Updated 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 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.

Two reports, one about the status of each of the fisheries and one about effects of minimum mesh size regulation changes, based on data time series to 2019, were finished in 2020 and 2021, respectively. This report is an update of the status of each fishery using additional data through to 2021.

Main data solicitation and synthesis

The A/OFRC project team organized phone calls and/or emails with Manitoba Natural Resources and Northern Development (NRND) staff to obtain historical and ongoing fisheries 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 1973-2021 and 2. Annual commercial gill net catch per unit effort (CUE) 1973-2021. The following fishery-independent (i.e., NRND) data sets were also made available: 1. Index survey netting data 1979-2003, 2. Index survey netting data 2009-2021 and 3. Lake Winnipeg small mesh index survey data 2012-2020. Not all of the sauger and walleye caught were identified to the species level in the small mesh NRND index survey. Given the data available, their demonstrated patterns and intercorrelations, we explored several alternative analytical approaches to understanding the population dynamics of walleye, sauger and lake whitefish in Lake Winnipeg and the status of the fishery.

Main analytical approaches

The assessments 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 lake whitefish populations were stationary, or if key population processes fundamentally changed over time, i.e., exhibited nonstationary dynamics. Nonstationary fish population dynamics are increasingly reported and can lead to unreliable fishery assessments if not accounted for in assessments. 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.

Available data about fish age and length were assessed for potential use with statistical catch-at-age models, but were unsuitable for a variety of reasons. State-space biomass dynamic models (SSBDMs) are used for fishery assessment when data about catch at age, or length, are not available. Nevertheless, SSBDMs, of intermediate complexity, are superior to models recommended to assess data-poor fisheries. As such, results of SSBDMs constitute the best available scientific information given the data.

We used a SSBDM to assess the lake wide population size (biomass) and the status of each of the walleye, sauger and lake whitefish fisheries. For this update on the status of these fisheries, we focused on the two top-performing model/data scenarios used in A/OFRC (2020) (Table ES1). As in A/OFRC (2020), both were 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 that are included in the update.

Data/model Scenarios:	Walleye	Sauger	Lake whitefish
1. Commercial catch 1973-2021; CUEs 1973-2021 (Commercial 1973-2021, NRND index netting 1979-2003, 2009-2021, NRND small mesh 2012-2020 (for walleye and sauger))	√	√	√
6. Commercial catch 1973-2021; CUEs 1973-2021 (NRND index netting 1979-2003, 2009-2021, NRND small mesh 2012-2020 (for walleye and sauger))	√	√	√
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

Except for the NRND index CUE time series updated to 2021, the trends in the remaining three index CUE time series generally matched the commercial CUE time series. With the addition of the 2020 and 2021 CUE data, correlations between the commercial CUEs and the 2009-2021 NRND index CUEs were no longer significant, while the estimated correlations among the commercial CUEs and the remaining index CUEs, particularly 1979-2003, 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 continued to confirm their utility for the purpose of quantitative fishery assessment. All four CUEs were retained.

The top-performing model (lowest DIC score) changed between 2019 and 2021, Further, the differences among the DICs of the four models was less than 3, suggesting that more than a single model is plausible. Given this uncertainty, together with the high social and economic importance of the Lake Winnipeg walleye fishery, we sought to generate the most robust stock assessment results possible for management purposes. Consequently, we prioritized walleye for the application of model averaging, specifically Bayesian model averaging (BMA), e.g., Jiao et al. (2008). Such an approach sidesteps the model selection uncertainty problem, such as was the case here, where the "best-selected" model changed between assessments.

We suggest that B_{msy} is a useful *targe*t biomass reference point for this fishery, i.e., a desirable state to be sought via management, if the goal is maximum sustainable yield. We further suggest that $1/2B_{msy}$ be used as a *threshold biomass* reference point[1]. Below this reference point, there is a high probability that productivity would be so impaired that sustainability of the fishery would be at significant risk.

The harvest in 2021 increased 69% and 29% from 2020 and 2019, respectively, which caused an increase in the fishing mortality rate (about 0.25/yr) such that the fishing mortality rate in 2021 was the highest in the time series since 2010. The walleye population was not as strong as in 2019, due to slightly lower biomass and greater catches than in years previous. Nevertheless, the Bayesian model averaged results indicated that the walleye fishery remained strong in 2021 (Table ES2). At 53% of the carrying capacity, there was just a 43% chance that biomass was below the *target* biomass reference point of B_{msy}; at 55%, it was about as likely as not that overfishing had occurred; and the probability that the population biomass was lower than $1/2B_{msy}$, the *threshold* biomass reference point, was just 0.08%. Based on the model averaged results under either S1 or S6, the walleye population

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[1] With the addition of 2 years of data to the analysis, the direction of change in the estimated probabilities that walleye 'overfishing' had occurred, and that walleye were 'overfished', prompted A/OFRC to delve into an extra analysis at the request of PCFM to address misapprehension about risk. These terms are common in fisheries research and management, but they tend not to be as readily understood among managers and fishers, conveying more risk to the fishery than may actually be the case. In this update, for all 3 species, we do not use the term 'overfished', but refer simply to probabilities that the stock was above or below accepted management reference points, B_{MSY} and $1/2B_{MSY}$. 'Overfishing' (as opposed to 'overfished') remains reported as earlier, with respect to fishing mortality, F. For walleye, we initially used the more conservative threshold for 'overfished' (B_{MSY}). Walleye had a very low probability of being 'overfished' in 2019 (0.06), and there remains less than a 50% chance that the walleye population was 'overfished' in 2021, according to that *target* reference point. Here we report also a more liberal *threshold* reference point, e.g., $1/2B_{MSY}$. A second analysis for walleye based on this threshold reference point indicated a very low probability (0.0008) that walleye were overfished in 2021, consistent with evidence that the population is estimated to remain very close to ½ K, where it is maximally productive. Taken together, the analyses continue to indicate that the walleye fishery remains far from imminent collapse.

status remained sufficiently good in 2021 that, based on our experience, it could be expected to gain a passing stock status score under the MSC certification scheme.

Table ES2. Summary of the status of the walleye fishery in 2019 and 2021 based on the best performing data scenario and hypothesis about population productivity (r).

Year	Depletion (B/K) (higher is better)	Probability of overfishing the population $P(F>F_{msy})$ (lower is better)	Probability of the population biomass being below $1/2B_{msy}$ $P(B<0.5B_{msy})$ (lower is better)	Probability of the population biomass being below B_{msy} $P(B<B_{msy})$ (lower is better)
2019[1]	0.69	0.01		0.06
2021[2]	0.53	0.55	0.0008	0.43

[1] based on data/model combination S1H3

[2] based on BMA under S1

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, i.e., scenario S6. Nevertheless, that model/data/*r* combination indicated that there was relatively low probability (28%) that the biomass in 2021 was less than the threshold reference point $1/2B_{msy}$.

Until there are data of sufficient quantity and quality to use models more complex than SSBDMs, we recommend that model averaged model/data/*r* combinations under S1, i.e., that include all the available time series, including the commercial CUE series, be considered for walleye assessment and management purposes. As the top-performing model may change in each assessment, as will inferences about the cause of the changes, we recommend that assessments of this nature be updated annually, prior to setting regulations, that will then be based on the best available scientific evidence.

Sauger

As in A/OFRC (2020), sauger population and fishery statuses continued to be 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 inferences about sauger population dynamics.

Also as in A/OFRC (2020), the degree of change in population productivity, the carrying capacity, biomass dynamics and fishing mortality rate over time continued to be 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 2021 sauger biomass increased from 47% of the carrying capacity in 2019 (Table ES3), to 56% in 2021, when the commercial CUEs were excluded. The probability that overfishing occurred in 2021 fell to less than 1% and the probability that the 2021 population biomass was less than B_{msy} decreased to 40% when commercial CUE data were excluded (Table ES3). Bayesian model averaging has not been completed for sauger at this time.

Table ES3. Summary of the status of the sauger fishery in 2019 and 2021 based on the best model/data scenario and hypothesis about population productivity (r).

Year	Depletion (B/K) (higher is better)	Probability of overfishing the population, $P(F>F_{msy})$ (lower is better)	Probability of the population being below B_{msy}, $P(B<B_{msy})$ (lower is better)
2019[1]	0.47	0.19	0.54
2021[2]	0.56	<0.01	0.40

[1] data/model combination S6H1

[2] data/model combination S6H2

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 appeared to be for walleye (and, to a lesser extent, lake whitefish; see below). 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, increased minimum mesh size allowed in the south basin since 2020, and/or ecosystem-related changes that changed the catchability of sauger in the commercial gear (E. Sveinson and R. Smith, pers. comm.).

The quantity and quality of the available commercial sauger data were such that model/data selection uncertainty was high enough that model/data combinations that relied on the commercial catch rates were not sufficiently robust and reliable for credible assessments of neither population nor fishery status. Consequently, until there is an opportunity to implement model averaging for sauger and/or better data are available to support better assessment models, we suggest that the top performing data scenario (S6), which excluded commercial CUEs, be considered for assessment and management of the sauger fishery.

Lake whitefish

Visual inspection revealed some discrepancies between the trend in commercial lake whitefish CUE time series and trends in the CUE time series calculated from the fishery-independent gillnet index survey data. Most noteworthy was a large increase in the lake whitefish NRND index CUE in 2020, when the CUE was approximately five times that of the previous high year in the 2009-2021 index survey. The CUE remained higher than usual in 2021, at approximately 3.5 times that of the previous high year in the survey. Statistically, the estimated correlations among the commercial CUE time series and CUEs from the NRND index surveys, particularly 1979-2003 and 2009-2021, 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 biomass was well below B_{msy} regularly between the late 1980s and around 2010. The probability of both overfishing and the lake whitefish population biomass being below B_{msy} dropped to very low levels after 2010, then increased slightly in recent years before dropping to less than 1% in 2021. Bayesian model averaging has not been completed for lake whitefish at this time.

The lake whitefish population and fishery statuses in 2021 were strong. The whitefish population biomass was well above that sustainable at MSY at 77% of carrying capacity. Both the probability that overfishing had happened, and that the lake whitefish population biomass was below B_{msy} were ~1% (Table ES4). Excluding the commercial CUE data, these probabilities were 1% and 8%, respectively. These indicators suggest that the status of the 2021 lake whitefish population was excellent to the extent that, in our experience, it could be expected to gain a passing stock status score under the MSC certification scheme.

Table ES4. Summary of the status of the lake whitefish fishery in 2019 and 2021 based on the best model/data scenario and hypothesis about population productivity (r).

Year	Depletion (B/K) (higher is better)	Probability of overfishing the population, $P(F>F_{msy})$ (lower is better)	Probability of the population biomass being below B_{msy}, $P(B<B_{msy})$ (lower is better)
2019[1]	0.67	0.13	0.10
2021[1]	0.77	0.01	0.01

[1] based on data/model combination S1H1

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 is an opportunity to complete model averaging for lake whitefish, and/or better data are available to support more complex assessment models, we suggest that the top performing combination (S1H1), 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 for walleye and lake whitefish rely heavily on the commercial (fishery-dependent) CUEs. 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.

- There is a need for a multispecies fisheries improvement project (FIP) that should include the eventual development of species-specific management plans that include threshold and limit reference points to guide management of removals. The FIP should involve all parties and be lake wide in scope.

1. BACKGROUND

The A/OFRC[1] completed an independent assessment of the status of the Lake Winnipeg fisheries for walleye, sauger and lake whitefish in August of 2020 (A/OFRC 2020). That assessment included fishery-dependent and -independent data up to and including 2019 and showed that the walleye and lake whitefish populations were strong in 2019 but, depending on the data source used, the sauger population biomass was well below the biomass at MSY, likely due to poor recruitment over a sustained period. In view of the effects of the pandemic on the fishery and the potential changes that can be expected to occur in such dynamic fisheries, PCFM entered another third-party, grant in aid of research agreement with the A/OFRC to update the status of these three fisheries up to and including 2021, i.e., the most recent year for which data are available.

Project Objectives

The primary objective of this analysis was to use the same state of the art methods as were used in A/OFRC (2020) to update previous quantitative population and fishery status assessments for Lake Winnipeg walleye, sauger and lake whitefish to 2021.

This report describes the analysis, results and conclusions of A/OFRC's use of fishery assessment tools and techniques for updating the population dynamics and fishery statuses for Lake Winnipeg walleye, sauger and lake whitefish.

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[1] 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 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).

Study Approach

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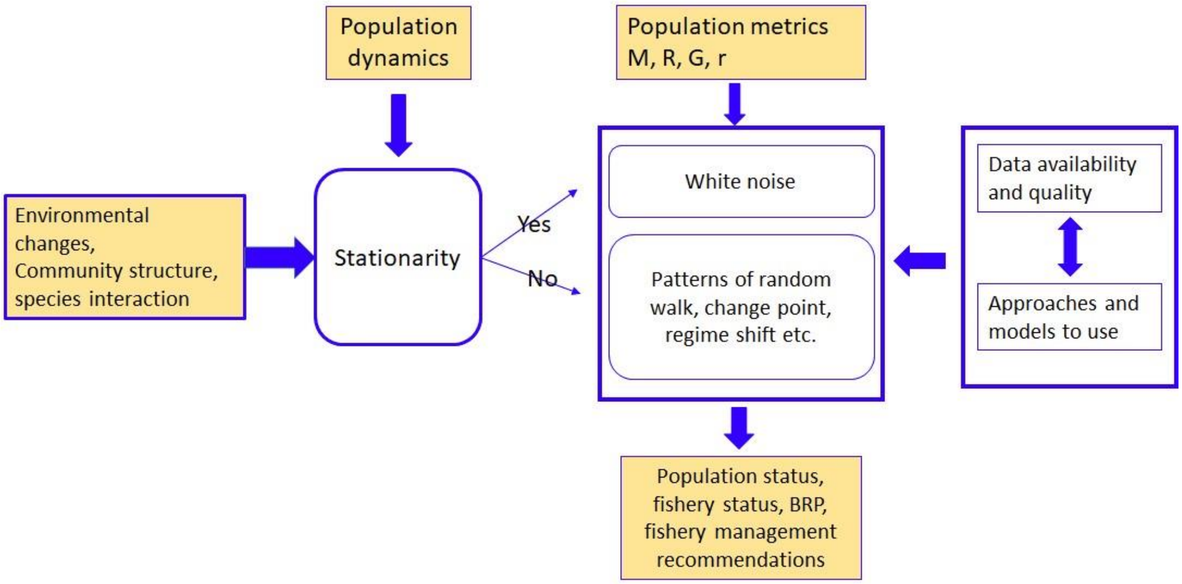

Figure 1. General approach to fishery assessment for the Lake Winnipeg walleye, sauger and lake whitefish fisheries

2. DATA AVAILABILITY AND SYNTHESIS

A/OFRC (2020) provides details regarding data availability and synthesis. Raw commercial catch and effort (# of deliveries) data for walleye, sauger and lake whitefish from 2020 and 2021 were provided by NRND/FFMC and compiled by A/OFRC.

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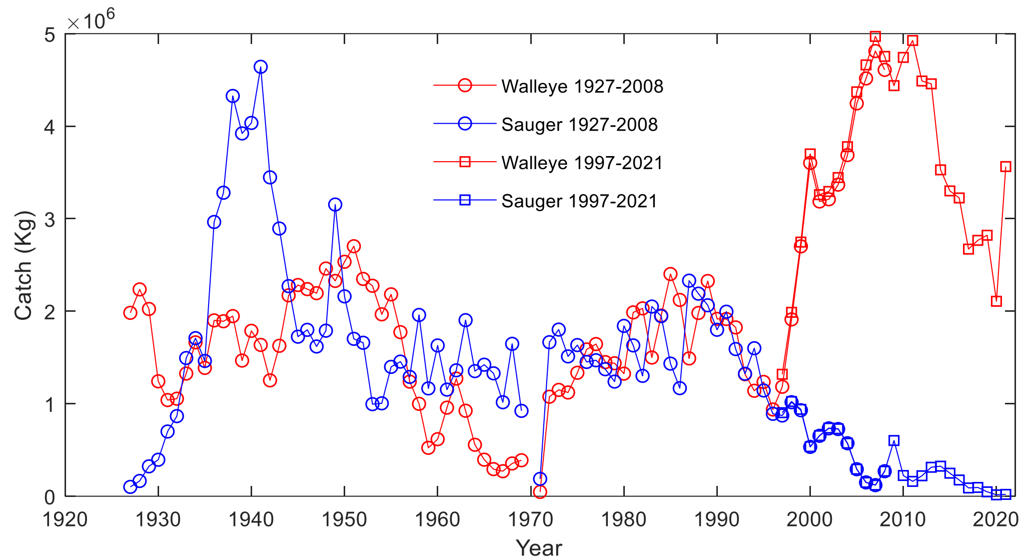

Figure 2a: Walleye and sauger catches from the Lake Winnipeg commercial fishery excluding releases and discards.

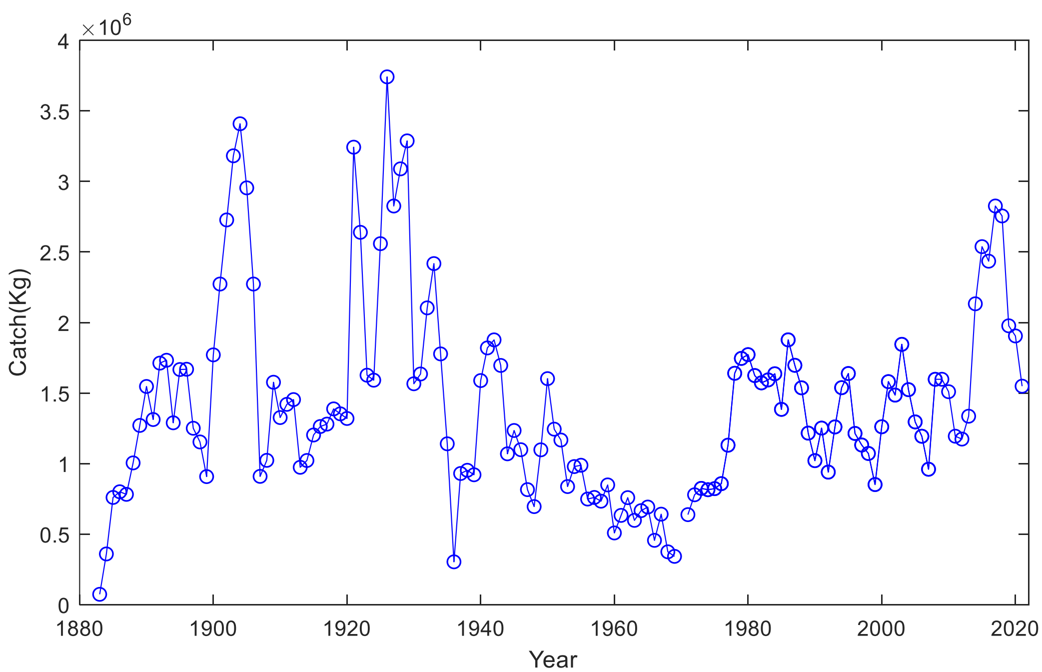

Figure2b: Whitefish catches from the Lake Winnipeg commercial fishery.

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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 included 2020 and 2021 data, for each of walleye, sauger and lake whitefish, for the 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 NRND) and three fishery-independent (hereinafter index CUE) surveys (Figures 6a, 6b, 6c) that were used in A/OFRC (2020). Several novel sample sites were added to the index survey protocol in 2019 because of the availability of a second survey crew (Kevin Casper, NRND, 75 - 7th Avenue, Gimli MB R0C 1B0); therefore, to minimize bias, we adjusted the 2019 basin-specific and lake-wide index CUEs such that the 2019 CUEs for all three species were standardized and thus directly comparable with the CUEs from the 2009 to 2018 surveys. Sites were also added to the index survey in some areas in 2020 and 2021 (Kevin Casper, NRND, 75 - 7th Avenue, Gimli MB R0C 1B0, email), so the raw 2020 and 2021 NRND CUEs were also standardized to be directly comparable with the CUEs from the 2009 to 2019 surveys.

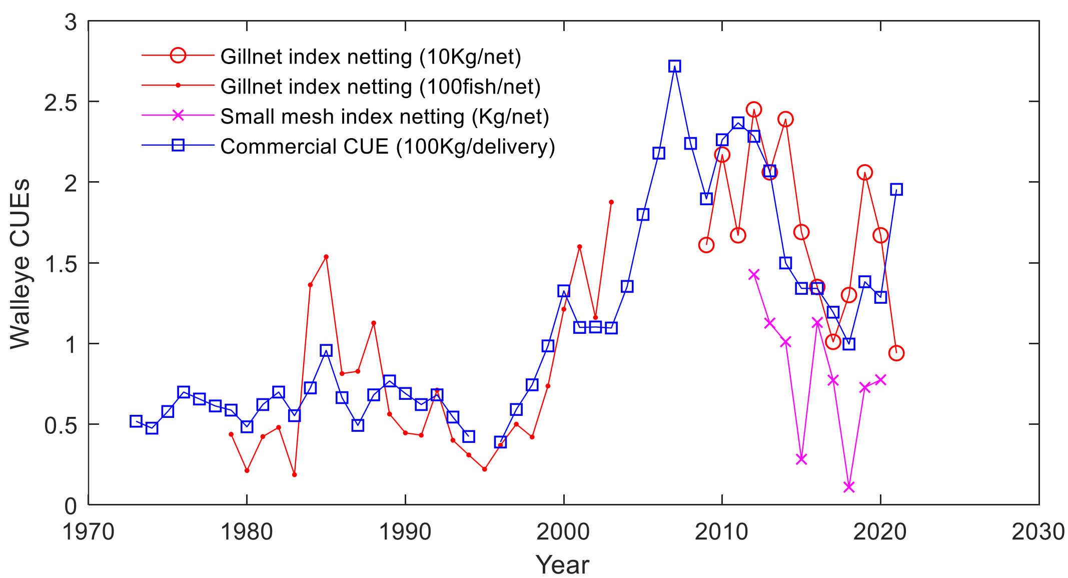


Figure 6a: Lake-wide CUEs for walleye in Lake Winnipeg. Values preceding the units in legend indicate scaling factors for each series.

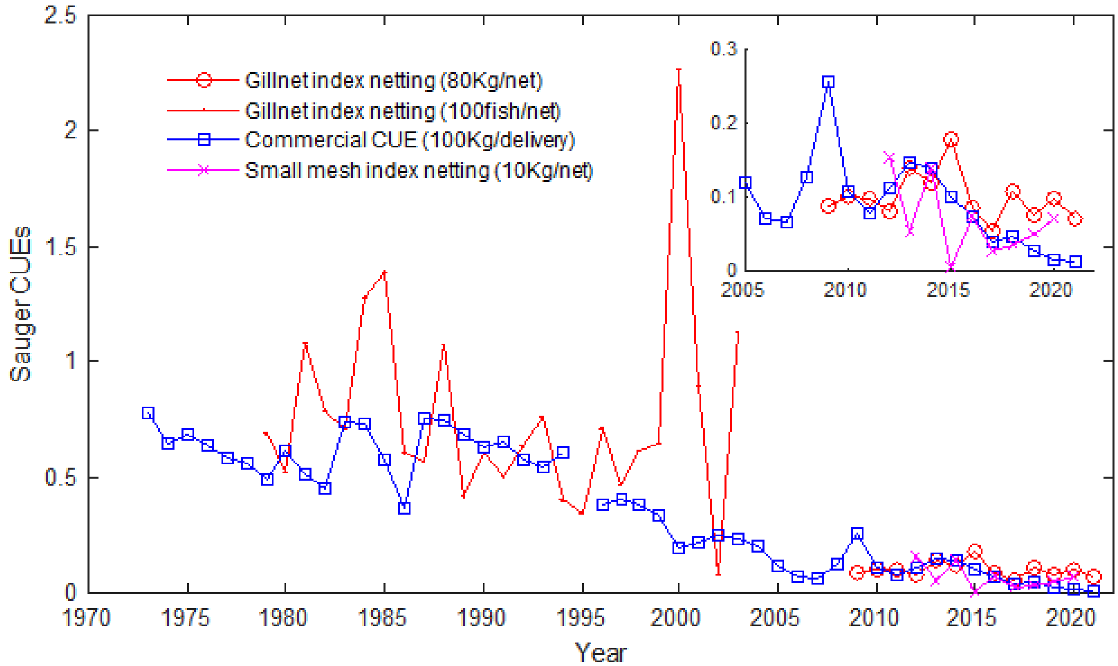


Figure 6b: Lake-wide CUEs for sauger in Lake Winnipeg. Values preceding the units in legend indicate scaling factors for each series.

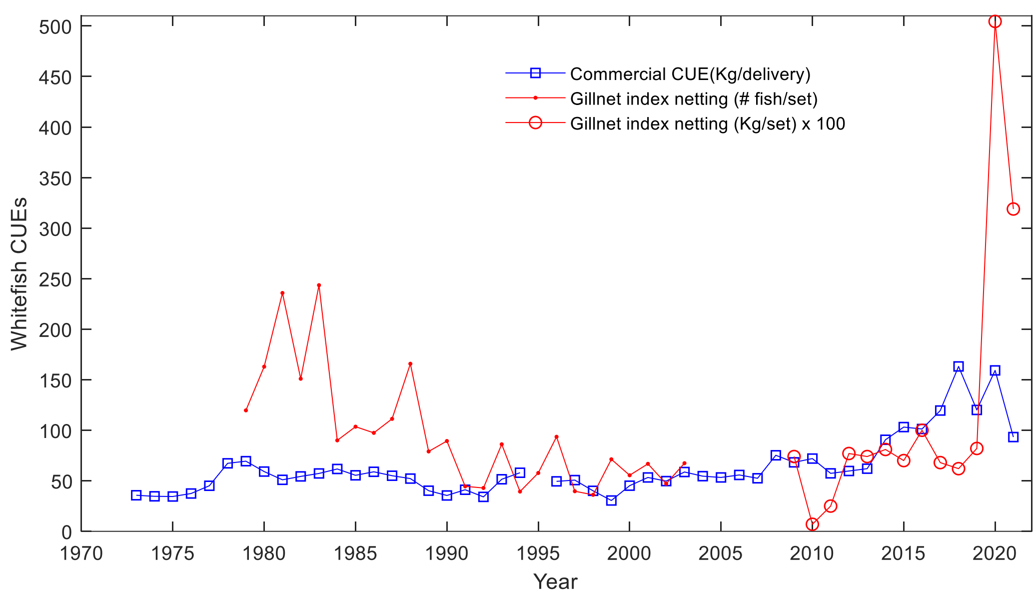


Figure 6c: Lake-wide CUEs for lake whitefish in Lake Winnipeg. Values preceding the units indicate scaling factors for each series.

3. ANALYTICAL METHODS

3.1 CATCH RATES

Methods for estimating catch rates did not vary from A/OFRC (2020).

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; 2012). On Lake Winnipeg, such information was not available from commercial catches. As described in A/OFRC (2020) we employed a SSBDM (see Table A1 for equations) in a Bayesian analytical framework to assess the 2020 and 2021 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 2013-2020).

For this update, we omitted the scenarios with catches adjusted for misreporting because outcomes were insensitive to the assumptions of those scenarios. Given the validated assumption that there is a single stock in Lake Winnipeg we also omitted the scenarios with basin-specific dynamics for walleye leaving two of the six combinations of SSBDM with different types of data (hereinafter model/data scenarios) that were analyzed for walleye, sauger and lake whitefish in A/OFRC (2020) (Table 1). Scenario 1 (S1) used all the available commercial catch data and all available CUE data for each of walleye, sauger and lake whitefish and 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.

As in A/OFRC (2020), the two model/data scenarios 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 using a Bayesian framework (see A/OFRC 2020, Appendix 1). S6 had different *r* time blocks that were estimated based on the DIC.

Table 1: The two top-performing SSBDM data scenarios and hypotheses about how productivity (*r*) might have changed on Lake Winnipeg from A/OFRC (2020).

Data/model Scenarios:	Walleye	Sauger	Lake whitefish
1. Commercial catch 1973-2021; CUEs 1973-2021 (Commercial 1973-2018, NRND index netting 1979-2003, 2009-2021, NRND small mesh 2012-2020)	√	√	√
6. Commercial catch 1973-2021; CUE 1973-2021 (NRND index netting 1979-2003, 2009-2021, NRND small mesh 2012-2020)	√	√	√
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)			

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); with the notable exception of 2021 (Table 6a), trends in the three fishery-independent CUEs essentially matched the trend in the commercial CUE time series. In 2021, the trajectories of the commercial CUE and the NRND index CUE departed with a large increase in the commercial CUE and a large decrease in the NRND index CUE. Statistically, the estimated correlations between the commercial CUE time series and CUEs from the 2009-2021

NRND index surveys were lower, 0.41 in 2021 vs 0.69 in 2019, and were no longer highly significant with the addition of the 2020 and 2021 data to the series (Table 2).

Table 2: Correlations among four CUE time series available for walleye and used in the assessment including 2020 and 2021. P values of the correlations are in parentheses.

	NRND index 1979-2003	NRND index 2009-2021	NRND small mesh index 2012-2020
Commercial CUE	0.75 (<0.0001)	0.41 (0.16)	0.77 (0.01)
NRND index 2009-2021			0.52 (0.15)

Lack of significant correlations (alpha=0.05) between the NRND small mesh index CUEs and the NRND CUE was mainly due to the relatively short time series (9 years) of the small mesh survey and the different size selectivity. However, the reasons for the large discrepancy in CUE trends from the 2021 commercial fishery and the NRND index surveys are unclear (Fig 6a). The correlation changed from 0.62 to 0.41, and the p-value changed from 0.05 to 0.16 after the data were updated from 2019 to 2021. Notwithstanding the limited number of years of the three discontinuous index CUEs, and potential concerns about the commercial CUEs (LWTF 2011), the consistent trends across these multiple sources continue demonstrate 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 parentheses.

	NRND index 1979-2003	NRND index 2009-2021	NRND small mesh index 2012-2020

Commercial	-0.19 (0.36)	0.31 (0.31)	0.43 (0.25)
NRND index 2009-2021			-0.25 (0.52)

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 NRND index surveys.

4.1.3 LAKE WHITEFISH

Visually, there were discrepancies among trends in whitefish commercial and index CUEs. (Figure 6c). Most noteworthy was a large increase in the lake whitefish NRND index CUE in 2020, when the CUE was approximately five times that of the previous high year in the 2009-2021 index survey. The CUE remained higher than usual in 2021, at approximately 3.5 times that of the previous high year in the survey. 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 2009-2021 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.

	NRND index 1979-2003	NRND index 2009-2021
Commercial	0.37 (0.07)	0.48 (0.09)

4.2 POPULATION AND FISHERY STATUS

4.2.1 WALLEYE

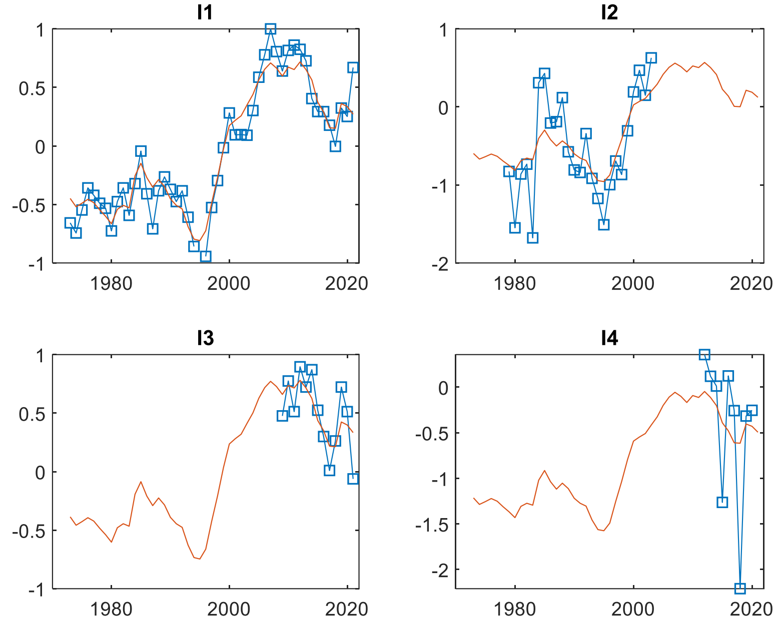
The top performing SSBDM model/data combination was identified by the lowest deviance information criterion (DIC), or DIC score. Unlike in A/OFRC (2020), when hypothesis H3 performed best under S1, with the additional data from 2020 and 2021, productivity hypothesis H4, which assumed *r* to be constant, performed best. However, there was slightly weaker support for all models evaluated. Under such circumstances, it is generally agreed as good practice to employ a model averaging methodology such as Bayesian model averaging (BMA), (e.g., Jiao et al. 2008, 2009) where a suite of models competes to fit the data, and are weighted based on their performance, i.e., their DIC scores. Model averaging mitigates the problem of model selection uncertainty. We used Bayesian model averaging to generate walleye stock status estimates that used the information from all the models we evaluated, thus providing the most robust picture possible of the walleye stock status in 2021.

Table 5: DIC estimation from the walleye model/data scenarios and four *r* hypotheses.

	S1	S6
r followed random walk process (H1)	55.09	35.68
Three *r* periods (H2)	53.33	27.10
Two *r* periods (H3)	54.45	27.57
constant *r* (H4)	52.69	31.30

Except for the commercial (I1) and NRND index (I3) CUEs in 2021, the fits of the best (i.e., lowest DIC) data/hypothesis combinations of S1/H4 and S6/H2 to the four CUE time series were reasonably good, capturing the major trends in all four cases (Figure 8). The large differences in the 2021 commercial CUE and the NRND index are reflected in the differences between observations and model fits. The other models also fit the data reasonably well, although the figures are not included here.

(8a)



(8b)

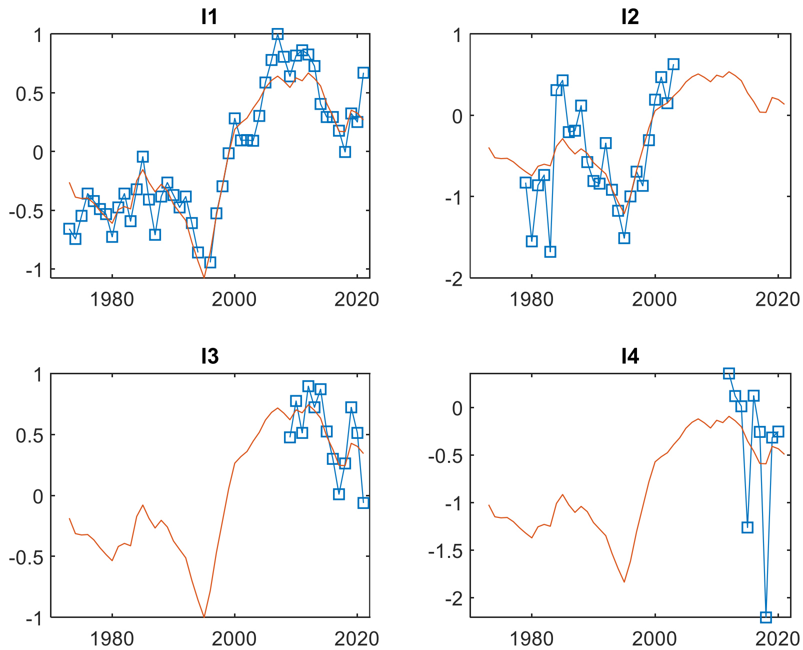


Figure 8: Model estimated walleye CUEs from S1/H4 (8a, brown lines) and S6/H2 (8b) in comparison with the observed CUEs (blue line with square markers). I1 = commercial CUE, I2=NRND 1979-2003, I3=NRND 2009-2021, I4=NRND small mesh survey

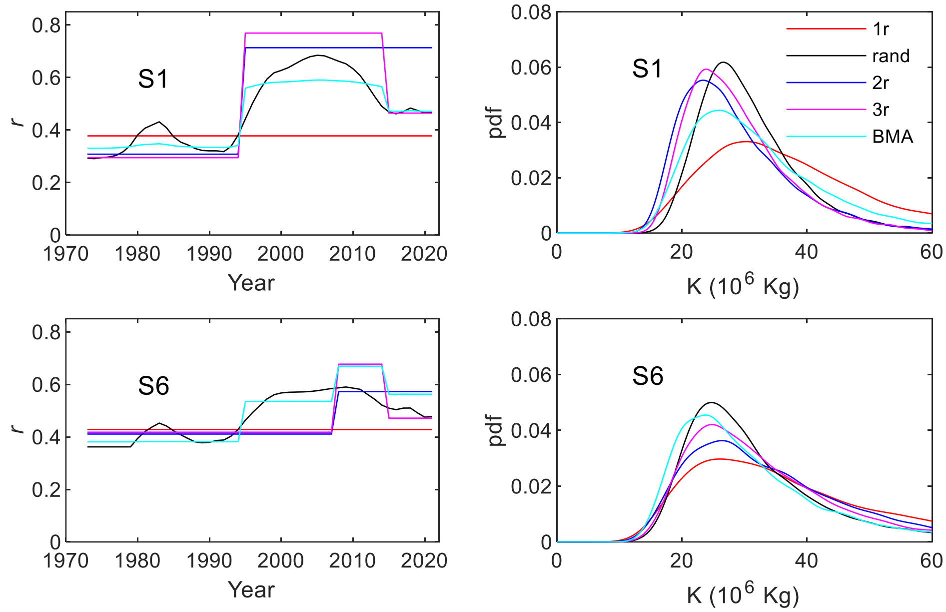


Figure 9: Walleye population productivity (*r*) and carry capacity (K) as estimated from S1and S6 and the four hypotheses regarding r. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) and BMA=Bayesian model averaged.

Under S1, 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). While the fishing mortality rate in 2019 was the lowest in the time series since the early 1970s, it was much higher in 2021, at about F=0.25 (Figure 10). Under S6, the fishing mortality rate in 2021 was approximately twice what it was in 2019, at about F=0.5 (Figure 10).

The BMA result indicated that the walleye population status was strong in 2021 with the population biomass being stable at just above B_{msy}, i.e., at ~53% of the carrying capacity (K) (Table 6).

Table 6: Posterior mean estimates of walleye population depletion (B_{2021}/K) in 2021 among the two model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.53	0.31

Three *r* periods (H2)	0.56	0.29
Two *r* periods (H3)	0.60	0.34
constant *r* (H4)	0.49	0.28
Model averaged	0.53	0.31

Overfishing can be defined as a level or rate of fishing mortality that jeopardizes the long-term capacity of a stock or stock complex to produce MSY on a continuing basis (NEFMC 2021). The probability 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 MSY (F_{msy}), i.e., $P(F>F_{msy})$ (Figure 11). Overfishing is a process that may or may not lead to a stock becoming overfished. Periodic overfishing, e.g., where $P(F>F_{msy})$ is high, of an abundant stock, i.e., one that is above B_{msy}, will not necessarily lead to a stock becoming overfished. For instance, F in a subsequent year could be adjusted such that the projected biomass B stays above some pre-determined population biomass threshold.

The model averaged probability of overfishing the walleye in 2021 increased to 55% (Table 7, Figure 11). This increase is attributable to a slight decline in the fishable biomass in 2021 and a large increase in the catch, and thus F.

Table 7: Posterior probability of overfishing the walleye population in 2021, $P(F_{2021}>F_{msy})$, among the two model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.53	0.86
Three *r* periods (H2)	0.57	0.88
Two *r* periods (H3)	0.08	0.71
constant *r* (H4)	0.75	0.95
Model averaged	0.55	0.82

A/OFRC (2020) used $P(B<B_{msy})$ as the *limit* biomass reference point from which to draw inferences about stock exploitation status; however, few management agencies use $P(B<B_{msy})$ as the *limit* biomass reference point, perhaps because it is quite conservative, especially for species with life histories better able to cope with higher harvests. B_{msy} is more commonly used as a *target* biomass reference point, e.g., Northeast Fisheries Management Council (NEFMC) (NEFMC 2021). The target biomass reference point is

analogous with DFO's Sustainable Fisheries Framework upper stock reference point which is a target reference point that is "determined by productivity objectives for the stock, broader biological considerations, and social and economic objectives for the fishery" (DFO 2009).

The Mid-Atlantic Fisheries Management Council (MAFMC) uses a *threshold* biomass reference point: if B/B_{msy} is less than 0.5, the stock is declared overfished, and a rebuilding plan is implemented (MAFMC 2020). The overfishing definition control rules of the Northeast Fisheries Management Council (NEFMC) calls for action when biomass is below a threshold biomass reference point of 1⁄4 or 1⁄2 B_{msy}, depending on the species (NEFMC 2021). The NEFMC also defines overfished as when stock biomass is below a minimum biomass threshold, such that the probability of successful spawning production is low. The threshold biomass reference point of the NEFMC is analogous with DFO's Sustainable Fisheries Framework limit reference point, which marks the boundary between the cautious and critical zones. When there is a high probability that a fish stock level falls below this point, there is a high probability that its productivity will be so impaired that serious harm will occur (DFO 2009).

Thus, the probability that the Lake Winnipeg walleye population biomass (B) was below $1/2B_{msy}$ in any given year, i.e., ($B<1/2B_{msy}$) is a useful indicator of the likelihood that the population was overexploited, and if any management action may be required to maintain sustainability.

There was a high probability that the walleye population biomass was < B_{msy} on a regular basis before the productivity increased in the late 1990s. The probability that the walleye population biomass was < B_{msy} was low after the increase in population productivity during the 2000s, but increased again between 2012 and 2015. Because of the high biomass, the increased probability of overfishing in 2021 lead to a very low probability of the biomass falling below the $1/2B_{msy}$ and moderate probability of below B_{msy}. The model averaged probability that the walleye population biomass was below $1/2B_{msy}$ in 2021 was 0.08% (Table 8a); the model averaged probability that the walleye population biomass was below B_{msy} in 2021 was 43% (Table 8b, Figure 11).

Table 8a: Posterior probability of the walleye population biomass falling below $1/2B_{msy}$ in 2021, $P(B_{2021}<1/2B_{msy})$ among the two model/data scenarios, the four hypotheses regarding *r*, and model averaged.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.0007	0.35
Three *r* periods (H2)	0.0002	0.40
Two *r* periods (H3)	0.0001	0.10
constant *r* (H4)	0.0018	0.44
Model averaged	0.0008	0.28

Table 8b: Posterior probability of the walleye population biomass falling below B_{msy} in 2021, $P(B_{2021}<B_{msy})$ among the two model/data scenarios, the four hypotheses regarding *r*, and model averaged.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.41	0.92
Three *r* periods (H2)	0.34	0.94
Two *r* periods (H3)	0.24	0.87
constant *r* (H4)	0.59	0.96
Model averaged	0.43	0.91

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 because the estimated biomass was much lower under S6 (Figure 10). Overall, S6 was more pessimistic about the walleye status than was S1 (Tables 6 – 8a,b). The estimated posterior $P(F>F_{msy})$ and $P(B<B_{msy})$ under S6 were both higher under all four hypotheses on *r* in 2021 (Figure 11).

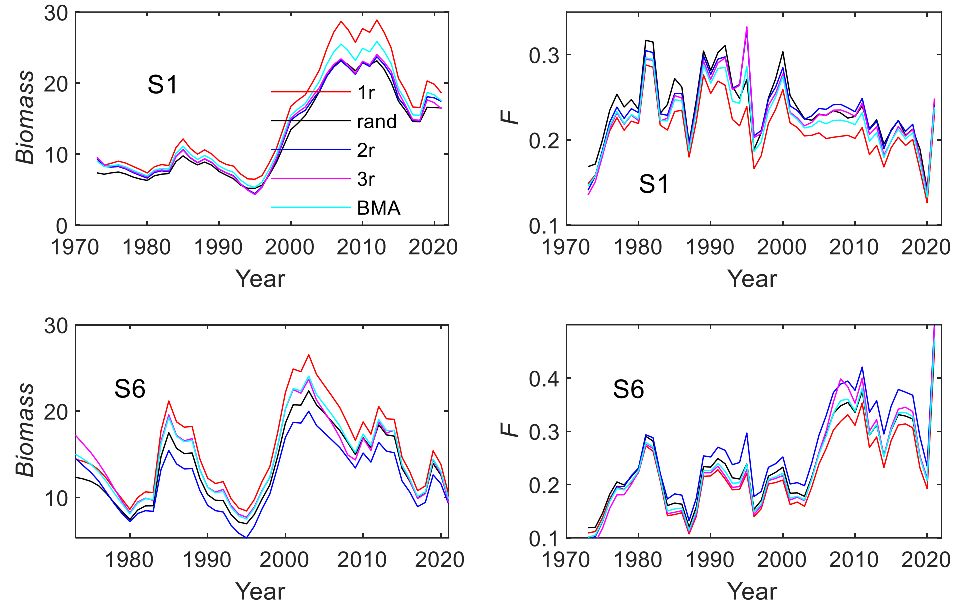


Figure 10: Walleye population size (B) and fishing mortality rate (F) as estimated from S1 and S6 and the four hypotheses regarding r. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) and BMA=Bayesian model averaged (see Table 1).

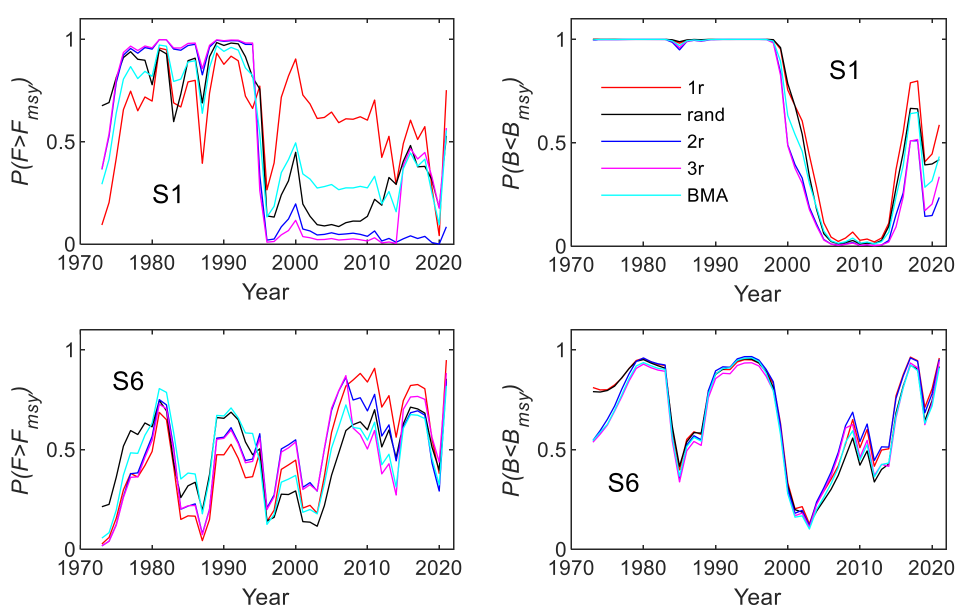


Figure 11: The probability of overfishing, P(F>F_{msy}), and biomass being below B_{msy}, P(B<B_{msy}), for walleye as estimated from S1 and S6 and the four hypotheses regarding r.

1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) and BMA=Bayesian model averaged (see Table 1).

For a given data scenario, e.g., S1 or S6, the constant r (H1) and two-step r (H2) hypotheses generate similar results in terms of the dynamics of the catch at F_{msy}, MSY, and surplus production relative to the reported catch (Figure 12). Under S1, the reported catch in 2021 was slightly below the catch at F_{msy} for both H4 and H2 but under S6, the catch in 2021 exceeded the catch at F_{msy}.

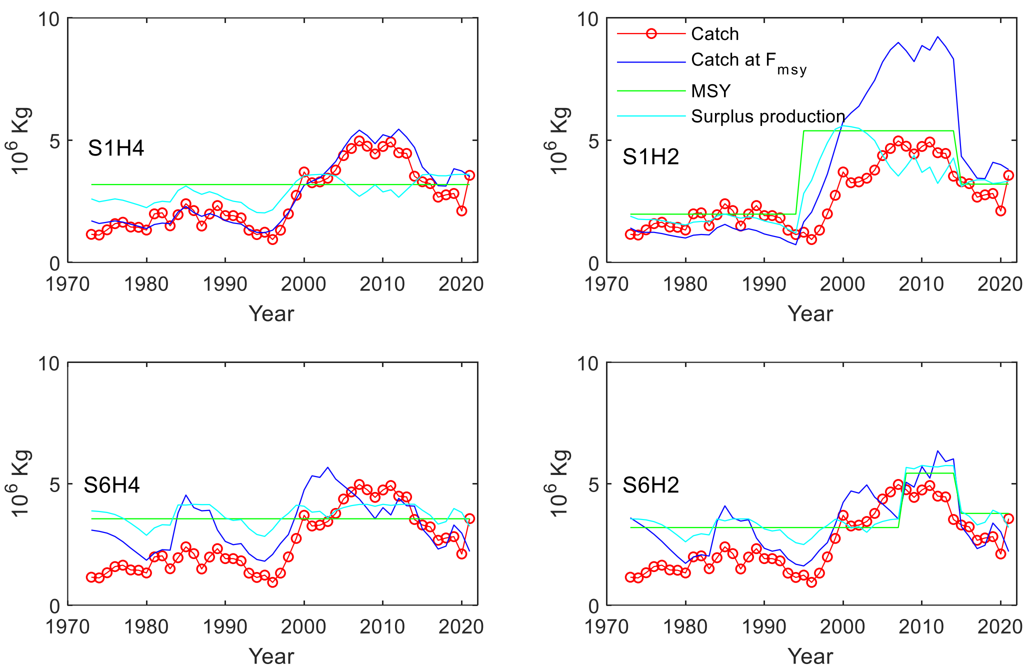


Figure 12: Comparison of walleye catch, MSY, surplus production and catch at F_{msy} based on the S1 model/data scenario and the constant and three-period *r* hypotheses (upper) and the S6 model/data scenario and the constant and three-period *r* hypotheses (lower).

4.2.2 SAUGER

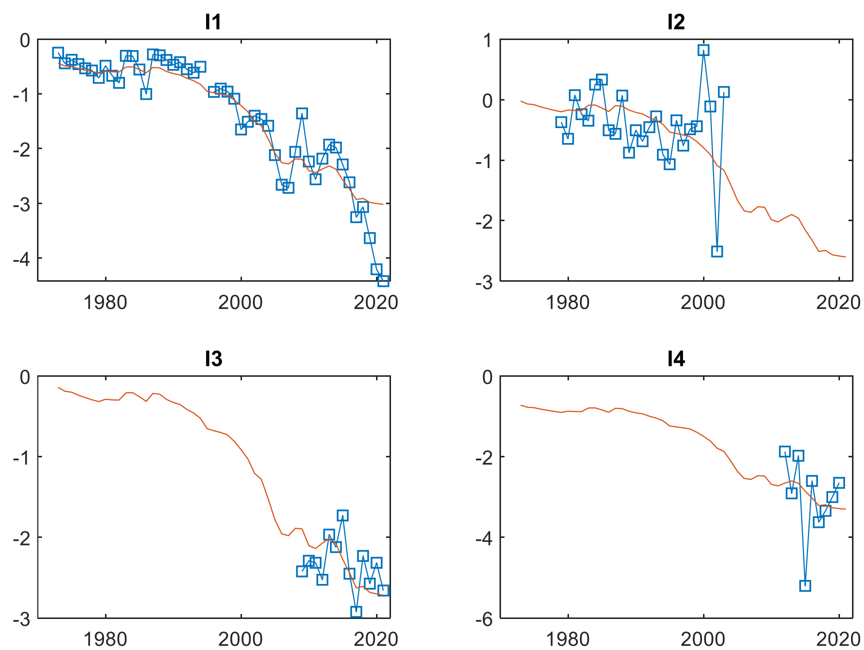
Bayesian model averaging has not been completed for sauger at this time. Hypothesis H2, when the sauger population productivity parameter *r* was blocked into three time periods, performed best, as indicated by its lowest DIC scores under both S1 and S6 The DIC score for the two-period *r* hypothesis (H3) was very close to that of H2 under S6 but not under S1 (Table 9).

Table 9: DIC estimation from the two data scenarios and four *r* hypotheses for sauger.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	-109.83	-66.02
Three *r* periods (H2)	-131.73	-81.49
Two *r* periods (H3)	-120.22	-78.86
constant *r* (H4)	-110.07	-44.91

Except for 2020 and 2021, when large negative residuals occurred with the commercial CUEs, the fits of the S1/H2 and S6/H2 data/hypotheses combinations to the four observed CUE time series were reasonably good, capturing the major trends of all four series (Figures 13a and b, respectively). The other models also fit the data reasonably well, although the figures are not included here.

(13a)



(13b)

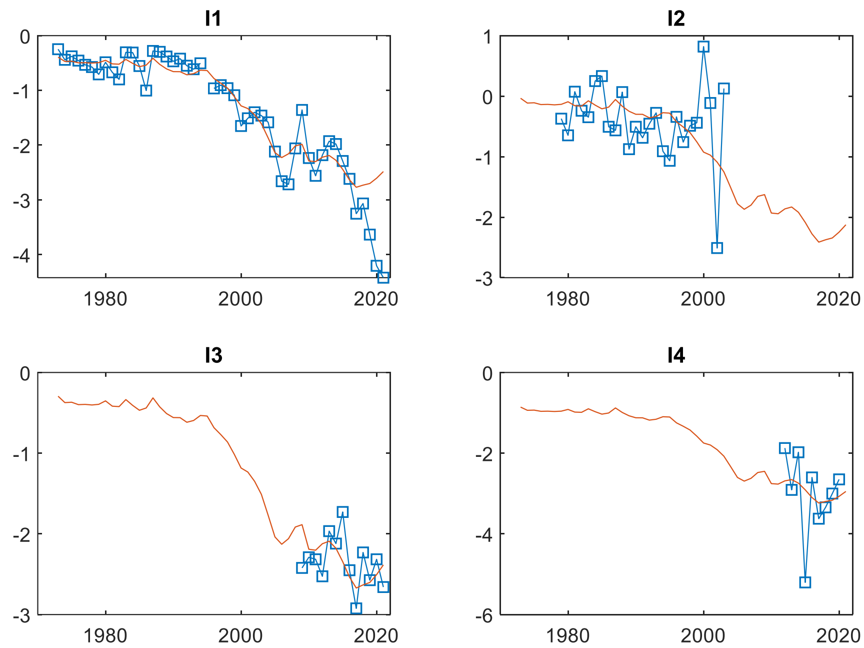


Figure 13: Model estimated sauger CUEs from S1/H2 (a, brown lines) and S6/H2 (b) in comparison with the observed CUEs (blue line with square markers). I1=commercial CUE (kg/delivery), I2= NRND index 1979-2003, I3=NRND index 2009-2021, I4=NRND Lake Winnipeg Small mesh index.

The analysis continues to indicate that sauger productivity was nonstationary; it was greater before the mid-1990s and lower after that (Figure 14). As in A/OFRC (2020), 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 CUE time series was included (S1 vs S6 in Figures 14-15); as was the case in 2019, sauger biomass in 2021 was much greater, but more sensitive to the various hypotheses about productivity, and fishing mortality lower, under S6 than under S1 (Figure 15).

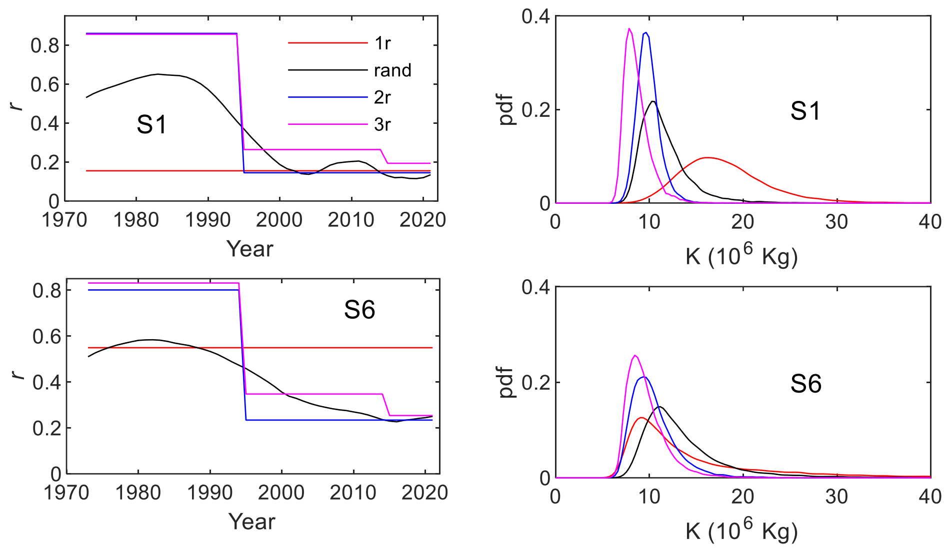


Figure 14: Estimated sauger population growth rate (*r*) and carry capacity (K) under model/data scenarios S1and S6. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1)

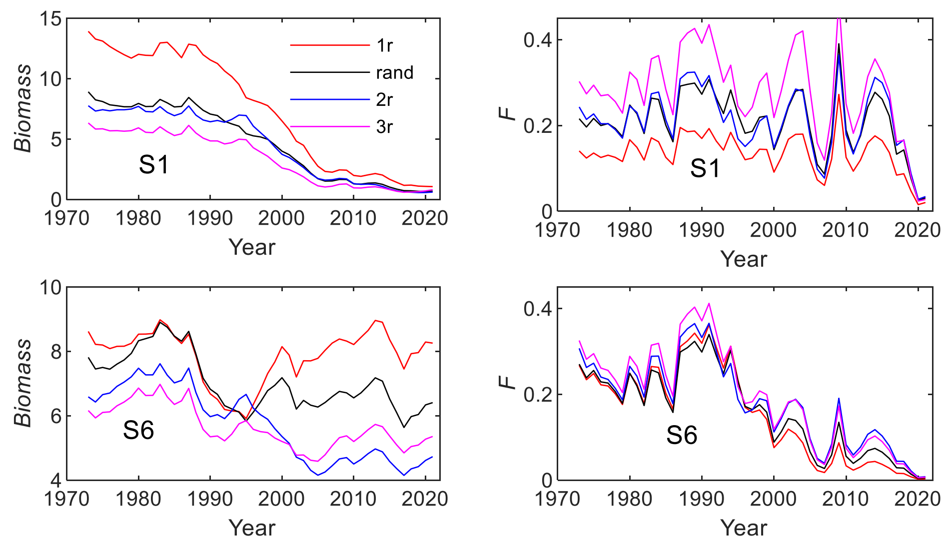


Figure 15: Estimated sauger biomass (B) and fishing mortality rate (F) under model/data scenarios S1 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

The probability of overfishing dropped further in 2021 under both S1H2 and S6H2, and the difference in probability that the population biomass was below B_{msy} remained; it was 100% under S1H2 and dropped to around 40% under S6H2 (Figure 16).

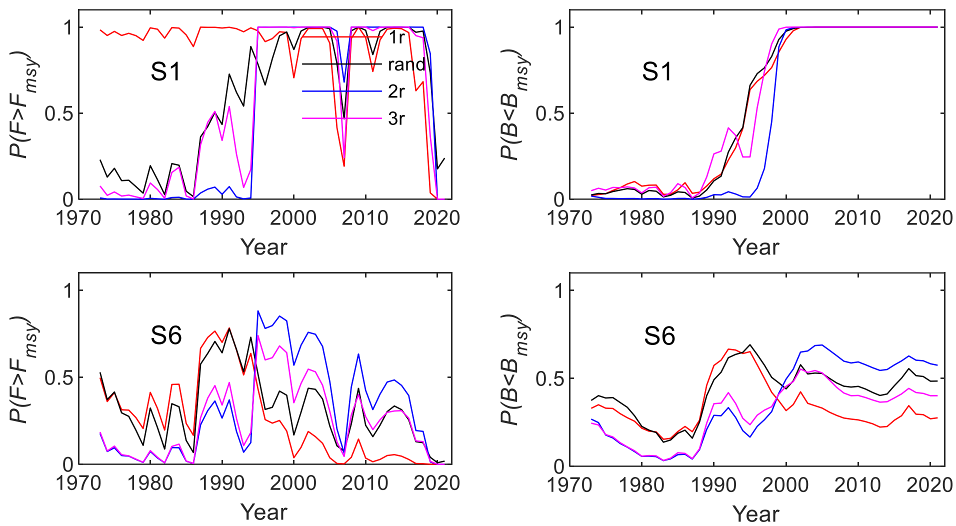


Figure 16: Estimated probability of overfishing, P(F>F_{msy}), and biomass being below B_{msy}, P(B<B_{msy}), for sauger under model/data scenarios S1 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods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

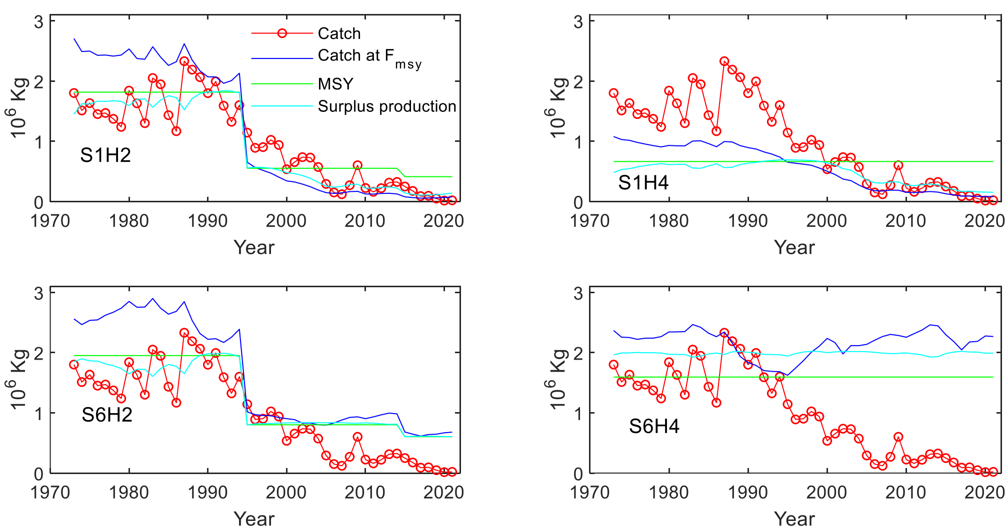


Figure 17: Comparison of sauger catch, MSY, surplus production and catch at F_{msy} based on the examples of the S1H2, S1H4, S6H2 and S6H4.

Sauger biomass was unchanged from 2019, being estimated at ~6-9% of the carrying capacity (K) in 2021 under S1. Sauger biomass increased from 47% for K in 2019

(A/OFRC 2020) to 56% of K in 2021, under S6H2 (Table 10). The probability that overfishing occurred in 2021 was almost zero, Table 11), and the probability that the population biomass was below B_{msy} in 2021 remained at 100% under S1H2 but dropped from 54% in 2019 (A/OFRC 2020) to 40% in 2021 under S6H2 (Table 12).

Table 10: Posterior mean estimate of depletion (B_{2021}/K) of sauger population in 2021 from the two model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.06	0.51
Three *r* periods (H2)	0.09	0.56
Two *r* periods (H3)	0.06	0.46
constant *r* (H4)	0.06	0.69

Table 11: Posterior probability of overfishing sauger in 2021, $P(F_{2021}>F_{msy})$ from the two model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.24	0.02
Three *r* periods (H2)	<0.01	<0.01
Two *r* periods (H3)	<0.01	<0.01
constant *r* (H4)	<0.01	<0.01

Table 12: Posterior probability of sauger biomass being below B_{msy} in 2021, $P(B_{2021}<B_{msy})$ from the two model/data scenarios and four hypotheses regarding *r*.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	1	0.48
Three *r* periods (H2)	1	0.40
Two *r* periods (H3)	1	0.57
constant *r* (H4)	1	0.28

4.2.3 LAKE WHITEFISH

As previously (A/OFRC 2020), data constraints 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. As in A/OFRC (2020), under data scenario S1, hypothesis H1, when *r* followed a random walk process, performed best, as indicated by its lowest DIC score (Table 13). Also as was the case in A/OFRC (2020), under S6, the three-period *r* hypothesis (H2) had the lowest DIC score, though the other three hypotheses were close. All scenarios continue to be 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.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	683.62	273.64
Three *r* periods (H2)	689.25	268.97
Two *r* periods (H3)	688.75	269.31
constant *r* (H4)	684.95	269.95

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.

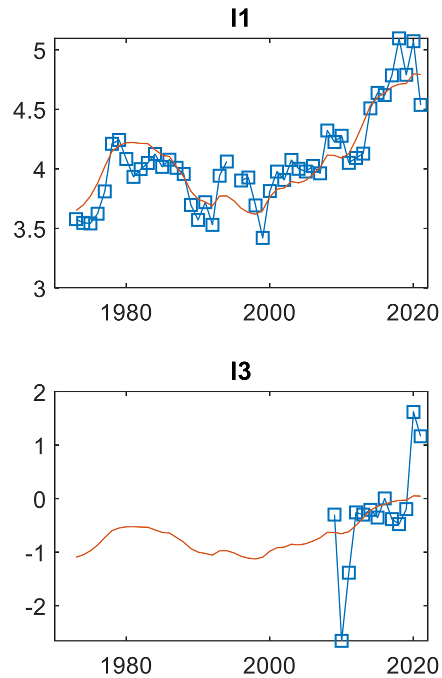


Figure 18: Model estimated lake whitefish CUEs of from S1H1 (brown lines) in comparison with the observed CUEs (blue line with square markers). I1=commercial CUE (kg/delivery), I2= NRND index 1979-2003 (#/net), I3=NRND index 2009-2021 (kg/net).

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).

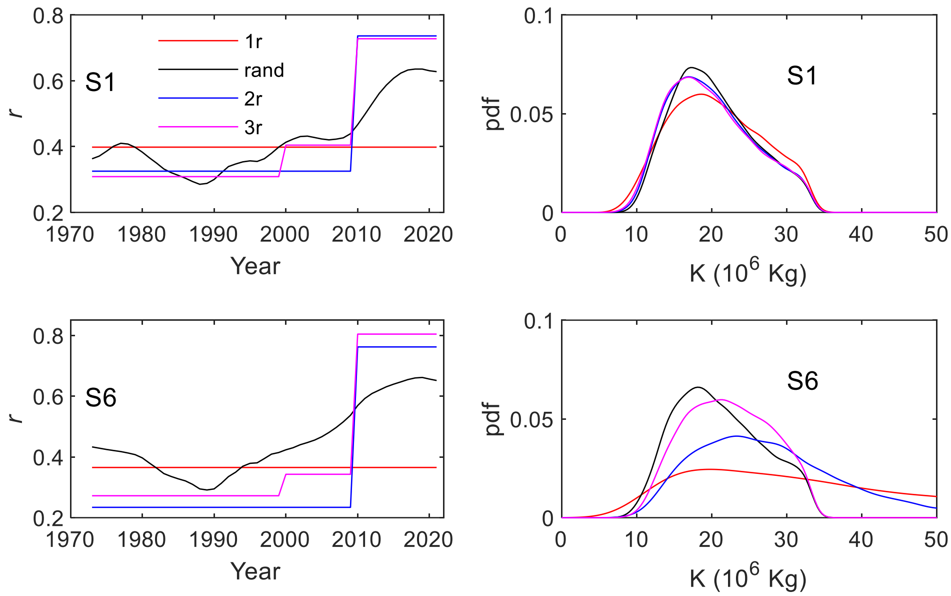


Figure 19: Estimation of the lake whitefish productivity (*r*) and carry capacity (K) from model/data scenarios S1 and S6 and the four hypotheses regarding *r*. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

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 probabilities of overfishing, $P(F>F_{msy})$, and biomass being blow B_{msy}, $P(B<B_{msy})$, (Figure 21) and surplus production and MSY (Figure 22). Under S1H1, estimates of depletion (B_{2019}/K) indicated that whitefish in 2021 were not depleted at 77% of K.

mean

Neither was whitefish biomass below B_{msy} in 2021 ($P(B<B_{msy})<0.01$), nor had overfishing likely occurred in 2021 ($P(F>F_{msy})<0.01$). Under S6H2, it was even less unlikely that the biomass fell below B_{msy} in 2021 ($P(B<B_{msy})=0.08$) compared with 2019 ($P(B<B_{msy})=0.26$). The probability that overfishing occurred dropped from ($P(F>F_{msy})=0.57$) (A/OFRC 2020) to ($P(F>F_{msy})<0.01$) in 2021 (Tables 14-16). The probability of overfishing and the probability of biomass being lower than B_{msy} continued to be slightly greater if *r* was assumed constant r (H4) (Figure 21).

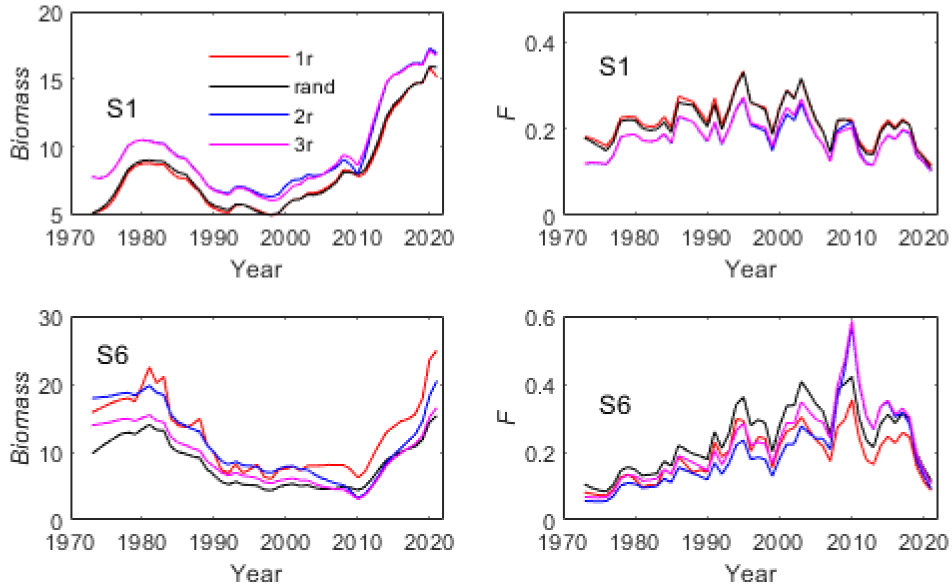


Figure 20: Estimation of whitefish biomass and fishing mortality rate (F) from model/data scenarios S1 and S6 and the four hypotheses regarding r (see Table 1).

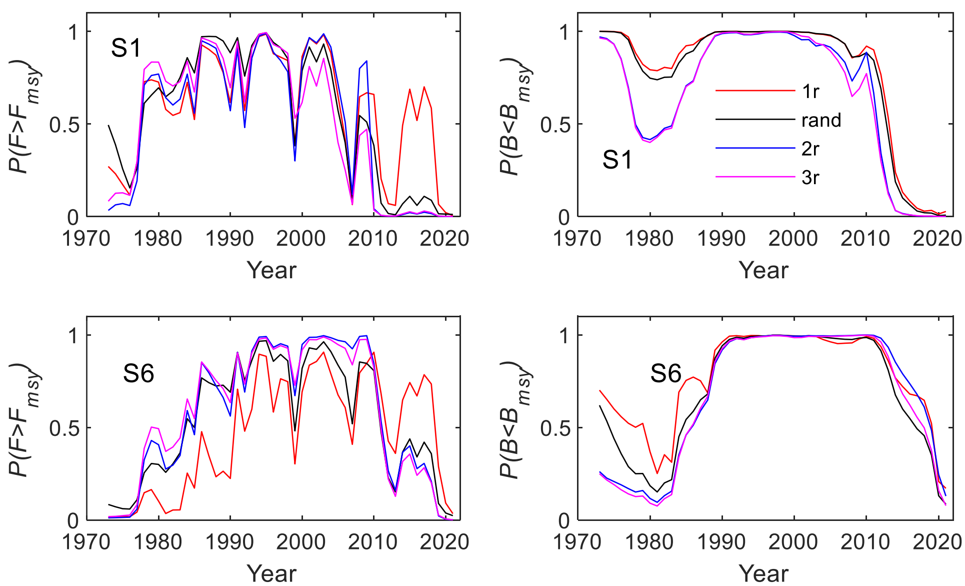


Figure 21: The probability of overfishing, P(F>F_{msy}), and of lake whitefish biomass being below B_{msy}, P(B<B_{msy}), as estimated from S1 and S6. 1r= constant *r* (H4), rand= *r* followed random walk (H1), 2r=two *r* periods (H3), 3r=three *r* periods (H2) (see Table 1).

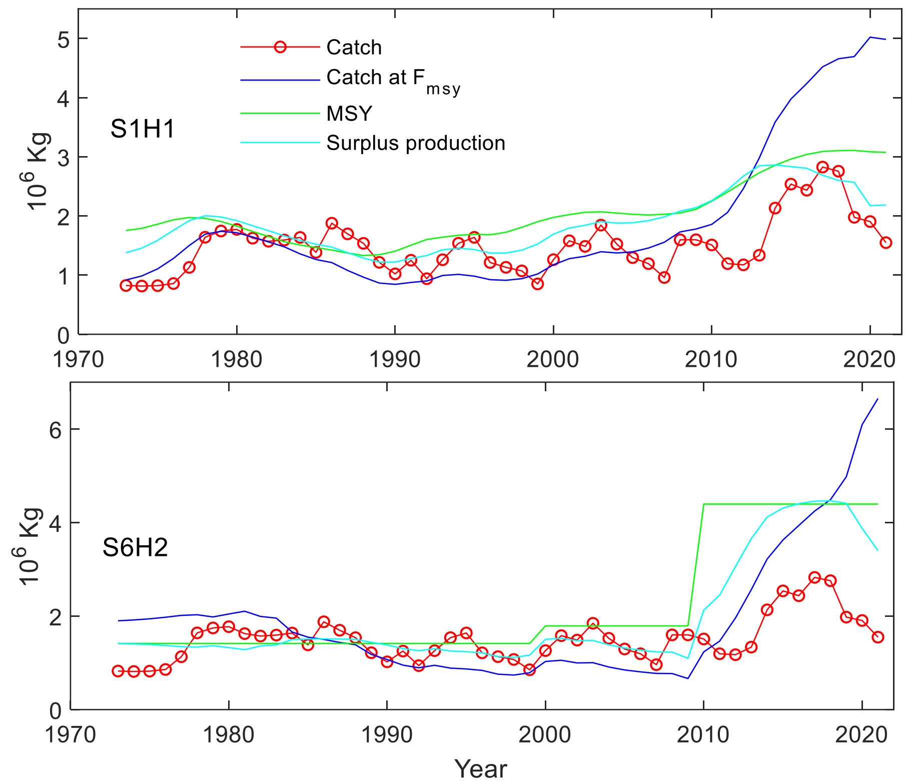


Figure 22: Comparison of lake whitefish catch, MSY, surplus production and catch at F_{msy} levels based on the examples of the S1H1 and S6H2.

Table 14: Posterior mean estimate of depletion (B_{2021}/K) from the two model/data scenarios for whitefish population.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.77	0.73
Three *r* periods (H2)	0.83	0.74
Two *r* periods (H3)	0.84	0.72
constant *r* (H4)	0.73	0.69

Table 15: Posterior probability of overfishing the lake whitefish population in 2021, $P(F_{2021}>F_{msy})$.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.01	0.03
Three *r* periods (H2)	<0.01	<0.01
Two *r* periods (H3)	<0.01	<0.01
constant *r* (H4)	0.01	0.02

Table 16: Posterior probability of lake whitefish biomass being less than B_{msy} in 2021, $P(B_{2021}<B_{msy})$.

Hypothesis on *r*	S1	S6
r followed random walk process (H1)	0.01	0.08
Three *r* periods (H2)	<0.01	0.08
Two *r* periods (H3)	<0.01	0.13
constant *r* (H4)	0.03	0.17

5. CONCLUSIONS

5.1 WALLEYE

The status of the walleye population and fishery was less robust to alternative model/data scenarios than in 2019, i.e., model/data selection uncertainty was higher. Unlike in 2019, when all four CUE time series indicated the same narrative about walleye population dynamics (A/OFRC 2020), there was a considerable difference between the commercial and index CUEs in 2021. The reasons for this difference remain unknown, but there are issues with both CUE time series, e.g., they lack reliable estimates of commercial catch and effort and deficiencies with the index netting survey sample design, that will need to be addressed to begin to understand why such differences occur.

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 biomass was below B_{msy} and $1/2B_{msy}$ on a regular basis before the productivity increased in the late 1990s. The probability of the biomass being below B_{msy} and $1/2B_{msy}$ was low during the 2000s, after productivity increased, but increased again between 2012 and 2015. The probability of the biomass being below B_{msy} had dropped steadily since then but increased in 2021 due to the largest commercial harvest since 2013. Nevertheless, the probability of the biomass being below $1/2B_{msy}$ was practically zero in 2021 indicating that no management action is required at this juncture.

The model with the lowest DIC scored changed between the 2019 and 2021 assessments presenting a model selection challenge. The differences among DICs of the four models is less than 3, suggesting that more than a single model is plausible. We employed Bayesian model averaging (BMA), e.g., Jiao et al. (2008) to generate the most robust stock assessment results possible for management purposes. Such an approach avoids model selection trouble, such as was the case here, when the "best-selected" model changed from 2019 to 2020.

The walleye fishery was not as strong as in 2019 due to slightly lower biomass combined with much higher catches than in recent years. The Bayesian model averaged results indicated that the walleye fishery was moderately strong in 2021 (Table ES2). Biomass was ~53% of the carrying capacity, the probability that overfishing occurred was 55%, and the probability that the population biomass was below $1/2B_{msy}$ was 0.08%. The harvest in 2021 increased 69% and 29% from 2020 and 2019 respectively, which caused an increase in the fishing mortality rate (about 0.25/yr) such that the fishing mortality rate in 2021 was the highest in the time series since 2010. Based on the model averaged results under S1, the walleye population status was sufficiently good in 2021 that, based on our experience, it could be expected to gain a passing stock status score under the MSC certification scheme.

Lastly, it appears that changes in mesh-size regulations may have had the unintended consequence of increasing fishing effort and catches (within overall multi-species quotas), consistent with results of management strategy evaluations (MSEs) modelled by A/OFRC (2021).

5.2 SAUGER

As reported in A/OFRC (2020), 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 2021 sauger biomass increased from 47% of the carrying capacity in 2019, to 56% in 2021, when the commercial CUEs were excluded. The probability that overfishing occurred in 2021 fell to less than 1% and the probability that the population biomass was below B_{msy} in 2021 decreased to 40% when commercial CUE data were 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). 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, increased minimum mesh size allowed in the south basin since 2020, and/or ecosystem-related changes that changed the catchability of sauger in the commercial gear (E. Sveinson and R. Smith, pers. com).

As with walleye, the sauger biomass model with the lowest DIC score changed between the 2019 and 2021 assessments presenting a model selection challenge because the differences among DICs of the four models is less than 3, suggesting that more than a single model is plausible. Model averaging should be considered for future assessment and management purposes. Such an approach can avoid the problem of model selection, such as the case here, when the “best-selected” model changed between 2019 and 2020.

We recommend that, until such time and necessity as model averaging can be implemented, and/or there are data of sufficient quantity and quality to use models better than SSBDMs, that the top performing data scenario (S6), which excluded commercial CUEs, be considered for assessment and management of the sauger fishery.

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 biomass was below B_{msy}, and overfishing happened regularly, between the late 1980s and around 2010. The probability of both overfishing and of biomass being below B_{msy} dropped after 2010 and increased in recent years.

In 2021, lake whitefish population and fishery statuses were strong. The population was well above B_{msy}; the probability that the population biomass was below B_{msy} was 10%, and the probability that overfishing happened was 13%. When the fishery-dependent CUE data series was not included in the analysis, the probability that the population biomass was below B_{msy} was greater at 23%, and the probability of overfishing remained at 13% (Tables 14-16). 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. These indicators suggest that the status of the 2021 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.

The model with the lowest DIC score did not change between the 2019 and 2021 assessments for lake whitefish. Nevertheless, a model selection challenge remains because the differences among DICs of the four models can be less than 3, suggesting that more than a single model is plausible. Model averaging should be considered for future assessment and management purposes. Until such time and necessity as model averaging can be implemented for this species, and/or there are better data available to support better 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 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 engaging with NRND in a cooperative approach to initiating 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. One such example would be the utilization of the commercial fishing industry as a partner of NRND to expand the spatial and temporal extent of the survey under a refined index survey sample design.

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, assessment model and fishery management:

- The current assessments rely heavily on the commercial (fishery-dependent) CUEs. 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 fisheries catch and effort (the other critical component of fishery dependent data to potentially 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.

- The model averaging approach may be considered for future application of the stock assessment results given that the differences among DICs of the 4 models can be less than 3, such as in the walleye and whitefish cases. Such an approach can also avoid model selection trouble when the "best-selected" model changes from year to year.

- NRND and stakeholders should take the findings here, as well as the extra data sensitivity analyses in the appendices to (A/OFRC 2020 and 2021), into account when considering management decisions including mesh size restrictions and the seasonal openings and closings of the commercial and recreational fisheries.

- There is a need for a multispecies fisheries improvement project (FIP) that should include the eventual development of species-specific management plans that include threshold and limit reference points to guide management of removals.

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