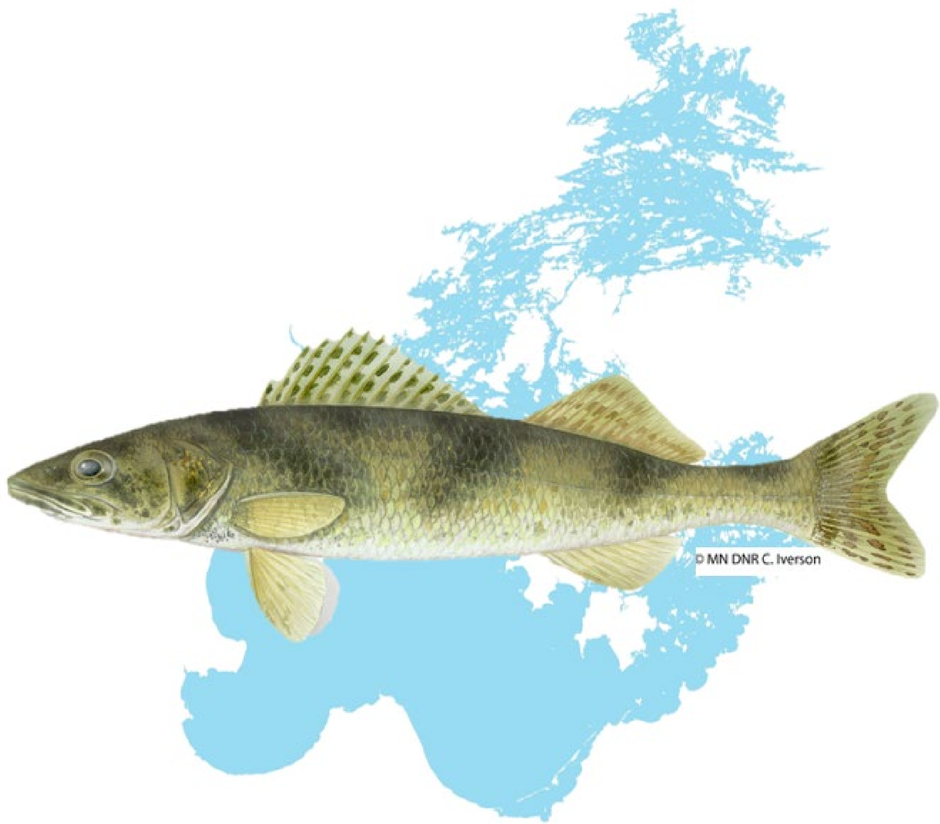
Minnesota Department of Natural Resources
Special Publication 193, January 2025

DEPARTMENT OF NATURAL RESOURCES

Stock Status and Safe Harvest Level Evaluation for Sauger in Minnesota Waters of Lake of the Woods



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INTRODUCTION

Sauger (*Sander canadensis*) are a widely distributed percid species found exclusively in freshwaters of North America. Throughout their range, Sauger abundance and distribution have declined due to several factors including over exploitation and habitat alteration (e.g. channelization, migration barriers, and water flow fluctuations (Hesse 1994; Fincel et al. 2019). Sauger are typically found in large turbid rivers (and some larger lakes) and can have expansive migratory ranges. Creation of large impoundments has resulted in lower turbidity and temperature in addition to loss of and isolation from important spawning areas (Hesse 1994; McMahon and Gardner 2001; Jaeger et al. 2005). Over exploitation of Sauger (commercial and/or recreational harvest) has also been attributed to population declines in Lake Erie, Lake Manitoba, Lake Winnipeg, and several large Tennessee rivers (Nepszy 1977; Kitterman and Bettoli 2011).

Lake of the Woods is managed as a high-quality multi-species fishery and is intensively monitored through a variety of management activities such as gamefish population assessments and recreational creel surveys. Primary Minnesota Department of Natural Resources (MNDNR) creel surveys conducted on Lake of the Woods are the summer and winter south shore surveys. The main goal of these surveys is to monitor angler fishing pressure and harvest of primary game fishes (i.e., Walleye *Sander vitreus* and Sauger, Talmage 2018). Additionally, harvest of other popular gamefish is also monitored along with trends in angler demographics and behaviors.

Historically, there was a commercial fishery in Minnesota waters of Lake of the Woods for Sauger which ended in 1985. This commercial fishery may have had some impacts on population dynamics in the early part of the subsequently discussed 1991 to 2005 time period. Also of note: Lake of the Woods is an international resource with activities that may affect the status of the Sauger stock in Minnesota waters which occur on the Canadian side of the border and vice versa. For example, Sauger have been, and continue to be a component of the commercial fishery in Sector 5 (the sector bordering Big Traverse) which may have an impact on Sauger stocks in Minnesota, though the estimated commercial harvest is relatively low compared to the recreational harvest in Minnesota waters (OMNRF and MNDNR 2004, MNDNR and OMNRF 2017).

Walleye and Sauger are managed according to specific population objectives and safe harvest levels. Population objectives are evaluated using three-year moving averages while safe harvest levels are evaluated using six-year averages. Safe harvest level for Walleye is derived using a Thermal-Optical Habitat Area (TOHA) model (Lester et al. 2004), which estimates a safe annual harvest of 540,000 pounds (MNDNR and OMNR 2017). Morphoedahpic Index (MEI) partitioning resulted in a total potential yield for all species of 4.9 pounds per acre (1,114,800 pounds) based on total dissolved solids of 138 mg/l and mean depth of 26.1 feet (MEI =18.6). The total potential yield was then partitioned by species using existing research and knowledge of population status. The potential yield for Sauger was estimated using simulation modeling; whereby fishing mortality (assumed to be constant for each time period base) is equal to natural mortality ($F=M$) as a conservative estimate of safe harvest (Radomski 1999, MNDNR and OMNRF 2017). This management strategy produces an annual target exploitation rate of 25% and safe harvest levels ranging from 122,000 to 438,000 pounds (55,000 to 200,000 kilograms) annually from 1988 to 1999 (Radomski 1999). Safe harvest level for Sauger was set at 250,000 pounds, which is slightly below the mid-point of the Radomski (1999) estimates of safe harvest based on exploitation rates (MNDNR and OMNR 2017; Talmage et al. 2018).

From 2005-2023 annual harvest exceeded the safe harvest threshold for Sauger in 8 of 10 years in which annual harvest was estimated (Figure 1). There are concerns over expanding fishing pressure documented during the winter fishery on Lake of the Woods and increasing harvests in summer (Appendix 1). Several factors have led to increased pressure in the winter ice fishery. While advances in technology have played a role, sleeper houses (e.g., private wheelhouses, resort sleeper houses) and improved accessibility have largely driven the increase. Sleeper fish house (private and resort) popularity continues to increase and is additive to overall fishing pressure, though anglers fishing in sleeper houses are not likely attentively fishing for the entire duration of their trip. Working in concert with the increased sleeper houses, a resort-maintained plowed pay-road system on Lake of the Woods allows relatively easy access to most vehicles and wheeled (sleeper) fish houses, whereas in the past travel was primarily limited to vehicles capable of traversing deep snow (Nelson 2023). Kennedy (2016) suggested that year-to-year winter fishing pressure is the biggest unknown, regarding fisheries management for Minnesota waters of Upper Red Lake. Increasing winter fishing pressure has led to concerns of over exploitation of fish populations, especially Walleye and Sauger. This increased winter pressure on Lake of the Woods coupled with the increasing summer harvest (Appendix 1) has led to the current fishing regulations. On March 1, 2019, the winter aggregate bag limit for Walleye and Sauger was reduced from 8 to 6 and from 2 to catch and release only on the Rainy River (including Four Mile Bay) from March 1 to April 14. The objectives of this evaluation are to provide an updated overview of the stock status of Sauger and reevaluate the safe harvest level for Sauger that reflect the current status of the Lake of the Woods fishery in Minnesota waters.

STUDY AREA

This analysis focuses on the Minnesota waters of Lake of the Woods. Minnesota's portion of Lake of the Woods (317,000 acres) lies primarily within Muskeg, Big Traverse, and Little Traverse Bays. Big Traverse Bay and Muskeg Bay are largely devoid of bottom structure and islands. Little Traverse Bay is similar to the Ontario waters of Lake of the Woods, with numerous islands and reefs. The Minnesota waters are relatively shallow, with maximum depths of less than forty feet in all three of the major basins. In addition to the connectivity to Canadian waters, the Rainy River (the largest tributary to Lake of the Woods) also supports a robust recreational Walleye and Sauger fishery. Sauger are able to move between Canadian and Minnesota waters and between Lake of the Woods and Rainy River, meaning that the Sauger stock in Minnesota waters is not a closed population.

METHODS

Sauger population data was derived from standardized population assessments that have been conducted annually since 1983 (Wingate and Schupp 1984). Briefly, assessment surveys were conducted using overnight multifilament experimental gillnet sets (i.e., 250 x 6-foot; five 50-foot mesh panel: 0.75, 1.0, 1.25, 1.5, 2.0 inch bar mesh). All Sauger were enumerated, measured for length and weight, sex was determined, and sagittal otoliths were removed from a subsample of individuals for age determination. From 1983 to 1990 age determination was made using scales, while all Sauger ages were assigned using sagittal otoliths starting in 1991. For this analysis, time-series data from 1991 through present was used because otolith assigned ages are more reliable.

Inconsistent MNDNR angler creel data for Lake of the Woods dates to the 1960s. The creel survey schedule has varied across time, but there has never been more than a four consecutive year period where the Lake of the Woods summer (access based) and winter (1981-2022 roving, 2023-present access based) south shore creel surveys were not conducted. Other creel surveys that have been conducted with varying frequency targeting Walleye and Sauger anglers include the Northwest Angle summer creel survey (roving) and the Rainy River spring (roving) and fall (roving) creel surveys. In recent years, the summer south shore creel survey, and Rainy River fall creel survey have been completed in two out of four years. The winter south shore creel survey and the Rainy River spring pressure estimate have been conducted annually. A winter bag limit reduction for Sauger from 14 to 8 and was implemented in 2005, therefore, an emphasis will be placed on two distinct time periods to describe Sauger population dynamics and harvest characteristics (1991 to 2004 and 2005 to 2023). Also of note, the winter bag limit for Sauger was further reduced to six in 2019. We chose to not include a third time period due to limited time series available for analysis and the relative triviality (two fish bag reduction for one season would equates to ~14% Sauger harvest reduction under the most liberal harvest scenario; MNDNR unpublished data) of the change in comparison to a bag reduction of six fish.

Stock Status Evaluation

Several stock status evaluation tools including biological performance indicators (BPIs) were used in this analysis to help identify over exploitation of fish stocks. Because there are no developed BPI tools for Sauger that that we are aware of, BPIs were developed largely based on the Walleye BPIs from Gangl and Periera (2003). In addition to the BPIs based on Gangl and Periera (2003), Johnston et al. (2012) observed that Sauger condition increased significantly as abundance declined in Lake Winnipeg, Manitoba, so condition was added to the suite of BPIs examined for Sauger. Overall, the similarities in biology and the overlap between the recreational Walleye and Sauger fisheries provides some confidence that the Gangl and Periera (2003) BPIs are reasonable for evaluating the Sauger population for potential over exploitation. These thresholds were defined using professional judgement informed by a combination of percentiles (from the Lake of the Woods dataset) and in some cases, the relationship between relative abundance and the BPI (if the relationship was significant). Generally, the threshold values were set at approximately the upper or lower 10-25th percentile (depending on the BPI) with the idea that the suite of proposed thresholds will be sensitive enough to detect over exploitation in a timely manner without being overly sensitive to natural variability in the Sauger population. Basically, if multiple BPIs are at the extreme of the normal range of the Lake of the Woods Sauger dataset, there may be evidence of over exploitation or some other disturbance to the health of the population. There is some uncertainty about the relative responsiveness of this approach to over exploitation because the Lake of the Woods Sauger population has never experienced severe over exploitation and as mentioned previously, we are unaware of any BPI tools that have been developed for Sauger though Johnston et al. (2012) suggests that condition may be relatively responsive to changes in abundance.

In generally, Sauger stock trends are evaluated based on three-year moving averages of annual growth, recruitment, and mortality for management purposes. General trends in stock-recruitment metrics were examined using three-year moving averages to identify possible indicators of over exploitation of the Lake of the Woods Sauger stock. Metric definition and calculations are described below. For more detail please see Gangl and Periera (2003) and Nelson (2020). Analyses and estimates were generated using SAS (Statistical Analysis System), Program R (R Core Team 2019), and Microsoft Excel. Generally, changes across time were analyzed via linear regression, while differences between time periods (1991-2004 versus 2005-2023) were tested using a student's t-test, and correlation between BPIs was examined using the Pearson correlation coefficient. All the statistical tests were conducted using annual data while the general trends were examined graphically based on three-year moving averages.

Growth for the purposes of this analysis is the change in length between time periods (i.e., 1991-2004, 2005-2023). This change can be examined at the population or individual level. As noted by Carlander (1942), adult Sauger in Lake of the Woods display very little sexual dimorphism in terms of length, therefore, growth can be viewed as an aggregate of both sexes. Growth was estimated using both empirical length at age data from gillnet surveys as well as model estimated length at age information. Annual length-at-age is the mean total length at a specified age *t*. The traditional von Bertalanffy growth model is $L_t = L_\infty\left(1 - e^{-k(t-t_0)}\right)$ where *Lt* is length-at-age, $L\infty$ is the asymptotic length, *k* is the growth rate, and t_0 is the theoretical age at which the fish would have a length of 0. Density dependent processes govern fish growth; thereby, influencing other biological characteristics such as condition and rates of maturation. Johnston et al. (2012) suggest that length and age at maturity may not be as responsive to changes in abundance as Walleye due to differences in life history strategies (i.e. mature earlier and at smaller sizes with more nutrient rich eggs), though the general trend of increased growth and decreased age and length at maturity were observed with decreased abundance. We investigated condition using both relative weight (Anderson and Neumann 1996) and length-weight residuals as opposed to just length-weight residuals as in Johnston et al. (2012). Because relative weight had a slightly stronger relationship with relative abundance in Lake of the Woods and there was extremely high (r = 0.99) correlation between the two metrics, we only presented relative weight in this document. Lastly, individual logistic models were fit to obtain rates of maturation (i.e. female age and length of 50% mature; Gangl and Periera 2003).

Recruitment is defined as the number of fish that survive to a specific age or size each year (Allen and Hightower 2010). For this analysis, Sauger recruitment was defined as the number of age-2 to age-5 fish sampled during fall gillnetting and was expressed as an index or year-class strength. The year-class strength index was the least squares mean (LSMEANS statement in PROC GLM (SAS Institute Inc. 2008) of the natural logarithm transformed age-wise catch per unit effort (CPUE) (ln CPUE+1) for age-2 to age-5 Sauger (Pereira et at. 2000). Twenty-fifth and 75th percentiles, were calculated to allow interpretation of year-class strength (i.e., below the 25th is weak, while above the 75th is strong).

Relative abundance is an expression of population density and was defined as relative abundance or catch per unit effort (CPUE). For this analysis, catch per unit effort was calculated as *C/f* = CPUE where *C* is the total number of Sauger caught per year and *f* is the unit of effort expended (i.e., number of gill nets deployed). Analysis of relative abundance trends is limited to near-shore gillnets (≤20 feet of water) because offshore gillnets were not added to the sampling protocol until 2002. Twenty-fifth and 75th percentiles were calculated to allow interpretation of relative abundance.

Mortality is a rate at which individuals are lost from a population and is expressed as total, natural, and fishing mortality. Several mortality rates were calculated in this analysis based on age-wise CPUE for age 3 to 9 Sauger (Radomski 1999) and are summarized in Table 1. Instantaneous natural mortality (*M*) was calculated using the predictive equation described by Pauly (1980), with an assumed mean annual water temperature of 48.86^{o} F (9.367^{o} C) and von Bertalanffy growth parameters ($L\infty$ and *k;* calculated as described previously) either reported or calculated for specified time-periods.

Age composition of female Sauger was estimated using the Shannon diversity index (Marteinsdottir and Thorarinsson 1998). The Shannon diversity index is a diversity metric that accounts for richness (number of age classes) and evenness (abundance of each age class) within a population; with higher values representing a more heterogenous distribution of ages. Having a diversity of ages in the population ensures that the population is replacing itself. Over exploitation results in a more homogenous age distribution (Gangl and Pereira 2003). Gill net catch rates of larger-bodied (>14") Sauger were used as a surrogate for spawner abundance and were also used to define mortality trends. Nearly all Sauger are mature (>98% of both males and females) at fourteen inches.

Harvest Evaluation

Sauger population size and weight was estimated by dividing the estimated number and weight of harvested Sauger per year by the exploitation rate described above. These values were then used to estimate safe harvest levels based on an instantaneous fishing mortality rate of (F=M) for each period of time. Safe harvest levels were the average of the estimates of the specified period.

RESULTS

Stock Status Evaluation

Since 1991, mean length at age-3 has shown no significant trend (p = 0.33, R^2 = 0.03; Figure 2). Prior to this evaluation, no BPI thresholds had been established for Lake of the Woods Sauger; however, chronically exceeding 12 inches at age-3 would suggest a substantial increase in growth and was set as the proposed threshold for growth as expressed in length at age-3 (Table 2). Mean length at age remained unchanged if broken into two time periods (t = 1.01, p = 0.32; 1991-2005, 2006-2023), but the von Bertalanffy parameters described by Radomski (1999; Table 3; Figure 3) suggest growth has increased.

A measure of condition such as relative weight is directly impacted by density dependent processes. There was a significant negative correlation between relative abundance and relative weight (r= -0.49, p = 0.03). The upper 15th percentile for Lake of the Woods Sauger relative weight is 91.2 so we used 91 as the maximum threshold for relative weight for Sauger (Table 2). Generally, the three-year moving average for Sauger relative weight only exceeded the threshold three times between 1991 and 2023; most recently in 1999 (Figure 4). Relative weight declined significantly through time (p < 0.01, $R^{2\,=}$ 0.23) and was significantly higher in the 1991 to 2004 time period (mean = 89.73) than the 2005 to 2023 (mean = 86.73) time period (t = 2.59, p = 0.02).

Minimum thresholds for length and age at 50% mature for female Sauger were proposed to be set at 11 inches and age-3 respectively; and are approximately the 25th percentile for each parameter (Figures 5 & 6). Length and age at 50% mature for female Sauger are not significantly correlated (r = 0.20, p = 0.29), but both show a positive though insignificant (p = 0.57 and 0.15 respectively) trend since 1991. However, during the 2005-2023 time period, length at 50% mature was flat and has shown a downward trend since 2014, but still exceeds 11 inches. There were no significant differences between time periods for length (t = -0.34, p = 0.73) or age (t = -1.50, p = 0.14) at 50% mature.

Since 1991, Sauger year-class strength has had an average index value of 1.16 and has fluctuated from 0.13 (1991) to 2.62 (2006) with a significant positive trend (p = 0.05, R^2 = 0.12; Figure 7). From 1991 to 2021, the 25th and 75th percentiles (weak and strong year-class distinction) are 0.7 and 1.6, respectively. A minimum threshold of 0.5 is proposed for year class strength. Sauger recruitment did not fall below the proposed threshold of 0.5 during the 2005 to 2023 time period. It was below the threshold five times during the 1991 to 2004 time period including most recently in 2004 resulting in average year class strength being significantly lower in the 1991-2004 time period than the 2005-2023 time period (t = -2.59, p = 0.01).

Sauger relative abundance (as measured by gillnet catch rate) has ranged from 5.4 to 30.8 per net since 1991, with a significant increasing trend (p = <0.01, R^2 = 0.37; Figure 8). Relative abundance has not fallen below the long-term (1991-2023) average of 16.3 per net since 2006. Relative abundance significantly (t = 4.98, p = <0.01) increased from the 1991-2004 (mean = 11.4 Sauger per net) time period to the 2005-2023 (mean = 19.9 Sauger per net) time period. Ten Sauger per net (approximately the 20th percentile) is suggested as a minimum relative abundance threshold.

Apart from F, all other mortality rates were lower than those reported by Radomski (1999). However, both mean total instantaneous and annual mortality (Z & A) decreased from 1991-2004 to 2005-2023 (Table 4; Appendix 2). During both time periods fishing mortality (F) exceeded natural mortality (M). Exploitation rates ranged from 19% to 36% and averaged 26% from 1991-2004 and 20% for 2005-2023. Annual A estimates do not vary if described as an average of the annual individual estimates or as a composite (average number per age group per time period) of the specified time periods. Total annual mortality for age-3 to 9 Sauger have decreased from 39.5 to 36.4% on average but are presently at 45%. Female age diversity has not changed significantly between time periods (t = -0.22, p = 0.82) or through time (p = 0.51, R^2 = 0.01; Figure 9). Over the past decade, age diversity has fallen below the 25th percentile of 1.14 three times and is above the proposed threshold of 1.0. Sauger abundance greater than 14 inches is also higher in the 2005-2023 time period than the 1991-2004 time period (t = -2.90, p = 0.01) increasing significantly through time (p = 0.01, R^2 = 0.19; Figure 10), with catches exceeding two per net all but two years from 2011 to 2020. Notable declines have been observed the past three years, but still exceed the proposed threshold of 0.9 per net.

Harvest Evaluation

From 1991 to 2004 annual estimated Sauger harvest ranged from ~ 85,000 to 525,000 pounds and from ~ 100,000 to 575,000 pounds from 2005 to 2023. Estimated Sauger biomass averaged ~ 950,000 pounds from 1991-2004 and ~ 1,500,000 pounds from 2005 to 2023. This 36% increase in biomass is also observed in gill net abundance (12.4 per net to 17.7 per net; Table 5). Radomski (1999) reported safe harvest levels ranged from ~ 100,000 to 440,000 pounds with an average of ~ 240,000 pounds, using the $F=M$ mortality rate from 1988 to 1995 (approximately equivalent to and exploitation rate of 25%). Applying this fishing mortality rate ($F=M$) safe harvest projections ranged from ~ 70,000 to 700,000 pounds from 1991-2004 and from ~100,000 to 600,000 pounds from 2005-2023. From 1991 to 2004, Sauger harvest averaged just over 200,000 pounds and did not exceed the conservative fishing mortality rate ($F=M$; ~225,000 pounds). From 2005 to 2023, Sauger harvest averaged just over 300,000 pounds also not exceeding the conservative fishing mortality rate (~330,000 pounds), though the $F=M$ safe harvest threshold was exceeded on an annual basis five out of the previous ten years that harvest estimates have occurred including the most recent three consecutive years for which harvest has been estimated while 25% exploitation has been exceed three times since 2005. Harvesting at a 25% exploitation rate resulted in an average harvest of 376,000 pounds from 2005-2023 (Figure 11).

DISCUSSION

A variety of proposed BPIs were used to assess Sauger stock status for signs of over exploitation. A definition of over exploitation is as follows: "a fishery resource is being overexploited, if, because of fishing, yields no longer can be maintained at or near potential, or there is good reason to believe that the resource is predisposed to collapse or displacement" (OMNR 1983). In general, population level impacts resulting from over exploitation are declines in abundance, changes in yield, altered age structure or reduced mean age, increased growth, reduced length and age at first maturity, and increased variance in recruitment (Spangler 1977; OMNR 1983).

Growth BPI trends of Lake of the Woods Sauger are open to interpretation depending on selection of temporal scale, but we expect to see density dependent effects. When density decreases to a certain level, resource availability increases resulting in faster growth and earlier maturation. There was no significant temporal trend in three of the four growth parameters since 1991. There is, however, a significant decline in relative weight between time periods and through time. Condition is also strongly correlated to relative abundance. There is no correlation between relative abundance and the remaining growth BPIs including mean length at age-3 (p = 0.20, r = -0.24), length at 50% mature (p = 0.97, r = -0.01), or age at 50% mature (p = 0.16, r = 0.25). This is consistent with the Johnston et al. (2012) description of the Sauger population in Lake Winnipeg, Manitoba, where Sauger condition responded quickly to changes in abundance while changes to maturity schedules and length at age were not as readily apparent. However, if population abundance decreased severely, we may observe increased growth and earlier maturation much like the response of Sauger in Lake Winnipeg to very low abundances and Walleye populations to over exploitation (Reid and Momot 1985). Even without reaching very low relative abundance, maturation of Lake of the Woods Sauger has been inversely related to somatic growth since 1991.

Since 2005, there has been no significant trend in any of the growth BPIs other than relative weight, although over the last few years both age at 50% mature and condition (the growth metrics proposed for assessing sustainability objectives) have both trended towards their individual thresholds. Neither of these objectives have reached the threshold, but they may if the trend from the most recent surveys continues. Lastly, growth responses often occur after a serious decline in population size; thus, growth may not be a suitable parameter for earlier detection of over exploitation (Gangl and Pereira 2003) though condition appears to be very responsive to relative abundance.

Recruitment success varies from year to year in most fish populations due to several factors (Maceina and Pereira 2007). An indicator of over exploitation would be low adult abundance resulting in a weak year-class being produced the following year; however, there is no relationship between Sauger relative abundance in relation to the strength of the following year's cohort or trawl catch per unit effort (CPUE). At the present, Sauger year-class strength is best predicted by August trawl CPUE and calculated length on 15 August; however, what determines the strength of a given age-class upon being recruited to gill nets is still unknown (i.e., abiotic and/or biotic). Sauger recruitment is cyclical and has notably increased since the early 1990s with several strong year-classes being produced over the past decade. As expected, this improved production results in higher abundance as demonstrated by the correlation of the strength of a given year-class relative to catches two years later (p = 0.01; r = 0.44).

As each age class contributes unequally to reproductive efforts due to differences in fecundity and egg quality, maintaining a stock with high age diversity is important (Gangl and Pereira 2003). A notable increase in CPUE of Sauger greater than 14 inches is a favorable indication of mortality over past three decades. Of note, however, is the recent decline in the past three-years for catches of larger Sauger in combination with increases in total annual mortality. These declines follow a period above average harvest documented in 2019 and 2020.

Relative abundance is a coarse tool for making assumptions for overall population density and caution should be given when interpreting results and making management decisions. Several spatiotemporal factors can influence a gear's catchability. However, annual monitoring at fixed locations using the same gear type helps to reduce variability and when combined with other population/individual data such as age, length, weight, sex, and stage of maturity, several insights can be gleaned and prove valuable to resource managers. For instance, relative abundance is moderately correlated to harvest ($p = 0.11$, $r = 0.35$). Due to this correlation, setting a safe harvest level at 250,000 pounds during a period of lower Sauger abundance (as observed in the 1990s) was reasonable and fell within the safe fishing mortality rate of $F=M$ or an exploitation rate of 25%. As previously discussed, substantial increases in Sauger abundance over the past decade warranted an updated overview of 2018-2023 safe harvest yield. Using the same mortality parameters; safe harvest levels over the past two decades would fall in the range of 330,000 to 430,000 pounds annually. Additionally, the overall safe harvest based on MEI simulation exceeds 1 million pounds. The Radomski (1999) analysis drove the species-specific partitioning for Sauger. When considering the entire potential yield for Minnesota waters in over 1 million pounds and six year moving average for harvest of all species is ~950,000 pounds annually, this suggests that the species-specific MEI partitioning was likely extremely conservative for Sauger at 250,000 pounds since ~90% of all pounds of fish harvested are Walleye and Sauger. Thus, production and consequently potential yield is going to be higher in these species than other species that are less targeted for harvest by anglers, likely resulting in a higher potential yield for Sauger than estimated by Talmage et al. (2018).

MANAGEMENT IMPLICATIONS

Based on historical trends in Sauger population attributes (i.e., growth, recruitment, and mortality) over the past thirty years, it is evident that harvest has been sustainable. However, maturation rates have declined over the past decade and catches of large Sauger have declined in the past three years. Coinciding with large-bodied catches is the recent increase in total annual mortality following a period of during which harvest exceeded 450,000 pounds occasionally and exploitation rates near 30%.

The potential yield and safe harvest level for Sauger is set at 250,000 pounds (113,600 kilograms) and is extremely conservative based on contemporary population abundance. However, this safe harvest level was approximately equivalent to a 25% exploitation rate for the time period in the Radomski (1999) analysis. As demonstrated in this evaluation, harvesting Sauger at a 25% exploitation rate over the past twenty-years would equate to ~ 375,000 pounds annually (170,100 kilograms) or ~ 1.25 (pounds/kilograms per acre/hectare) which has been referenced as sustainable for Walleye for lakes in Northern Ontario that are of low productivity (Colby and Baccante 1996). Minnesota waters of Lake of the Woods are not low productivity, thus it should be able to support higher level of sustainable harvest than low productivity lake in Northern Ontario. Additionally, Radomski (2003) points out that though Sauger harvest targets have been in place as a management strategy for Lake of the Woods Sauger, management actions primarily consisted of changing the target in response to angler harvest and changes in relative abundance (primarily driven by recruitment) of Sauger. Therefore, rather than setting a safe harvest level in terms of biomass an alternative is to maintain exploitation at or below 25% using a moving average to account for variability and non-annual creel survey schedules. Rates of exploitation from catch curves would be monitored annually and evaluated in terms of harvest for years in which both summer and winter south shore creel surveys are conducted simultaneously (every two out of four years) to verify safe exploitation rates are not being exceeded.

In addition to the change to the Sauger safe harvest level. We also suggest using the following proposed BPI thresholds as a mechanism for detecting possible over exploitation:

- Mean relative weight less than 91
- Female age at 50% mature greater than 3 years
- Age diversity of mature females greater than 1.0
- Near-shore gill net relative abundance of Sauger greater than 14 inches greater than 0.9 Sauger per net
- Year class strength index greater than 0.5
- Near-shore gillnet relative abundance greater than 10 Sauger per net

This suite of BPI thresholds could be combined to develop fisheries quantity objectives that are likely to detect over exploitation and could trigger management actions to address potential over exploitation in a timely and meaningful fashion.

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TABLES

Table 1. Mortality parameters and estimation methods used in this analysis.

Mortality Parameter	Estimation Method
Instantaneous total mortality (*Z*)	Catch curve slope - Log catch rates of age 3-9
Instantaneous natural mortality (*M*)	From Pauly (1980)
Instantaneous fishing mortality (*F*)	$Z - M$
Annual total mortality (*A*)	$1\text{-}e^{(-Z)}$
Exploitation rate (*u*)	$F*A/Z$

Table 2. Biological performance indicators (BPIs) for Sauger sampled during September gill netting (GN) in Minnesota waters of Lake of the Woods from 1991-2023. BPIs were derived by using percentiles and relationships between CPUE threshold and BPI relative to the historic dataset to inform professional judgement.

BPI Parameter	Population Metric	BPI Threshold (minimum)	Current 3-Year Average	10-Year Trend	Propose for use in management plan
Mean length at age-3	Growth	12	11.0	Stable	No
Mean relative weight	Growth	91	86.9	Decreasing	Yes
Female length at 50% maturity	Growth	11	11.2	Decreasing	No
Female age at 50% maturity	Growth	3.0	3.3	Stable	Yes
Age diversity of mature females	Mortality	1.0	1.3	Stable	Yes
Abundance > 14" (near-shore GN CPUE)	Mortality	0.9	1.2	Stable	Yes
Year-class strength	Recruitment	0.5	1.2	Stable	Yes
Abundance (near-shore GN CPUE)	Recruitment	10.0	19.0	Stable	Yes

Table 3.Von Bertalanffy growth curves for Sauger based on parameters from Radomski 1999, 1991-2004, and 2005-2023 age data.

Time Period	L∞	k	t_0
Radomski (1999)	16.09	0.31	- 0.17
1991-2004	16.40	0.30	-1.01
2005-2023	16.26	0.27	-1.41

Table 4. Mortality rates between specified time periods for log transformed CPUE of age 3 - 9 Sauger.

Mortality Parameter	Radomski (1999)	1991-2004 (annual average of estimates)	2005-2023 (annual average of estimates)	1991-2004 (composite)	2005-2023 (composite)
Instantaneous total mortality (*Z*)	0.63	0.58	0.46	0.58	0.46
Instantaneous natural mortality (*M*)	0.4	0.24	0.22	0.24	0.22
Instantaneous fishing mortality (*F*)	0.23	0.35	0.27	0.35	0.24
Annual total mortality (*A*)	0.47	0.44	0.36	0.44	0.37
Exploitation rate (*u*)	0.17	0.26	0.21	0.26	0.19

Table 5. Sauger harvest characteristics from 1991-2004, and 2005-2023.

Year	Near-shore Abundance (number/net)	Estimated Harvest (lbs)	Exploitation Rate (u)	Estimated biomass (lbs)	*F=M* (24%)
1991	18.8	223,354	16%	1,387,650	326,212
1992	13.4	113,685	26%	440,509	103,556
1993	8.8	161,286	36%	454,291	106,796
1994	6.1	117,450	35%	334,992	78,751
1995	6.8	85,100	13%	642,143	150,956
1998	12.2	249,713	17%	1,434,166	337,147
1999	14.5	231,213	37%	626,366	147,247
2000	9.9	111,445	37%	300,420	70,623
2001	16.3	244,531	30%	817,135	192,094
2002	20.1	184,899	27%	689,075	161,989
2003	12.3	341,887	24%	1,408,128	331,025
2004	9.2	524,693	18%	2,914,573	685,164
1991-2004 Mean	12.4	215,771	26%	954,121	224,297
2005	9.5	295,710	21%	1,399,499	308,495
2006	14.2	104,084	21%	492,596	108,584
2007	20.4	199,488	13%	1,577,504	347,733
2012	17.0	480,342	25%	1,948,580	429,530
2013	15.1	405,664	25%	1,638,604	361,201
2016	20.8	337,665	17%	1,962,138	432,518
2018	24.1	345,382	13%	2,605,519	574,340
2019	21.3	574,756	31%	1,847,189	407,180
2022	16.8	290,002	29%	1,015,902	223,937
2023	17.5	165,484	30%	545,217	120,183
2005-2023 Mean	17.7	319,858	22%	1,503,275	331,370

FIGURES

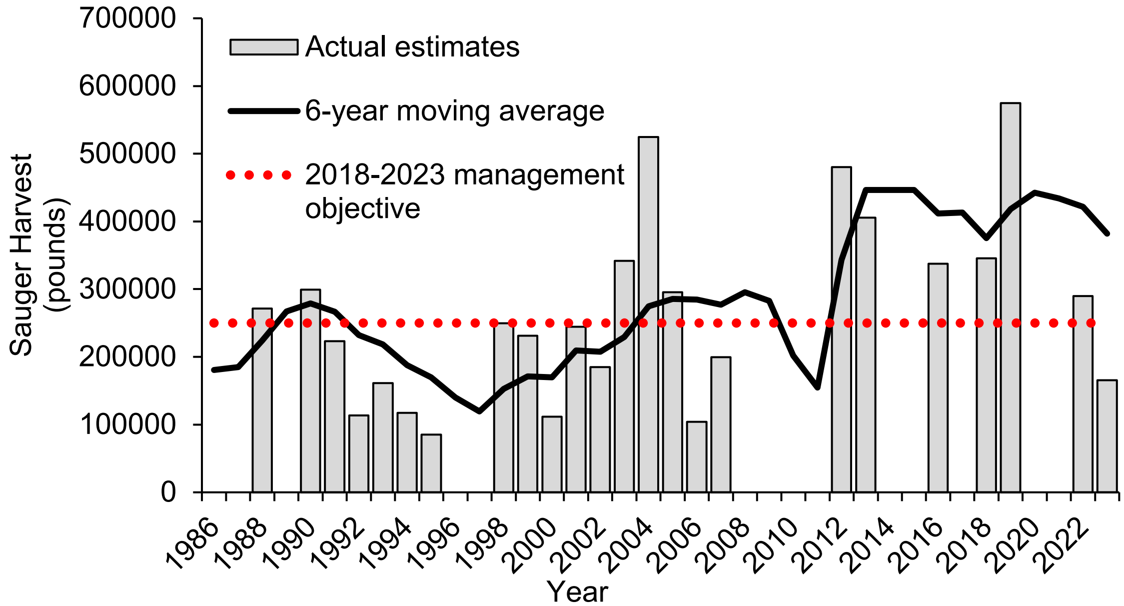

Figure 1. Annual harvest estimates and six-year moving averages (calculated based on previous six years excluding unsurveyed years) for total annual harvest for Sauger from 1986 to 2023 (black line). Horizontal red dotted line denotes current safe harvest level (250,000 pound; 114,000 kilograms). Grey bars denote harvest estimates from summer and winter south shore creel surveys.

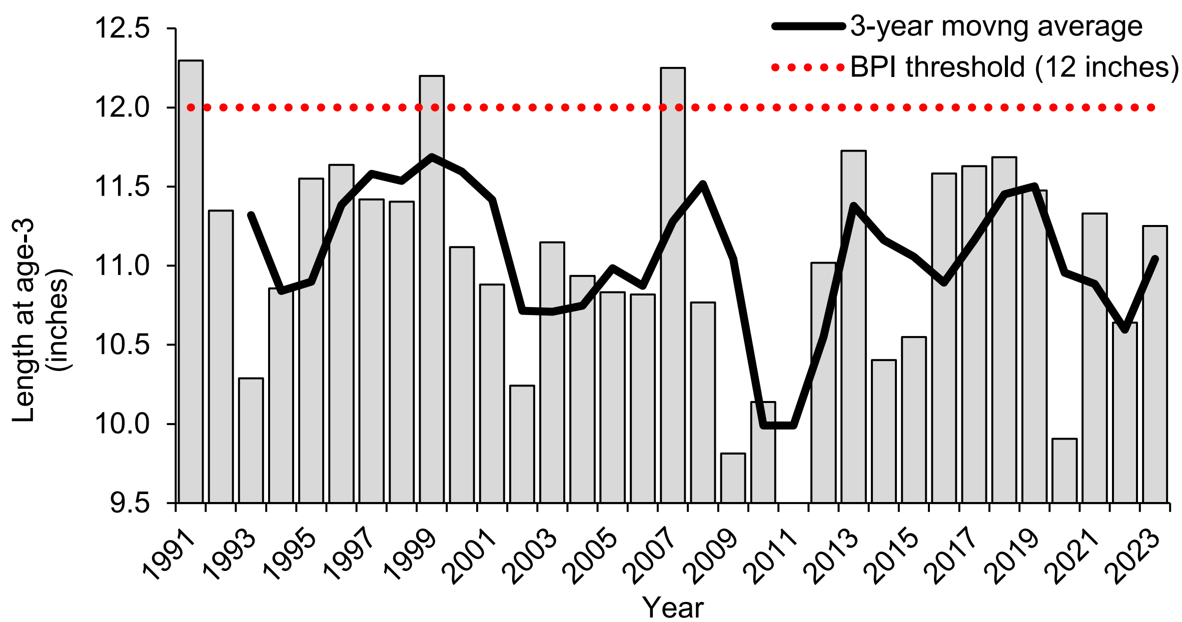

Figure 2. Mean length at age-3 for Sauger sampled during September gill netting in Minnesota waters of Lake of the Woods from 1991-2023. Notes: BPI threshold is proposed not

implemented. Y-axis does not begin at zero. Length at age-3 2011 were not calculated because age-3 Sauger of both sexes were not captured.

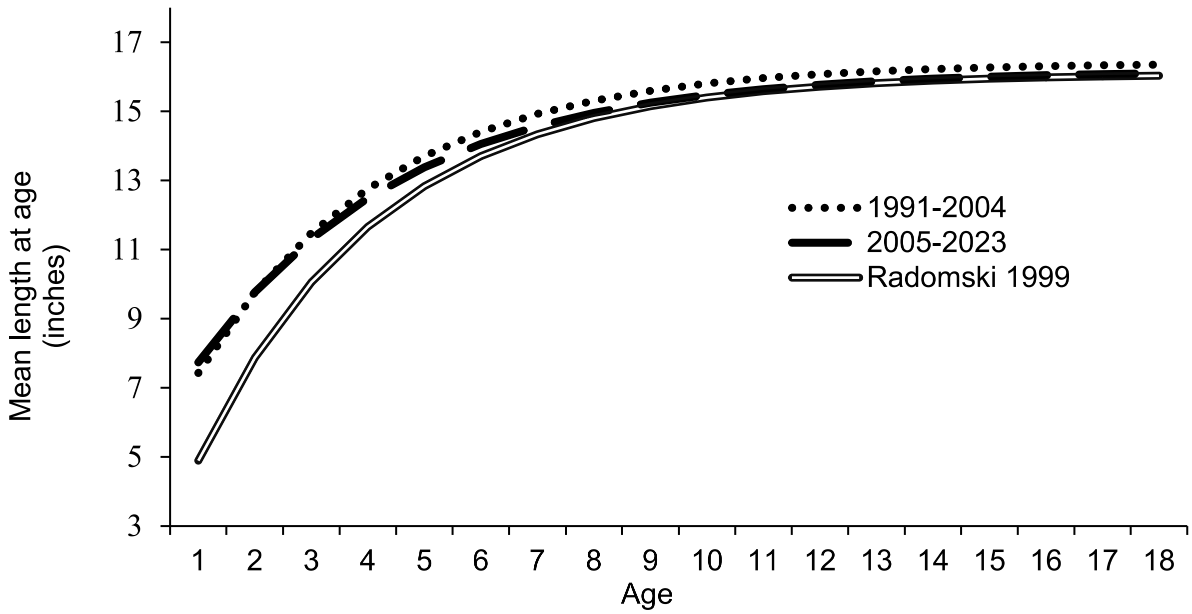

Figure 3. Von Bertalanffy growth curves for Sauger based on parameters from 1991-2004, and 2005-2023 age data.

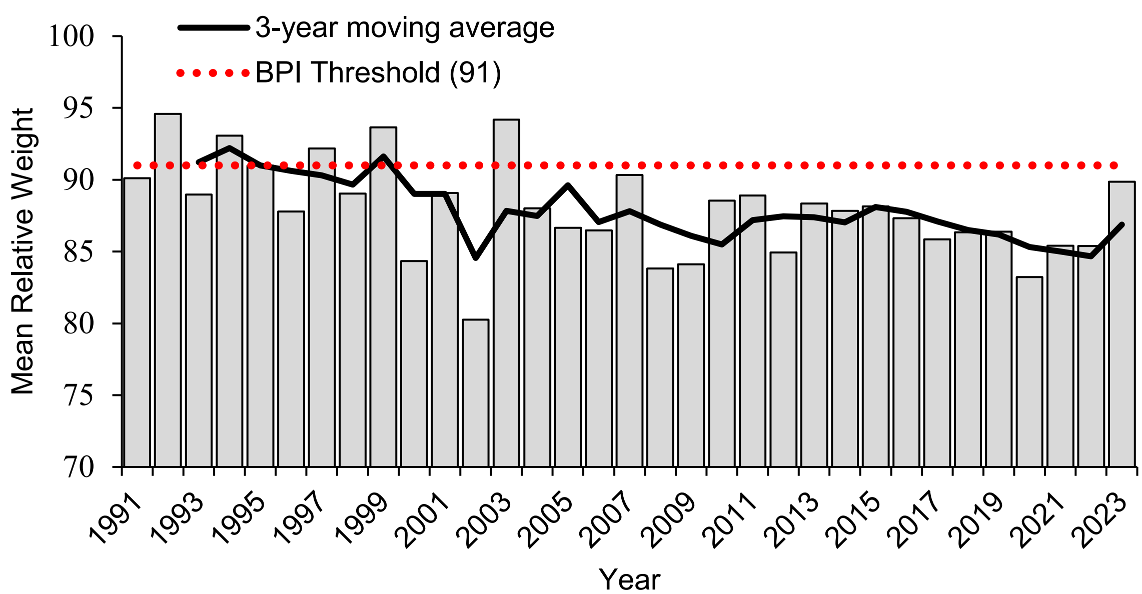

Figure 4. Mean relative weight for Sauger captured in near-shore waters of Lake of the Woods from 1991 to 2023. Notes: BPI threshold is proposed not implemented. Y-axis does not begin at zero.

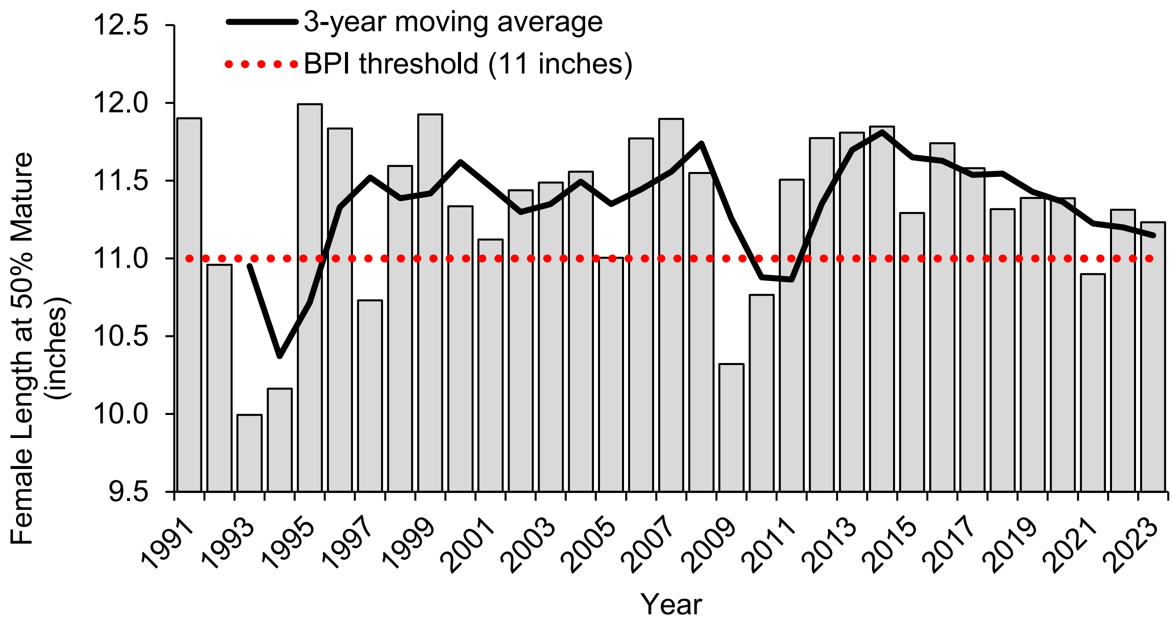

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Figure 5. Mean length at 50% maturity (inches) for female Sauger captured in near-shore waters of Lake of the Woods from 1991 to 2023. Notes: BPI threshold is proposed not implemented. Y-axis does not begin at zero.

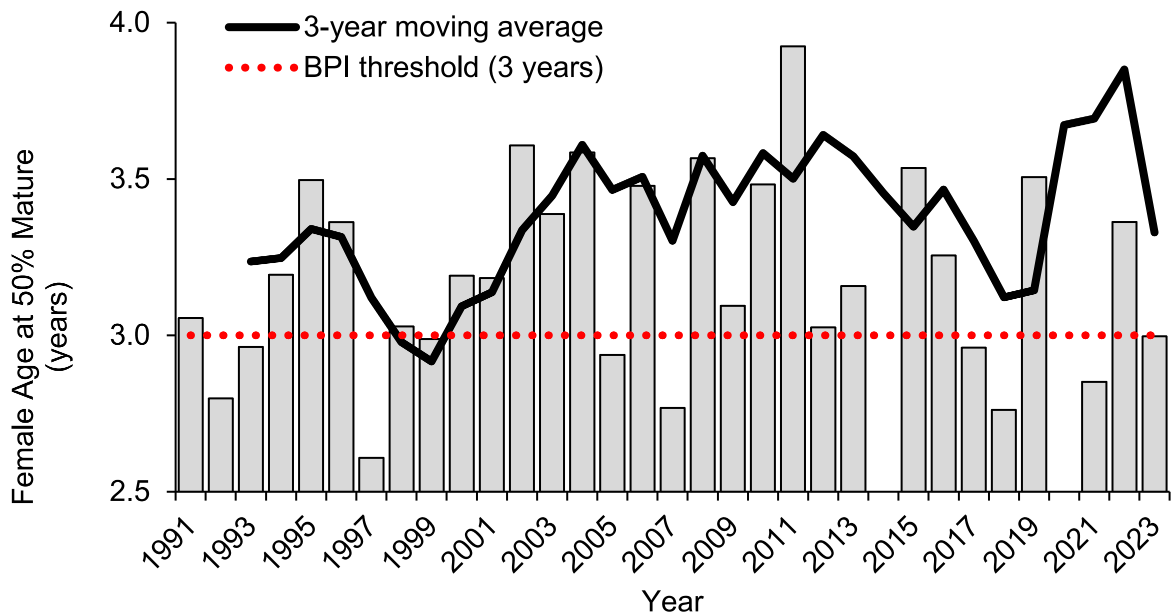

Figure 6. Mean age at 50% maturity (years) for female Sauger captured in near-shore waters of Lake of the Woods from 1991 to 2023. Notes: BPI threshold is proposed not implemented. Y-axis does not begin at zero.

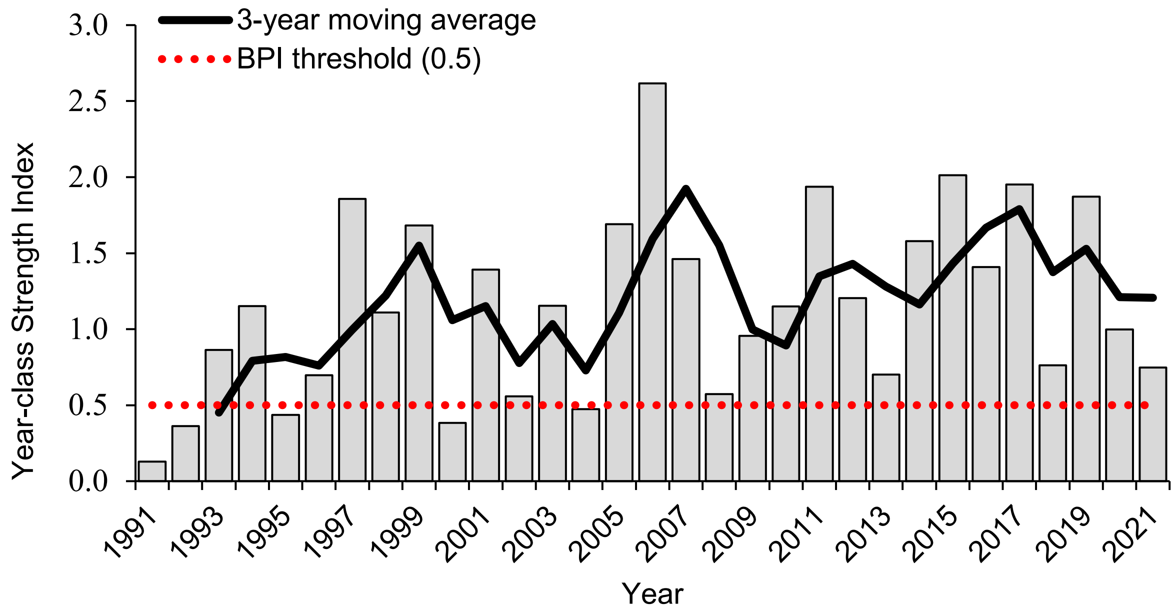

Figure 7. Sauger year-class strength, based on least squares means of natural log transformed age-2 to age-5 gill net CPUE, from September gill netting in Minnesota waters of Lake of the Woods from 1991-2021. Note: BPI threshold is proposed not implemented.

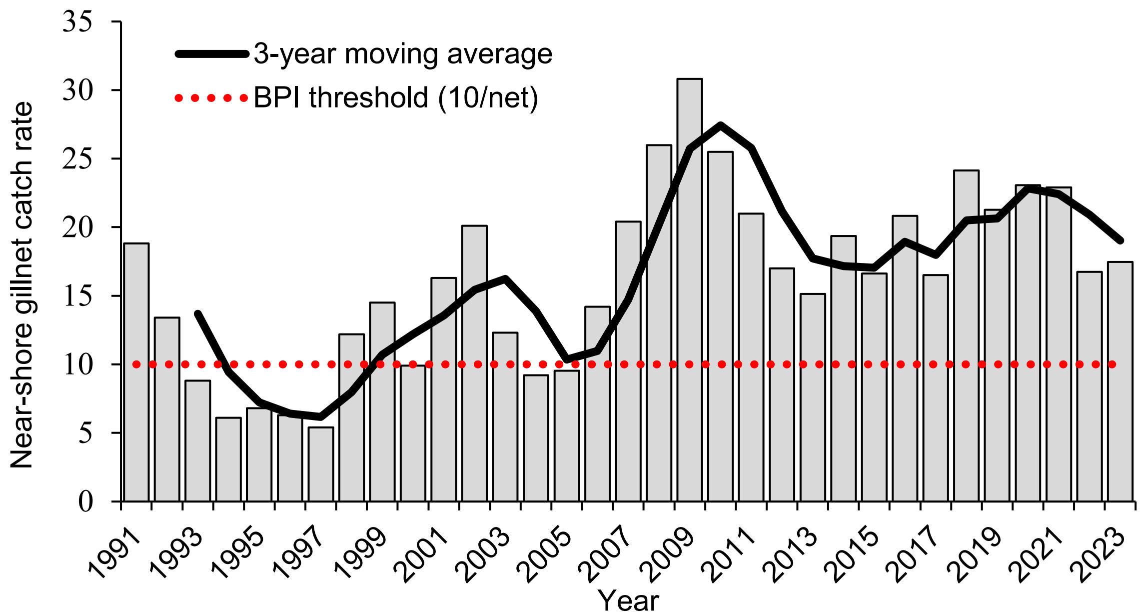

Figure 8. Sauger near-shore gill net catch rates (number per net) from September gill netting in Minnesota waters of Lake of the Woods from 1991-2023. Notes: BPI threshold is proposed not implemented.

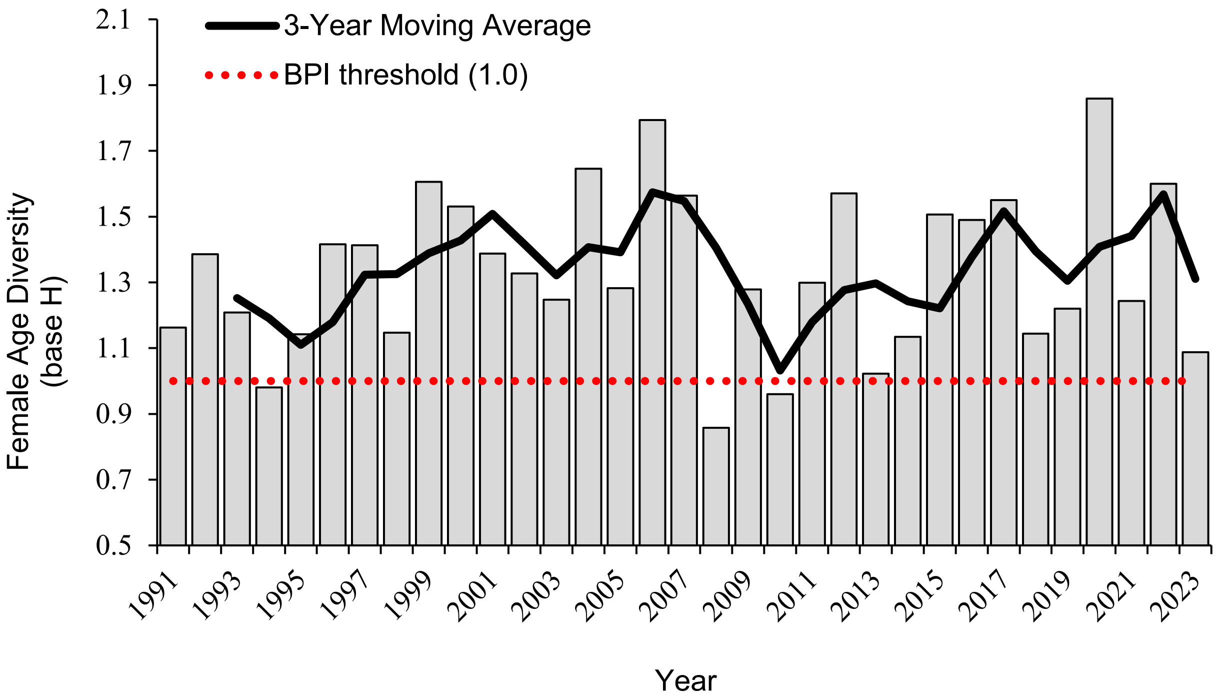

Figure 9. Female age diversity of Sauger from September gill netting in Minnesota waters of Lake of the Woods from 1991-2023. Notes: BPI threshold is proposed not implemented. Y-axis does not begin at zero.

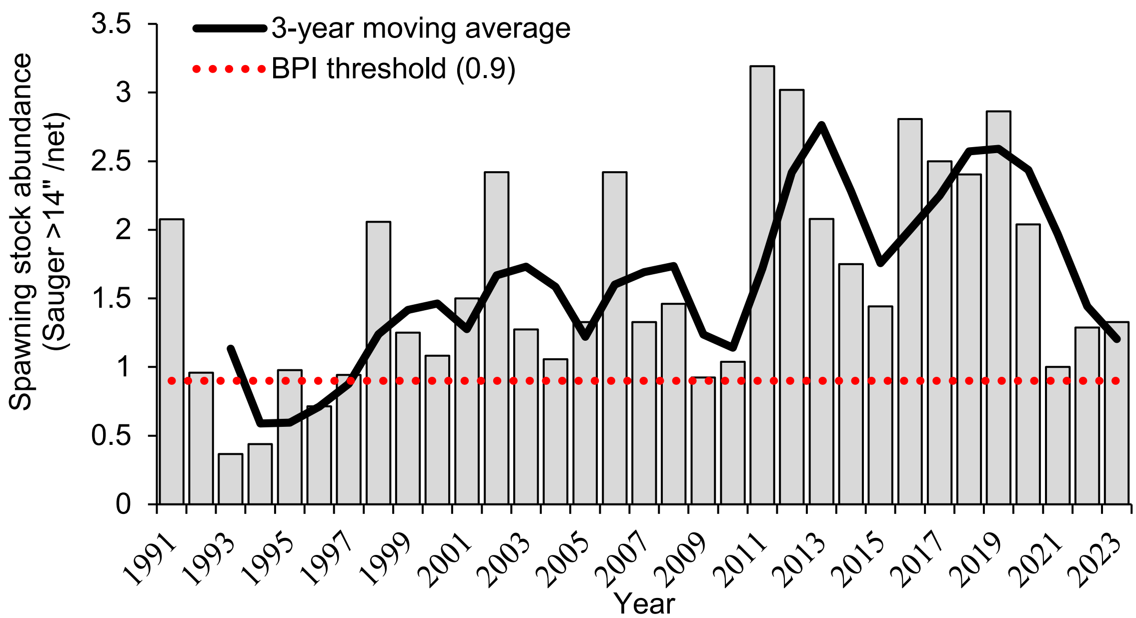

Figure 10. Near-shore gill net catch rates (number per net) for Sauger > 14 inches from September gill netting in Minnesota waters of Lake of the Woods from 1991-2023. Note: BPI threshold is proposed not implemented. Notes: BPI threshold is proposed not implemented.

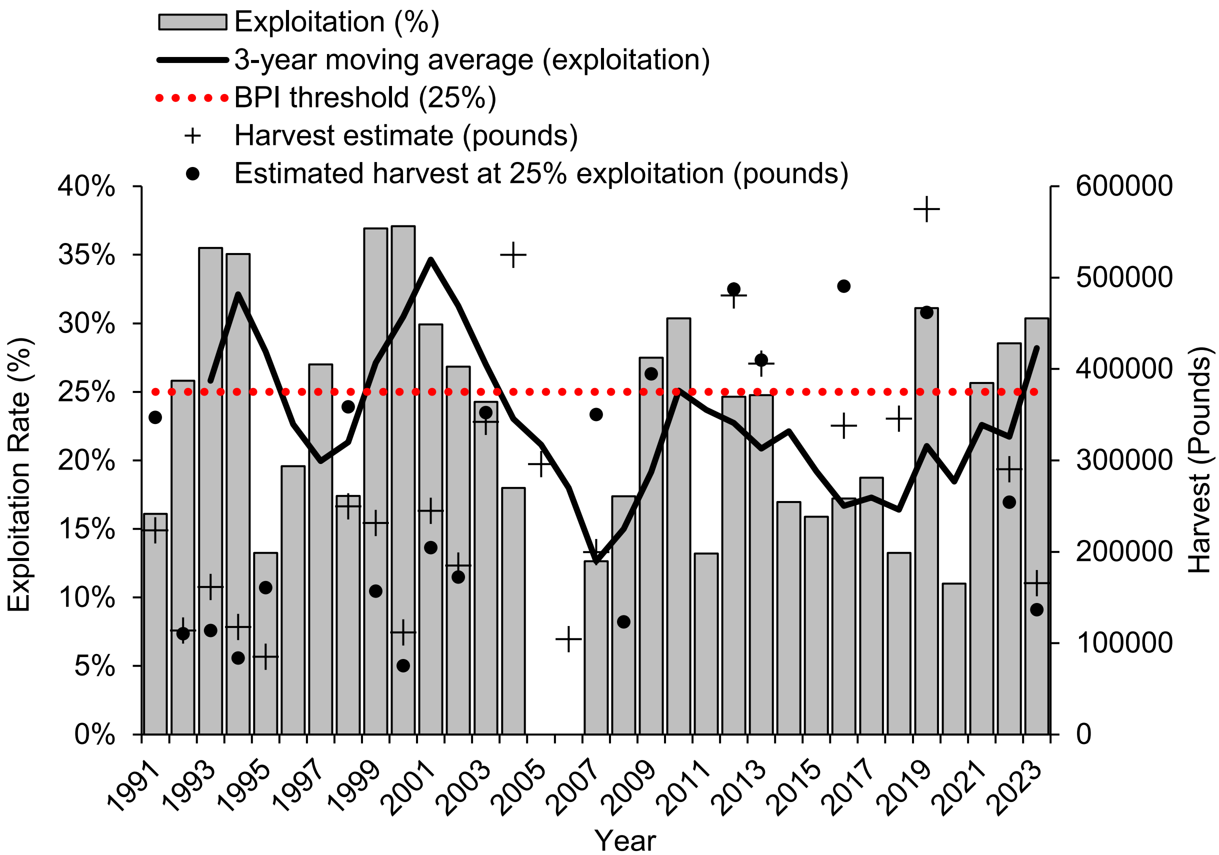

Figure 11. Exploitation rates (%), harvest estimates (pounds), and harvest under a 25% exploitation scenario for Minnesota waters of Lake of the Woods from 1991-2023. Notes: BPI threshold is proposed not implemented.

APPENDICES

Appendix 1. Angler pressure and Sauger harvest, by weight (pounds), 1981-2023. Minnesota waters of Lake of the Woods summer south shore, Lake of the Woods winter south shore, spring Rainy River, fall Rainy River, and summer Northwest Angle creel surveys. For winter surveys the year of the survey is the year in which the survey ended. Winter creel surveys start in December and are completed in March. Dashed lines represent year for which data were not collected or have not been summarized by publication. Note: LOW is Lake of the Woods, RR is Rainy River, and NWA is Northwest Angle.

Year	Summer LOW Pressure	Summer LOW Harvest	Winter LOW Pressure	Winter LOW Harvest	Spring RR Pressure	Spring RR Harvest	Fall RR Pressure	Fall RR Harvest	Summer NWA Pressure	Summer NWA Harvest	Total Pressure	Total Harvest
1981	321,124	15,380	---	---	---	---	---	---	---	---	na	na
1982	552,575	16,493	---	---	---	---	---	---	---	---	na	na
1983	421,974	17,384	401,467	160,899	---	---	---	---	---	---	na	na
1984	504,477	15,672	---	---	---	---	---	---	---	---	na	na
1985	846,989	16,930	---	---	---	---	---	---	---	---	na	na
1986	796,705	35,377	---	---	---	---	---	---	---	---	na	na
1987	721,944	41,877	---	---	---	---	---	---	---	---	na	na
1988	564,789	40,090	649,226	231,359	---	---	---	---	---	---	na	na
1989	628,230	51,062	---	---	---	---	61,301	2,300	---	---	na	na
1990	986,044	60,073	764,088	239,051	29,548	484	54,744	2,104	---	---	na	na
1991	904,081	35,440	925,682	187,914	42,895	89	---	---	---	---	na	na
1992	660,436	28,318	747,063	85,367	27,697	40	---	---	---	---	na	na
1993	787,416	42,546	741,322	118,740	33,978	32	---	---	---	---	na	na
1994	757,847	36,914	643,575	80,536	50,336	258	---	---	55,203	860	na	na
1995	662,934	34,476	502,712	50,624	62,799	585	---	---	64,288	733	na	na
1996	657,534	17,422	---	---	61,521	496	---		53,961	376	na	na
1997	846,370	41,994	---	---	32,097	20	53,446	1,105	---	---	na	na
1998	789,385	47,643	906,587	202,070	56,310	709	50,946	3,267	---	---	na	na
1999	638,634	30,836	960,853	200,377	52,613	42	74,603	1,504	---	---	na	na
2000	916,541	34,148	799,342	77,297	35,359	172	72,543	1,086	---	---	na	na
2001	745,983	28,783	1,196,923	215,748	40,853	45	---	---	---	---	na	na
2002	675,129	22,380	943,611	162,519	67,193	33	79,818	1,177	31,277	119	na	na
2003	809,994	58,335	1,559,161	283,552	76,736	201	70,548	2,527	---	---	na	na
2004	811,341	38,762	1,938,509	485,931	50,993	52	67,777	839	---	---	na	na
2005	792,835	45,739	1,542,822	249,971	45,021	29	88,196	2,031	---	---	na	na
2006	591,679	33,136	1,034,476	70,948	---	---	---	---	---	---	na	na
2007	593,861	28,944	1,453,530	170,544	---	---	---	---	14,397	315	na	na
2012	865,678	110,573	1,632,044	369,769	132,090	1,193	51,131	1,499	49,722	1,036	na	na
2013	833,344	87,951	1,963,605	317,713	74,534	187	46,265	2,007	---	---	na	na
2016	638,412	57,643	1,478,862	280,022	78,885	777	42,024	3,087	---	---	na	na
2017	---	---	2,047,408	325,109	151,725	3,099	---	---	---	---	na	na
2018	646,361	66,583	1,940,690	278,799	57,235	83	42,940	1,921	---	---	na	na
2019	759,389	95,361	2,102,782	479,395	46,053	---	33,459	1,069	---	---	na	na
2020	---	---	2,785,560	461,240	---	---	---	---	---	---	na	na
2021	---	---	2,723,055	312,769	117,679	---	---	---	---	---	na	na
2022	674,276	32,513	2,627,299	257,489	49,351	---	56,215	1,809	---	---	na	na
2023	600,837	44,390	3,182,049	121,094		---			---	---	na	na
2018-2023	670,216	59,712	2,560,239	318,464	67,580	83	44,205	1,600	49,722	1,036	3,391,961	380,895

Appendix 2. Sauger mortality estimates from log transformed catch rates for age-3 to 9 near-shore captured Sauger from 1991-2023.

Year	Instantaneous total mortality (Z)	Annual total mortality (A)	Instantaneous natural mortality (M)	Instantaneous fishing mortality (F)	Exploitation rate (u)	Exploitation rate (u) 3-year average
1991	0.43	0.35	0.24	0.20	0.16	---
1992	0.57	0.44	0.24	0.34	0.26	---
1993	0.74	0.52	0.24	0.50	0.36	0.26
1994	0.73	0.52	0.24	0.49	0.35	0.32
1995	0.40	0.33	0.24	0.16	0.13	0.28
1996	0.48	0.38	0.24	0.25	0.20	0.23
1997	0.59	0.45	0.24	0.36	0.27	0.20
1998	0.45	0.36	0.24	0.22	0.17	0.21
1999	0.76	0.53	0.24	0.53	0.37	0.27
2000	0.77	0.54	0.24	0.53	0.37	0.30
2001	0.64	0.47	0.24	0.41	0.30	0.35
2002	0.59	0.45	0.24	0.36	0.27	0.31
2003	0.55	0.42	0.24	0.32	0.24	0.27
2004	0.46	0.37	0.24	0.22	0.18	0.23
2005	0.21	0.19	0.22	---	---	0.21
2006	0.18	0.16	0.22	---	---	0.18
2007	0.37	0.31	0.22	0.15	0.13	0.13
2008	0.43	0.35	0.22	0.21	0.17	0.15
2009	0.58	0.44	0.22	0.36	0.27	0.19
2010	0.63	0.47	0.22	0.41	0.30	0.25
2011	0.38	0.32	0.22	0.16	0.13	0.24
2012	0.54	0.42	0.22	0.32	0.25	0.23
2013	0.54	0.42	0.22	0.32	0.25	0.21
2014	0.43	0.35	0.22	0.21	0.17	0.22
2015	0.41	0.34	0.22	0.19	0.16	0.19
2016	0.43	0.35	0.22	0.21	0.17	0.17
2017	0.45	0.36	0.22	0.23	0.19	0.17
2018	0.38	0.32	0.22	0.16	0.13	0.16
2019	0.64	0.47	0.22	0.42	0.31	0.21
2020	0.35	0.30	0.22	0.13	0.11	0.18
2021	0.55	0.43	0.22	0.33	0.26	0.23
2022	0.60	0.45	0.22	0.38	0.29	0.22
2023	0.63	0.47	0.22	0.41	0.30	0.28
1991-2004 Annual Average	0.58	0.44	0.24	0.35	0.26	---
2005-2023 Annual Average	0.46	0.36	0.22	0.27	0.21	---
1991-2004 Composite	0.58	0.44	0.24	0.35	0.26	---
2005-2023 Composite	0.46	0.37	0.22	0.24	0.19	---