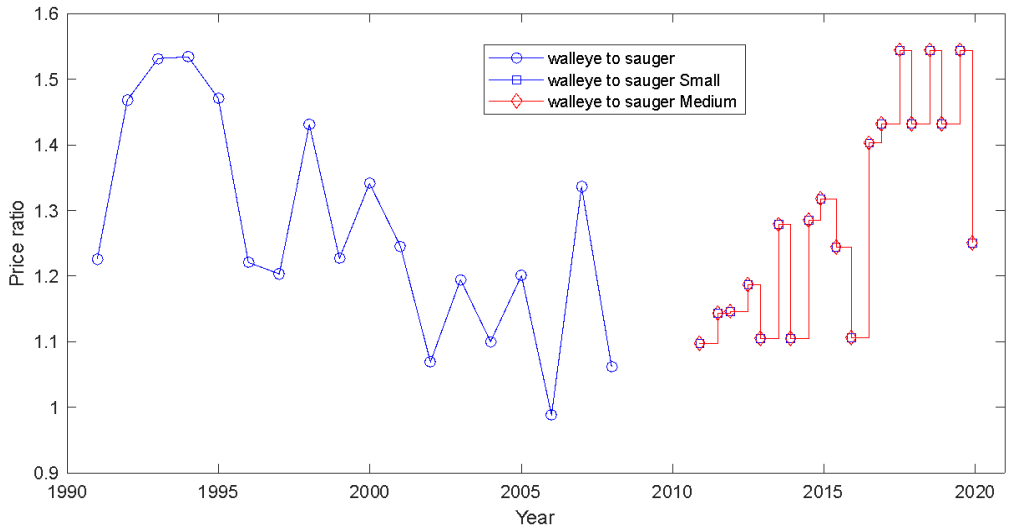

Figure 3: Annual ratios of walleye to sauger prices.

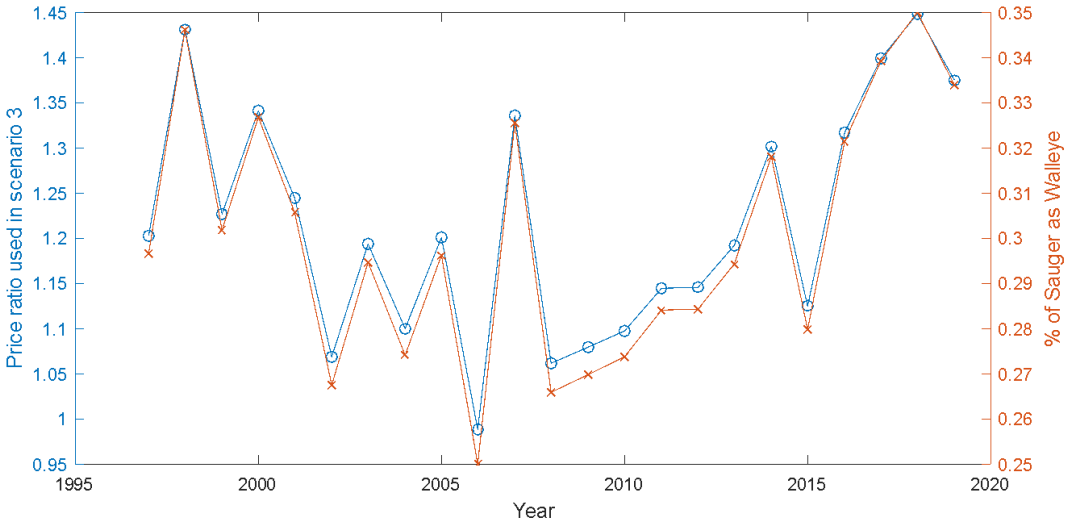

Figure 4: Annual finalized price ratio and the corresponding % of sauger misreported as walleye based on fishers' belief that 25-35% of the commercial walleye catch is actually sauger.

Notwithstanding that available evidence indicated no population structure in Lake Winnipeg walleye (Backhouse-James et al. 2011), we compared commercial walleye catches in the North, Channel and South basins (Figure 5) to better understand the contribution of potential differences in basin-specific trends on lake-wide population and fishery statuses. Commercial catches from the North and South basins decreased faster than in the Channel region since 2013, but all three showed similar patterns.

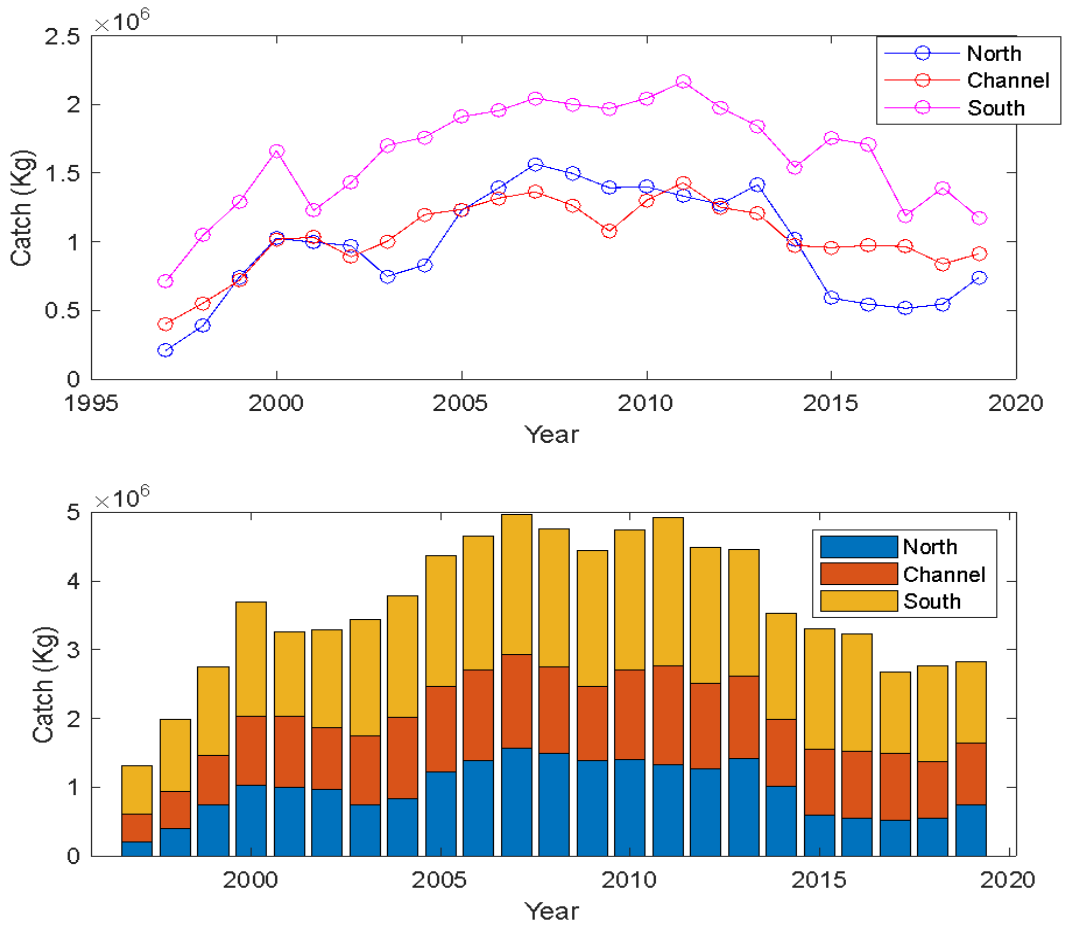

Figure 5: Basin-specific commercial catches of walleye in Lake Winnipeg, 1997 to 2019.

Catch rate, i.e., catch per unit effort (CUE) data represent units of relative biomass and/or abundance. CUE time series are widely used for fishery assessment globally (Hilborn and Walter 1992; Quinn and Deriso 1999). We acquired sufficient data, for each of walleye, sauger and lake whitefish, to be able to use four separate catch rate time series: a fishery-dependent (hereinafter commercial) catch rate series from the commercial fishery (commercial catch and effort data provided by FFMC and ARD) and three fishery-

independent (hereinafter index CUE) surveys (Figures 6a, 6b, 6c). Numerous novel sample sites were added to the survey protocol in 2019 because of the availability of a second survey crew (Kevin Casper, ARD, 75 - 7th Avenue, Gimli MB R0C 1B0, email); therefore, we calculated the 2019 basin-specific and lake wide index CUEs such that the 2019 CUEs for all three species were standardized to the 2009 to 2018 surveys.

We found no credible data sources about commercial by-catch or discarding, so these removals were not included in the assessment. Different survey gear and methods were used for the gill net indexing surveys in 1979-2003 than in 2009-2019, so the surveys were treated as independent. The 1979-2003 index CUE values were digitized from figures in LWTF (2011). Four lake-wide indices were scaled (see scaling factors in the keys to Figures 6a, 6b. and 6c), to aid visual comparison. The basin-specific index CUEs for walleye and lake whitefish between 2009-2019 were also analysed (Figures 7a, b).

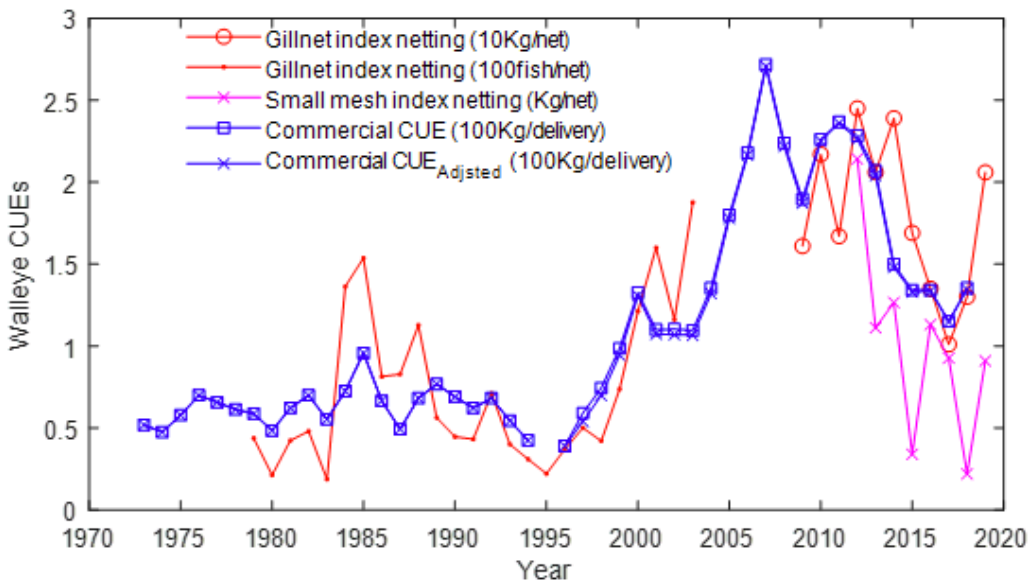

Figure 6a: Lake-wide CUEs for walleye in Lake Winnipeg. Values preceding the units indicate scaling factors for each series.

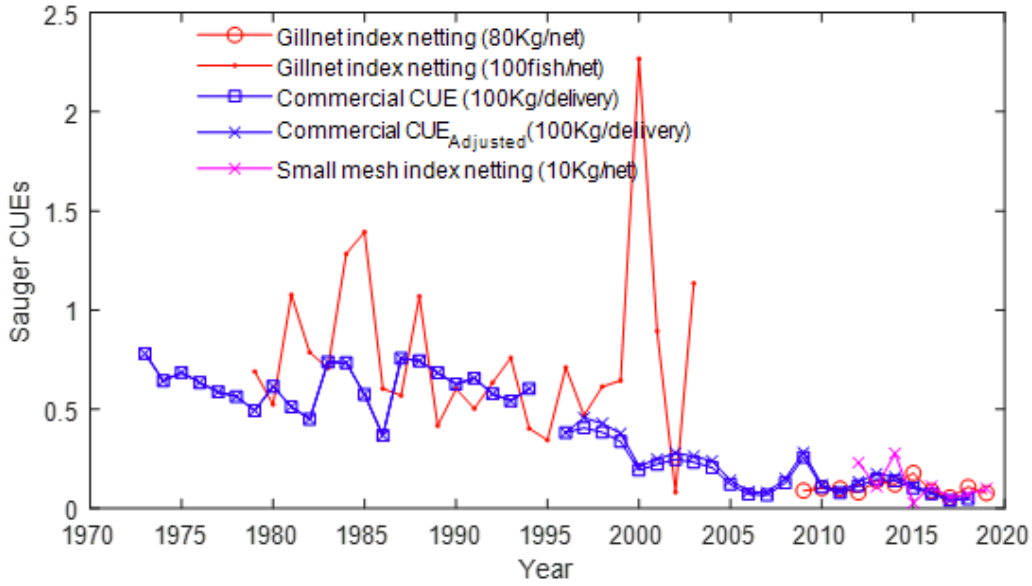

Figure 6b: Lake-wide CUEs for sauger in Lake Winnipeg. Values preceding the units indicate scaling factors for each series.

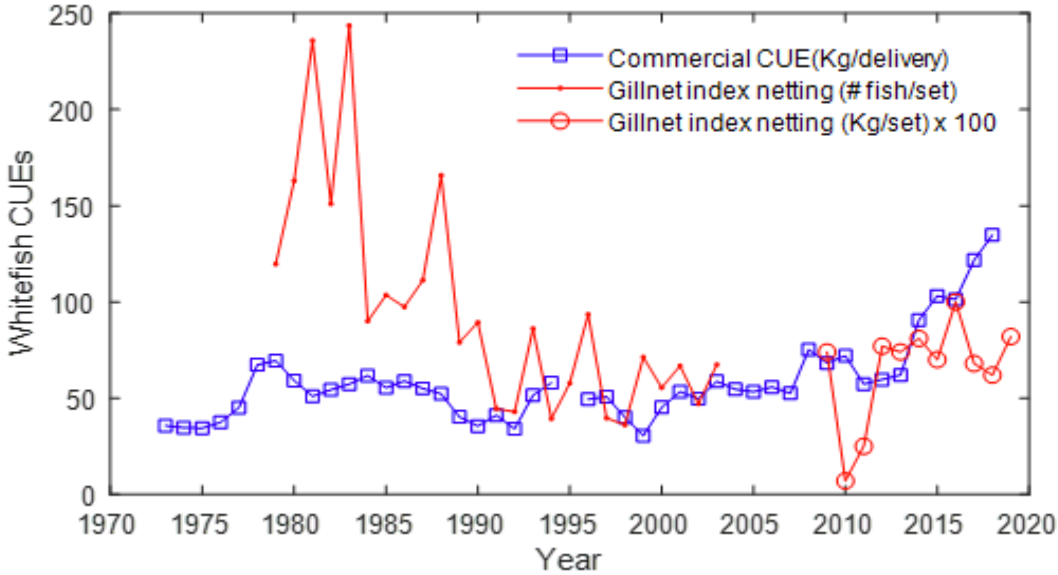

Figure 6c: Lake-wide CUEs for lake whitefish in Lake Winnipeg. Values preceding the units indicate scaling factors for each series.

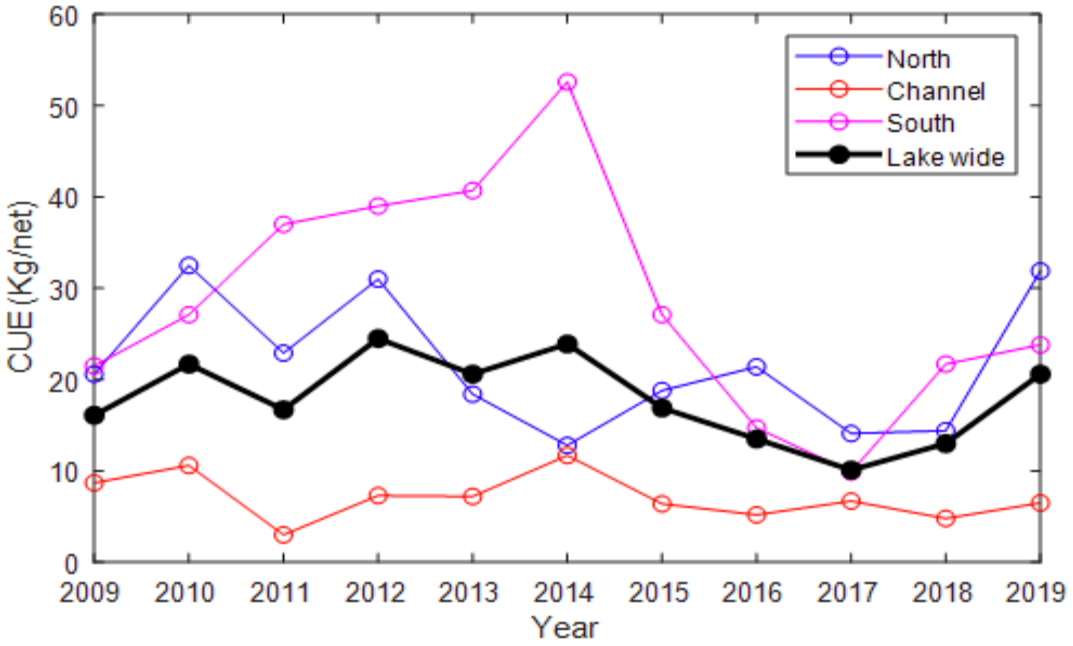

Figure 7a: Basin-specific CUEs for walleye from the 2009-2019 gillnet indexing survey on Lake Winnipeg.

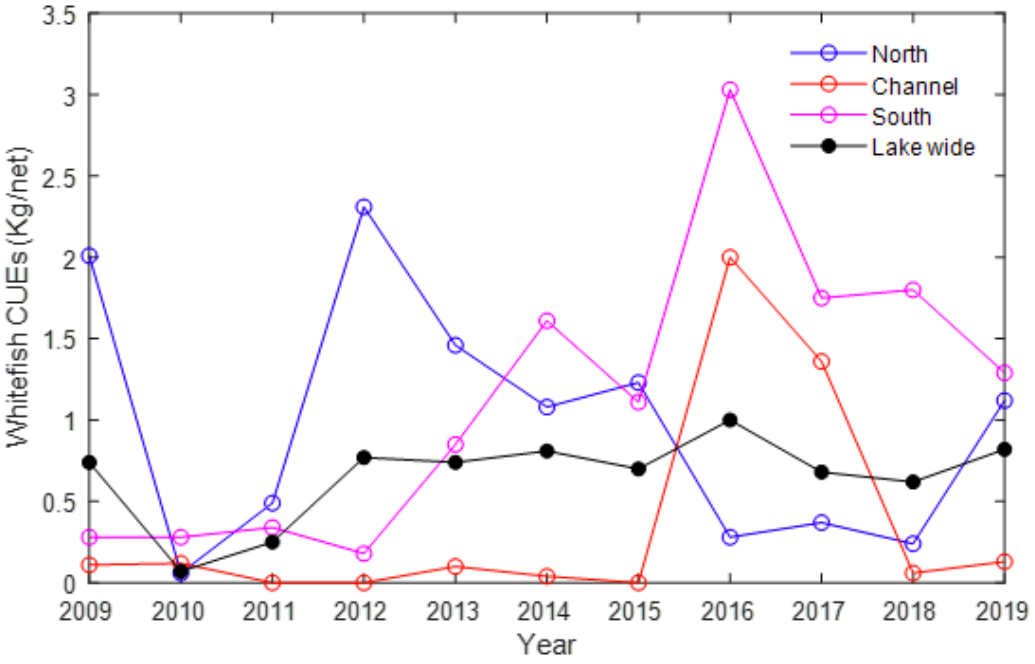

Figure 7b: Basin-specific CUEs for whitefish from the 2009-2019 gillnet indexing survey on Lake Winnipeg.

Life history data, e.g., growth and maturity, from the 1979-2003 and 2009-2019 index gill net surveys were analysed (1) to determine which among a range of potential models available for population and fishery status assessment were most appropriate given the type, quantity and quality of these data, and (2) to gain further insight to plausible, post-hoc explanations of population trends not readily inferred from the results of models otherwise constrained (see Appendices).

3. ANALYTICAL METHODS

3.1 CATCH RATES

The index nets used in different years varied; for example, in the 2009-2019 gillnet surrey, the 2'' mesh set in the southern basin decreased from 25 feet to 12.5 and the 6'' mesh increased from 12.5 feet to 25 feet for all three basins. We used equation (1) to estimate the catch per unit effort of biomass of walleye, sauger and lake whitefish per net for the 2009-2019 survey (Figure 6a. 6b, 6c). The commercial and index CUE time series were analysed by regression to examine their correlations and respective trends.

$$I_y = \sum_{mesh} qB_y S_{LMesh} E_{Mesh} \qquad (1)$$

3.2 STATE-SPACE BIOMASS DYNAMIC MODELS

State-space biomass dynamics models (SSBDM) are used for fishery assessments when data about catch at age, or length, are not available in either or both of fishery-dependent and independent data (de Valpine and Hasting 2002; Jiao et al. 2009; 2011). On Lake Winnipeg, such information was not available from commercial catches. We therefore selected a SSBDM (see Table A1 for equations) in a Bayesian analytical framework to assess the population and fishery statuses for Lake Winnipeg walleye, sauger and lake whitefish fisheries, given relatively long and reliable time series of commercial catch data (Figure 2a and 2b) and four time series of relative abundance or biomass (CUE) data, i.e., one commercial CUE series (kg/delivery) and three index CUE series (1979-2003, 2009-2019, small mesh 2013-2019).

Given the various states in which we found all of the available data, we were able to develop six combinations of SSBDM with different types of data (hereinafter model/data

scenarios) that could be appropriately analyzed for walleye, three for sauger and two for lake whitefish (Table 1).

● Scenario 1 (S1) used all the available unadjusted (for misreporting) commercial catch data and all available CUE data for each of walleye, sauger and lake whitefish.

● Scenarios 2 (S2) and 3 (S3) used the same data as S1, except with catches adjusted for misreporting of sauger as walleye. We developed two additional model/data scenarios: one the same as S1 that assumed a 25% misreporting rate in the southern basin, i.e., S2, and another also the same as S1, in which commercial walleye catch was adjusted by linear interpolation of the price ratio over time and assuming the highest and lowest price ratios correspond to 35% and 25% misreporting respectively, i.e., S3.

● Scenarios 4 (S4) and 5 (S5) additionally explored basin-specific walleye population dynamics S4 used basin-specific commercial catches for the period of 1997-2019, basin specific commercial CUE data and basin-specific index CUE data from 1997-2003, and 2009-2019. S5 used adjusted commercial catches corrected for walleye misreporting in the southern basin, as in S3.

● Finally, Scenario 6 (S6) omitted the commercial CUE time series, and used only the index CUE data, to evaluate the relative influence of the commercial CUEs on the results of those analyses that included them.

The sauger population and fishery status assessment was constrained by lack of available data to scenarios S1, S3 and S6. The lake whitefish assessment was further constrained to just S1 and S6.

Examination of all data trends for these fisheries indicated the strong possibility of nonstationary population dynamics and considerable uncertainty about population productivity, particularly how each population's productivity may have changed over time. Depending on the species, various model/data scenarios (S1-S6 for walleye, S1, S3, S6 for sauger, and S1, S6 for lake whitefish) were selectively combined with two or more of four alternate hypotheses regarding how the population productivity parameter (r) may have changed. Under hypothesis 1 (H1), r followed a random walk process, under hypothesis 2 (H2), a two-step r parameter was blocked into three time periods, under hypothesis 3 (H3), a one-step r was blocked into two periods, and finally under hypothesis 4 (H4), the r parameter was constant. For each species, the year(s) in which r changed in H2 and H3 was determined by intuitive computation on alternate years of change. A stochastic estimation of the year that productivity changed was also estimated through a Bayesian framework (see Appendix 1). S6 had different r time blocks that were estimated based on the DIC

Table 1: SSBDM model/data scenarios and hypotheses about how productivity (*r)* might have changed on Lake Winnipeg

Data/model Scenarios:	Walleye	Sauger	Lake whitefish
1. Commercial catch 1973-2019; CUEs 1973-2019 (commercial 1973-2018, ARD index netting 1979-2003, 2009-2019, ARD small mesh 2012-2019)	√	√	√
2. S1 but with south basin commercial walleye and sauger catches adjusted based on assumed 25% of sauger reported as walleye from 1997-2019	√		
3. S1 but with south basin commercial walleye and sauger catches adjusted based on annual variation in price ratio of walleye to sauger	√	√	
4. Basin specific walleye dynamics with commercial walleye catch 1997-2019, walleye CUEs 1997-2019 (commercial 1997-2018, ARD index netting 1997-2003, 2009-2019, ARD small mesh 2012-2019)	√		
5. Basin specific walleye dynamics with commercial walleye catch 1997-2019 adjusted to correct for misreporting, walleye CUEs 1997-2019 (commercial 1997-2018, ARD index netting 1997-2003, 2009-2019, ARD small mesh 2012-2019)	√		
6. Catch 1973-2019; CUE 1973-2019 (ARD index netting 1979-2003, 2009-2019, ARD small mesh 2012-2019)	√	√	√
Scenarios were selectively combined, where possible, with the following hypotheses on walleye population productivity (*r*): H1. *r* followed a random walk process H2. three *r* periods (two-step) H3. two *r* periods (one-step) H4. constant *r* (no step)			

values. The basin-specific data series were too short (1997-2019) to block *r* on time, so only the constant (H4) and random walk (H1) hypotheses were analyzed in each of S4 and S5.

4. ASSESSMENT RESULTS

4.1 CATCH RATE CORRELATIONS

4.1.1 WALLEYE

Visually, trends in the four walleye CUE time series were consistent (Figure 6a); trends in the three fishery-independent CUEs essentially matched the trend in the commercial CUE time series. Statistically, the estimated correlations among the commercial CUE time series and CUEs from the ARD index surveys, particularly 1979-2003 and 2009-2019, were highly significant (Table 2).

Table 2: Correlations among four CUE time series available for walleye and used in the assessment. P values of the correlations are in the parenthesis.

	ARD index 1979-2003	ARD index 2009-2019	ARD small mesh index 2012-2019
Commercial CUE	0.75 (<0.0001)	0.62 (0.05)	0.72 (0.07)
ARD index 2009-2019			0.62 (0.10)

Lack of significant correlations (alpha=0.05) between the ARD small mesh index CUEs and the two ARD CUEs, both large mesh, was mainly due to the relatively short time series (8 years) of the small mesh survey. The commercial CUE was highly significantly correlated with both large mesh index CUEs, even the 2009-2019 survey with only 11 years of data. Thus, despite the limited sample sizes of the three discontinuous index CUEs, and potential concerns about the commercial CUEs (LWTF 2011), the consistent trends across these multiple sources demonstrated the utility of the commercial CUEs for purposes of quantitative assessment of the walleye population and fishery statuses.

4.1.2 SAUGER

Visually, there were discrepancies among the four sauger CUE time series, especially around the year 2000 (Figure 6b). Statistically, the correlations among these time series were not significant (Table 3).

Table 3: Correlations among four CUE time series available for sauger and used in the assessment. P values of the correlations are in the parenthesis.

	ARD index 1979-2003	ARD index 2009-2019	ARD small mesh index 2012-2019
Commercial	-0.01 (0.95)	0.39 (0.26)	0.49 (0.27)
ARD index 2009-2019			-0.18 (0.67)

Lack of significant correlations among CUEs was likely due to both high variability of the time series of the index CUEs and the relatively short time series of the two most recent surveys. The commercial CUE time series was not significantly correlated with CUEs from either of the ARD large mesh index surveys.

4.1.3 LAKE WHITEFISH

Visually, there were discrepancies among trends in whitefish commercial and index CUEs. (Figure 6c). There was no clear trend in the commercial CUEs between the 1970s and early 2010s, but they increased after that. Statistically, the correlations among the commercial CUEs and index CUEs were weak for the 1979-2003 time series and insignificant for the 2009-2019 time series.

Table 4: Correlations among three CUE time series available for lake whitefish and used in the assessment. P values of the correlations are in the parenthesis.

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	ARD index 1979-2003	ARD index 2009-2019
Commercial	0.37 (0.07)	0.28 (0.42)

4.2 POPULATION AND FISHERY STATUS

4.2.1 WALLEYE

The top performing SSBDM model/data combination was identified by the lowest deviance information criterion (DIC), or DIC score. Productivity hypothesis H3, which allowed for *r* to change over 2 periods (one-step), performed best; there was weaker support for models with constant productivity (H4), and change in *r* over three periods (two-steps; H2), but only when catch-adjusted data were included (scenarios S2 and S3). Time series data available to evaluate basin-specific scenarios S4 and S5 began in 1997, so only models assuming *r* was constant (H4) or varied randomly (H1) could be compared, the former performing better given its lower DIC score (Table 5).

For all four model/data/*r* combinations with sufficient data to test between the two-period *r* and three-period *r* hypotheses (H3 and H2, respectively) H3 was best fitted to the data in scenarios S1, S2 and S3 as indicated by the lowest DIC scores (Table 5). The step between the first and second periods occurred between 1994-1997, and the step between the second and third periods occurred about 2012 (Appendix 1, Figure A1).

Table 5: DIC estimation from the six walleye model/data scenarios and four *r* hypotheses. Highlighted DIC scores indicate the best performing hypothesis on *r* for each model/data scenario.

	S1	S2	S3	S4	S5	S6
r followed random walk process (H1)	44.15	42.01	43.48	110.46	110.65	31.86
Three *r* periods (H2)	40.89	40.09	39.99			21.74
Two *r* periods (H3)	39.57	39.18	38.89			22.13
constant *r* (H4)	41.04	39.94	39.52	104.25	104.48	26.88

The fits of the S1/H3 combination to the four CUE time series were reasonably good, capturing the major trends in all four cases (Figure 8). The other models also fit the data reasonably well, although the figures are not included here.

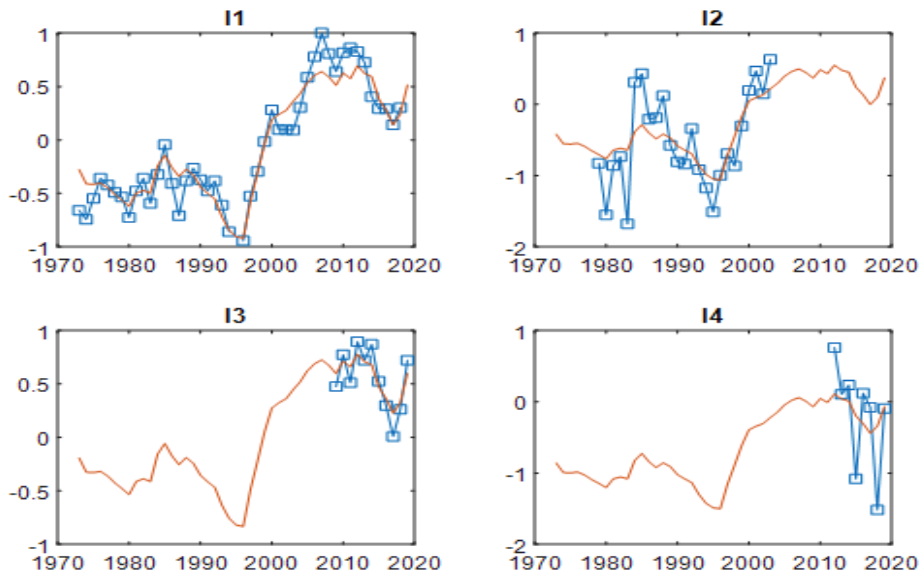

Figure 8: Model estimated walleye CUEs from S1/H3 (brown lines) in comparison with the observed CUEs (blue line with square markers). I1 = commercial CUE, I2=ARD 1979-2003, I3=ARD 2009-2019, I4=ARD small mesh survey

Overall, walleye population productivity was highly nonstationary, increasing rapidly after the mid-1990s (Table 5, Figure 9), leading to an increase in walleye biomass, B (Figure 10), that then triggered higher commercial catches (Figure 1) and a corresponding increase in the fishing mortality rate (F) (Figure 10). Estimates of the biomass dynamics (Figure 10), carrying capacity (K) (Figure 9) and changes in F over time (Figure 10) were remarkably robust to different combinations of models and hypotheses about changes in the system, and data available to test them. Results were also remarkably robust to different model/data combinations about how system productivity changed given different available data. Under model/data scenario S6, without commercial CUE included, estimates of B and F were robust to the four hypotheses about how productivity, *r*; might have changed. However, estimates of B and F were different from the scenarios that included the commercial CUE time series.

Under S1-S3, although lake-wide walleye biomass decreased from a peak of >20M kg after 2013, coincident with the collapse of the rainbow smelt in the north basin (Thorstensen et al. 2020), this decline was reversed after 2015, such that the estimated biomass in 2019 remained much higher than it was in the 1970s and 1980s (Figure 10). The fishing mortality rate in 2019 was the lowest in the time series since the early 1970s (Figure 10).

The risk of overfishing is represented by the probability that the fishing mortality rate (F) in any given year was above the widely used reference point for the fishing mortality at maximum sustainable yield (MSY), i.e., $P(F>F_{msy})$, Figure 11). A high risk of overfishing was a regular occurrence in this fishery before the late 1990s. The risk of overfishing dropped substantially afterwards, staying low until around 2012 when the risk of overfishing increased for several years before dropping again to a low level after 2015.

The risk that the population was overfished is the probability of the biomass (B) in any given year falling below the biomass at maximum sustainable yield, i.e., $P(B<B_{msy})$. There was a high probability that the walleye population was overfished on a regular basis before the productivity increased in the late 1990s. The risk of being overfished was low during the 2000s, after the increase in population productivity, but increased again between 2012 and 2015.

When the commercial CUE data were removed from the analysis (S6), the estimated historical biomass was more dynamic due to the relatively strong influence of the index CUEs and the lack of population monitoring between 2004-2008, the period when commercial catch was relatively high. The estimated fishing mortality in recent years was higher under S6 than under S1-S3 because the estimated biomass was much lower under S6 (Figure 10). Despite the differences in the estimates between S6 and S1-S3, the estimated $P(F>F_{msy})$ under S6 was less than 50% under all four hypotheses on *r* in 2019. The depletion in 2019, i.e., (B_{2019}/K), was greater (60-70%) under S6 than S1-S3, though biomass remained close to B_{msy} at around 42-47% of the carrying capacity (Figure 10).

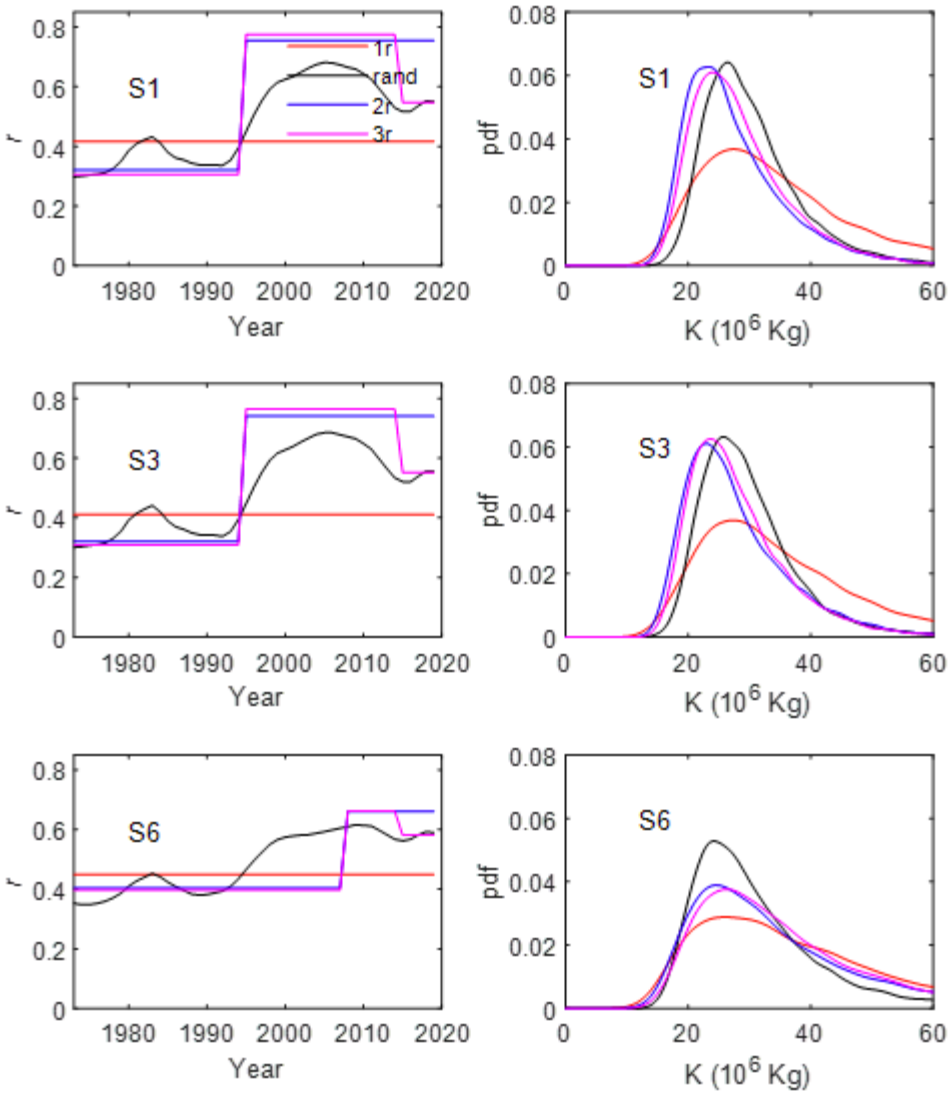

Figure 9: Walleye population productivity (*r*) and carry capacity (K) as estimated from S1, S3 and S6 and the four hypotheses regarding r. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2).

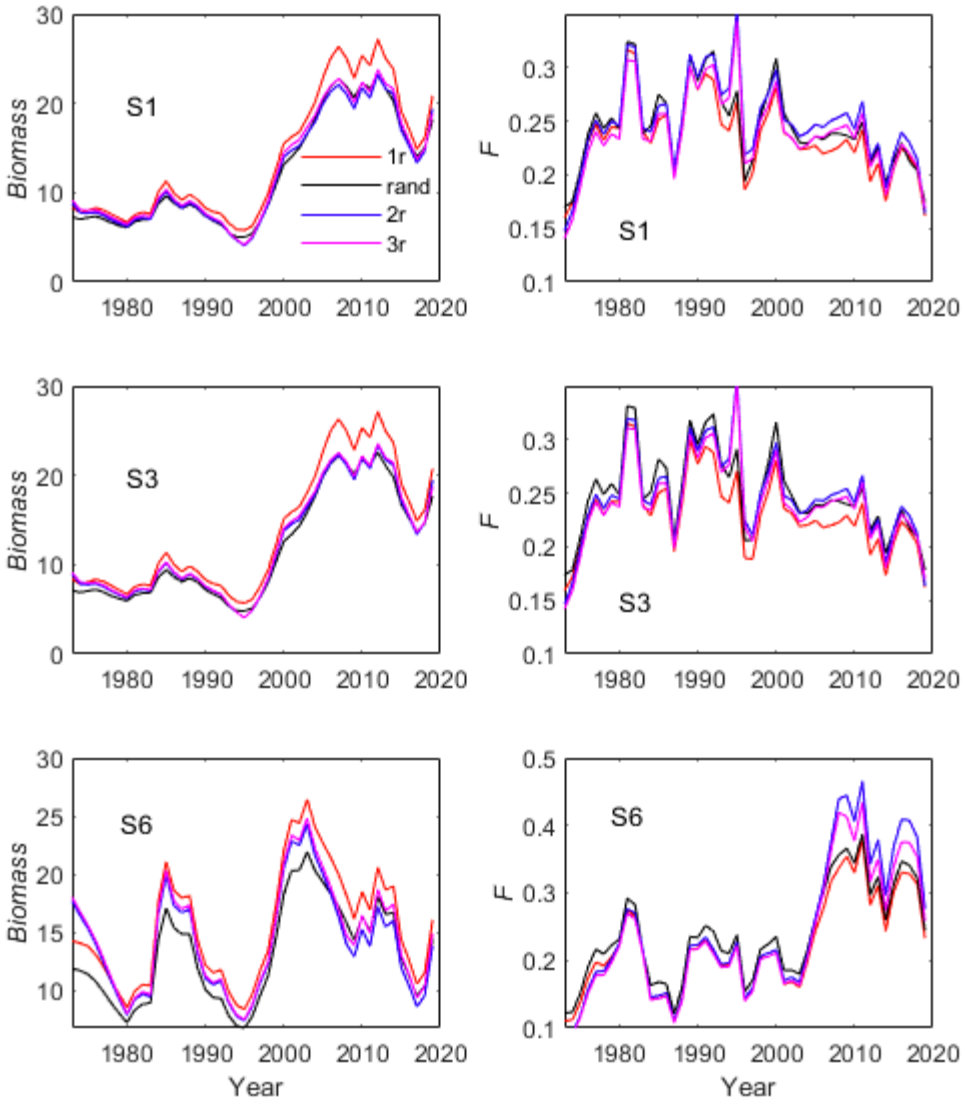

Figure 10: Walleye population size (B) and fishing mortality rate (F) as estimated from S1, S3 and S6 and the four hypotheses regarding r. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

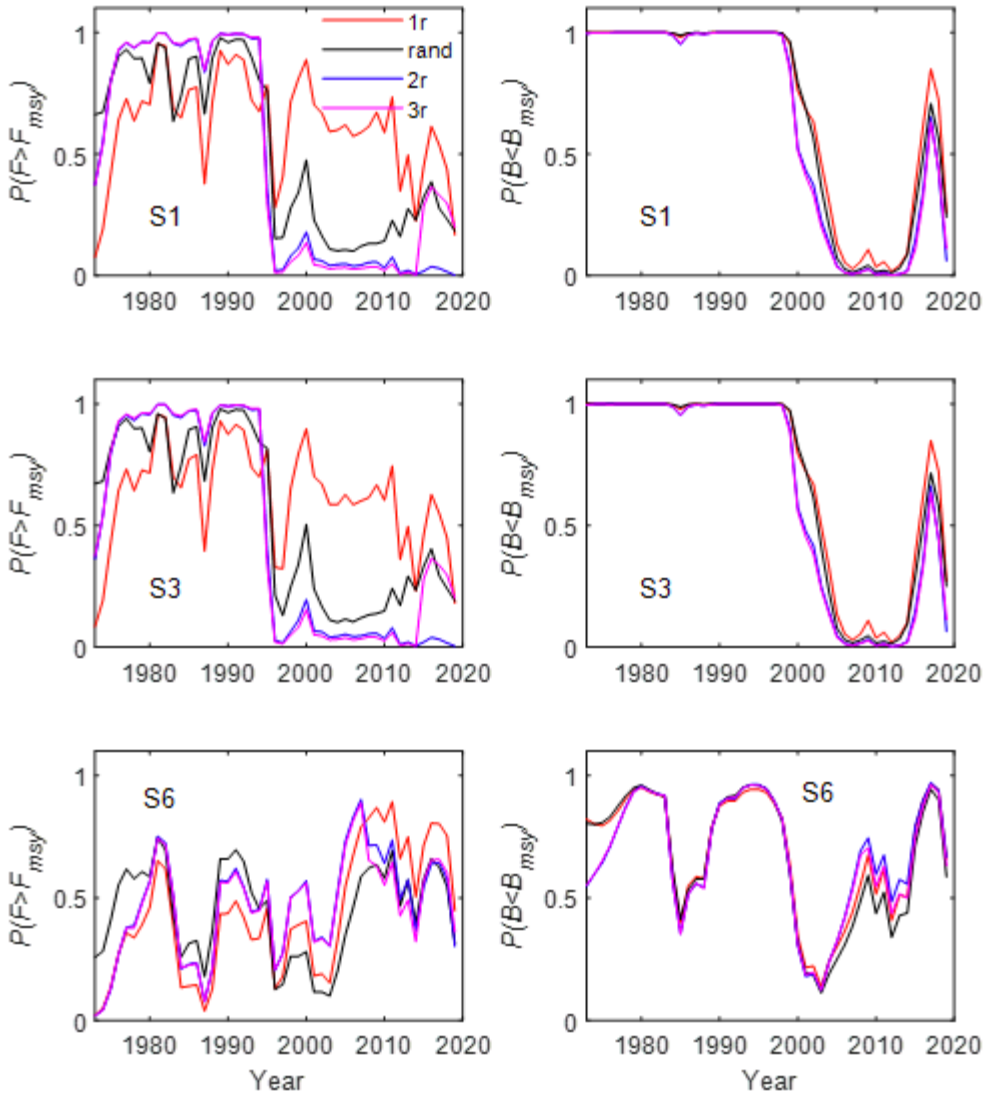

Figure 11: The risk of overfishing, $P(F>F_{msy})$, and being overfished, $P(B<B_{msy})$, for walleye as estimated from S1, S3 and S6 and the four hypotheses regarding r. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

Based on both combinations S1H2 and S1H3, the productivity in 1970s and 1980s was relatively low, which resulted in low maximum sustainable yield (MSY); commercial catches during those periods were at times greater than MSY. This situation changed during the late 1990s when the population productivity increased over a short period (Figure 12) and triggered the higher commercial catches of the 2000s (Figure 12). Harvest has been

below MSY since the mid- to late 1990s, which explains the higher population size and relatively low risk of the population being overfished. Since 2014, the commercial catch has been below the surplus production level consistent with an increasing population size and a low risk of overfishing (Figure 12). The combinations S1H3 and S3H3 both indicated that the walleye population and fishery statuses were strong in 2019 with the population biomass at ~69% of the carrying capacity (K) (Table 6), the risk that overfishing was occurring in 2019 at 1% (Table 7), and the risk that the population was overfished at 6% (Table 8).

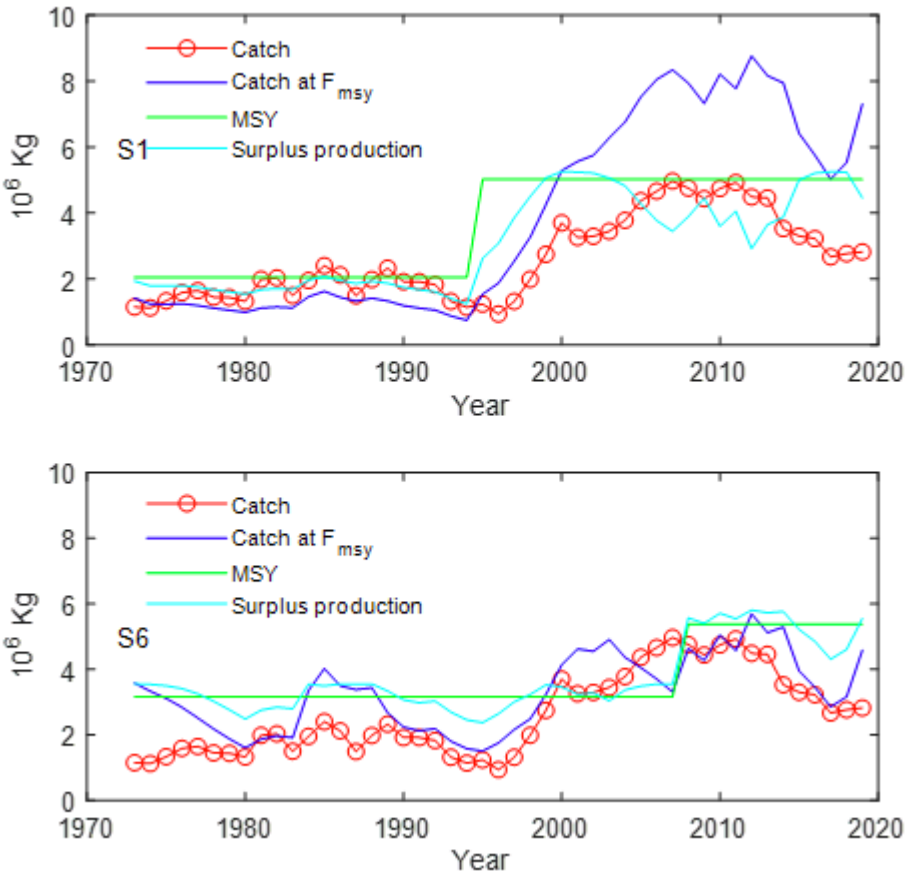

Figure 12: Comparison of walleye catch, MSY, surplus production and catch at F_{msy} based on the S1 model/data scenario and the two-period *r* hypothesis (H3) (upper) and the S6 model/data scenario and the two-period *r* hypothesis (H3) (lower).

Under scenario S6, the intuitive year of change estimation algorithm did not yield the same results as the stochastic estimation algorithm about the year that productivity changed. Under S6, the top performing model was the three r-period hypothesis (H2), in which 2007 was the first year that productivity changed as indicated by the smallest DIC score (Figure

9). Accordingly, productivity from the 1970s to the early 2000s was higher under S6H2 than under S1H3 - S3H3, resulting in lower risk of overfishing and being overfished during this period than under S6H3 (Figure 12). The change in productivity in 2007 was not as great as under S1H-S3 Consequently, commercial catches in the 2010s resulted in relatively greater F, lower biomass, and greater $P(F>F_{msy})$ and $P(B<B_{msy})$ under S6 than under the S2 and S3 model/data scenarios (Tables 7 and 8, Figures 11 and 12). A stochastic estimation showed that the productivity increased in the mid-1990s when the one-step *r* hypothesis (H3) was used, under both S1 and S6 (Figure A1); therefore, we conducted further analysis assuming the year of change in walleye population productivity was 1995 (see Figure A4). In that case, the estimated *r*, MSY and surplus production under S6 were very similar to those under S1-S3.

Scenarios that included the H1 and H2 hypotheses had DIC scores not much greater than H3 hypothesis, and they both showed similar decreasing trends in walleye productivity since about 2014 (Figure 9). If biologically real, this apparent decrease in productivity should not be ignored because it could affect the management of the walleye fishery. Such possible changes in productivity are difficult to detect and need to be further monitored and investigated.

Results of basin-specific biomass dynamic models indicated that population productivity was different among basins; growth rate was least in the northern, and greatest in the channel region (Figure A5). Because of the negative correlation between *r* and K, the values of K were opposite; the channel region had the smallest K. Although there are differences in estimates of B and F across the basins, in all cases, the estimated risk of overfishing, $P(F>F_{msy})$, was lower than 25% in recent years and the risk of the population being overfished, $P(B<B_{msy})$, was less than 50% (Figure A5).

Table 6: Posterior median estimates of walleye population depletion (B_{2019}/K) among the six model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S2	S3	S4	S5	S6
r followed random walk process (H1)	0.60	0.60	0.59	0.80	0.79	0.47
Three *r* periods (H2)	0.66	0.66	0.66			0.44
Two *r* periods (H3)	0.69	0.69	0.69			0.42
constant *r* (H4)	0.59	0.59	0.59	0.79	0.79	0.44

Table 7: Posterior median estimates of risk of overfishing the walleye population in 2019, $P(F_{2019}>F_{msy})$. N=north basin, C= channel, S= south basin

Hypothesis on *r*	S1	S2	S3	S4 (N, C, S)	S5 (N, C, S)	S6
r followed random walk process (H1)	0.18	0.19	0.19	0.01,0.19,0.02	0.01,0.18,0.02	0.31
Three *r* periods (H2)	0.20	0.20	0.20			0.36
Two *r* periods (H3)	0.01	0.01	0.01			0.30
constant *r* (H4)	0.17	0.18	0.18	0.10,0.44,0.23	0.10,0.46,0.23	0.45

Table 8: Posterior median estimates of risk of the walleye population being overfished in 2019, $P(B_{2019}<B_{msy})$. N=north basin, C= channel, S= south basin

Hypothesis on *r*	S1	S2	S3	S4 (N, C, S)	S5 (N, C, S)	S6
r followed random walk process (H1)	0.24	0.24	0.25	0.04,0.32,0.13	0.05,0.33,0.15	0.59
Three *r* periods (H2)	0.11	0.12	0.11			0.63
Two *r* periods (H3)	0.06	0.06	0.06			0.67
constant *r* (H4)	0.26	0.27	0.27	0.07,0.53,0.33	0.08,0.56,0.33	0.66

4.2.2 SAUGER

A more restricted set of combinations could be used to assess the sauger population and fishery statuses than for walleye. Hypothesis H2, when the sauger population productivity parameter *r* was blocked into three time periods, performed best, as indicated by its lowest DIC scores under S1 and S3. The DIC score for the two-period *r* hypothesis (H3) was very close to that of H2 under S1 and S3 (Table 9). The H3 and H2 hypotheses had even smaller DICs when the catch adjusted data were used (S3, Table 9). Under S6, the random walk hypothesis (H1) resulted in the lowest DIC score.

Table 9: DIC estimation from the three model/data scenarios and four *r* hypotheses for sauger. Highlighted DIC scores indicate the best performing hypothesis on *r* for each model/data scenario.

Hypothesis on *r*	S1	S3	S6

r followed random walk process (H1)	-120.46	-117.12	-68.85
Three *r* periods (H2)	-127.03	-122.83	-35.42
Two *r* periods (H3)	-126.48	-121.87	-36.43
constant *r* (H4)	-118.85	-114.79	-43.07

A stochastic estimate of the year(s) in which *r* changed, and the DIC scores, indicated that sauger productivity very probably changed in 1994-1997 and again in 2013-2015, under S1 and S3 (Figure A2). Estimates of the year when *r* changed were less clear under S6 than under S1 (Figure A2) and S3 (not shown).

The fits of the S1/H3 combination to the four observed CUE time series were reasonably good, capturing the major trends of all four series (Figure 13). The other models also fit the data reasonably well, although the figures are not included here.

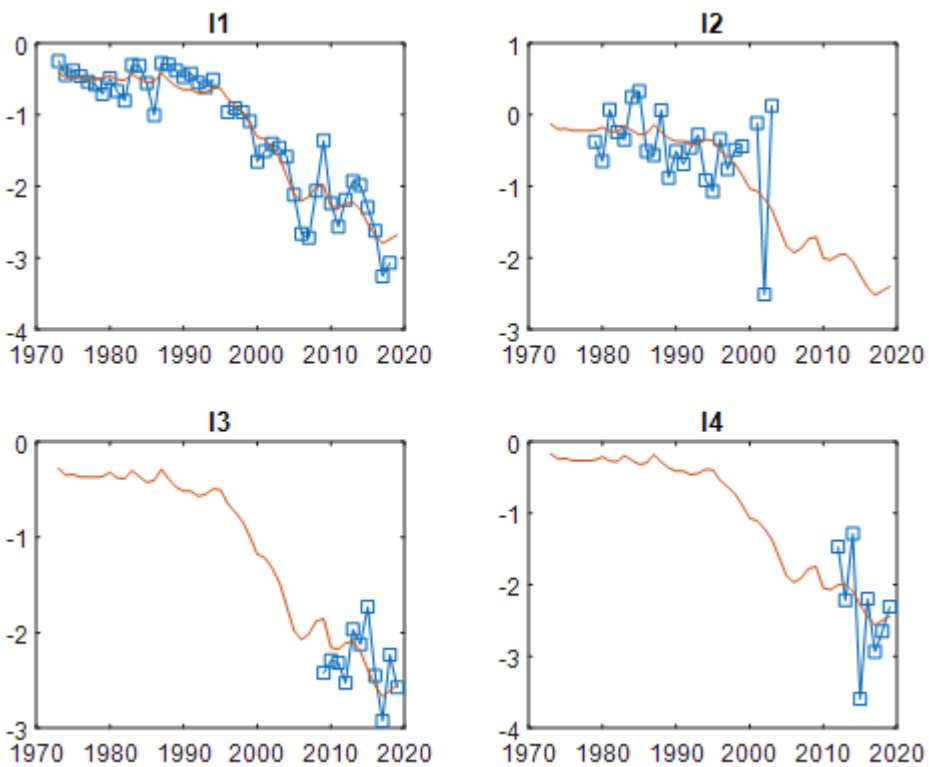

Figure 13: Model estimated sauger CUEs from S1/H3 (brown lines) in comparison with the observed CUEs (blue line with square markers). I1=commercial CUE (kg/delivery), I2=

ARD index 1979-2003, I3=ARD index 2009-2019, I4=ARD Lake Winnipeg Small mesh index.

Sauger productivity was nonstationary; it was greater before the mid-1990s and lower after that (Figure 14). The degree of change in productivity, carrying capacity (K), biomass (B) and fishing mortality rate (F) over time were largely influenced by whether the commercial CUEs were used (S1 and S3 vs S6 in Figures 14-15); biomass was greater and fishing mortality lower under S6 than under S1 and S3.

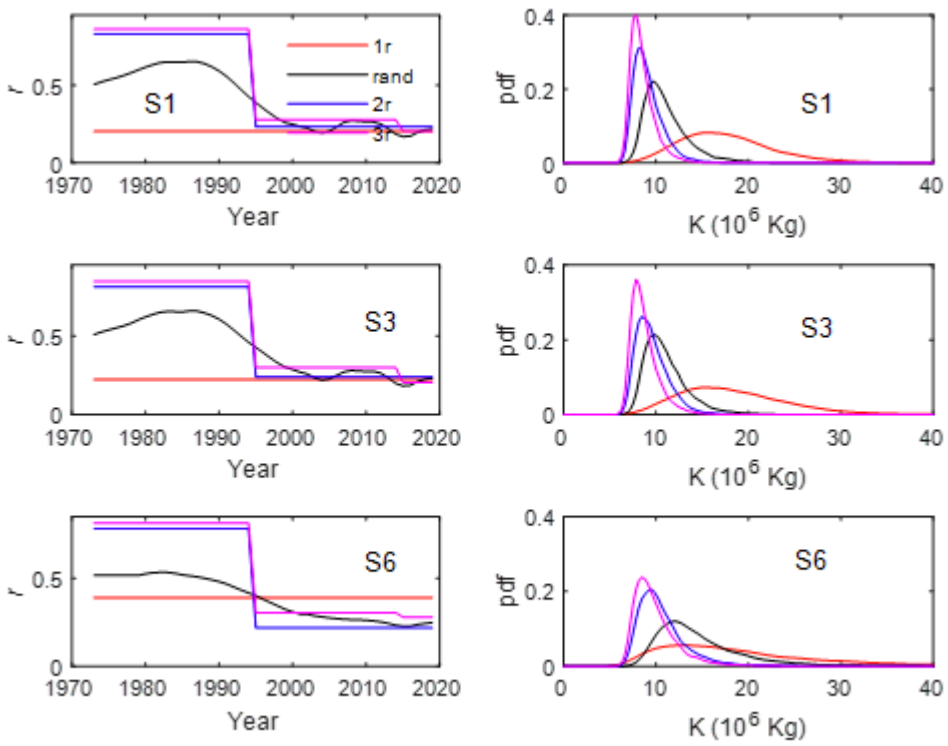

Figure 14: Estimated sauger population growth rate (*r*) and carry capacity (K) under model/data scenarios S1, S3 and S6. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1)

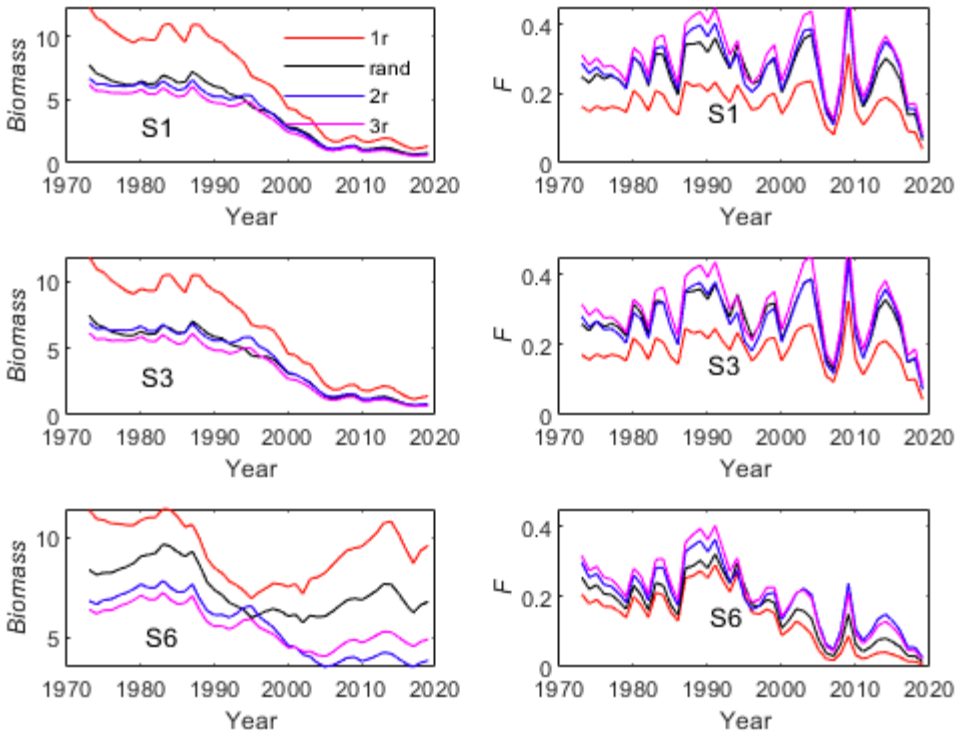

Figure 15: Estimated sauger biomass (B) and fishing mortality rate (F) under model/data scenarios S1, S3 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

The risk of overfishing dropped in 2019 in all three scenarios, but the risk that the population was overfished was different; it was 100% under S1 and S3, but around 40-60% under S6 (Figure 16).

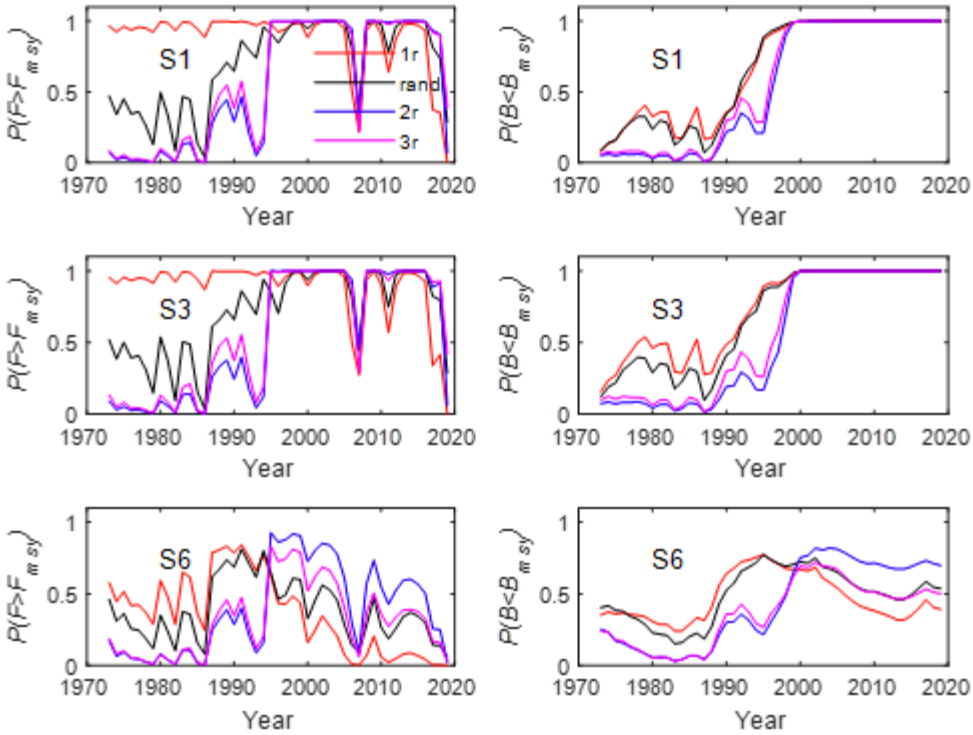

Figure 16: Estimated risk of overfishing, $P(F>F_{msy})$, and being overfished, $P(B<B_{msy})$, for sauger under model/data scenarios S1, S3 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

Sauger productivity in 1970s and 1980s was relatively higher than in more recent times, which resulted in higher maximum sustainable yield (MSY). Catches during those periods were close to MSY but lower than catch at F_{msy}, but this situation changed during the mid-late 1990s when productivity decreased and possibly triggered the lower landings of the 2000s (Figure 17).

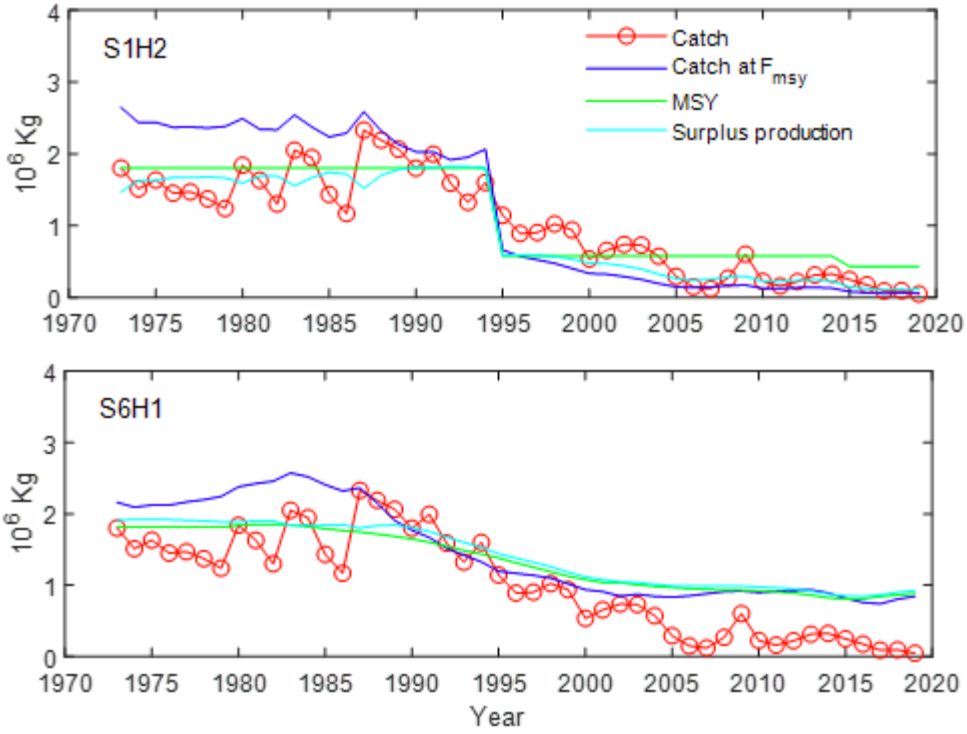

Figure 17: Comparison of sauger catch, MSY, surplus production and catch at Fmsy based on the examples of the S1H2 and S6H1.

Sauger biomass was estimated at ~7-8% of the carrying capacity (K) in 2019 under S1 and S3, but was greater, at 47%, under S6H1 (Table 10). The risk that overfishing occurred in 2019 was less than 50% (39% under S1H2 and 19% under S6H1, Table 11), and the risk that the population was overfished in 2019 was 100% under S1H2 and S3H2, but 54% under S6H1 (Table 12).

Table 10: Posterior median estimate of depletion (B_{2019}/K) of sauger population from the three model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S3	S6
r followed random walk process (H1)	0.08	0.08	0.47
Three *r* periods (H2)	0.07	0.08	0.73
Two *r* periods (H3)	0.08	0.09	0.66
constant *r* (H4)	0.08	0.09	0.58

Table 11: Posterior median estimate of risk of overfishing for sauger in 2019, $P(F_{2019}>F_{msy})$.

Hypothesis on *r*	S1	S3	S6
r followed random walk process (H1)	0.28	0.29	0.19
Three *r* periods (H2)	0.39	0.42	0.20
Two *r* periods (H3)	0.07	0.06	0.01
constant *r* (H4)	<0.01	<0.01	0.18

Table 12: Posterior median estimate of risk of being overfished for sauger in 2019, $P(B_{2019}<B_{msy})$.

Hypothesis on *r*	S1	S3	S6
r followed random walk process (H1)	1	1	0.54
Three *r* periods (H2)	1	1	0.16
Two *r* periods (H3)	1	1	0.26
constant *r* (H4)	1	1	0.39

4.2.3 LAKE WHITEFISH

Data constraints further restricted the lake whitefish stock assessment to just scenarios S1 and S6, which allowed us to investigate the relative effects of the commercial CUE data on inferences about the lake whitefish population and fishery status based on index CUE data alone. Under S1, hypothesis H1, when *r* followed a random walk process, performed best,

as indicated by its lowest DIC score (Table 13). Under S6, the three-period *r* hypothesis (H2) had the lowest DIC score, though the other three hypotheses were close. All scenarios were indicative of strong nonstationary productivity in the lake whitefish population.

When commercial CUEs were included in the analysis (S1), stochastic estimates of the year that *r* changed, and the DIC scores, indicated that the lake whitefish productivity likely changed around 2010; no clear year in which *r* might have changed emerged when commercial CUE data were excluded (S6), though combination S6H2 had marginally lower DIC score than the other combinations (Figure A3, Table 13).

Table 13: DIC estimates from the two model/data scenarios and four *r* hypotheses for lake whitefish. Highlighted DIC scores indicate the best performing hypothesis on *r* for each model/data scenario.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	627.28	251.51
Three *r* periods (H2)	631.31	248.81
Two *r* periods (H3)	630.51	249.02
constant *r* (H4)	628.21	250.63

The fits of combination S1H1 to each of the three lake whitefish CUE time series were good, balancing the major trends of all three series with the influence of the commercial CUE greater because, although potentially less reliable, it was the longest series (Figure 18). Other models also fit the data reasonably well, although the figures are not included here.

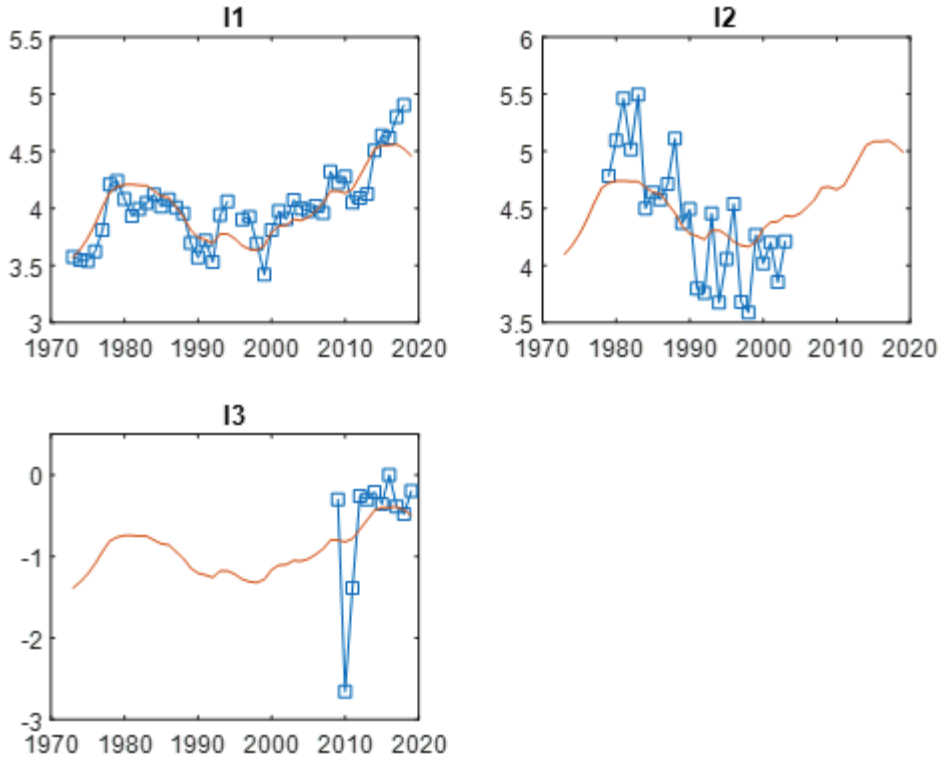

Figure 18: Model estimated lake whitefish CUEs of from S1H1 (brown lines) in comparison with the observed CUEs (blue line with square markers). I1=commercial CUE (kg/delivery), I2= ARD index 1979-2003 (#/net), I3=ARD index 2009-2019 (kg/net).

Productivity of lake whitefish tended to be low in the later 1980s and early 1990s but reached greater than historical values after 2010 (Figure 19). The corresponding *r* values estimated under S6 were very close to those under S1 (Figure 19).

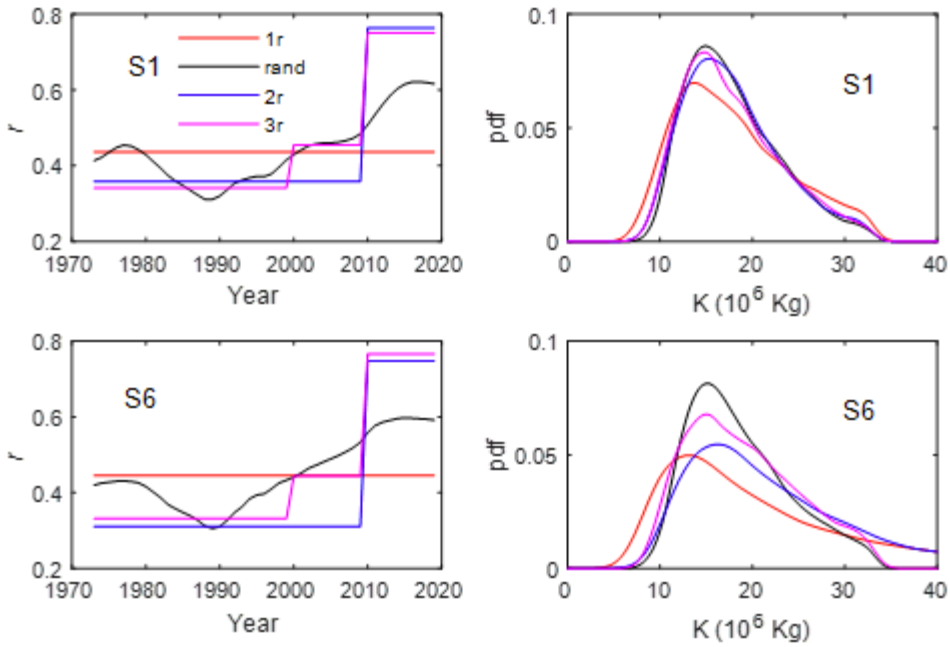

Figure 19: Estimation of the lake whitefish productivity (*r*) and carry capacity (K) from model/data scenarios S1 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

Estimates of the lake whitefish biomass (B) dynamics (Figure 20), carrying capacity (K) (Figure 19) and changes in fishing mortality rate (F) over time (Figure 20) were remarkably robust to the selection of the four alternate hypotheses about *r*. This robustness to selection uncertainty was reflected in the risks of overfishing, $P(F>F_{msy})$, and being overfished, $P(B<B_{msy})$, (Figure 21) and surplus production and MSY (Figure 22). Under S1, estimates of depletion (B_{2019}/K) indicated that whitefish in 2019 were not depleted; neither were whitefish overfished ($P(B<B_{msy})=0.10$), nor had overfishing likely occurred ($P(F>F_{msy})=0.13$). Under S6H2, it was also unlikely to be overfished ($P(B<B_{msy})=0.26$), nor had overfishing likely occurred ($P(F>F_{msy})=0.57$) (Tables 14-16). The risk of overfishing and the risk of being overfished did tend to be greater if *r* was assumed constant r (H4) (Figure 21).

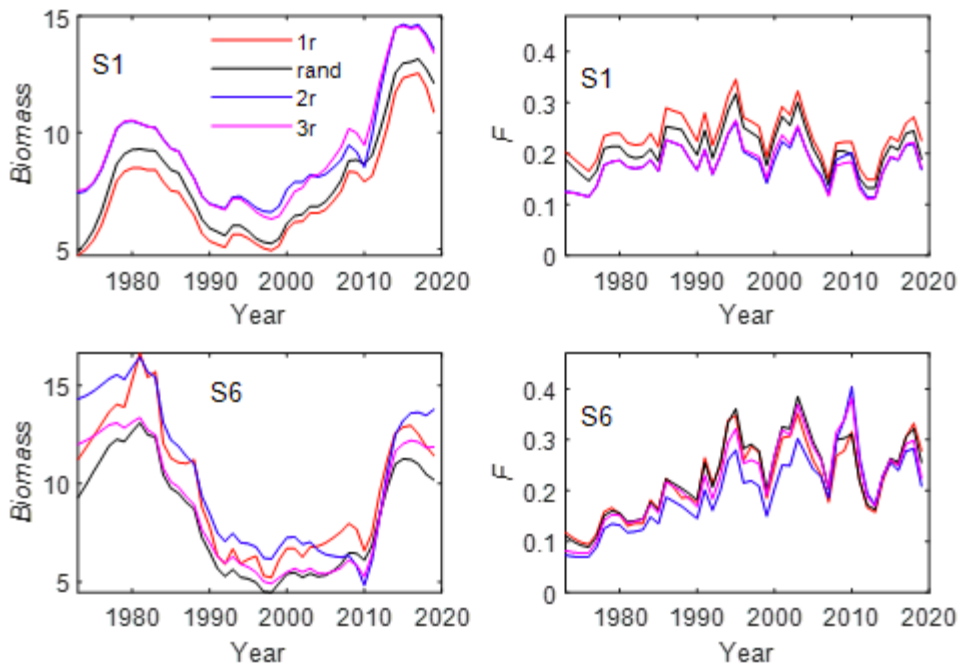

Figure 20: Estimation of whitefish biomass and fishing mortality rate (F) from model/data scenarios S1 and S6 and the four hypotheses regarding r (see Table 1).

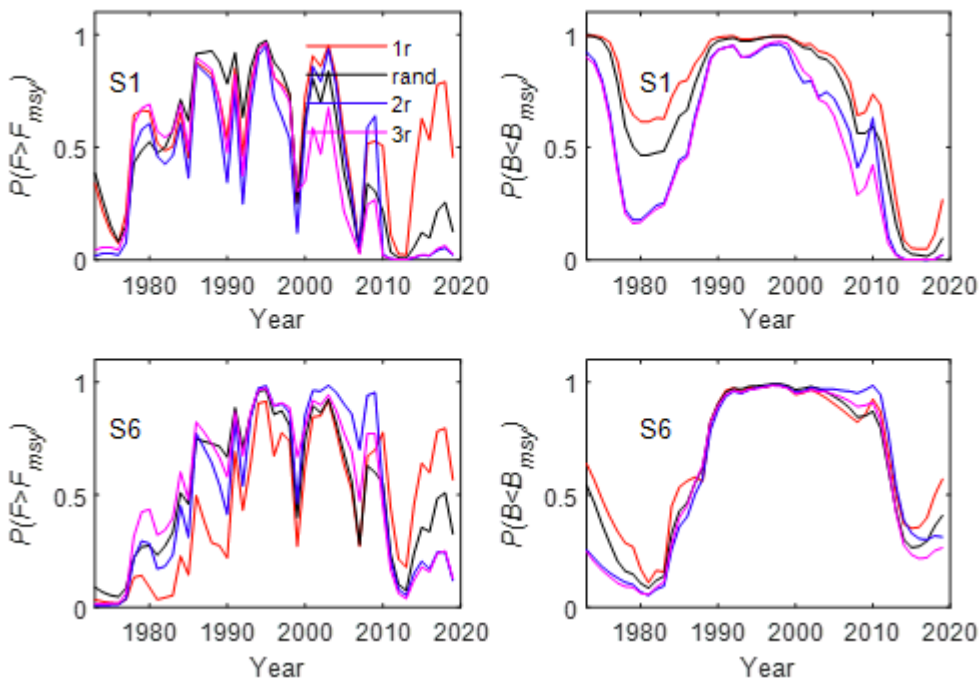

Figure 21: The risk of overfishing, $P(F>F_{msy})$, and of being overfished $P(B<B_{msy})$ as estimated from S1 and S6 for the lake whitefish population. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

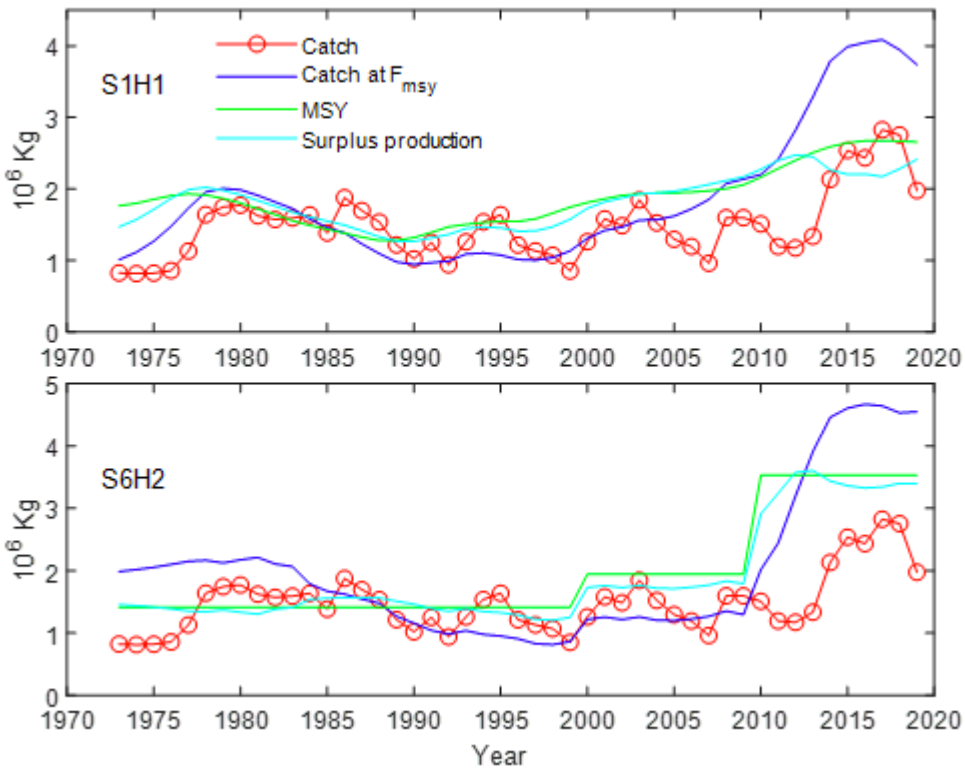

Figure 22: Comparison of lake whitefish catch, MSY, surplus production and catch at Fmsy levels based on the examples of the S1H1 and S6H2.

Table 14: Posterior median estimate of depletion (B_{2019}/K) from the two model/data scenarios for whitefish population.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.67	0.54
Three *r* periods (H2)	0.74	0.62
Two *r* periods (H3)	0.74	0.60
constant *r* (H4)	0.60	0.48

Table 15: Posterior median estimate of risk of overfishing in 2019, $P(F_{2019}>F_{msy})$ for the lake whitefish population.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.13	0.33
Three *r* periods (H2)	0.02	0.13
Two *r* periods (H3)	0.02	0.12
constant *r* (H4)	0.46	0.57

Table 16: Posterior median estimate of risk of being overfished in 2019, $P(B_{2019}<B_{msy})$ for the lake whitefish population.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.10	0.41
Three *r* periods (H2)	0.02	0.26
Two *r* periods (H3)	0.02	0.31
constant *r* (H4)	0.27	0.57

5. CONCLUSIONS

5.1 WALLEYE

The status of the walleye population and fishery was robust to alternative model/data scenarios, i.e., model/data selection uncertainty was low. The consistently strong fits of the models to the observed CUE series, particularly the combination of model/data scenarios S1 and S3 with the one-step population productivity parameter (i.e., S1/H3 and S3/H3), was largely attributable to the strong correlations among the four CUE time series. Remarkably, although the various CUE time series covered different periods of time (only the commercial CUE series covered the entire period of 1973 to 2019), all four indicated the same narrative about population dynamics.

The decline in walleye biomass from a peak of >20M kg was reversed after 2017. By 2019, it remained greater than it was in the 1970s and 1980s. There is a high probability that the walleye population was overfished on a regular basis before the productivity increased in the late 1990s. The risk of being overfished was low during the 2000s, after productivity

increased, but increased again between 2012 and 2015. The risk of being overfished has continued to drop steadily since then.

Greater population productivity since the late 1990s may be due to some, yet to be established, combination of increased eutrophication (e.g., Schindler et al. 2012), increased smelt biomass in the north basin (e.g., Scott et al. 2011), and/or the periodic life history strategy of percids generally (e.g., Zhang et al. 2018), such that walleye can occasionally recruit a very large year class, leading to populations that periodically exceed carrying capacity. Such changes were also reflected in the life history of walleye in Lake Winnipeg with more rapid individual growth and earlier maturation in the 1990s, but slower growth and later maturation after 2015, especially in the north basin (Appendix 2). The recent decrease in productivity, detected by models with the two-step productivity parameter, indicates a need for ongoing monitoring and enhanced data collection in the coming years to avoid negative outcomes for the fishery. Further, the effects of such a surge of a predator population on its own dynamics, on its forage base and the general fish community (for example, not implausibly, the concurrent decline of sauger biomass) have yet to be determined and are beyond the scope of this study.

Overall, the walleye fishery was strong in 2019. Biomass was high at ~69% of the carrying capacity, the risk that overfishing occurred was 1%, , and the risk that the population was overfished was 6%, the result of stable biomass in the north basin and recent increases in biomass in the channel and south basin, combined with reduced commercial catch. The fishing mortality rate in 2019 was the lowest in the time series since the early 1970s.

The picture was less optimistic when the commercial CUE was excluded and only the three index CUE series were used in the analysis, and a recent decline in biomass was similarly detected. Even so, the population status was sufficiently good that, based on our experience, it could be expected to gain a passing score under the MSC certification scheme.

We recommend that, until such time and necessity as there are data of sufficient quantity and quality to use models more complex than SSBDMs, combinations S1/H3 and S3/H3 and model averaging should be considered for assessment and management purposes.

We expect that low commercial walleye catch anticipated in 2020 due to the COVID-19 pandemic, the consequent lowered demand for walleye, and lower than normal fishing

effort, should mean that the already strong status of the walleye population and fishery will continue in 2020.

5.2 SAUGER

The sauger population and fishery statuses were less robust to alternative model scenarios than they were for walleye, i.e., model/data selection uncertainty was high such that we could not identify a top-performing model. This uncertainty was largely attributable to weak correlations among the various CUE series indicating alternative narratives about sauger population dynamics. Sauger population productivity was nonstationary; productivity fell sometime between 1994-1997 and likely fell again sometime between 2013-2015, coincident with the collapse of the rainbow smelt population in the north basin. Sauger productivity was greater, as was MSY, in the 1970s and 1980s than afterwards. Commercial catches during the 1970s and 1980s were close to MSY, but lower than the catch at F_{msy}. This situation changed during the mid-late 1990s when the sauger population growth rate appears to have decreased. This rate change caused much lower productivity and probably contributed to the lower catches of the 2000s.

In 2019, sauger biomass was ~7-8% of the carrying capacity (K) under S1 and S3 but was better at 47% under S6H1 (Table 10). The risk that overfishing had occurred ranged between 19%-39%, and risk that the population was overfished was 45%-100%, all of this variation dependent upon the combination of model/data scenario with an hypothesis about how productivity was likely to have changed.

There were strong effects of the commercial CUE data on the results that should not be ignored. The very weak correlations among the commercial CUEs and the index CUEs suggest that either the commercial CUE is not as reliable an indicator of sauger relative abundance, as seemed to be the case for the commercial walleye CUE series (and, to a lesser extent, the commercial lake whitefish CUEs), and/or that the ARD index CUE data may not be as reliable an index of sauger relative abundance, as seemed to be the case for the ARD CUE series for walleye.

Commercial CUE data may be unreliable because of putative spatial and temporal changes in commercial fishing effort targeting sauger since the late 2000s, avoidance and/or discarding of sauger as walleye abundance and relative price surged, and possible ecosystem-related changes that may have changed the catchability of sauger in the

commercial gear. Index CUE data may be unreliable because of temporal discontinuities in the surveys, missing and/or spurious catch and effort data from some areas in some years, and insufficient environmental information to allow for CUE data standardization.

The scenario that includes all the available time series, including the commercial CUE series, i.e., S3, particularly the S3H3 combination is the most precautionary among those we examined. While S6H2 indicates a further recent decline in the productivity of the sauger population, it also indicates that the sauger was not being overfished in 2019. Based on our experience, the current sauger population status could be expected to improve in future years if harvest and fishing mortality are carefully managed to limit the probability of overfishing to <50%.

As noted for the walleye population, the apparent decrease in sauger population productivity should not be ignored because it could affect the management of the fishery. Such changes are difficult to detect and need to be further monitored and investigated.

We suggest that a sauger management plan is urgently needed, and that any such plan should include initiatives such as enhanced monitoring, including index survey improvements, commercial sauger catch sampling, and a commercial fishers log book program designed to improve the quantity and quality of commercial sauger CUE data. A sauger management plan could also include development of a harvest control rule that could be used to sufficiently limit annual commercial and recreational sauger catches until the available data indicate the population is at or close to the biomass at MSY.

5.3 LAKE WHITEFISH

The lake whitefish stock assessment was based on two scenarios, both of which indicated strong nonstationarity in productivity. It tended to be lower in the later 1980s and early 1990s and exceeded historical values after 2010. Lake whitefish were overfished, and overfishing happened regularly, between the late 1980s and around 2010. The risk of both overfishing and of being overfished dropped after 2010 and increased in recent years.

In 2019, lake whitefish population and fishery statuses were strong. The population was well above B_{msy}; the risk that the population was overfished was 10%, and the risk that overfishing happened was 13%. When the fishery-dependent CUE data series was not included in the analysis, the risk that the population was overfished was greater at 23%, and

the risk of overfishing remained at 13% (Tables 14-16). These indicators suggest that the status of the 2019 lake whitefish population was good to the extent that, in our experience, the stock status could be expected to gain a passing score under the MSC certification scheme.

Although the differences between the results of the S1H1 and S6H2 model/data scenario/*r* combinations were small, i.e., both paint a similar picture of the status of the lake whitefish population and fishery. Until there are better data available to support more complex assessment models, we suggest that combination S1H1 should be considered for the ongoing assessment and management of the lake whitefish fishery because this combination includes all of the available data and had the lowest DIC score among the S1 models.

6. RECOMMENDATIONS

Regarding the second conclusion by the Task Force in 2011, that because of the lack of data, it was unable to recommend changes to recommended allowable harvest, this report demonstrates, despite certain data limitations which continue to exist, that there are now data available of sufficient quality and quantity to support assessments necessary for managers and stakeholders to begin the process of developing reliable guidance, such as harvest policies, about how the fishery should be managed, to the mutual benefit of all stakeholders, now and in the future.

Consistent with the third conclusion by the Task Force, we suggest that the PCFM consider initiating a third-party review of the current assessment and management system. It may be possible for the PCFM to engage with ARD in a cooperative approach to such a technical review. The review should also include specific recommendations to improve the fisheries assessment and management system on Lake Winnipeg. One such example could be the utilization of the commercial fishing industry as a partner of ARD to expand the spatial and temporal extent and refine the sample design of the index surveys.

The A/OFRC study team's understanding of the details of the current assessment system have significantly increased since we began this research. We would be pleased to engage in a more informed discussion about possible approaches to initiating an independent review. In the meantime, we provide the follow specific recommendations for future data collection and fishery management:

- The current assessments rely heavily on the commercial (fishery-dependent) CUEs. Neither fishery-dependent nor -independent data could be standardized for any species because of the lack of related information about environmental factors or, in the case of the 1979-2003 ARD index survey, space and time information. Fishery-dependent data should be collected, by way of a fishers' logbook program and database, to allow reliable, and standardized, estimates of targeted effort, catch, discards and releases.

- Recreational fishery catch and effort (the other critical component of fishery-dependent data to include in stock assessments) should be collected, by way of creel censuses and/or an angler diary program, and database, to allow reliable estimates of targeted recreational effort, catch, discards and releases.

- Commercial stakeholders' knowledge about prices and their opinions about reasons for changes in historical harvest were synthesized and partly included in our assessment (e.g., price ratio and its influence on walleye-sauger misreporting). Such information and approaches may be better considered using surveys and workshops with fishers' representatives.

- The PCFM should consider working with other stakeholders to initiate a third-party review of the current assessment and management system, including specific recommendations to improve the fisheries assessment and management system.

- ARD and stakeholders should take the findings here, as well as the extra data sensitivity analyses in the appendices, into account when considering management decisions including mesh size restrictions and the seasonal openings and closings of the commercial and recreational fisheries.

- The role of rainbow smelt in the Lake Winnipeg ecosystem, the interrelationships between smelt and commercially and recreationally important species, and effects on the stakeholders are poorly understood. The PCFM should cooperate with other stakeholders to support monitoring and research to improve understanding of the effects of smelt on the commercial and recreational fisheries.

- The process to develop a management plan for sauger should include all affected parties in a structured decision-making process facilitated by an independent third party.

7. ACKNOWLEDGEMENTS

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Appendix 1: Supplementary tables and figures

Table A1: Models and their equations used in the report.

Models and equations	**Parameter description**
von Bertalanffy growth model $L_{age} = L_{\infty}(1 - e^{-k(age - t_0)})$	L_{age} : length at age L_{∞} : asymptotic size k : growth coefficient t_0 : age when length is 0
Maturity logistic model $\text{logit}(P_m) = a + b \times age$ or $\text{logit}(P_m) = a + b \times length$ $Y_i \sim B(P_{m,i})$	P_m : probability of maturity a and b : parameters in the log-linear model Age and Length: fish age and length Y_i : binary observations of mature or not of fish i
State-space biomass dynamic model $B_t = B_{t-1} + r_{t-1} B_{t-1} (1 - B_{t-1}/K) e^{\varepsilon_1}$ $I_{t,i} = q_i B_t e^{\varepsilon_2}$	B_t : biomass at year t I_t : CUE in year t r_t : population productivity (growth rate) in year t K : carrying capacity ε_1 and ε_2 are process and observation errors

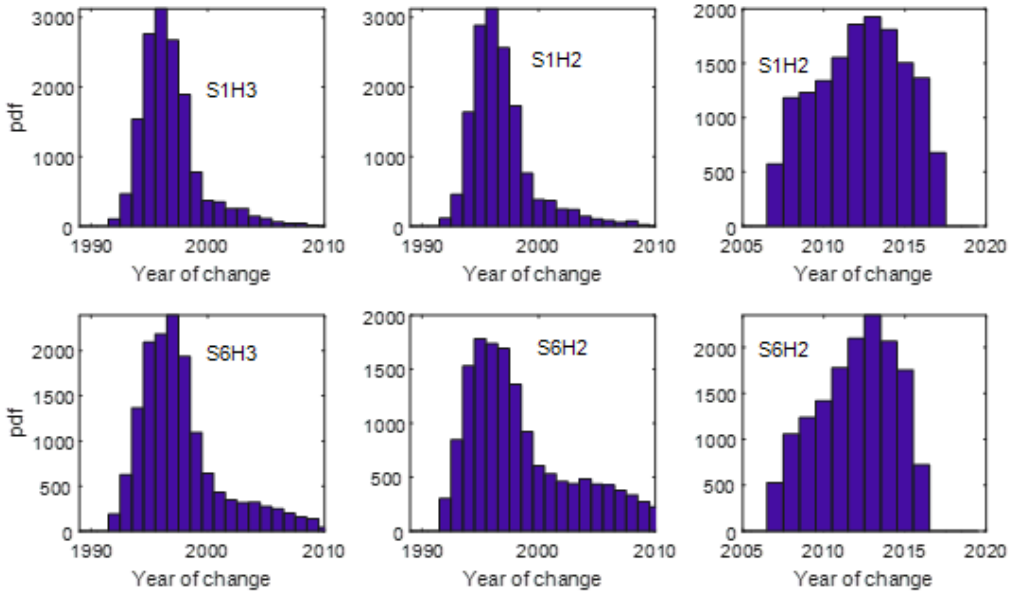

Figure A1: Stochastic estimation of the year of change in walleye productivity (r) shown as posterior pdfs in the S1H3, S1H2, and S6H3 and S6H2 scenarios. Left panels show year of change under H3. Middle panels show year of first change (step 1) under H2, and right panels show year of change (step 2) under H2 for S1 (top row) and S6 (bottom row), respectively.

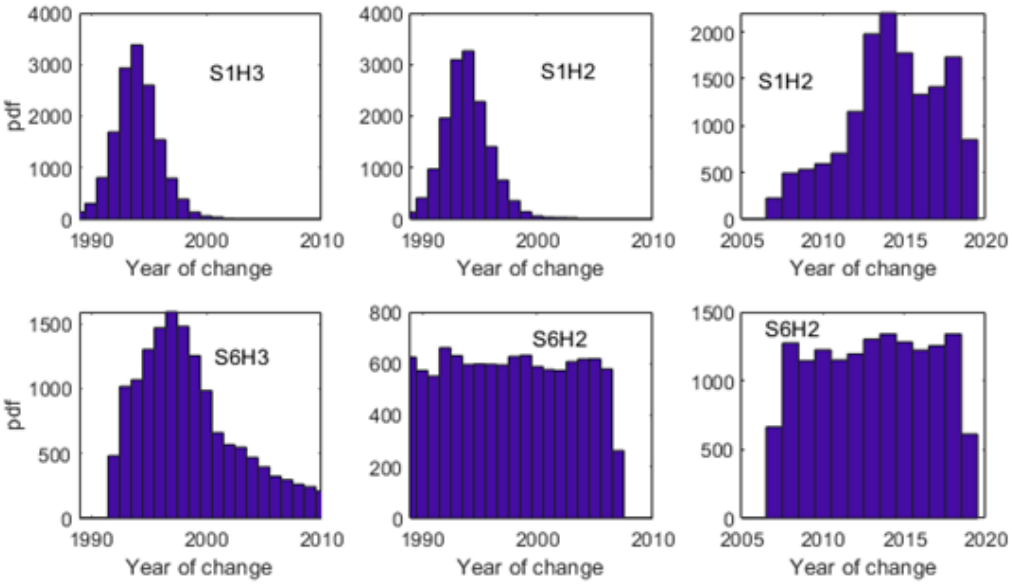

Figure A2: Stochastic estimation of the year of change in sauger population productivity (r) shown as posterior pdfs in the S1H2, S1H3, and S6H2 and S6H3 scenarios. Left panels show year of change under H3. Middle panels show year of first change (step 1) under H2,

and right panels show year of second change (step 2) under H2 for S1 (top row) and S6 (bottom row), respectively.

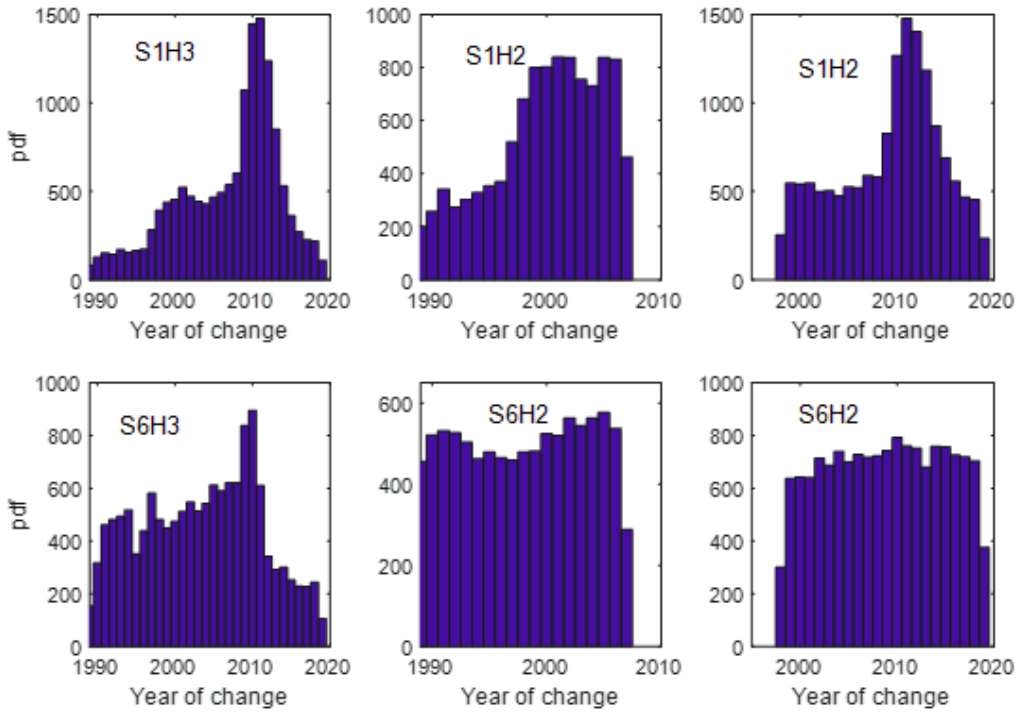

Figure A3: Stochastic estimation of the year of change in lake whitefish population productivity (r) shown as posterior pdfs in the S1H2, S1H3, and S6H2 and S6H3 scenarios. Left panels show year of change under H3. Middle panels show year of first change (step 1) under H2, and right panels show year of second change (step 2) under H2 for S1 (top row) and S6 (bottom row), respectively.

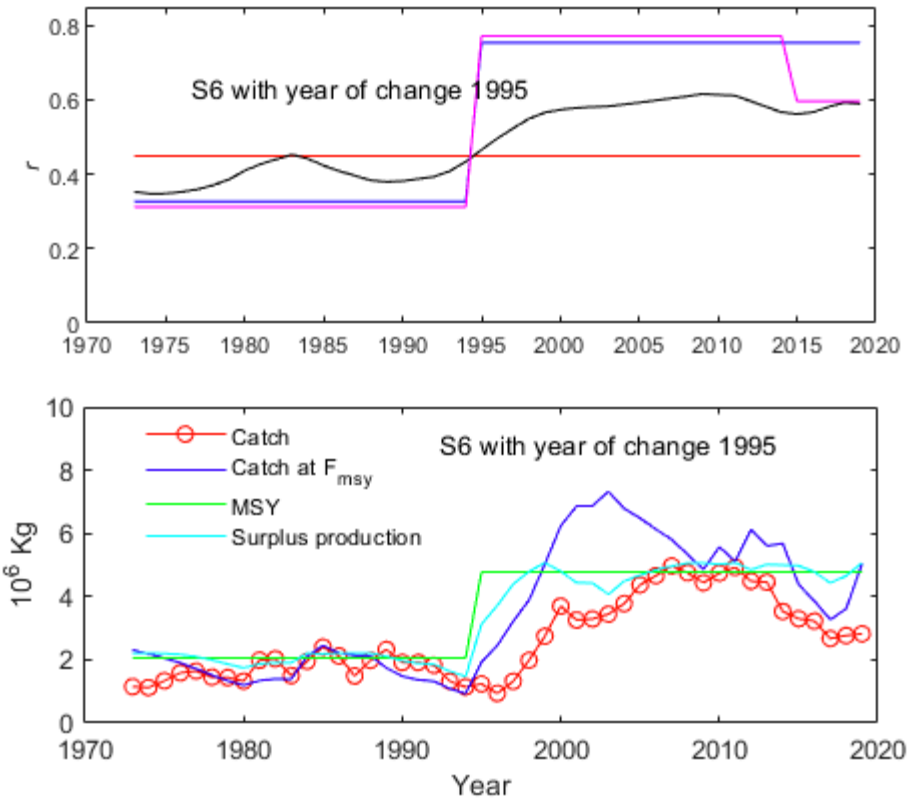

Figure A4: Walleye model/data scenario S6 with three-period *r* hypothesis (H2), year of first *r* change 1994-1995 and year of second *r* change as 2014-2015.

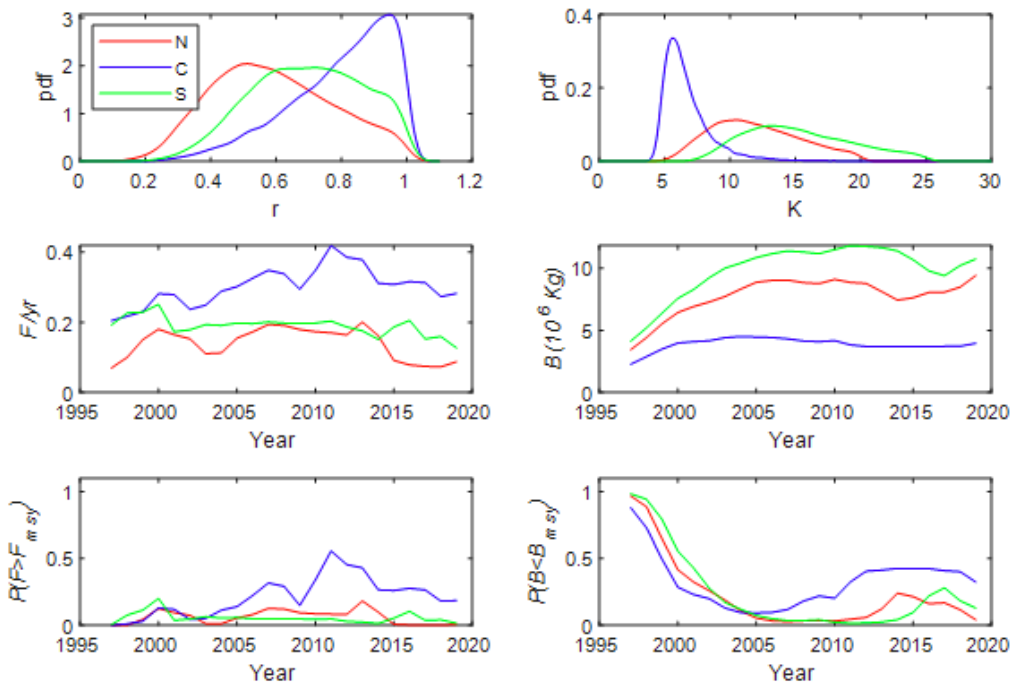

Figure A5. Basin-specific probability density functions for walleye population productivity (r) and carrying capacity (K) in 2019, recent trends in walleye fishing mortality (F), biomass, and the risk of overfishing, P(F>Fmsy), and being overfished, P(B<Bmsy).

Appendix 2: Supplemental information and preliminary analyses regarding growth and maturity

The following sections provide supplemental information about the fishery assessment and describe the methods and results for our preliminary analyses regarding growth and maturity of Lake Winnipeg walleye, sauger and whitefish. These analyses proved useful for understanding the fishery and establishing the most appropriate methods with which to approach its assessment. The results of the following work on walleye growth and maturity are necessary components of any future evaluation of the effects of alternate minimum (and maximum) mesh size policies on the population and the fishery.

A2.1 WALLEYE GROWTH

The various indexing surveys (1979-2003 and 2009-2019) have been ongoing for more than 30 years in total, such that the quantity and quality of the age-length and weight data are sufficient for an analysis of walleye growth in Lake Winnipeg (Figure A6). The von Bertalanffy (VB) model, widely used to capture fish growth patterns (von Bertalanffy, 1938), was used to fit the data (Table A1). A preliminary analysis on the residuals (Figure A6 and A7) after fitting the VB model, indicates that growth is gender-specific and can be highly heterogeneous, both across basins and years. We then applied non-linear mixed effect models to explore the growth variation among basin, gender and years (Lindstrom and Bates 1990; Jiao et al. 2010; Ma et al. 2017). Such analyses will aid our understanding of potential life history variation but can also assist us to infer potential reasons for non-harvest related drivers of population dynamics (, e.g., Zhang et al. 2019). In many cases, such analysis can also provide the foundations for conducting age- or size-structured fishery assessments.

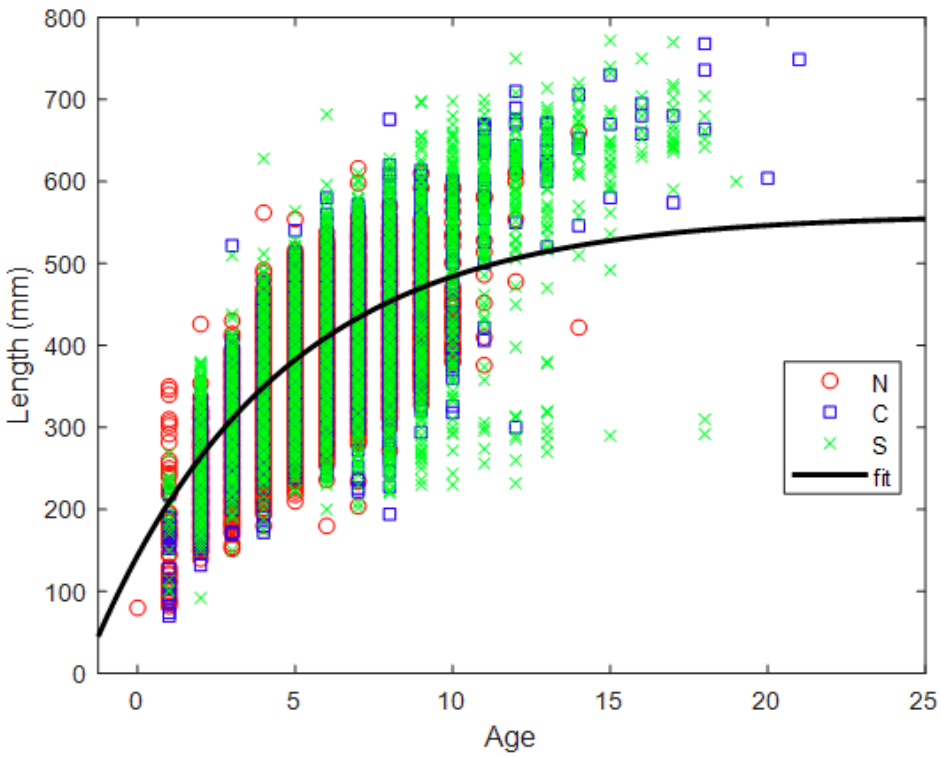

Figure A6: Observed length at age of walleye in the 3 regions. N-north basin; C-channel region; S-south basin. Fit is the global fitting, i.e., not considering differences in basin and time.

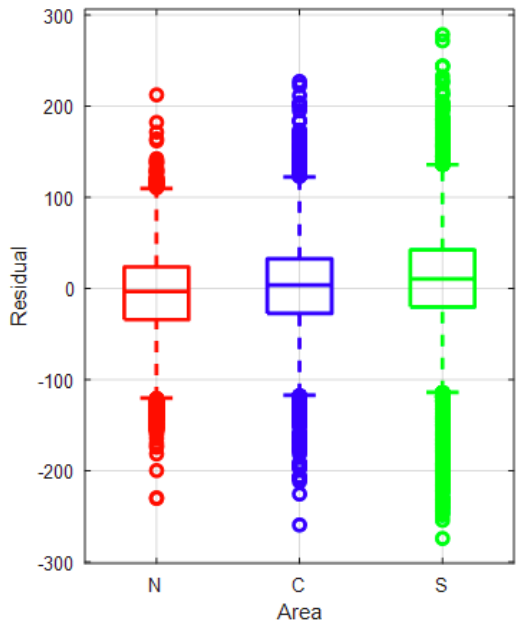

Figure A7: Box plot of the residuals after the VB model fitting given the 3 regions. N-north basin; C-channel region; S-south basin.

Differences in growth among basins and years were found to be significant (Table A2). The temporal variation in growth of Lake Winnipeg walleye (Figure A8) can affect population dynamics. As shown in the residual plot (Figure A7) and the year specific growth curve fitted through a nonlinear mixed VB model, the growth was lower in late 1970s and early 1980s, higher in the 1990s and early 2000s, but lower since 2014. This pattern is consistent across all three basins (Figure A9).

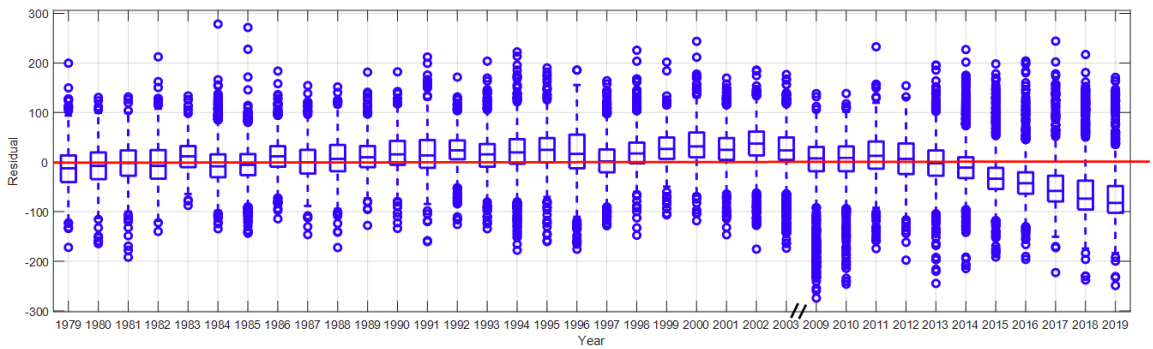

Figure A8: Box plot of the residuals after the VB model fitting given observation years.

Table A2: Comparison of the nonlinear mixed effect models with the von Bertalanffy fixed effect model

Model description	AIC
$L \sim f(age)$	975312
$L \sim f(age + k\|area + L_\infty\|area)$	560561
$L \sim f(age + k\|year + L_\infty\|year)$	537592
$L \sim f(age + k\|area \times year + L_\infty\|area \times ye$	533978

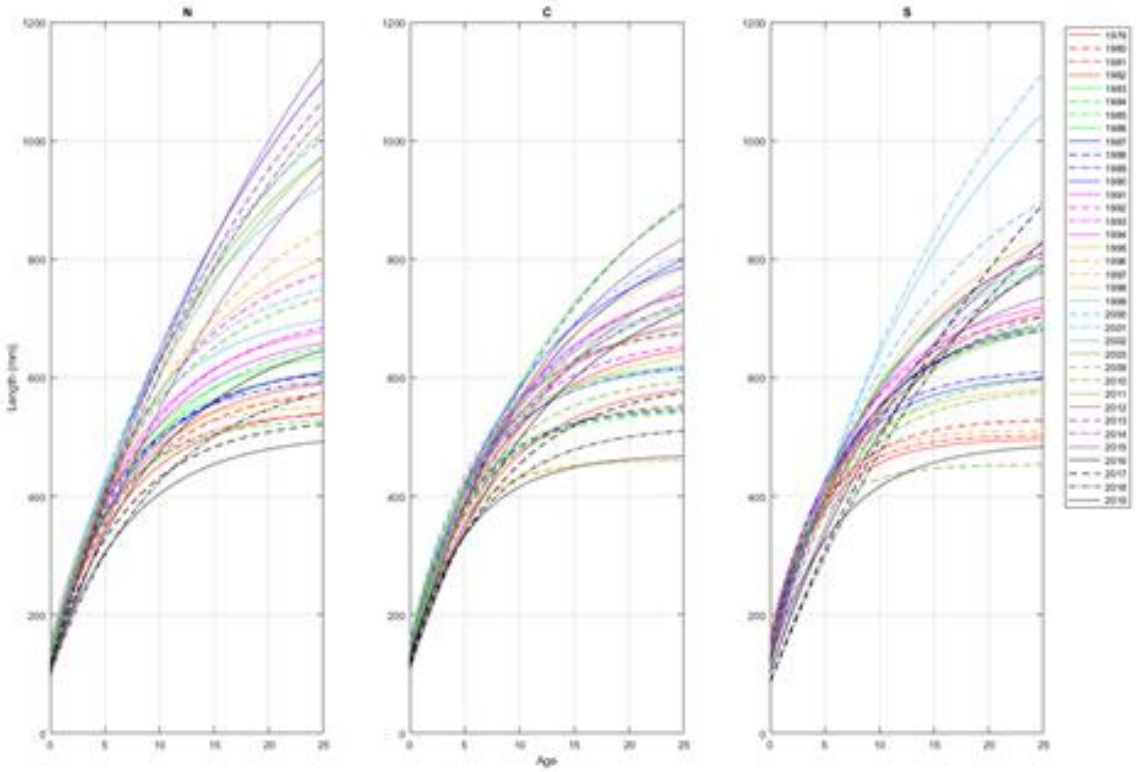

Figure A9: Variation in growth (sexes combined) for the three basins. N=north, C=channel, S=south

Interestingly all the fishes older than age 15 were from surveys after 2012. The 6’’ inch mesh in the 2009-2019 survey may account for this observation but it may also indicate more older fishes in the lake since 2012, especially in the southern basin (Figure A6)

A2.2 WALLEYE MATURITY

Maturation rates of walleye may vary with fish density or environmental conditions (see Table A1 for equations). Binary observations of fish maturity status were assumed to follow a binomial distribution and logit of probability of maturity is assumed to have a linear relationship with age or length. Functional relationships between maturity and age/length are often elusive, hindering our ability to properly incorporate population dynamics into fishery assessments, including forecasts of fishery responses to alternative management strategies. After a synoptic visualization of the percentage of fishes mature

among basin and genders, we used generalized mixed effect models to explore how maturation varies by gender as well as spatial and temporal variation in maturity.

Maturity of walleye in Lake Winnipeg was found to vary significantly spatially (among basins), temporally (over time), and by gender after generalized linear mixed models were used to model fish maturity by fitting to the binary data (mature or immature). According to AICs scores of the respective models, the mixed effect models with consideration of basin area, gender and years are the models recommended in analyzing the age-specific maturity and length-specific maturity (Table A3). There are clear differences in maturity between male and females, with males maturing earlier, as well as differences among basins; northern basin fishes mature later than in southern areas (Figure A10). Maturity changed also over time in the1970s- early 1980s. Both male and female walleye tended to mature later in the northern and southern basins in recent years (Figures A11-A13).

Table A3: comparison of the generalized linear mixed effect models with the generalized linear fixed effect maturity model

Model description	AIC
$P_m \sim f(age)$	63868
$P_m \sim f(age + a\|area + b\|area)$	50608
$P_m \sim f(age + a\|sex + b\|sex)$	51868
$P_m \sim f(age + a\|area \times sex + b\|area \times sex)$	43076
$P_m \sim f(age + a\|area \times sex \times year + b\|area$	34653
$P_m \sim f(Length)$	63440
$P_m \sim f(Length + a\|area + b\|area)$	51910
$P_m \sim f(Length + a\|sex + b\|sex)$	44597
$P_m \sim f(Length + a\|area \times sex + b\|area \times s$	39072
$Pm \sim f(Length + a\|area \times sex \times year + b\|$	35012

Lake wide, south basin fishes reached the age at which 50% are mature (A50) at a much younger age (age 3.7) than north basin fishes (age 8.06), with the fishes from channel basin being intermediate (age 4.69) (Figure A9). Lake wide, males reached A50 at a considerably younger age (age 3.58) than did females (6.58) (Figure A9).

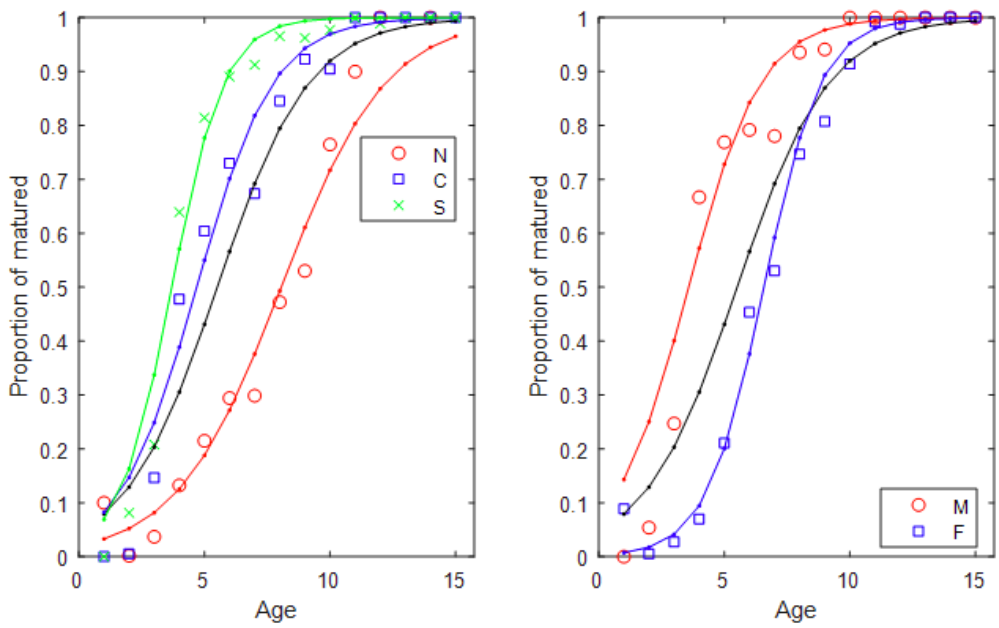

Figure A10: Observed proportion mature by age (symbols) and the estimated maturity based on the generalized linear mixed effect models (curves). (black curve is the global fitting without considering area or gender)

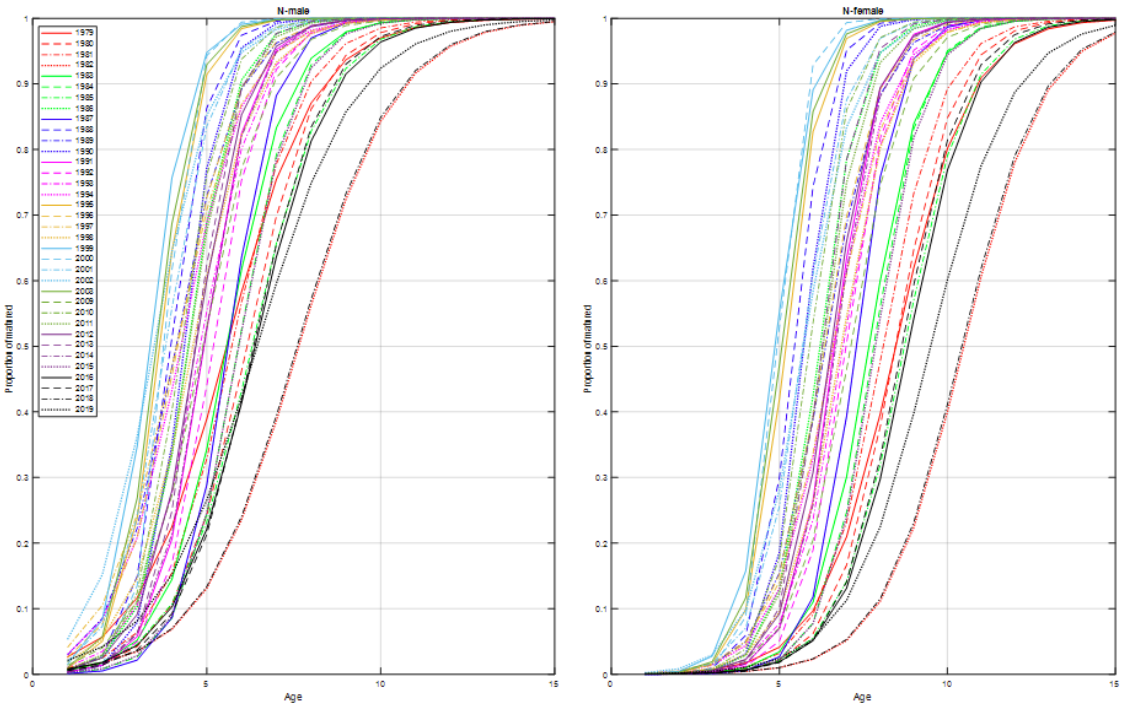

Figure A11: Estimated maturity in the north basin given year based on the generalized linear mixed effect model.

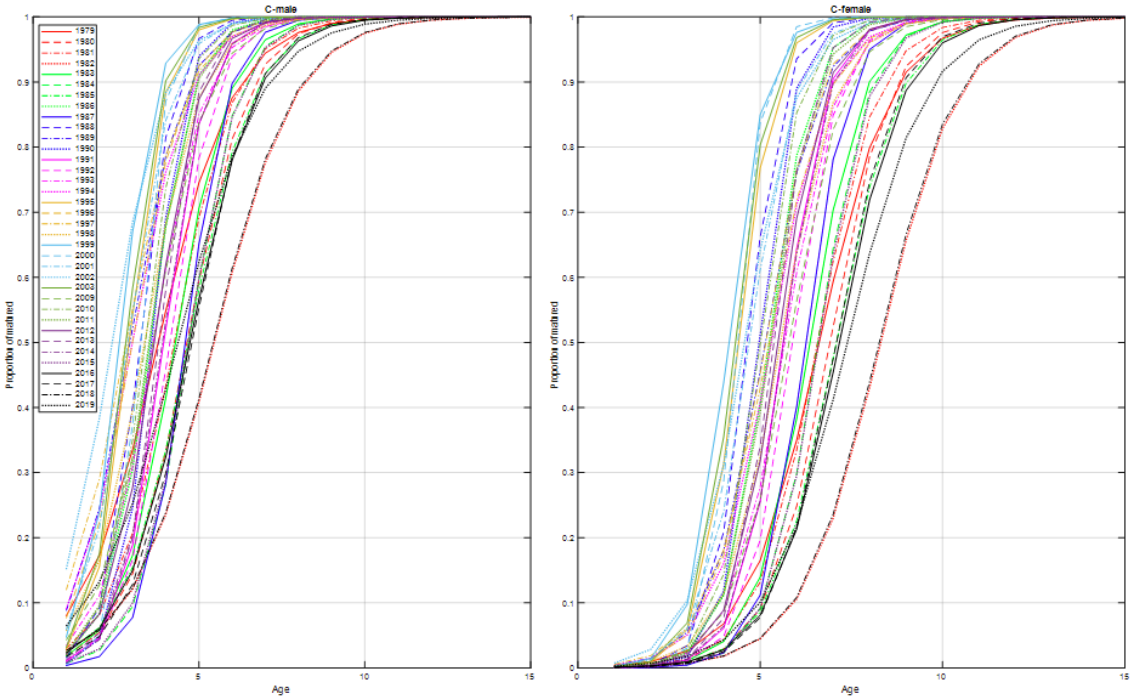

Figure A12: Estimated maturity in the Channel basin given year based on the generalized linear mixed effect model.

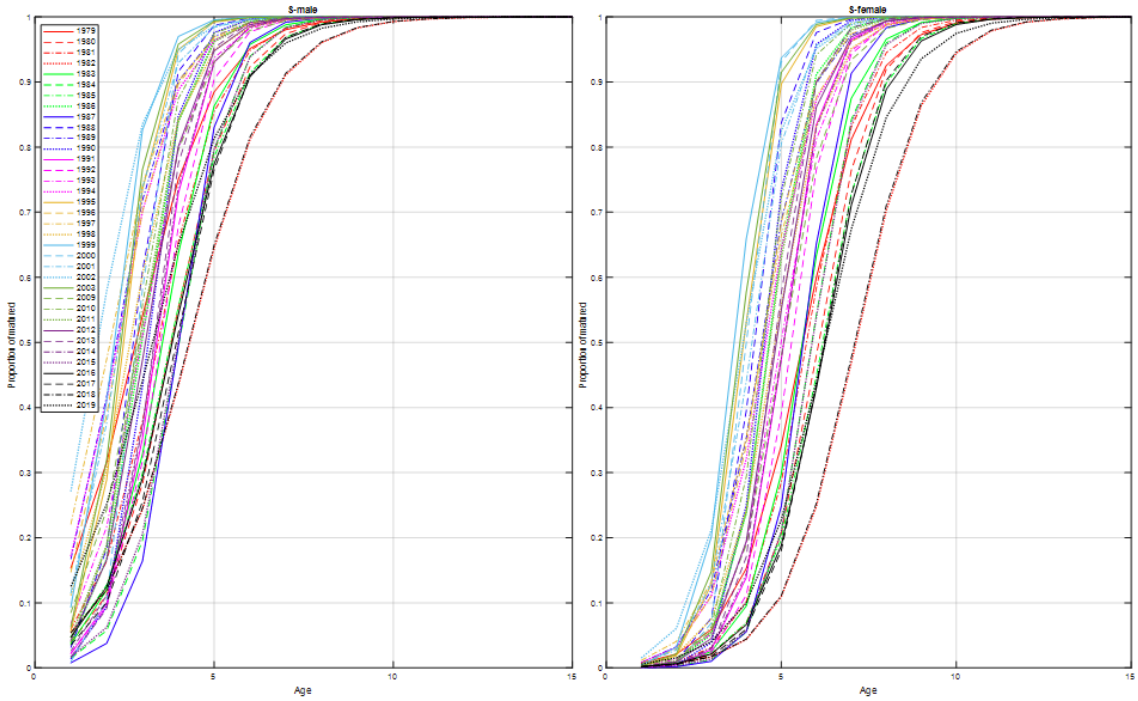

Figure A13: Estimated maturity in the south basin given year based on the generalized linear mixed effect model.

A similar analysis was completed to estimate the maturity of Lake Winnipeg walleye given length but is not presented here, but both A50 (age at which 50% of the fish reach maturity and L50 (the length at which 50% of the fish reach maturity) are illustrated here to demonstrate the change of maturity both in age and size over time and space (Figures A14-A15). Clearly males mature earlier than females, and fishes in southern basin mature earlier than in northern basin both in age and size. Fishes in recent years tend to mature later in age (especially after 2014) but smaller in size (especially in most recent three years).

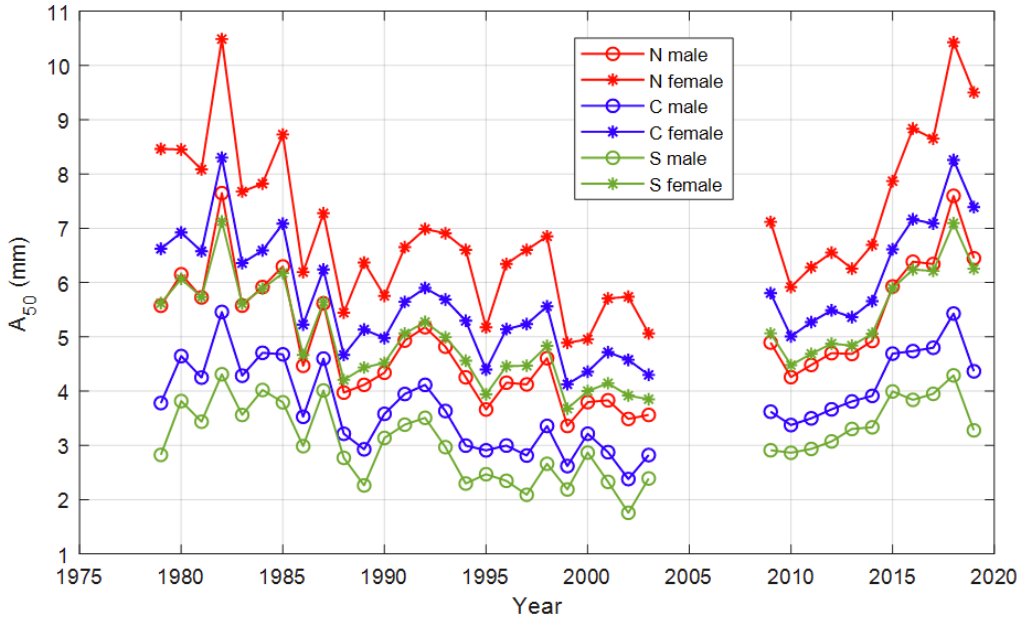

Figure A14: Changes of A_{50} over time.

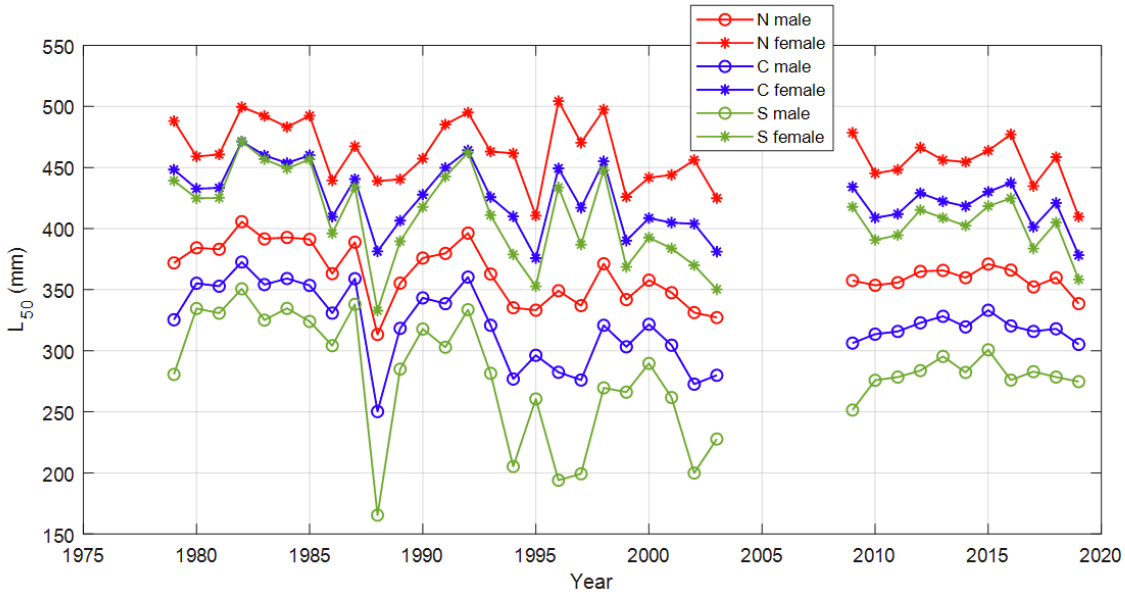

Figure A15: Changes of L_{50} over time.