Fisheries Branch Report

Lake Manitoba
Fish Stock Assessment

Manitoba Natural Resources and Indigenous Futures

Lake Manitoba Fish Stock Assessment 2023

Executive Summary

Lake Manitoba Walleye and Sauger were assessed using a Bayesian formulation of Schaefer surplus production modeling developed by Froese and others (2023). Modeling was repeated using two data streams as indices of abundance: index netting data from 2009 to 2023, and fisher delivery data from 1996 to 2023.

Walleye stock biomass is above the level required to produce the maximum sustainable yield supported by large year classes hatched in 2013 and 2018. Walleye harvest rates are lower than the rates that would lead to the maximum sustainable yield even while rates have been increasing over the past three years. The commercial harvest of 922 tonnes in the 2023/24 fishing year was higher than the recommended maximum sustainable yield of 875 tonnes, but there was excess biomass in the stock.

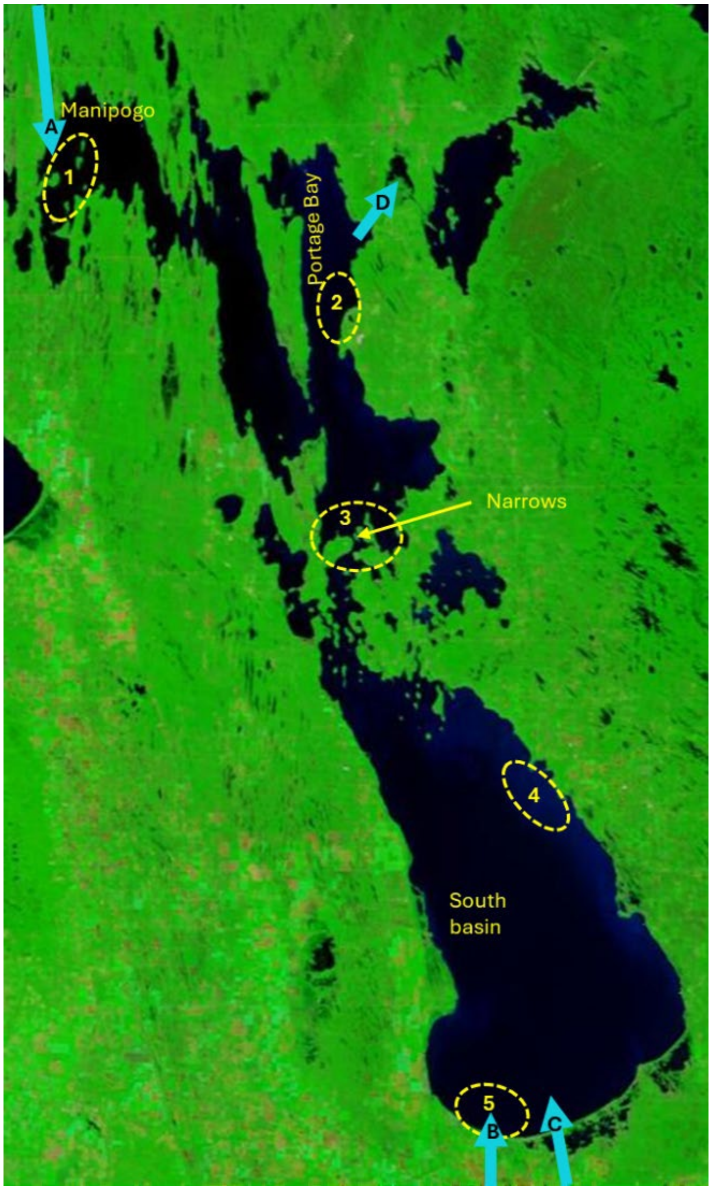
Sauger stock biomass is smaller than the size required to produce the maximum sustainable yield, but the stock is growing. The two data streams of abundance are equivocal as to whether the harvest rate is excessive. Index netting data suggests harvest rates are not too high. The most conservative estimate of maximum sustainable yield calculated for Lake Manitoba Sauger, 90 tonnes, is recommended until the stock achieves a biomass consistent with the maximum sustainable yield. In the 2023/24 commercial fishing year, 107 tonnes of Sauger were declared.

Modeling of index netting data produced a natural mortality estimate for Lake Manitoba Walleye of M = 0.25, and a generation time of 9.64 years.

Introduction

Lake Manitoba is listed as the thirty-third largest lake in the world with a surface area of 466,000 hectares. The lake is shallow, so that surface area of 466,000 ha can expand and contract a lot depending on the surface elevation of the lake. There is a control structure where Lake Manitoba empties out of Portage Bay and into the Fairford River. The control structure was built in the 1960s to maintain a minimum pool in Lake Manitoba in excess of 810 feet above sea level, and a maximum elevation of 813 feet above sea level.

The north basin and south basin differ hydrologically. The south basin is something of a blind appendix to the extensive lake and river complex that connects a group of headwater lakes to Lake Winnipegosis, through Waterhen Lake, the north basin of Lake Manitoba, Lake St. Martin, and finally Lake Winnipeg. The south basin has a relatively low turnover because it has little inflow. The major inflow to the south basin is the Whitemud River delivering an annual average of 11.9 m^3s^{-1} into the south basin volume of 3107 km2 (Last 1980). The Waterhen River is the largest inflow to the north basin and to Lake Manitoba as a whole, delivering 81.3 m^3s^{-1} to a north basin which has a volume of 1593 km2. The north basin boasts 523 km of shoreline or 328 m of shoreline for every square kilometre of surface area. By contrast, the south basin has a meagre 392 km of shoreline enclosing its waters: only 126 metres of shoreline for every square kilometre of water. The differences in water residency times can be great; a speedy two years in the north basin, and as long as twenty-eight years in the south basin (Last 1980) (Map 1).



Map 1: False colour image of Lake Manitoba showing major inflows as blue arrows: A) Waterhen River, B) Whitemud River, C) Portage Diversion, and the outflow D) Fairford River. Yellow dashed ellipses approximate the locations of index netting sites: 1) Manipogo, 2) Steeprock, 3) the Narrows, 4) Lundar, and 5) Whitemud. The portion of the lake north of the Narrows throughout the text is referred to as the north area.

Page (2011) measured chemical differences in 2005 and 2006 between the basins. She found total phosphorus to be 82% higher in the south, chlorophylla 180% higher in the south, turbidity 145% higher in the south (NTUs), and transparency higher in the north. Operation of the Portage Diversion continues to elevate turbidity and productivity of the south basin compared to the north.

The Portage Diversion can be the major inflow to the entire lake when it is operating. The diversion has been in operation since 1970. It was built to shunt over 700 m^3s^{-1} of flood waters from the Assiniboine River northward thirty kilometres to the southernmost extremity of Lake Manitoba, thereby offering some level of flood protection to the city of Winnipeg. The diversion does not operate every year. When it is in operation, it brings high levels of phosphorous and fine sediments to the south basin.

Large coastal marshes exist around Lake Manitoba behind beach ridges. The largest of these is Delta Marsh at the very southern end of Lake Manitoba. While the Portage Diversion can pull 700 m^3s^{-1} out of the Assiniboine River, the diversion is only competent to convey 60% of that volume through Delta Marsh. Discharge beyond 60% of capacity blows out into the marsh during large floods.

Lake Manitoba has been a commercial fishery since 1895. It also has a long history as a recreational fishery, and an even longer one as a subsistence fishery. There are no restrictions on subsistence harvest. Angling limits have changed since described in the 2020 stock assessment (Klein 2020). No special angling restrictions exist particular to Lake Manitoba. The species regulations are the same as for the rest of the Southern Fishing Division in Manitoba:

Species		**Possession Limit**	**Size Restriction**
Bigmouth Buffalo	*Ictiobus cyprinellus*	0	
Brown Bullhead	*Ameiurus nebulosus*	25	
Burbot	*Lota lota*	6	None over 70 cm
Freshwater Drum	*Aplodinotus grunniens*	10	None over 60 cm
Goldeye	*Hiodon alosoides*	10	
Lake Whitefish	*Coregonus clupeaformis*	10	
Northern Pike	*Esox lucius*	4	None over 75 cm
Walleye and/or Sauger	*Sander vitreus* and/or *S. canadensis*	4	None over 55 cm
Yellow Perch	*Perca flavescens*	25	
All other species		No limit	

The Lake Manitoba commercial fishery has a maximum allowable commercial quota of 907.2 tonnes round weight of Walleye (*Sander vitreus*) and Sauger (*Sander canadensis*) combined. In 2015, there were 554 fishers eligible for licensing. If the total allowable quota was equally divided among them, each fisher would have 1638 kg of quota. Commercial fishers were split into Category 'A' and Category 'B' in 1987 depending on whether or not they had caught an average of at least 200 kg per year in the preceding three years. Category A licenses can be transferred to new individuals wishing to become fishers. Category B licenses cannot be transferred once the holder is done their fishing career; the license retires with the fisher. Birth years of B license holders in 2015 ranged from 1918 to 1969 with a median of 1949. The B license holders are steadily aging out of the fishery as intended back in 1987. There were 441 Category A licenses in 2015 and 113 Category B licenses. Eligibility to acquire an A license requires a minimum age of 18 years, two years fishing experience, and residency in a rural municipality or the unorganized territory adjacent to Lake Manitoba. In order to transfer the right to acquire a license, an A license fisher makes an application through the regional fisheries manager to sell their fishing enterprise to a prospective fisher. The actual tenure to acquire a license remains the property of the Crown but is transferred along with the enterprise as a courtesy to the fisher and to enhance the confidence and stability required for a fisher to invest in a fishing enterprise.

In 2022, a buydown of eligibility was initiated where fishers who wanted to leave the fishery could do so on a willing buyer/willing seller basis and receive $7000 in compensation for the extinction of their access to the commercial fishery. By the time of writing (July 2024), the Province of Manitoba had bought back Lake Manitoba fishery access from seventy-five fishers.

The regular commercial season for most species only operates in winter and has done since 1905. The fishing season begins when ice makes after November 1st; that is, a fisher may only set their nets through the ice, they may not set in open water. Anxious fishers have been known to set their first nets using planks and sheets of plywood to distribute their weight over thin, early ice. Due to the vagaries of wind and weather, first deliveries have been made anywhere from the second week of November to the first week of December. The long-term median start date is in the fourth week of November. The regular commercial fishing season ends on March 31.

The minimum mesh size allowed in the large mesh winter season is 95 mm, 3¾”. The maximum mesh size allowed in the fishery is 127 mm, or 5” stretched mesh.

In 1985, a 76 mm, 3”, fishery officially began, although hearsay and delivery records suggest some 3” fishing started a few years before. When the 3” fishery is operating, a fisher may continue to fish nets from 3¾” – 5”, but nothing between 3” and 3¾”; 76 – 95 mm. That said, the legal tolerance is 3 mm before a fisher must remove a net from the water and charges are laid when a 4 mm tolerance is exceeded. In practice, the gap between small mesh and large mesh can be as small as 79 – 92 mm.

The large mesh fishery begins to capture Walleye at a fork length of 350 mm. The small mesh fishery already catches Walleye at 300 mm and because the length:frequency curves, particularly for smaller meshes, are skewed to the right, no size of Walleye between 300 and 680 mm is protected when the 3” fishery is operating. The steep ascending limb of the 3” mesh curve reflects the size gap between one-year-old and two-year-old Walleye in the population. There are not many fish below 300 mm to be caught, only a few very fast growing one-year-olds, and a few slow growing two-year-olds.

Initially, the small mesh season lasted for 5 weeks. By 1992, the small mesh season had been extended from January 1 to March 15. In subsequent years, the close date was moved earlier to the end of February, and then in 2005 the open window was moved two weeks later; January 15 to March 15 where it has remained since. In an attempt to offset the impact of the harvest of premature fish caused by the smaller mesh, the season for large mesh winter fishing was shortened from March 31 to March 15 coinciding with the small mesh close date. The small mesh fishery in the north basin was discontinued in 2001 restoring the March 31 season end date in that fishing area. In 2011, flooding of Lake Manitoba resulted in a very large year class of Northern Pike (*Esox lucius*). By 2013, the irruption of pike was making small mesh fishing on Lake Manitoba difficult. Pike ate most of the Yellow Perch (*Perca flavescens*) targeted by the small mesh nets leaving few perch available to the fishery. At the same time, remaining fish gilled in the small mesh nets baited pike into the nets. Pike became entangled by their teeth, and while struggling would roll the nets into a much shallower profile that no longer fished effectively. Disentangling rolled up pike from their nets cost fishers additional time to remove the pike, which are of relatively low value. As a result, fishers became progressively less interested in fishing small mesh and since the 2017/18 season have agreed not to fish small mesh in exchange for the opportunity to fish in the south basin until the end of March instead of March 15. So, small mesh fishing has not occurred in the north end of Lake Manitoba since 2001, while in the south basin is has only occurred minimally beginning in 2013, and not at all after 2017.

Carp Fishery

Common Carp (*Cyprinus carpio*) is an invasive species to Lake Manitoba having arrived sometime in the middle 20th century. Fishers may pursue carp year-round with an additional license. Fishers can use gill nets or beach seines to capture carp. The minimum mesh size allowed in the gillnet fishery is 203 mm, 8" stretch, and the maximum 250 mm, or 10" stretch mesh. There is no quota on carp. Mullet is a colloquial name for any mix of sucker species. Mullet caught as bycatch in the carp fishery may be retained for sale. On Lake Manitoba, mullet will refer to primarily White Sucker (*Catostomus commersoni*), with a very small percentage of Shorthead Redhorse (*Moxostoma macrolepidotum*). In 2014, when a smoked market for Freshwater Drum (*Aplodinotus grunniens*) briefly emerged in Russia, that species was also permitted under carp licenses. Russia embargoed the fish the following year over Canada's support for Ukraine during Russia's annexation of Crimea, but the drum fishery found new markets on a small scale. In 2023, just 673 kg of Freshwater Drum were delivered from Lake Manitoba.

Spring Creek Mullet Fishery

When Lake Manitoba tributaries swell with snowmelt running off the land in springtime, White Suckers ascend streams and drains to spawn. Commercial fishers may purchase an additional license to capture the mullet using trap nets, hoop nets, or other impoundment gear. The gear may not block more than two thirds of the channel width and must be checked daily. Sites are granted on a stream-by-stream basis. There is no quota on mullet. Some streams, like those along the north shore of Lake Manitoba are not permitted due to concerns for Walleye spawning. Conservation Officers may close sites on a location-by-location basis if they consider the operation is negatively affecting spawning migrations of other species, Walleye in particular. Usually no bycatch is allowed, but in 2013 at the request of fishers to help dampen the irruption of pike, an allowance for 65 tonnes was made in the spring creek fishery. Only a few thousand pike were caught, as was the case the following year under a smaller allowance.

The maximum sustainable yield for Lake Manitoba Walleye was suggested last year at 632 tonnes based on total annual catch and the size of average deliveries declared on the daily catch records since 1996. A second maximum sustainable yield was suggested at 874 tonnes based on the average catches in the index netting programme run in September since 2009. In addition to both of those maximum sustainable yields, there is also the annual lake quota of 907 tonnes. The annual lake quota is for the combined catch of Walleye and Sauger. The commercial Walleye catch in the 2022/23 fishing year was almost 821 tonnes, the highest it had been since 1957 when deliveries of 867 tonnes were declared. The 2023/24 fishing year had higher deliveries still, exceeding both maximum sustainable yield estimates, and with total declared production of 922 tonnes, eclipsing the lake quota before even including the Sauger deliveries for the year. To give an impression of how great the catch was last year, one would have to look back to the year 1955 – sixty-eight years ago – to find the last year with as much production; predating the start of any careers among Lake Manitoba fishers still active today.

When Sauger are included in the combined total of quota species, the 2022/23 fishing year produced 926 tonnes of large percids: fully nineteen tonnes more than the quota, and the highest combined production since 1991. The 2023/24 fishing year produced a combined total of 1028 tonnes, exceeding the two-species quota by 121 tonnes, and bringing in the greatest volume of Lake Manitoba Walleye and Sauger since 1966.

Not only did total deliveries increase, but the average size of the deliveries increased, indicating higher abundance of fish. The average Sauger delivery declared on a daily catch record during the 2022/23 fishing year was 12.1 kg. During the 2023/24 fishing year that number increased to 14.6 kg. The difference in Walleye deliveries was even more dramatic, jumping from 97.4 kg per delivery in 2022/23 to 138.8 kg per delivery in 2023/24.

The catch history available in the two-time series, daily catch records since 1996 and index netting data since 2009, represent one-way trips from very low stock levels of Walleye and Sauger to higher stock abundance. Very high in the case of Walleye. According to Hilborn and Walters (1992), when using surplus production modeling to interpret such data, good approximations of intrinsic growth rate can be had, but estimates of carrying capacity should be interpreted with caution. This assessment builds on last year's modeling by extending the contrast in the data series with very high catches and catch rates but continues to analyse a pattern that is a one-way trip of increasing stock abundance.

Consistent with last year's assessment, the Walleye and Sauger stocks were evaluated on a whole lake basis and by area. The Lake Manitoba commercial fishery has been managed as a single stock, but the north area and the south basin fish do not present as a common pool. Fish from the two areas differ in condition and in life history traits. The habitats of the two areas are also different. Even management has differed between the areas in terms of season lengths and minimum allowable mesh sizes (Klein 2020, 2023).

This assessment is an update of the Lake Manitoba Walleye and Sauger stock assessments done last year (Klein 2023) to include the data from the 2023/24 fishing year and index netting information from the fall of 2023. Last year, surplus production modeling was used instead of catch-at-age methods because the index netting programme effort among areas had been inconsistent in recent years; 2019 and 2021 in particular. The index netting effort was good in 2023, and the catch-at-age methods will be beneficial in next year's assessment. In this assessment, surplus production modeling will be used again.

In addition to updating estimates of biomass, harvest levels, and maximum sustainable yields for Walleye and Sauger in Lake Manitoba, this assessment also updates life history measures and dynamic rate functions of the Walleye stocks.

Methods

Surplus Production Modeling

Model

Surplus production modeling was done using the Schaefer model. The fundamental estimands are the intrinsic growth rate of the stock, r, and the carry capacity, K:

$$B_t = B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_{t-1} \tag{1}$$

$$\frac{C}{E} = qB_t \tag{2}$$

Where B_t is the stock biomass in year t, B_{t-1} is the biomass in the year preceding year t, C_{t-1} is the catch in the year preceding the year t, q is catchability, and C/E is the catch per unit effort. Surplus production modeling was performed using the Bayesian Schaefer Model in CMSY++ (Froese *et al* 2023).

The Schaefer model assumes a symmetrical production function. This assumption of symmetry makes the interpretation of the biomass required to produce the maximum sustainable yield, B_{MSY}, one half of the carrying capacity. The harvest fraction that would lead to the maximum sustainable yield, F_{MSY}, is one half of the estimate of the intrinsic growth rate of a stock. And, unsurprisingly, the maximum sustainable yield that can be harvested is just B_{MSY} multiplied by F_{MSY}.

The total commercial catch for a year is the total of all daily catch records submitted by fish buyers for that species plus any private sales directly to restaurants, stores, or final consumers by the fishers, plus any end of season declarations by a fisher. The end of season declaration is a record submitted to Fisheries Branch of fish that were caught during the season under the authority of the fisher's license, but that the fisher elected not to sell during the commercial season and instead kept on hand in order to sell after the closure of the season. The forms of the fish as they were declared are recorded and standard conversion factors are used to convert all weights as declared to round weight (green weight), to generate the total commercial catch. The conversion factors from delivered form to round weight for Walleye and Sauger are: 1.1 times for gutted fish, 1.4 times for headless dressed fish, and 2.4 times for fish sold as fillets; per the Manitoba Commercial Fishing Guide (https://www.gov.mb.ca/nrnd/fish-wildlife/pubs/fish_wildlife/fish/commercial_fishing_guide_2024_2025.pdf). The total commercial catch in a given year for a species is C_t in equation (1).

Daily catch records (DCRs) are receipts given to fishers upon first sale of their fish. Recorded on the DCR is the identity of the fisher who produced the catch, the date of the delivery, the bulk weight of the delivery by species, size, form, and grade. The geometric mean of all the daily catch records in a year for an area, or for the whole lake, can be the C/E in equation (2). C/E in equation (2) may also be derived from the index netting programme catch, which has been described by Klein (2020, 2023).

Whether fish stocks were modeled using daily catch records as the index of abundance in equation (2), or using index netting programme results, the total catch in equation (1) was that of the commercial fishery. Nonetheless, I refer in the rest of this document to ‘fisheries dependent’ and ‘fisheries independent’ models depending on the index of abundance used. Where daily catch records serve as the index of abundance in equation (2), I call the model ‘fishery dependent’. Where the index of abundance is generated by the index netting programme, I call the model 'fishery independent’. Angling catches and subsistence net catches are not included in the total harvest.

Models were evaluated using multiple diagnostics. Retrospective analyses compared the model estimates of biomass and fishing pressure in the current year to one, two, and three years previous by recalculating parameters after dropping out the most recent years one at a time. Prior and posterior distributions of intrinsic growth rate, carrying capacity, and maximum sustainable yield, buy the amount of overlap in their distributions. The same was done for the starting relative (to carrying capacity) biomass, final biomass, and an intermediate biomass. Residuals of model fits were assessed for patterns using runs tests. Posterior parameter estimates of intrinsic growth rate, carrying capacity, and catchability were assessed for the degree of autocorrelation, evaluation of trace plots, the number of effective samples, and the potential scale reduction factor. Graphical outputs of these analyses for each retained assessment model appear in Appendix 1.

Walleye

Surplus production modeling of Lake Manitoba Walleye was completed for the whole lake, and by basin using commercial daily catch records and index net catches as indices of abundance. Catch totals for the north area or south basin excluded deliveries at Eddystone and Vogar packing sheds, because it is not known in what proportions fish from either basin has been delivered to these sheds at the nexus. It was found however, that deliveries to those sheds at the Narrows, Eddystone in particular, were numerous enough to run the fishery dependent model for the Narrows area in addition to north area and south basin model runs. The mean total Walleye per daily catch record by year was used as the commercial index of abundance. The fishery independent index of abundance used the total weight of Walleye caught in index netting meshes of 76 mm stretch measure and larger. The mean value of all the sets by basin, or for the entire lake were calculated without weighting by index netting area where different efforts among areas existed. The five areas are Whitemud, Lundar, the Narrows, Steep Rock, and Manipogo. The fishery dependent data series is available from 1996 to 2023. The fishery independent data series begins in 2009 but has some gaps among years and locations. There are not yet enough years of index netting data from the Narrows area to bother with fishery independent modeling there (Table 1).

Table 1. The number of index net sets in Lake Manitoba by site. Manipogo and Steeprock are north area sites. Lundar and Whitemud are in the south basin. The Narrows is a newer site begun in 2021.

	North		South		Narrows
	Manipogo	Steeprock	Lundar	Whitemud	Narrows
2009	9	11	11	11	
2010	12	11	10	11	
2011	10	11	8	11	
2012	11	7	7	8	
2013	11	11	10	11	
2014	11	11	11	11	
2015	11	11			
2016					
2017	11	10	10	8	
2018	11	11	10	4	
2019	9	9			
2020	9	9	5	7	
2021		9			12
2022	9	9	9	5	6
2023	9	8	7	5	8

Biomass priors were added to the fishery dependent whole lake model. At the start of the time series, 1996, and in 2010, when the Lake Manitoba Walleye stock was known to be depleted, the ratio of stock biomass to the virgin biomass was set at a range of 0.1 to 0.4.

CMSY++ provides an option to add effort creep; a factor that attempts to compensate for the fact that fishers get better at their vocation over time (Palomares and Pauly 2019). In the fishery dependent models, effort creep was set to 1%, a low level relative to most fisheries with a nod to some improvements in the Lake Manitoba fishery since 1996 (Klein 2023). In the fishery independent models, no effort creep was applied, since the index netting programme, by design, strives to be consistent in effort, or at least methodology, among years.

Sauger

Many different models were developed to understand the state of the Sauger stocks in Lake Manitoba using CMSY++. Sauger were assessed on a lakewide basis, and by basin. As with Walleye, Sauger were assessed using fishery dependent and independent indices of abundance. Among the fishery dependent models, one version of the whole lake model used data from 1970 to 2023. Total catch is available much further back in time, however the total number of deliveries was available back to 1970, so an ersatz index of abundance could be had by dividing the total production of each year by the total number of deliveries. Not the greatest index of abundance, but valuable to compare with the model outputs because the data stream predates the small mesh fishing that began in the 1980s. For that reason, relative biomass priors were set between 40% and

80% of carrying capacity. There is higher confidence in data since 1996 when electronic records started being collected, particularly because the catch per daily catch record is available. Also available since 1996 is the packing shed information, so catch and effort can be divided by basin. Fishery dependent analyses time series were therefore begun with 1996 data, except where north area stocks were concerned where the start year was 2001. The north area time series was shortened because the fishers there abandoned small mesh fishing in 2001. Consistent catchability was traded off against five years of data. The decline of the Sauger stock was already well underway in 1996 and 2001, so a prior range of relative stock abundance was set for those models at 10% – 30% of carrying capacity. To lessen the effects of a one-way trip on the fishery independent models, catch from 1996 was retained, however indices of abundance were only available from the beginning of the index programme in 2009. Intermediate relative biomass priors were pinned in 2008 at 1% to 5% of the carrying capacity, except for the north area where some level of recovery was expected to have begun by 2008, and so the upper end of the relative biomass prior was set at 10% of carrying capacity. Further, by the end of the time series, 2023, after twenty-two years it was expected that the north area Sauger stock should have largely recovered from the effects of small mesh fishing except for the potential loss of fish to the south basin. Therefore, a prior was set for the final relative biomass between 30% and 50% of carrying capacity. No final relative biomass priors were set for any of the other models (Table 2).

Table 2. Bayesian Schaefer surplus production models used in CMSY++ for Lake Manitoba Sauger. DCR refers to daily catch records being used as the index of abundance. Where index nets is listed as the index of abundance, it refers to the total average weight of Sauger per net set in mesh sizes greater than or equal to 64 mm stretch measure. NA means no prior value was assigned.

Stock	Index of abundance	Index of abundance data year range	Catch data year range	Prior estimate of r	Start biomass prior (B/K)	Inter-mediate biomass prior year	Inter-mediate biomass prior (B/K)	Final biomass prior (B/K)	Effort creep
Whole lake	DCR	1970-2023	1970-2023	0.3-0.7	0.4-0.8	2008	0.01-0.05	NA	1%
Whole lake	DCR	1996-2023	1996-2023	0.3-0.7	0.1-0.3	2008	0.01-0.05	NA	1%
Whole lake	Index nets	2009-2023	1996-2023	0.3-0.7	0.1-0.3	2008	0.01-0.05	NA	0%
North area	DCR	2001-2023	2001-2023	0.3-0.7	0.1-0.3	2008	0.01-0.1	0.3-0.5	1%
North area	Index nets	2009-2023	2001-2023	0.3-0.7	0.1-0.3	2008	0.01-0.1	0.3-0.5	0%
Narrows	DCR	1996-2023	1996-2023	0.3-0.7	0.1-0.3	NA	NA	NA	1%
South basin	DCR	1996-2023	1996-2023	0.3-0.7	0.1-0.3	2008	0.01-0.05	NA	1%
South basin	Index nets	2009-2023	1996-2023	0.3-0.7	0.1-0.3	2008	0.01-0.05	NA	0%

As was done with Walleye in CMSY++, effort creep for Sauger was set to 1% in the fishery dependent models and zero in the fishery independent models.

Priors were set for intrinsic growth rate in all Sauger models between 0.3 and 0.7. The index of abundance in the fishery dependent models is the mean delivery size of Sauger per daily catch record, in each fishing year. In the fishery independent models, the index of abundance is the mean weight of total Sauger catch per index netting programme net set in meshes of 64 mm stretch measure and larger.

Growth

The von Bertalanffy growth function was used to model growth in Walleye by stock. Modeling was done using the BayesGrowth package in R (Smart 2023). Priors used in modeling female Walleye were 700 mm (s.e. = 50 mm) for asymptotic length, and 140 mm (s.e. 15 mm) for length at age zero. The maximum model error was set at 100. All the same values were retained among models for male Walleye except the asymptotic length was reduced to 650 mm in recognition of the smaller ultimate sizes achieved by male Walleye relative to female Walleye in any population. Data used in the growth models were from the most recent three years of the index netting programme where relative weights have been steady among the three fishing areas (Klein 2023). Growth was modeled for both sexes in each of the three fishing areas. Posterior parameter distributions and correlation among parameter distributions are displayed graphically in Appendix 2.

Maturity

Age and length maturity ogives of Walleye were estimated using the AquaticLifeHistory package in R (Smart *et al* 2016). Ogives were fit with a generalised linear model using a logit link function. The point at which 50% of fish in a given stock and of a given sex are mature was taken as the age or length at maturity. The modeled point at 95% maturity is also presented to convey the age when nearly all fish are mature. Data were from the most recent three years of the index netting programme where relative weights have been steady among the three fishing areas. Maturity was modeled for both sexes in each of the three fishing areas. Point estimates of maturity are listed in tabular form in the assessment document. Graphical representations of maturity ogives are available in Appendix 3.

Natural Mortality

Natural mortality rates among female Walleye were estimated using multiple models commonly used in natural mortality estimation, which were then weighted and the models averaged in NOAA's Natural Mortality Tool to generate an average natural mortality rate for female fish of either species in all three fishing areas. Natural mortality was only estimated for female fish of each species in each of the three fishing areas. The data used in the modeling was the most recent three years available from the index netting programme. The maximum age Walleye caught in the history of the index netting programme was twenty years in the north area and sixteen in the south basin. The Narrows area is a much shorter time series, having begun in 2021. The maximum age Walleye from the Narrows that has been caught is just twelve years, so for modeling, the midpoint of the south and north maximum ages was selected; eighteen years. Growth coefficients and asymptotic lengths come from the von Bertalanffy growth models in this assessment document. Likewise, ages at maturity are those estimated in this assessment. Where water temperatures were required, five degrees centigrade was used.

Year Class Strength

Walleye year class strengths were calculated as mean z-score values for each year class as it appeared in the index netting programme. Z-score values for averaging were developed for each age available between the age of four and ten in each year of netting based on the number of individuals of either sex caught in the index netting programme.

Data were presented in their raw z-score values and as residuals in a detrended format so their size relative to adjacent year classes could be compared. Detrended simply refers to the residuals relative to a loess smoother (span = 0.65) that was run through the time series of z-score values.

Results

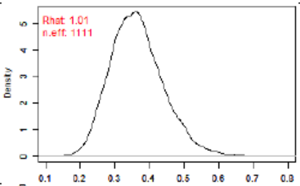
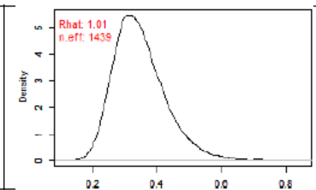
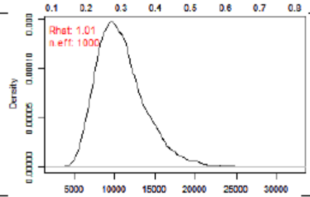
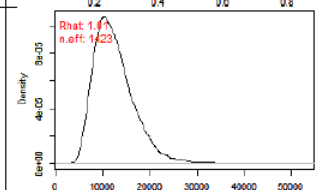
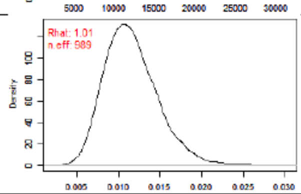
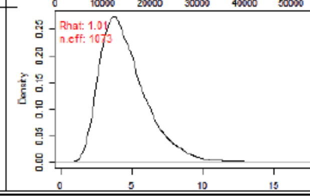
Walleye

Surplus Production Modeling

The fishery dependent model for the whole of Lake Manitoba commercial Walleye fishery was run initially with no priors, but a runs test showed a strong pattern in the residuals, so the model was run again with biomass priors of 10% - 40% of the carrying capacity in 1996 and 2010, a period when the Walleye stock was known to be depleted. The addition of the biomass priors diminished the pattern in the residuals and improved the consistency of the model in retrospective analyses (Figure 1). The results for whole lake, fishery dependent, Walleye surplus production modeling that follow are for the model with biomass priors.

The fishery dependent data stream produced an estimate of intrinsic growth rate of 0.359 (95% credibility interval: 0.233 – 0.533), slightly higher than the growth rate proposed by the fishery independent data stream, 0.336 (95% C.I.: 0.218 – 0.534). Concordantly, the estimate of carrying capacity for the whole lake was estimated smaller by the fishery dependant data at 10,431 tonnes (95% C.I.: 6196 t – 18,138 t), while the fishery independent estimate was then slightly larger at 11,738 t (95% C.I.: 6189 t – 22,804 t) (Table 3).

Table 3.Modeled estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the Lake Manitoba commercial Walleye fishery and the posterior distributions of each estimate. The estimates in the left column are based on total catch, lakewide, using daily catch records as the index of abundance. The estimates in the righthand column are based on total commercial catch using the index netting catch of Walleye as the unit of abundance. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

r = 0.359		r = 0.336	
K = 10,431 t		K = 11,783 t	
q = 0.001123		q = 4.277	

When fishery independent data were used as the index of abundance, the relative biomass results were slightly less optimistic than the fishery dependent data. The fishery independent data suggested the ratio of biomass in 2023 to the biomass that would support the maximum sustainable yield (B/B_{MSY}) was 1.030 (95% C.I.: 0.741 – 1.337). Based on the daily catch record data, the ratio was estimated at 1.282 (95% C.I.: 1.054 – 1.523). The retrospective trend using either index of abundance is similar. In both cases, the estimate of the ratio has not changed much, but the historic view of B/B_{MSY} has progressively decreased as new data become available (see Figure 1 for fishery dependent case and notice the model migrating to the right as new years are added).

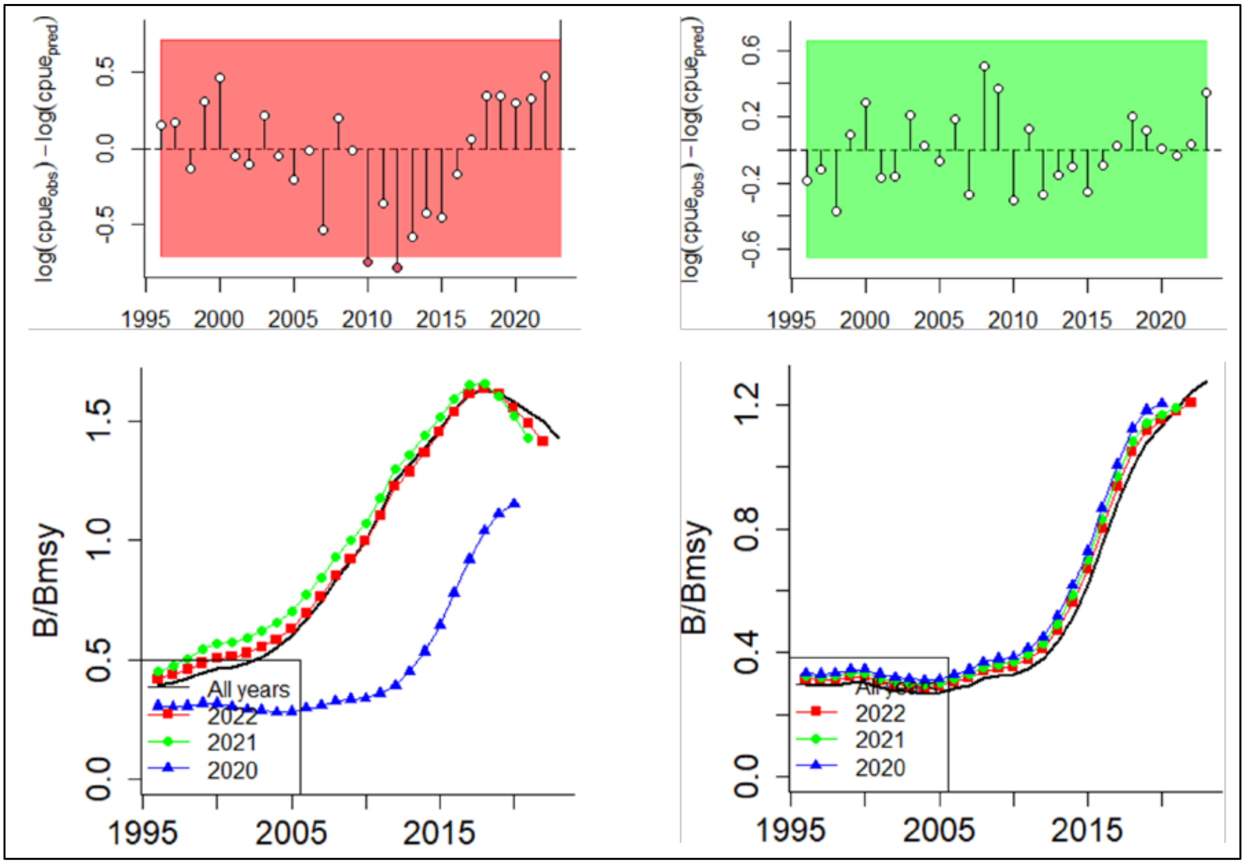


Figure 1. Model diagnostics for the whole lake, fishery dependent, model of Walleye biomass in Lake Manitoba from 1996 to 2023. The top row shows the residuals of the daily catch record model fit. The bottom row shows the retrospective analyses of the estimated relative stock biomass generated by sequentially dropping out one year's data at a time for the past three years. The left column shows the results of the model with no priors. The right column shows the results with biomass priors of 10% - 40% in 1996 and 2010 in order to convince the model to keep the stock at low relative abundance until the irruption actually began.

Both data streams suggest that B_{2023} is larger than the point of recruitment impairment with 100% certainty: using one half B_{MSY} as the point of recruitment impairment. The model based on index netting abundance is 57.2% sure that the biomass in 2023 is larger than B_{MSY}. The model based on the daily catch record data is much more certain the stock is above B_{MSY} at 99.2% certainty (Figure 2).

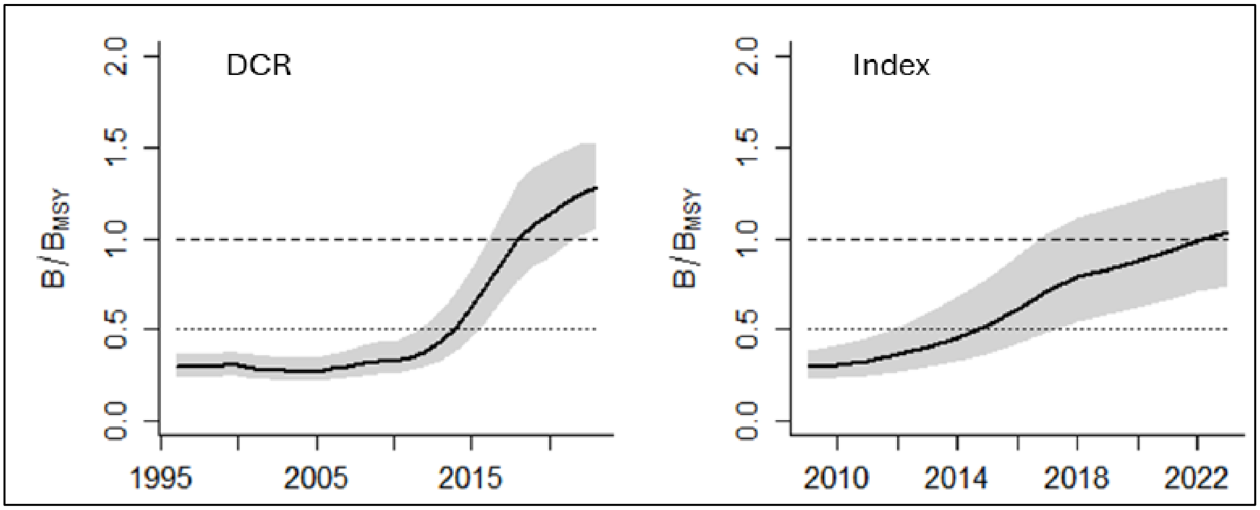


Figure 2. Relative biomass of whole lake, Lake Manitoba Walleye expressed as the estimated biomass in a given year divided by the biomass that would support the maximum sustainable yield. The left frame represents the estimate using fishery dependent daily catch record information. The right frame represents the estimate using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

The harvest fraction estimated using the fishery independent data is 0.142 (95% C.I.: 0.062 – 0.332). The estimate of the harvest fraction that would lead to the maximum sustainable yield is 0.168 (95% C.I.: 0.109 – 0.267). The ratio of F/F_{MSY} then is 0.840 (95% C.I.: 0.441 – 1.559). In the fishery dependent case, the model believes the 2023 rate of exploitation is lower at 0.127 (95% C.I.: 0.042 – 1.222). The fishery dependent model also thinks the rate that would deliver the maximum sustainable yield is higher at 0.180 (95% C.I.: 0.117 – 0.266). The ratio of harvest rate to the rate that would deliver the maximum sustainable yield according to the fishery dependent data is 0.713 (95% C.I.: 0.416 – 1.222). The trend in the relative harvest rate is very similar regardless of which index of abundance is used. Both indices suggest the harvest rate fell below unity in 2010 and have followed the same ups and downs since (Figure 3).

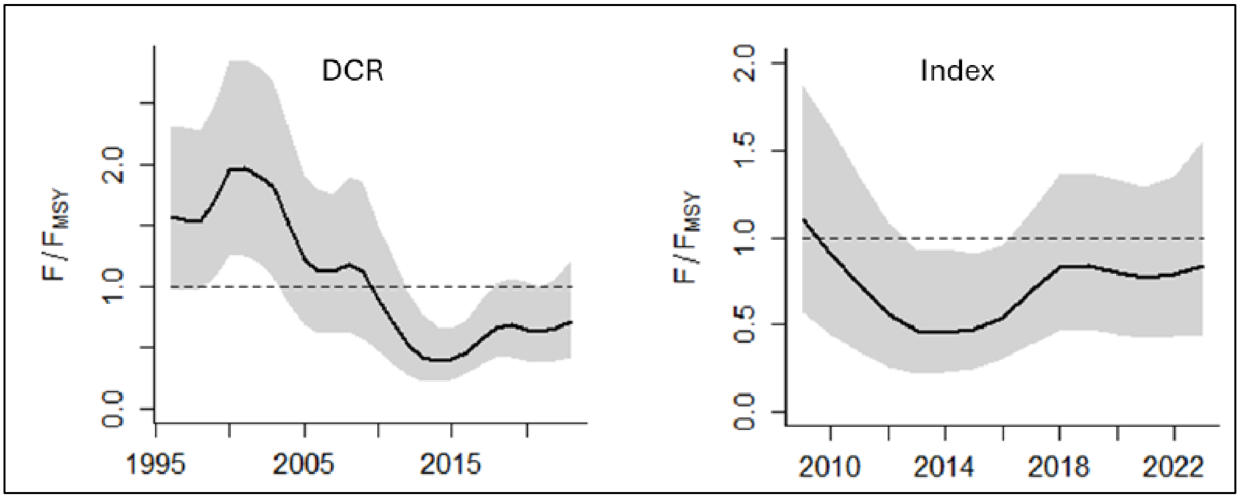


Figure 3. Relative harvest rate of whole lake, Lake Manitoba Walleye expressed as the estimated harvest rate in a given year divided by the harvest rate that would lead to the maximum sustainable yield. The left frame represents the estimate using fishery dependent daily catch record information. The right frame represents the estimate using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

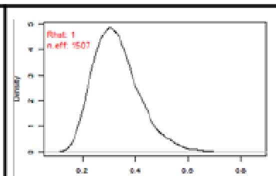
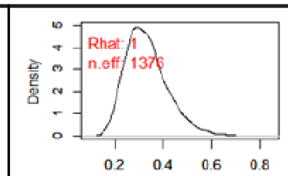
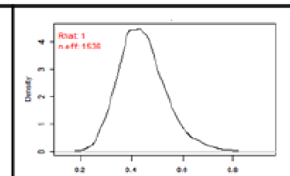
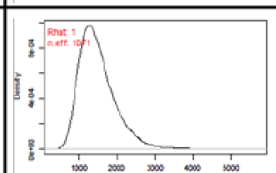
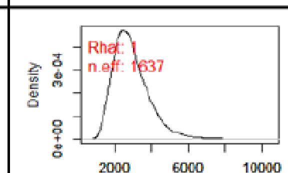
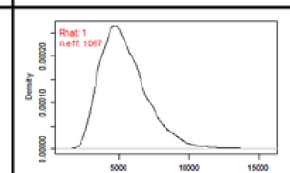
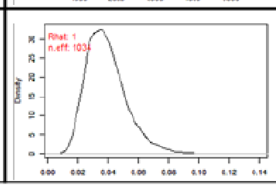
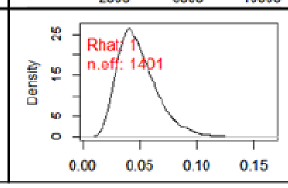
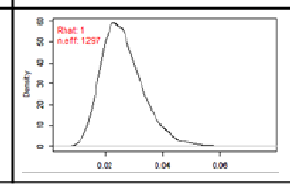
The probability that $F_{2023} < F_{MSY}$ is higher according to the fishery dependent relative to the fishery independent model. In the fishery dependent model, the probability is 0.89 that $F_{2023} < F_{MSY}$. In the fishery independent model, the probability is 0.71.

The whole lake estimate of maximum sustainable yield according to the fishery dependent model is 933 tonnes (95% C.I.: 683 t – 1301 t). The fishery independent model suggests an even larger maximum sustainable yield at 987 tonnes (95% C.I.: 697 t – 1474 t).

In addition to whole lake modeling, the Lake Manitoba Walleye stock was also modeled by area. The index netting series at the Narrows is just three years old, so there was not much value in trying to model the fishery independent case yet. The fishery dependent data were ignored in the area-specific modeling last year (Klein 2023). However, there are a significant number of deliveries made at the sheds of the Narrows, which is just Eddystone these days. Over the twenty-eight years of commercial data, the Narrows have averaged 1113 deliveries per year ranging from 258 to 1980. As a result of the richness of data, the Narrows was modeled as its own area this year using the fishery dependent data.

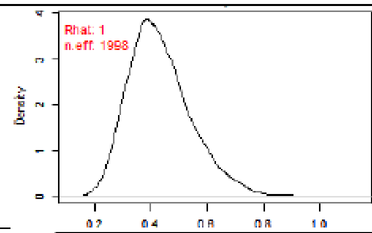
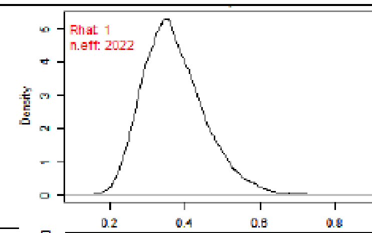
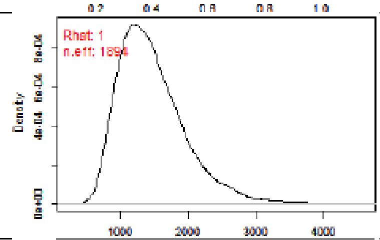
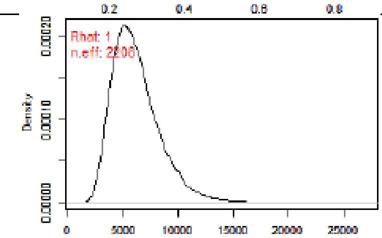
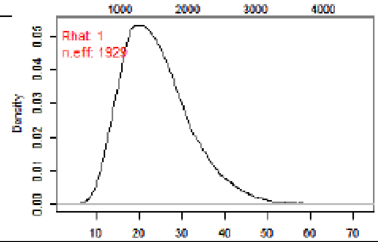
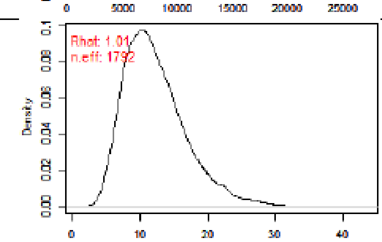
Using commercial daily catch records as the units of abundance, the north area of Lake Manitoba displayed an estimate of intrinsic growth rate at 0.320 (95% C.I.: 0.189 – 0.532). In the Narrows, the estimate was almost the same at 0.319 (95% C.I.: 0.193 – 0.530). The south basin estimate of intrinsic growth rate was much higher at 0.436 (95% C.I.: 0.284 – 0.654). The estimate of carrying capacity in the north was 1414 tonnes (95% C.I.: 801 t – 2674 t). The Narrows estimate was 2767 tonnes (95% C.I.: 1472 t – 5334 t). And the south basin estimate of carrying capacity was 5135 tonnes (95% C.I.: 2855 t – 9381 t) (Table 4).

Table 4. Estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the Lake Manitoba commercial Walleye fishery modeled by lake area, and the posterior distributions of each estimate. All columns are based on the total Walleye deliveries per year and the mean amount declared on the daily catch records. The estimates in the left column are for the north area of Lake Manitoba. The estimates in the centre column are for the Narrows (Eddystone and Vogar sheds). The estimates in the righthand column are for the south basin. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

	North		Narrows		South	
r	0.320		0.319		0.436	
K	1501 t		2927 t		5396 t	
q	0.0390		0.0480		0.0263	

Parameter estimates were different when modeled with index netting catch as the index of abundance instead of the commercial daily catch record data. The north area of the lake displayed the faster intrinsic growth rate at 0.418 (95% C.I.: 0.250 – 0.692). The south exhibited a slower rate at 0.362 (0.235 – 0.565). The estimates of carrying capacity meanwhile were very close to fishery dependent estimates. In the north area, the carrying capacity was estimated at 1393 tonnes (95% C.I.: 764 t – 2686 t). In the south basin, the carrying capacity of Walleye was estimated at 5858 tonnes using index netting abundance (95% C.I.: 3077 t – 11,466 t) (Table 5).

Table 5. Estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the Lake Manitoba commercial Walleye fishery modeled by lake area, and the posterior distributions of each estimate. Parameter estimates are based on the total Walleye deliveries per year and the mean index netting catch per set in each area. The estimates in the left column are for the north area of Lake Manitoba. The estimates in the righthand column are for the south basin. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

<table>
<tr><th></th><th colspan="2">North</th><th colspan="2">South</th></tr>
<tr><td>r</td><td>0.418</td><td>
</td><td>0.362</td><td>
</td></tr>
<tr><td>K</td><td>1393 t</td><td>
</td><td>5858 t</td><td>
</td></tr>
<tr><td>q</td><td>23.12</td><td>
</td><td>11.54</td><td>
</td></tr>
</table>

The fishery dependent model in the north area estimated Walleye to have a much higher relative abundance than did the estimate based on the index netting programme. The model based on daily catch records estimates the north basin biomass in 2023 was 1043 tonnes (95% C.I.: 544 t – 2073 t). Biomass of that size would be 1.48 times the biomass required to generate the maximum sustainable yield (95% C.I.: 1.19 – 1.72). The model using index netting abundance estimates a smaller biomass in 2023 at 796 tonnes (95% C.I.: 412 t – 1556 t). The two models estimated very similar biomasses at maximum sustainable yield. The fishery dependent case put B_{MSY} at 707 tonnes (95% C.I.: 401 t -1337 t). The fishery independent model calculated B_{MSY} at 697 tonnes (95% C.I.: 382 t – 1343 t), so the ratio B_{2023}/B_{MSY} is 1.16 (95% C.I.: 0.85 – 1.42). The fishery independent model is completely certain that the stock is above the point of recruitment impairment and demonstrates a 0.85 probability that $B_{2023} > B_{MSY}$. The fishery dependent model is 99.8% sure $B_{2023} > B_{MSY}$ (Figure 4).

The Narrows was only modeled with fishery dependent data. The Walleye stock biomass estimate in 2023 was 1471 tonnes (95% C.I.: 736 t – 2999 t). The biomass required for the maximum sustainable yield was estimated at 1383 tonnes (95% C.I.: 736 t – 2667 t). The ratio of biomass in 2023 to the biomass for maximum sustainable yield was 1.07 (95% C.I.: 0.78 – 1.40). There is 100%

chance that biomass is above the point of recruitment impairment, and a probability of 0.71 that $B_{2023} > B_{MSY}$ (Figure 4).

There is high congruency between the fishery dependent and the fishery independent estimates of biomass in the south basin. The model using daily catch record data estimates the south basin biomass at 3110 tonnes (95% C.I.: 1636 t – 5619 t). The model using index netting data estimates the biomass at 2929 tonnes (95% C.I.: 1539 t – 5733 t). Estimates of the biomass needed for the maximum sustainable yield were lower in the fishery dependent model owing to the higher estimate of intrinsic growth rate. The estimate of B_{MSY}, according to the fishery dependent model, was 2567 tonnes (95% C.I.: 1428 t – 4691 t), whereas the fishery independent model estimated B_{MSY} = 2929 tonnes (95% C.I.: 1539 t – 5733 t). The ratios of B_{2023}:B_{MSY} were 1.21 (95% C.I.: 0.94 – 1.45) for the fishery dependent model and 1.03 (95% C.I.: 0.73 – 1.34) for the fishery independent model. Both models are completely certain that the south basin Walleye stock is above the point of recruitment impairment. The chances that $B_{2023} > B_{MSY}$ is 0.94 in the fishery dependent model, and 0.56 in the fishery independent model (Figure 4).

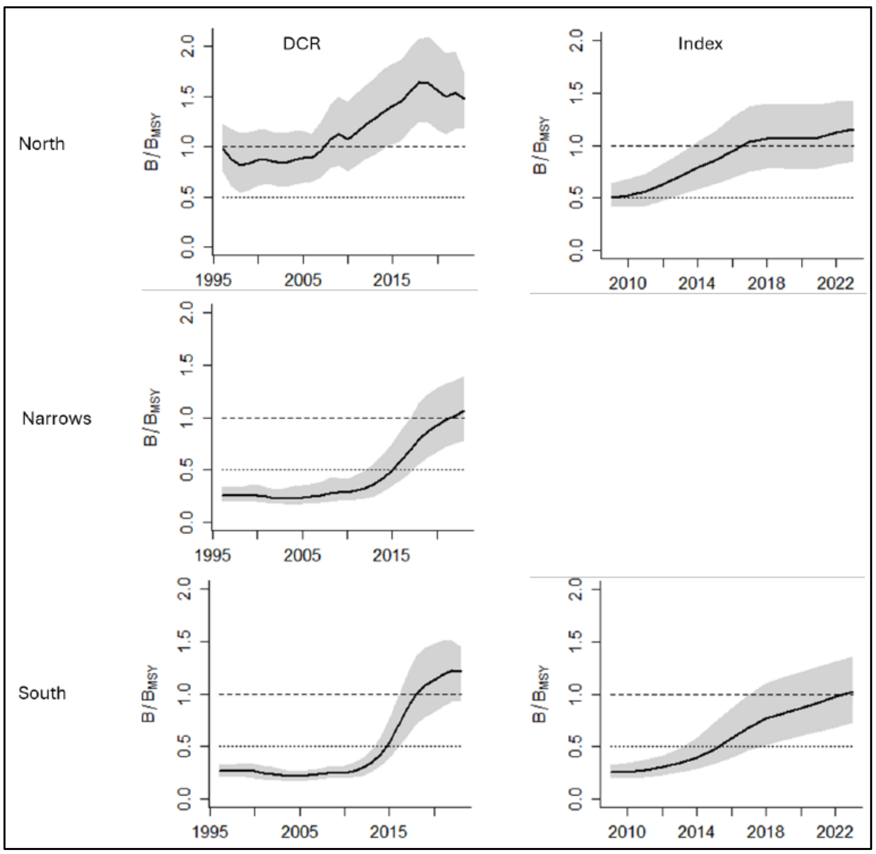


Figure 4. Relative biomass of Lake Manitoba Walleye by area expressed as the estimated biomass in a given year divided by the biomass that would support the maximum sustainable yield. The left column represents the estimates using fishery dependent daily catch record information. The right column represents the estimates using fishery independent index netting data. Top row is the northern area of Lake Manitoba. The middle row is the Narrows area (Eddystone and Vogar sheds. No index netting series.) The bottom row is the south basin models. Shaded areas are the 95% credibility intervals.

As it was in whole lake analyses, all the area-wise models suggest the fishing rates are favourable; less that the rate that would result in the maximum sustainable yield. In the north area, the estimated removal rate using fishery dependent data is at 9.5% (95% C.I.: 4.4% - 20.5%). Using the fishery independent data stream, the removal rate is estimated at 12.5% (95% C.I.: 5.7% - 26.9%). However, the estimated harvest rate that would lead to the maximum sustainable yield is also higher according to the fishery dependent data at 16.0% (95% C.I.: 9.4% - 26.6%) than the estimate derived from the fishery independent data of 20.9% (95% C.I.: 12.5% - 34.6%), so the ratios of harvest rate to that which would lead to the maximum sustainable yield turn out to be very similar between the two data streams. Where the model used daily catch record information, the ratio was 0.599 (95% C.I.: 0.345 – 1.038). Where the model used index netting abundance, the north area fishing rate was estimated to 0.596 (95% C.I.: 0.340 – 1.063). Models formulated with either data stream are also in agreement on how little uncertainty there is relative to the fishing rate. The fishery dependent model is 96.6% certain that $F_{2023} < F_{MSY}$, and the fishery independent model is similarly certain at 96.9% (Figure 5).

At the Narrows, the fishery dependent model calculated a harvest percentage for the maximum sustainable yield very much like the rate in the north area at 16.0% (95% C.I.: 9.6% - 26.5%). The calculated fishing rate, however, is higher at 13.6% (95% C.I.: 6.0% - 30.5%) suggesting a relative exploitation of 0.85 (95% C.I.: 0.46 – 1.58) with a probability of 0.70 that $F_{2023} < F_{MSY}$ (Figure 5).

In the south basin, the model fed by fishery dependent data calculated the highest harvest fraction at maximum sustainable yield among all the model permutations at 21.8% (95% C.I.: 14.2% - 32.7%). The estimate from the model using fishery independent data was more modest 18.1% (95% C.I.: 11.8% - 28.2%). The estimate of the actual harvest fraction of south basin Walleye in 2023 according to the fishery dependent model was 15.6% (95% C.I.: 7.7% - 33.4%) for a relative harvest rate ratio of 0.72 (95% C.I.: 0.40 – 1.35). The model suggests a probability of 0.85 that $F_{2023} < F_{MSY}$. By way of comparison, the model informed by fishery independent data for south basin Walleye estimated a removal rate of 16.3% in 2023 (95% C.I.: 7.1% - 37.3%) yielding a relative harvest rate of 0.90 (95% C.I.: 0.47 – 1.70) with broad uncertainty and just a 0.63 probability that $F_{2023} < F_{MSY}$ (Figure 5).

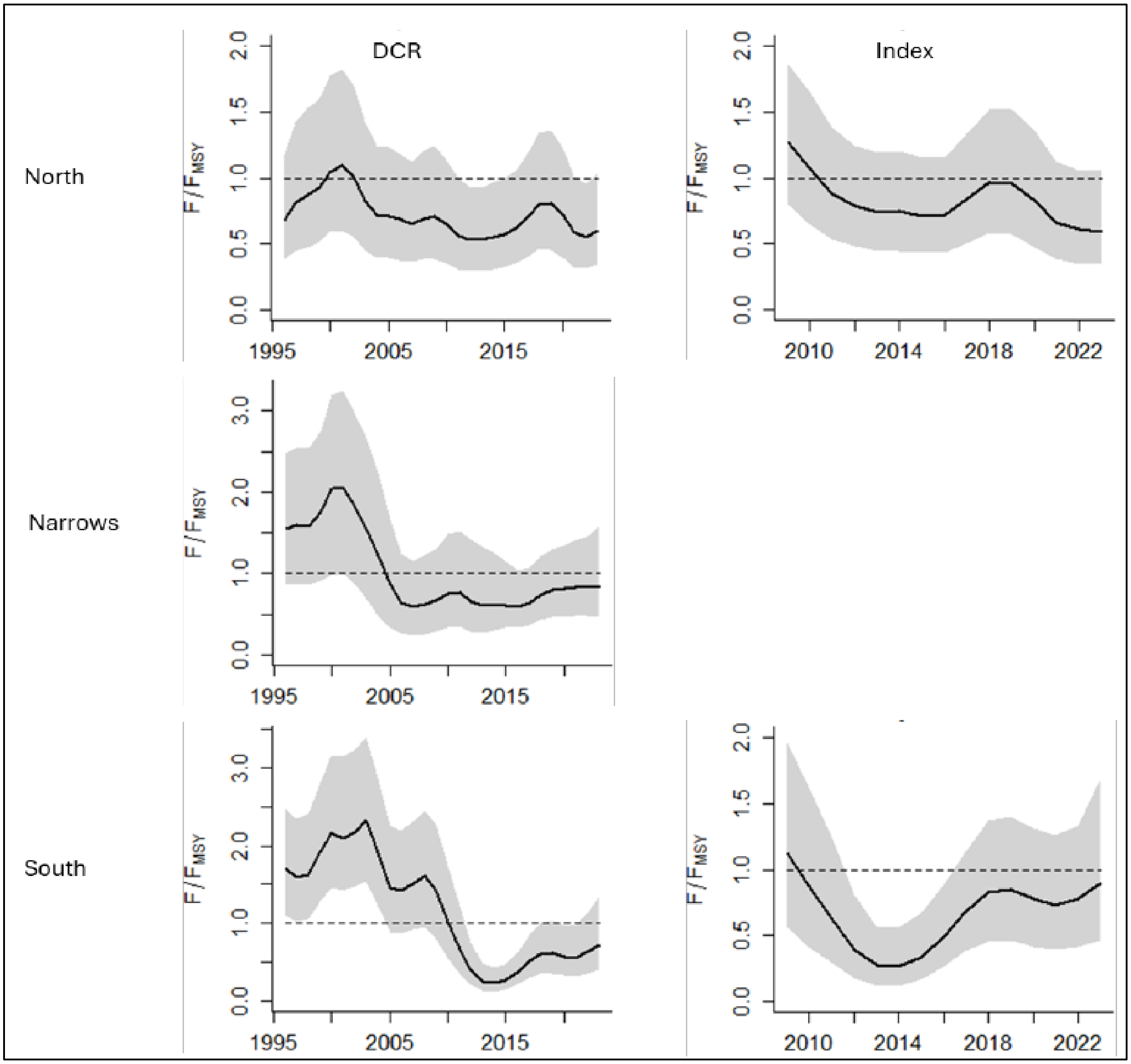


Figure 5. Relative harvest rate of Lake Manitoba Walleye by area expressed as the estimated harvest rate in a given year divided by the harvest rate that would lead to the maximum sustainable yield. The left column represents the estimates using fishery dependent daily catch record information. The right column represents the estimates using fishery independent index netting data. Top row is the northern area of Lake Manitoba. The middle row is the Narrows area (Eddystone and Vogar sheds. No index netting series.) The bottom row is the south basin models. Shaded areas are the 95% credibility intervals.

Sauger

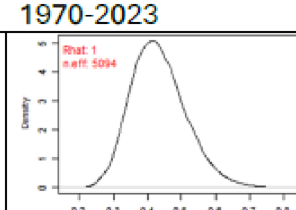
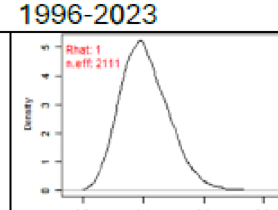
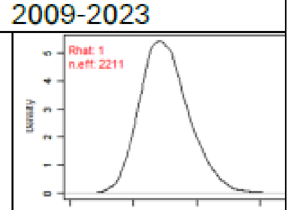
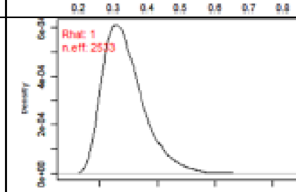
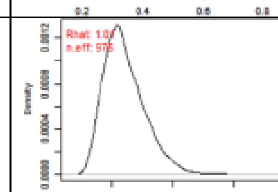
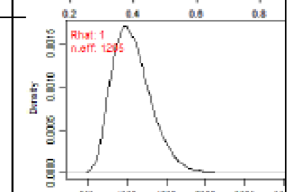
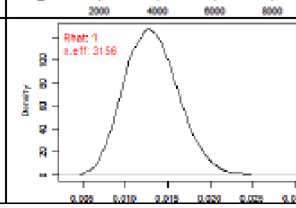
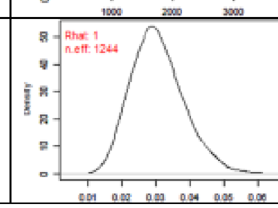
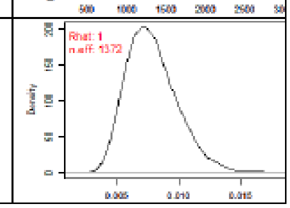
Surplus Production Modeling

Whole Lake Models

Estimates of Sauger intrinsic growth rates for the whole lake models are higher when using fishery independent data than when fishery dependent data are used. Index netting abundance suggested the intrinsic growth rate of Sauger is 0.497 (95% C.I.: 0.369-0.667). When daily catch record delivery size was used in modeling, the two whole lake models produced similar estimates of growth rate. The model using average delivery size since 1970 estimated intrinsic growth rate at 0.426 (95% C.I.: 0.295-0.611), while the model using the geometric mean delivery size since 1996 estimated 0.399 (95% C.I.: 0.269-0.577) (Table 6).

The model using the longer time series determined the Lake Manitoba carrying capacity for Sauger was much larger than the models whose time series began in 1996. The longer time series model estimated carrying capacity at 2775 tonnes (95% C.I.: 1792 t – 4735 t). The fishery dependent model beginning in 1996 estimated the carrying capacity at 1152 tonnes (95% C.I.: 674 t – 2032 t). The fishery independent model estimated Lake Manitoba could support 1054 tonnes of Sauger (95% C.I.: 688 t – 1633 t) (Table 6).

Table 6. Estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the Lake Manitoba commercial Sauger fishery modeled as a single, whole-lake stock, and the posterior distributions of each estimate. Parameter estimates are based on the total Sauger deliveries per year. The estimates in the left column are for mean deliveries since 1970. The centre column contains the parameter estimates for the geometric mean delivery each year since 1996. The estimates in the righthand column use index netting abundance since 2009 as the measure of abundance. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

	DCR				Index Netting	
	1970-2023		1996-2023		2009-2023	
r	0.426		0.399		0.497	
K	2775 t		1152 t		1047 t	
q	0.0130		0.0299		0.00760	

The different whole lake models have different impressions of where the stock biomass sits are relative to the point of recruitment impairment. The model using average delivery size since 1970 is the most pessimistic among the three models. It suggests there is only a 12.7% chance that the stock is above the point of recruitment impairment and that the median estimate of biomass relative to the carrying capacity is just 0.38. When geometric means of the commercial deliveries since 1996 are used to inform the model and the historic abundance of Sauger is hidden, the model median estimate of relative abundance improves to 0.56 with a probability of 0.73 that the biomass is above the point of recruitment impairment. The most optimistic model is the fishery independent one where the index programme data is used as the index of abundance. In that case, the model has not seen the historic potential biomass and the index of abundance has only risen since implementation in 2009. The fishery independent model believes with 99.6% certainty that the stock is above the point of recruitment impairment, and that the stock is at 84% of the biomass required to produce the maximum sustainable yield (Figure 6).

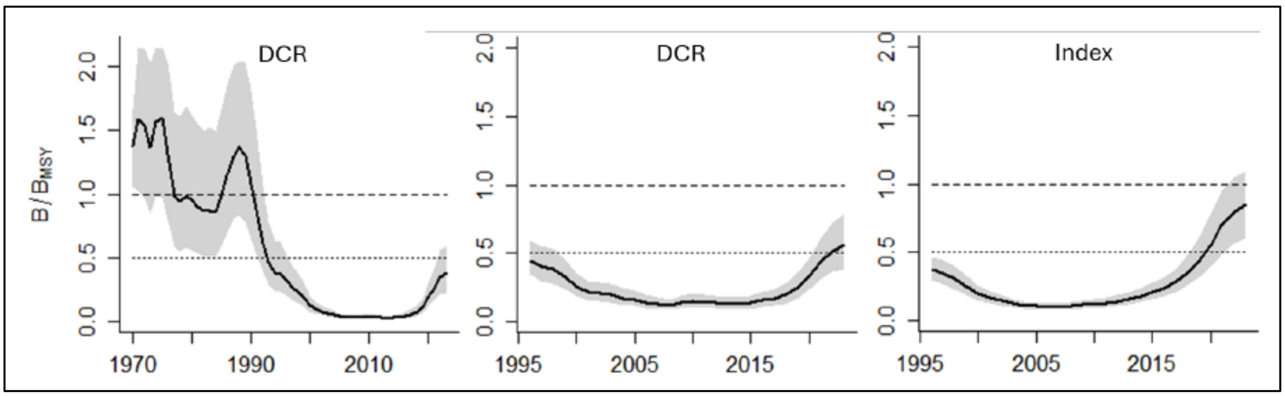


Figure 6. Relative biomass of Lake Manitoba Sauger on a lakewide basis expressed as the estimated biomass in a given year divided by the biomass that would support the maximum sustainable yield. The left frame represents the estimates using average catch back to 1970. The centre frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

None of the models estimates the Sauger biomass to be at the level needed to produce the maximum sustainable yield. The fishery independent model is closest at 85% (95% C.I.: 0.60 – 1.10) allowing an 11.5% chance the biomass in 2023 was actually above the biomass needed to generate the maximum sustainable yield. The shorter fishery dependent model estimates the Sauger biomass in 2023 was 0.56 (95% C.I.: 0.38 – 0.78) of the biomass for maximum yield. The lowest estimate was the long time series which figured the stock is at only 0.38 (95% C.I.: 0.22 – 0.60) of the biomass at maximum yield (Figure 6). Neither of the fishery dependent models estimated there was any chance that the Sauger biomass had yet reached the amount required to produce the maximum yield.

Regardless of which lakewide model was considered, all appear to agree that relative stock size has been increasing. The models disagree on the trend in harvest rates. The fishery dependent model starting in 1970 suggests the relative harvest fraction has been decreasing since 2003. The other two whole lake models – the two with shorter time series – both estimate the relative harvest fraction to have been increasing since 2013 in the case of the fishery dependent model, and since 2014 in the case of the fishery independent model (Figures 6 and 7).

Where the trends land in 2023 differed among models. The fishery dependent model beginning in 1970 suggests the relative harvest fraction in 2023 was 1.158 times (95% C.I.: 0.434-3.840) the rate that would lead to the maximum sustainable yield. This is actually due to the precautionary programming of the model wherein the harvest fraction at the maximum sustainable yield departs from the Schaefer production function when the stock is estimated to be below the point of recruitment impairment by linearly reducing the harvest fraction at maximum sustainable yield so that management advice from the model results in faster recovery and guards against depensation. The actual ratio of the harvest fraction to what would lead to the maximum sustainable yield is 0.88, with only a 38% chance of exceedance. The shorter-term fishery dependent model suggests exploitation is 1.576 times (95% C.I.: 0.823-3.288) what it ought to be and that there is only an 8.5% chance this is not the case. The fishery independent model of whole lake fishing pressure believes that harvest fraction is only 0.903 times (95% C.I.: 0.499-1.684) the rate that would lead to the maximum sustainable yield, but the model reserves a 37.3% chance the harvest fraction might actually be too high (Figure 7).

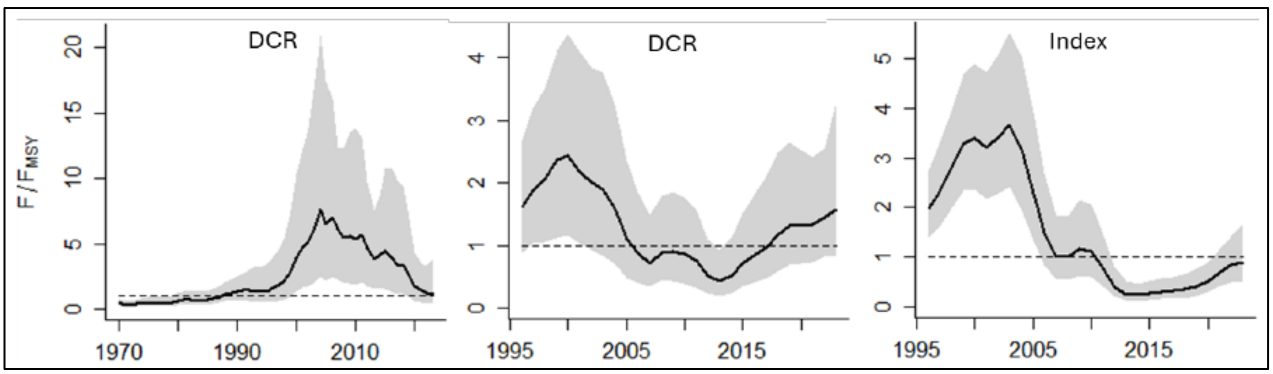


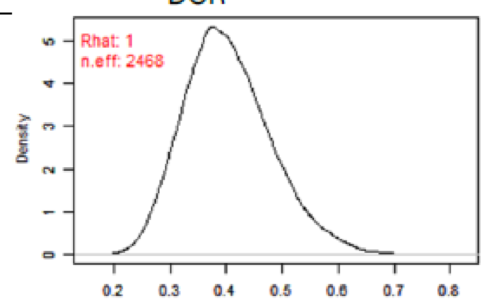
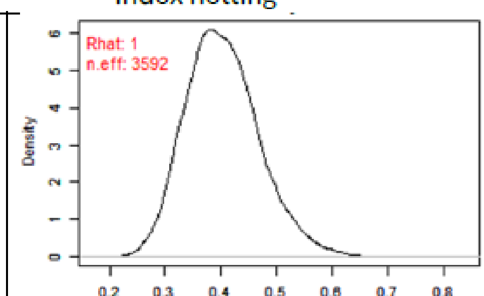
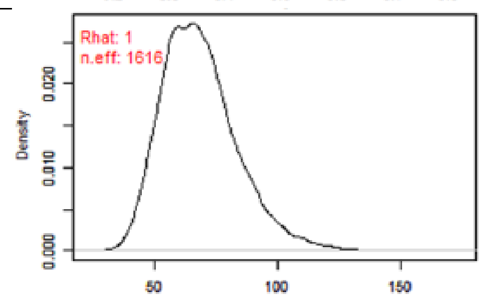
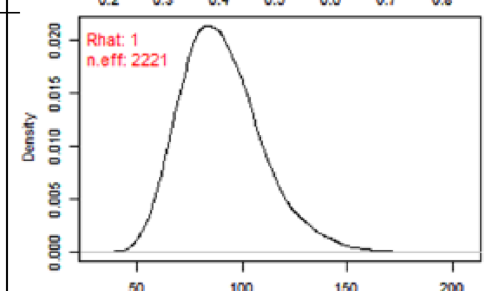
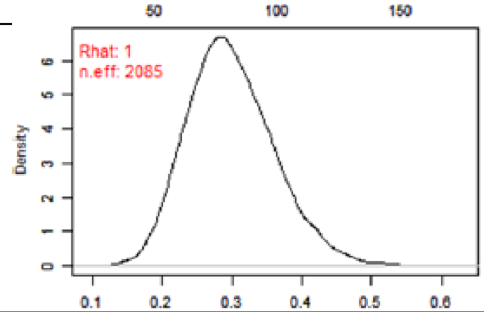
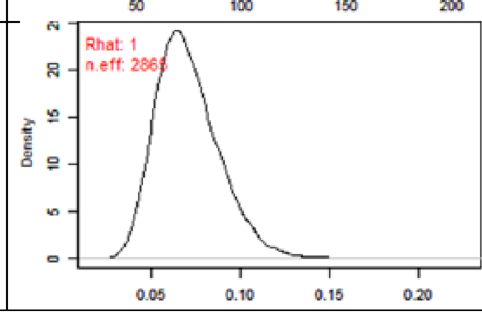
Figure 7. Relative harvest rate of Lake Manitoba Sauger on a lakewide basis expressed as the estimated harvest rate in a given year divided by the fishing rate that would lead to the maximum sustainable yield. The left frame represents the estimates using average catch per daily catch record back to 1970. The centre frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

The maximum sustainable yield calculated by the long time series fishery dependent model was 296 tonnes (95% C.I.: 211 t – 443 t). This is higher than either of the shorter time series models where the fishery dependent model from 1996 estimated the maximum sustainable yield at 115 tonnes (95% C.I.: 77 t – 178 t), and the fishery independent model estimated the maximum sustainable yield at 130 tonnes (95% C.I.: 93 t – 187 t).

North Area Specific Model

Whether the fishery independent data or the fishery dependent data was used to model the north area of Lake Manitoba Sauger, the estimate of intrinsic growth rate in the stock was similar. The fishery dependent model estimated growth at 0.397 (95% C.I.: 0.270-0.578). The fishery independent model estimated growth at 0.400 (95% C.I.: 0.290-0.548). The fishery independent model estimated the carrying capacity to be 21% larger than the estimate of the fishery dependent model. The fishery independent model estimated the carrying capacity to be 88.5 tonnes (95% C.I.: 58.3 t – 135.6 t). The fishery dependent model estimated the carrying capacity to be smaller at 67.2 tonnes (95% C.I.: 44.3 t – 105.0 t) (Table 7).

Table 7. Estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the north area Lake Manitoba commercial Sauger fishery, and the posterior distributions of each estimate. Parameter estimates are based on the total Sauger deliveries per year. The estimates in the left column are for geometric means of the daily catch records each year. The estimates in the righthand column use index netting abundance since 2009 as the measure of abundance. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

	DCR		Index netting	
r	0.397		0.400	
K	67.2 t		88.5 t	
q	0.294		0.0685	

Both models estimate the Sauger stock biomass in the north area of Lake Manitoba to be above the point of recruitment impairment, though just barely in the fishery dependent model. That model estimates the biomass in 2023 is 0.51 times the biomass required to produce the maximum sustainable yield (95% C.I.: 0.37-0.68) with a probability of 0.55 that the stock is above the point of recruitment impairment and complete certainty that the stock is smaller than the amount required to produce the maximum sustainable yield. The independent model estimates the 2023 biomass at 0.90 times the biomass for maximum sustainable yield (95% C.I.: 0.70-1.10). The fishery independent model is completely certain that the stock is above the point of recruitment impairment but only offers a 0.16 probability that the stock may be large enough to generate the maximum sustainable yield (Figure 8).

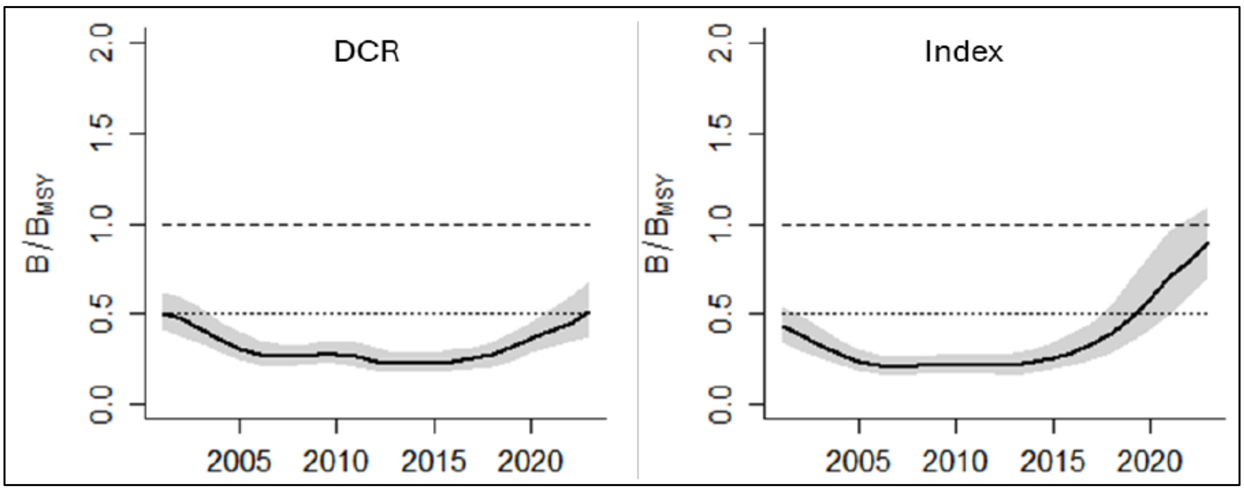


Figure 8. Relative biomass of Lake Manitoba Sauger in the northern part of the lake expressed as the estimated biomass in a given year divided by the biomass that would support the maximum sustainable yield. The left frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

Relative harvest rates in the north basin shows the same long-term trend of improvement since 2004 regardless of which index of abundance is used. Both models also agree that the current rate of harvest is below the rate that would lead to the maximum sustainable yield. The fishery dependent model estimates the rate of harvest relative to the rate for maximum sustainable yield at 0.73 (95% C.I.: 0.40-1.44) with a 0.16 probability the harvest rate might actually be excessive. The fishery independent model estimates the relative harvest rate at a small 0.30 (95% C.I.: 0.17-0.53). The independent model is completely certain the harvest rate in 2023 was less than the rate that would lead to the maximum sustainable yield (Figure 9).

The north area models estimated very small potential yields of Sauger. The fishery dependent model estimated a maximum sustainable yield of just 6.6 tonnes (95% C.I.: 4.9 t – 9.2 t). The fishery independent model thought there were slightly more Sauger to be had with a maximum sustainable yield of 8.8 tonnes (95% C.I.: 6.2 t – 12.6 t).

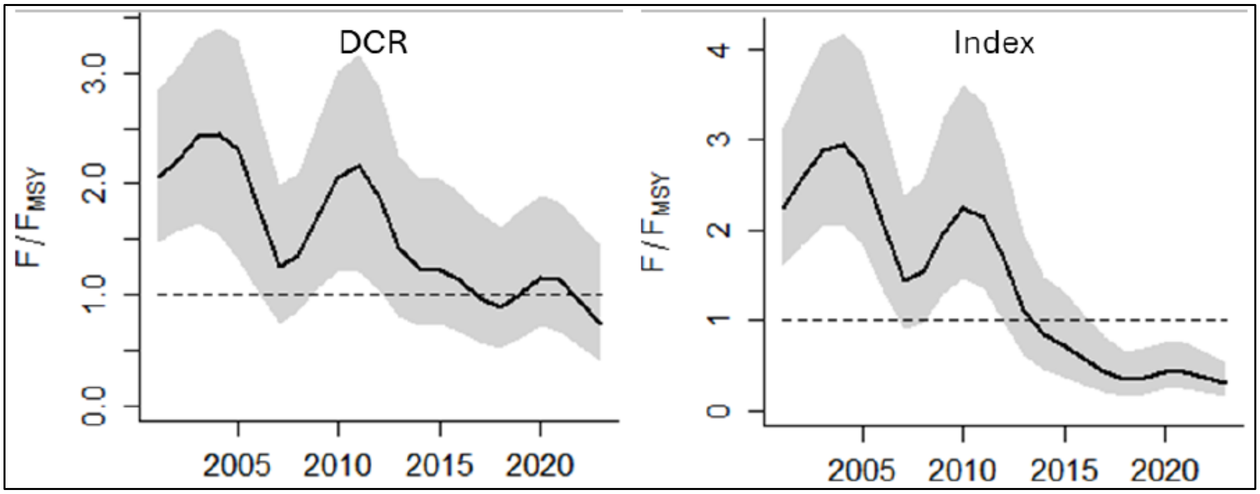


Figure 9. Relative harvest rate of Lake Manitoba Sauger in the northern part of the lake expressed as the estimated harvest rate in a given year divided by the fishing rate that would lead to the maximum sustainable yield. The left frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

Narrows

Commercial Sauger deliveries to the Eddystone and Vogar packing sheds were excluded from the basin specific assessments because both basins are geographically close to those areas. Upon examination of the number of deliveries per year, it was evident that Sauger deliveries to the Narrows sheds could be numerous in some years, 1162 deliveries in 2022. Therefore, a fishery dependent model was run for Narrows area packing sheds. The index netting programme only has three years of data from the Narrows to date, so it was not worth running a fishery independent model yet.

Parameter estimates for the Narrows should be interpreted with caution. The intrinsic growth rate is estimated to be 0.361 (95% C.I.: 0.255-0.516). The carrying capacity is estimated to be 225 tonnes (95% C.I.: 130 t – 412 t).

In 2023 the relative stock size is estimated to have climbed above the biomass required for maximum sustainable yield at 118 tonnes (95% C.I.: 61 t – 233 t). The model is 99.97% certain the stock is larger than the point of recruitment impairment and 62.5% sure the biomass is greater than the biomass required for maximum sustainable yield. The fishing rate was estimated to have been a little excessive for the past three years leading up to 2023, but in 2023 the harvest fraction fell to an acceptable rate again at 0.83 of the fishing rate that would produce the maximum sustainable yield (95% C.I.: 0.41-1.66). The probability that the harvest fraction was above the rate for maximum sustainable yield was 0.70 (Figure 10).

The Narrows model estimated a maximum sustainable yield of 20.4 tonnes (95% C.I.: 12.8 t – 33.2 t).

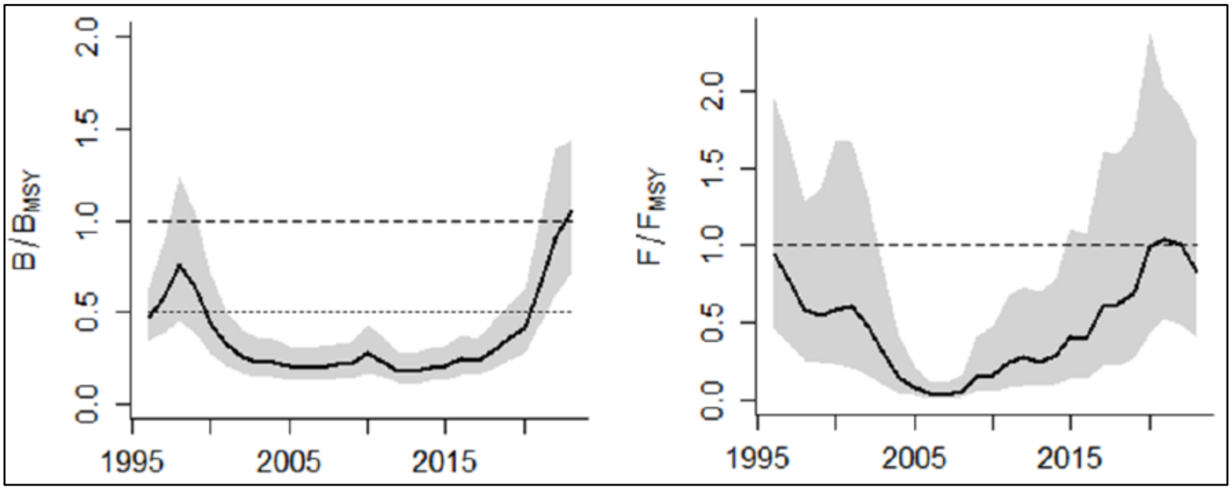
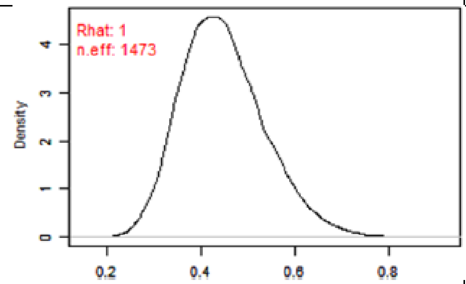
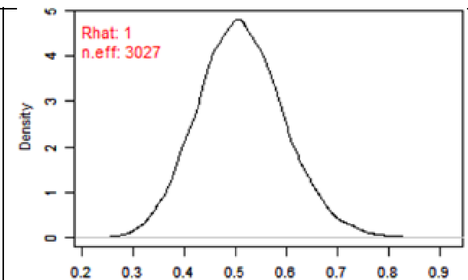
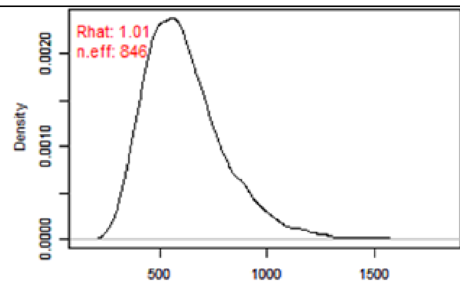
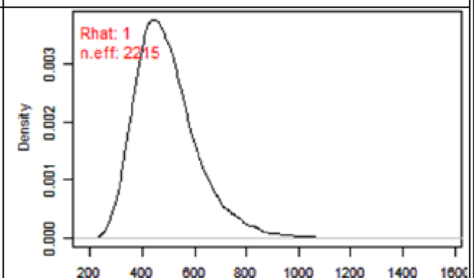
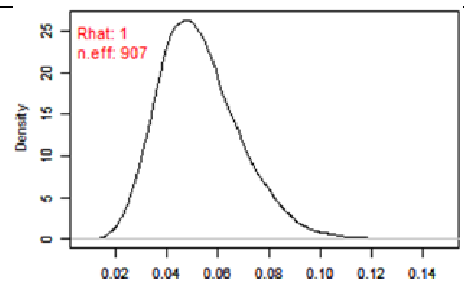
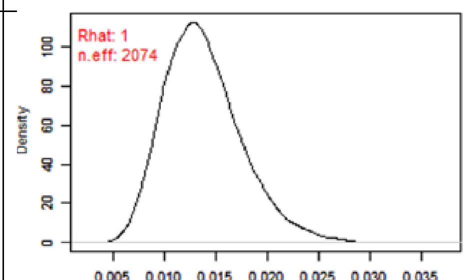


Figure 10. Relative biomass (left frame) and relative harvest rate of Sauger at the Narrows of Lake Manitoba estimated from the daily catch records produced by the Eddystone and Vogar packing sheds from 1996 to 2023.

South Basin

The south basin models exhibited higher intrinsic growth rates than the north area, and so, higher than the whole lake resilience as well. The fishery dependent model estimated growth rate at 0.440 (95% C.I.: 0.295-0.644). The fishery independent model estimated the intrinsic growth rate at 0.508 (95% C.I.: 0.352-0.687). The fishery dependent model estimated carrying capacity at 585 tonnes (95% C.I.: 335 t – 1084 t). The fishery independent model estimated carrying capacity at 479 tonnes (95% C.I.: 313 t – 806 t) (Table 8).

Table 8. Estimates of the intrinsic growth rate, r, the carrying capacity, K, and the catchability, q, in the south basin Lake Manitoba commercial Sauger fishery, and the posterior distributions of each estimate. Parameter estimates are based on the total Sauger deliveries per year. The estimates in the left column are for geometric means of the daily catch records each year. The estimates in the righthand column use index netting abundance since 2009 as the measure of abundance. *Rhat* is the potential scale reduction factor. *n.eff* is the number of effective samples.

	DCR		Index netting	
r	0.440		0.508	
K	585 t		479 t	
q	0.0509		0.0134	

According to the fishery dependent model, in 2023, the south basin Sauger stock biomass just eked over the level required for maximum sustainable yield with a ratio of 1.00 (95% C.I.: 0.72-1.33) and a probability of 0.51 that the ratio was at least unity. The fishery independent model is more optimistic calculating the south basin Sauger stock biomass at 1.22 times the stock size needed to support the maximum sustainable yield (95% C.I.: 0.93-1.53). As with the fishery dependent model, the fishery independent model is 100% certain the stock biomass is above the point of recruitment impairment, however it allows a 7.4% chance that may not be true for the biomass required to produce the maximum sustainable yield (Figure 11).

Both models, fishery dependent and fishery independent, recognise an increasing trend in harvest rate relative to the rate that would deliver the maximum sustainable yield. The increase in harvest fraction began in 2013 according to both models. The fishery dependent model calculated the harvest rate to be excessive; 1.15 times the rate at maximum sustainable yield (95% C.I.: 0.59-2.17) with a 0.66 probability of exceedance. The fishery independent model meanwhile figured the harvest rate was almost exactly at the maximum sustainable yield rate at unity (95% C.I.: 0.54-1.81) with a 49.5% chance the harvest rate was too high (Figure 12).

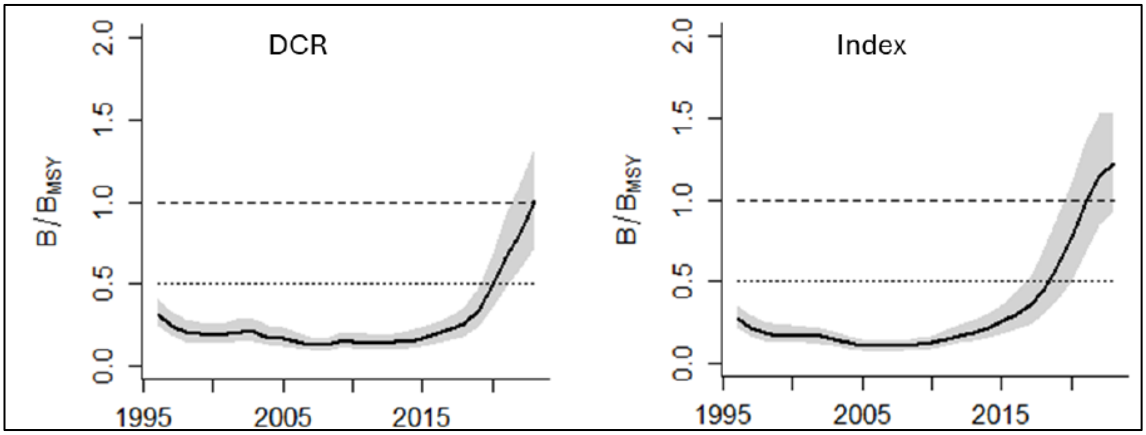


Figure 11. Relative biomass of Lake Manitoba Sauger in the south basin of the lake expressed as the estimated biomass in a given year divided by the biomass that would support the maximum sustainable yield. The left frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

South basin sustainable yields were estimated at 64.2 tonnes (95% C.I.: 43.0 t – 101.6 t) by the fishery dependent model, and almost the same at 60.8 tonnes (95% C.I.: 43.2 t – 88.7 t) by the fishery independent model.

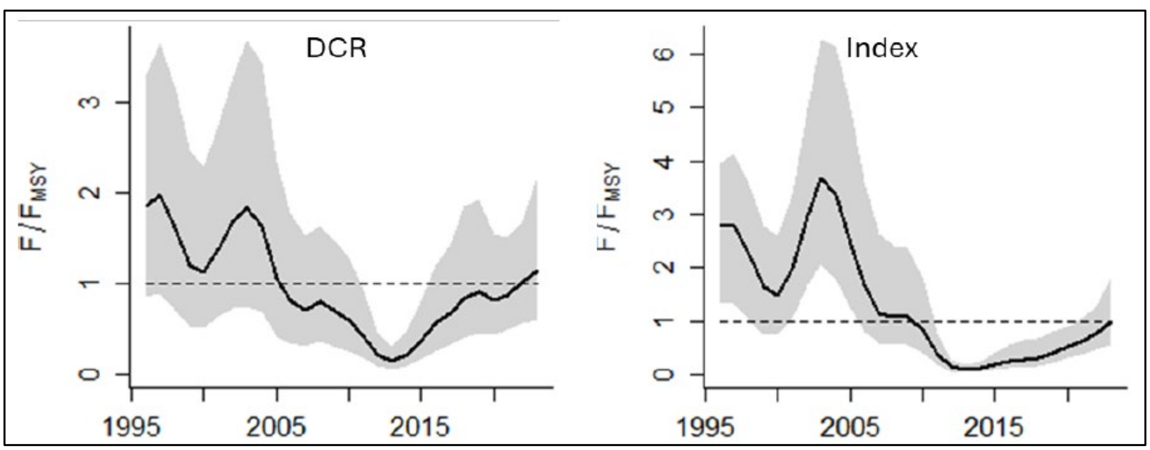


Figure 12. Relative harvest rate of Lake Manitoba Sauger in the south basin of the lake expressed as the estimated harvest rate in a given year divided by the fishing rate that would lead to the maximum sustainable yield. The left frame depicts the model using individual daily catch records since 1996. The right frame represents the model using fishery independent index netting data. Shaded areas are the 95% credibility intervals.

Walleye Life History

Growth

Walleye growth is faster and asymptotes at a shorter length in the south of Lake Manitoba than in the north. In all three areas – north, Narrows, and south – females grow larger than males (Figure 13). The largest asymptotic length was observed in north basin females. The shortest asymptotic length was displayed by male fish in the Narrows. North basin females were the oldest fish that could be collected. Brody growth coefficients range from 0.15 yr-1 in north area females to 0.40 yr-1 in south basin males. Number of effective samples were highest in Narrows males and lowest in south basin males. The number of effective samples were very similar among all female sites for the asymptotic length and the Brody growth coefficient (Table 7). All potential scale reduction factors were equal to unity.

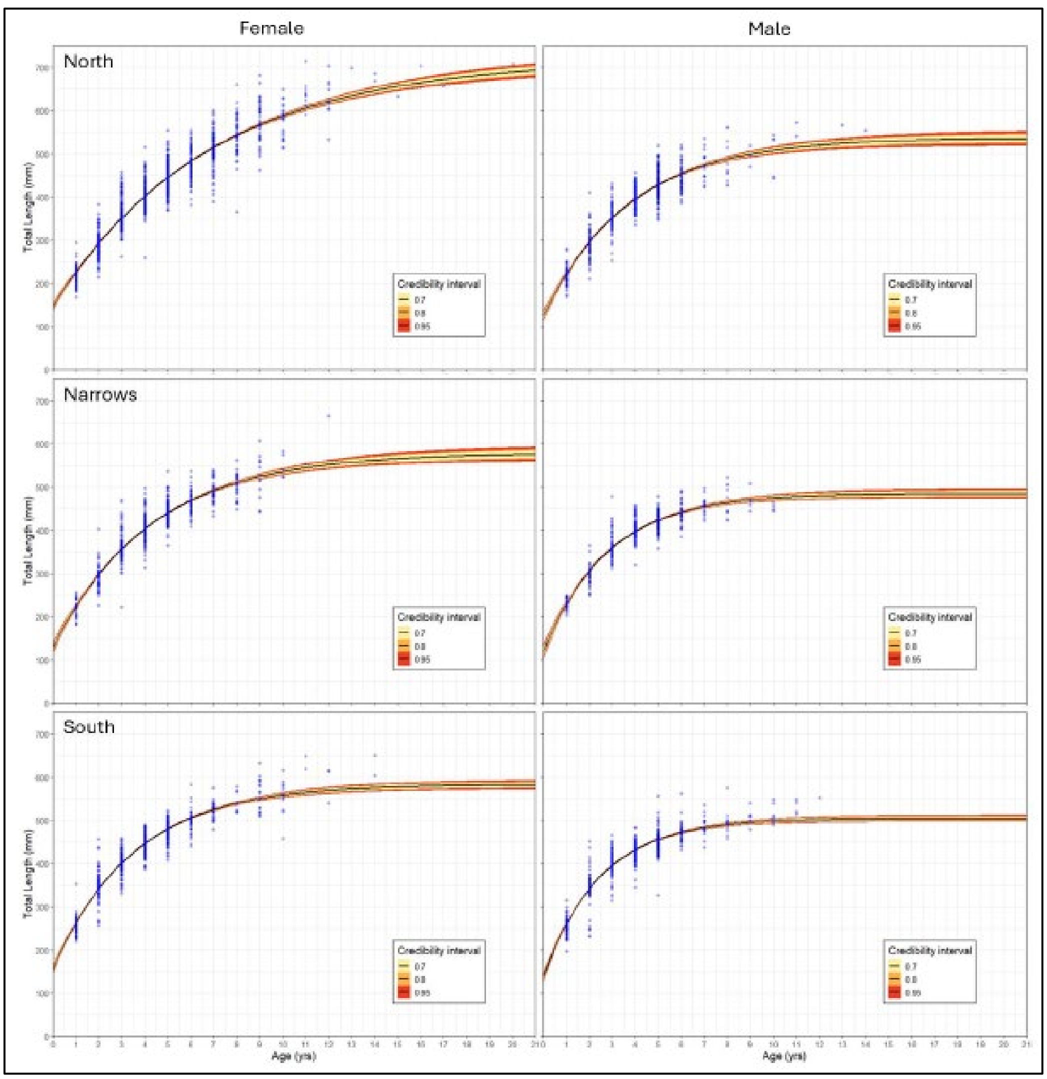


Figure 13. von Bertalanffy growth curves of Lake Manitoba Walleye using index netting data from 2021 to 2023. Left column is female Walleye. Right column is male Walleye. Top row is north area fish. Centre row is based on Narrows area fish. Lower row is south basin fish.

Table 7. Length at infinite age and Brody growth coefficients for Walleye in the three areas of Lake Manitoba. Data are from the index netting programme from 2021 to 2023.

Sex	Area	L^{∞}			k		
		Mean	s.d.	N_eff	Mean	s.d.	N_eff
Female	North	718	12.4	2761	0.15	0.01	2603
	Narrows	578	9.6	2942	0.24	0.01	2694
	South	583	5.9	2925	0.28	0.01	2937
Male	North	536	9.1	2993	0.27	0.01	2748
	Narrows	485	5.8	3778	0.36	0.02	3394
	South	504	4.3	2410	0.40	0.02	2116

Maturity

Walleye mature at younger ages in the south basin than in the Narrows or north area by about half a year at the 50% mature mark. To reach 95% maturity, the gap between the south basin and other areas increases to almost a full year among female Walleye. Differences exist between the south basin and the two other fishing areas as well when length at maturity is considered. The south basin Walleye reach 50% maturity at a length around 20 mm longer than the other areas (Table 8).

Table 8. Maturity schedules of Lake Manitoba Walleye based on index netting samples from 2021 to 2023. Maturities based on age represent the age of fish at the time of spawning. Maturities based on length are the measured lengths in the September preceding spawning. Maturity ogives for each fishing area are available in Appendix 3.

	Sex	North		Narrows		South	
		Estimate	Std Err	Estimate	Std Err	Estimate	Std Err
Age at 50% maturity	Female	5.64	0.049	5.78	0.059	5.15	0.045
	Male	4.24	0.056	4.12	0.067	3.69	0.049
Age at 95% maturity	Female	7.14	0.110	7.21	0.139	6.29	0.102
	Male	5.34	0.108	5.24	0.121	4.62	0.082
Length at 50% maturity	Female	427	2.02	431	1.93	449	1.59
	Male	360	2.48	360	2.92	382	2.25
Length at 95% maturity	Female	488	4.44	476	4.22	488	3.39
	Male	407	4.35	402	4.35	418	3.01

Natural Mortality

Lake Manitoba Walleye natural mortality rates were only estimated for female Walleye. The NOAA Natural Mortality Tool produced a median estimate of the natural mortality rate among north area females of 0.25 with a 95% confidence interval between 0.24 and 0.26. The Narrows index netting data led to a weighted median natural mortality rate of 0.28 (95% C.I.: 0.27-0.29). And the south basin netting suggested a weighted median natural mortality rate of 0.31 (95% C.I.: 0.29 – 0.32) for female Walleye (Figure 14).

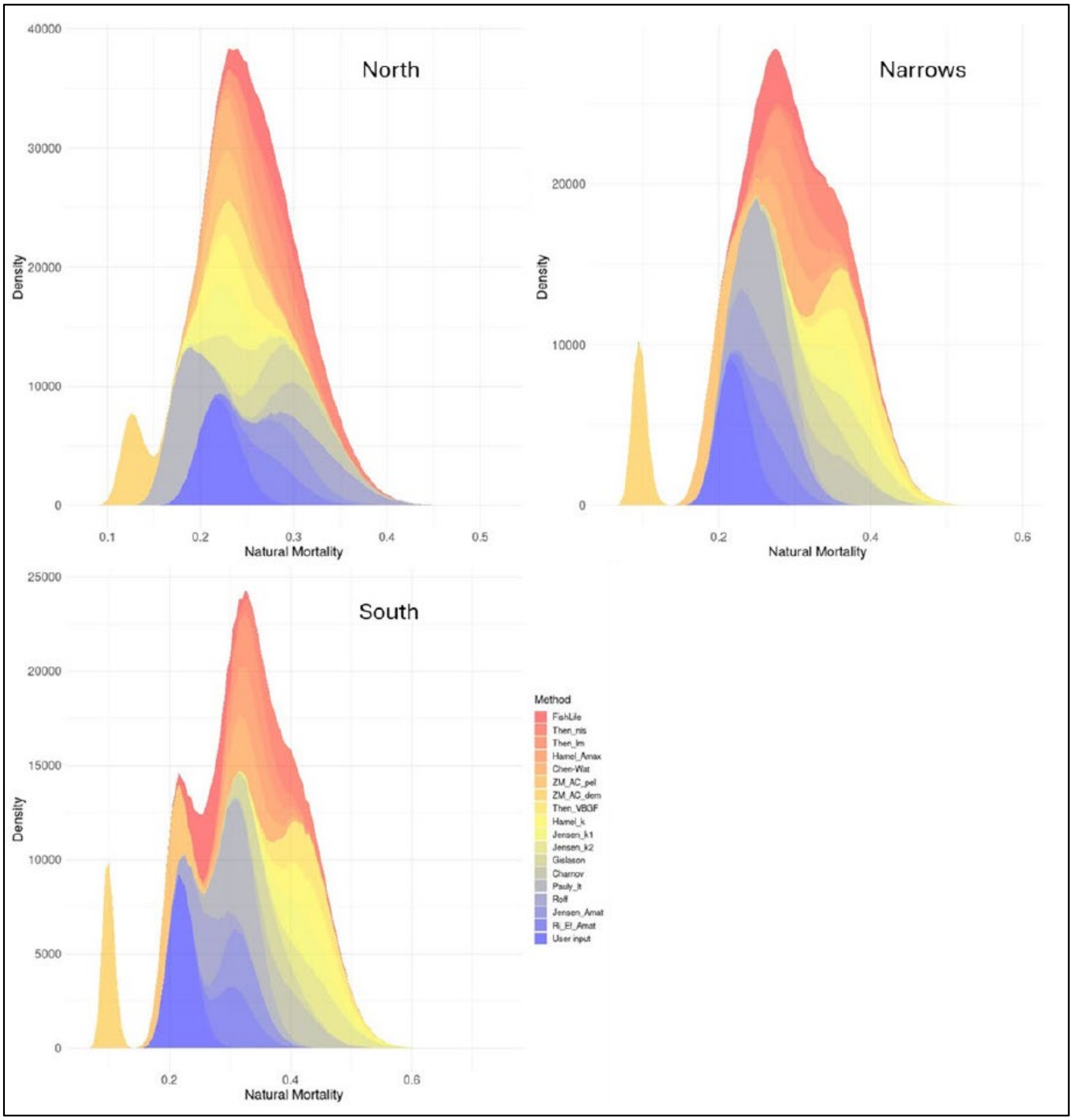


Figure 14. Composite densities of natural mortality estimates of female Lake Manitoba Walleye. Upper left panel is the density for north area females. Upper right panel is the density for Narrows area female Walleye. Lower left panel is the density for south basin female Walleye.

Recruitment

Abundance of Lake Manitoba Walleye has been increasing since the 2010-year class entered the index netting program as four-year-olds. Two exceptional year classes are supporting the commercial Walleye fisheries on Lake Manitoba: the 2013-year class, which is now aging out of the fishery; and the 2018-year class which was right on the 95 and 102 mm web in the 2023/24 fishing season. Average year classes were produced in 2014 and 2017. Year classes in 2012, 2015 and 2016 were the poorest extant in the fishery. The 2019-year class appears poor, but there is only one year of data so far to support that statement (Figure 15).

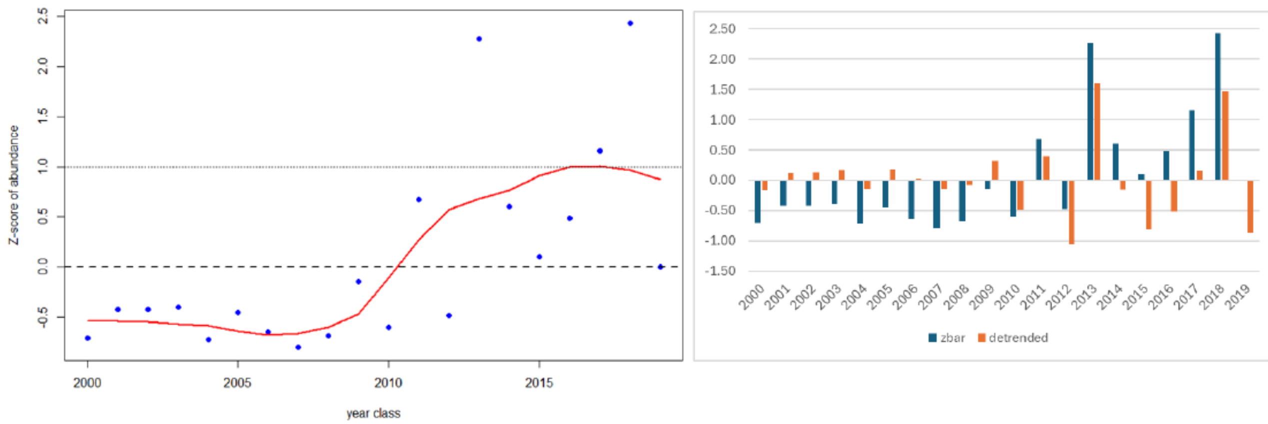


Figure 15. Z-score estimates of Lake Manitoba Walleye year class strengths based on index netting data from 2009 to 2023. The left panel shows the LOESS smoother (span = 0.65) used to produce the detrended values (residuals) in the right panel. The right panel depicts the year class strengths in standard deviations in blue, and the detrended values in orange.

Discussion

Walleye

Surplus Production Modeling

Surplus production modeling suggests the Lake Manitoba Walleye stock was in a good place in 2023. Biomass was above the level required to produce the maximum sustainable yield, and harvest pressure was less than the rate that would lead to the maximum sustainable yield. This was the case whether using daily catch record data from 1996 to 2023 as the index of abundance or using index netting programme data from 2009 to 2023 as the index of abundance. The positive position of Walleye was consistent whether viewed across the entire lake or separated into north and south basin stocks (Figures 2 – 5).

Models that were informed by daily catch records were consistently more optimistic about the state of the Walleye stocks than models informed by index netting data. Fishery dependent models believed relative biomass to be higher than did fishery independent models (Figures 2 and 4), and relative harvest rates of Walleye were lower according to fishery dependent models (Figures

3 and 5). The fishery independent estimates of biomass and harvest rates were less optimistic and so calculated a smaller probability that the Walleye stocks were more abundant than B_{MSY} and that they were being fished at a lower rate than F_{MSY}, but there was also greater uncertainty in the estimates produced by the fishery independent data (Tables 2 – 4).

The greater uncertainty associated with the index netting data stream further diminished the probability that the Walleye stocks appeared in favourable territory when fishery independent data were used in modeling. There are reasons that potentially explain the greater optimism of the fishery dependent models. The more favourable results derived from the fishery dependent models may be a manifestation of changes in fisher behaviour, suggesting perhaps that the modest effort creep of 1% that was used to offset technological and behavioural efficiencies might have been insufficient to offset fishers' adjustments to the stock abundance.

In 2015 there were 554 fishers eligible to buy a commercial fishing license for the Lake Manitoba winter Walleye and Sauger fishery (Klein 2020). Some of that number held non-transferable access to the fishery and will have retired since 2015. The number of eligible fishers was further reduced beginning in 2023 when the Province of Manitoba initiated a buydown of commercial license eligibility. The Province offered fishers $7000 to forfeit their ability to purchase a winter license. At the time of writing (July 2024), seventy-five fishers had elected to retire their eligibility to fish, 13.5% of the 2015 population of eligible fishers. It is reasonable to assume that these fishers who chose to leave the fishery, if they produced fish, were among the smaller producers and so the effect of their retirement would have been to increase the mean delivery size, giving the appearance of greater abundance.

The recent half of the index netting time series is more erratic than the first half and has been characterised by missing data and smaller numbers of net sets (Table 1). The result is that there is less information to lift the model estimates of intrinsic growth rate and carrying capacity in recent years.

With the addition of the 2023 data and based on the estimates of intrinsic growth rate and carrying capacity using fishery dependent data, the model suggests the maximum sustainable yield for Lake Manitoba Walleye is 933 tonnes per year (95% C.I.: 683 t – 1301 t). Using the fishery independent data stream, the estimate of maximum sustainable yield is even higher at 987 tonnes (95% C.I.: 697 t – 1474 t); another reason the fishery independent model believes the biomass in 2023 is closer to the biomass required to the maximum sustainable yield than the fishery dependent model. When the assessment was separated by area, the models suggest lower total aggregate maximum sustainable yields at 890 tonnes according to the fishery dependent data, and 896 tonnes according to the fishery independent data. Estimates by area were consistent between data sources and suggested that the potential yield from the north area is only about a quarter of what the south basin can produce. According to the daily catch record data, the Narrows can produce 221 tonnes of Walleye per year (95% C.I.: 153 t – 327 t). The Narrows estimate was borrowed to produce the fishery independent total estimate of maximum sustainable yield.

In view of the uncertainty in the modeling results and demonstrated inability to stop fishing before the quota is exceeded, a precautionary estimate of maximum sustainable yield is practical – assuming the sustainable yield might be used as a target. The cumulative total maximum sustainable yield of 890 tonnes would be the most precautionary estimate of yield from the

Walleye models explored to date. Another precautionary approach would be to include the lowest lakewide estimate of the intrinsic growth rate, 0.3356 (95% C.I.: 0.2181 – 0.5344) from the fishery independent model, and the lowest estimate of carrying capacity 10,431 tonnes (95% C.I.: 6196 t – 18,138 t) from the fishery dependent model. The maximum sustainable yield calculated thus would be 875 tonnes of Walleye. A precautionary estimate of carrying capacity is worth considering on the grounds that carrying capacity can be a tricky target to hit using surplus production modeling where abundance in the data timeseries has been a one-way trip of increase (Hilborn and Walters 1992).

Trends vary depending on the model and extent of what is considered a stock. Both whole lake models suggest relative fishing pressure has been increasing for the past three years following a two-year dip. The longer trend in each model has been an increase in the relative fishing rate since 2014 (Figure 3). In the south basin, the fishery dependent and the fishery independent models both suggest the relative fishing rate has been increasing since 2014. Notwithstanding the increased relative fishing rate, the south stock has also been increasing in size since 2009, because the harvest rate has remained below the rate that would produce the maximum sustainable yield. For the first time since the stock size in the south basin began to increase, the model based on daily catch records indicated the relative stock size actually shrank a little in 2023. That differs from the model informed by index netting where 2023 finally saw the stock jump in size past the size required to produce the maximum sustainable yield. In the north area, both data streams suggest the stock has been growing since at least 2009, but where daily catch records were used to inform the model, the relative stock abundance has apparently begun to decrease over the most recent five-year period. There is no discernible trend in relative fishing rates in either the fishery dependent, or the fishery independent model for the north basin. If pressed, one could say the relative fishing rate has been decreasing since 2009, but it is not a strong pattern (Figures 4 and 5).

Sauger

Surplus Production Modeling

Sauger display mixed status depending on the area of Lake Manitoba under consideration. The north area of the lake supports a growing Sauger stock that has still not reached the biomass required to produce the maximum sustainable yield but has achieved a biomass in excess of the point of recruitment impairment. The south basin has achieved a stock size capable of producing the maximum sustainable yield and overfishing has just begun in 2022 or 2023. The Narrows is intermediate geographically and in stock status, happily. The stock around the Narrows is large enough to support the maximum sustainable yield, and overfishing is not occurring.

The north area stock is still growing (Figure 8) spurred by a long trend of decreasing relative harvest fraction (Figure 9). Modeling of the north stock was truncated to a 2001 start, because in 2001 the fishers elected to stop fishing small (76 mm) mesh noticing high catch rates of juvenile Walleye. Catchability since 2001 has therefore been consistent with a minimum commercial net size of 95 mm, allowing that the fishers will adjust the most common mesh size in the fishery to the most abundant size Walleye. The two data streams of abundance data follow similar patterns of abundance and fishing pressure, though the fishery dependent model is tracking commercial delivery size of a fishery that has a minimum allowable mesh size of 95 mm, and the fishery independent model uses a minimum mesh size of 64 mm stretch measure. Possibly because Sauger mature at a size smaller than would be gilled in a 95 mm mesh, the fishery independent model is more optimistic on the stock status than the fishery dependent model.

Neither model estimates a very large potential stock size in the north area; yet. The commercial abundance data has almost reached the level available at the beginning of the time series, and the shorter time series of fishery independent abundance is probing new highs every year. As a result, the harvest potential for Sauger in the north area is tiny compared to the south, just an average of 7.7 tonnes for the two models. In recent years, the commercial Sauger harvest in the north has not exceeded three tonnes.

Most of the Sauger action is in the south basin of Lake Manitoba where the fishery dependent model estimated a potential maximum sustainable yield of 64.2 tonnes, and the fishery independent model estimated the maximum sustainable yield at 60.8 tonnes. Fishery dependent and fishery independent models alike trace similar evolutions; fishing pressure peaked in 2003 and then decreased for a decade until in 2013 the relative harvest rate started to climb again to the point where both models now believe overfishing is occurring (Figure 12). The south basin harvest in 2023 was well beyond the maximum sustainable yield at 95.6 tonnes. If we take the fishery dependent model estimate of relative abundance, there was no room to overfish, but the fishery independent model suggests there is stock biomass in excess of the amount needed to produce the maximum sustainable yield (Figure 11). The biomass recovery began when the small mesh fishing ended in the south basin in 2013. It may be that the relative stock abundance was even lower than estimated, because the catchability of Sauger did change when the mesh size change occurred.

There was not enough data to model the Sauger catch at the Narrows by any means other than the daily catch record totals, so the maximum sustainable yield estimate for the Narrows of 20.4 tonnes was applied to the fishery independent total of north and south estimates. The total of all three basin estimates using the fishery dependent data was 91.2 tonnes, compared to 90.0 tonnes for the fishery independent data. These estimates of the maximum sustainable yield are smaller than the whole lake models beginning in 1996. The whole lake fishery dependent model suggests 115.3 tonnes is the maximum sustainable yield. The fishery independent model suggests Lake Manitoba is able to produce 130.1 tonnes of Sauger. Each of the most recent two fishing years – 2022 and 2023 – have produced the same total harvest of Sauger, 106.6 tonnes. This volume would appear to be excessive as neither the fishery dependent, nor the fishery independent whole lake model estimate the Sauger stock to be fully recovered (Figure 6), even though the fishery independent model for the whole lake estimates the harvest fraction is below the level that should lead to the maximum sustainable yield (Figure 7).

The evidence since 1996 suggests most of Lake Manitoba's Sauger stock is already fully exploited, with the exception of the small portion of the catch that could come from the north area (~8.5%). At no time since 1996 however, has the stock been at the levels that predate the decline of the Sauger stock. When the time series is extended back to 1970 with an ersatz measure of the average delivery size, the model suggests the maximum sustainable yield could be as large as 296.4 tonnes (Table 6). Also worth noting is that the estimate from the long series includes fifteen years of fishing before the small mesh fishery began, but when the Walleye stock was already reduced. Walleye and Sauger are competitors, so it is more precautionary to believe the more modern models while the Walleye stock has been abundant. Adding 90 tonnes of Sauger to the 875 tonnes of potential Walleye would make a combined quota of about 965 tonnes for Lake Manitoba's large percids in 2024.

Walleye Life History

A few life history traits were examined in this assessment even though they are not yet part of the abundance and fishing estimates. The main goal of the effort here was to estimate the generation time of Walleye.

The first of the life history traits examined was growth using the original von Bertalanffy growth equation where asymptotic length, the Brody growth coefficient, and length at age zero are the estimands. In this assessment a Bayesian formulation of the original von Bertalnffy equation was used. Separate growth functions were created for the north area, the Narrows, and the south basin (Table 7). The north area curve for female Walleye is the most meaningful. Dozens of north area females older than ten were caught in the last three years of index netting. The oldest was twenty years, and five fish were longer than 700 mm. The oldest female from the Narrows was just twelve years old, while the oldest from the south basin was fourteen. The male counterparts for each area were fourteen, ten, and twelve (Figure 13). It is axiomatic of the von Bertalanffy growth function that the asymptotic length and the Brody growth coefficient are correlated (see Appendix 2). Where the age data is truncated, the asymptotic length is not very meaningful, and due to the high correlation between the growth coefficient and asymptotic length, the Brody growth coefficient does not have much utility either. This is not terribly important here, but it will have implications further on when estimating mortality rates.

Maturity schedules were calculated by length and age. The north area female fish appeared to mature at a smaller size than their southern counterparts. The difference was about 20 mm (Table 8). This gap may not be as great as it appears. The index netting programme progresses from north to south in its execution during a time of year (September) when fish are growing rapidly. The first fish caught in the index netting programme at the Manipogo site in the north basin will have been caught a full month before the last fish is caught and measured at the Whitemud site in the south basin. Some growth also occurs between the end of the index programme and the time of spawning the next spring. Age is a more precise measure of Lake Manitoba Walleye spawning schedules. The south basin female Walleye matured at a younger age than the north area and Narrows area females. This would be the expectation due to temperature differences alone, but it may be that cropping also played a hand in the result. Older, larger, and therefore more likely to be mature fish are censored from the index netting programme by the commercial fishery of the south. The age at 50% maturity among north area female Walleye is 5.64 years. Maturity ogives for both sexes in all three areas are available for viewing in Appendix 3.

Natural mortality rates were estimated for female Walleye alone but done for all three fishing areas. In the north area the natural mortality rate was estimated at 0.25. In the Narrows, the weighted estimate was 0.28. The south basin had the largest estimate of natural mortality rate among female Walleye at 0.31. The median estimates of natural mortality increase as the index netting data move southward. So too does the spread of the estimates (Figure 14). The south basin density estimate of natural mortality has three, almost four, modes. This effect is the result of the censoring of large, older females while the stock continues to recover from overfishing. Mortality estimators reliant on growth rate and asymptotic length are disproportionately affected relative to those reliant on maximum age. The precautionary approach is to disregard south basin and Narrows natural mortality estimates until the stock demographics in those areas have fully recovered from historic overfishing. Therefore, the natural mortality rate estimate for Lake Manitoba female Walleye in the interim is 0.25 (95% C.I.: 0.24 – 0.26), or an annual natural mortality rate of 22%.

Pulling together the age at maturity and the natural mortality rate estimates from the past three years of index netting data, the best estimate of generation time for Lake Manitoba Walleye is 9.64 years.

Walleye Recruitment

Walleye recruitment has been improving (Figure 15). How much recruitment has improved is difficult to say. The stock size is growing (Figure 2), but interpreting year class strengths is challenging. The recruitment index is based on fish four- to ten-years-old. Until 2013, small mesh fishing in the south basin was cropping two- and three-year-old Walleye before they could be compared to fish in year classes since 2013. This means all year classes previous to 2011 are affected by pre-recruit (to the index netting programme) cropping in addition to a small spawning stock. From 2011 onward there does appear to be an increasing trend in recruitment as the stock size builds. Two-year classes have been outstanding: the 2013-year class has been the largest recorded and is just now leaving the fishery; almost as large was the 2018-year class, which now is the biggest contributor to the commercial fishery. Fitting a stock-recruitment curve to the index netting data gives a false impression that the biomass required to produce the maximum sustainable yield is somewhere around 2500 tonnes. When the year classes before 2011 are excluded, the stock-recruitment curve (Beverton-Holt) asymptotes at a much larger stock size, though not as large as the surplus production model findings of 5215 tonnes (daily catch records) and 5892 tonnes (index netting programme). The interim estimate of the stock size required to produce the maximum sustainable yield based on stock-recruitment data is 3757 tonnes. There is not yet enough stock-recruitment information to justify reconsidering the stock advice from the surplus production models.

Conclusion

The Lake Manitoba Walleye stock in 2023 was larger than the stock size required to produce the maximum sustainable yield on the strength of two tremendous year classes, 2013 and 2018. Surplus production modeling using index netting data suggested a 57% chance this was the case, while fishers' delivery data suggested with 99% certainty this was the case. The commercial harvest rates of Walleye are lower than the harvest rates that would lead to the maximum sustainable yield, although the relative harvest rate is trending upward. The most precautionary estimate of maximum sustainable yield is 875 tonnes. The aggregate maximum sustainable yields of area-wise modeling are 890 tonnes using fisher deliveries, and 896 tonnes using index netting data. Whole lake modeling produced higher potential maximum sustainable yields, but because the data series represents a one-way trip of increasing abundance, the precautionary estimates are recommended. In the 2023/24 fishing year, 922 tonnes of commercial Walleye were declared to have been harvested from Lake Manitoba. The size of the harvest compared to the maximum sustainable yield estimates is consistent with the increasing relative harvest fraction, though it is still not bigger than unity. The trajectory of relative biomass was equivocal depending on the modeled area and data stream used to represent abundance.

Sauger biomass in Lake Manitoba is increasing but has not yet reached the level of abundance required to furnish the maximum sustainable yield. Modeling based on fisher delivery data suggests with 92% certainty that overfishing is occurring on the Sauger stock. Modeling informed by index netting on the other hand is 63% sure this is not the case. The difference here is due to smaller mesh sizes available in the index netting model, and this is model that should be considered. That said, the trend in harvest rate is increasing. The provisional maximum sustainable yield for Lake Manitoba Sauger is 90 tonnes. This is the aggregate of area-wise modeling. The whole lake model put maximum sustainable yield at 130 tonnes. To achieve that volume, the stock will need to be larger than the biomass at maximum sustainable yield. The declared commercial harvest in the 2023/24 fishing year was 107 tonnes.

References:

Froese, R., H. Winker, G. Coro, M. Palomares, A.C. Tsikliras, D. Dimarchopoulou, K. Touloumis, N. Demirel, G.M.S. Vianna, G. Scarcella, R. Schijns, C. Liang, and D. Pauly. 2023. New developments in the analysis of catch time series as the basis for fish stock assessments: The CMSY++ method. Acta Ichthyologica et Piscatoria 53: 173-189.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, dynamics and uncertainty. Routledge, Chapman & Hall. 570 pp.

Klein, G.M. 2023. Lake Manitoba Fisheries Stock Assessment 2022. Manitoba Economic Development, Investment, Trade, and Natural Resources; Fisheries Branch Manuscript Report. 30 pp.

Klein, G.M. 2020. Lake Manitoba Fisheries Stock Assessment 2020. Manitoba Natural Resources and Northern Development; Fisheries and Wildlife Branch Manuscript Report. 24 pp.

Last, W.M. 1980. Sedimentology and Post-Glacial History of Lake Manitoba. MSc Thesis, Department of Earth Sciences, University of Manitoba. 333 pp + appendices.

Page, E.C.M. 2011. A Water Quality Assessment of Lake Manitoba, a Large Shallow Lake in Central Canada. MSc Thesis, Department of Biological Sciences, University of Manitoba. 174 pp + appendices.

Palomares, M.L.D. and D. Pauly. 2019. On the creeping increase of vessels' fishing power. Ecology and Society 24: article 31.

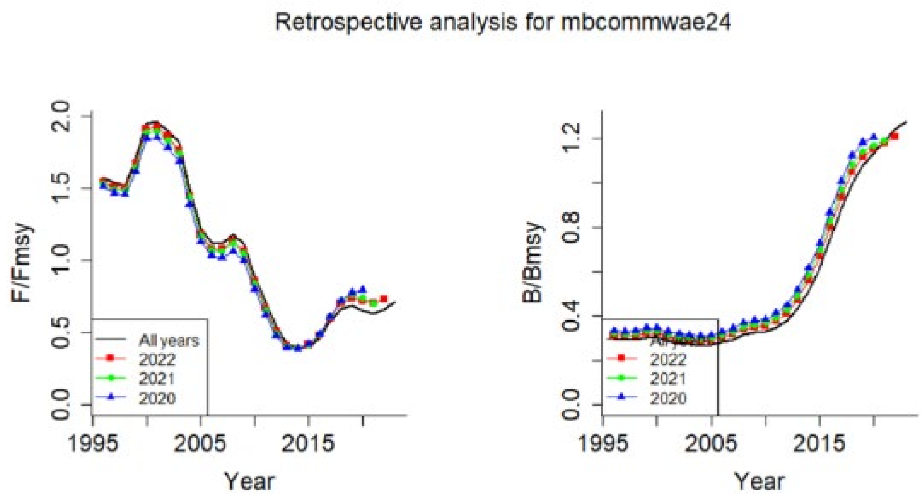
Smart, J. 2023. BayesGrowth: Estimating fish growth using MCMC analysis. *https://github.com/jonathansmart/BayesGrowth*

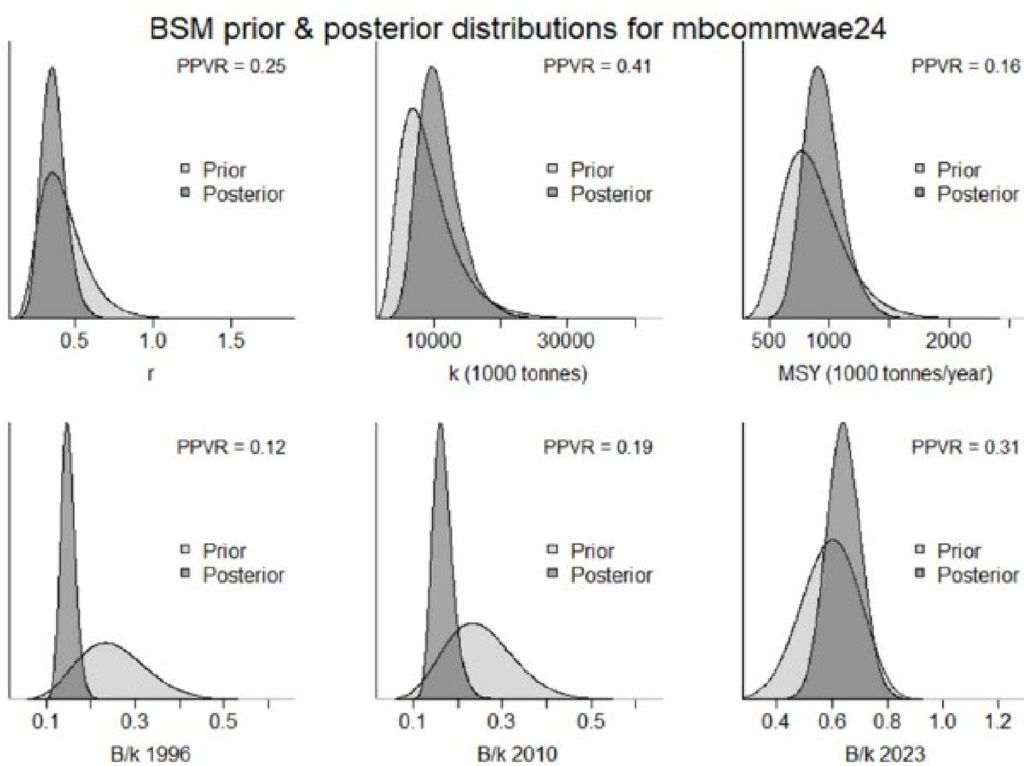
Smart, J.J., A. Chin, A.J. Tobin, and C.A. Simpfendorfer. 2016. Multimodel approaches in shark and ray growth studies: strengths, weaknesses, and the future. Fish and Fisheries 17: 955-971.

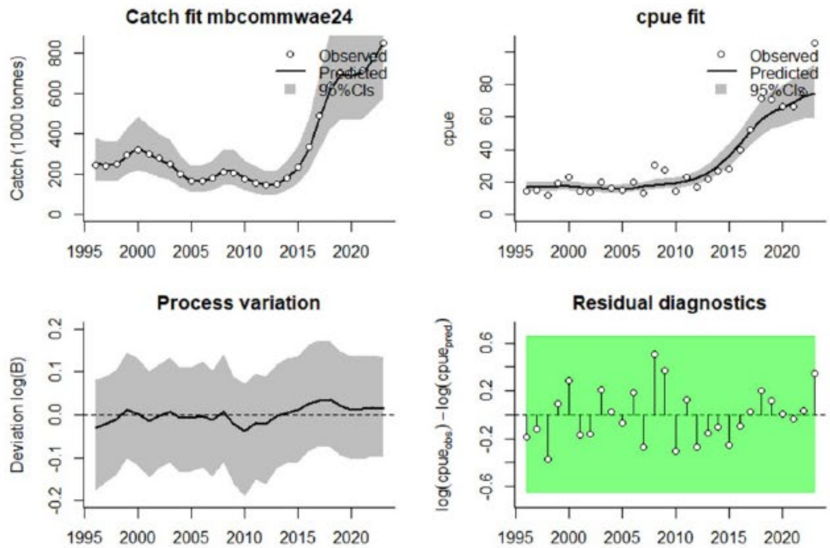
Appendices:

Appendix 1. Model diagnostics

A1.1 Walleye
A1.1.1 Fishery dependent
A1.1.1.1 Whole lake



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Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Observed
Predicted
95%CIs
Process variation
Deviation log(B)
Residual diagnostics
$\log(cpue_{obs}) - \log(cpue_{pred})$

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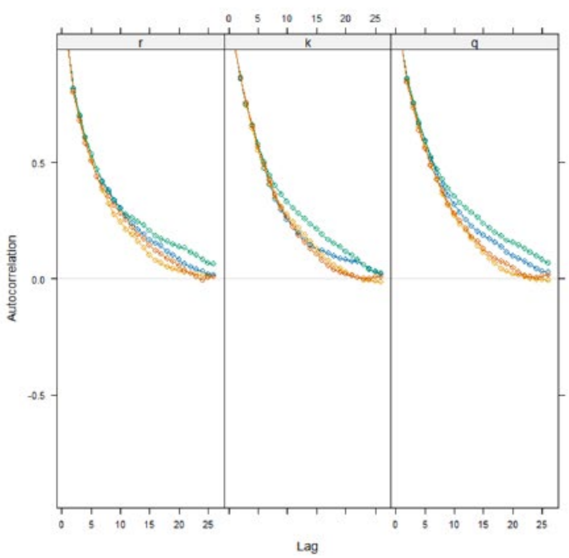
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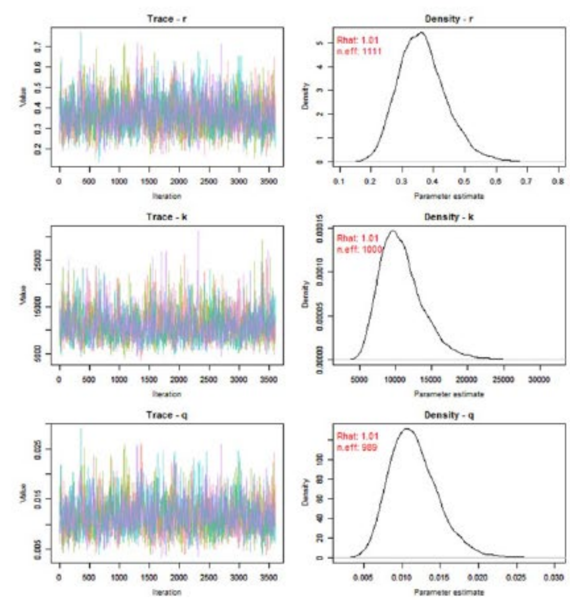
k
q
Autocorrelation
Lag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Density - r
Rhat: 1.01
n.eff: 1111
Trace - k
Density - k
Rhat: 1.01
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Density - q
Rhat: 1.01
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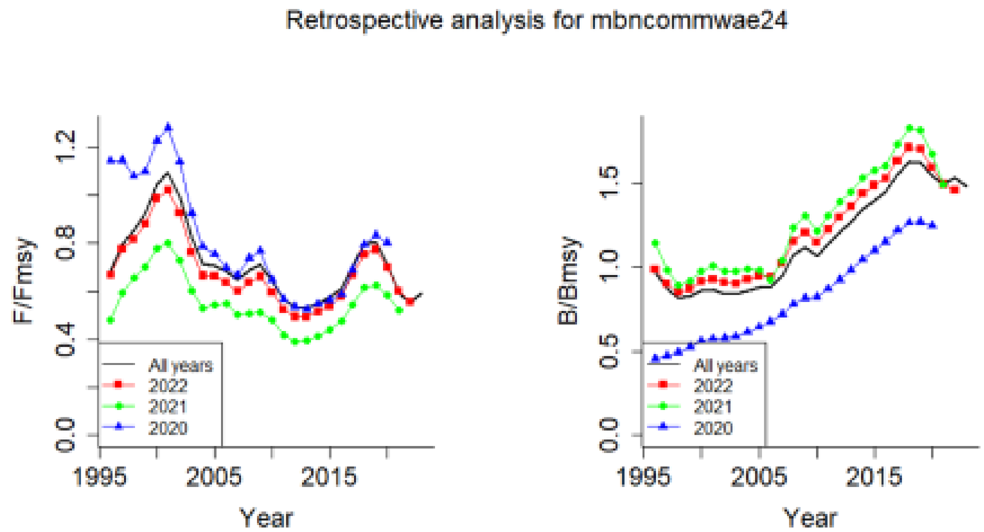
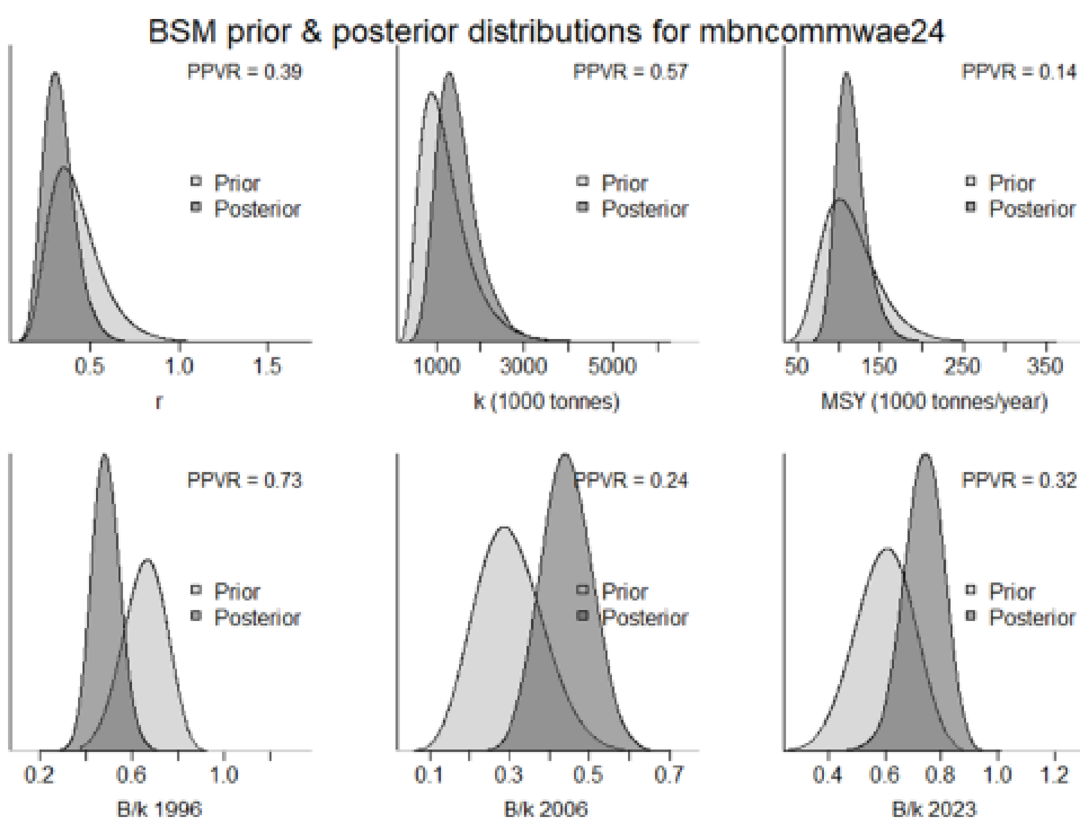
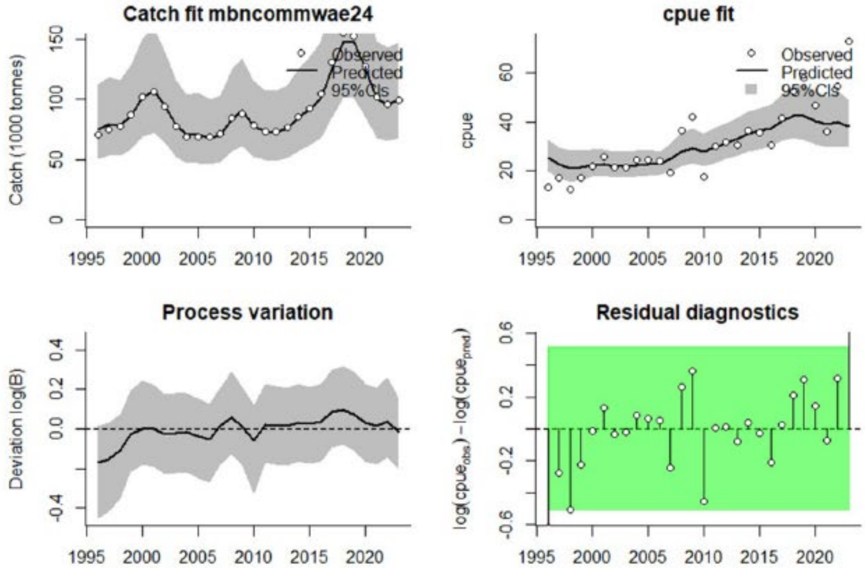
Value
Iteration
Density
Parameter estimate

A1.1.1.2 North Area






Catch fit mbncommwae24
Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Observed
Predicted
95%CIs
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) − log(cpue_pred)

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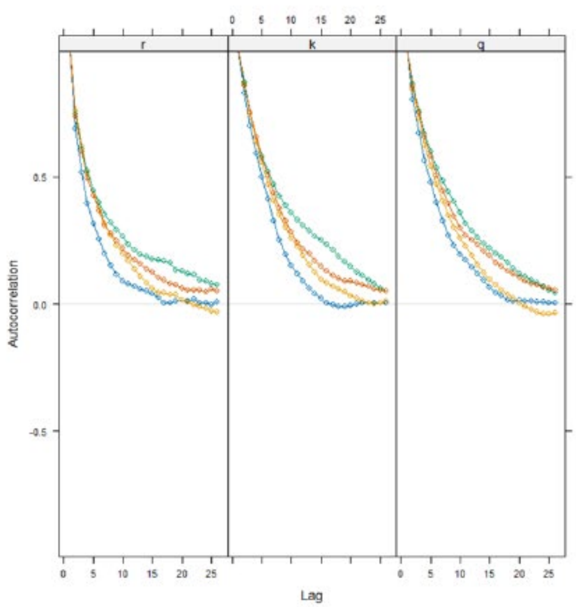
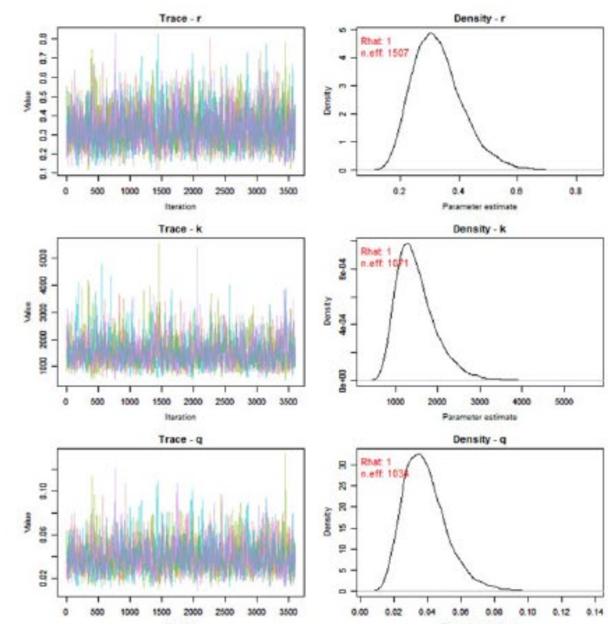

r
k
q
Autocorrelation
Lag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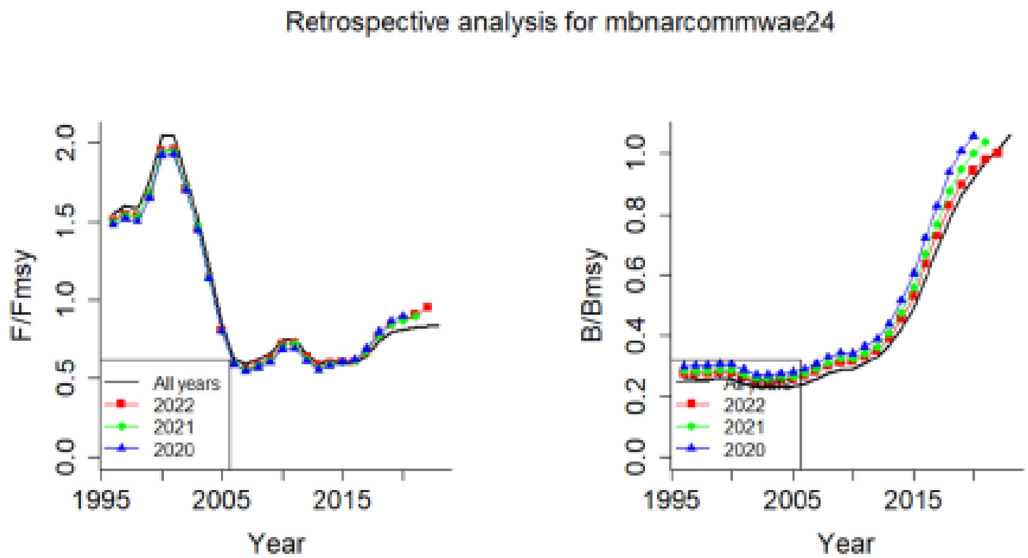
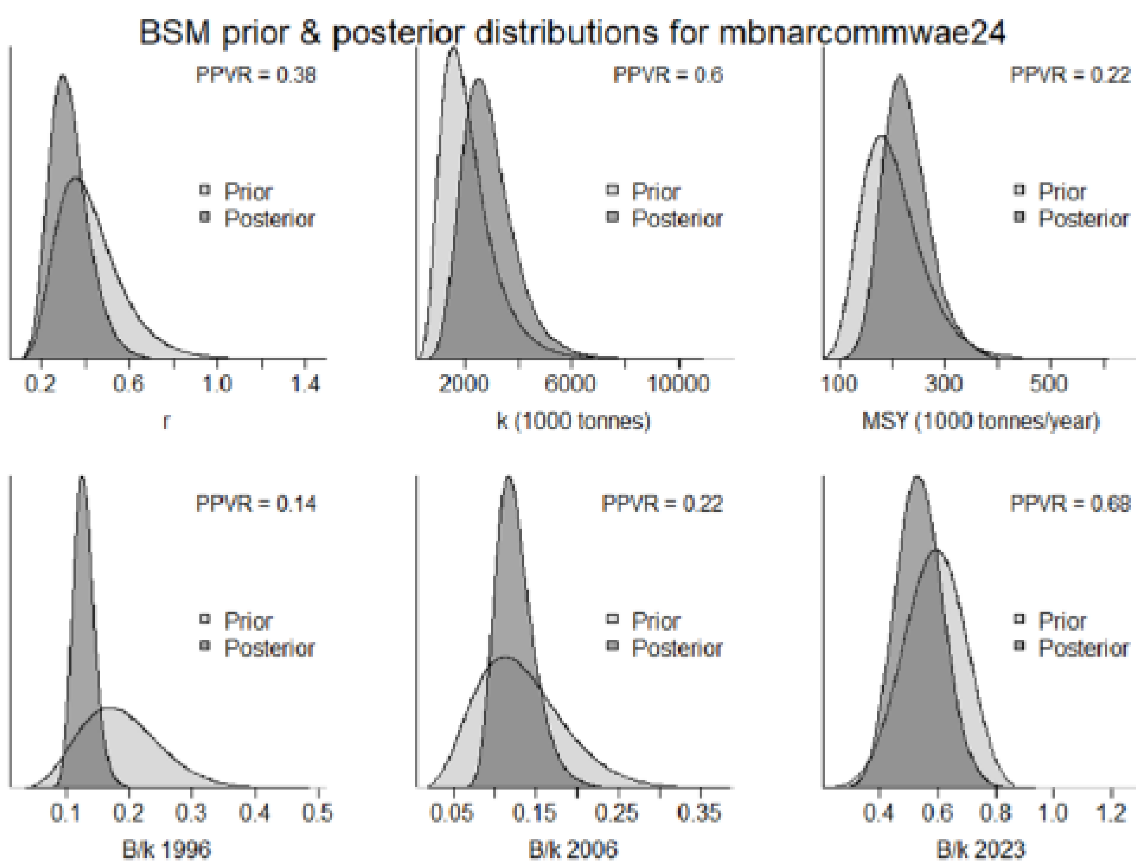
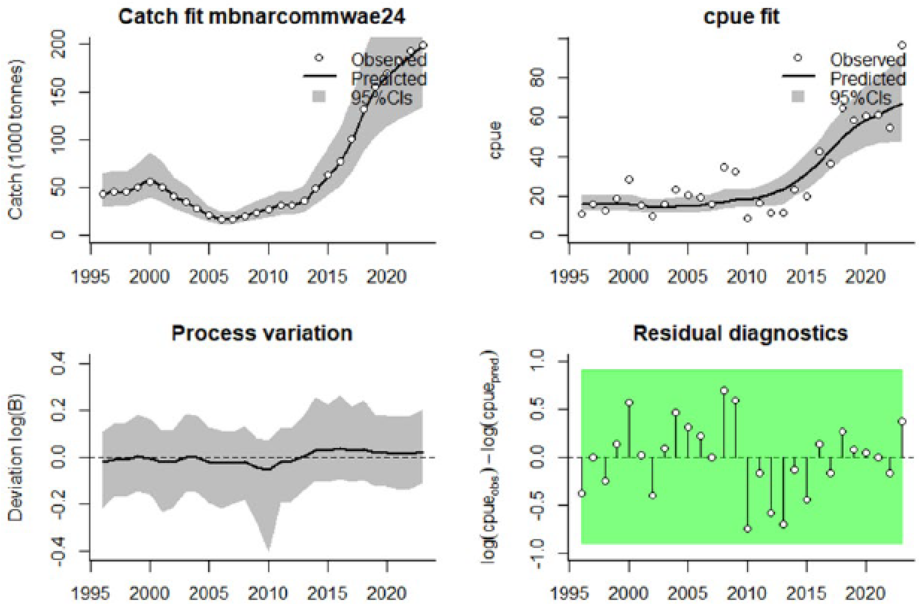
Trace - k
Density - k
Trace - q
Density - q
Value
Density
Iteration
Parameter estimate

A1.1.1.3 Narrows






Catch fit mbnarcommwae24
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
$\log(cpue_{obs}) - \log(cpue_{pred})$

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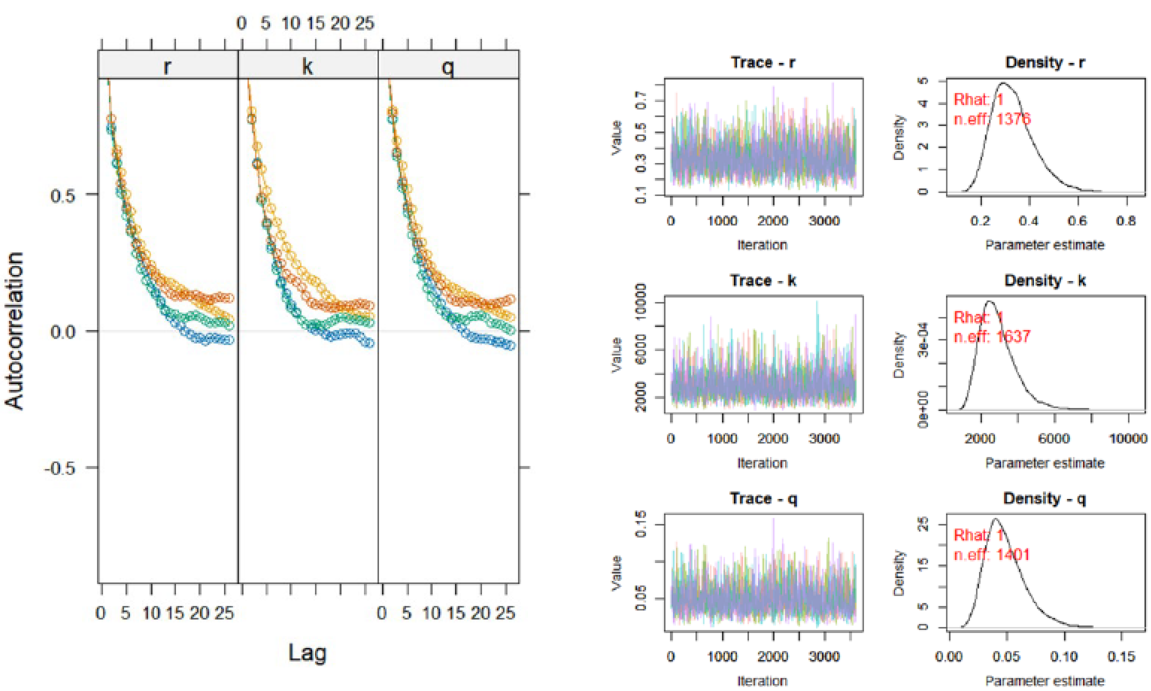
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k
q
Autocorrelation
Lag
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Trace - k
Density - k
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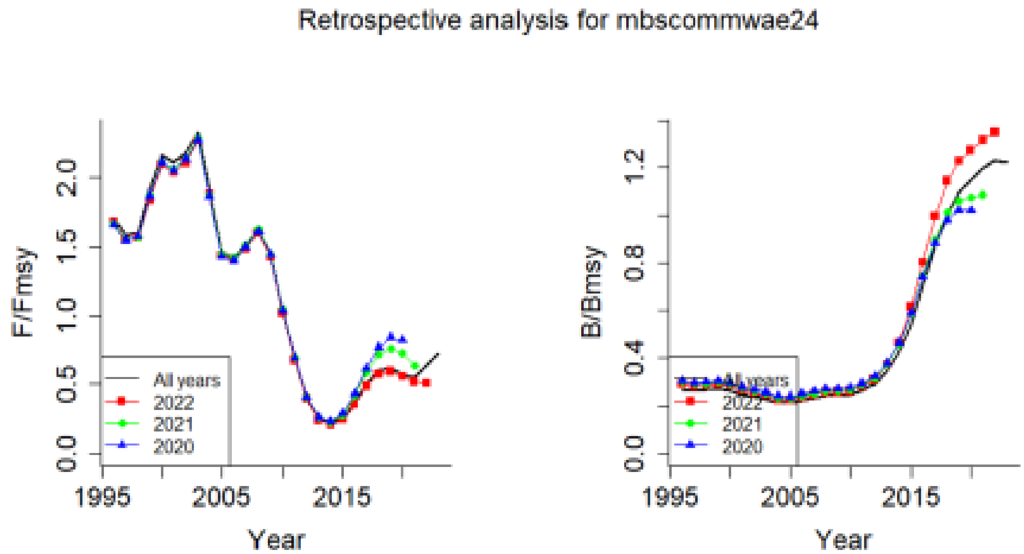
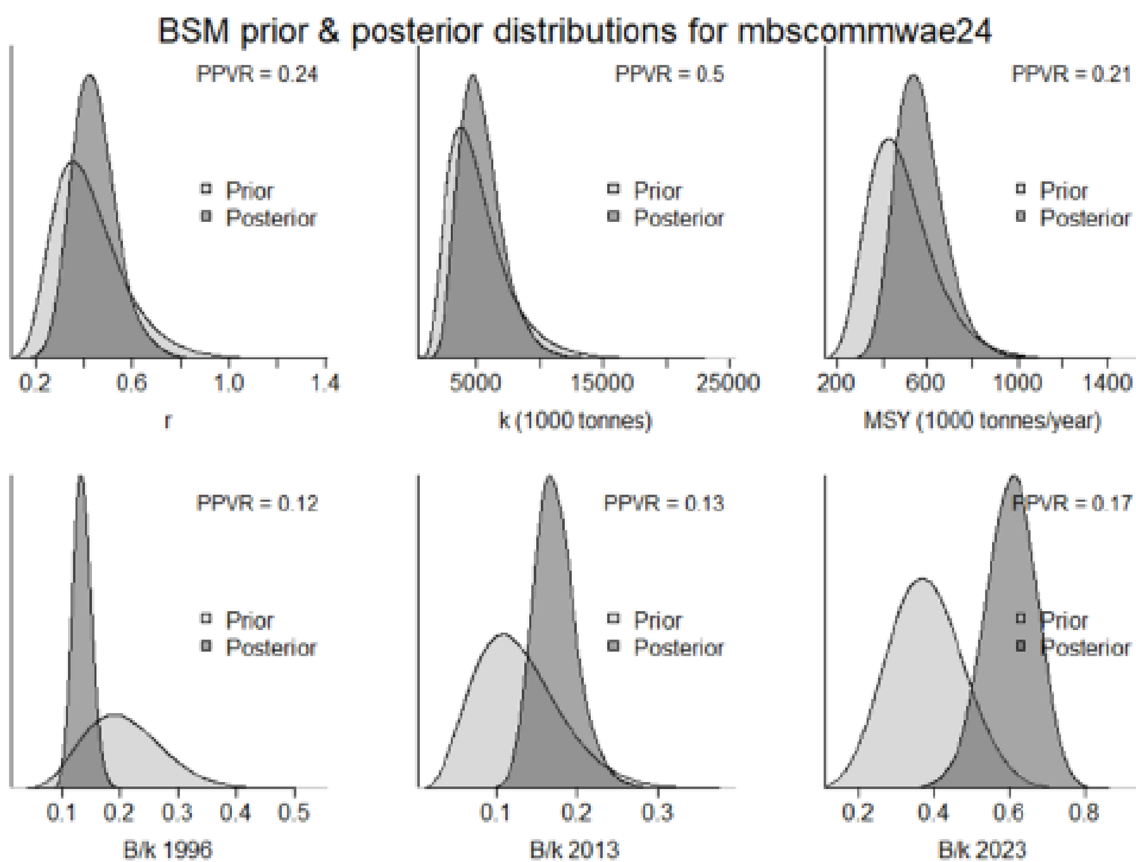
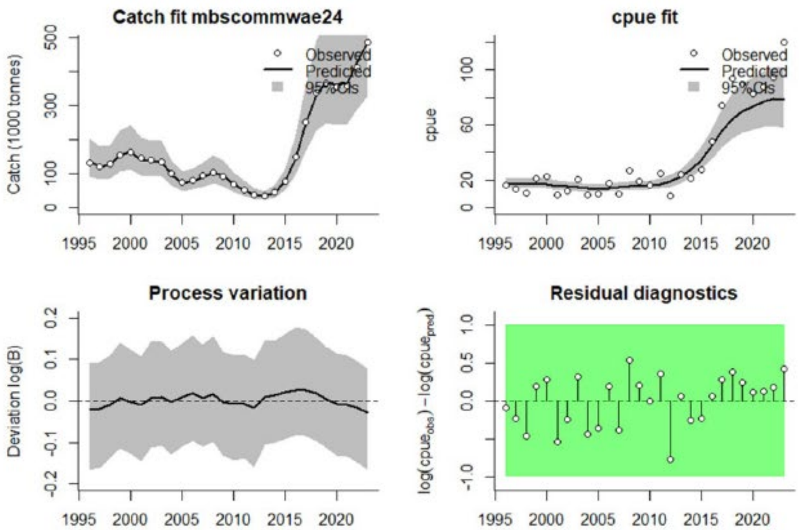
n.eff: 1637
Trace - q
Density - q
Rhat: 1
n.eff: 1401
Value
Iteration
Density
Parameter estimate

A1.1.1.4 South Basin






Catch fit mbscommwae24
Catch (1000 tonnes)
Observed
Predicted
95% CIs
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
$\log(cpue_{obs}) - \log(cpue_{pred})$

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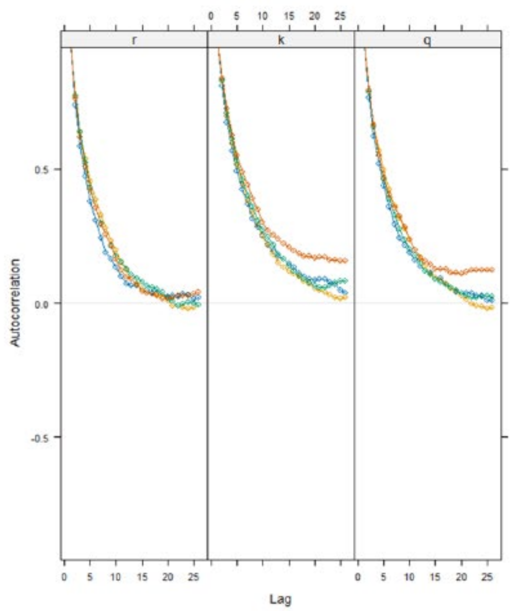
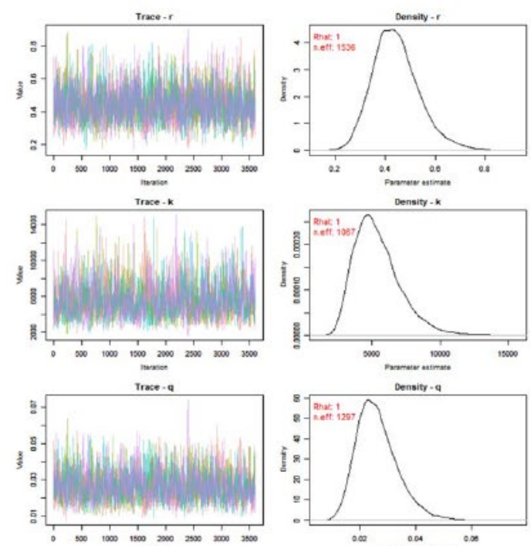

r
k
q
Autocorrelation
Lag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Density - r
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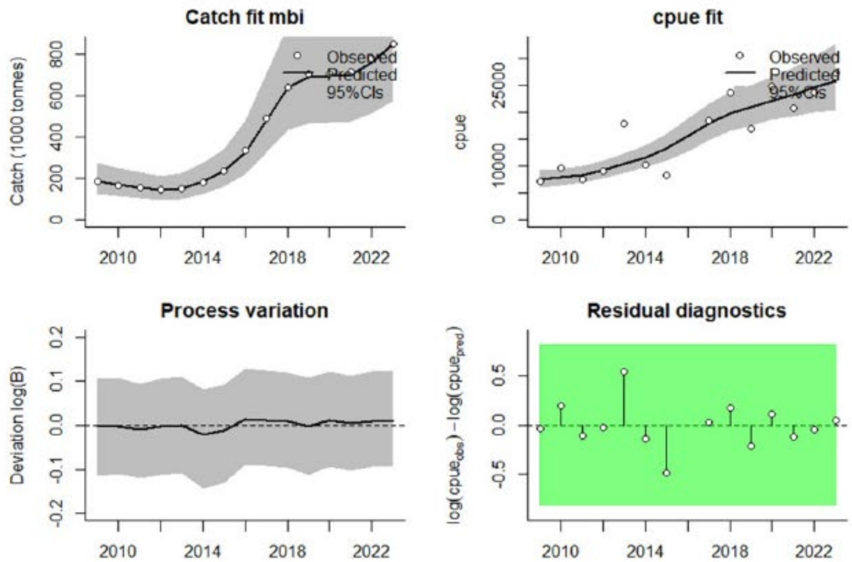
Trace - k
Density - k
Rhat: 1
n.eff: 1067
Trace - q
Density - q
Rhat: 1
n.eff: 1297
Iteration
Parameter estimate

A1.1.2 Fishery Independent

A1.1.2.1 Whole Lake



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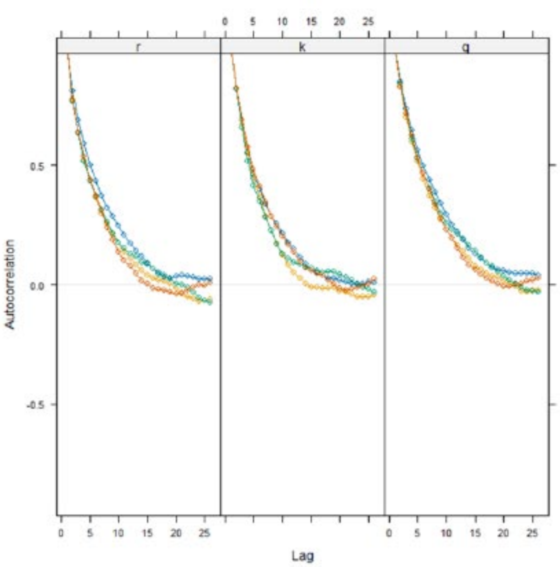
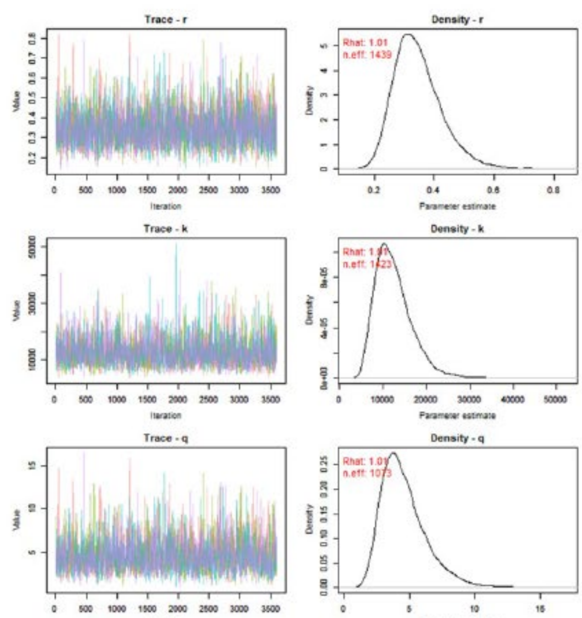
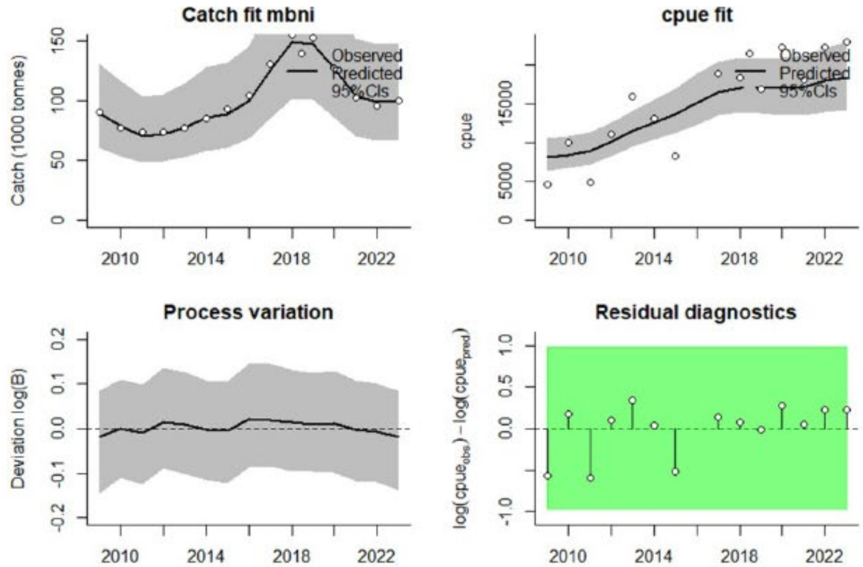
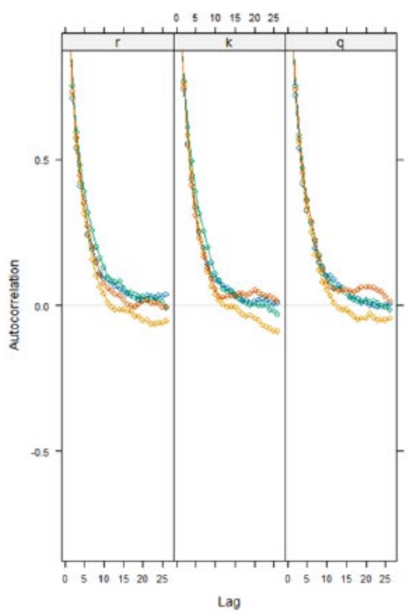




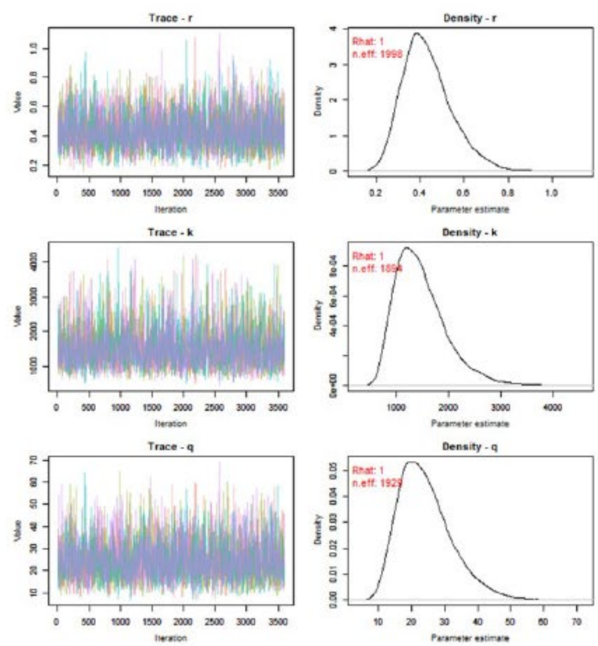


Catch fit mbni
Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)

DIC = 81.6

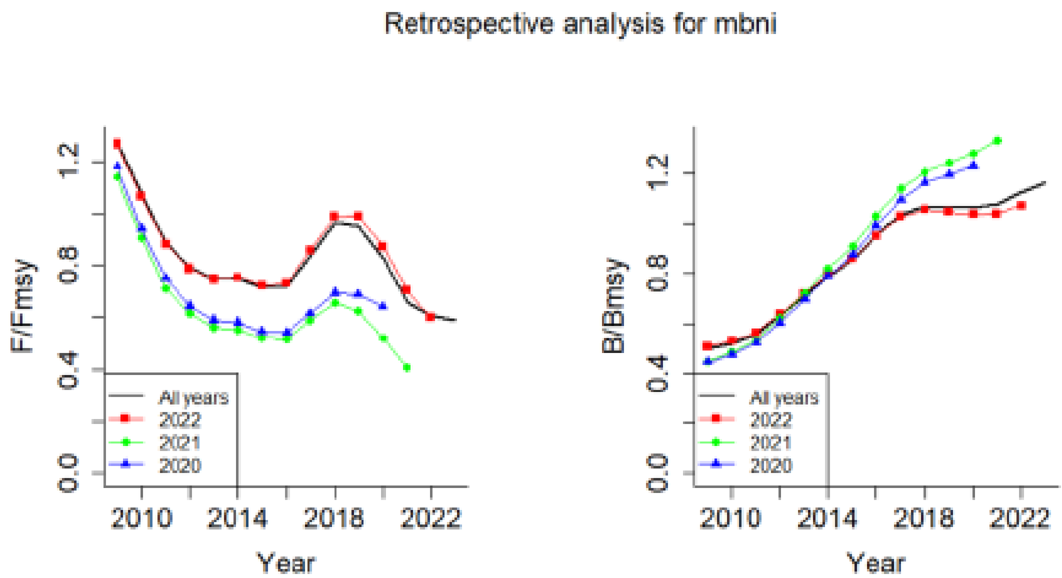


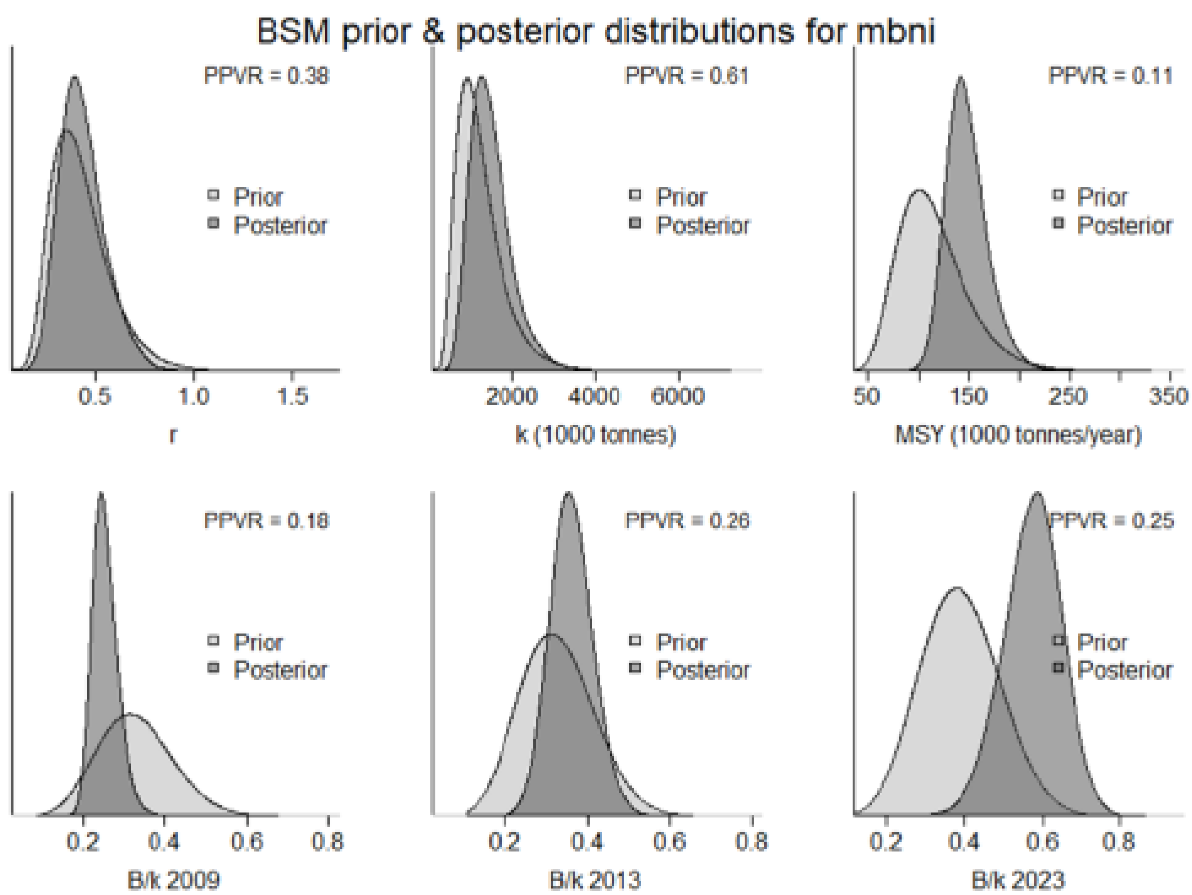
r
k
q
Autocorrelation
Lag

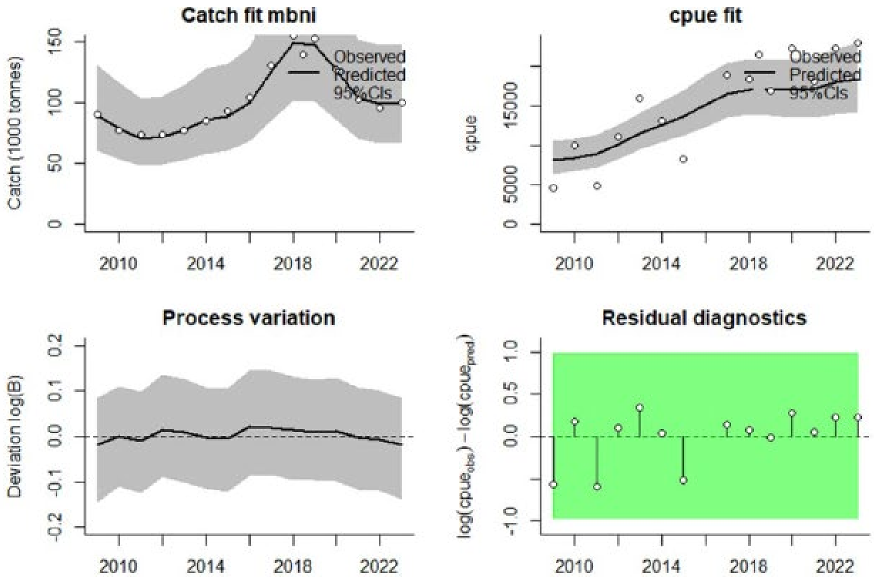


Trace - r
Density - r
Rhat: 1
n.eff: 1998
Trace - k
Density - k
Trace - q
Density - q
Iteration
Parameter estimate

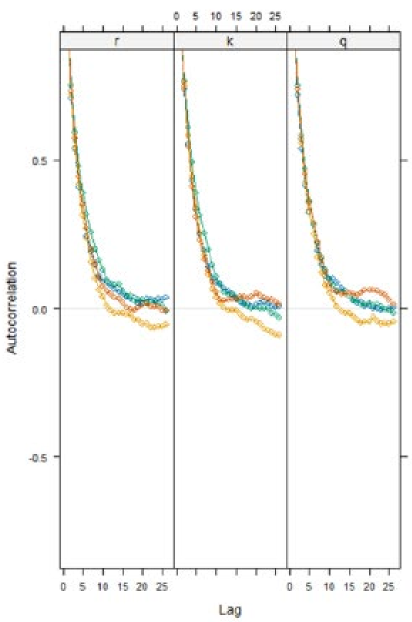
A1.1.2.2 North Area

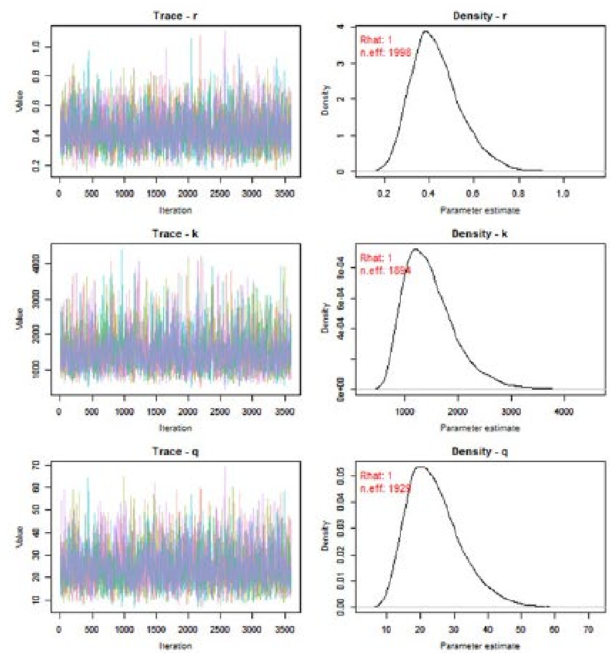




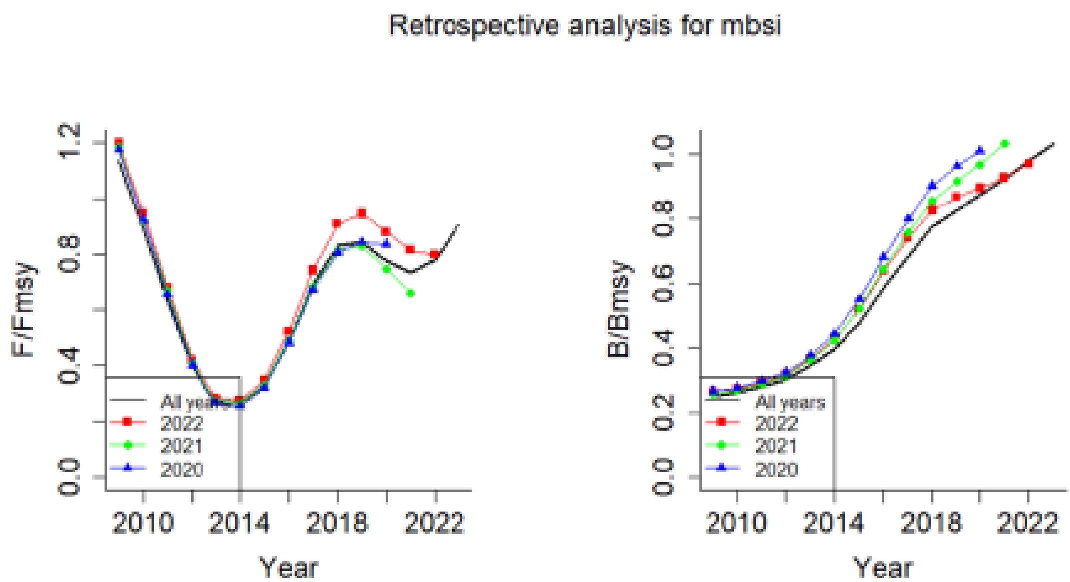

Catch fit mbni
Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)
2010
2014
2018
2022

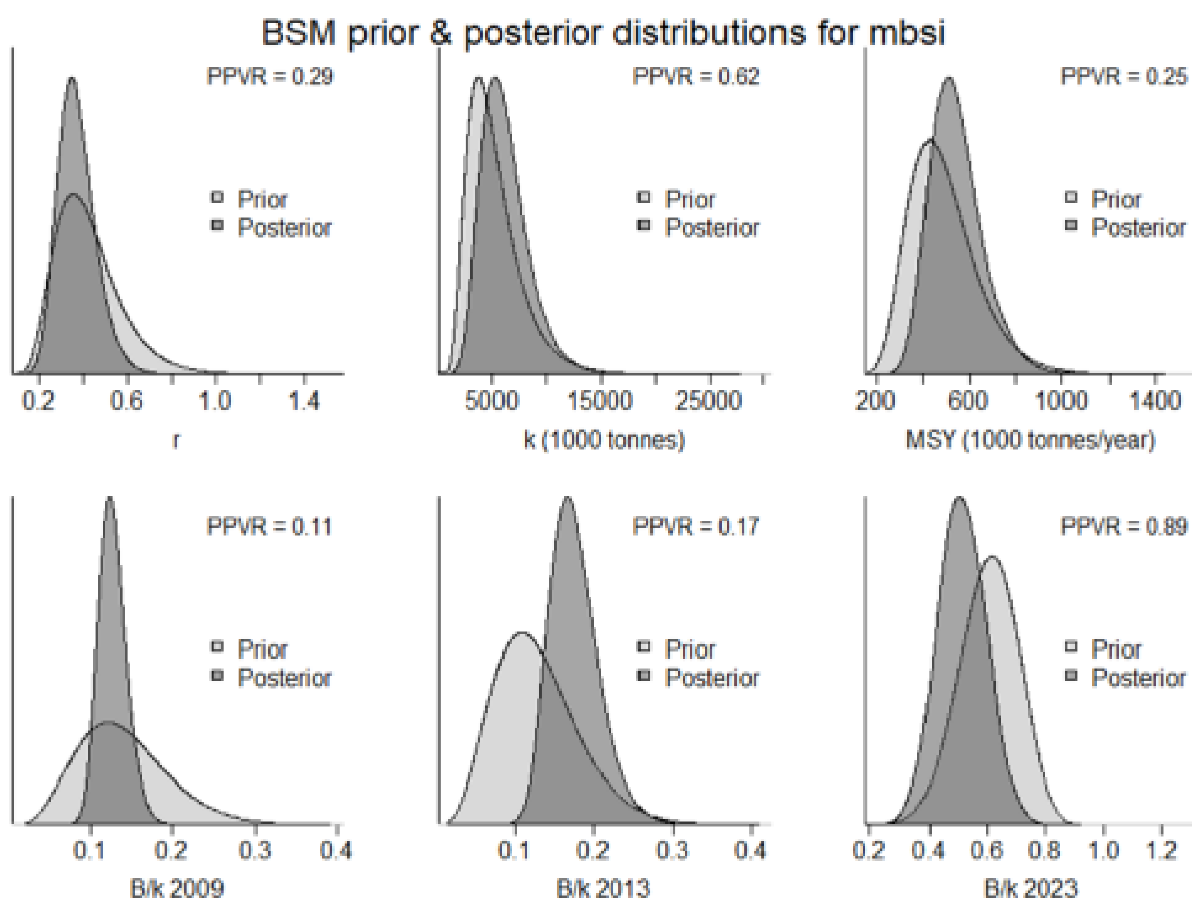
DIC = 81.6

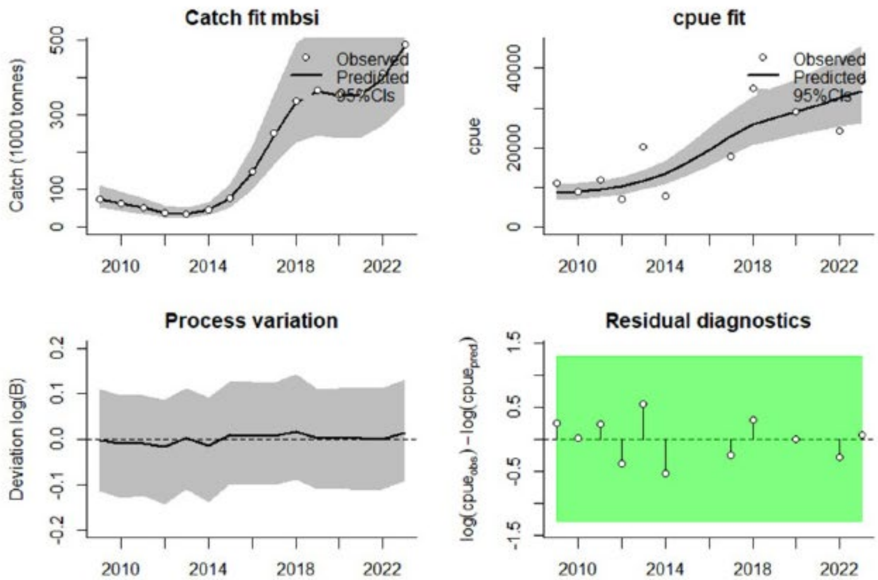

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Rhat: 1
n.eff: 1998
Trace - k
Density - k
Rhat: 1
Trace - q
Density - q
Rhat: 1
Value
Iteration
Density
Parameter estimate

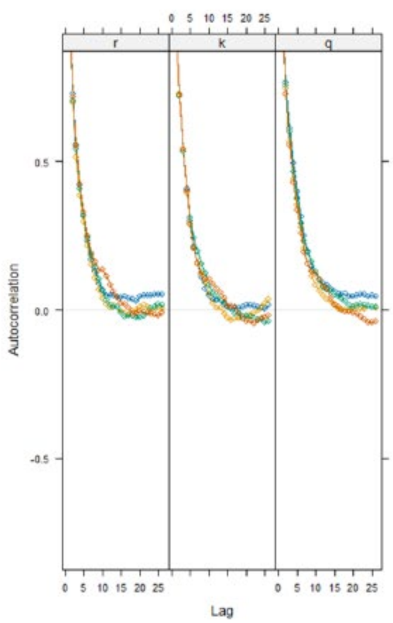
A1.1.2.3 South Basin

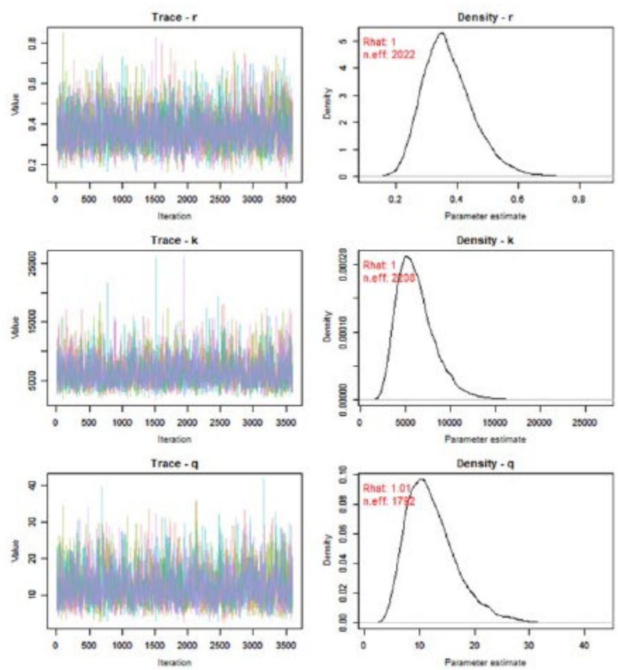





Catch fit mbsi
Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Observed
Predicted
95%CIs
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)

DIC = 25.3

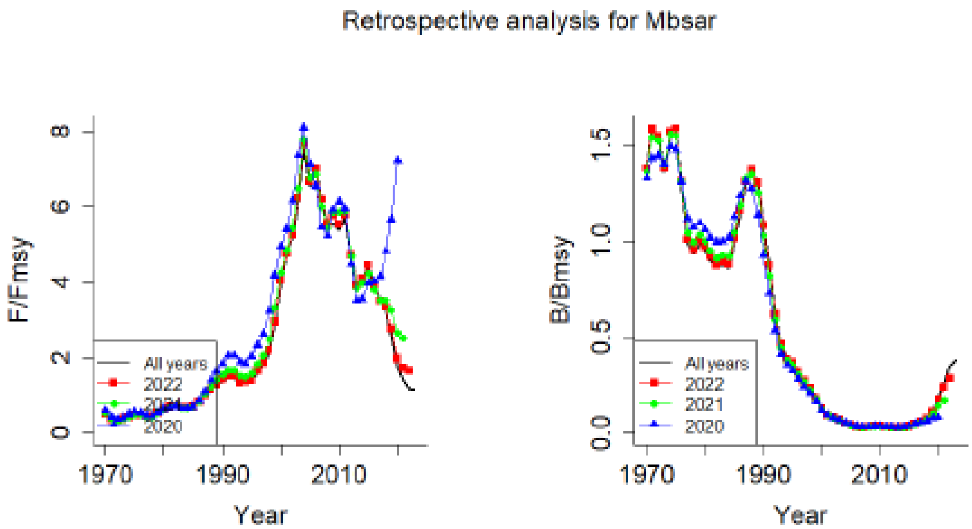

r
k
q
Autocorrelation
Lag

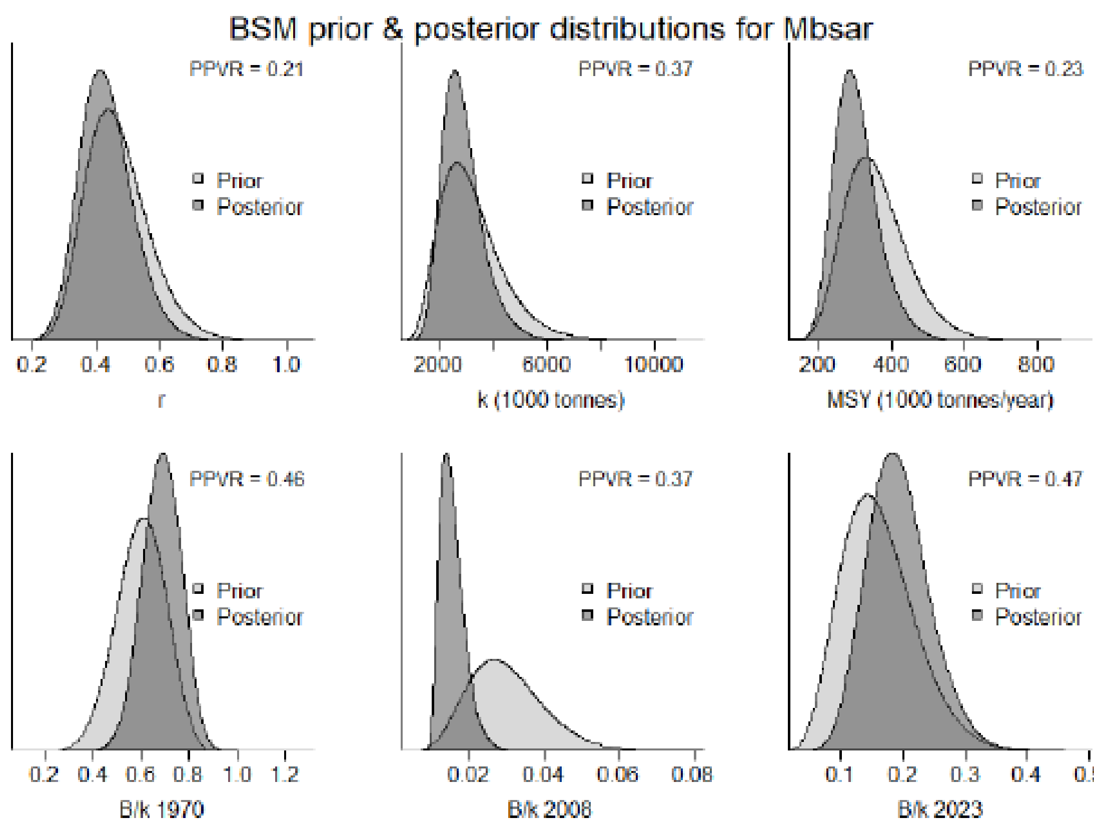

Trace - r
Density - r
Rhat: 1
n.eff: 2022
Trace - k
Density - k
Trace - q
Density - q
Rhat: 1.01
Value
Iteration
Density
Parameter estimate

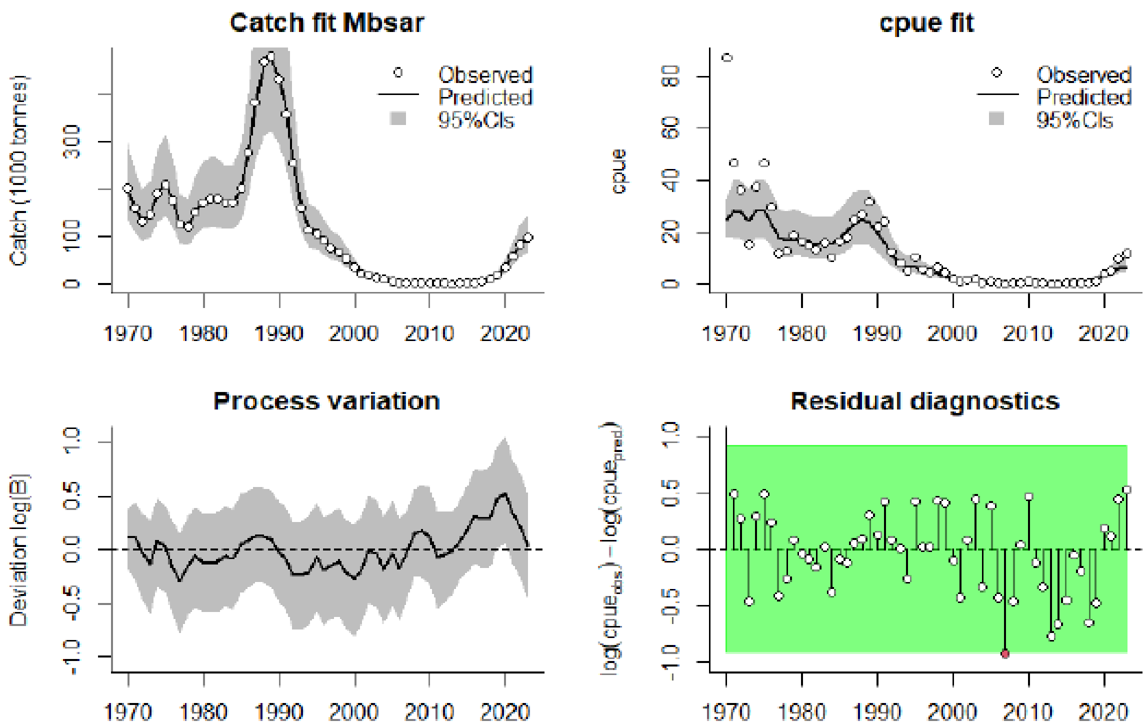
A1.2 Sauger

A1.2.1 Fishery Dependent

A.1.2.1.1 Whole lake since 1970

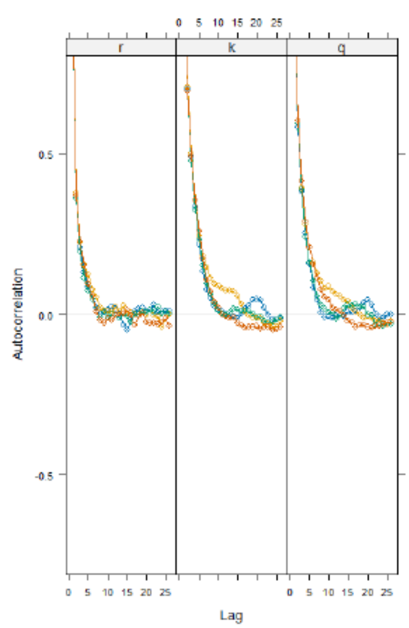




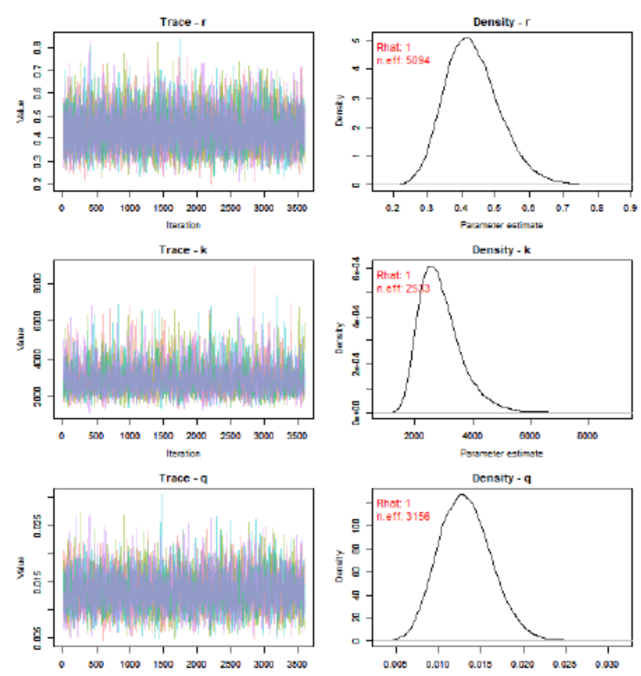


Catch fit Mbsar
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
Observed
Predicted
95%CIs
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)

DIC = -397.5

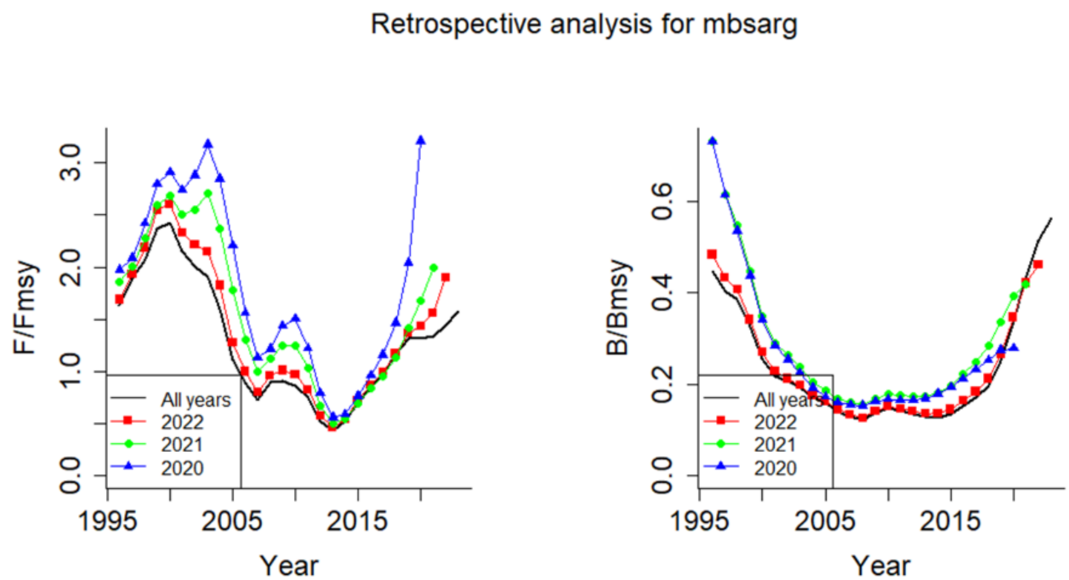


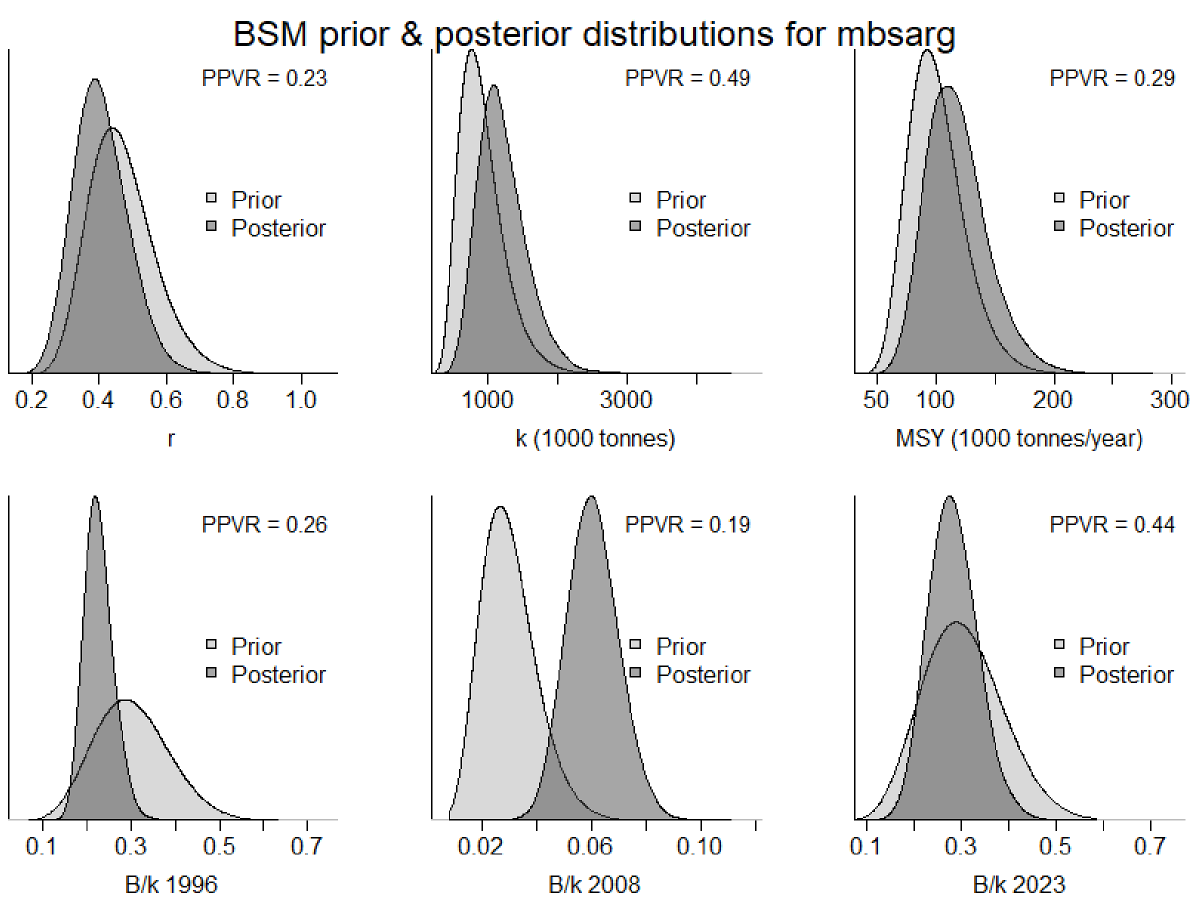
r
k
q
Autocorrelation
Lag

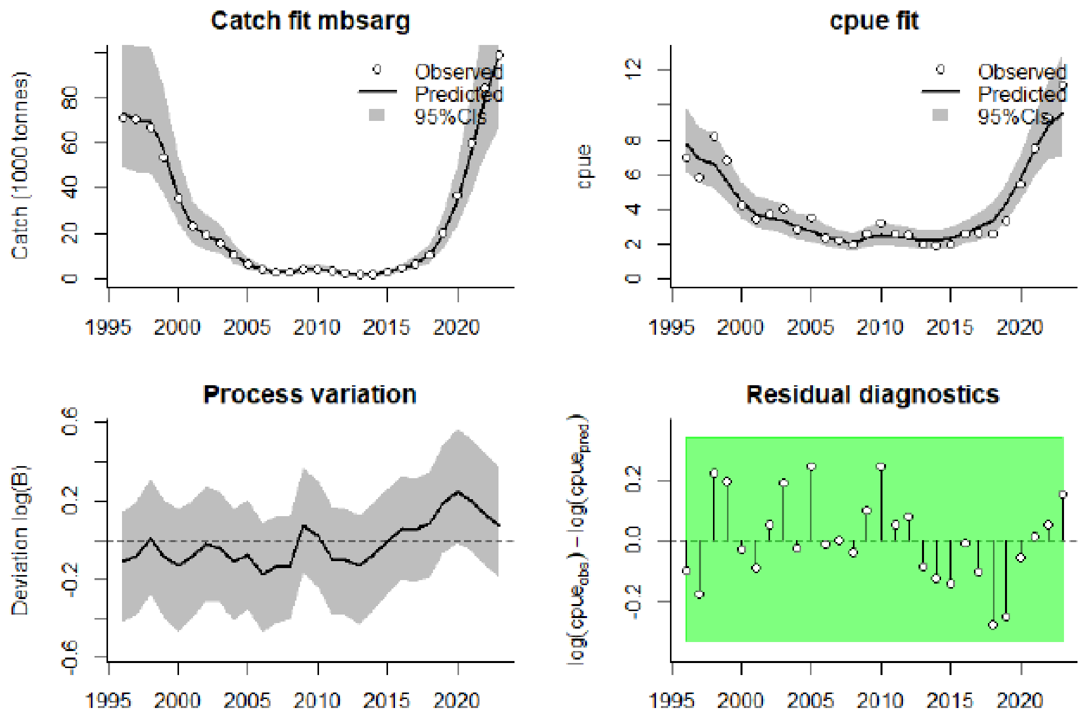


Trace - r
Density - r
Rhat: 1
n.eff: 5094
Trace - k
Density - k
Rhat: 1
Trace - q
Density - q
Rhat: 1
n.eff: 3156
Iteration
Parameter estimate
Value
Density

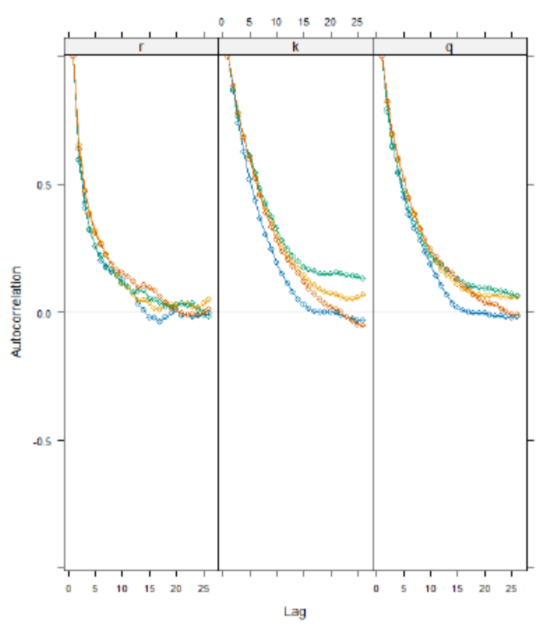
A1.2.1.2 Whole lake since 1996

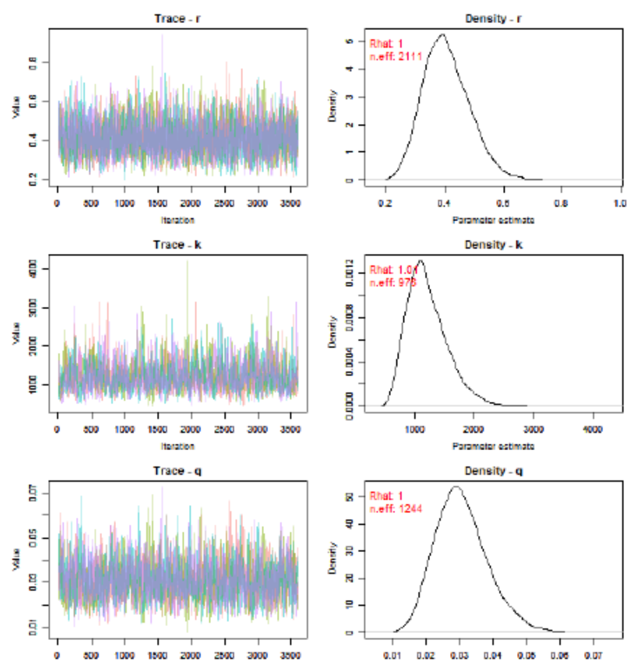




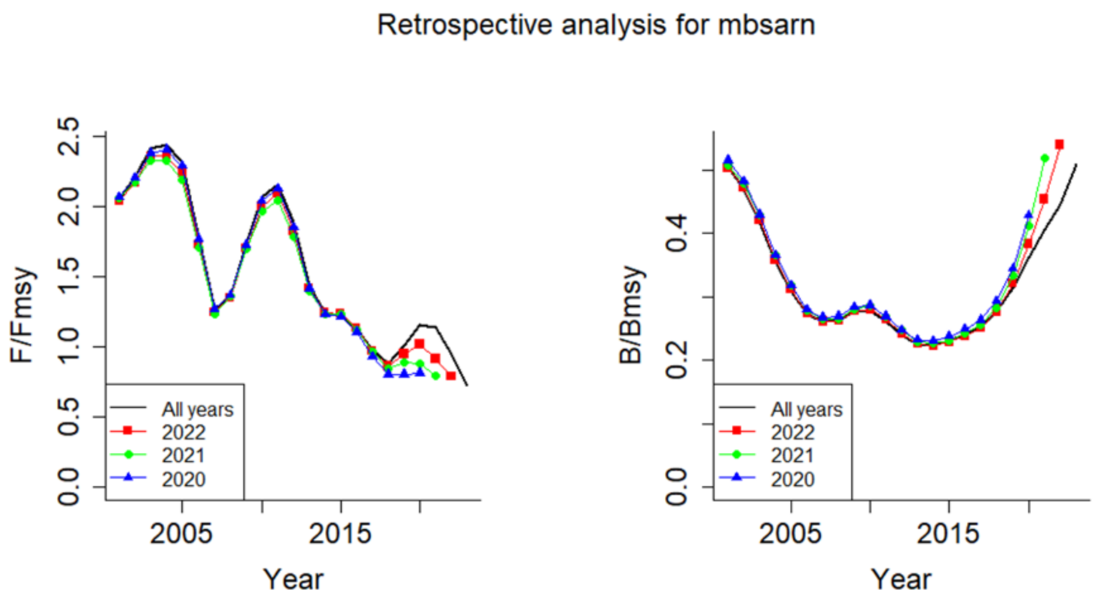

Catch fit mbsarg
Catch (1000 tonnes)
Observed
Predicted
95%CIs
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
$\log(cpue_{obs}) - \log(cpue_{pred})$

DIC = -279.4

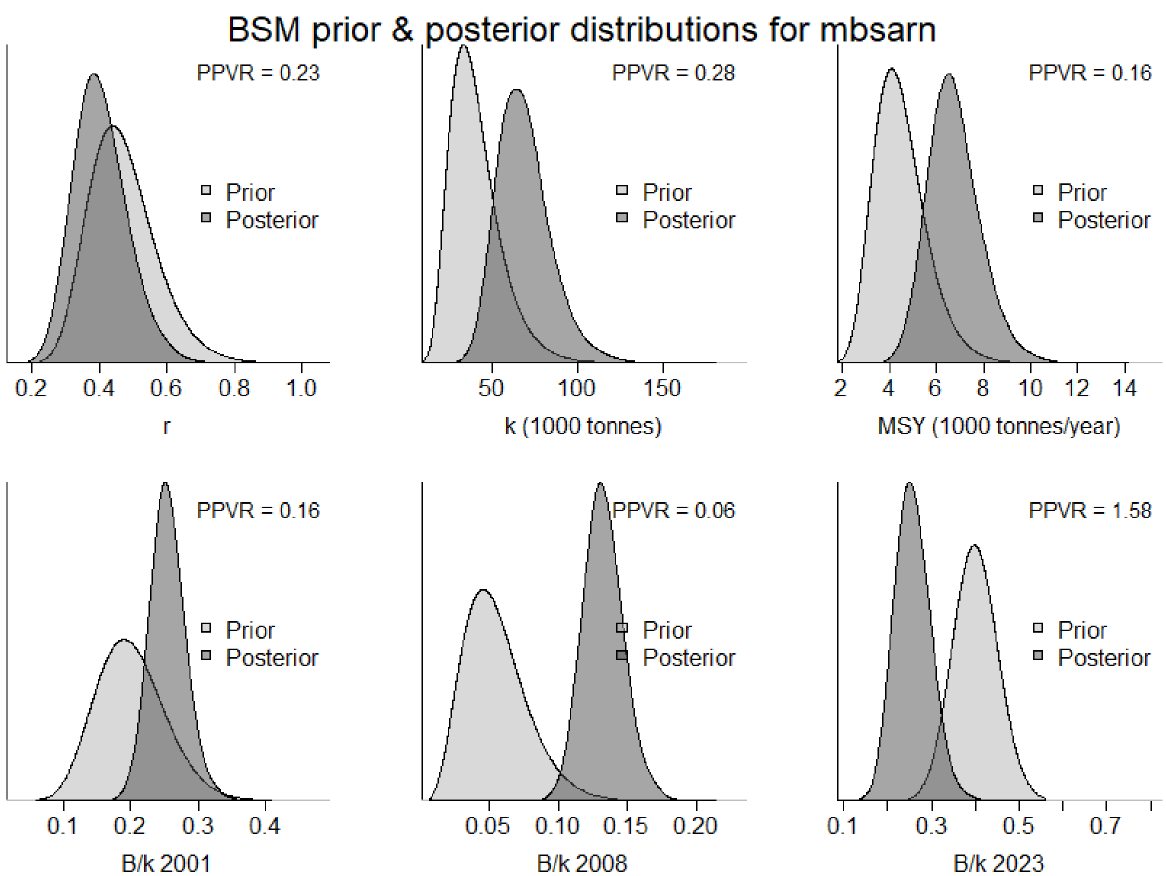

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Rhat: 1
n.eff: 2111
Trace - k
Density - k
Trace - q
Density - q
Rhat: 1
n.eff: 1244
Value
Iteration
Density
Parameter estimate

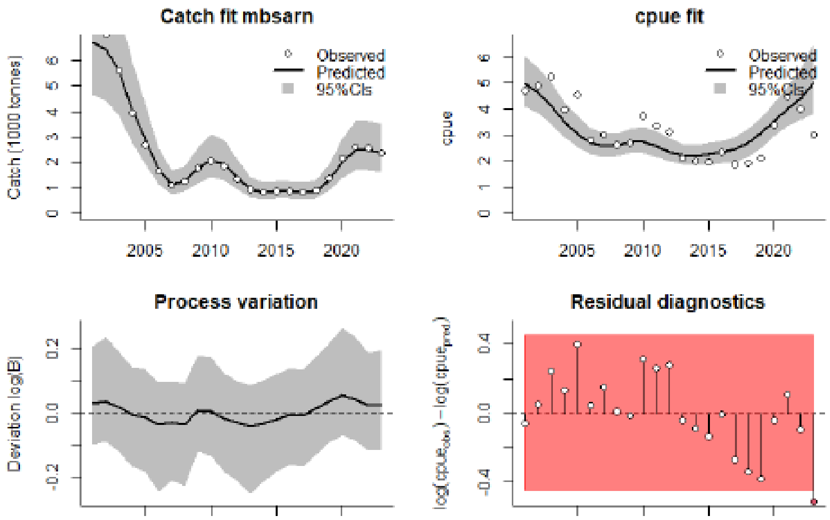
A1.2.1.3 North



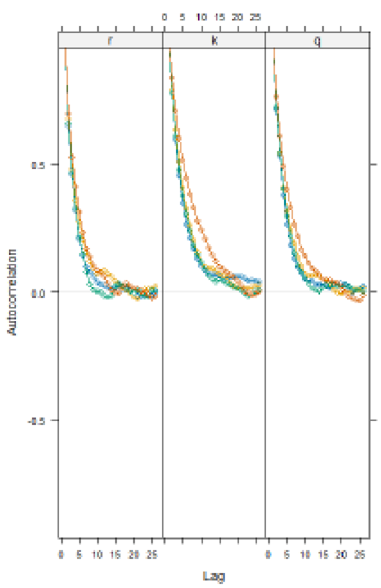
Retrospective analysis for mbsarn
F/Fmsy
Year
B/Bmsy
All years
2022
2021
2020

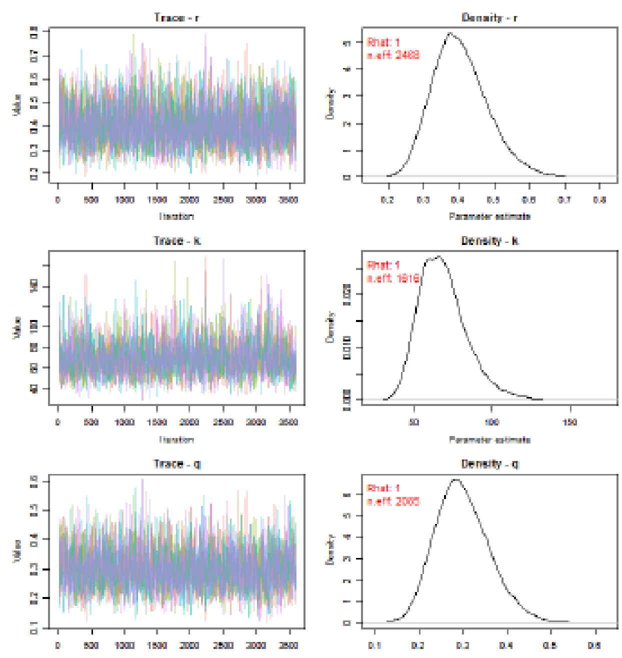


BSM prior & posterior distributions for mbsarn
PPVR = 0.23
PPVR = 0.28
PPVR = 0.16
Prior
Posterior
r
k (1000 tonnes)
MSY (1000 tonnes/year)
PPVR = 0.16
PPVR = 0.06
PPVR = 1.58
B/k 2001
B/k 2008
B/k 2023

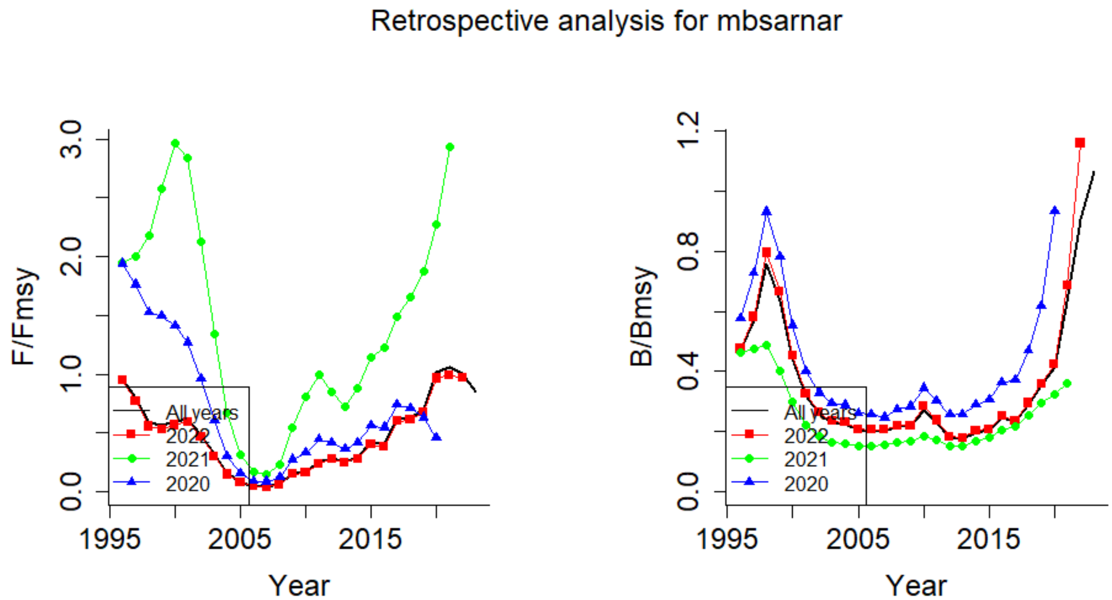

Catch fit mbsarn
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) − log(cpue_pred)

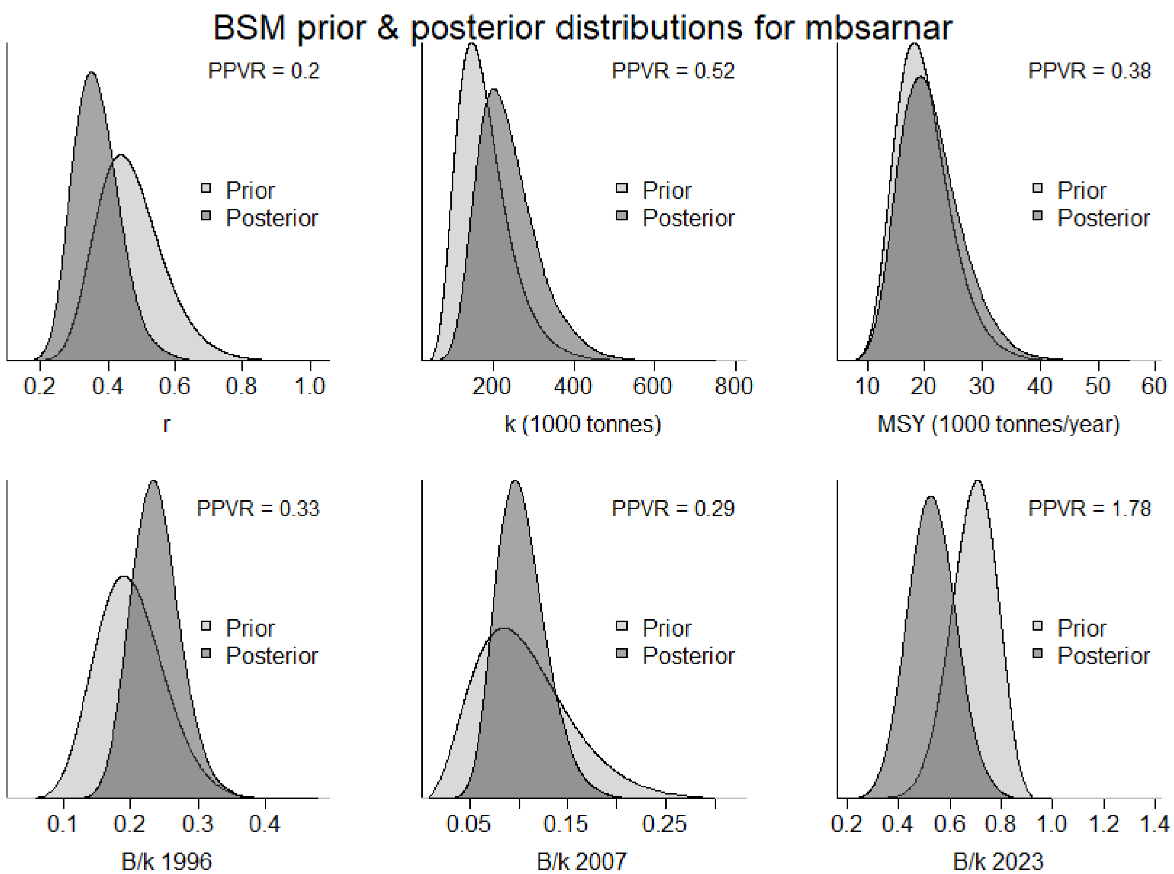
DIC = -225.5

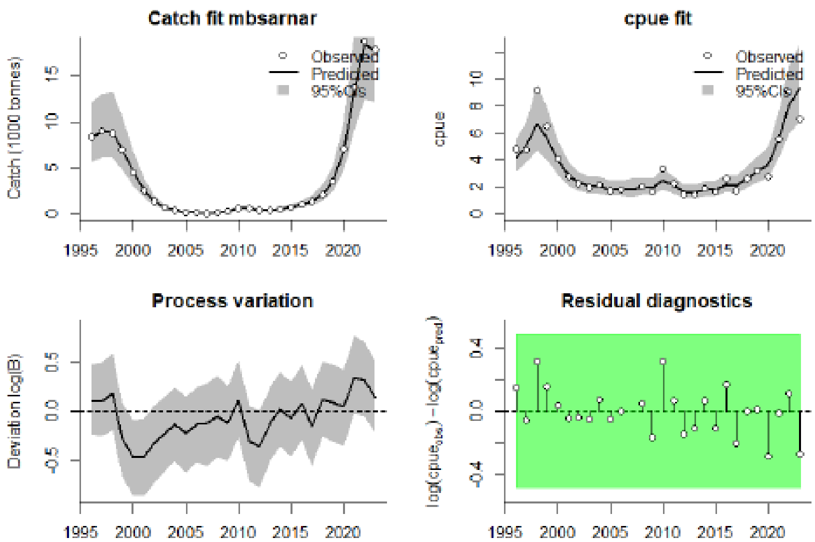

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Rhat: 1
n.eff: 2488
Trace - k
Density - k
Rhat: 1
n.eff: 1616
Trace - q
Density - q
Rhat: 1
n.eff: 2005
Value
Iteration
Density
Parameter estimate

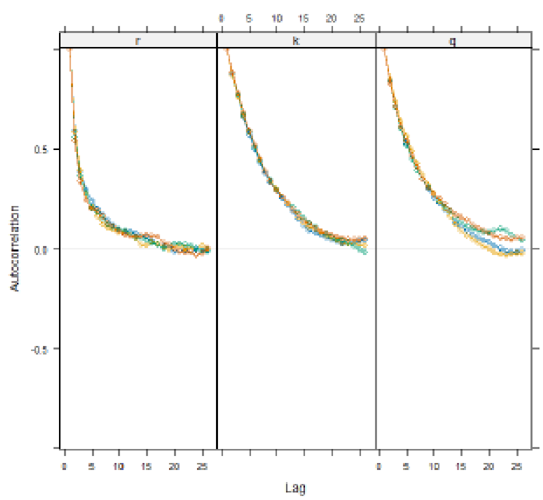
A1.2.1.4 Narrows

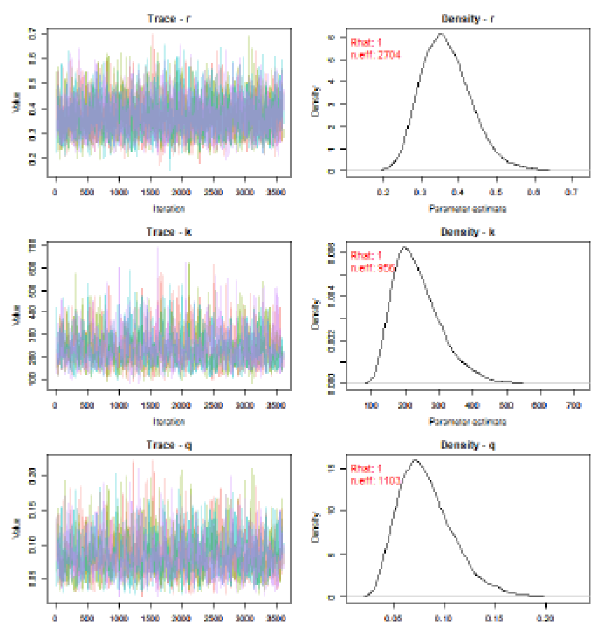




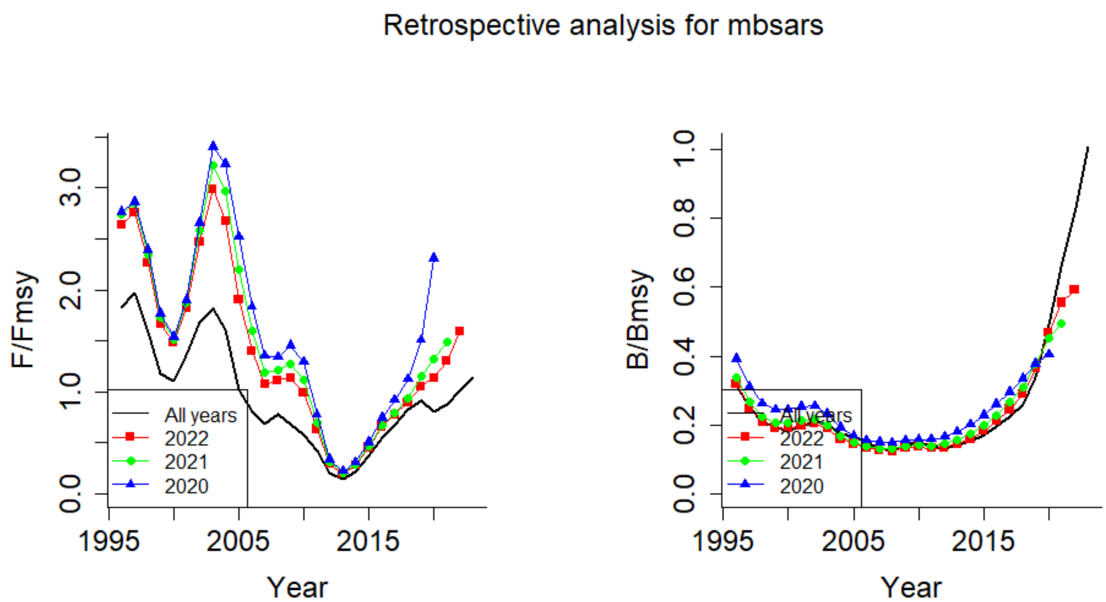

Catch fit mbsarnar
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics

DIC = -290.5

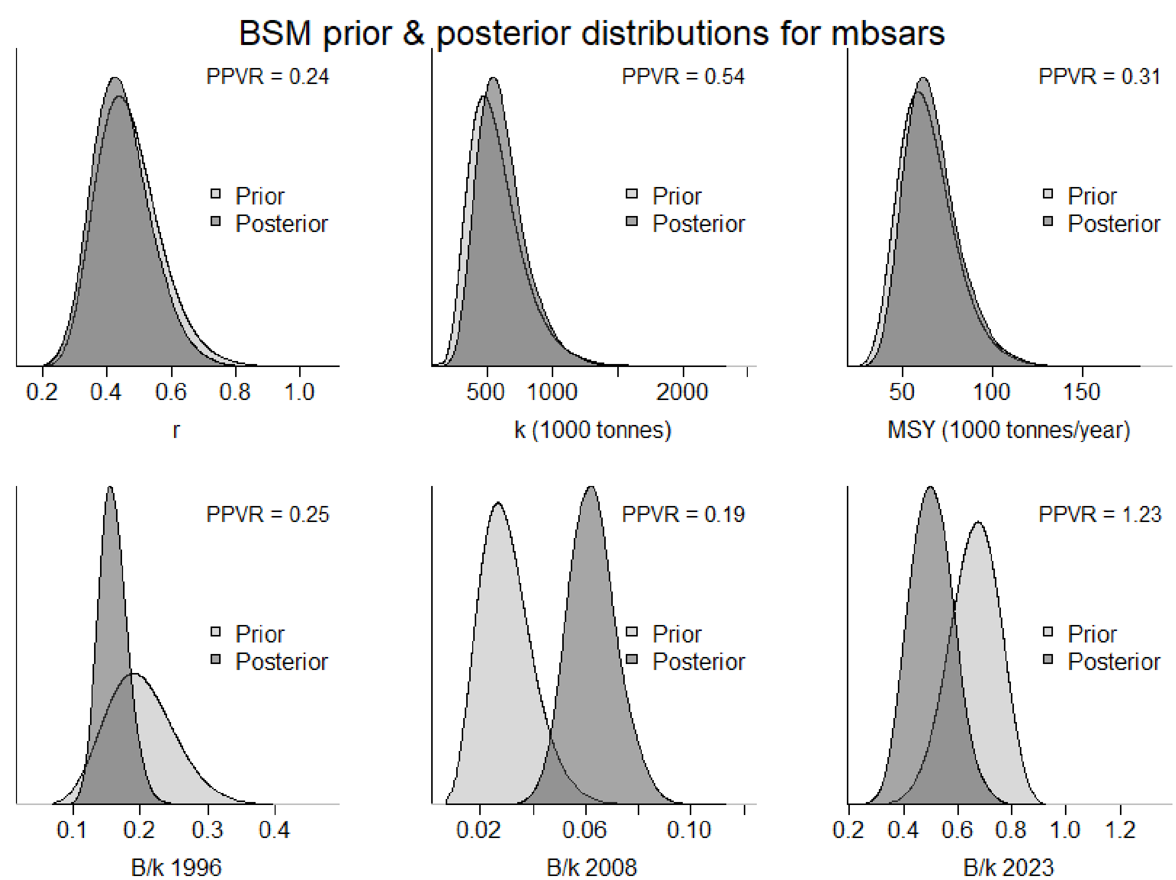

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Trace - k
Density - k
Trace - q
Density - q
Value
Iteration
Density
Parameter estimate

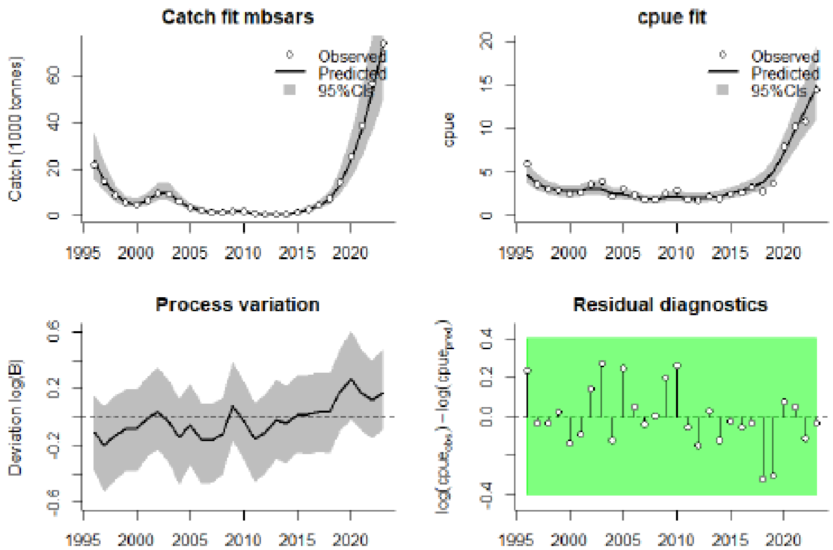
A1.2.1.5 South



Retrospective analysis for mbsars
F/Fmsy
0.0
1.0
2.0
3.0
1995
2005
2015
Year
All years
2022
2021
2020
B/Bmsy
0.0
0.2
0.4
0.6
0.8
1.0

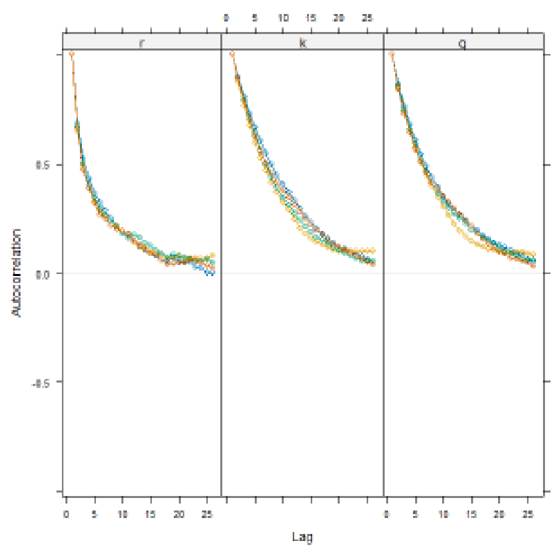


BSM prior & posterior distributions for mbsars
PPVR = 0.24
PPVR = 0.54
PPVR = 0.31
Prior
Posterior
0.2
0.4
0.6
0.8
1.0
r
500
1000
2000
k (1000 tonnes)
50
100
150
MSY (1000 tonnes/year)
PPVR = 0.25
PPVR = 0.19
PPVR = 1.23
0.1
0.2
0.3
0.4
B/k 1996
0.02
0.06
0.10
B/k 2008
0.2
0.4
0.6
0.8
1.0
1.2
B/k 2023

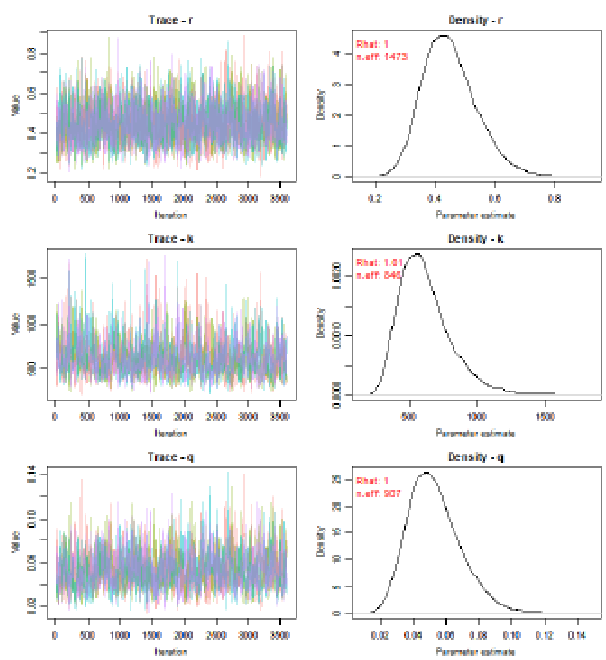


Catch fit mbsars
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)

DIC = -284.5



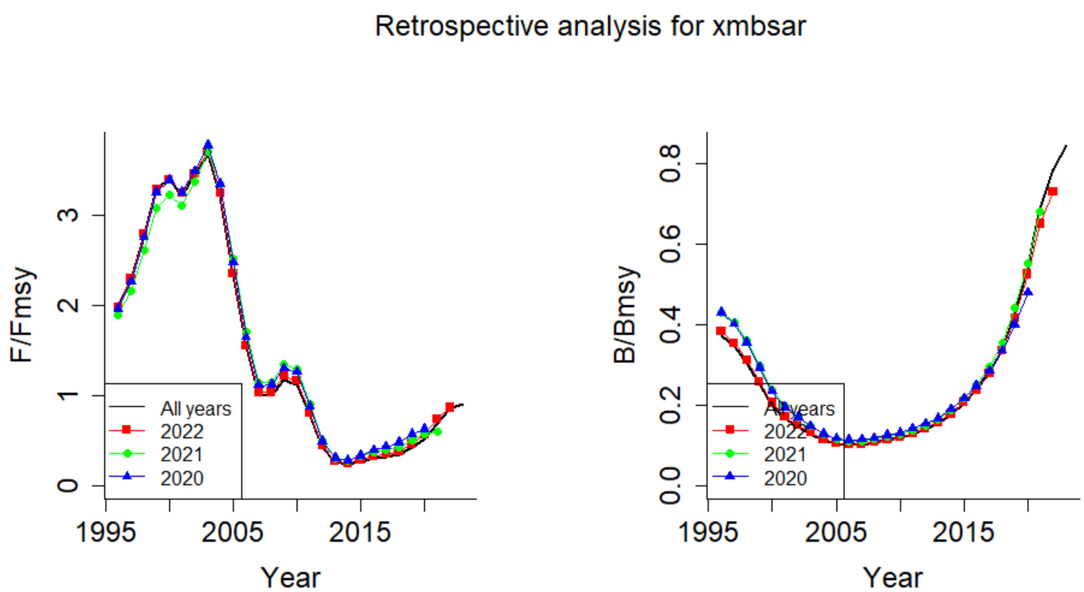
r
k
q
Autocorrelation
Lag

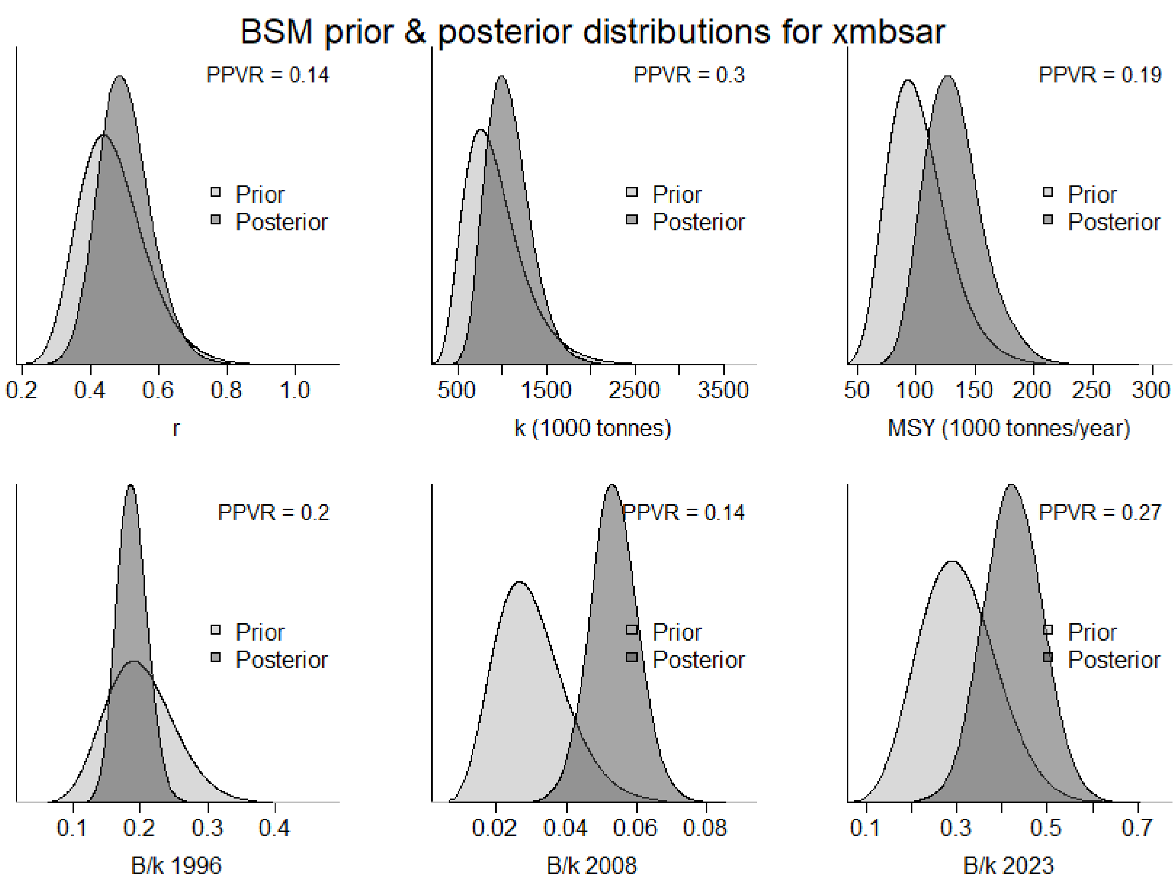


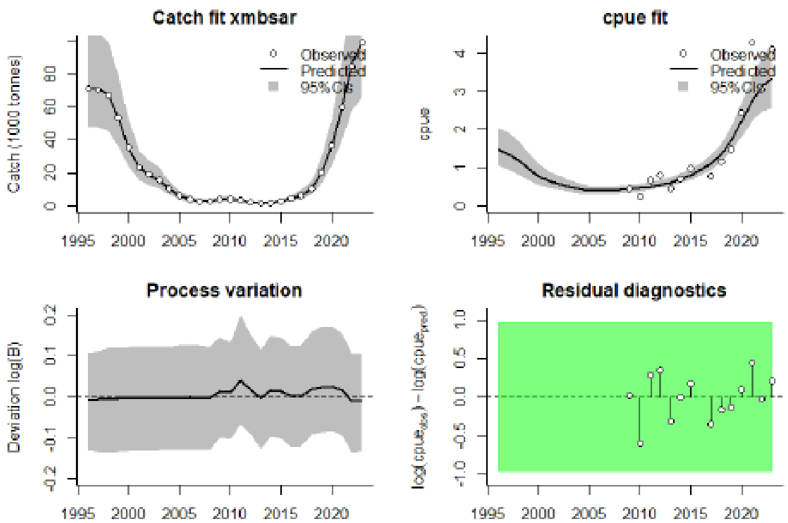
Trace - r
Density - r
Rhat: 1
n.eff: 1473
Trace - k
Density - k
Rhat: 1.01
Trace - q
Density - q
Rhat: 1
Value
Iteration
Density
Parameter estimate

A1.2.2 Fishery Independent

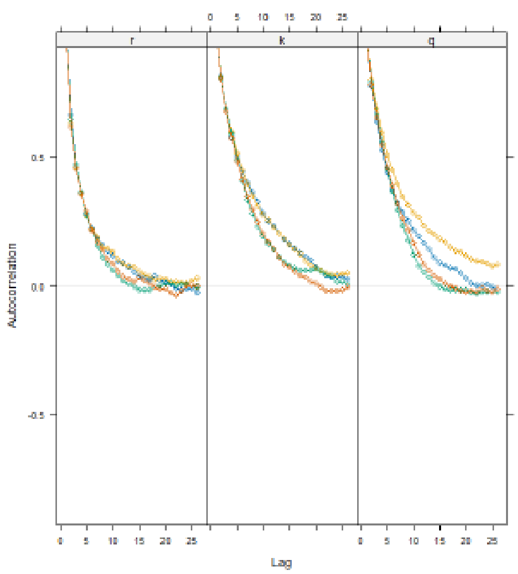
A.1.2.2.1 Whole Lake

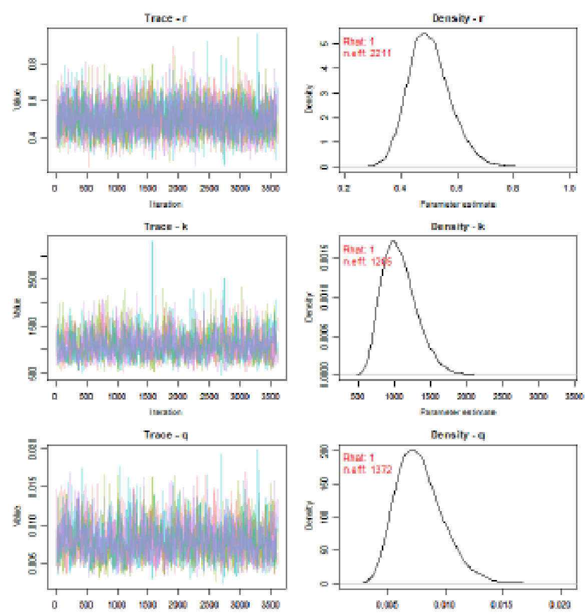




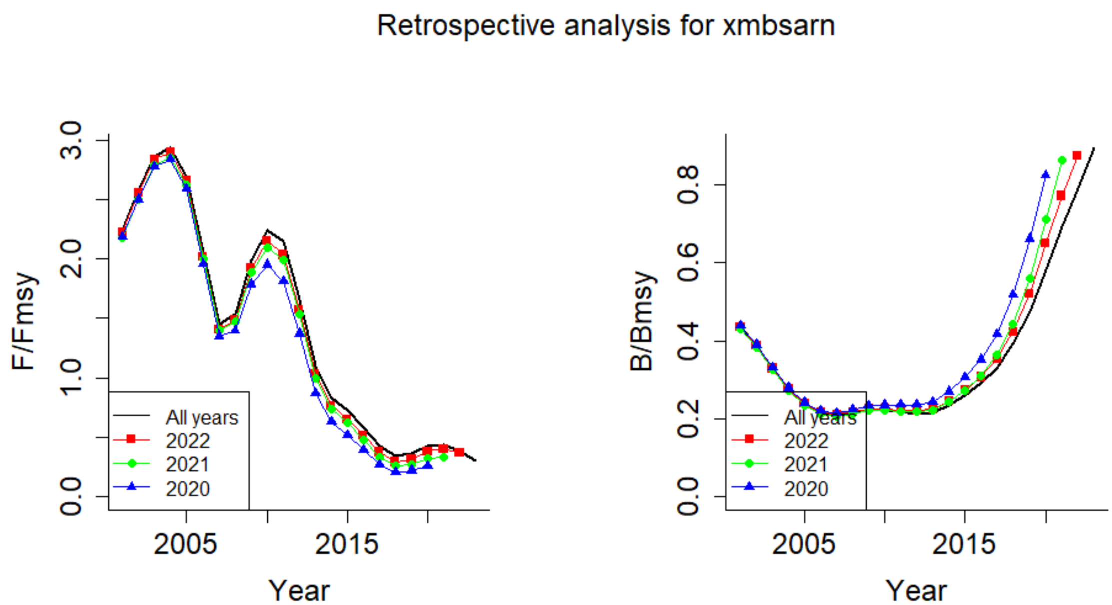

Catch fit xmbsar
Observed
Predicted
95% CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics

DIC = -346.3

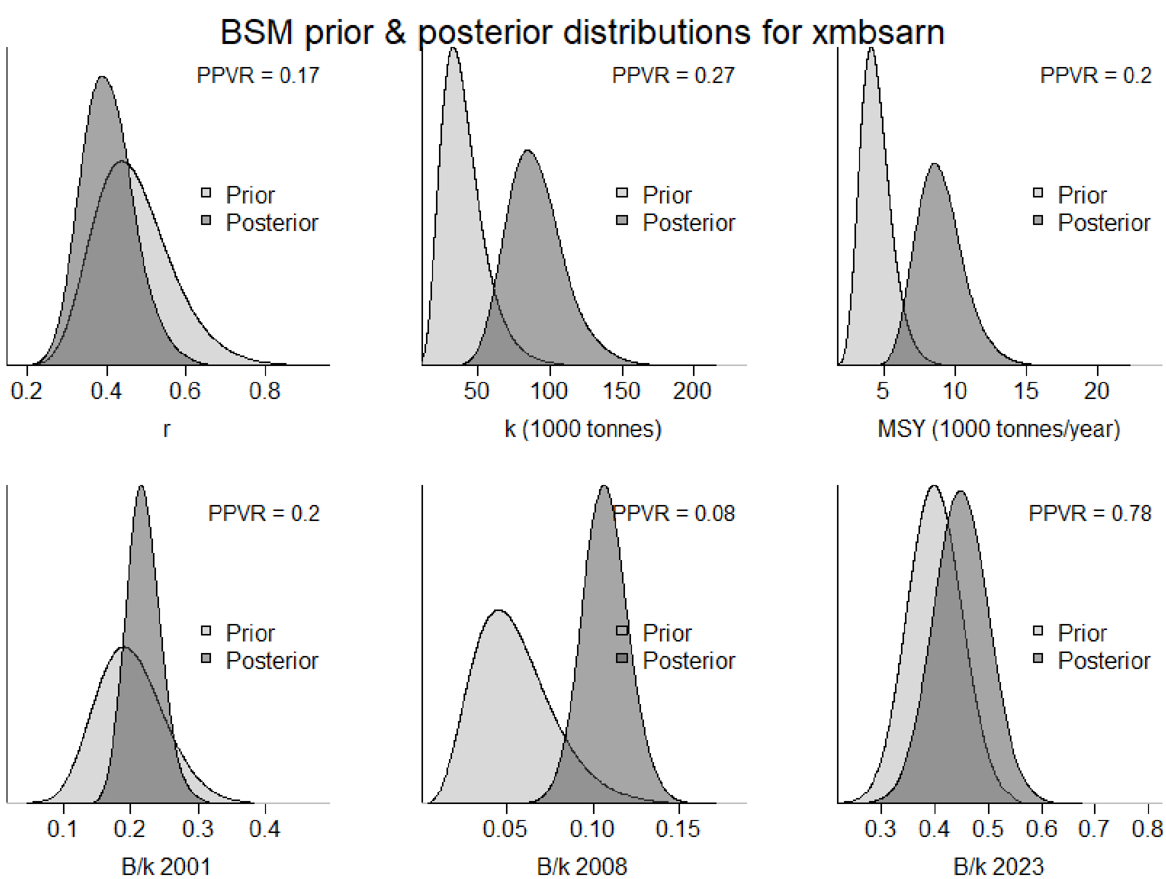

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Trace - k
Density - k
Trace - q
Density - q

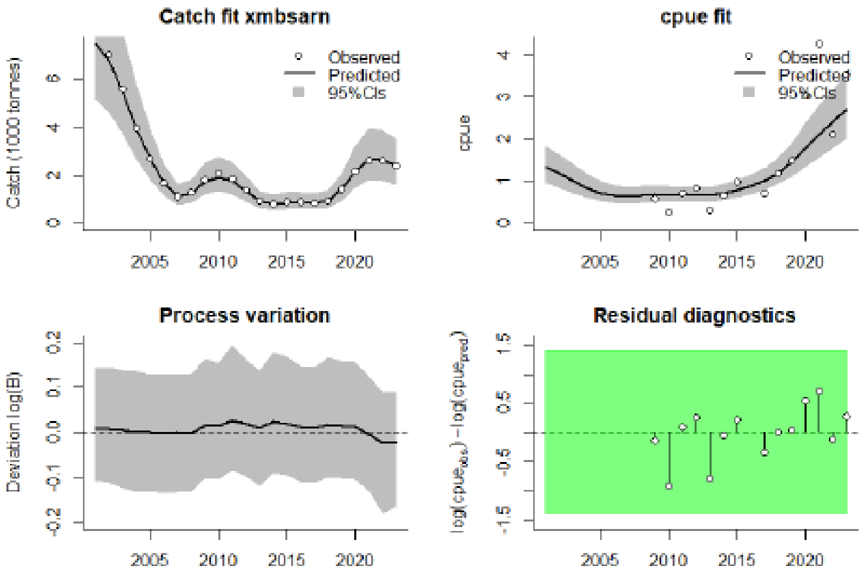
A1.2.2.2 North



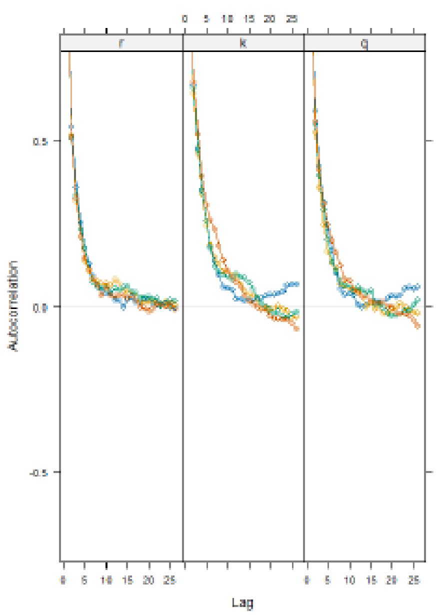
Retrospective analysis for xmbsarn
F/Fmsy
0.0
1.0
2.0
3.0
2005
2015
Year
All years
2022
2021
2020
B/Bmsy
0.0
0.2
0.4
0.6
0.8
2005
2015
Year
All years
2022
2021
2020

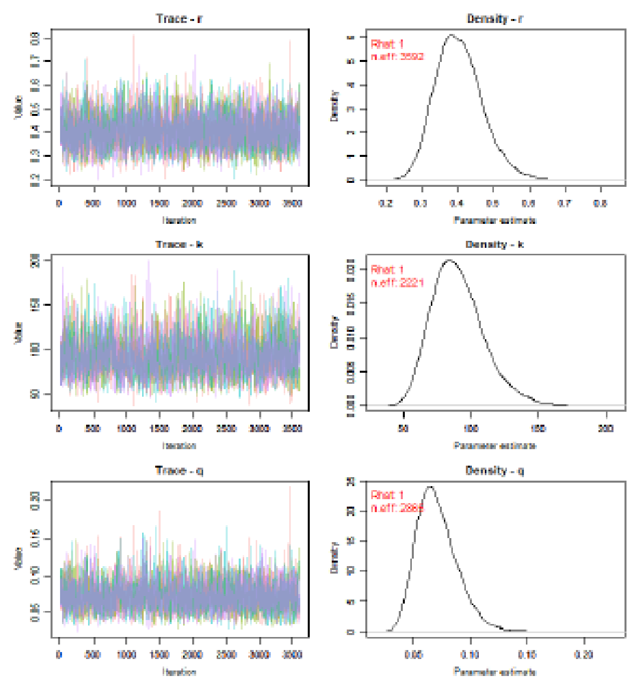


BSM prior & posterior distributions for xmbsarn
PPVR = 0.17
Prior
Posterior
0.2
0.4
0.6
0.8
r
PPVR = 0.27
Prior
Posterior
50
100
150
200
k (1000 tonnes)
PPVR = 0.2
Prior
Posterior
5
10
15
20
MSY (1000 tonnes/year)
PPVR = 0.2
Prior
Posterior
0.1
0.2
0.3
0.4
B/k 2001
PPVR = 0.08
Prior
Posterior
0.05
0.10
0.15
B/k 2008
PPVR = 0.78
Prior
Posterior
0.3
0.4
0.5
0.6
0.7
0.8
B/k 2023

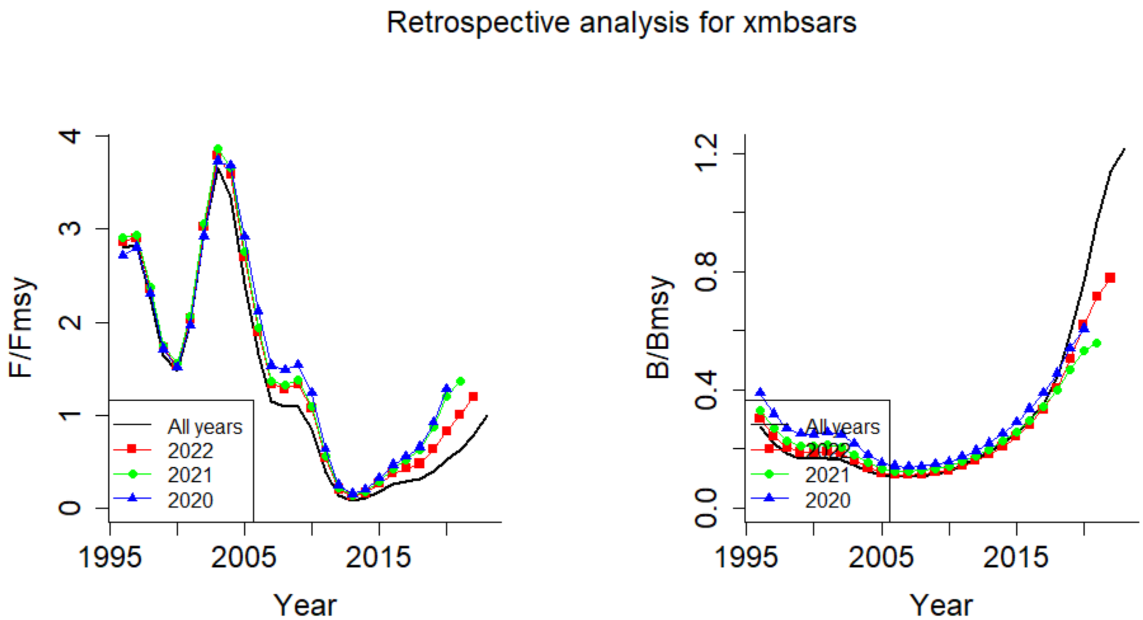

Catch fit xmbsarn
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics
log(cpue_obs) - log(cpue_pred)
2005
2010
2015
2020

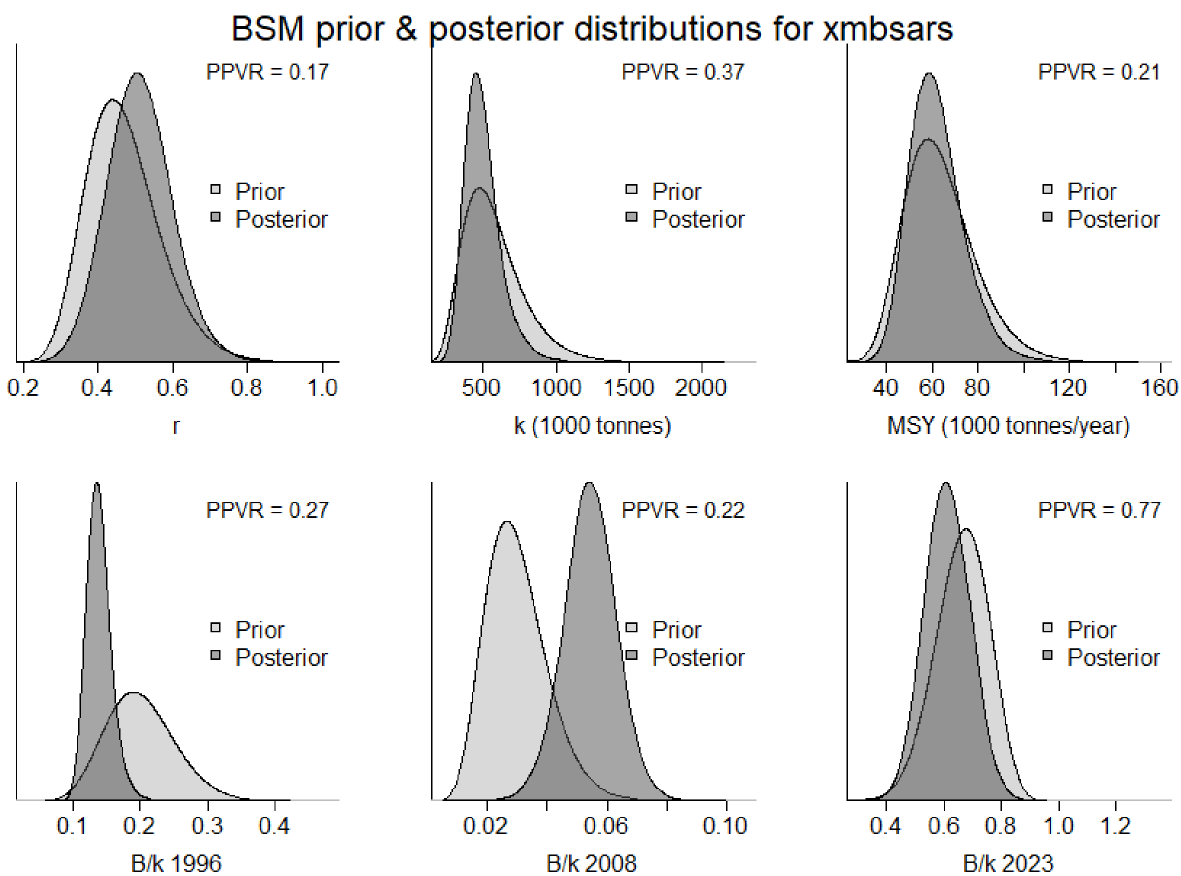
DIC = -274.7

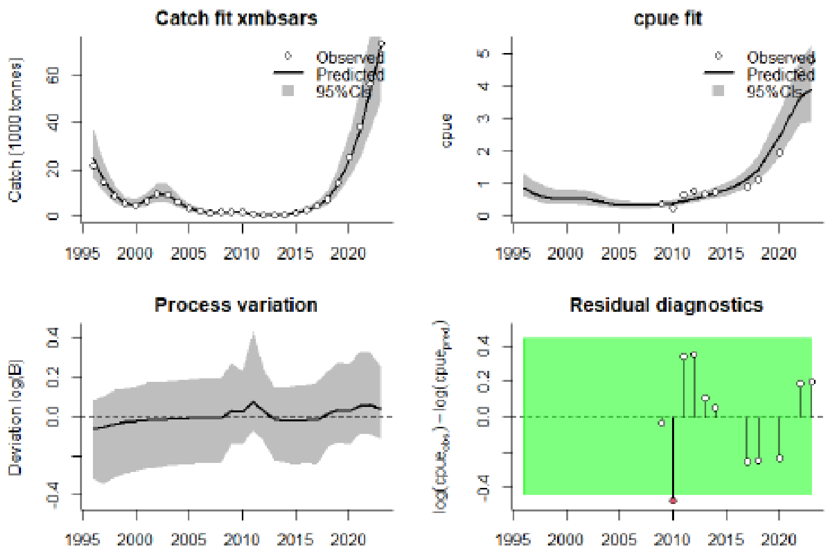

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Rhat: 1
n.eff: 3592
Trace - k
Density - k
Rhat: 1
n.eff: 2221
Trace - q
Density - q
Rhat: 1
Iteration
Value
Density
Parameter estimate

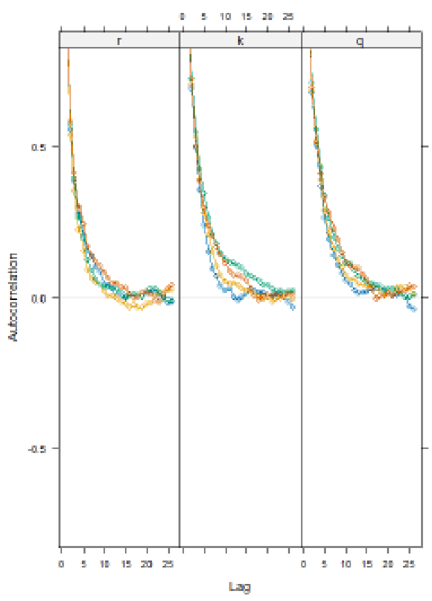
A1.2.2.3 South

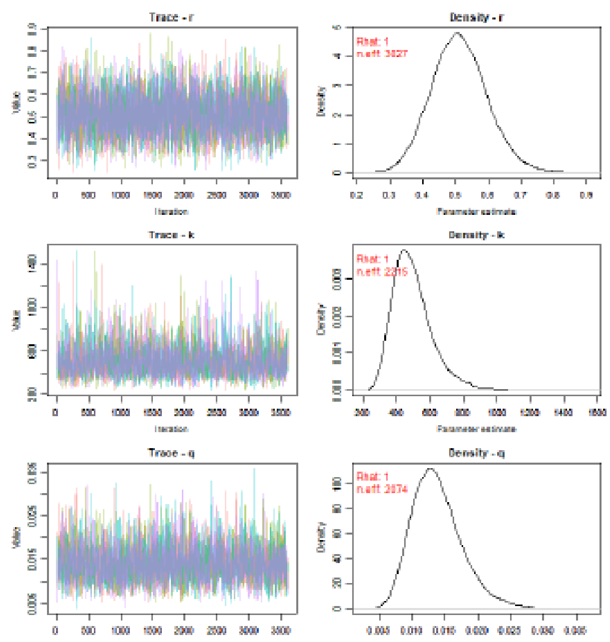

Retrospective analysis for xmbsars
F/Fmsy
B/Bmsy
Year
Year
All years
2022
2021
2020
1995
2005
2015
0
1
2
3
4
0.0
0.4
0.8
1.2


BSM prior & posterior distributions for xmbsars
PPVR = 0.17
PPVR = 0.37
PPVR = 0.21
PPVR = 0.27
PPVR = 0.22
PPVR = 0.77
Prior
Posterior
r
k (1000 tonnes)
MSY (1000 tonnes/year)
B/k 1996
B/k 2008
B/k 2023


Catch fit xmbsars
Observed
Predicted
95%CIs
Catch (1000 tonnes)
cpue fit
cpue
Process variation
Deviation log(B)
Residual diagnostics

DIC = -344.6

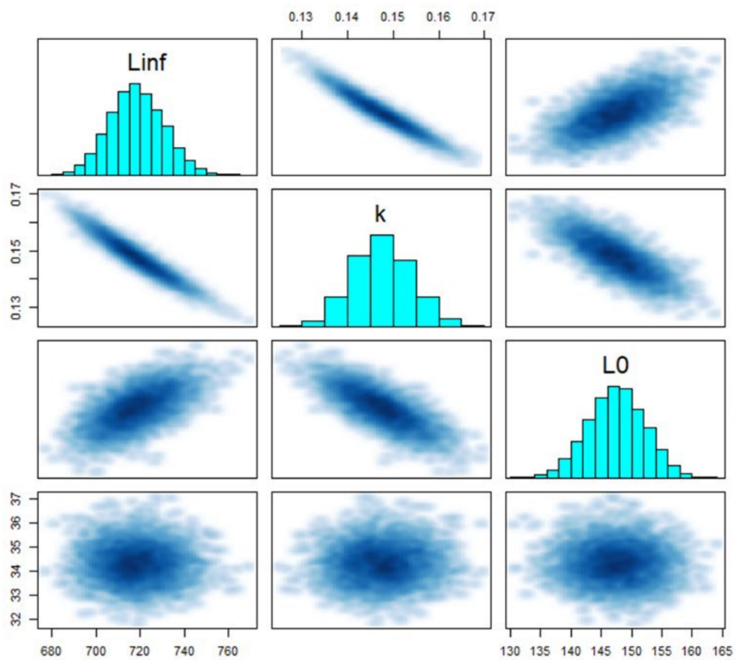

r
k
q
Autocorrelation
Lag


Trace - r
Density - r
Trace - k
Density - k
Trace - q
Density - q

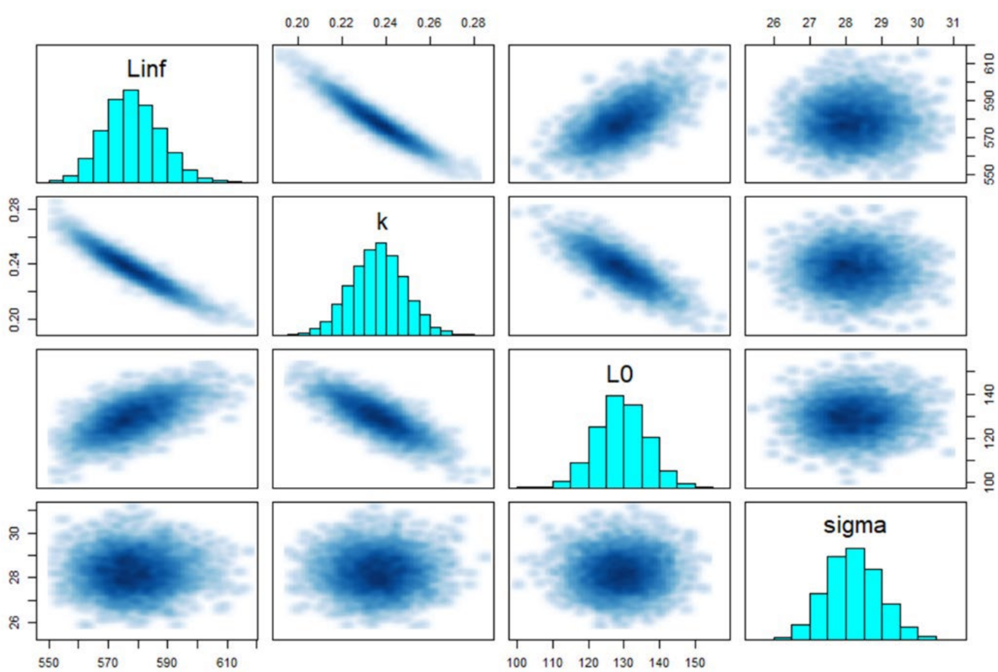
Appendix 2. von Bertalanffy growth parameters for Lake Manitoba Walleye. Probability distributions of each estimated parameter are on the northwest to southeast diagonal. Correlations among parameters are graphed in the remaining cells.

A2.1 Females

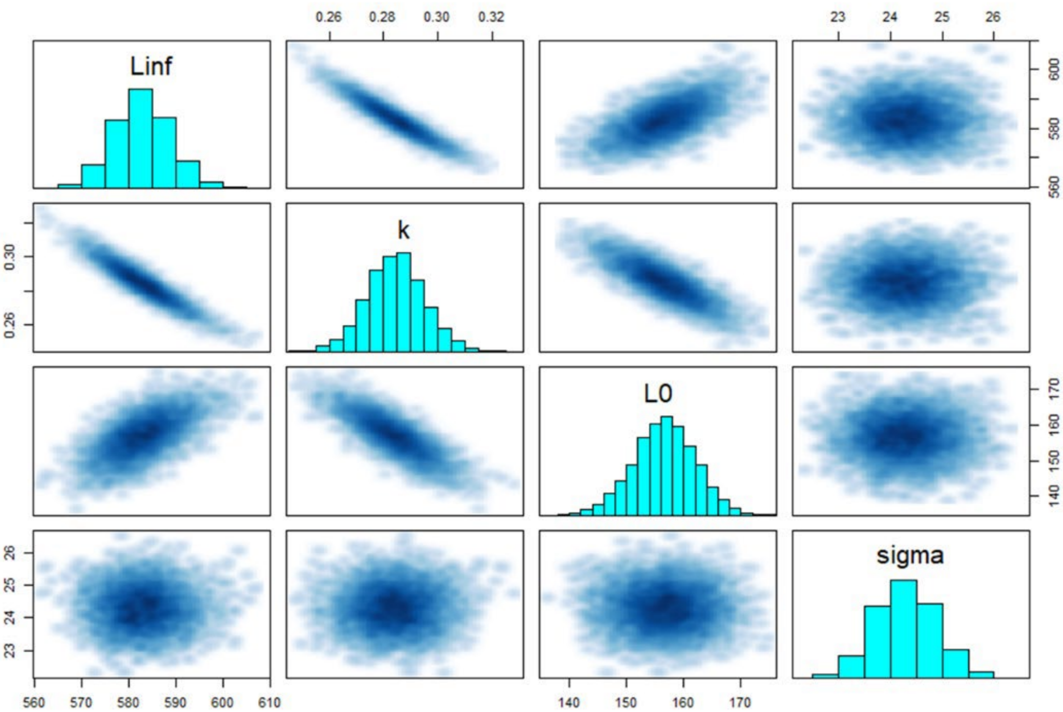
A2.1.1 North area females



A2.1.2 Narrows females

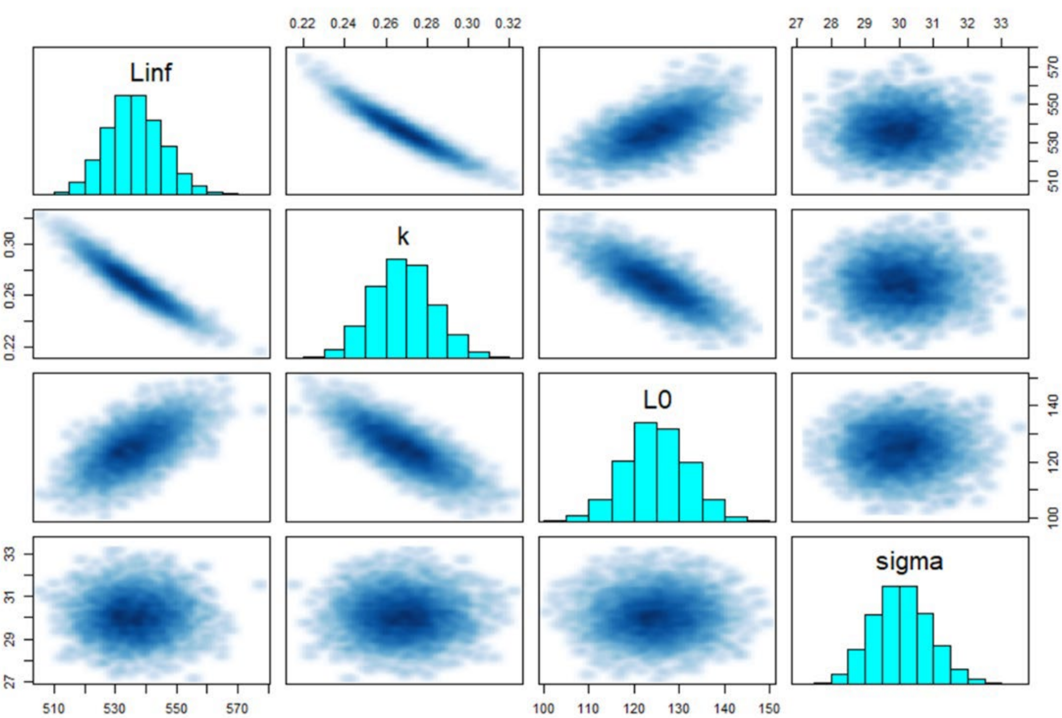


A2.1.3 South basin females

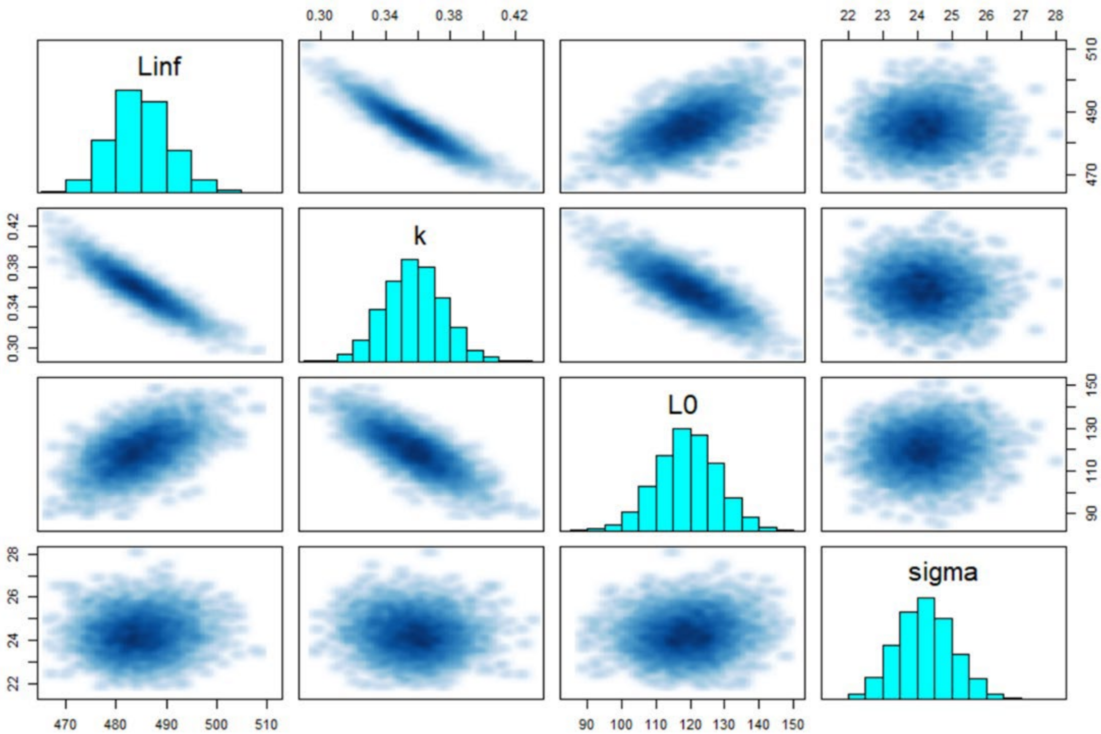


A2.2 Males

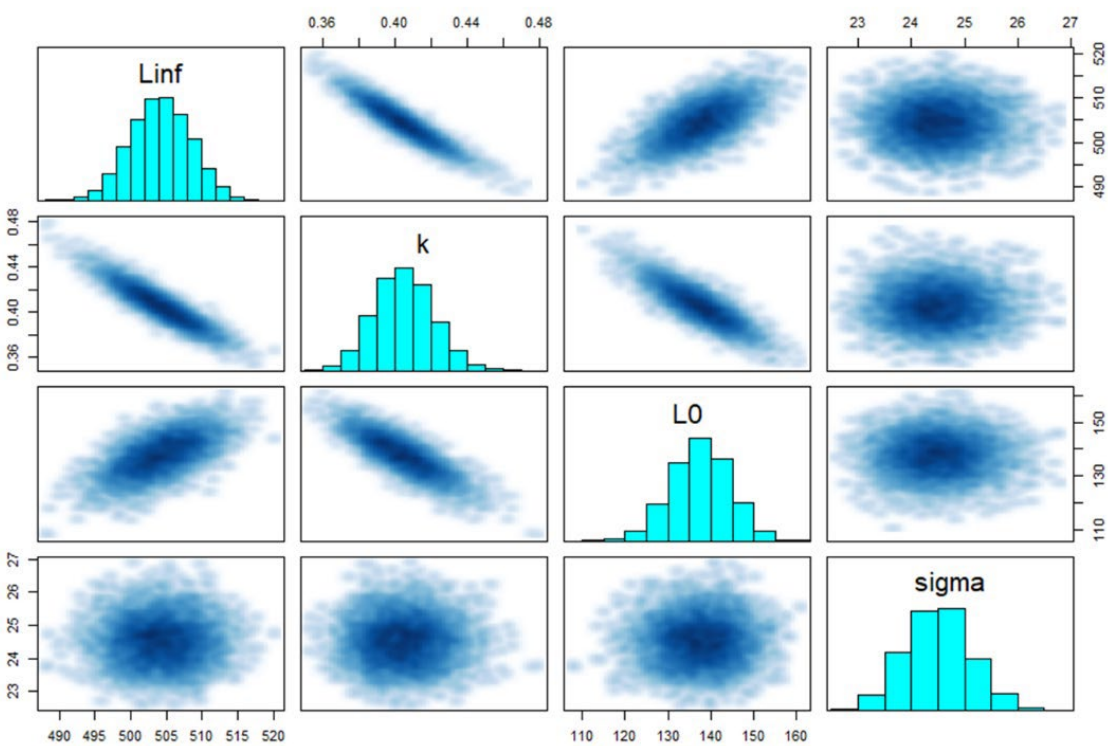
A2.1.1 North area males



A2.2.2 Narrows males

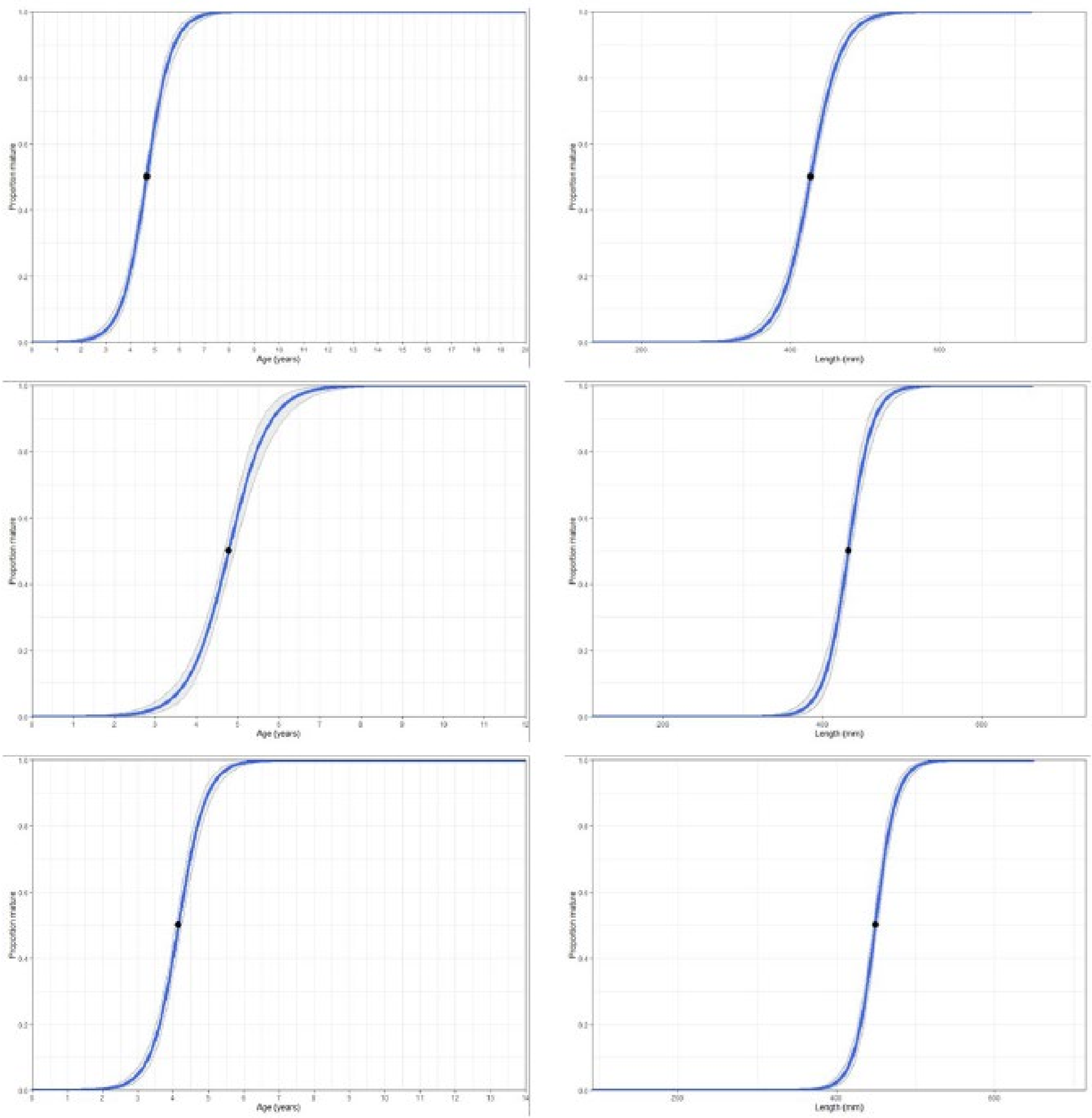


A2.2.3 South basin males



Appendix 3. Maturity ogives for Lake Manitoba Walleye.

A3.1 Maturity ogives for female Lake Manitoba Walleye. Left column is the proportion mature at age. Right column is the proportion mature at length. Top row represents the north area of the index netting programme. Middle row represents the narrows area. Lower row represents the south basin.



A3.2 Maturity ogives for male Lake Manitoba Walleye. Left column is the proportion mature at age. Right column is the proportion mature at length. Top row represents the north area of the index netting programme. Middle row represents the narrows area. Lower row represents the south basin.