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Jonathon Beard
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September 28, 2017

Dear Jonathon,

The final report for Project 2012.1230 entitled *Evaluating Movements of Chinook Salmon Between Lakes Michigan and Huron* is attached. I am pleased to say that we accomplished our objectives, helped managers put our findings into practice, and came in under budget.

The objectives of this project were to estimate the extent of inter-lake movement of Chinook Salmon between lakes Huron and Michigan and to incorporate these movements into analytical tools, such as statistical catch-at-age (SCA) and predator-prey models currently in use to help managers determine how many fish to stock. Our hypothesis was that the movement rate of Chinook Salmon from Lake Huron to Lake Michigan had increased from 1990 to 2014 and that this movement had contributed to an increase in abundance of salmon in Lake Michigan and a decrease in Lake Huron. Accounting for these movements would be relevant to determining stocking rates of Chinook Salmon in both lakes.

The major tasks in this study were to: 1) acquire and organize data; 2) conduct analyses of the data to test the hypothesis and measure rates of movement; 3) incorporate the movement results into analytical tools in use to assess Chinook Salmon populations and to help determine their stocking rates; and 4) use the two-lake models to test a range of Chinook Salmon stocking rates for managers to consider.

We described the work done on task 1 in our first progress report (Clark and Bence 2013) and subsequently in the “Methods” sections of our two publications (Clark et al. 2016 and 2017).

We conducted multiple analyses to accomplish task 2. Our initial, exploratory analyses were described in progress our reports. First, we developed two-lake matrices showing regions (statistical districts) of release and recovery for all CWT Chinook Salmon from 1993–2010 (Clark and Bence 2013). These matrices provided a broad overview of movements between lakes and lake regions. Second, we made preliminary estimates of the source composition of Chinook Salmon in the Lake Michigan fishery (Clark and Bence 2014a). This analysis suggested that Lake Huron-origin fish could contribute as much as 18% of the Chinook Salmon harvested in Lake Michigan. Third, we used generalized linear models (GLMs) to help describe changes in capture locations and to help determine suitability of various components of the CWT database for evaluating Chinook Salmon movements (Clark and Bence 2014b). This analysis showed that year, season, lake region, and source of recoveries were important explanatory factors that should be considered when analyzing tag recoveries.

Finally, we described more rigorous analyses in two articles published in the peer-reviewed *North American Journal of Fisheries Management* that showed our hypothesis should be accepted. The first article (Clark et al. 2016) demonstrated that the major trends observed in the past 20 years in the catch per effort (CPE) of Chinook Salmon were statistically significant ($P = 0.05$). In particular, we showed that CPE increased significantly in Lake Michigan and decreased significantly in Lake Huron in the early 2000s. We suggested that inter-lake movement was probably a contributing factor in these changes. Analyses in the second article (Clark et al. 2017) confirmed that our suggestion was correct by showing direct evidence of changes in inter-lake movements based on changes in capture locations of CWT Chinook Salmon in both lakes. In addition, we showed that these changes were associated with changes in the relative abundances of Alewives between lakes.

To accomplish task 3, we worked with members of the Lake Michigan Salmonid Working Group who were responsible for keeping and running the quantitative models to help make stocking decisions. The supplement to this final report (Clark and Bence 2017a) describes how we incorporated inter-lake movements into the models. We used these models to estimate the abundances of three subpopulations of Chinook Salmon in Lake Michigan: the subpopulation produced by fish stocked in Lake Michigan, the subpopulation produced by fish stocked in and migrating from Lake Huron, and the subpopulation produced by fish reproducing naturally in both lakes. We also developed a predator demand simulator to estimate the amount of forage consumed by these subpopulations, as well as, populations of other species of trout and salmon stocked into the lake (Clark and Bence 2017b). The simulator allows one to evaluate the relative effect of increasing or decreasing stocking rates of each type of predator on the forage base.

Finally, to accomplish task 4, we used the models to predict the effects of a range of stocking rates (Clark and Bence 2017a). We evaluated stocking rates based on their effect on the predator-prey ratio in Lake Michigan. Given the predator-prey ratio of 0.05 that managers were using as a target for Lake Michigan, we estimated that the optimal stocking rate was 1.2–1.5 million fingerlings per year. Also, given that over 90% of the fish stocked into northern Lake Huron were travelling to Lake Michigan to feed, the distribution of these fish across stocking sites in Lake Michigan and northern Lake Huron would have little effect on the predator-prey ratio.

Sincerely,

Richard D. Clark, Jr.
Adjunct Professor and Visiting Scientist

cc: Dr. James Bence

References cited in cover letter

Clark, R. D., Jr., and J. R. Bence. 2013. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2013 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2014a. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. January 15, 2014 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2014b. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2014 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr., J. R. Bence, R. M. Claramunt, J. E. Johnson, D. Gonder, N. D. Legler, S. R. Robillard, and B. D. Dickinson. 2016. A spatially explicit assessment of changes in Chinook Salmon fisheries in lakes Michigan and Huron from 1986 to 2011. North American Journal of Fisheries Management 36:1068-1083.

Clark, R. D., Jr. and J. R. Bence. 2017a. The effects of inter-lake movements on Chinook Salmon abundances in lakes Michigan and Huron. Supplement to Final Report GLFT 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2017b. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. February 28, 2017. Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. J. R. Bence, R. M Claramunt, J. A. Clevenger, M. S. Kornis, C. R. Bronte, C. P. Madenjian and E. F. Roseman. 2017. Changes in movements of Chinook Salmon between lakes Huron and Michigan after Alewife population collapse. North American Journal of Fisheries Management (in press).

Final Report

Project Title:	Evaluating Movement of Chinook Salmon Between Lakes Michigan and Huron
GLFT Project Number:	2012.1230
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Sponsoring Organization:	Quantitative Fisheries Center Department of Fisheries and Wildlife Michigan State University 375 Wilson Road, Room 101 East Lansing, MI 48824
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Key Search Words:	Chinook Salmon, Alewives, Species Interactions, Movement Behavior, Fisheries Management, Population Dynamics, Tags and Tagging

Abstract

The purpose of this project was to estimate the extent of inter-lake movement of Chinook Salmon *Oncorhynchus tshawytscha* between lakes Huron and Michigan and to incorporate these movements into analytical tools, such as statistical catch-at-age (SCA) and predator-prey models currently in use to help managers determine how many fish to stock. Our hypothesis was that the movement rate of Chinook Salmon from Lake Huron to Lake Michigan had increased from 1990 to 2014 and that this movement had contributed to an increase in abundance of salmon in Lake Michigan and a decrease in Lake Huron. Accounting for these movements would be relevant to determining stocking rates of Chinook Salmon in both lakes. We acquired data from preexisting datasets from collaborating agencies, including data on: 1) tag and recovery locations of coded-wire-tagged (CWT) Chinook Salmon; 2) recreational fishing catch and effort for regions within each lake; 3) numbers and locations of Chinook Salmon stocked; and 3) indices of yearling-and-older (YAO) Alewife *Alosa pseudoharengus* abundance by lake. We organized these data into spatial (lakes and lake subregions) and temporal (years and seasons) strata for combined analyses. First, we showed that catch per effort (CPE) of Chinook Salmon, an index of population abundance, had increased in Lake Michigan over the same time period that CPE had decreased in Lake Huron. While many factors could have been involved in these changes, we concluded that inter-lake movement of Chinook Salmon from Huron to Michigan was likely a contributing factor. Second, to provide direct, physical evidence of movement, we analyzed the pattern of capture locations of CWT Chinook Salmon released in each lake. Also, we used indices of abundance of Alewife populations in the two lakes to determine if any changes in movements we found were correlated with changes in Alewife abundance. Alewife populations collapsed in Lake Huron in 2003, but remained comparatively abundant in Lake Michigan. Alewives are the preferred food of Chinook Salmon in the Laurentian Great Lakes, so changes in their relative abundances between lakes would provide a biological motive for salmon to change their movement patterns. We analyzed the pattern of tag recoveries before, during, and after Alewife collapse (1993–2014). We contrasted the patterns for salmon released at Swan River in northern Lake Huron and Medusa Creek in northern Lake Michigan. These two sites were equidistant from the boundary between lakes and had the most extensive and complete CWT data. We examined recovery patterns during April–July, when salmon were primarily occupied by feeding, and August–October, when salmon were primarily occupied by spawning. We found evidence that the Swan River salmon shifted their feeding location from Lake Huron to Lake Michigan after the collapse. Over years, proportions of Swan River salmon captured in Lake Michigan increased in correspondence with the decline in Alewives in Lake Huron. Mean proportions of Swan River salmon captured in Lake Michigan were 0.13 (SD, 0.14) before (1993–1997) and 0.82 (SD, 0.22) after (2008–2014) and were significantly different (Pairwise permutation test: Z=2.80, P=0.01). In contrast, proportions of Medusa Creek salmon captured in Lake Michigan did not change. Means were 0.98 (SD, 0.05) before and 0.99 (SD, 0.01) after. The mean distance to the center of the coastal distribution of Swan River salmon shifted 357 km (SD, 169) during April–July, from central Lake Huron before to central Lake Michigan after. In contrast, the coastal distributions of salmon during August–October were centered on the release sites, which suggested that salmon returned to release sites to spawn regardless of their feeding locations. This shift in inter-lake movement during April–July was equivalent to increasing the stocking rate within Lake Michigan by 30%. Based on these findings, managers should consider coordinating Chinook Salmon stocking policies for these two lakes. Third, to assist with coordination, we developed two-lake Chinook Salmon SCAs and management projection models in cooperation with the Lake Michigan Salmonid Working Group. These models

incorporated our estimates of inter-lake movements and allowed assessment of the contribution and impact of Chinook Salmon from three sources: 1) hatchery fish stocked into Lake Michigan; 2) hatchery fish stocked into Lake Huron; and 3) wild fish reproduced in both lakes. These models showed that the abundance of wild and Lake Huron-stocked salmon increased in Lake Michigan from 1990 to 2015. In 2014–2015, the subpopulation of salmon derived from fish stocked directly into Lake Michigan was only 36% of the total lake-wide population. Eleven percent of the total population was derived from fish stocked into Lake Huron, and 53% were wild fish derived from natural reproduction in both lakes. We concluded that a good management approach would be to combine all of Lake Michigan and northern Lake Huron (MH1 and MH2) into a single Chinook Salmon management unit. Finally, we tested a range of Chinook Salmon stocking rates using the two-lake models. We estimated that the optimal stocking rate for the suggested Chinook Salmon management unit was from 1.2–1.5 million fingerlings per year, given the current movement patterns, mortality rates, and levels of natural reproduction. This optimum was based on achieving a target predator-prey ratio of 0.05, which was the value used by managers to help guide stocking rates. Changing the distribution of stocked fish between lakes would have little effect on the optimal stocking rate, because movement patterns and survival rates of salmon stocked into northern Lake Huron were similar to salmon stocked directly into Lake Michigan.

Background/Overview

1. Big changes have occurred in the distribution and abundance of Chinook Salmon *Oncorhynchus tshawytscha* throughout lakes Michigan and Huron in the past 20 years (Clark et al. 2016a and 2017). These included steep declines in abundances in some regions of the lakes, even when stocking rates were maintained at high levels. We proposed to describe and measure a potentially important reason for these changes; inter-lake movements of fish. We suspected that some changes in regional abundances of Chinook Salmon were related to changes in abundance and distribution of their favorite prey, Alewives *Alosa pseudoharengus*. Alewife populations collapsed in Lake Huron in 2003, but remained comparatively abundant in Lake Michigan. Following the collapse of Alewives, Chinook Salmon in the southern and western parts of Lake Huron became emaciated and their populations also collapsed. However, salmon populations remain physically healthy and seasonally abundant in northern and eastern Lake Huron. Even though lakes Huron and Michigan are connected by the Straits of Mackinaw, a broad, deep channel with no barriers to fish passage, studies of tagged salmon before the Alewife collapse (1990s) showed that the inter-lake movement of Chinook Salmon was minimal (Adlerstein et al. 2007 and 2008). These results supported the prevailing management structures which were designed to organize and coordinate Chinook Salmon management by individual lakes. For example, management within the state of Michigan was coordinated by Lake Basin Teams and international and interstate management across the lakes was coordinated by Lake Committees through the Great Lakes Fishery Commission (GLFC). Thus, Chinook Salmon fishing regulations and stocking policies were developed separately by lake, with minimal attention to inter-lake coordination.

Nonetheless, we suspected that the previously established movement patterns could have changed as a result of the change in relative abundances of Alewives between lakes. We hypothesized that Chinook Salmon in northern and western Lake Huron persisted at comparatively high levels because they had changed their feeding locations from Lake Huron to Lake Michigan to take advantage of the more abundant Alewives in Lake Michigan. Accounting for these movements would be relevant to determining stocking rates of Chinook Salmon in both lakes. The purpose of this project was to examine the inter-lake movements, population dynamics, and management of Chinook Salmon from a two-lake perspective for lakes Huron and Michigan. Specifically, we proposed to estimate the extent of inter-lake movements of Chinook Salmon and to incorporate the movements into the analytical tools that managers were using to help determine how many fish to stock.

2. We made one change in the work performed in comparison to the original work plan. During the course of the study, managers changed the analytical tools they were using to help develop and monitor stocking policies. They began using the Predator-Prey Ratio Analysis (PPRA) in 2014 (Jones et al. 2014; Lake Michigan Salmonid Working Group 2017). Therefore, we incorporated inter-lake movements into the PPRA, instead of the Decision Analysis (DA) model (Jones et al. 2008) that we had mentioned in our original work plan. This change was reported previously in a progress report (Clark and Bence 2016b).

Outcomes

3. We estimated inter-lake movement rates over a 21-year period (1993–2014) and related the changes that occurred to the relative abundances of Alewives in lakes Huron and Michigan. We confirmed that Chinook Salmon originating in northern Lake Huron had changed their movement patterns over time. The mean distance to the center of the coastal distribution of salmon released at

Swan River a site in Lake Huron shifted 357 km (SD, 169) during April–July, from central Lake Huron in 1993–1997 to central Lake Michigan in 2008–2014. Changes in coastal distribution for Chinook Salmon have not been documented previously. Studies in the Pacific Ocean have shown that different Chinook Salmon stocks maintained consistent coastal distributions through time even when environmental factors, such as food distribution and water temperatures, changed substantially. Also, when tagged salmon from stocks with different genetic backgrounds were released at the same site, they displayed different coastal distributions. This led to the hypothesis that coastal distributions were controlled more by genetic differences in the stocks than by environmental factors. However, we showed that changes in environmental factors (food distribution) could be more important than originally thought. We showed that they can cause large and persistent changes in coastal distributions even for stocks released at the same site and from the same genetic background. In addition, we described coastal distributions and minimum distances travelled for Chinook Salmon stocks in lakes Huron and Michigan using similar methods to those used previously for stocks in the Pacific Ocean. This allowed direct comparisons of Chinook Salmon movement patterns between Great Lakes stocks and Pacific Ocean stocks. We showed that movement patterns were similar in both places in terms of the overall sizes of the coastal distributions and the minimum distances travelled by fish of different ages.

4. This project did not directly contribute to the education and advancement of graduate or undergraduate students focused on the Great Lakes Fishery.

5. We regularly discussed potential approaches for analyzing data and communicated the progress of our work with members the Lake Michigan Salmonid Working Group (LMSWG) and the Lake Michigan Technical Committee (LMTC). We also attended several Lake Committee Meetings for both Lake Michigan and Lake Huron. We shared all the datasets that we produced with those groups and helped them incorporate the data into models and analyses they were using to analyze Chinook Salmon stocking rates. These efforts helped us to build new relationships with biologists and managers from all around lakes Michigan and Huron.

Randy Claramunt of Michigan Department of Natural Resources (MDNR) contributed to our project and was identified as a collaborator in our initial proposal, but we also added other important collaborators during the course of study. These included Jim Johnson and John Clevenger of MDNR, Dave Gonder of Ontario Ministry of Natural Resources (OMNR), Nick Legler of Wisconsin Department of Natural Resources (WDNR), Steve Robillard of Illinois Department of Natural Resources (ILDNR), Ben Dickenson of Indiana Department of Natural Resources (INDNR), Matt Kornis and Chuck Bronte of U.S. Fish and Wildlife Service (USFWS), and Chuck Madenjian and Ed Roseman of U.S. Geological Survey (USGS). Most of these collaborators were members of the Lake Michigan Salmonid Working Group as organized by the GLFC. The contributions of all our collaborators were reflected in the success of our publications (Clark et al. 2016a and 2017), which they coauthored.

6. Our findings that large numbers of Chinook Salmon were entering Lake Michigan from Lake Huron had important action implications that were immediately put into practice. This was due largely to the fact that we worked directly with managers throughout the project, and we built the inter-lake movements into their existing management models at their request. The Lake Michigan Salmonid Working Group used our inter-lake movement rates to: 1) recalculate estimates of the percent of the Chinook Salmon population that was wild and naturally produced; 2) estimate the abundance of Chinook Salmon feeding on the forage base of Lake Michigan; and 3) estimate the Chinook Salmon-Alewife predator-prey ratio for Lake Michigan. See Clark et al. (2017) for details. In addition, our models, modified to account for inter-lake movements, have been used to

help estimate Chinook Salmon Stocking rates (Lake Michigan Salmonid Working Group 2017). Also, MDNR managers plan to continue placing CWTs into Chinook Salmon released at Swan River in northern Lake Huron to monitor future rates of inter-lake movement. Stocking rates of Chinook Salmon were reduced in 2017 for Lake Michigan. One of the reasons for the cut was our findings that the salmon moving in from Lake Huron in recent years were equivalent to stocking up to 30% more fish directly into Lake Michigan.

7. The most important benefit from our project was the improvement in the ability of managers to evaluate stocking rates of Chinook Salmon in Lake Michigan. We provided estimates of numbers of stocked salmon that were travelling into the lake from Lake Huron so that they could be accounted for in the evaluations, and we helped improve the estimates of the abundances of wild fish by including stocked Lake Huron fish into percent wild estimates.

Related Efforts

8. This project was part of a broader effort to improve the methods for evaluating trout and salmon stocking rates for Lake Michigan. That effort began with a critical review of the current methods of evaluating stocking policies (Clark 2012). One of the things suggested in the review was that Lake Michigan managers might be able to learn from the collapse of Alewives and Chinook Salmon in Lake Huron. This suggestion led to a series of workshops in which biologists and managers from lakes Huron and Michigan got together to discuss Chinook Salmon and Alewife issues. These workshops were facilitated by Clark and Michael Jones of the Quantitative Fisheries Center and John Dettmers of the GLFC. They were funded by the GLFC. The workshops led to the development of the PPRA (Jones et al. 2014), which includes a series of models that estimates Chinook Salmon and Alewife abundances and biomasses with catch-at-age analyses, then computes the Chinook Salmon-Alewife biomass ratio. The biomass of Chinook Salmon cannot be estimated properly without estimates of the numbers of stocked fish coming in from Lake Huron. This project provided those estimates. Clark and Jones are also working on a related project funded by the GLFT (Project 2014.1446) that will help identify the origins of wild Chinook Salmon in Lake Michigan, including those from Lake Huron tributaries.

9. This work inspired a project to better assess Lake Michigan Lake Trout populations (GLFT Project 2017.1721). Estimates of the abundance and biomass of Lake Trout are also used in the PPRA and need to be improved.

Communication/Publication of Findings

10. We described our findings in eight progress reports submitted to the Great Lakes Fishery Trust (GLFT) (Clark and Bence 2013, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, and 2017a), two papers published in the peer-reviewed *North American Journal of Fisheries Management* (Clark et al. 2016 and 2017), and four oral presentations at scientific conferences (Clark 2013; Clark et al. 2014, 2016b; Reilly et al. 2015).

11. We made a significant effort to keep other researchers, managers, and anglers appraised of our progress during the course of the study. We attended and discussed our work at the Lake Michigan Technical Committee (LMTC) and Salmonid Working Group (LMSWG) meetings sponsored by the Great Lakes Fishery Commission (GLFC) in winter and summer of 2013, 2014, 2015, and 2016. And finally, we presented our work at several meetings sponsored by other

fisheries agencies to communicate our findings to their staffs and constituent groups (Clark 2016a and 2016b; Clark 2017).

12. We previously uploaded the progress reports for the project. We uploaded the two peer-reviewed publications separate from this final report. We attached supplemental report (Clark and Bence 2017b) to this final report. We do not request that GLFT restrict access to these materials.

13. **Manuscripts.** A cover memo was uploaded to website to identify which of the project objectives were satisfied by the publications and reports.

14. **Compilation reports.** We attached a supplimental report (Clark and Bence 2017b) to this document to describe the final objective of our work, which was to incorporate the inter-lake movement rates into the quantitative tools used by managers and to the use those tools to evaluate a range of stocking options.

Discussion

See Discussion sections of our publications (Clark et al. 2016 and 2017) and Supplement to Final Report report (Clark and Bence 2017b).

References

Adlerstein, S. A., E. S. Rutherford, D. Clapp, J. A. Clevenger, and J. E. Johnson. 2007. Estimating seasonal movements of Chinook salmon in Lake Huron from efficiency analysis of coded wire tag recoveries in recreational fisheries. North American Journal of Fisheries Management 27(3):792-803.

Adlerstein, S. A., E. S. Rutherford, R. M. Claramunt, D. F. Clapp, and J. A. Clevenger. 2008. Seasonal movements of Chinook salmon in Lake Michigan based on tag recoveries from recreational fisheries and catch rates in gill-net assessments. Transactions of the American Fisheries Society 137:736-750.

Clark, R. D., Jr. 2012. Review of the Lake Michigan Red Flags Analysis. Quantitative Fisheries Center Technical Report T2012-01. Michigan State University, East Lansing. 37 pp.

Clark, R. D., Jr. 2013. Is our traditional single-lake management approach sufficient to ensure sustainability of fisheries in the Great Lakes? Oral presentation at the International Association of Great Lakes Research (IAGLR) Conference, Session on Salmonine Sustainability in the Great Lakes. Purdue University, West Lafayette, IN.

Clark, R. D., Jr., and J. R. Bence. 2013. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2013 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2014a. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. January 15, 2014 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2014b. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2014 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr., J. R. Bence, I. Tsehaye, C. Madenjian, D. Warner, S. Riley, J. He. 2014. Lake-wide Chinook Salmon abundances in lakes Michigan and Huron correlate with changes in alewife abundance and between-lake migration patterns. Oral presentation at the IAGLR Conference, Session on Responses of Fish and Fisheries to the Recent Food Web Changes in Lake Huron. McMaster University, Hamilton, ON.

Clark, R. D., Jr. and J. R. Bence. 2015a. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. January 15, 2015 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2015b. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2015 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. 2016a. Inter-lake movement of Chinook Salmon between lakes Michigan and Huron. Oral presentation at the Michigan Department of Natural Resources, Fisheries Division Management Team Meeting. February 17, 2016. Lansing, MI.

Clark, R. D., Jr. 2016b. Chinook Salmon Movement between Lake Huron and Lake Michigan. Oral presentation at the Joint Lake Huron and Lake Michigan Citizens Fishery Advisory Committee Meeting sponsored by Michigan Department of Natural Resources, Fisheries Division. June 22, 2016. Clare, MI.

Clark, R. D., Jr. and J. R. Bence. 2016a. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. January 15, 2016 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2016b. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. July 15, 2016 Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr., J. R. Bence, R. M. Claramunt, J. E. Johnson, D. Gonder, N. D. Legler, S. R. Robillard, and B. D. Dickinson. 2016a. A spatially explicit assessment of changes in Chinook Salmon fisheries in lakes Michigan and Huron from 1986 to 2011. North American Journal of Fisheries Management 36:1068-1083.

Clark, R. D., Jr., R. Reilly, J. R. Bence, R. M Claramunt, J. A. Clevenger, M. S. Kornis, C. R. Bronte, C. P. Madenjian and E. F. Roseman. 2016b. Most Chinook Salmon stocked into northern Lake Huron have been feeding in Lake Michigan since the collapse of Alewives in Lake Huron. Oral presentation at the 76th Midwest Fish and Wildlife Conference, Grand Rapids, MI.

Clark, R. D., Jr. 2017. Should we treat Lake Michigan and Lake Huron as one lake? Oral presentation at the Ludington Regional Fisheries Workshop, Sponsored by Michigan Sea Grant, West Shore Community College, Scottville, MI.

Clark, R. D., Jr. and J. R. Bence. 2017a. Evaluating movements of Chinook Salmon between lakes Michigan and Huron. February 28, 2017. Progress Report to the Great Lakes Fishery Trust. Project number 2012.1230.

Clark, R. D., Jr. and J. R. Bence. 2017b. The effects of inter-lake movements on Chinook Salmon abundances in lakes Michigan and Huron. Supplement to Final Report GLFT 2012.1230.

Clark, R. D., Jr. J. R. Bence, R. M Claramunt, J. A. Clevenger, M. S. Kornis, C. R. Bronte, C. P. Madenjian and E. F. Roseman. 2017. Changes in movements of Chinook Salmon between lakes Huron and Michigan after Alewife population collapse. North American Journal of Fisheries Management (in press).

Jones, M. J., J. R. Bence, E. B. Szalai, and Wenjing Dai. 2008. Assessing stocking policies for Lake Michigan salmonine fisheries using decision analysis. In: D. F. Clapp and W. Horns editors. The State of Lake Michigan in 2005. Great Lakes Fishery Commission Special Publication 08-02. pp 81-88.

Jones, M., R. Clark, and I. Tsehaye. 2014. Workshops to revise and improve the Lake Michigan red flags analysis. Science Transfer Project Completion Report. Great Lakes Fisheries Commission. Ann Arbor, MI.

Lake Michigan Salmonid Working Group. 2017. Summary of the Predator/Prey Ratio Analysis for Chinook Salmon and Alewife in Lake Michigan. http://www.glfc.org/pubs/lake_committees/michigan/PPR%20Summary%20for%20Outreach_Final_LMC%20approved%205-15.pdf .

Reilly, R., R. D. Clark, Jr., and J. R. Bence. 2015. Evaluating changes in feeding behavior through movement patterns of Chinook Salmon. Oral presentation at the IAGLR Conference, Food Webs and Ecosystem Session, University of Vermont, Burlington, VT.

The Effects of Inter-Lake Movements on Chinook Salmon Abundances in Lakes Michigan and Huron

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Introduction

In the past 20 years, big changes have occurred in the distribution and abundance of Chinook Salmon *Oncorhynchus tshawytscha* throughout lakes Michigan and Huron (Clark et al. 2016 and 2017). We showed that one important cause of these changes was an increase in the movements of salmon from Lake Huron to Lake Michigan (Clark et al. 2017). In addition, we showed that this increase in inter-lake movement was correlated with changes in the relative abundances of Alewives *Alosa pseudoharengus* between lakes. Alewife populations collapsed in Lake Huron in 2003, but remained comparatively abundant in Lake Michigan. For almost 20 years, managers have been trying to adjust stocking rates of Chinook Salmon in Lake Michigan to compensate for known increases in natural reproduction. Their goal is to achieve and maintain a balance between predator and prey populations. Now, it appears that managers will also need to adjust stocking rates for salmon migrating in from Lake Huron. To help them do so, we developed quantitative models that account for these inter-lake movements. The primary purpose of this report was to describe these models and to use them to assess the effects of inter-lake movements of fish on the abundances of Chinook Salmon in the two lakes. In addition, we used the models to evaluate a range of stocking options for the two-lake system based on the predicted effects of each option on the predator-prey ratio in Lake Michigan.

Methods

Two-lake models. – We used two different approaches to incorporate inter-lake movements of stocked Chinook Salmon into two-lake models. First, we treated Lake Huron as though it were merely a stocked tributary of Lake Michigan. We estimated the number of salmon contributed to Lake Michigan (NLH_y) by Lake Huron each year $\boldsymbol{y}$ as:

$$NLH_y = NMH1_y * PLM_y \tag{1}$$

where $NMH1_y$ was the number stocked into statistical district MH1 of Lake Huron and PLM_y was the proportion of CWT Chinook Salmon released in MH1 and recovered in Lake Michigan in year y. Hereafter, we will refer to the model using this approach as the "Tributary Model". Using this approach was reasonable because large proportions of these MH1 salmon were shown to be travelling into Lake Michigan, and they were the majority of all Chinook Salmon planted into Lake Huron (Clark et al. 2017). For this approach, we fitted a statistical catch at age (SCA) model to Chinook Salmon catch and fishing effort data from Lake Michigan only, as Lake Huron was considered a tributary that only supplied recruits. We used the SCA model described by Tsehaye et al. (2014a) and used AD Model Builder (ADMB) (Fournier et al. 2012) to implement the model.

Second, we treated MH1 and MH2 of Lake Huron as though they were part of Lake Michigan after 2001. This approach was reasonable because we determined that after 2001, 90-100% of the salmon stocked into MH1 were travelling to Lake Michigan (Clark et al. 2017), which means that they displayed nearly the same movement patterns as salmon stocked directly into Lake Michigan. No Chinook Salmon have been stocked into MH2, but Swan River was near the boundary of MH1 and MH2, so catches in MH2 paralleled those of MH1 (Clark et al. 2016). The main difference between this second model and the Tributary Model was that we combined the catch and effort of MH1 and MH2 with the catch and effort of Lake Michigan after 2001 before we fit the Chinook Salmon SCA model. Thus, the combined catch and effort data was treated as though we were modeling one big lake or one independent lake system. Hereafter, we will refer to this second model as the "One Big Lake Model".

We estimated annual abundances for 3 subpopulations of Chinook Salmon in these models: 1) Lake Michigan-stocked fish; 2) Lake Huron-stocked fish; and 3) unmarked fish. These unmarked fish would include wild Lake Michigan fish, wild Lake Huron fish, and unmarked stocked fish. Hereafter, we will refer to these unmarked fish as wild fish, because relatively few stocked fish were unmarked after 2001. By then mass marking of stocked fish with either oxytetracycline or CWTs was taking place. We applied the ADMB estimates of total annual mortality by age to annual recruitment estimates for each subpopulation to estimate their total abundances by age and year. These recruitment estimates were made annually by the LMSWG. Annual recruitment of Michigan-stocked fish was simply the total number stocked in Lake Michigan each year. Annual recruitment to Lake Michigan of Huron-stocked fish was the total number stocked in Lake Huron each year times the proportion of CWT Huron-stocked fish recovered in Lake Michigan for the year (Equation 1). Annual recruitment of wild fish was calculated from the percent wild fish obtained in the catch for the year, which was calculated annually by LMSWG and averaged 53% from 2002–2015. We also estimated the total number (stocked plus wild) of Chinook Salmon in Lake

Michigan that had originated in Lake Huron. To make the estimate of wild Lake Huron fish, we assumed that the percent wild of fish migrating in from Lake Huron each year was the same in Lake Michigan.

We also estimated the seasonal abundance of Chinook Salmon in northern Lake Huron (MH1+MH2). Abundance estimates from the SCA model were for the start of each year, which would parallel abundances during the April–July feeding season as defined by Clark et al. (2017). We used these estimates to represent the number of fish feeding on the Lake Michigan forage base and to predator-prey models in use for Lake Michigan (Jones et al. 2014). However, we can also use the models to estimate the seasonal abundance of Chinook Salmon in northern Lake Huron by taking into account their location by lake based on CWT recoveries. The USFWS has made annual estimates of the percent of Huron-stocked fish recovered in Lake Michigan from 2011–2015. These estimates ranged from 90–96% during April–July, which means 4–10% remained in Lake Huron. In addition, Clark et al. (2017) found that 90% of the Huron-stocked fish returned to their stocking sites in Lake Huron during August–October. Thus, we estimated the seasonal abundance of Chinook Salmon in Lake Huron by assuming 4–10% of the model estimated number were located in Lake Huron during April–July and 90% were located in Lake Huron during August–October. We estimated the number in August–October by assuming that 80% of the total annual instantaneous mortality had occurred by mid-September. That is, the mortality adjustment factor was calculated as 9.5 months divided by 12 months equals 0.8. To determine if these model estimates of seasonal abundance were reasonable, we compared them to seasonal estimates of CPE from the MDNR angler survey. We expected that the seasonal pattern of CPE and abundance pattern form the model would be similar because CPE was an index of abundance.

Evaluation of alternative stocking policies. – The model currently used to help evaluate stocking policies in Lake Michigan is the Predator-Prey Ratio Analysis (Jones and Clark 2014, Lake Michigan Salmonid Working Group 2017). This analysis estimated the predator-prey ratio each year as the biomass ratio of Chinook Salmon/Alewives. It used estimates of abundance and mean weight at age to calculate biomasses. Abundances were estimated with SCAs for Chinook Salmon (Tsehaye et al. 2014a) and Alewives (Tsehaye et al. 2014b). The PPRA also contained a projection model which predicted abundances and PPRs for six years into the future, given planned stocking rates. We used our two-lake SCAs along with the projection model to evaluate a range of stocking options for Chinook Salmon. These options were evaluated based on their predicted effect on the Chinook Salmon-Alewife predator-prey ratio. We tested the effects of Chinook Salmon stocking rates of from 0.0–3.0 million fingerlings per year for the two-lakes combined (Lake Michigan plus MH1 of Lake Huron). This range bracketed the actual combined stocking rate in 2013–2015 of 2.4 million fingerlings per year, which was comprised of 1.7 million for Lake Michigan and 0.7 million for MH1 of Lake Huron.

Results

Two-lake models. – We found no practical differences in the SCA estimates of abundance and mortality rates for Chinook Salmon made with the Tributary Model or the One Big Lake Model (Figure 1). Henceforth, we will only use estimates derived from the Tributary Model, which is also the model currently used by the Lake Michigan Salmonid Working Group.

Relative abundances of the three subpopulations of Chinook Salmon in Lake Michigan (Lake Michigan-stocked fish, Lake Huron-stocked fish, and wild fish) changed over the years (Figure 2). Generally, abundances of wild fish and Lake Huron-stocked fish increased over the years. The number of Lake Michigan-stocked fish increased from 1967 to 1986 and then decreased from 1986 to 2015. These changes in abundances changed the composition of the total lake population over the years (Figure 3). The estimated percent of the total population (stocked plus wild fish) of Chinook Salmon in Lake Michigan that originated from Lake Huron increased from 6% in 2002 to 25% in 2015, and Lake Huron fish averaged 20% of the total population in 2009–2015 (Figure 4).

As expected from the seasonal recovery patterns of tagged Chinook Salmon (Clark et al. 2017), the model-estimated abundance of salmon fluctuated widely from spring to fall in northern Lake Huron (Figure 5). The pattern of fluctuations in abundance was similar to the pattern of fluctuations in CPE from the MDNR Angler Survey.

Evaluation of alternative stocking policies. – Chinook Salmon stocking rates of 1.2–1.5 million fingerlings per year for the entire lake system (Lake Michigan plus MM1 and MM2) achieved the target PPR of 0.05 after being rounded off to two decimal places (Figure 6). A rate of 1.3 million gave a PPR closest to 0.05, and thus was considered the optimal stocking rate.

Discussion

Two-lake models. – The similarity in the estimates of the Tributary and One-Big-Lake models was due to the fact that fishing effort and catch were low in MH1 and MH2 in relation to effort and catch in all of Lake Michigan. For example, in 2014 the fishing effort for trout and salmon in MH1+MH2 versus Lake Michigan was 84,380 versus 2,180,240, respectively, and catches were 4,030 versus 241,700, respectively. Thus, there does not appear to be a compelling reason to use one model over the other, unless the relative differences in fishing effort and catch between lakes changes.

Our modelling analysis suggested that the subpopulation of Chinook Salmon in Lake Michigan derived from fish stocked directly into the lake has decreased since 1986 (Figure 2). Reasons for this decline included cuts in stocking rates in 1998, 2006, and 2013. However, our analysis suggested that these cuts were ineffective in reducing the total abundance of all Chinook Salmon in the lake, because total abundance remained fairly constant at about 12 million from 1986–2013 (Figure 1). The cuts in fish stocked directly into the lake were replaced by stocked fish migrating from Lake Huron and wild fish produced in both lakes (Figures 2 and 3). Wild fish have been the most abundant subpopulation since 2006, and this is not surprising given that estimates of the percent wild at age 1 have been averaging 53%. The subpopulation of all salmon originating in Lake Huron (stocked plus wild fish) has become more abundant since 2000, and made up 24% of the total Lake Michigan population in 2015 (Figure 4).

The total abundance of Chinook Salmon did decline in 2014 and 2015 following a 50% cut in the Lake Michigan stocking rate in 2013 (Figure 1). Our model analysis suggested that the reason for this was that the abundance of the wild subpopulation had peaked in 2002 and levelled off or decreased afterward (Figure 2). Also, the abundance of the Lake Huron subpopulation peaked in 2011 and levelled off afterward. This suggested that natural reproduction and migration had reached capacity. Thus, by 2013 cuts in stocking did reduce total abundance and were not compensated for by increases in natural reproduction and migration.

Our model estimates of seasonal abundance of Chinook Salmon in Lake Huron appear to be reasonable, at least from the standpoint that the pattern in estimated abundance matches the pattern in CPE (Figure 5). It is well known by managers and anglers that this same pattern occurs in varying degrees at every major stocking site and natural spawning stream across the two lakes. Net pens and other techniques have been used in the past to try to improve the return rates to stocking sites (e.g., Johnson et al. 2007).

Evaluation of alternative stocking policies. – We estimated that the optimal stocking rate for the entire lake system (Lake Michigan plus MH1 and MH2) was 1.3 million fingerlings per year, given the current movement patterns, mortality rates, and levels of natural reproduction (Figure 6). This optimum was based on achieving a target predator-prey ratio of 0.05, which was the value used by managers to help guide stocking rates. We also found that a range of rates from 1.2–1.5 million fingerlings per year also achieved a ratio of 0.05 after the predicted ratio was rounded to two decimal places.

No matter how many fingerlings they decide to stock, managers also need to determine the distribution of fish among stocking sites in the lake system,. Our findings suggested that the distribution scheme should consider fish stocked into northern Lake Huron along with fish stocked into Lake Michigan. We found that more than 90% of Chinook Salmon stocked into northern Lake Huron have been captured in Lake Michigan since 2002 (Clark et al. 2017). This means that adjusting the distribution of stocked fish between the two lakes would have little effect on the total abundance of Chinook Salmon feeding on the forage base in Lake Michigan or on the CPEs in Lake Michigan during April–July. Consequently, managers should consider combining northern Lake Huron and Lake Michigan as a single Chinook Salmon management unit.

References

Clark, R. D., Jr., J. R. Bence, R. M. Claramunt, J. E. Johnson, D. Gonder, N. D. Legler, S. R. Robillard, and B. D. Dickinson. 2016. A spatially explicit assessment of changes in Chinook Salmon fisheries in lakes Michigan and Huron from 1986 to 2011. North American Journal of Fisheries Management 36:1068-1083.

Clark, R. D., Jr. J. R. Bence, R. M Claramunt, J. A. Clevenger, M. S. Kornis, C. R. Bronte, C. P. Madenjian and E. F. Roseman. 2017. Changes in movements of Chinook Salmon between lakes Huron and Michigan after Alewife population collapse. North American Journal of Fisheries Management (in press).

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimal Methods Software 27:233-249.

Johnson, J. E., S. P. DeWitt, and J. A. Clevenger, Jr. 2007. Causes of variable survival of stocked Chinook salmon in Lake Huron. Michigan Department of Natural Resources, Fisheries Division, Fisheries Research Report 2086, Ann Arbor, Michigan.

Jones, M., R. Clark, and I. Tsehaye. 2014. Workshops to revise and improve the Lake Michigan red flags analysis. Science Transfer Project Completion Report. Great Lakes Fisheries Commission. Ann Arbor, MI.

Lake Michigan Salmonid Working Group. 2017. Summary of the Predator/Prey Ratio Analysis for Chinook Salmon and Alewife in Lake Michigan. http://www.glfc.org/pubs/lake_committees/michigan/PPR%20Summary%20for%20Outreach_Final_LMC%20approved%205-15.pdf .

Tsehaye, I., M. L. Jones, T. O. Brenden, J. R. Bence, and R. M. Claramunt. 2014a. Changes in the Salmonine community of Lake Michigan and their implications for predator–prey balance. Transactions of the American Fisheries Society 143:420–437.

Tsehaye, I., M. L. Jones, J. R. Bence, T. O. Brenden, C. P. Madenjian, and D. M. Warner. 2014b. A multispecies statistical age-structured model to assess predator–prey balance: application to an intensively managed Lake Michigan pelagic fish community. Canadian Journal of Fisheries and Aquatic Sciences 71:1–18.

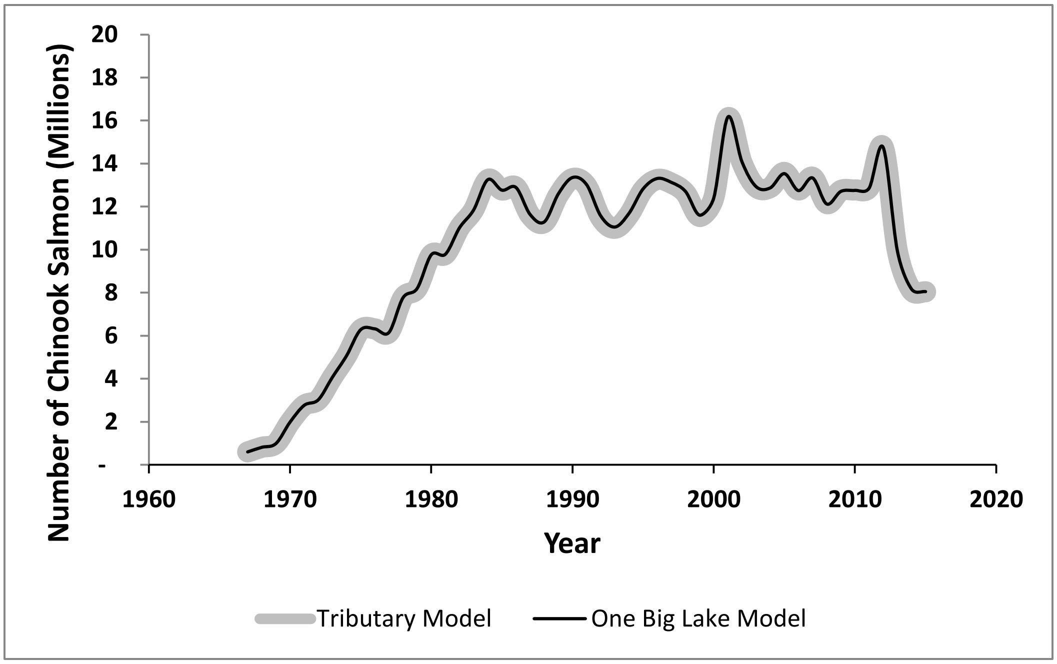

Figure 1. – Estimated total number of Chinook Salmon by year in Lake Michigan using two different SCA approaches.

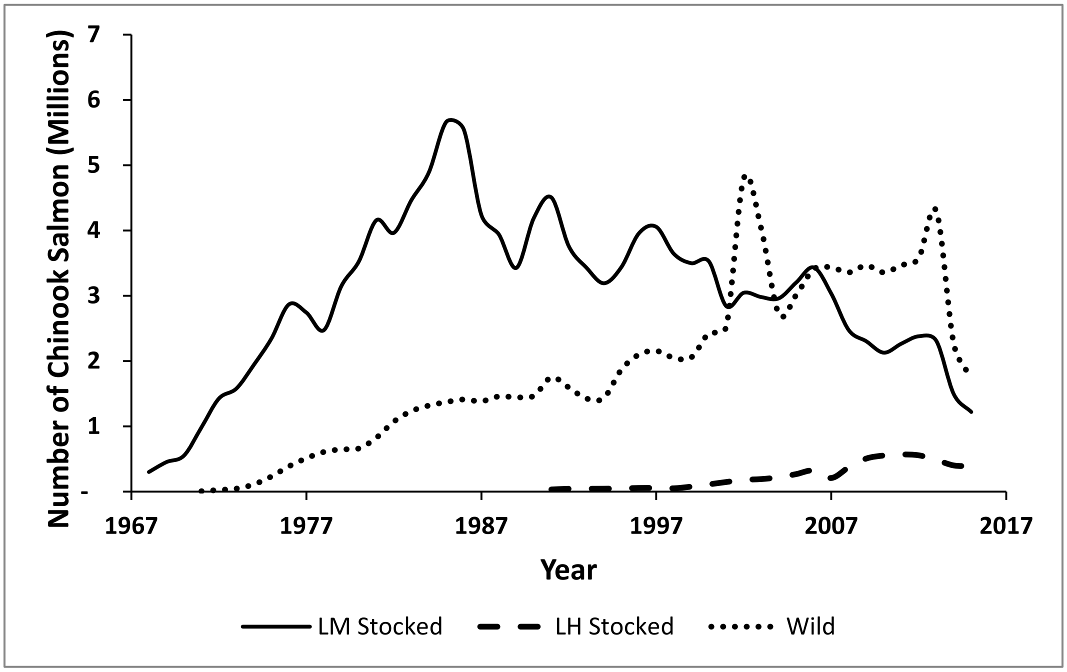

Figure 2. – Estimated total abundance by year of three subpopulations of Chinook Salmon in Lake Michigan. Subpopulations were based on the origin the fingerlings that produced them.

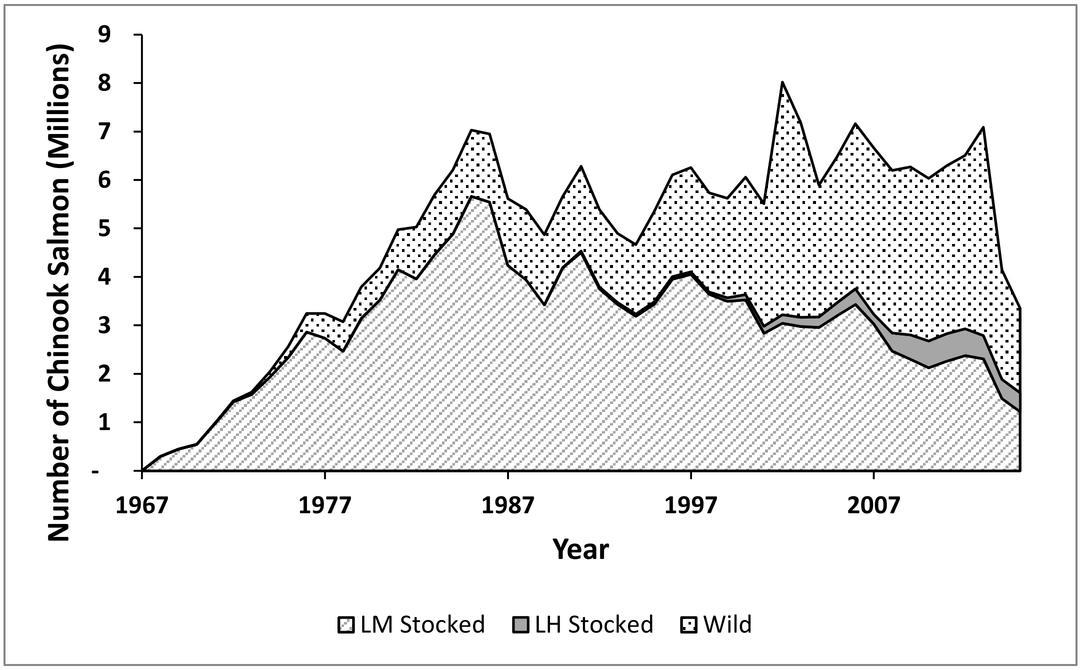

Figure 3 – Changes by year in the composition of the total Chinook Salmon population in Lake Michigan as comprised of the three subpopulations from different origins.

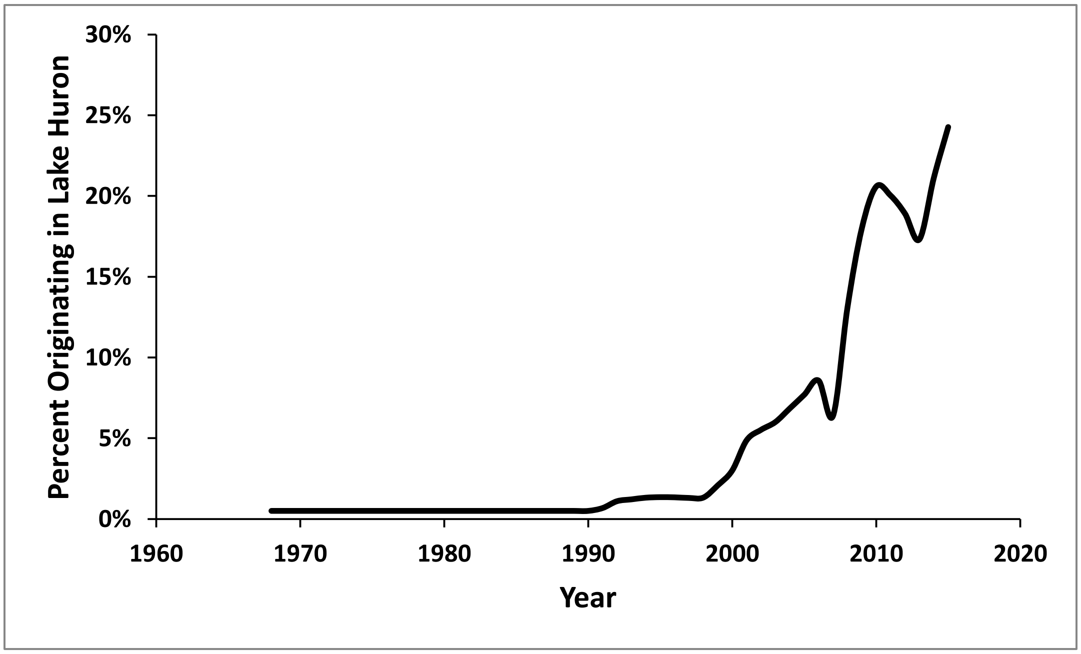

Figure 4 – Changes by year in the percent of the total Lake Michigan Chinook Salmon population (stocked plus wild fish) that originated from Lake Huron.

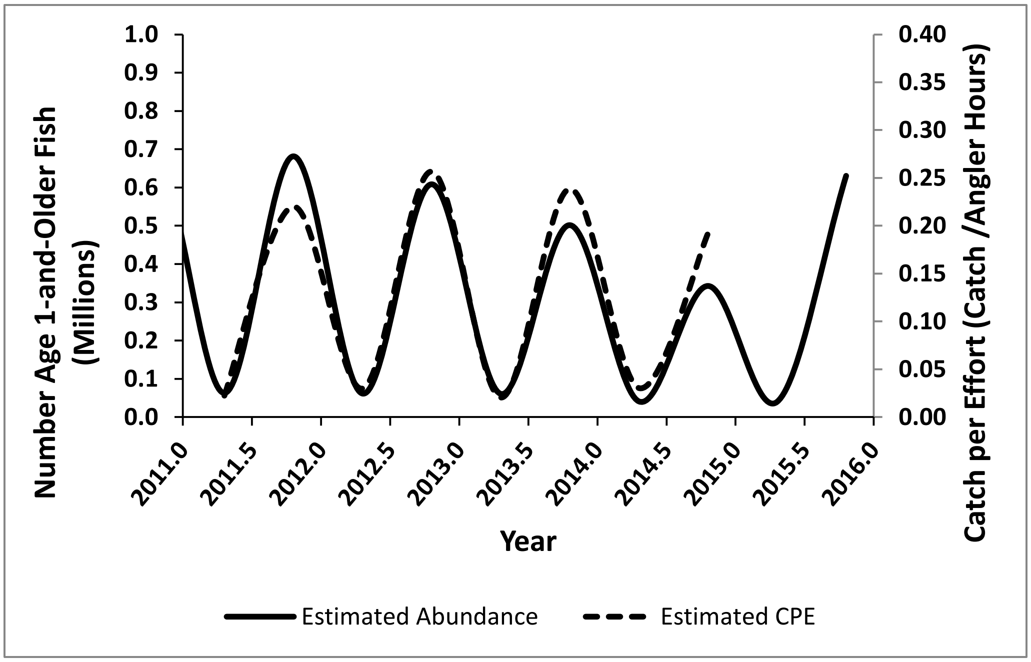

Figure 5 – Model estimated seasonal abundance of Chinook Salmon in Lake Huron (left axis) compared to seasonal CPE estimated by MDNR angler survey (right axis). Seasonal estimates were made at two times in the year and were plotted in fractions of years. That is, estimates for Apr–July (high points) were assumed to occur at year+0.3 and estimates for August–October (low points) were assumed to occur at year+0.8.

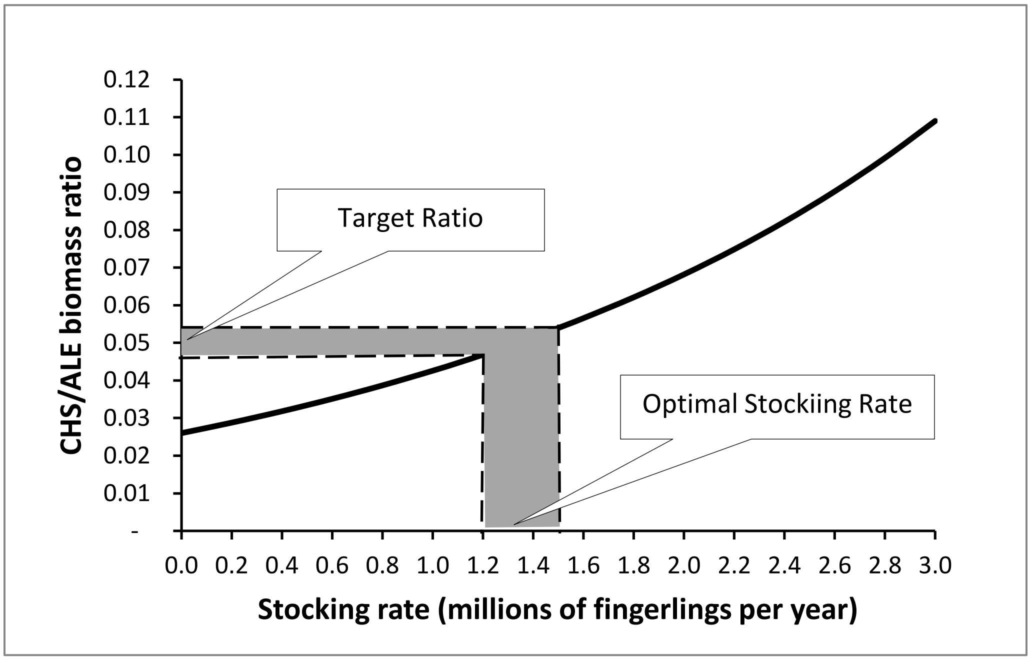

Figure 6 – Estimated predator-prey ratio for a range of Chinook Salmon stocking rates. The management target ratio is 0.05. The optimal stocking rate to achieve the target is 1.3 million fingerlings.