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Mortality, Exploitation, Movement, and Stock Size of Saginaw Bay Walleyes, 2012–2023, Based on Tag Return Analysis

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Mortality, Exploitation, Movement, and Stock Size of Saginaw Bay Walleyes, 2012–2023, Based on Tag Return Analysis

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Abstract

Robust estimates of mortality, exploitation, and abundance are essential to sound fisheries management and sustainable fish populations. We used mark and recapture analysis from a long-term jaw tagging program to generate these metrics for Saginaw Bay Walleyes. A total of 33,898 Walleyes were jaw tagged in Saginaw Bay tributaries during spring spawning runs from 2012–2023 which generated 6,424 tag reports from anglers. Tag returns from 140,784 Walleyes tagged since 1981 were corrected for nonreporting by anglers (1.54724 multiplier) as well as for angler failure to notice tags (1.51429 multiplier) for a combined correction factor of 2.34297. Total annual mortality rate and recreational fishing exploitation rate averaged 0.4407 and 0.2160 during the study period with few differences in estimates of mortality or exploitation from Walleyes tagged in the Tittabawassee River versus other locations around the bay. The Lincoln-Peterson population estimate of Saginaw Bay Walleyes averaged 1,348,886 fish between 2012 and 2023. This value is believed to represent age-4+ individuals and underrepresent Walleyes age-3 and younger because tagging took place during the spawning run. Indeed, the mean age of Walleyes in the study group ranged between 6 and 8 years old in recent years. Similar methods allowed for estimating the size of the spawning run in the Tittabawassee River, which ranged from a low of 172,245 Walleyes in 2005 to a high of 520,417 Walleyes in 2021. Movement data from angler tag returns indicated that 13.7% of Saginaw Bay Walleyes migrated into Lake Huron but that value is an underestimate because of our inability to correct for fishing effort. Generally, Walleyes migrating into the main basin of Lake Huron were larger than their bay-resident counterparts and were more likely to be females. Overall, mortality and exploitation rates were found to be within sustainable boundaries outlined in the Saginaw Bay Walleye and Yellow Perch Recreational Management Plan.

Introduction

Walleye *Sander vitreus*, a native predator of Saginaw Bay, Lake Huron (Roth et al. 2013), once supported a substantial commercial fishery that produced the largest yield in Lake Huron and the second largest yield in the Great Lakes behind Lake Erie (Hile and Buettner 1959; Baldwin et al. 2002). This fishery, yielding an annual average of 495 metric tons until its collapse in the mid-1940s, declined due to year-class failures caused by deteriorating water quality, habitat degradation, and invasive species (Schneider and Leach 1977); it was formally closed in 1970 (Keller et al. 1987) after being largely nonexistent for decades. Walleye recovery efforts began with clean water legislation in the late 1970s (Haas and Schaeffer 1992; Fielder and Baker 2004) and fingerling stocking by the Michigan Department of Natural Resources (MDNR) in the early 1980s (Haas and Schaeffer 1992). This reestablished a recreational Walleye fishery in Saginaw Bay (Fielder et al. 2014), but the population remained below carrying capacity and dependent on stocking (Fielder 2002). Major gains in reproduction and adult abundance began after 2003 when Lake Huron's food web shifted dramatically due to the collapse of the invasive Alewife *Alosa pseudoharengus* population (Riley et al. 2008; Riley and Roseman 2013), which had long preyed on newly hatched Walleye fry (Kohler and Ney 1980; Brandt et al. 1987; Brooking et al. 1998). In the absence of Alewives, Walleye reproductive success in Saginaw Bay increased over 1,700% (Fielder et al. 2007; Fielder and Briggs 2025), while the number of fish in the recreational harvest and the number of Walleyes harvested per hour of fishing effort rose by 238% and 387% respectively. By 2024, the Saginaw Bay stock of age-2+ Walleyes exceeded 13 million fish (MDNR, unpublished data); stocking ceased in 2006, and formal recovery targets were met in 2009 (Fielder and Thomas 2014). This occurrence stands as one of the Great Lakes' greatest fishery recovery stories (Fielder and Baker 2019).

Assessment of managed fish stocks, like Saginaw Bay Walleyes, is essential to understand and quantify the parameters and rates of fishery and population dynamics (Hilborn and Walters 1992; Haddon 2001; Pope et al. 2010). The foundation of such stock assessment is the ability to estimate mortality and exploitation rates. Some of the earliest methods for estimating these metrics involved tagging fish and monitoring the rates of tag reports over time (Schnabel 1938; Ricker 1948; Adams 1951); tag or band-based methods were further refined in the 1960s and 1970s (Jolly 1965; Robson and Youngs 1971; Seber 1972). Brownie et al. (1985) went on to further develop these methods with a series of models for estimating mortality and exploitation from a tagged or banded group of organisms.

Since the 1980s, fisheries managers recognized they needed the ability to gauge fundamental metrics of the Walleye population and fishery status to assess sustainability in Saginaw Bay. Accordingly, the MDNR began a jaw tagging program in 1981 to estimate Walleye mortality, exploitation, and abundance, and to assess fishery status. Electrofishing, usually in tributaries to the Saginaw River, is used each year to collect and tag Walleyes during the spring spawning run. The uniquely numbered tags are then reported by anyone who encounters them, typically recreational anglers. Brownie Model 1 (Brownie et al. 1985), hereafter the Brownie model, is designed for catch-and-kill extractions when year-specific recovery rates and survival rates are desired and used for data analysis.

In 2012, the Michigan DNR recoded the Walleye tagging analysis into AD Model Builder (ADMB) using numerical fitting procedures to incorporate annual tag shedding rates (derived by Vandergoot et al. 2012) and to produce more accurate estimates (Fielder 2014). This new model replaced earlier deterministic approaches—initially the Fortran 77 program ESTIMATE (Brownie et al. 1985), which while generally robust, could not accommodate annual tag loss. Fielder (2014) analyzed Saginaw Bay Walleye jaw tag returns from 1981–2011, providing estimates of total mortality, tag recovery rate (exploitation rate), fishing mortality, and natural mortality. The study showed the newer ADMB numerical estimation model produced results that largely agreed with the deterministic version but was more accurate overall. The numerically fit model version is now the basis for all analyses.

The goal of this manuscript is to update the tag return data set from our long-term jaw tagging program and analyze Saginaw Bay Walleye jaw tag reports from 2012–2023 with the Brownie model. Specifically, we will (1) update estimates of important population metrics including mortality, exploitation, and abundance, (2) relate these estimates to recent management initiatives and fishery performance, (3) make recommendations for the future of the study and analytical options, and (4) archive our findings for further analyses. Fielder (2014) noted that nonreporting is a common and chronic problem in tagging studies and made use of a series of reward tags to develop a nonreporting correction factor. We will test the effects of the assumptions involved with correcting for such nonreporting on mortality, exploitation, and population estimates. We will also quantify the phenomenon of anglers failing to notice jaw tags, which can create an additional source of error beyond just nonreporting. Finally, we will compare mortality and exploitation calculated from tags applied to Walleyes in the Tittabawassee River to those developed from other tagging locations in Saginaw Bay tributaries to test the sensitivity of the Brownie model estimates to tagging location.

Methods

Tagging

We defined Saginaw Bay as the waters of Lake Huron that lie southwest of a line between Au Sable Point and Point Aux Barques (Figure 1). Walleyes were collected from the Tittabawassee River and occasionally other Saginaw Bay tributaries (Figure 1) by 230-volt DC electrofishing during the height of their annual spring spawning run every year since 1981. These fish are Saginaw Bay Walleyes that use the Tittabawassee and other rivers for spawning and principally inhabit the bay outside the spawning period (Fielder 2014), although some individuals leave for other areas of Lake Huron (Hayden et al. 2014). In most years, tagging occurred during the last week of March or the first week of April and was usually completed within 5 days. Walleyes were tagged with a #12 butt-end Monel band 5.26 mm wide and 0.51 mm thick (National Band and Tag Company of Newport Kentucky; Figure 2). Tags were stamped with a unique number and a return postal address until 2023 when the postal address was replaced with an Internet URL address that leads to an online reporting form. Captured Walleyes were also externally sexed and measured for total length during the tagging process.

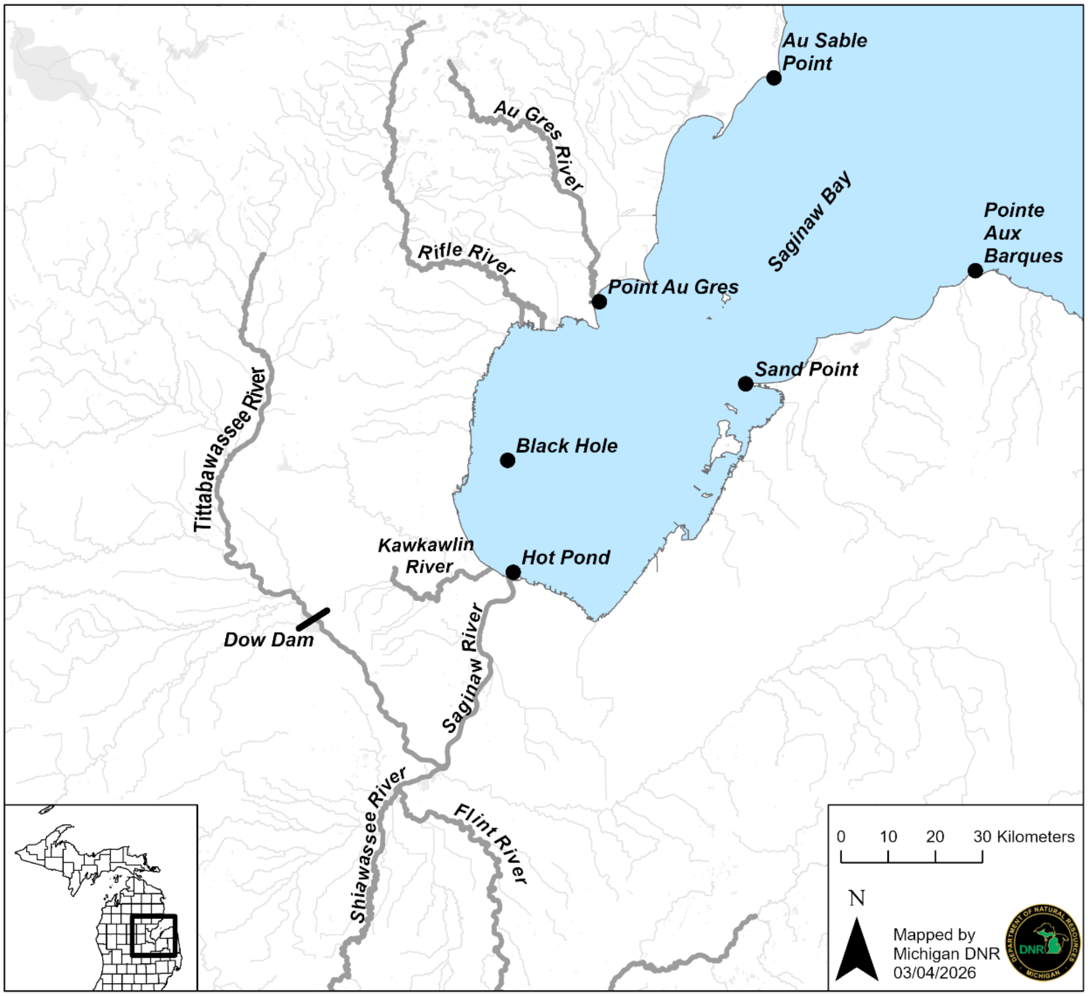

Figure 1. Major tributaries and other Walleye jaw tagging locations in Saginaw Bay, Lake Huron.

Figure 2. Monel jaw tag affixed to a Saginaw Bay Walleye

Age structures were collected from a subsample of around 200 Walleyes each year between 1981 and 1993. Beginning in 1994 a subsample of one day's tagging effort, usually about 700 fish, was selected near the peak of the spawning run (when sex ratios were closest to 1:1) for scale or dorsal spine collection. Aging was initially performed with scales but was switched to dorsal spines around 1998. The number of age structures was reduced to 300 each year starting in 2015 to coincide with the number of fish randomly selected to receive reward tags used to calculate nonreporting correction factors.

The number of Walleyes tagged each year was less than 1,000 until 1983 when a tagging goal of 3,000 fish per year was set for the remainder of the study. Tagging was initially limited to fish ≥381 mm to ensure vulnerability to the recreational fishery until 2015 when the minimum length limit, and accordingly the tagging length threshold, was reduced to 330 mm. Walleye tagging typically occurred at Dow Dam on the Tittabawassee River. Walleyes were also tagged in various locations around the bay mostly before 1991 and after 2013 and intensively in the Flint River from 1998–2000 (Figure 1; Table 1).

Table 1. Number of jaw tags applied to Walleye in Saginaw Bay, Lake Huron, by year and tagging location, 2012–2023. Black Hole, Hot Pond, Point Au Gres, Saginaw River, and Sand Point were used historically but did not have tags applied in the last 10 years. See supplementary material for data from the entire 1981-2023 time series.

Year	Au Gres River	Flint River	Kawkawlin River	Rifle River	Shiawassee River	Tittabawassee River	Total by year for all rivers
2012	0	0	0	0	0	3,000	3,000
2013	0	0	0	0	0	2,997	2,997
2014	300	0	700	0	1,000	1,000	3,000
2015	181	0	725	0	469	1,625	3,000
2016	150	0	750	50	127	1,923	3,000
2017	0	981	700	0	0	1,319	3,000
2018	0	692	609	0	0	1,700	3,001
2019	0	0	0	0	0	3,000	3,000
2020	0	0	100	0	0	800	900
2021	0	0	250	0	0	2,750	3,000
2022	0	0	659	0	160	2,181	3,000
2023	0	300	223	0	0	2,477	3,000
Total for all years	631	1,973	4,716	50	1,756	27,771	36,897

Demographics

Biological data from the tagged lot of Walleyes were used to characterize the age and sex structure of the fish represented by tagging each year and provide some indication of age-at-first-maturity for both sexes. The age data were not normally distributed; therefore, we used the nonparametric Kruskal-Wallis test (Sokal and Rohlf 1981) to test for significant differences in age structure across the various spawning tributaries where spines were collected during 2014–2020. The Dunn-Bonferroni post hoc test was used to identify individual differences among rivers.

Tag Reports

Tags were primarily reported by anglers harvesting Walleye in the recreational fishery since there is no commercial Walleye fishery in Saginaw Bay. Most tag reports occurred within the bay, but some came from other parts of Lake Huron which allowed the analysis of movement within the recreational fishery. Angler participation in tag reporting was periodically encouraged with public awareness campaigns and over time anglers became accustomed to reporting jaw tags. Initially most anglers mailed the tag and capture information to the MDNR mailing address stamped on the tag; more recently anglers have used the Internet URL to complete electronic tag reports. The reported capture location of each tagged Walleye was assigned a latitude and longitude for analysis of movement. Anglers reporting tags were contacted if additional information was needed about the harvested fish and all anglers received a follow-up thank you letter that included information on the history of their fish such as when and where it was first tagged.

Correction for Nonreporting

Tagging programs rely on angler participation for reporting tagged Walleye. Noncompliance with tag reporting is a common problem with tagging studies, especially with ongoing programs where anglers may grow complacent with their participation (Haas et al. 1988; Pollock et al. 1991; Vandergoot et al. 2012). Accordingly, reward tags are often used to develop a correction factor for nonreporting (Haas et al. 1988). Correction factors are multipliers; a correction factor of 1.0 would be no adjustment for nonreporting and a correction factor of 1.5 would yield a 50% increase in observed tag returns when adjusted for nonreporting. A Walleye jaw tagging study on Lake Erie used $100 reward tags on 10% of tagged fish to develop a correction factor of 2.73 (Thomas and Haas 2000). The nonreporting rate for Lake Erie was later updated using the same methods and resulted in a similar correction factor of 2.80 (Thomas and Haas 2005). As an extension of the study on Lake Erie, in 2000 Fielder and Thomas (2006) used the same reward tag methods on Saginaw Bay Walleyes and calculated a nonreporting correction factor of 2.33. In each study, the non-reporting correction factors were calculated from the difference in reports between the reward tags and the non-reward tags using the assumption that reward tags were always returned.

Fielder (2014) recognized that nonreporting of jaw tags was worsening in Saginaw Bay and developed a correction factor for tags reported between 1981–2011. The author hypothesized that the initial nonreporting correction factor in 1981 was 1.43 and then fitted a line using the 2.33 correction factor calculated for Saginaw Bay in 2000 (Fielder and Thomas 2006) and a 4.03

correction factor calculated from $100 acoustic telemetry tag rewards applied to Tittabawassee River Walleyes during 2011(Hayden et al. 2014). A power function was selected for nonreporting line fitting because visual inspection of the scatter plot of calculated correction factors appeared to worsen over time, resulting in an upward curve as opposed to a linear relationship. Observed tag reports for 1981–2011 were the product of the actual number of tags reported and the year-specific correction factor.

Beginning in 2014 reward tags were applied to 10% of collected Walleyes, or 300 fish most years through 2023 (Table 2), to provide an annual correction factor for non-reward tag reports. Fielder (2014) observed that the nonreporting correction factor can have a substantial effect on the tag return analysis estimates. As a result, the correction factor for our analysis was calculated from years when both reward tags and non-reward tags were reported. We used a composite correction factor calculated from all 19 years of reward and non-reward jaw tag reports because the plot of the correction factor through time, based on reward tags alone, was no longer curved as in Fielder (2014).

Table 2. Number of $100 reward jaw tags, by year and location, applied to Walleye in Saginaw Bay, Lake Huron, 2000 and 2014–2023. Only years when reward tags were applied are shown.

Year	Au Gres River	Flint River	Kawkawlin River	Rifle River	Shiawassee River	Tittabawassee River	Total by year for all rivers
2000	0	0	0	0	0	299	299
2014	0	0	100	0	100	100	300
2015	50	0	50	0	100	100	300
2016	50	0	50	50	50	100	300
2017	0	100	100	0	0	100	300
2018	0	100	100	0	0	100	300
2019	0	0	0	0	0	300	300
2020	0	0	100	0	0	200	300
2021	0	0	0	0	0	300	300
2022	0	0	0	0	0	300	300
2023	0	0	0	0	0	300	300
Total for all years	100	200	500	50	250	2,199	3,299

Failure to Notice Tags

Nonreporting of jaw tags might reflect a variety of angler behaviors. The incentive to assist with the study may not be great enough for anglers to take time to report tags, or anglers might fail to notice the small tag affixed to the fish's left upper jaw. The $100 reward tag correction would not overcome angler failure to notice the tag, or provide a correction for it, since reward tags did not look outwardly different than an ordinary non-reward jaw tag. Hayden et al. (2014) offered a $100 reward for Saginaw Bay Walleyes that had both an external T-bar anchor tag and a surgically implanted acoustic telemetry transmitter, both of which were novel and obvious. This resulted in a correction factor of 3.38, which was considerably higher than the correction factor of 2.33 that was calculated by Fielder and Thomas (2006). Our interest in angler failure to notice jaw tags stemmed from the much higher rate of reporting for the acoustic telemetry transmitters and their accompanying external T-bar anchor tag compared to reward jaw tags. There were no reward jaw tags applied to our Walleyes in 2011 to directly compare to the 3.38 correction factor developed from Hayden et al. (2014), but the reporting rates they observed with novel tags is so much greater than the reward jaw tag reporting rates observed in Lake Erie and Saginaw Bay that it led us to question how often anglers fail to notice jaw tags.

Three hundred vinyl laminated disk tags from Floy Tag & Manufacturing in Seattle, Washington, were added to the jaw tagging study in 2017 and 2018(Table 3), presenting a highly visible option compared to jaw tags. Red vinyl laminated disk tags with a diameter of 19mm were applied to Walleyes during the same time as the annual jaw tagging operation; fish tagged with a vinyl laminated disk were not jaw tagged. The disks were bright red in color and offered a $100 reward. They were affixed to the left opercle by using a metal awl to pierce the gill cover; the disk tag included a stem with a corresponding locking plate that was affixed to the underside of the gill cover to anchor the tag in place (Figure 3). We calculated the magnitude of angler failure to notice tags as the difference between the reward jaw tag return rate and the reward disk tag return rate within the first year the tags were at large. Subsequent failure to notice correction factors were a composite calculated from the total tag reports in 2017–2018.

Table 3. Number of $100 reward disk tags by year and location applied to Walleye in Saginaw Bay Lake Huron, 2017–2018.

Year	Flint River	Kawkawlin River	Tittabawassee River	Total for all rivers
2017	100	100	100	300
2018	100	100	100	300
Total for both years	200	200	200	600

Figure 3. Floy brand vinyl laminated disk tag affixed to a Walleye to evaluate failure to notice jaw tags in Saginaw Bay during 2017–2018.

Accounting for Nonreporting and Failure to Notice in the Brownie Model

Due to the sensitivity of the Brownie model to nonreporting and potential oversight, we compared the effect of the correction factors on estimates of Saginaw Bay Walleye total annual mortality and exploitation. Model analysis was performed with a correction factor calculated from the reward to non-reward tag return differences and a second model run that reflected both the correction for nonreporting and the added correction for failure to notice from the disk to jaw tag comparisons. Estimates of total annual mortality and exploitation rate were then compared to examine differences in magnitude stemming from the two different correction factors. We used overlap of error bars (+/- 1.96 of the SE of the estimate) to determine statistical significance; error bars that did not overlap were considered statistically different.

We developed a combined nonreporting correction factor for the two sources of nonreporting; failure to report observed tags and failure to notice tags. The combined correction factor was calculated by first converting each correction factor to a probability of successfully noticing or successfully reporting a tag, which was the reciprocal of the correction factor. We then used a simulation based on 1,000 hypothetical tags at large and hypothetical high (0.4) and low (0.2) exploitation rates. For example, the hypothetical low exploitation rate of 0.2 yielded a simulated 200 tags caught, and the product of this value and the probability of successfully noticing a tag provided a value of noticed tags. The probability of successfully reporting a tag was then applied, yielding a final number of tags successfully noticed and reported. The combined, sequential correction factor was calculated as the quotient of the original number of tags caught (200) and the final number of tags noticed and reported. Our calculation of correction factors was sensitive to the number of digits past the decimal; calculations were based on 15 digits past the decimal but reported to no more than 5 digits past the decimal for brevity. The remainder of our analysis used the combined correction factor for both nonreporting and failure to notice in model estimates unless otherwise noted.

Tag Return Data Analysis

In 2012, the MDNR began using ADMB software (Fournier et al. 2012) for the Walleye tag return data analysis. This software uses numerical fitting procedures to incorporate annual tag shedding rates calculated by Vandergoot et al. (2012) and to produce more accurate estimates of mortality and exploitation (Fielder 2014). The ADMB version of the Brownie model replaced earlier deterministic approaches which, while generally robust, could not accommodate annual tag loss.

We compiled reported tags into a tag return matrix of number reported by year for each year that tagging was conducted; the yearly interval was from tagging occasions and not based on a calendar year. This "fishing year", April 1 in year X to March 31 in year X+1, has the advantage of spanning the time period of a single age for Walleyes as opposed to having fish age one year within the analysis period and was consistent with the fishing year designation used in the harvest reporting for the fisheries (Fielder et al. 2014). Although we tagged about 3,000 Walleyes each year, there weren't enough tags deployed to split our analysis by maturity, sex, or age. Prior to 2005, Saginaw Bay Walleyes ≥381 mm were usually sexually mature or would be first time spawners the following year. As Walleye growth rates slowed by 2005 (Fielder and Briggs 2025), and when the minimum length limit in the recreational fishery dropped to 330 mm in 2015, these length criteria included some immature size groups. However, immature fish were rare in the spawning runs from which fish were collected for tagging and not represented by our analysis.

The Brownie model we used for tag return analyses included year specific survival and recovery rates (Fielder 2014). Each run of the model resulted in estimates of two parameters, annual survival 'S' and recovery rate 'f', for each year except that survival 'S' could not be calculated for the last year in the time series. Recovery rate is functionally equivalent to exploitation rate $'u'$ and an alternative expression of exploitation rate is the quotient of the first-year tag returns and the number of Walleye tagged the same year. While the underlying assumption that natural mortality is not realized until the one-year mark in the spring is likely not met, it is reasonable to believe that most natural mortalities on adult fish will not be realized until after winter or during spring spawning stress. Following the convention of Fielder (2014), this first-year expression of u is termed the direct expression of exploitation rate. While it does not always exactly match the recovery rate f, Fielder (2014) reported that the two varied very little.We expressed the 95% confidence intervals as +/- 1.96 the SE of the parameter estimate and calculated them from the ADMB-reported SD following parameter estimation.

Once estimates of S and u were available from tag returns analyses, other related mortality components were easily calculated (Pine et al. 2003). We calculated annual mortality A as $A = 1\text{-}S$. Instantaneous (per capita) total mortality rate Z was then calculated as ln(A)/-1. Instantaneous fishing mortality F was calculated as ($Z\ u$)/A. Instantaneous natural mortality M was computed as $Z\text{-}F$, and total annual natural mortality rate as $v = MA/\mathrm{Z}$. Estimates of total annual mortality (A) are contrasted with the same values estimated by catch curve and cohort-based analysis as reported by Fielder and Briggs (2025), and in some instances to those generated by a statistical catch-at-age (SCAA) model specific to Saginaw Bay Walleye (Fielder and Bence 2014).

We compared model estimates of total annual mortality and exploitation rate between tagged fish only from the Tittabawassee River and the larger tagging population that included other locations (Table 1) to determine the influence of a more diverse tagging population on these estimates. We distinguished between initial tag shedding within the first 21 d at large and long-term tag shedding occurring each year; the initial tag shedding for the MDNR tagging method was 1% and the long-term tag shedding was 8%, meaning that 8% of the study Walleyes at large each year shed their tags (Vandergoot et al. 2012).

Population Estimate

We estimated the numerical abundance of adult Saginaw Bay Walleye using the Fielder (2014) adaptation of the Ricker (1975) Lincoln-Peterson formula for a two-sample estimate. Fielder (2014) derived the population estimate $\hat{N}$ as the quotient of the estimated harvest from the MDNR creel survey n_2 and the exploitation rate u from the tag return analyses:

$$\widehat{N} = \frac{n_2}{u}$$

This method requires several assumptions including (1) survival of tagged Walleye is 100% the first year of life, that is, natural mortality is not a factor until the conclusion of the fishery; (2) the Walleye population is closed to immigration and emigration; and (3) capture probability is equal among all tagged and untagged Walleye represented by this population estimate. While fully meeting these assumptions is improbable, they may not be entirely violated. As stated earlier, most natural mortality is probably not realized until over winter or during the spring spawning period, both of which occur after most of the fishery has taken place. While Walleye are known to immigrate and emigrate to and from Saginaw Bay, tag returns can also be realized from outside the bay. Thus, the second assumption of tags representing fish at large is not fully violated. While the assumption of the tagged lot of fish reflecting the larger population is fundamental to all tagging or marking studies, Fielder (2014) experimented with methods to account for its violation and found the simpler adaptation of the Ricker Lincoln-Peterson equation to yield about the same result.

The tagging efforts in Saginaw Bay tributaries during the Walleye spawning migration often result in recaptures of tagged fish from previous days' electrofishing. These recaptures provide the ability to estimate spawning run size based on the Schnabel (1938) method described by Ricker (1975) and Van Den Avyle and Hayward (1999); however, electrofishing in the Tittabawassee River usually took place about 1.6 km below Dow Dam and the timing and location of the collections underestimates the likely run size. We hypothesized that another 10% of the observed spawning run immediately below Dow Dam exists at each 1.6 km stretch below the electrofishing area over a total of 24 km. Given that the spawning run stretches over multiple weeks each year, we conservatively estimated that the total Walleye spawning run size is twice that of the Schnabel estimate. We report both the Schnabel estimate at Dow Dam and the expanded "full river run" estimate for the Tittabawassee River below Dow Dam.

Movement

We used a geographic information system (ArcGIS; Esri, Redlands, California) to analyze Walleye movement. First, we generated a map of all returns over the entire time series, 1981–2023 and then plotted jaw tag recovery locations reported by anglers each season. The resulting maps of tag returns allowed us to visually inspect the distribution of Walleyes during spring (March–May), summer (June–August), fall (September–November) and winter (December–February). We did not split our analysis for years before and after the invasion of dreissenid mussels because Fielder (2014) found no effect of dreissenid mussels on Walleye distribution. We were especially interested in emigration of Walleyes from Saginaw Bay from 1981–2002 and from 2003–2023. The modern period represented Walleye resurgence, dominated by wild fish at high abundance with no Alewives in Lake Huron's main basin, and the years before 2003 represented Walleye distributions at lower abundance and dominated by stocked fish and the availability of an Alewife prey base in the main basin (Fielder and Thomas 2014). We also evaluated differences in emigration by sex for all years combined and established 508 mm total length (TL) as a cutoff to examine movement between smaller and larger fish. Significant differences in these comparisons were tested based on independence using the Chi-square test (Sokal and Rohlf 1981) and we used Yate's correction for continuity because the 2x2 tables had only 1 degree of freedom. All expected counts were above 5 and significance was determined at $\alpha \leq 0.05$.

The spatial distribution of tag returns may reflect changes in fish behavior as well as angler effort since the ratio of fishing effort from within to outside of Saginaw Bay has likely changed over time and we were unable to correct for this change. Movement analyses were therefore limited to tagged fish captured during June–September when some Walleyes are known to reside outside of Saginaw Bay (Hayden et al. 2014). Limiting the analyses to these four months guarded against confounding our results by incorrectly categorizing a tag recovery for a fish which emigrated from Saginaw Bay between June and September but was captured within Saginaw Bay during a pre- or post-spawn migration.

Results

A total of 140,784 Walleyes have been tagged since this study began in 1981 (Table 1), with 16,338 non-reward jaw tags reported by anglers (5,293 non-reward jaw tag reports since 2012; Appendix 1). Nearly all of the tag returns (98.8%) were from the recreational fishery in Saginaw Bay and Lake Huron while only 0.3% of tag returns were reported by commercial fisheries from non-Michigan waters of Lake Huron where commercial Walleye harvest is allowed.

Demographics

The age structure of Walleyes in Saginaw Bay changed through time. The age composition of tagged Walleyes grew older in the 1980s and early 1990s with the mean going from 2.7 in 1981 to nearly 8.0 years old by 1999 (Fielder 2014). In recent years the age structure has varied with tagged Walleyes typically being between 6 and 8 years old (Table 4). Generally, males first appear in electrofishing collections around age-3 and females around age-4; male Walleye will commonly occupy spawning tributaries first and linger longer than females. The overall proportion of sex has been 60% males and 40% females across all tagging locations combined since the Saginaw Bay Walleye population reached recovery targets in 2009. The tagging operation typically lasts for about one week, making it challenging to determine the timing of collections in relation to the peak of the spawning run. As a result, sex ratios are partially an artifact of sampling timing.

Table 4. Age composition (percent) of Walleyes, male (M) and female (F), sampled from all Saginaw Bay tagging locations during spring electrofishing, 2012–2023. No age-1 fish were sampled. Data before 2014 is limited to collections in the Tittabawassee River. See supplementary material for data from the entire 1981–2023 time series.

Year-Sex	Age-2	Age-3	Age-4	Age-5	Age-6	Age-7	Age-8	Age-9	Age-10	Age-11	Age-12	Age-13	Age-14+	Mean Age
2012-F	0	0.3	1.8	12.5	13.8	30.8	17.8	13.3	3.4	2.3	1.3	1.8	0.8	7.4
2012-M	0	2.8	4.4	11.6	9.1	22.6	19.0	9.9	8.0	2.8	3.0	2.8	4.2	7.8
2013-F	0	0.2	4.8	9.9	17.1	16.6	24.7	12.5	9.2	1.2	1.8	0.5	1.7	7.6
2013-M	0	7.0	19.9	8.4	13.9	10.1	14.1	9.8	10.6	1.9	2.2	0.5	1.6	6.8
2014-F	0	0.3	12.4	20.7	8.4	10.5	8.4	15.8	8.7	5.3	4.3	0.6	4.6	7.6
2014-M	0	11.4	36.2	14.0	5.7	6.2	3.6	8.5	7.3	3.6	1.4	0.5	1.3	5.9
2015-F	0	0	15.7	30.1	13.3	2.4	2.4	6.0	13.3	8.4	4.8	0	3.6	7.2
2015-M	0	0.5	27.3	21.5	10.2	3.9	5.4	6.3	7.3	2.9	6.3	2.4	5.9	7.1
2016-F	0	0	2.3	33.3	17.2	8.0	1.1	4.6	5.7	8.0	9.2	5.7	4.5	7.9
2016-M	0	2.8	4.2	10.3	15.0	4.7	3.8	7.5	13.6	13.1	11.3	8.9	4.8	9.0
2017-F	0	1.7	10.0	8.3	33.3	26.7	5.0	1.7	1.7	3.3	3.3	3.3	1.7	6.9
2017-M	0.4	18.0	13.0	3.3	13.8	23.8	5.4	1.3	3.3	4.6	7.1	1.7	4.2	6.8
2018-F	0	0	4.2	6.7	2.5	29.4	20.2	9.2	5.9	4.2	5.9	5.9	5.9	8.6
2018-M	0	2.8	14.4	16.1	8.3	17.8	14.4	6.1	3.9	3.9	4.4	2.8	5.1	7.4
2019-F	0	0	3.1	15.3	10.4	13.5	30.7	8.6	5.5	0.6	0	4.9	7.3	8.0
2019-M	0	2.9	8.0	13.1	6.6	10.2	15.3	13.9	8.0	6.6	3.6	2.9	8.8	8.4
2020-F	0	1.0	2.1	8.2	13.4	11.3	16.5	19.6	13.4	2.1	1.0	2.1	9.3	8.6
2020-M	0	6.4	8.9	12.8	10.3	11.3	10.3	19.7	9.9	5.9	3.0	0	1.5	7.4
2021-F	0	0	5.2	17.8	23.7	5.9	8.1	5.9	8.9	8.1	5.9	0.7	9.6	8.3
2021-M	0	4.2	23.0	16.4	9.1	5.5	4.8	9.1	6.7	2.4	4.8	4.2	9.6	7.6
2022-F	0	0	5.6	29.0	35.8	8.0	4.9	3.1	3.1	3.7	2.5	1.9	2.4	6.8
2022-M	0	7.2	21.0	21.0	21.0	6.5	8.0	3.6	2.2	1.4	2.9	1.4	3.6	6.3
2023-F	0	0	14.0	28.9	25.4	13.2	7.9	1.8	1.8	1.8	2.6	0	2.7	6.4
2023-M	0	7.5	19.4	22.0	18.8	9.7	7.0	1.6	2.2	2.7	2.7	0.5	5.9	6.5

Age structures were collected across six different rivers between 2014–2020 (Table 5). Significant differences in mean age of Walleye occurred among locations in four of the six years. Mean age of Walleyes in tributaries within the Saginaw River system were significantly different from one another in some years and the Au Gres River consistently exhibited an older age structure of Walleyes compared to other locations. (Table 5).

Table 5. Mean age of Walleye, by spawning tributary sampled that year, within the Saginaw Bay watershed, 2014–2020. Statistical differences within years were determined by the Kruskal-Wallis test; a Dunn-Bonferroni post hoc test was used to identify individual differences among rivers. Means with a letter in common are not significantly different at α=0.05. Blank cells indicate that there was no collection made in that river in that year.

Year	Au Gres River	Flint River	Kawkawlin River	Tittabawassee River	Shiawassee River	Rifle River	Statistical Significance
2014			6.19a	7.49b	5.90a		*P*<0.001 *H*=68.8 df=2
2015	9.74a		6.92b	6.24b	7.07b		*P*<0.001 *H*=30.1 df=3
2016	10.24a		8.16b	8.18b	8.10b	9.26ab	*P*<0.001 *H*=22.6 df=4
2017		7.06a	7.69b	6.14c			*P*<0.001 *H*=35.6 df=2
2018		7.60a	7.87a	8.25a			*P*=0.068 *H*=5.4 df=2
2019				8.19			NA
2020			8.00a	7.68a			*P*=0.243 *H*=1.4 df=1

Correction Factors

The reward disk tags applied to Walleye in 2017 and 2018 to test for failure to notice were reported alongside the reward jaw tags for about 80 days after tagging but then reports trailed off precipitously. The mean Julian return date for reward disk and reward jaw tags was statistically significantly different in 2017 (*H*=26.924, df=1, *P*<0.0001) and 2018 (*H*=5.314, df=1, *P*=0.0212); limiting the comparison to the first 80 days the tags were at large eliminated the significant difference. Further, anglers reported catching some Walleye with wounds that looked like eroded holes where the disk tags were affixed suggesting that there were retention issues with the reward disk tags beyond 80 days. For these reasons, comparisons between the reward jaw tags and reward disk tags were limited to the first 80 days after tagging. In 2017, reward disk tags (n=25) were reported at a 67% greater rate than reward jaw tags (n=15), indicating angler failure to notice jaw tags. In 2018 there were 28 reward disk tags and 20 reward jaw tags reported, or a 40% failure to notice rate for jaw tags. We calculated a composite correction factor of 1.51429 for failure to notice and a corresponding probability of successfully noticing a jaw tag of 0.66038 (Appendix 2).

Correction factors for nonreporting by anglers were estimated annually for 2000–2008 and 2014–2023 and ranged from a low of 1.08434 in 2003 to a high of 5.01505 in 2002. A linear regression of the yearly correction factors indicated no relationship between year and nonreporting correction factor (R^2 =-0.02, F=0.642, df=1,17, P=0.435); the values of the two highest nonreporting correction factors (2002 and 2007) were omitted as outliers since they occurred late in the year 2000 reward tag series and were estimated from just 12 and 2 reward tags. Since there was no relationship between year and nonreporting correction factor, we calculated a combined nonreporting correction factor of 1.54724 for all years and a probability of successfully reporting a noticed tag of 0.64631 (Appendix 3).

We calculated a joint correction factor of 2.34297 by applying the probabilities of successfully noticing a jaw tag and then successfully reporting the noticed tag to our simulation of 1,000 tags at large and two hypothetical exploitation rates (Appendix 4). This means that willful nonreporting by anglers in combination with the failure to notice a jaw tag by some anglers was 2.34 times that of uncorrected tag report rate, or about 134% more. The recreational exploitation rate (u) and recreational fishing mortality (F) increased 54.7% when adjusting for nonreporting alone and 134% when also accounting for failure to notice.

Estimates of Mortality and Exploitation Rates

Walleye total annual mortality (A) ranged from a low of 0.0961 in 1997 to a high of 0.6386 in 1981 based on the model run of all tagging locations and both correction factors applied (Table 6). The tag recovery rate (f), which is the same as exploitation rate (u), ranged from a low of 0.0388 in 1982 to a high of 0.3182 in 2023. The Brownie model conformed to the assumptions for fitting year-specific survival (Brownie et al. 1985; χ^2=60.26, df=861, P>0.999).

Table 6. Brownie model estimates of Walleye total annual survival (*S*), instantaneous total mortality (*Z*), instantaneous total fishing mortality (*F*), instantaneous total natural mortality (*M*), total annual mortality (*A*) and tag recovery rate (f, which is the same as exploitation rate u) from all Saginaw Bay tagging locations, 2012–2023. Correction factors for nonreporting and failure to notice were applied. 2SE = two standard errors of the estimate which approximates a 95% confidence interval. Blank spaces in the last row are due to estimates not being estimable for the last year in the time series except for tag recovery rate. See supplementary material for data from the entire 1981-2023 time series.

Year	*S*	2SE	*Z*	2SE	*F*	2SE	*M*	2SE	*A*	2SE	f or u	2SE
2012	0.8220	0.0559	0.1960	0.0680	0.1299	0.0104	0.0661	0.0653	0.1780	0.0559	0.1180	0.0089
2013	0.6615	0.0465	0.4132	0.0703	0.1695	0.0117	0.2438	0.0676	0.3385	0.0465	0.1388	0.0093
2014	0.4445	0.0322	0.8108	0.0724	0.3218	0.0191	0.4890	0.0684	0.5555	0.0322	0.2205	0.0126
2015	0.5863	0.0415	0.5339	0.0708	0.3066	0.0194	0.2273	0.0640	0.4137	0.0415	0.2376	0.0133
2016	0.6089	0.0423	0.4961	0.0695	0.2256	0.0159	0.2705	0.0650	0.3911	0.0423	0.1778	0.0116
2017	0.4971	0.0393	0.6989	0.0790	0.3854	0.0239	0.3135	0.0705	0.5029	0.0393	0.2773	0.0151
2018	0.5098	0.0416	0.6738	0.0817	0.3254	0.0225	0.3485	0.0740	0.4903	0.0416	0.2367	0.0146
2019	0.5504	0.0810	0.5971	0.1471	0.3505	0.0303	0.2466	0.1260	0.4496	0.0810	0.2639	0.0150
2020	0.4620	0.0708	0.7723	0.1534	0.2166	0.0261	0.5557	0.1576	0.5381	0.0708	0.1509	0.0215
2021	0.4310	0.0364	0.8417	0.0844	0.2314	0.0203	0.6103	0.0782	0.5690	0.0364	0.1564	0.0125
2022	0.5789	0.0533	0.5467	0.0921	0.3842	0.0269	0.1625	0.0776	0.4211	0.0533	0.2960	0.0159
2023											0.3182	0.0181

Walleye total annual mortality estimates from tag returns for all tagging locations combined was more variable than the estimates generated by MDNR's statistical-catch-at-age model (Fielder and Bence 2014; MDNR, unpublished data) and were similar to estimates from point-in-time catch curves reported by Fielder and Briggs (2025; Figure 4). Walleye total annual mortality and exploitation estimates from tags applied in the Tittabawassee River only and tags applied at all locations were also similar (Appendix 5). Examination of the overlap in error bars for *A* and u indicated that the estimates from the two approaches were not statistically different except for estimates of total annual mortality in 2000 (Figure 5).

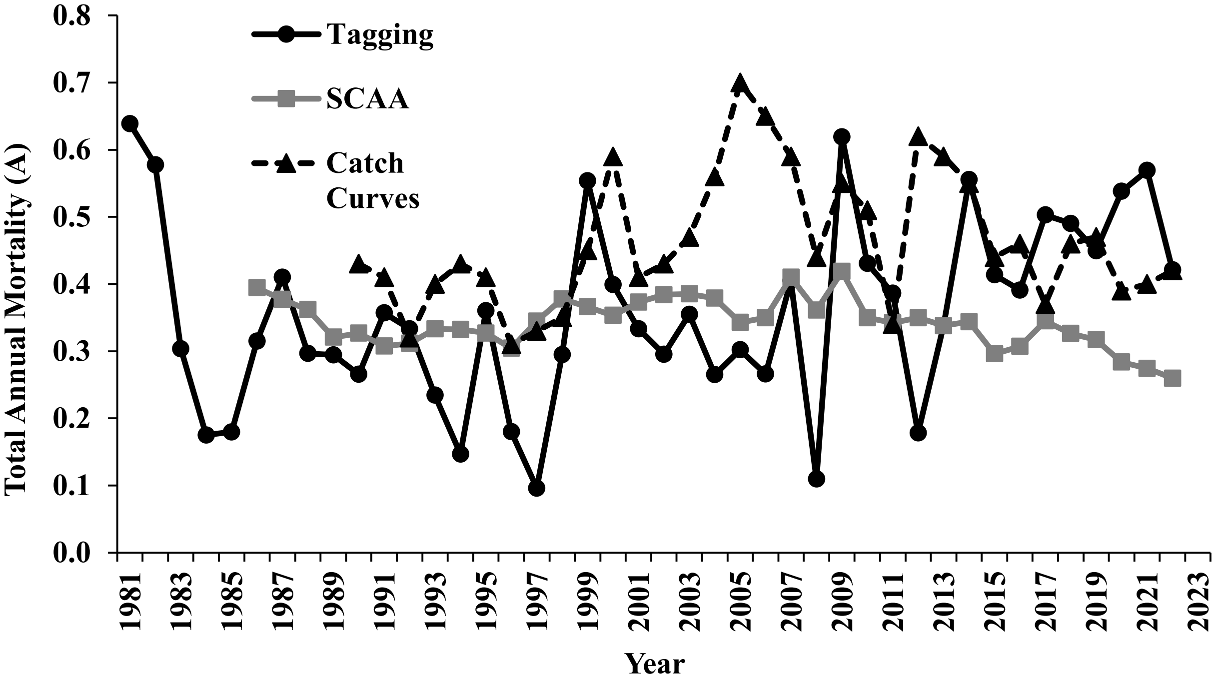

Figure 4. Trends in total annual mortality (*A*) of Saginaw Bay Walleyes among three estimation methods, 1981–2023. Estimates are from Brownie model analysis of jaw tag returns (tagging; returns from all tagging locations combined), the MDNR statistical catch-at-age model estimate for age-4+ and from point-in-time catch curves.

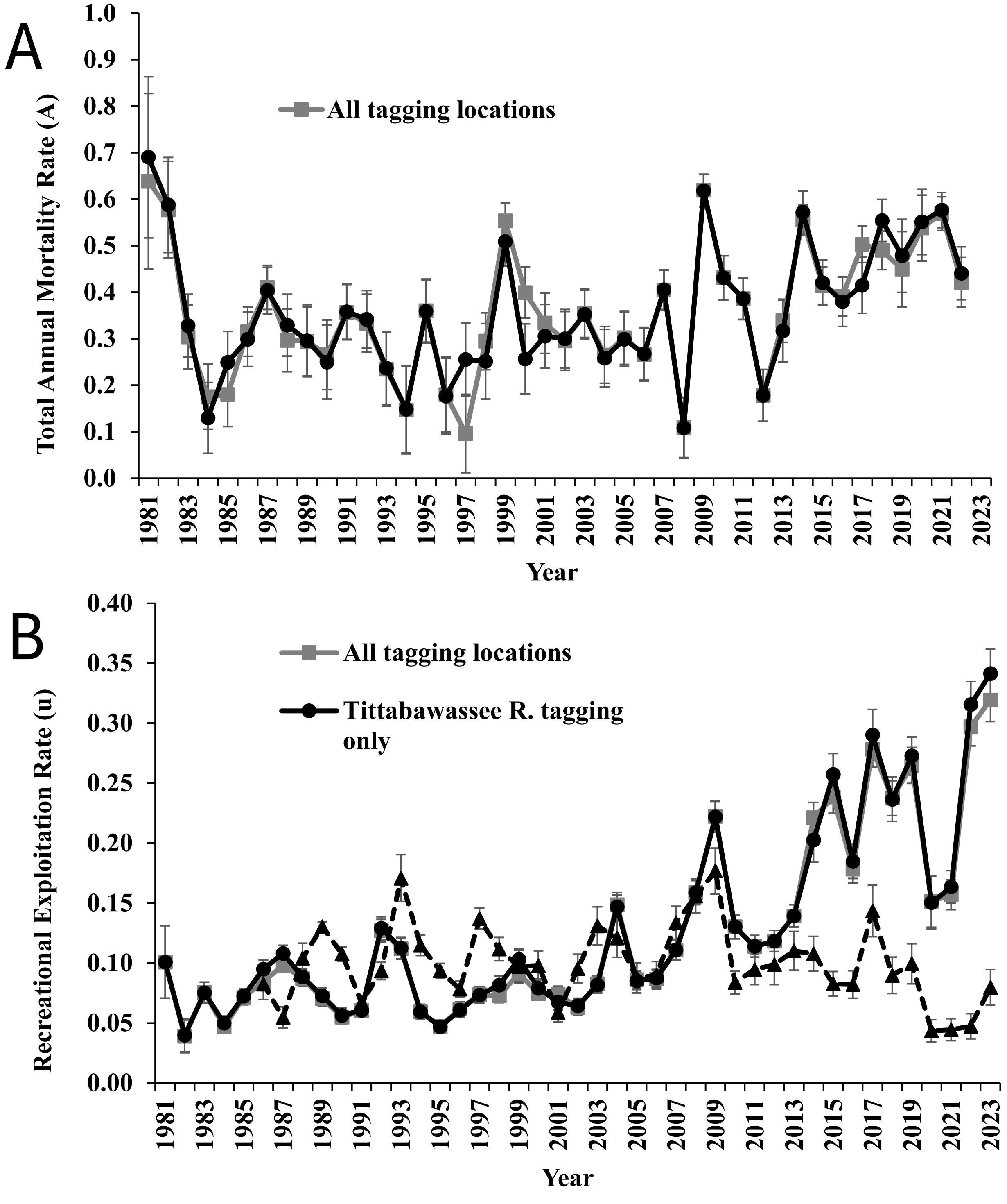

Figure 5. Trends in Saginaw Bay Walleye total annual mortality rate (A; A) and recreational fishing exploitation rate (u; B) estimated by tag return analysis using nonreporting and failure to notice correction factors, 1981–2023. No estimate of A is possible in 2023. Trends reflect all tagging locations combined and those limited to the Tittabawassee River. Estimate of u for age-4+ Walleyes from the MDNR SCAA model are included for comparison. Error bars are +/- 2 SE.

Population Estimates

The Walleye population estimate based on the Fielder (2014) adaptation of the Ricker Lincoln-Peterson formula for a two-sample estimate peaked at 2.7 million fish in 2007 and averaged 1,348,886 from 2012–2023 (Figure 6). It is difficult to know what segment of the population this estimate represents because age composition varied by year. The MDNR also generated a Walleye population estimate for Saginaw Bay using a statistical-catch-at-age model (Fielder and Bence 2016). That estimate, based on age-3 and older fish, closely matched the Ricker Lincoln-Peterson population estimate until 2007, when the two estimates began to diverge.

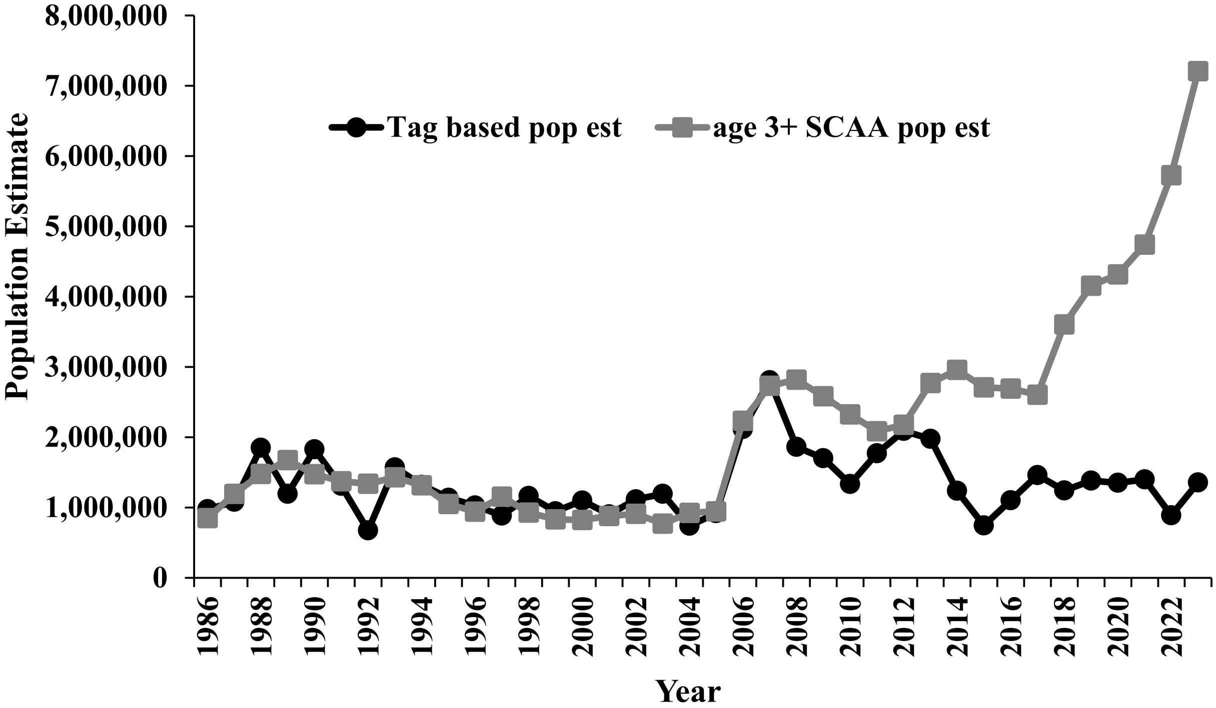

Figure 6. Walleye population estimates for Saginaw Bay based on the recreational fishing exploitation rate and recreational harvest estimates for the all-locations tag-based method, 1986–2023. The estimate for age-3+ Walleye from the MDNR's SCAA model is included for comparison. Year is based on fishing year which runs from April 1 in year 'X' to March 31 in year 'X+1'.

Our ability to estimate the magnitude of the various spawning runs of Walleye was limited to data from a subset of years at the Tittabawassee River tagging location. The size of the Tittabawassee River Walleye run ranged from a low of 34,449 fish (full river run of 172,245 fish) in 2005 to a high of 104,083 fish (full river run of 520,417 fish) in 2021 (Table 7).

Table 7. Estimated number of fish in the Walleye spawning run in the Tittabawassee River, 1999–2023, from the Schnabel mark and recapture population estimate method. The estimated full river run accounts for unsampled lengths of the river and the entire duration of the spawning run. Insufficient data were available to generate estimates in 2002 and 2020.

Year	Schnable estimate	Estimated full river run
1999	66,162	330,000
2000	26,584	132,918
2001	89,459	447,297
2002	-	-
2003	202,543	506,358
2004	79,512	397,561
2005	34,449	172,245
2006	54,973	274,867
2007	45,350	226,752
2008	108,812	544,061
2009	200,293	1,001,463
2010	98,541	492,705
2011	57,770	173,140
2012	52,314	261,570
2013	54,891	274,457
2014	83,333	416,667
2015	134,375	671,875
2016	143,950	719,750
2017	74,286	371,429
2018	104,000	520,000
2019	69,574	347,872
2020	-	-
2021	104,083	520,417
2022	31,526	157,628
2023	48,276	241,380

Movement

We received 16,966 Walleye tag reports from 1981–2023 with sufficient information to assign a latitude and longitude to the capture location, 1,448 (8.5%) of which were reported from outside of Saginaw Bay (Figure 7). There were 6,055 (35.7%) tag returns from June–September; of those 827 (13.7%) were reported from locations outside of Saginaw Bay. There were significantly more Walleyes reported from outside the bay during the post-resurgence period (2003–2023, 14.7%) compared to years before Walleye resurgence (1981–2002, 11.8%; Table 8, Appendix 6; $\chi^2=10.556$, df=1, $P=0.001$). When the frequency of tag recoveries was compared across sex of fish for all years, females were more prevalent outside the bay (20.4%) than males (8.8%; Table 8, Appendix 7; $\chi^2=161.817$, df=1, $P<0.001$). Similarly, Walleye greater than

508 mm TL were significantly more likely to be reported from outside the bay (19.3%) than fish ≤508 mm TL (6.4%; Table 8, Appendix 8; χ^2=209.667, df=1, *P*<0.001). Walleye tag recoveries were most frequent during spring (43%) and least frequent in fall (7%; Appendix 9); however, seasonality of tag reports is highly dependent on temporal distribution of fishing effort.

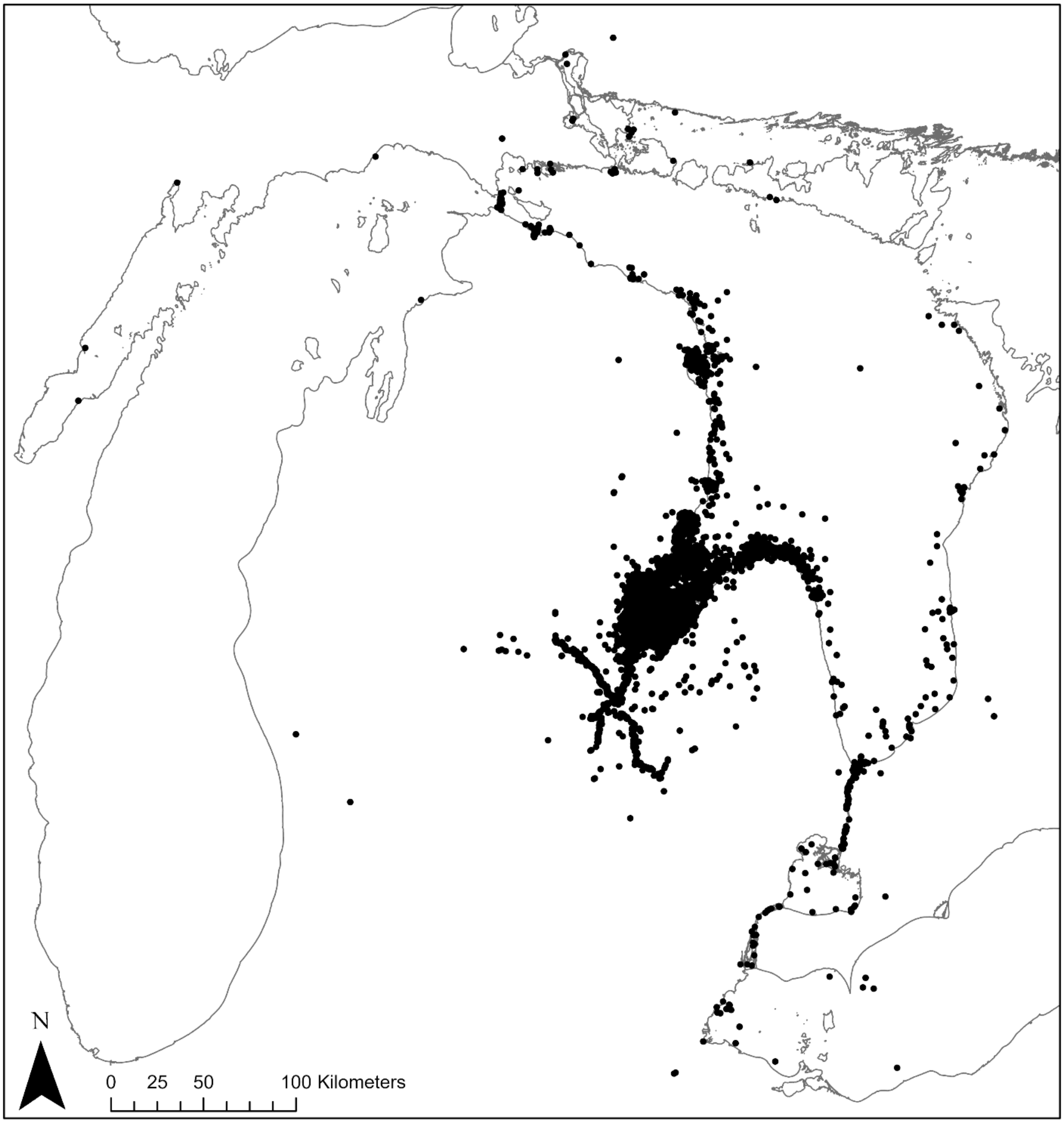

Figure 7. Capture locations of jaw-tagged Saginaw Bay Walleye reported by anglers, 1981–2023. Each dot represents one fish.

Table 8. Proportion of Walleye jaw tags reported from outside Saginaw Bay by pre- (1981–2002) and post- (2003–2023) Walleye resurgence periods, sex, and size group.

Strata	Variable	Percent of returns outside of Saginaw Bay
Period	Pre-resurgence	11.8
Period	Post-resurgence	14.7
Sex	Female	20.4
Sex	Male	8.8
Length	>508 mm TL	19.3
Length	≤508 mm TL	6.4

Discussion

The total annual mortality rate estimated from tag returns of Saginaw Bay Walleyes since 2012 (0.4407) has increased relative to the long-term mean during 1981–2023 (0.3578). This change representing age-4+ fish (Table 6) appeared to be driven by recreational fishing mortality which increased 165% since Walleye recovery targets were attained in 2009 (Table 6). Increasing the recreational harvest of the Walleye population was a management objective implemented by the MDNR in 2015 (Fielder et al. 2020a) and based on tag-based estimates of recreational fishing mortality, that target has been achieved since 2009.

Our estimate of mean total annual mortality since 1981 (0.3578) compares closely to the mean total annual mortality estimated by the SCAA model for age-4+ Walleyes (0.3420; Figure 5). The catch curve based mean total annual mortality estimate (0.4621) is higher, which may be due to the estimation method including fish as young as age-1. While these estimates of total annual mortality rates are regarded as sustainable the current Saginaw Bay Walleye management plan (Jolley et al. 2025) recommends that total annual mortality not exceed 0.40. Since 2012 the mean tag-based total mortality estimate (0.4407) and the catch curve total mortality estimate (0.4700) have exceeded that recommend value; however, most of the management plan is based on the SCAA-calculated total mortality estimate, which was 0.3128 for age-4+ fish during the same period.

The tag-based estimates of exploitation rates that we calculated for the recreational fishery and those generated by the SCAA model aligned closely until about 2010 when they departed sharply (Figure 6; the years since 2010 correspond to the era of enhanced Walleye recruitment and attainment of recovery targets). The departure between tag-based and SCAA estimates of exploitation continue to puzzle fishery managers. Both methods are estimating total annual mortality and exploitation rate, albeit with very different methods and theory. Generally, SCAA is regarded as a state-of-the-art method (Quinn and Deriso 1999; Maunder 2003; Hilborn 2012) that provides age-based estimates while tag-based methods are generally limited to annualized estimates and pooling of ages. What remains unclear is if differences in tag-based and SCAA estimates reflect age-based dynamics or result from differences in harvest vulnerability of study fish. Statistical catch-at-age methods draw from collections of harvested Walleye across all of Saginaw Bay and even Lake Huron, while tag-based estimates are principally from fish collected in the Tittabawassee River spawning run. To account for estimate inconsistencies due to differences in harvest vulnerability, Tittabawassee River fish would need to have greater harvest vulnerability than the Walleye reflected in the larger mixed Saginaw Bay Walleye population. The differences in estimation between the two techniques prevented the tag-based methods from being used as auxiliary information in an integrated version of the SCAA model (Fielder and Bence 2014). Instead, the two estimation methods provide for a range of estimates that managers can evaluate against reference points and management targets.

Similarly, our estimates of Walleye population size closely aligned until 2008 when tag-based and SCAA methods began to depart (Figure 6). This coincides with the Walleye population approaching carrying capacity as indicated by growth rates observed by Fielder and Briggs (2025). While Saginaw Bay Walleyes have trended towards a later age-at-maturity over our time series the difference is about 1 year of age which is unlikely to account for the departure between the SCAA model estimate and that of the tagged lot. Inspection of SCAA population estimates for age-4 and 5 Walleye were closer to the tagged-based estimate but did not track as well as the age-3 estimate before 2007. In general, as growth slowed after 2007 and Walleye matured later, the proportion of younger fish in the spawning run that served as the tagging lot declined. Accordingly, the tagged population estimate began to reflect an older, and thus smaller, proportion of the overall population and there is evidence to support this in the age structure of the tagged lot over time (Tables 4 and 5). Koenigbauer (2024) documented larger female Walleye earlier in the spawning run in the Tittabawassee River and smaller Walleye later in the run. These size-based behavioral differences may affect age structure as well, depending on the timing of the electrofishing collections for tagging.

It is again unclear if these departures in population estimates reflect some collective differences in vulnerability to harvest or something else. The population estimates are calculated from the estimates of exploitation rate, so it is not surprising that differences in methods are reflected in the population estimates. It is possible that the SCAA method is reflecting additional recruitment sources, but the tag-based population estimate method is the quotient of the exploitation rate from tag reports and all the harvest as reported by the MDNR's creel survey program. As such, the estimate is not an estimate of the Tittabawassee River Walleye population but that of the Saginaw Bay population. Our attempt to estimate the magnitude of the Tittabawassee River spawning migration (Table 7) indicates that it may only be ¼ to ½ of the total tag-based population estimate. The steady total population trend of just over 1 million Walleyes over the previous 11 years is not consistent with the 387% increase in angler harvest rate as indicated by the creel survey, suggesting that the true population trajectory is likely better represented by the SCAA method.

The validity of tag-based estimates of mortality, exploitation, and abundance relies on the full reporting of all harvested tagged fish and corrections must be used because this is never achieved in most tagging studies. The total correction factor of 2.34297 that we calculated, which reflects both nonreporting and failure to notice, indicates that only 42.7% of jaw tags that pass through the hands of anglers are ever reported. While correction factors mathematically account for underreporting they remain an important source of uncertainty and potential error. This study may be the first to quantify angler failure to notice tags which was substantial at

34% more than the number of tags successfully reported. The lack of a trend in nonreporting over the study period suggests that compliance has probably reached a plateau and will remain at this rate unless angler reporting habits change in the future. Further refinement of nonreporting correction factors may not warrant the expense, which in our study cost about $12,000 per year in reward payments for a 10% subset of reward-tagged fish at large annually. The newest estimate of the nonreporting correction factor (1.54724) is slightly less than the 1.5752–1.6679 range used by Fielder (2014) and considerably less than the 2.33 value calculated for 2000. While the use of annual reward tags since 2014 has possibly affected angler motivation to report tags more often, some level of nonreporting appears to be inevitable and likely cannot be further improved.

Capture locations for jaw tag returns suggest emigration rates for Walleye are influenced by population density, sex, and size. A higher proportion of Walleye were captured outside of Saginaw Bay during the post-resurgence period of higher Walleye density. Additionally, females were more likely to emigrate than males and larger fish were more likely to emigrate than smaller fish. Walleyes are sexually dimorphic and females are generally larger than males at most ages (Lester et al. 2000). Therefore, it is unclear if sex, size, or both are influencing this behavior. Furthermore, our analysis across periods does not explain if emigration rates differed because of changes in the food web (Pothoven et al. 2017), available thermal refugia (Peat et al. 2015), summer hypoxia (Meyer 2023), or other reasons.

Other tagging-based projects have compared emigration rates for Walleye in the Saginaw Bay watershed. Hayden et al. (2014) used acoustic telemetry tags to track Walleye from the Tittabawassee River into Saginaw Bay and the main basin of Lake Huron. Their results showed 37% of the Walleye tagged in the Tittabawassee River emigrated from Saginaw Bay into Lake Huron compared to just 8.5% of jaw tag returns. Furthermore, sex did not influence Walleye movement in their study, in contrast to our results. Walleye in Lake Erie did not demonstrate sex-based differences in home range based on a telemetry study by Bihun et al. (2025). Brenden et al. (2015) estimated Lake Erie and Lake St. Clair spawning populations accounted for 26% of the Walleye harvested in Saginaw Bay by recreational anglers during 2008–2009. This time series falls within the post-resurgence period when we estimated a higher proportion of Walleye emigrating out of Saginaw Bay during summer. Conversely, Hayden et al. (2019) showed limited exchange of Walleye between Lake Huron and Lake Erie through the Huron-Erie Corridor despite jaw tag returns from this region. It is possible that ability to detect migrations of Walleye within some strata, like sex or size, is greater because of the larger sample sizes afforded by jaw tagging studies compared to acoustic telemetry. Alternatively, emigration by some Walleyes from Saginaw Bay that is based on sex or size may be unique to Saginaw Bay and Lake Huron.

Walleyes face tradeoffs for migrating out of Saginaw Bay. Walleye that reside in Saginaw Bay all year experience warmer temperature regimes and have higher consumptive demands compared to fish emigrating to Lake Huron (Madenjian et al. 2018). Additionally, the forage base is different in the two regions. Pothoven et. al. (2017) found Round Goby *Neogobius melanostomus* and Rainbow Smelt *Osmerus mordax* were more prevalent in diets for Walleye from the main basin of Lake Huron and invertebrates, Yellow Perch *Perca flavescens*, and Gizzard Shad *Dorosoma cepedianum* were more prevalent in Walleye diets from Saginaw Bay in 2009–2011, after the Lake Huron Alewife population collapsed. Furthermore, forage biomass in Saginaw Bay is lower in the post-resurgence period after Alewife collapse (Fielder and Briggs 2025), and a higher Walleye population with lower forage abundance may motivate more

Walleye to emigrate from Saginaw Bay. Additionally, a Walleye residing in Saginaw Bay needs to consume 10%–18% more prey than a fish that emigrates from Saginaw Bay to have the same growth rate due to differences in thermal conditions and the corresponding effects on metabolism (Pothoven et al. 2017).

Walleye migrating out of Saginaw Bay create consequences for other species like stocked salmonids. Several locations along the Michigan shoreline of Lake Huron are stocked with salmonids; Walleye emigrating from Saginaw Bay to the furthest southern and northern extent of Lake Huron during April and May constitute a source of predation on newly stocked fish (Fielder et al. 2023). Our data suggests a higher proportion of Walleye are emigrating out of Saginaw Bay in the post-resurgence period which could further diminish survival rates of stocked fish. This result could influence preferred stocking windows and should be considered when making stocking decisions.

The recreational management plan developed for Saginaw Bay Walleye and Yellow Perch (Jolley et al. 2025) incorporates Walleye population metrics from a variety of sources including harvest estimates for main basin recreational, tribal, and commercial fisheries across Lake Huron. Fielder et al. (2020b) suggested managing the Walleye population using a statistical-catch-at-age model which accounts for main basin and Saginaw Bay fisheries to provide well-informed stock assessments. The spatial distribution of jaw tag returns in our study further reinforces how Saginaw Bay is an open system and Walleye use a significant portion of Lake Huron, which must be considered when managing the population.

Recommendations

1. Continue using tag-based methods to estimate total annual mortality, exploitation, and population size of Saginaw Bay Walleye for an additional five years and then re-evaluate the need for future tagging studies.
2. Discontinue reward jaw tagging for the next five years. Use and apply the correction factors calculated and reported in this report in the future.
3. Diversify tagging locations each year when possible as a means to help optimize the estimation process.
4. Make fishery management decisions based on estimates of vital statistics like total annual mortality, exploitation, and population size from the SCAA model and the tag-based Brownie model, considering the results from each as a likely range that true values fall within.
5. Continue to supply 'thank you' letters or emails to anglers who report tagged Walleye to validate the importance of the information they provide and foster continued cooperation.

Supplementary Material

Supplementary material is available from the MDNR Fisheries Division's online library catalog, FishCat. Historic data provided in supplementary material is derived from Fielder et al. (2000). To accommodate readers viewing a printed version of this article, the URL for the supplementary material is https://www2.dnr.state.mi.us/publications/pdfs/DNRFishLibrary/FisheriesReports/FR048_supp_material.xlsx

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Appendices

Appendix 1. Walleye non-reward jaw tags from all Saginaw Bay tagging locations reported from the 2012–2023 fishing year (April 1 in year X to March 31in year X+1). No correction is applied for nonreporting or failure to notice by anglers. See supplementary material for data from the entire 1981-2023 time series.

Year Tagged	Fishing Year 2012	Fishing Year 2013	Fishing Year 2014	Fishing Year 2015	Fishing Year 2016	Fishing Year 2017	Fishing Year 2018	Fishing Year 2019	Fishing Year 2020	Fishing Year 2021	Fishing Year 2022	Fishing Year 2023	Total of each year's tags
2012	143	117	126	70	18	21	24	3	2	0	0	1	525
2013	0	235	139	63	24	23	4	4	2	0	0	2	496
2014	0	0	279	111	34	23	14	7	1	2	2	1	474
2015	0	0	0	267	101	86	42	22	10	7	6	3	544
2016	0	0	0	0	240	155	56	29	11	3	2	10	506
2017	0	0	0	0	0	329	82	48	10	6	4	2	481
2018	0	0	0	0	0	0	254	107	38	16	12	10	437
2019	0	0	0	0	0	0	0	331	77	24	22	18	472
2020	0	0	0	0	0	0	0	0	46	13	11	5	75
2021	0	0	0	0	0	0	0	0	0	195	144	50	389
2022	0	0	0	0	0	0	0	0	0	0	333	198	531
2023	0	0	0	0	0	0	0	0	0	0	0	363	363
Total tags reported per fishing year	143	352	544	511	417	637	476	551	197	266	536	663	5,293

Appendix 2. Calculation of Saginaw Bay Walleye jaw tag failure-to-notice correction factor (A) based on comparisons of reward jaw tags to reward disk tag returns, 2017–2018 (B). Analysis restricted to first 80 days of tag reports to overcome tag shedding issue for vinyl laminated disk tags. Calculations proved sensitive to number of digits; actual calculations were carried out to 15 places past the decimal.

A

Correction factor for failure to notice = 0.08833 / 0.05833 = 1.51429

Probability of successfully noticing a jaw tag = 1 / 1.51429 = 0.66038

B

Year	Disk tags deployed	Jaw tags deployed	Disk tags reported	Jaw tags reported
2017	300	300	25	15
2018	300	300	28	20
Total	600	600	53	35
Proportion reported from total deployed			0.08833	0.05833

Appendix 3. Calculation of Saginaw Bay Walleye jaw tag nonreporting correction factor (A) based on comparisons of reward (B) to non-reward (C) tag returns, 2000–2023. Years are fishing year which is from April 1 in year 'X' to March 31 in year 'X'+1. Calculations in 2000 were limited to tags deployed in the Tittabawassee River. All tagging locations were combined for other years. Calculations proved sensitive to number of digits; actual calculations were carried out to 15 places past the decimal. There is no data possible for the blank cells because of the matrix of years in tables 3A and 3C.

A

	Non-reward	Reward
Numbers tagged	27300	3299
Numbers reported	4621	864
% reported	0.16927	0.26190

Correction factor for nonreporting = 0.26190 / 0.16927 = 1.54724
Probability of successfully reporting a tag = 1 / 1.54724 = 0.64631

B

Year tagged	Number tagged	2000	2001	2002	2003	2004	2005	2006	2007	2008	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
2000	299	20	9	12	4	8	3	2	2	2	0	0	0	0	1	0	0	0	0	0	63
2014	300										59	17	4	2	4	0	1	0	0	0	87
2015	300											50	10	13	6	2	1	0	1	0	83
2016	300												32	26	11	2	0	1	0	0	72
2017	300													58	16	7	3	1	0	0	85
2018	300														63	31	8	1	2	2	107
2019	300															54	18	4	0	4	80
2020	300																31	11	10	6	58
2021	300																	34	26	13	73
2022	300																		61	19	80
2023	300																			76	76
Total	3,299	20	9	12	4	8	3	2	2	2	59	67	46	99	101	96	62	52	100	120	864

C

Year tagged	Number tagged	2000	2001	2002	2003	2004	2005	2006	2007	2008	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
2000	2,999	97	60	24	37	31	12	12	6	9	1	0	0	0	0	0	0	0	0	0	289
2014	2,700										281	112	34	23	14	7	1	2	2	1	477
2015	2,700											272	102	88	43	22	10	7	6	3	553
2016	2,700												240	155	57	29	11	3	3	10	508
2017	2,400													332	85	49	10	6	4	2	488
2018	2,401														255	110	40	16	12	10	443
2019	2,700															334	79	26	22	18	479
2020	600																47	14	12	5	78
2021	2,700																	198	145	50	393
2022	2,700																		343	203	546
2023	2,700																			367	367
Total	27,300	97	60	24	37	31	12	12	6	9	282	384	376	598	454	551	198	272	549	669	4,621

Appendix 4. Calculation of joint correction factor (A) across two hypothetical exploitation rates (u; B) for failing to notice a Saginaw Bay Walleye jaw tag and then failing to report tags that are noticed. Calculations proved sensitive to number of digits; actual calculations were carried out to 15 places past the decimal.

A

Joint (sequential) correction factor for failure to notice and then failure to report under a high U scenario = 400 / 171.72380 = 2.34297

Joint (sequential) correction factor for failure to notice and then failure to report under a low U scenario = 200 / 85.36190 = 2.34297

Check applying probabilistic formulation of joint probability from correction factors = 1.54723 x 1.51429 =2.34297

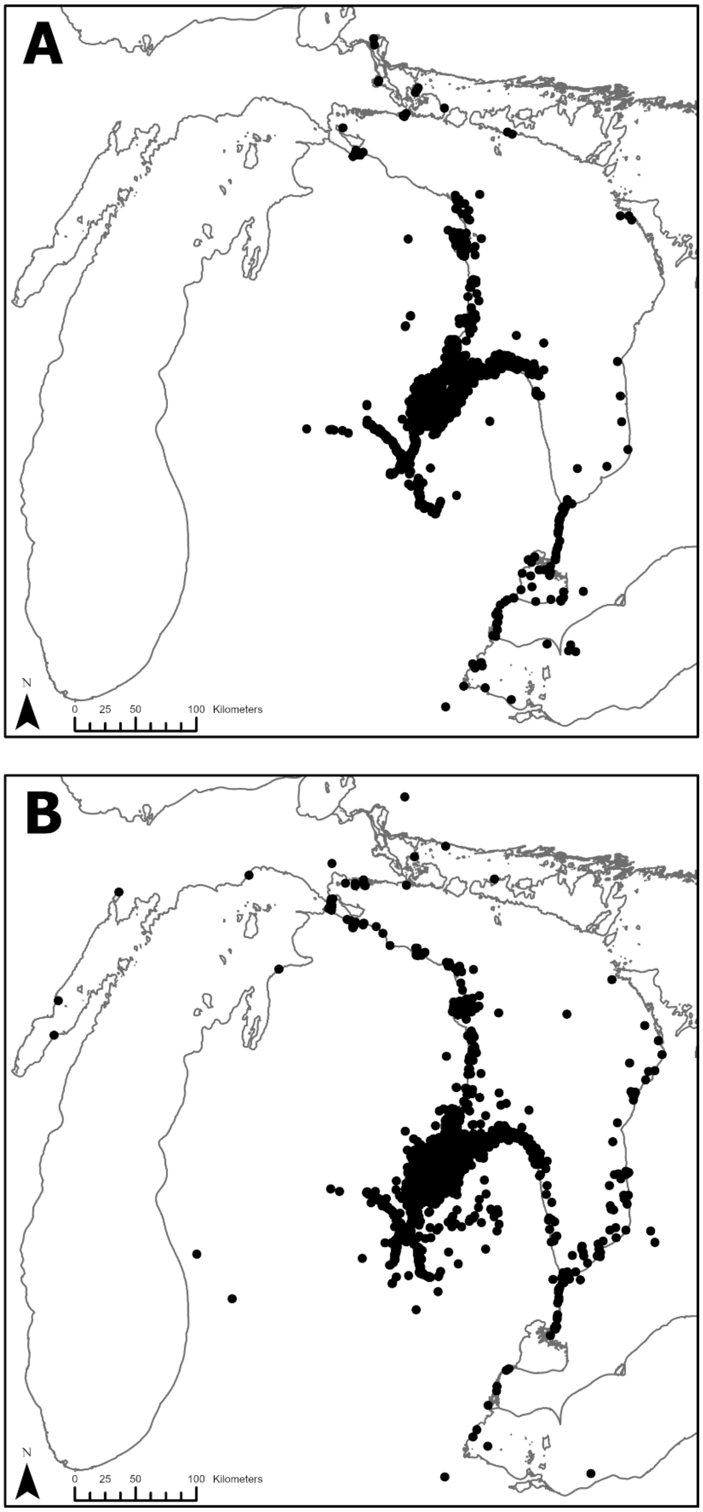
Probability of successfully noticing and reporting a Walleye jaw tag in Saginaw Bay = 1 / 2.3497 = 0.42681

B

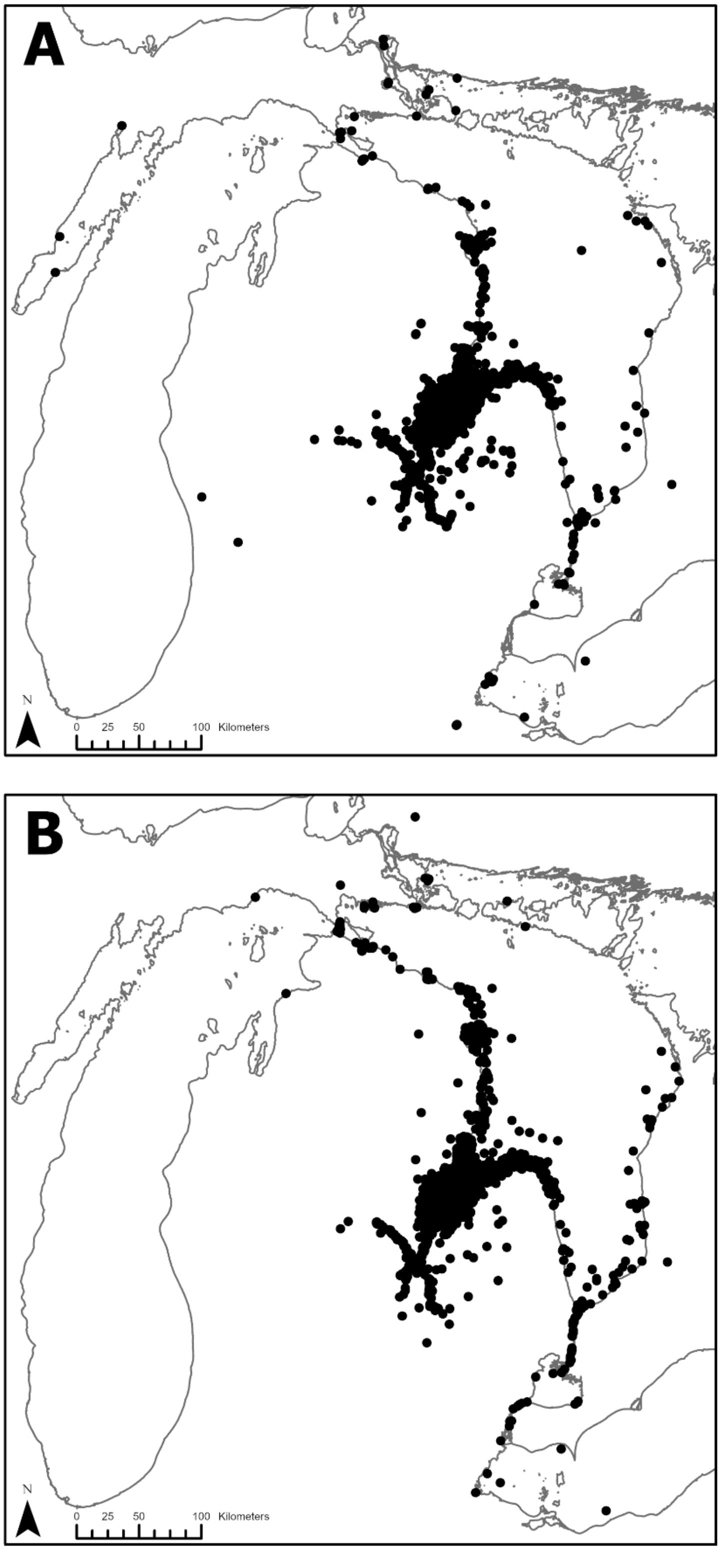
	high u	low u
Hypothetical tags at large	1000	1000
Hypothetical exploitation rate	0.4	0.2
Tags caught	400	200
Proportion of tags successfully noticed	0.66038	0.66038
Tag number successfully noticed	264.15	132.08
Proportion of tags successfully reported	0.64632	0.64632
Tag number successfully noticed & reported	170.72380	85.36190
Proportion of tags caught, noticed & reported	0.42681	0.42681
Joint (sequential) correction factor	2.34297	2.34297

Appendix 5. Brownie model estimates from tag returns limited to fish tagged in the Tittabawassee River with correction factors for nonreporting and failure to notice applied, 1997–2023. Estimates are total annual survival (S), instantaneous total mortality (Z), instantaneous total fishing mortality (F), instantaneous total natural mortality (M), total annual mortality (A) and tag recovery rate (f) which is the same as exploitation rate (u), and their two standard errors. Estimates are not possible for the last year in the time series except for tag recovery rate. ND means undeterminable. See supplementary material for data from the entire 1981-2023 time series.

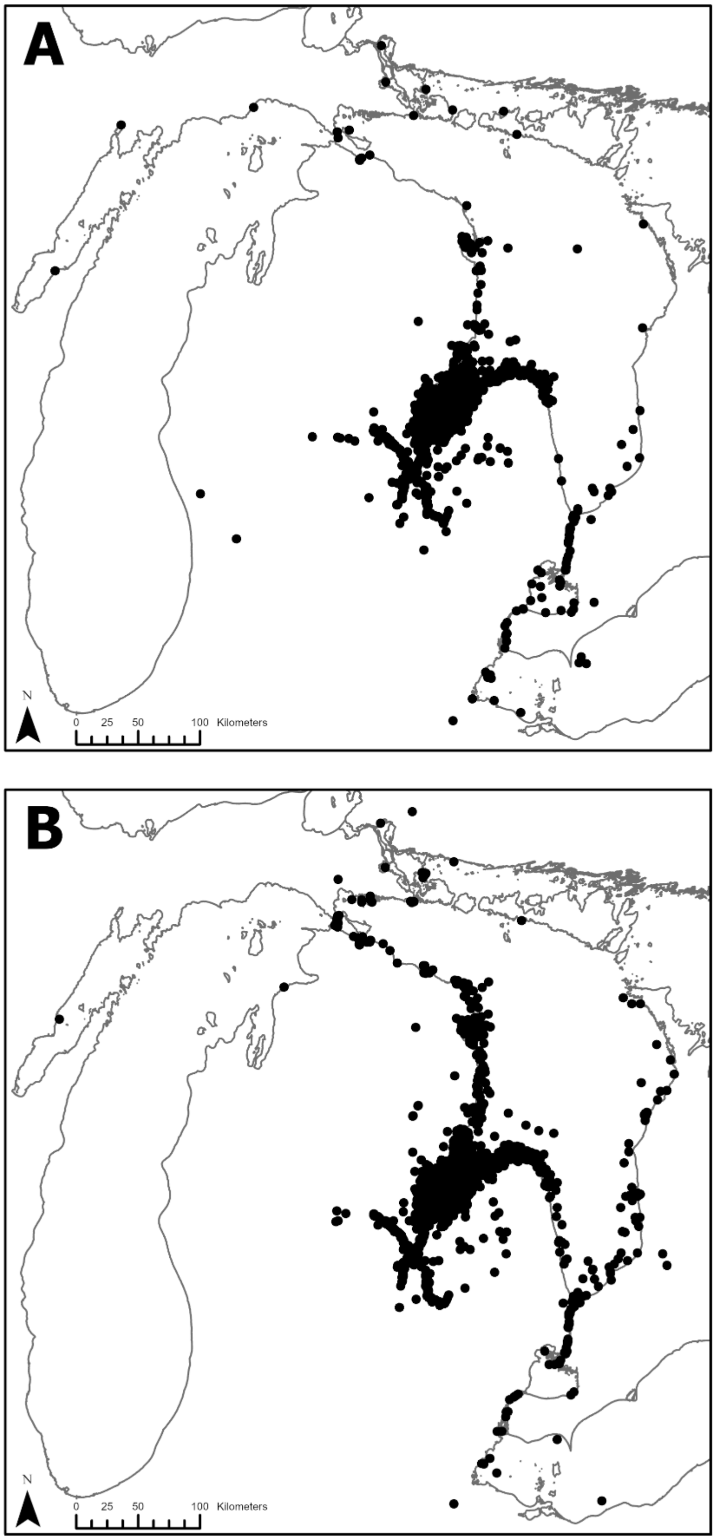
Year	S	2SE	Z	2SE	F	2SE	M	2SE	A	2SE	f or u	2SE
1997	0.7448	0.0784	0.2947	0.1053	0.0843	0.0077	0.2104	0.1036	0.2552	0.0784	0.0730	0.0067
1998	0.7485	0.0815	0.2897	0.1089	0.0935	0.0085	0.1961	0.1075	0.2515	0.0815	0.0812	0.0077
1999	0.4911	0.0529	0.7111	0.1077	0.1435	0.0119	0.5676	0.1056	0.5089	0.0529	0.1027	0.0088
2000	0.7434	0.0754	0.2965	0.1014	0.0910	0.0089	0.2055	0.0992	0.2566	0.0754	0.0787	0.0075
2001	0.6944	0.0682	0.3648	0.0982	0.0803	0.0080	0.2845	0.0968	0.3056	0.0682	0.0673	0.0067
2002	0.6999	0.0631	0.3568	0.0902	0.0762	0.0075	0.2805	0.0890	0.3001	0.0631	0.0641	0.0064
2003	0.6478	0.0527	0.4341	0.0813	0.1006	0.0088	0.3336	0.0800	0.3522	0.0527	0.0816	0.0072
2004	0.7417	0.0619	0.2988	0.0834	0.1694	0.0121	0.1295	0.0797	0.2583	0.0619	0.1464	0.0099
2005	0.7014	0.0581	0.3547	0.0828	0.1007	0.0086	0.2539	0.0813	0.2986	0.0581	0.0848	0.0073
2006	0.7322	0.0572	0.3117	0.0782	0.1013	0.0085	0.2104	0.0766	0.2678	0.0572	0.0871	0.0072
2007	0.5947	0.0427	0.5196	0.0718	0.1418	0.0105	0.3779	0.0704	0.4053	0.0427	0.1106	0.0083
2008	0.8916	0.0649	0.1147	0.0728	0.1674	0.0114	ND	ND	0.1084	0.0649	0.1582	0.0099
2009	0.3820	0.0351	0.9622	0.0918	0.3443	0.0209	0.6179	0.0860	0.6180	0.0351	0.2211	0.0129
2010	0.5691	0.0479	0.5637	0.0841	0.1698	0.0137	0.3939	0.0805	0.4309	0.0479	0.1298	0.0100
2011	0.6138	0.0451	0.4880	0.0734	0.1435	0.0119	0.3446	0.0708	0.3862	0.0451	0.1135	0.0091
2012	0.8220	0.0559	0.1960	0.0680	0.1299	0.0104	0.0661	0.0653	0.1780	0.0559	0.1180	0.0089
2013	0.6831	0.0667	0.3811	0.0977	0.1669	0.0127	0.2141	0.0921	0.3169	0.0667	0.1388	0.0093
2014	0.4278	0.0449	0.8490	0.1050	0.2997	0.0235	0.5493	0.1083	0.5722	0.0449	0.2020	0.0185
2015	0.5796	0.0491	0.5455	0.0846	0.3326	0.0250	0.2129	0.0772	0.4204	0.0491	0.2564	0.0174
2016	0.6206	0.0535	0.4771	0.0861	0.2314	0.0197	0.2457	0.0797	0.3794	0.0535	0.1840	0.0142
2017	0.5851	0.0605	0.5361	0.1034	0.3738	0.0302	0.1623	0.0939	0.4150	0.0605	0.2893	0.0211
2018	0.4458	0.0453	0.8080	0.1016	0.3438	0.0293	0.4642	0.0936	0.5542	0.0453	0.2358	0.0185
2019	0.5217	0.0789	0.6506	0.1512	0.3696	0.0335	0.2810	0.1274	0.4783	0.0789	0.2717	0.0158
2020	0.4490	0.0705	0.8007	0.1570	0.2177	0.0281	0.5830	0.1595	0.5510	0.0705	0.1498	0.0219
2021	0.4234	0.0381	0.8595	0.0899	0.2428	0.0224	0.6167	0.0824	0.5766	0.0381	0.1629	0.0135
2022	0.5592	0.0572	0.5812	0.1022	0.4145	0.0323	0.1667	0.0857	0.4408	0.0572	0.3144	0.0191
2023											0.3403	0.0205



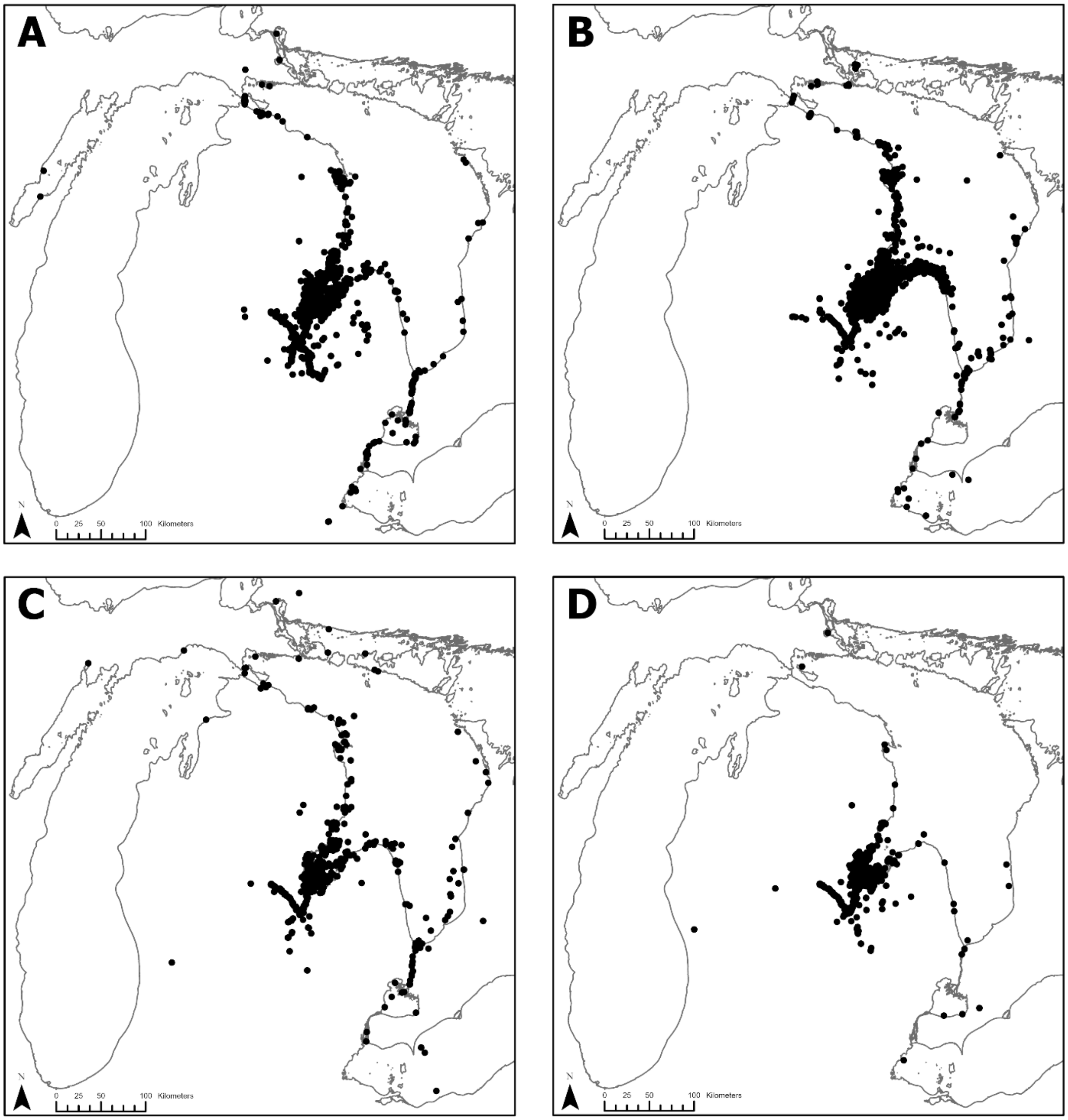
Appendix 6. Capture locations of angler reported Saginaw Bay Walleye jaw tags before Walleye resurgence (1981–2002; A) and after Walleye resurgence (2003–2023; B). Each dot represents one fish.



Appendix 7. Capture locations of angler reported Saginaw Bay Walleye jaw tags for male (A) and female (B) fish, 1981–2023. Each dot represents one fish.



Appendix 8. Capture locations of angler reported Saginaw Bay Walleye jaw tags, by size, 1981–2023. Sizes are ≤508 mm TL (A) and >508 mm TL (B). Each dot represents one fish.



Appendix 9. Capture locations of angler reported Saginaw Bay Walleye jaw tags during spring (A), summer (B), fall (C), and winter (D), 1981–2023. Each dot represents one fish.