Use of a Structured Approach to the Analysis of Management Options and Value of Information for a Recreationally Exploited Fish Population: A Case Study of Walleyes in Saginaw Bay

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Abstract
Saginaw Bay Walleyes *Sander vitreus* contribute to fisheries throughout Lake Huron including a recreational fishery and by-kill stemming from the state-licensed commercial fishery in the bay. Two critical uncertain states of nature exist concerning the true magnitude (catchability) of the by-kill and the future of Alewives *Alosa pseudoharengus* in Lake Huron, the latter being a strong determinant of Walleye recruitment. After consulting with fishery managers, a stochastic simulation model was developed and used to evaluate management options for the recreational fishery in the form of a decision analysis and the value of information for improved estimates of by-kill magnitude. Decision analysis sought to identify the maximum sustainable recreational harvest. Sustainable harvest was defined as the average across 250 stochastic simulations for each management option considered while penalizing any simulation year with a value of zero if sustainability criteria were exceeded. Decision analysis indicated that sustainable harvest would be maximized if recreational fishing mortality were increased 50% from recent levels. Realizing this potential, however, would require more intensive management to ensure that desired levels of fishing mortality occurred. Choices by managers for allocating surplus harvest are a matter of policy, but concerns over maintaining predation pressure on Alewives to suppress their resurgence may be reasons to manage conservatively by electing instead to maintain a higher predator abundance. The value of information analysis revealed that the improvement in the recreational fishery warrants investment in further research on the uncertainty over by-kill catchability.

Management of exploited fish populations requires formulating and implementing harvest policies in the face of considerable uncertainty about the dynamics of the fishery being managed. Many scholars have argued that this calls for a structured, formal approach that allows explicit consideration of uncertainty and risk and identifies opportunities for research to decrease the magnitude of critical uncertainties (Walters 1986; Lane and Stephenson 1998; Jones and Bence 2009; Irwin et al. 2011). There are relatively few examples illustrating the application of such an approach to freshwater recreational fisheries (Irwin et al. 2011), and even fewer that formally estimate the value of reducing uncertainty. Value of information analysis (see Chapter 12 in Morgan and Henrion 1990; Chapter 12 in Clemen and Reilly 2001; Hansen and Jones 2008) has rarely been applied to fisheries issues (but see Frederick and Peterman 1995; Vasconcellos 2003). Here we

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report on a case study of the population of Walleye *Sander vitreus* in Saginaw Bay, Lake Huron, in which a structured, decision analysis approach was employed to consider options for the recreational Walleye harvest and to assess whether reducing uncertainty about commercial by-kill mortality would be sufficiently valuable to warrant a research investment. The approach reported here has broad relevance to the management of relatively large populations of recreationally valuable fish stocks, especially where incidental catch of the species in commercial fisheries is perceived as an issue.

The Saginaw Bay (Figure 1) stock of Walleyes is the single largest source of Walleyes in Lake Huron (Schneider and Leach 1977, 1979) and has historically sustained the largest Walleye commercial fishery in the Great Lakes outside of Lake Erie (Baldwin and Saalfeld 1962). The stock declined and its fisheries collapsed in the mid-20th century due to a series of year-class failures (Schneider 1977; Schneider and Leach 1977, 1979). After closure of the commercial Walleye fishery in the early 1970s, improving conditions and the initiation of a fingerling stocking program in the early 1980s (Schneider 1977; Fielder 2002), a recreational fishery emerged (Fielder et al. 2014). Commercial fishing continued in Saginaw Bay for other species. Management of the stock has been based principally on statewide harvest regulations on the recreational fishery including a bag limit of 5 fish/d, a minimum length limit of 381 mm, and a spring spawning closure in tributaries to the open water. Stocking was discontinued in 2006 and recovery targets were achieved in 2009 (Fielder and Thomas 2014).

Alewives *Alosa pseudoharengus* have long been documented to be an impediment to Walleye recruitment usually via predation on newly hatched fry (Kohler and Ney 1980; Wells 1980; Brandt et al. 1987; Brooking et al. 1998) and have often been recognized as obstacles to Walleye recovery in the Great Lakes (Hurley and Christie 1977; Schneider 1977; Schneider and Leach 1977; Bowlby et al. 1991). Alewife populations collapsed in Lake Huron in 2003–2004 as part of a major ecological shift in the food web and have been scarce since (Riley et al. 2008; Dunlop et al. 2010; Riley and Roseman 2013). An analysis of explanatory forces to account for the Walleye’s recovery in Saginaw Bay found the disappearance of Alewives and release from their deleterious effects to be the chief reason (Fielder et al. 2007). The future of Alewives is uncertain (Riley et al. 2008); if populations remain scarce, Walleyes are expected to sustain strong year-classes, but if
they recover Walleye recruitment is expected to decline (Fielder et al. 2007).

Based on the results from tagging studies (Fielder 2014; Hayden et al. 2014), both commercial and recreational fisheries exploit this Walleye stock inside and outside Saginaw Bay. These include commercial trap-net and gill-net target fisheries in southern Ontario waters, bycatch (retention of untargeted caught Walleyes) in a tribal gill-net fishery in 1836 Treaty waters of Lake Huron (Figure 1), recreational fisheries both in and outside the bay, and by-kill (discard of dead Walleyes) in Saginaw Bay from the remaining commercial fishery. A statistical catch-at-age (SCA) model that was developed for Saginaw Bay Walleyes (Fielder and Bence 2014) has been shown to be sensitive to uncertainty about the magnitude of the Walleye by-kill.

During 2013 we led a structured decision analysis process to assess options for recreational fishery exploitation rates that explicitly accounted for uncertainty about (1) the true amount of Walleye by-kill in a state-licensed commercial fishery, and (2) future changes in the Alewife population and its impact on Walleye recruitment. Our objective with this analysis was to offer insights to managers into the development of new management goals and objectives for this stock, specifically with regard to the extent to which the recreational fishery may exploit Walleyes while remaining within the limits of sustainability. Secondly, we address whether management would benefit from refined estimates of state-licensed commercial by-kill in Saginaw Bay by conducting a value of information analysis, thereby determining the utility of reducing one element of uncertainty about Saginaw Bay Walleye management. The decision analysis was informed by a stochastic (system) model that simulated the dynamics of the Walleye stock and its exploitation.

METHODS

Structured decision making and management input. — Our approach to the development of new management objectives, strategies, and the testing of their relative performance followed the principles of structured decision making, or SDM. Structured decision making is a form of decision analysis with emphasis on a collaborative process involving stakeholders and decision makers (Irwin et al. 2011). In our case, we engaged the fishery managers of the Michigan Department of Natural Resources (DNR) who we were seeking to assist in the development of new management objectives and strategies. Between February 2013 and February 2014, we met three times to discuss management objectives, the current state of knowledge, and critical uncertainties. Performance measures and critical thresholds were also identified to help frame a basis for the simulation modeling. While there were other potential stakeholders, Fielder and Bence (2014) found that the recreational fishery and commercial by-kill collectively constituted the majority of total fishing mortality exerted on the stock. These were the mortality sources that were under the jurisdiction of the state fishery managers. As development of the simulation model progressed, discussions included feedback on the model structure and performance, so that they appropriately captured the primary considerations of Walleye management.

Aside from the existing state-wide recreational fishery regulations, the only state-based management rule that existed was a pledge that managers would annually revisit the decision to suspend Walleye stocking and may reinstate it if Alewives ever became abundant again. Alewife abundance is estimated annually by the bottom trawling and hydroacoustic survey of the U.S. Geological Survey (USGS) Great Lakes Science Center (GLSC). Analyses have suggested that a threshold of Alewife density existed at 20 age-1 and older Alewives per hectare such that densities less than that allowed for recruitment of Walleyes (Fielder et al. 2007; Fielder and Thomas 2014). Managers maintained that Walleye fingerling stocking likely would be resumed if and when Alewife density ever increased above this threshold in the future. This suggested one obvious management feature to include in the simulation model.

Objectives and performance measures. — Managers agreed that stock sustainability was a primary objective, as was the desire to manage for the greatest recreational harvest (in numbers) possible. On the other hand, managers were also concerned that a liberal harvest or allocation of Walleyes may lead to a reduced stock. To capture the idea of sustainability being a function of spawning stock, they identified the ratio of mature female spawning stock biomass (SSB) of Walleyes relative to the unfished SSB ($\beta_0$) as a metric representing a threshold of management concern. Specifically the proportion of years across multiple simulations for any given management scenario that dropped below 20% $\beta_0$ was designated as a performance measure to address sustainability with respect to the risk of recruitment overfishing. The threshold of 20% $\beta_0$ was chosen because it was in line with peak recruitment in the stock–recruitment function and was also the same value used on Lake Erie in its Walleye management evaluation (GLFC 2005).

The criteria for the detection of Walleye recovery from the degraded state that was defined by Fielder and Baker (2004) offered some additional basis for defining performance measures for future management. The principal benchmark for defining recovery was a mean TL of age-3 Walleyes (sexes combined) at or below 110% of the state average rate at the time of survey capture, which was 425 mm (for a September collection). This benchmark was based on the belief that mean TL at age could serve as a surrogate for growth rate, which is affected by density. When size at age is above this threshold (i.e., relatively high growth rates), the system should be able to support higher densities of Walleyes. Walleye mean TL at age 3 fell below this threshold for the third consecutive year in 2009 (Fielder and Thomas 2014).
and was the primary basis for declaring the stock had recovered.

With the above objectives and considerations in mind, mean Walleye TL at age 3 (relative to a benchmark of 425 mm), SSB ratio (the proportion of years SSB fell below 20% of $\beta_0$), and recreational harvest were therefore selected as the performance measures (Table 1). Our decision analysis and value of information analysis required the combination of these measures into one overall objective function. For this purpose we used the average recreational harvest (over years for a simulation) in which harvests were set to zero for years when one or both thresholds of sustainability (Walleye TL > 425 mm, SSB below 20% $\beta_0$) were violated. Hereafter, we refer to this function as “sustainable harvest.”

Critical uncertainties.—Managers emphasized that they remain uncertain about the future trends of Alewives in Lake Huron (Table 1). Although Alewives have not recovered after 12 years following their collapse, it remained unclear whether their continuing scarcity was due to lower productivity (bottom up) or suppression via predation (top down). Recognizing that Alewives were a strong determinant of Walleye recruitment (Fielder et al. 2007), their future was included as a critical uncertainty. After reflection, the managers and researchers concluded that a reasonable characterization of expert opinion would be that on-going suppression of Alewives was three times more likely than their resurgence. We examined the sensitivity of our conclusions to this choice of probabilities by repeating the analysis at a reduced 10% and 1% likelihood of Alewife recovery.

The second critical uncertainty was whether the true value of commercial by-kill was best reflected by the lower value estimated for the period when by-kill was directly observed by MacMillan and Roth (2012) or the larger value that reflected an extrapolation to the remainder of the year (Table 1). Most managers were skeptical that the true value was as great as the extrapolated value because the measurements were limited primarily to one fisher and because of the potential for seasonal differences outside the warmer months. However, they also conceded that the true value had to be greater than that reported for the observation period alone. To capture both this range and the likelihood of an intermediate value, we evaluated three values: the lower value, the maximum value, and an intermediate value half way between the other two. A 25% probability was assigned to the two lower and upper limit values and a probability of 50% to the intermediate value (Table 1). The assumed magnitude of by-kill directly affected the estimate of by-kill catchability from Fielder and Bence (2014), where the higher estimate of by-kill resulted in a catchability that was three times greater than that for the lower estimate of by-kill. In turn, the differing estimates of by-kill catchability affected most other population metrics and parameters estimated by the SCA model. Thus, when evaluating the effect

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Uncertainties</strong></td>
<td></td>
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<tr>
<td>By-kill low</td>
<td>State-licensed by-kill catchability is correctly depicted by 21,500 Walleyes for the May–August observed period. Assigned probability of 0.25.</td>
</tr>
<tr>
<td>By-kill medium</td>
<td>State-licensed by-kill catchability is correctly depicted by an intermediate value of 61,686 Walleyes, an extrapolated value for an entire year. Assigned probability of 0.5.</td>
</tr>
<tr>
<td>By-kill high</td>
<td>State-licensed by-kill catchability is correctly depicted by 102,872 Walleyes, an extrapolated value for an entire year. Assigned probability of 0.25.</td>
</tr>
<tr>
<td>Alewives recover</td>
<td>Alewives in Lake Huron follow a logistic population trend with a finite rate of increase, $R$, of 1.5. Assigned probability of 0.25.</td>
</tr>
<tr>
<td>Alewives remain scarce</td>
<td>Alewives in Lake Huron do not recover (follow a logistic population trend with a finite rate of increase, $R$, of 0). Assigned probability of 0.75.</td>
</tr>
<tr>
<td>Scalars (multipliers) of $F_{recreational}$ intensity</td>
<td>0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 × the current $F$</td>
</tr>
<tr>
<td><strong>Harvest policies</strong></td>
<td></td>
</tr>
<tr>
<td>Sustainable harvest</td>
<td>Average recreational harvest with zeros applied for years when other performance measure thresholds are exceeded. This measure to be maximized.</td>
</tr>
<tr>
<td>% years SSB &lt; 20% $\beta_0$</td>
<td>Percentage of years with SSB below 20% unfished level ($\beta_0$).</td>
</tr>
<tr>
<td>% years mean TL (age 3) &gt; 425 mm</td>
<td>Percentage of years that mean TL of age-3 Walleyes exceeds 110% of the state average growth rate (recovery index).</td>
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of the three alternative by-kill hypotheses, the simulation model had to be reparameterized with values from the SCA model fit to the appropriate by-kill value.

We developed a decision tree to graphically depict the potential decision framework (Figure 2). Other uncertainties also existed such as the future of recruitment, fishing effort, natural mortality, and catchability in the other fisheries aside from the by-kill. These uncertainties, however, were either accounted for by incorporating stochasticity about their relationships in the simulation model (e.g., stock–recruitment function and fishery catchability) or were treated as constants (effort and natural mortality).

Candidate recreational harvest policies and decision analysis.—Recognizing that the management agency principally had the most influence over the recreational fishery, analysis was limited to those extractions. In our simulations we evaluated a range of recreational fishing mortality rates. In particular, we varied recreational fishing mortality from 10% to 400% of recent levels, hereafter referred to as fishing intensity and applied as scalars (multipliers) to the current fishing mortality rate (Table 1) and represented by the notation “F value” such that $F1.5$ means 1.5 times the current fishing mortality. Managers were not ready to identify any new state-based management options for the recreational fishery, but did want to learn about how the population would likely respond to varying amounts of recreational harvest, with an emphasis on the upper limit to exploitation that would still keep the frequency of SSB falling below 20% of $\beta_0$ low and a mean TL of age-3 Walleyes $< 425$ mm.

The sustainable harvest for each level of fishing intensity was analyzed as a decision analysis according to Figure 2.

![Decision Tree](image)

**FIGURE 2.** Decision tree reflecting alternative harvest policies for varying levels of recreational fishing mortality ($F_{rec}$ depicted as low, medium, and high). In actuality, eight different levels were evaluated.
Decision analysis principally followed the methods of Peterman and Anderson (1999). This decision analysis was premised on the uncertain states of nature regarding by-kill catchability and future Alewife trends and their probabilities described in Table 1. The combined probabilities of these alternative states of nature were the product of their individual probabilities (Table 1). Thus, to calculate the average sustainable harvest for a given level of fishing intensity, a weighted average was calculated based on the simulation results for each of the six combinations of the uncertain states of nature and using the probabilities of those states as weights.

*Value of by-kill information.*—Expected value of perfect information (EVPI) served as our metric for the evaluation of the value of information and followed the methods of Clemen and Reilly (2001). The calculation of EVPI also used sustainable harvest as the objective function. The management options evaluated were the same as previously described for the recreational fishing mortality intensities (Table 1). The expected value after knowing the true model (elimination of uncertainty) was the average of the maximum performance (maximum sustainable harvest) obtained under conditions of high, medium, or low by-kill. Maximizing separately for each by-kill condition was premised on the idea that recreational fishing mortality, \( F \), could be optimized for the given by-kill level if this were known. The EVPI was the difference between that value and maximum value of the “best” management option when the same recreational \( F \) had to be applied regardless of by-kill because the true level of by-kill was unknown. In this case, that was the greatest sustainable recreational harvest across management options (the ranges of fishing intensities simulated) within the six combinations of the uncertain states of nature.

*Simulation model and time frame.*—For each of the six combinations of the uncertain states of nature, 250 simulations were conducted for each fishing intensity scenario (including the by-kill scenarios needed for the value of information analysis). Thus, there were 1,500 simulations for each fishing scenario. Each simulation was done over a 50-year time horizon, reflecting a desire that outcomes not be dominated by initial conditions. We chose to base decision analysis as well as scenario performance on the entire 50-year time span recognizing that the result would then be a reflection of both transient dynamics as the system moved toward a stationary set of results and long-term performance. When calculating the average sustainable harvest, the results for each uncertain state of nature were weighted by the assumed probability for that state. All model coding was performed in AD Model Builder (Fournier et al. 2012; AD Model Builder 2013).

The principal state variable modeled was the number of Walleyes by year at age represented by the exponential population equation (equation 1 in Table 2; symbols for Table 2 and their descriptions are delineated in Table 3). The model was formulated and parameterized based on the fitted SCA model from Fielder and Bence (2014) and represented ages 2–13+. The gill-net fisheries were estimated as a single fishery in that original analysis, and continue to share the same catchability and selectivity here in the simulation model, but their effort was broken out. Scenarios held effort constant at the average value observed in the various fisheries since Walleye recovery was achieved (based on values from 2004 to 2011).

Stochasticity was incorporated in each of the fisheries as an error term about catchability (\( q \)) either as a white-noise process error variation or random walk deviations (for the recreational fishery) for log-scale \( q \). The recreational catchability was modeled as time-varying in the simulation model to reflect the treatment of recreational catchability by Fielder and Bence (2014), thereby preserving parameter integrity. To ensure, however, that recreational catchability did not trend to extremes from the random walk process over long scenario durations, we limited the product of the recreational \( q \) and \( e_y \) from equation (3) in Table 2 to no more than twice or no less than one half of the starting \( q \) value. We did not have an estimate of the variance for the by-kill catchability, so we applied the estimated variance from the Ontario trap-net

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**Table 2.** Equations used in the stochastic simulation model for Saginaw Bay Walleyes (see Table 3 for symbol descriptions).

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<tr>
<th>Equation</th>
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<tbody>
<tr>
<td>( N_{a+1,y+1} = N_{axy}e^{-Z_{asy}y} = N_{axy}e^{-(M_a + F_{a,y})} )</td>
<td>1</td>
</tr>
<tr>
<td>( F(f)<em>{a,y} = s_adye</em>{y} )</td>
<td>2</td>
</tr>
<tr>
<td>( e_y = e_{y-1} \delta_{y-1} ) for recreational fishery only</td>
<td>3</td>
</tr>
<tr>
<td>( F_{a,y} = \sum F(f)_{a,y} )</td>
<td>4</td>
</tr>
<tr>
<td>( \ln \left( \frac{P_a}{S_a} \right) = \ln (\alpha^a) - \beta_yS_y - \beta_yA_y + \ln (e_yW) )</td>
<td>5</td>
</tr>
<tr>
<td>( \ln \left( \frac{P_a}{S_a} \right) = \ln (\alpha^a) - \beta_yP_y - \beta_yR_yW + \ln (e_yW) )</td>
<td>6</td>
</tr>
<tr>
<td>( A_{y+1} = A_y + RA_y \left( 1 - \frac{a_y}{2} \right) )</td>
<td>7</td>
</tr>
<tr>
<td>( Con_y = \frac{\left( \frac{N_{axy}}{1,522,618} \right)N_{y(720)}}{1} )</td>
<td>8</td>
</tr>
<tr>
<td>( C_{a,y} = F_{a,y}N_{a,y} \left( 1 - e^{-Z_{asy}} \right) )</td>
<td>9</td>
</tr>
<tr>
<td>( L_{3,y} = 505 - 2.7824786610^{-9} e^{1.62134774N_{y-2}} )</td>
<td>10</td>
</tr>
</tbody>
</table>
Recruitment was incorporated two ways, from natural reproduction and from stocking. The stock–recruitment (S/R) relationship was based on a Ricker model (Ricker 1975) and followed the methods of Fielder et al. (2007), which previously analyzed the S/R relationship of Saginaw Bay Walleyes. That work concluded that the abundance of Alewives was the single best determinant of Walleye recruitment for this stock as Alewives are a formidable predator and competitor on newly hatched percid larvae. We wanted an S/R function that reflected the sensitivity to Alewife abundance as demonstrated by Fielder et al. (2007), but one that was also responsive to changes in stock density in simulations. Therefore, we developed a new S/R function for wild recruits that used both stock (represented as number of eggs produced in 100,000 increments) and density of Alewives in Lake Huron following a

<table>
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<th>Symbol</th>
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<tr>
<td>$y$</td>
<td>Year</td>
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<tr>
<td>$a$</td>
<td>Age</td>
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**Index variables**

**State and control variables**

- $N$: Number of Walleyes
- $Z$: Instantaneous total mortality
- $M$: Instantaneous natural mortality
- $F_{(f)}$: Instantaneous fishing mortality for each individual fishery
- $F$: Instantaneous total fishing mortality
- $R_W^y$: Yearly wild recruitment
- $R_H^y$: Yearly hatchery recruitment
- $S_y$: Yearly stock size (100,000 egg increments)
- $A_y$: Yearly density of Alewives
- $P_y$: Yearly number of fingerlings planted
- $Con_y$: Yearly consumption of Alewives by Walleyes, expressed on a density unit
- $C_{a,y}$: Catch (harvest) from each of the fisheries
- $L_{3,y}$: Yearly mean TL of age-3 Walleyes
- $N_{y,y-2}$: Three-prior-year running average number of Walleyes

**Structural parameters**

- $s_a$: Age-specific selectivity for each fishery
- $q$: Catchability of each fishery
- $E_y$: Year-specific fishing effort for each fishery
- $\beta_A$: Ricker stock–wild recruitment parameter for Alewife density
- $\beta_P$: Ricker stock–hatchery recruitment parameter for number planted
- $\beta_W$: Ricker stock–hatchery recruitment parameter for wild recruitment
- $\alpha^W$: Ricker stock–wild recruitment parameter
- $\alpha^H$: Ricker–hatchery recruitment parameter
- $R$: Finite rate of increase for Alewives
- $k$: Carrying capacity for Alewives
- $\hat{a}$: Attack rate by Walleyes on Alewives
- $h$: Alewife handling time by Walleyes

**Distributional parameters and associated stochastic errors**

- $\varepsilon_W^y$: Yearly wild recruitment deviation
- $\varepsilon_H^y$: Yearly hatchery recruitment deviation
- $\varepsilon_q$: Catchability deviation for each value of $q$ (from a random-walk process for the recreational fishery or as white noise drawn from a normal distribution for all others)
- $\delta_q$: Yearly deviation from random-walk process for recreational fishery catchability
multivariate Ricker S/R function as described by Chen and Irvine (2001) and Haddon (2001).

To accommodate scenarios where stocking would resume because Alewifes again became abundant, a separate recruitment function for stocked fish was needed. Our stocked fish recruitment model predicted age-2 stocked Walleye recruits from fingerling stocking numbers 2 years earlier, following a Ricker model. The model was estimated using data from 1997 to 2005, although 2003 was omitted as an outlier; that year was a transitional year in recovery with unusual dynamics stemming from the initial disappearance of Alewifes and surge in reproductive success (Fielder and Thomas 2006). The model also included a coefficient for the effect of the abundance of wild recruits (equation 6 in Table 2) due to observations of a negative relationship between survival of stocked fish and wild fish recruitment from the same year ($R^2 = 0.48$), consistent with the general concept of stocking success being inversely related to natural reproduction (Laarmann 1978; Li et al. 1996).

Total recruitment in any given year in the simulation model was then the sum of wild recruitment $R^w$ and hatchery recruitment $R^h$, if any. Total recruitment was then incorporated in the population equation (equation 1 in Table 2) as the starting numbers of Walleyes (age 2) for each cohort. The simulated recruitment for both wild and hatchery recruitment included a stochastic component based on the observed process error in the S/R models.

Because Alewife density was an important determinant of wild recruitment, and because some management rules about Walleye stocking were defined on Alewife abundance, Alewife trends had to be part of the simulation model. We developed a separate Alewife population surplus production submodel (Hilborn and Walters 1992) based on a logistic function parameterized by the finite rate of increase, or $R$, (based on the intrinsic rate of increase) and the carrying capacity $k$ (equation 7 in Table 2).

To accommodate Alewife trends as a critical uncertainty, we incorporated two alternative futures for Alewifes in Lake Huron: (1) Alewifes return to high levels observed before 2004 over a 25-year period, providing that predation is not inhibitory, and (2) Alewifes remain scarce at the levels observed during 2004–2011. Both alternatives used the aforementioned logistic function, both with different finite rates of increase ($R$); for alternative 2, $R$ was simply set to zero. We estimated $k$ from the USGS GLSC Alewife bottom-trawl data, using the highest value observed over the time series (600 fish/ha) since 1996. Data were limited to the years since 1996 to align with the same range of years used in the derivation of the wild Walleye S/R function. We then estimated a value of $R$ (for alternative 1) that would result in the Alewife population increasing to $k$ over 25 years. Generally alternative 1 yielded an Alewife resurgence that exceeded the critical threshold of 20 Alewifes/ha within the first few years of each simulation. Walleyes regularly prey on Alewifes when present (Schaeffer 1994; Fielder and Thomas 2006), so Alewife numbers were further adjusted based on Walleye consumption. Walleye consumption of Alewifes was modeled based on a type II functional response of prey to predation (equation 8 in Table 2; Holling 1959). Parameters included the number of days per year that Alewifes are exposed to Walleye predation (270 d), the area of available Alewife habitat in Lake Huron (1,522,618 ha), which is necessary to convert Alewife abundance to density, the handling time (1 Alewife/d), and the attack rate. We estimated the attack rate parameter by comparing stomach contents (consumption) to estimated Alewife density, assuming the other functional response parameters were known. Total Walleye consumption of Alewifes was subtracted from the population predicted from the logistic population equation (equation 7 in Table 2) for the same year and the resulting number of Alewifes was used for Alewife abundance in the Walleye S/R function for wild Walleye recruits (equation 5 in Table 2). Although Alewifes are treated as an uncertainty in this analysis, the feedback of Walleye consumption also afforded some degree of performance measure in that Walleye abundance, as a function of management, had some degree of influence over Alewife trends.

The area of Alewife habitat in Lake Huron was a pivotal value in the calculation of Alewife abundance, used to convert numbers of Alewifes consumed to density units (Alewifes per hectare). Our value of habitat area was derived by first limiting Alewife habitat to the main basin of the lake and then subtracting the near-shore area based on the belief that warmer near-shore waters would not constitute habitat for age-1 and older Alewifes and also subtracting the midlake area (about 1.4 million ha) based on the description of Eshenroder and Burnham-Curtis (1999) that the midlake main basin is likely largely devoid of pelagic fishes. This process left us with the conservative estimate of 1,522,618 ha of adult Alewife habitat in the main basin of Lake Huron. We note that these calculations treat the trawl-swept area values for Alewife as reflective of actual Alewife densities (see He et al. 2015, for further discussion of this assumption).

To predict fall mean TL at age 3 in the simulations, we quantified the relationship between Walleye abundance (all ages combined) and the observed September mean TL for age-3 fish following the methods of Shuter and Koonce (1977). We regressed the log of the difference between the mean TL at age 3 and the largest observed length for that age against the log of the 3-year running average of estimated population abundance (age-2+ fish) for the first 3 years of the cohort. Length data were taken from the annual Saginaw Bay Fish Community Survey (Fielder and Thomas 2014) for 2003–2011, and the population values were from the SCA model projection (ages combined) from Fielder and Bence (2014) for the same years. Data were also available for years 1989–2002, but were not included in our analysis because they did not represent the growth dynamics of the recovered Walleye population. The resulting relationship
exhibited an $R^2$ of 0.70 and was significant at $P = 0.005$ ($F$-test). The predicted mean TL at age 3 was the observed maximum less the predicted value according to equation 10 in Table 2.

RESULTS

Recreational Fishery Performance

The greatest sustainable harvest was achieved at recreational $F_{1.5}$ (approximately 50% increase in the recreational fishing mortality) (Table 4). Although sustainability was taken into account, this level of fishery expansion ($F_{1.5}$) still exceeded the sustainability thresholds in some years. The proportion of years (with Alewives remaining scarce), for example, that SSB fell below 20% $\beta_0$ was 8% for $F_{1.5}$, while only 1% at $F_{1.0}$ (Figure 3E). Similarly, the proportion of years that the mean TL of age-3 Walleyes exceeded the target rose from 21% ($F_{1.0}$) to 26% ($F_{1.5}$) (Figure 3D). Proportional increases were even greater for scenarios that accounted for the recovery of Alewives (Figure 3). By defining a composite performance metric, the decision analysis accounted for these tradeoffs to yield an overall preferred option in light of the uncertainty and stochasticity, suggesting that these slight increases in risk were an acceptable tradeoff up to $F_{1.5}$.

When Alewives remained scarce, the mean Walleye SSB and mean TL of age-3 Walleyes (averaged within years across the 250 simulations) fell within their thresholds of sustainability up to a fishing intensity as great as $F_{3.0}$ for SSB and $F_{2.0}$ for mean TL of age-3 Walleyes (Figure 4A, B). These means, however, conceal the range of performance and exceedance of the sustainability criteria in some years, even at lower fishing intensities, and thus the lesser value of just $F_{1.5}$ indicated by the decision analysis as the preferred option. The performance of the recreational fishery, however, varied considerably with the uncertainty of future Alewife trends (Figures 3, 4). Walleye predation did not inhibit Alewife recovery in any scenario parameterized with the fitted finite rate of increase in the Alewife sub-model. In every instance, the hypothetical recovery and presence of Alewives reduced the sustainable intensity of the recreational fishery. To maintain the mean SSB above 20% $\beta_0$, fishing intensity would have to be reduced to at least $F_{0.5}$ (Figure 4C), and no degree of reduction in fishing intensity would prevent the mean TL of age-3 Walleyes from exceeding the target (Figure 4D). In spite of this, repeating the decision analysis at a lower probability of Alewife recovery (10% and 1% likelihood instead of 25% likelihood) did not change the outcome of the decision analysis.

Predictably the Walleye population size decreased with increasing fishing intensity across both possible Alewife futures (Figure 3C). Average recreational harvest itself continued to increase up to $F_{3.0}$, but gains in harvest beyond $F_{1.5}$ were marginal, with $F_{1.5}$ as 86% of the maximum. The corresponding upper limit of total annual mortality ($A$) for an $F_{1.5}$ was 0.41 (Figure 3F). By contrast, in the presence of Alewives, average SSB fell below 20% $\beta_0$ for $F_{1.0}$ (Figure 4C) corresponding to a total annual mortality of about 0.35 (Figure 3F). Of the two performance measures of sustainability, the ratio of SSB to unfished SSB appears to be somewhat more forgiving to the effect of harvest than the mean TL at age 3 threshold. The growth rate-based criterion reaches its threshold slightly before the SSB-based criterion does. For example, average SSB was at 20% $\beta_0$ at $F_{3.0}$ (Figure 4A), but mean TL at age 3 exceeded its threshold value at this $F$ (Figure 4B). Generally the two metrics agree, however. The sustainable maximum fishing intensity of $F_{1.5}$

<table>
<thead>
<tr>
<th>Recreational $F$ multiplier</th>
<th>Low by-kill rate and Alewives scarce</th>
<th>Low by-kill rate and Alewives recover</th>
<th>Medium by-kill rate and Alewives scarce</th>
<th>Medium by-kill rate and Alewives recover</th>
<th>High by-kill rate and Alewives scarce</th>
<th>High by-kill rate and Alewives recover</th>
<th>Expected value</th>
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</thead>
<tbody>
<tr>
<td>Joint probability</td>
<td>0.1875</td>
<td>0.0625</td>
<td>0.3750</td>
<td>0.1250</td>
<td>0.1875</td>
<td>0.0625</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>4.896</td>
<td>18.335</td>
<td>3.631</td>
<td>14.841</td>
<td>3.120</td>
<td>12.817</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>23.253</td>
<td>53.722</td>
<td>17.806</td>
<td>49.629</td>
<td>15.420</td>
<td>46.192</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>45.173</td>
<td>50.609</td>
<td>34.929</td>
<td>45.058</td>
<td>30.317</td>
<td>43.422</td>
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<tr>
<td></td>
<td>1.5</td>
<td>52.922</td>
<td>46.431</td>
<td>46.054</td>
<td>41.596</td>
<td>43.355</td>
<td>41.435</td>
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<tr>
<td></td>
<td>2.0</td>
<td>49.799</td>
<td>35.397</td>
<td>44.650</td>
<td>33.248</td>
<td>45.952</td>
<td>36.124</td>
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<tr>
<td></td>
<td>2.5</td>
<td>45.056</td>
<td>28.858</td>
<td>41.033</td>
<td>34.929</td>
<td>41.847</td>
<td>27.480</td>
</tr>
</tbody>
</table>
from the decision analysis approximately corresponds to an instantaneous recreational fishing mortality $F$ of about 0.13 of the fully selected ages.

### Value of By-Kill Information

The analysis of perfect information indicated a positive gain to the fishery in terms of sustainable harvest from knowing the true by-kill magnitude (Table 5). Because the unit for this values was the sustainable recreational harvest, derived by assigning zero to years when the sustainability criteria was exceeded, the magnitude of the value of the perfect information is not a representation of the actual gains in the numbers of Walleyes that would be harvested as a result from eliminating this uncertainty. As a proportion of the total expected value of the best decision, however, the EVPI amounts to about 6.7% as much. One might conclude then that the value of information is equivalent to about 6.7% of value of the recreational fishery.

Testing sensitivity of the value of information to a lesser probability of Alewife recovery (10% and 1% likelihood verses 25% likelihood of recovery) did reduce the EVPI from 6.7% of the fishery value to 5.2% and 4.3%, respectively.

### DISCUSSION

The decision analysis indicated that the Saginaw Bay Walleye population is capable of sustaining greater recreational harvest. The choice of whether to adopt management options that allow for increased harvest within limits of sustainability is partly a consideration of how conservative managers want to be. Walleye recovery in Lake Erie led to a management practice of annually determining the harvestable surplus and making allocation choices among the various fisheries and jurisdictions (GLFC 2005). In many years, this resulted in more liberal recreational harvest regulations than...
FIGURE 4. Mean Walleye spawning stock biomass (SSB) and mean TL of age-3 Walleyes and critical thresholds of management importance across 50-year forecasts of seven recreational fishing intensity management options, across two versions of future Alewife trends: (A, B) without Alewife recovery, and (C, D) with Alewife recovery.
the customary statewide regulations enforced by Michigan DNR. The Lake Erie approach was considered defensible because the regulations were regularly revisited and adjusted based on updated management information and model projections. Similarly, a decision to manage for a Saginaw Bay Walleye fishery closer to the limits of sustainability might necessitate more frequent stock assessments and the willingness to modify harvest regulations as needed based on the assessments of the risks to sustainability.

While not detailed in this analysis, it was clear from the simulations that population effects from one fishery in turn affected the other Walleye fisheries around the lake. The impact of increased allocation to recreational fisheries in Michigan on other Lake Huron Walleye fisheries was not part of the decision analysis. Any increased mortality of Walleyes (via increased allocation) will reduce the overall population and cause some degree of contraction in the other fisheries unless their fishing effort increased. Similarly, increased harvest from those fisheries would also have impacts on the Michigan fisheries. This underscores the need to begin to coordinate management of all the fisheries that exploit the Saginaw Bay stock of Walleyes in Lake Huron, if necessary by working under the aegis of the Great Lakes Fishery Commission as is done in Lake Erie (GLFC 2005). Increased exploitation of Walleyes, as a management option, has consequences beyond sustainability questions that need to be considered. The ongoing uncertainty regarding Alewife population recovery means that managers should be cautious about allocating additional surplus Walleyes as long as their role as a predator controlling Alewife recovery is not well understood.

The true magnitude of the commercial by-kill was one critical uncertainty identified at the outset of this analysis.

Fielder et al. (2014) estimated that the value of the recreational fishery of Saginaw Bay to Michigan in terms of economic activity generated was US$33 million per year between 2008 and 2010. As a follow up to MacMillan and Roth (2012), an expanded study of the Walleye commercial by-kill in Lake Huron was proposed, estimated to cost $496,000 (B. Roth, Michigan State University, personal communication). Amortized over our 50-year simulation period, the study cost would be $9,920/year. This is well below the EVPI of 5.5% ($2,211,000) of the annual recreational fishery value of $33 million total in economic activity (Fielder et al. 2014). From this we conclude that further research to eliminate or reduce the uncertainty over the by-kill catchability magnitude is justified. In addition to potential fishery gains from optimizing management in light of this added information, the Saginaw Bay Walleye SCA model would also be improved by better by-kill information.

By comparison with the by-kill question, the uncertainty over Alewife futures is another matter. While not the subject of its own value of information analysis, due to the complexity or inability to reduce that uncertainty, it unquestionably is a profound driver of all our simulations. Fielder et al. (2007) concluded that Alewife effects dwarf all other determinants of Walleye recruitment in Saginaw Bay. For our wild Walleye S/R function, we included stock size as we wanted that feedback from population trends, but any stock size effect seems to be vastly overshadowed by trends in Alewife abundance. Of the two sustainability-based performance measures, the maintenance of the SSB at or above 20% $\beta_0$ might be less consequential.

Our decision and value of information analysis was not highly sensitive to the probability of Alewife recovery, although the lower probability of 10% and 1% (versus 25% probability of Alewife recovery) did reduce the EVPI of by-kill catchability from 6.7% of the fishery value to 5.2% and 4.3%, respectively. This suggests that as the likelihood of Alewife recovery decreases the benefit of further by-kill research becomes less. The low sensitivity of the probability of Alewife recovery and the profound effects if Alewives do recover, as indicated in Figures 3 and 4, are not contradictory. The probability of recovery is a variable in testing management options, and a reduction to 10% or 1% probability was not consequential, but the effects of Alewives, if in fact they do recover, is a function of their influence on recruitment of Walleyes, which would be large.

Managers wanted to be able to evaluate the tradeoffs of management options partly on the basis of effects of Walleye predation on Alewives, and how that in turn modulated the effect of Alewives on Walleye recruitment. While these interactions were incorporated into our model and consequently the decision and value of information analysis, we do not feel we fully captured that complex dynamic. The abundance of Alewives in our model was a function of the expansion of Alewife densities across the total Alewife habitat of the lake.

### TABLE 5. Analysis of the expected value of perfect by-kill information (EVPI).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected value of “best” decision (maximum expected value from Table 4)</td>
<td>46,013</td>
</tr>
<tr>
<td>EVPI calculation:</td>
<td></td>
</tr>
<tr>
<td>Expected value if we know high by-kill model was true</td>
<td>46,072</td>
</tr>
<tr>
<td>Expected value if we know medium by-kill model was true</td>
<td>47,842</td>
</tr>
<tr>
<td>Expected value if we know low by-kill model was true</td>
<td>53,322</td>
</tr>
<tr>
<td>Expected value after knowing true by-kill model</td>
<td>49,079</td>
</tr>
<tr>
<td>EVPI</td>
<td>3,065</td>
</tr>
<tr>
<td>% EVPI of total fishery</td>
<td>6.7%</td>
</tr>
</tbody>
</table>
We rationalized a minimal value (1.5 million ha) in an attempt to maximize our model’s sensitivity to this dynamic, while others (He et al. 2015) have used a much greater estimate of Alewife habitat area of 3.2 million ha. Even if the Alewife density were underestimated, Walleye predation did not limit Alewife recovery in our simulations, so this was not a very consequential assumption to our analysis. We recognize that the ability of Alewives to be suppressed by predation is a function of the suite of all predators in Lake Huron. He et al. (2015) estimated that Walleyes in Lake Huron constituted about 10% of the collective consumption demand on available prey forms in the main basin since 2003. Very possibly Alewives cannot recover in the face of predation across all predators, but such an analysis was beyond the scope of this study.

Our simulation analysis was limited to the Saginaw Bay Walleye stock. Some Lake Erie Walleyes migrate to Lake Huron and contribute to the fisheries of that lake (Thomas and Haas 2005; Wang et al. 2007). Fielder and Bence (2014) estimated that Lake Erie fish averaged 8% as much as the Saginaw Bay stock fish did in their contributions to Lake Huron fisheries during 1986–2011, but averaged only 2.8% since 2004. Furthermore, since 2011 few tagged Walleyes from Lake Erie have been recovered in Lake Huron (Lake Erie Walleye Task Group of the Great Lakes Fishery Commission, unpublished data). If there were to be greater future contributions by Lake Erie fish, likely the realized fishery response would be slightly greater than the predictions in our analysis to reflect the supplementary catch. Predatory effects of Lake Erie Walleyes on Alewives might be another effect, but given the difficulty of documenting any limiting effect on Alewives by Saginaw Bay fish alone, we hypothesize that Lake Erie predation effects would be negligible.

Management of most inland recreational fisheries will likely continue to rely on regional harvest regulations, but in those instances when stakeholders and agencies need or expect more, the approach described here may serve as a basis to develop the required objectives and evaluate strategies. We concur with Peterman and Peters (1998) that decision analysis is highly appropriate for complex ecological applications for accounting for uncertainty and affording the ability to objectively rank candidate management actions. This approach, however, does require system-specific information and is most easily applied in data-rich environments; but if the value of the fishery is great enough, the investment in stock assessment may have already occurred. Using the principles of SDM to guide the decision analysis can help bring a more defensible process to management, ensuring the analysis reflects the best information available, and develop cooperation and ownership among stakeholders. For the Walleye population in Saginaw Bay this analysis offers a significant step forward. Further advancement will depend on more deliberate and refined objective setting by fishery managers and other stakeholders, as the agency seeks to craft harvest regulations that reflect the policies that appear to have the best performance characteristics.

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REFERENCES


