# Seasonal migration of salmonids in the Great Lakes interpreted from coded-wire-tag recoveries

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## Abstract

In the Laurentian Great Lakes, introduced Pacific salmonids are dominant pelagic predators and support valuable recreational fisheries. General declines in stocks during the 1980s prompted mass-tagging programs to investigate movements, and to inform assessments and stocking. Millions of smolts implanted with coded-wire-tags (CWTs) were released and recovered from fisheries, surveys, and weirs. In this paper, we consolidate and refine our previous analysis of Chinook salmon movements in lakes Michigan and Huron where we investigated feasibility of using CWT recoveries from different sources to study movements and analyzed seasonal movements in lakes Huron and Michigan. We based our study on recoveries from recreational fisheries and used Generalized Linear Models, and used recoveries from all sources to complement the analysis. We modeled recoveries by fishing trips to estimate spatially and temporally explicit abundance indices, and accounted for efficiency among recovery sources (charterboat reports, creel-clerk interviews, and dedicated-tag collections). Results show the feasibility of using recovery data from recreational fisheries to study movement. Since variation in recovery levels among recovery sources was significant, and larger than temporal or spatial variation, studies based on CWT recoveries need to consider efficiency to avoid biases. Distribution of tagged fish indicated displacements from southern areas towards the north from spring through summer, from inshore to offshore areas during summer, and back to near original stocking sites in the fall as spawning season approached. Movement patterns coincided with favorable water temperatures and prey distributions, and there were similarities with the published accounts of movement patterns exhibited by Chinook salmon in the Pacific Ocean from which Great Lakes populations originated. Seasonal changes in Chinook salmon distribution influence recreational fisheries, and stocking strategies should consider influences of movement patterns on fishing opportunities. Thus, our results have implications for fisheries management and also for tagging study design in the region and other large-scale systems.

**Introduction**

Chinook salmon (*Oncorhynchus tshawytscha*) were introduced to the Great Lakes in 1967 to help control exotic forage fishes, particularly alewife *Alosa pseudoharengus* and rainbow smelt *Osmerus mordax,* that had reached nuisance levels during the 1960s, and to create a sport fishery (Tody and Tanner 1966). Both objectives were realized as salmon stocking increased into the 1980s and the sport fishery contributed billions of dollars to the economy of the region (Keller et al. 1990). Currently, the species plays a key role in Great Lake ecosystems as a top predator and still supports profitable sport fisheries, although controlling abundance of nuisance prey is a feedback affecting Chinook salmon abundance because of growth effects on fecundity, age at maturity and recruitment (Riley et al. 2008, Adlerstein et al. 2008)

In the late 1980s, because of growing concerns about exceeding carrying capacity for salmonid predators in lakes Michigan and Huron (Kitchell and Crowder 1986), U.S. state resource agencies initiated a mass-marking and recovery program to estimate Chinook salmon natural reproduction and post-stocking survival, and to track fish movements. Since then, in Lake Michigan about 9,000,000 smolts implanted with coded-wire-tags (CWT) were stocked. As part of the marking program, about 4,000,000 smolts implanted with CWTs were stocked in Michigan waters of Lake Michigan from 1990-1994 (Table 1, Figure 1), and about 30,000 to 50,000 were released annually in Wisconsin waters. Most tagged fish in Lake Michigan were released in the central-east region (Figure 1) and the majority of recoveries from these stocking events were made by 1999.  In Lake Huron, over 4,000,000 CWT marked smolts were released between 1991 and 2000 mostly in northern and central management areas on the west side of the lake ((Table 1, Figure 1). Marked fish constituted about 15% of the total numbers of Chinook salmon stocked per year in each lake.

Several recovery programs were set in place to complement the CWT-mass tagging efforts.  Tagged fish were caught and recovered from multiple sources with

different efficiencies. Fish were caught by commercial fisheries, assessment operations, by chartered and non-chartered recreational fisheries, as well as from fishing at piers, ice shanties and shore. Tags were recovered by creel clerks, CWT collection specialists and volunteers, by resource agency personnel at weirs on spawning grounds, and also were reported by charter boat captains.

Information on Chinook salmon movement is indispensable for assessment and management. Reliable information on distribution and movements is needed to guide management decisions, particularly on stocking strategies (Johnson et al. 2005). Nevertheless, studies that describe the movements of Chinook salmon in the Great Lakes are scarce. In Lake Michigan, few studies available based on catch rates in recreational fisheries (Keller et al., 1990, Benjamin and Bence 2003), and tag recoveries from marked fish (Lake Huron Technical Committee and Lake Michigan Salmonid Working Group 2005, Johnson et al. 2005) have indicated that seasonal movements of Chinook salmon were significant and mostly associated with changes in relative abundance of prey fish (Keller et al. 1990). Based on the few studies available, Chinook salmon stocks in lakes Michigan and Huron are currently treated as a single management unit or stock (Johnson et al. 2005).  For Lake Michigan, justification for the single stock approach was based on movement information that had been derived from studies of Chinook salmon diet (Elliott, 1993). Although management does not explicitly account for movement, it is based on implicit views regarding mixing and movements of fish stocked in different locations.

In this study, we summarize information about the Chinook salmon CWT-marking program, and select results from two studies we performed on movement using CWT data. These studies investigated the feasibility of using CWT data from different recovery sources to describe and model seasonal movements of Chinook salmon within lakes Huron and Michigan (Adlerstein et al. 2007a, b). Our modelling studies of fish spatial and temporal distributions were based on Chinook salmon marked with CWTs, released and recovered in coastal waters of lakes Michigan and Huron along the Lower Peninsula of the State of Michigan. Data for the analysis were recovery rates of CWT

tagged fish from recreational fisheries. We also used absolute recoveries of CWT tagged fish from all sources of recovery to complement the modelling.

**MATERIAL AND METHODS**

**Analysis of CWT recoveries**

*General approach*

We used a regression approach and modeled CWT recovery numbers and recovery effort to develop spatially and temporally-explicit abundance indices. The efficiency to recover CWT from recreational fisheries, assessment surveys, and operations at weirs varied, and tag-recovery data from these sources cannot be combined and standardized because effort is in different units. Thus, we selected data from the recreational fisheries. Because we used fishing trips as unit of effort we selected recreational fisheries conducting fishing trips, which excludes fishing from piers, ice shanties and shore, for which the unit of effort is not a fishing trip. We analyzed the species composition of the catch to select only those trips that have a chance of fishing Chinook salmon. Further, there are two kinds of recreational fisheries conducting fishing trips (chartered and non-chartered) and three sources of CWT recoveries (clerk interviews, headhunters collections and captain reports), and thus the analysis requires consideration of the effort and efficiency in recovering tags. To that effect, we modeled CWT recoveries by trip using Generalized Linear Models (GLM) (McCullagh and Nelder 1989) and included the fishery-source of recovery as a predictor variable. We inferred seasonal movements under the assumptions that monthly variations in distribution are mainly due to movements where: 1) general decreases in catch rates in all study areas along the east shores of Lake Michigan and the west coast of Lake Huron (State of Michigan waters) are caused by movements offshore, thus in direction away from coastal areas of release, and 2) changes in the relative levels of recoveries by trips among areas along each coast where decreases in some areas co-occurred with increases in others are caused by latitudinal movements.

*Data for the analysis*

Data for our regression analysis represented recoveries of CWT fish from recreational fisheries in Michigan waters of Lake Michigan and Lake Huron (Figure 1).

4

We analyzed movement from fish released along the east coast of Lake Michigan and west coast of Lake Huron by selecting CWT recoveries of fish that were released in those areas. We used CWT data from the Michigan Department of Natural Resources (MDNR) CWT database, and fishery catch and effort data from the MDNR Creel, Charterboat and Headhunter Fishery databases. CWT recoveries were reported to or collected by the MDNR. Recoveries from the non-charter fishery were made by clerks during creel interviews and by headhunters. Recoveries from the charter fishery were reported by charterboat captains and also sampled by headhunters. Headhunters are CWT collection specialists employed by the MDNR to monitor the recreational salmonid fishery and inspect anglers' catch for Chinook salmon and other salmonids. Headhunters search exclusively for specimens with missing adipose fins, indicative of presence of CWT tags, and collect the fish snout/head and record recovery data. In contrast, creel clerks only occasionally collect tagged fish, instead concentrating on counts and interviews to measure recreational fishing effort and harvest.

Data from all sources of CWT recoveries were obtained from fish tagged and released as smolts. The CWT is an engraved piece of wire, 0.25-mm in diameter, and inserted in the snout of the fish prior to release. Tag loss was assumed to be negligible (Hale and Gray 1998). During tagging, the adipose fins were removed to allow external recognition of fish bearing CWT. Following tagging, each lot of stocked fish was evaluated for CWT retention and fin clip quality. Fish recovered were inspected for fin clips, and snouts were removed from those with missing adipose fins and transferred to laboratories for further processing, tag removal and code identification. Recovered fish have the snout removed for tag extraction and interpretation. The code is then read under a microscope, and the data are entered into the CWT database. Tagging and tag recovery procedures are described in detail in the MDNR web page (www.michigan.gov/dnr/0,1607,7-153-10364_10951_11301-97831--,00.html). CWT recovery programs and processing of tags were carried out through collaborative efforts of the U.S. Geological Survey-Great Lakes Science Center, MDNR, Chippewa-Ottawa Resource Authority, Ontario Ministry of Natural Resources, the U.S. Fish and Wildlife Service, and various fishing groups.

To analyze movement of fish released in Lake Michigan, we evaluated data from 1,987 CWT Chinook salmon recovered in Michigan waters of Lake Michigan in statistical districts MM4 to MM8 (Table 2) (Figure 1). Most recoveries were made in the central-east region and by charterboat captains (Table 2). Data were from 1993, when the Headhunter program started, until 1999 when most CWT from fish stocked in 1990-1994 had been recovered. To analyze movement of fish released in Lake Huron, we evaluated data from 3,366 CWT Chinook salmon recovered from all management areas in U.S. waters of Lake Huron (Table 2). Data were collected from 1993 until 2001. We complemented the analysis with data from absolute number of CWT recoveries from 10,049 CWT fish released in U.S. waters and recovered in U.S. and Canadian waters, and from 389 CWT fish released in Canadian waters and recovered in U.S. waters. These data were from all recovery sources, including modes of recreational fishing (volunteer returns) and non-recreational sources that were not included in the regression analysis (above). Data from fish that were released and recovered in Canada were not available for analysis.

Fishery data to estimate fishing effort consisted of catch information in the charterboat and non-charterboat fishery by fishing trip, date, fishing location, and site of the interview. To select fishing trips that had the potential to catch Chinook salmon we analyzed the species composition as the recreational fisheries in both lakes target multiple species and the chances of catching a particular species varies with the species targeted. We identified that Chinook salmon were practically absent in catches from the Michigan recreational fisheries when yellow perch were present both in chartered and non-chartered trips. Thus, we excluded trips with yellow perch. Based on this definition, we identified that the number of fishing trips that had the potential to catch Chinook salmon in each lake was about 15,000 trips per year

To pair CWT recoveries with the recovery effort, we aggregated the data on CWT recoveries and trips conducted in both recreational fisheries effort by month, statistical district of recovery, and type of fishery, and we matched the number of CWT fish with the corresponding effort for each source of recovery.

*Analysis*

For the GLM analysis of recovery data we used the following model:

$$g(\mu_{ymdg}) = \alpha + \delta_y + \phi_m + \lambda_d + \tau_g \quad (1)$$

where g () is a link function, $\mu$ is the expected number of CWT recovered by the corresponding number of trips, δ is the year, Ø is the month, λ the statistical district, and τ the source of tag recovery. The recovery source variable with four corresponding levels accounts for differences in efficiency among recovery sources. The models incorporated a binomial distribution to describe the probability of obtaining a given number of tags with the associated number of trips. Each trip was treated as a Bernoulli trial with the expected catch of CWT fish constrained between 1 and 0 (multiple recoveries occur but seldom because few fish are marked and daily fishing are limited to five salmonids, no more than three of which could be Chinook salmon (Rutherford 1997). We selected the best performing logit function, the canonical link for the binomial family. We investigated first-order interactions investigated but did not test for higher-order interactions. We tested significance of explanatory variables by analysis of deviance and examined model residuals and estimation of the dispersion parameter of the binomial models to check validity of the model assumptions. All tests were performed at the 95% confidence level. GLMs were run with routines contained in the S-Plus programming environment (Becker et al. 1988).

To complement the GLM analysis and expand the spatial distribution of CWT recoveries, we examined fish displacement using absolute CWT numbers of fish released and recovered in Lake Michigan in Michigan and Wisconsin waters and in Lake Huron in Michigan and Ontario waters.

**RESULTS**

An average of 15 and 20 coded-wire-tagged Chinook salmon was recovered from the catch of 1,000 trips in the recreational fisheries in Michigan waters of lakes Michigan

and Huron respectively. The main effect GLM incorporating statistical district, month, year and source of recovery explained 60% of the variability in tag recoveries by trip in Lake Michigan and 50% in Lake Huron (Table 3). In both regions, CWT recovery rates varied significantly among recovery sources, and by month, year and area. The difference among recovery sources was similar between lakes with highest rates for headhunters sampling chartered trips and lowest among creel clerks sampling non-chartered trips (Table 3). In Lake Michigan, the largest source of variation in recovery rate was among years, since CWTs were released up to 1994 and recoveries made up to 5 years later were very low. In Lake Huron, releases continued for several years and the difference in rates among recovery sources was more important (Table 3).

Main effects models guided our interpretation of longitudinal movements while interactions between month and statistical districts informed us about latitudinal movements. For Lake Michigan the main effect model indicated that recovery levels decreased from May to August and increased in September (Figure 2), suggesting that fish moved away from Michigan districts during spring and summer and back during September approaching the spawning season. Rates also were highest in central areas and among headhunters sampling charterboat fishing trips, and decreased after 1996 (Figure 2). The relative recovery levels among statistical districts varied significantly with month (district - month interaction: probability of Chi < 0.0001) suggesting latitudinal movements. The pattern observed was that rates in the most southern area in May were similar to those in neighboring areas to the north and decreased during June through August as levels in northern areas became relatively higher (Figure 3). By September the distribution among areas was similar to that in May (Figure 3). Based on these patterns, Chinook salmon presumably concentrated along the southeast coast of Lake Michigan in winter, and moved towards the central coast region in June and July. In Lake Huron, rates increased towards the end of the season in September and October, suggesting that fish moved away from Michigan districts before the fishing season started in spring and returned from regions outside of the study areas as spawning time approached. Also, rates were highest in central-northern areas and among headhunters sampling charter and non-charterboat fishing trips, and decreased after 1999 (Figure 3). Significant interaction between area and month (probability of Chi < 0.04) indicated that CWT recoveries by

8

trip did not vary in synchrony across statistical districts. The pattern observed was an increase in rates from south to north as the season progressed from May to August (Figure 3), suggesting fish movement in a northerly direction.

*GLMs of marked fish released in one statistical area of Lake Michigan and Lake Huron*

GLM results indicate that in Lake Michigan marked fish released in MM7 were recovered in all areas indicating movement from the release areas to other areas, although recoveries by trip were highest in the area of release (MM7). In particular in MM6 rates were not significantly different to those in MM7 (Figure 4). Similarly in Lake Huron, recoveries by trip were highest in the area of release MH3 but were recovered in all areas also indicating movement (Figure 4). In Lake Michigan, recovery rates decreased from May to July and increased to higher levels in September in all areas suggesting that Chinook salmon made seasonal movements to the west in spring and back. In Lake Huron, recovery levels in all areas increased from May to August suggesting that Chinook salmon also made seasonal movements to the west into near shore waters (Figure 4). In both cases, highest recovery levels occurred in fall. Further, interactions between month and area were significant in both lakes and indicate an increase in recoveries by trip from south towards the north as the season progressed. A similar pattern was shown by GLMs of recoveries from all release areas as shown in Figure 3.

Maps of the GLM-standardized CWT distribution presented in Figures 5 and 6 show changes in densities of Chinook salmon in both lakes in all areas and from south to north as the study season progressed. We interpreted these changes to be the result of movements westward and northward during the study season. These figures show that despite seasonal movements, most fish remained in, or returned to the release area where they concentrated to spawn.

*Absolute number of CWT recoveries to further assess longitudinal movements*

Absolute numbers of CWT recoveries from available datasets indicate movement of Chinook salmon between the east and west coast of Lake Michigan and west and east coast of Lake Huron. These numbers give further support to patterns found from the

GLM analysis. In Lake Michigan, 356 CWT Chinook salmon released in Michigan waters were recovered in Wisconsin in statistical districts WM1 to WM6, and 492 CWT released in Wisconsin waters of Lake Michigan were recovered in Michigan waters in statistical areas MM2 to MM8 (Table 4). In Lake Huron, about 400 fish released in Canadian waters were recovered in U.S. waters in statistical districts MH1 to MH6, and over 100 fish released in U.S. waters were recovered in Canada (Table 4). Also, 610 CWT Chinook salmon released in Lake Huron, mostly in MH1 were recovered in Lake Michigan (Table 4). Highest recoveries of Wisconsin tagged fish in Michigan were during July and August as well as those recoveries of Michigan tagged fish in Wisconsin. The Canadian tagged fish were recovered in U.S. waters in increasing numbers from April to July, then in decreasing numbers through October. Most of the fish tagged in the U.S. and recovered in Canada were found in November and April. These numbers indicate that regardless of region of origin (east or west shoreline), fish moved offshore, and probably became mixed as the summer progressed. If our GLM analysis would have been implemented without identifying the origin of the fish, seasonal movement could have been obscured by the longitudinal movement of fish in both lakes.

DISCUSSION

Our results showed that recoveries by trip of CWT Chinook salmon in recreational fisheries of the Lake Huron and Lake Michigan varied significantly among recovery sources and that this variation was larger than seasonal or spatial fluctuations. The magnitude of the variation, fairly similar in fisheries in both lakes, indicates that population studies based on unadjusted tag recoveries combined from several sources will be biased without accounting for differences in efficiency of the recovery source. The GLM coefficients derived in this study can be used to correct for this problem, where those for charterboat and headhunter recoveries were highest. Higher catches per trip in charter operations occurred because the numbers of anglers per boat were, on average, double that in non-charter operations, trips tended to be longer, number of rods per angler was higher and captains had greater experience in catching fish than non-charter anglers. Headhunters recovered tagged fish more efficiently than creel clerks and charterboat

captains since the program was specifically implemented to sample CWT fish, nevertheless the magnitude of the difference was previously unknown.

Results of our Chinook salmon movement studies are consistent with few available reports for the study region. Seasonal longitudinal movements of fish released in Lake Michigan and in Michigan waters derived from our GLM analysis are consistent with information from other related studies, although northwards movements have not been described. Our results show fluctuations in recoveries indicative of Chinook salmon movements away from the east coast during July and August and back in the fall and from southern areas towards the north from May through summer. For Lake Huron, there are no previous studies to compare our findings on Chinook salmon seasonal distribution. Based on CWT recovery rates, we found that Chinook salmon released along the west coast of the lake moved near shore during early spring and north during summer, returned mostly to areas near stocking locations in summer and fall, and moved east to deep over-winter areas. Results are consistent with observations on latitudinal seasonal changes in Chinook salmon distribution by Diana (1990). Diana (1990) did not investigate movement but attempted to collect sufficient Chinook salmon specimens for diet analysis along the western shore of Lake Huron and found that Chinook salmon were available only from near Port Huron in the south during May and from northern areas in July. Diana (1990) concluded that salmon migrated in a northerly direction in western Lake Huron during summer. We propose that Chinook salmon stocked along the western shore of Lake Huron over-winter in deep waters of Lake Huron and return towards the west coast in summer (where some fish return to stocking rivers to spawn in the fall). Evaluation of absolute number of CWT recoveries reinforced GLM results on movements away from the east coast of Lake Michigan during summer by indicating movement of fish released from Michigan waters into Wisconsin waters, and of fish released in Lake Huron from Michigan waters into Canadian waters. Finally, results on longitudinal and latitude movement are consistent with auxiliary analysis based on catch rates of Chinook salmon in gill net surveys by Adlerstein et al. (2007b) not reported here. Results showed catch rate fluctuations of all fish caught in these surveys indicative of Chinook salmon movement towards the north in starting in spring, away from Michigan

11

waters towards the west in late spring and summer, as well as within Michigan waters towards offshore deeper areas.

Chinook salmon movements found in this study can be related to environmental cues including warming water temperatures, thermocline development, and prey distribution, and also may be genetically influenced. The few previous studies of Chinook salmon movement in the Great Lakes suggest high mobility and seasonal migrations, and indicate that the most important drivers of their distribution are temperature and prey (Keller et al. 1990; Elliot 1993; Benjamin and Bence 2003). Both alleged drivers of salmon distribution experience seasonality (Brandt et al 1991), and are consistent with Chinook salmon movements away from nearshore areas in spring and towards nearshore areas in fall, and with northwards movements in spring to summer. Fish released in the west moved towards the east at the same time that fish released in the east moved west, suggesting that the described patterns resulted from movements away from nearshore areas in response to similar biological or environmental cues occurring along both coasts. Distributions of salmonines in the Great Lakes, as well as in the Pacific Ocean, are influenced by water temperature (Haynes and Keleher 1986; Haynes et al. 1986; Nettles et al. 1987; Olson et al. 1988; Aultman and Haynes 1993; Höök et al. 2004). Although Chinook salmon are most often found at temperatures around 10-12$^{o}$C (Stewart and Ibarra 1991; Walker et al. 2000; Hinke et al. 2005), during summer individuals can inhabit much warmer waters at temperatures up to 20$^{o}$C (Olson et al. 1988; Wurster et al. 2005). These higher temperatures are within the preference range of alewife prey (Brandt et al. 1991). During spring in the extreme south-eastern area of Lake Michigan where higher Chinook salmon densities were found, surface waters of around 8.5 - 16.5$^{o}$C are approximately 4 - 6$^{o}$C warmer than in the north and 2 - 4$^{o}$C warmer than in the west (Brandt et al. 1991). However, during summer when the thermocline is more pronounced, surface waters can exceed 20$^{o}$C. Thus, Chinook salmon likely moved offshore and deeper in the water column in response to these temperature changes.

In addition to water temperature, environmental cues for Chinook salmon movement likely include prey distribution. Alewives and rainbow smelt undergo seasonal lakewide migrations in the Great Lakes and are the major components of salmonines' diets (Madenjian et al. 2002; Rybicki and Clapp 1996) and Lake Huron (Diana 1990;

Dobiesz et al. 2003). Alewife move from deep wintering areas towards shallow waters in spring as water temperatures increase, and to deeper waters in the fall (Brown 1972; Argyle 1982; Brandt et al. 1991). Thus, decreasing catch rates of Chinook salmon nearshore found in this study could be explained by movements of prey offshore, where studies have reported higher densities of alewives during mid to late summer (Brandt et al. 1991; Warner et al. 2006). The northwards movement trend not only can be related to environmental cues but also is consistent with the hypothesis of genetic influence on movement of Chinook salmon. Chinook salmon populations in the northeast Pacific Ocean exhibit movement patterns that have been interpreted as being heritable (Myers et al. 2005). After ocean entry, Chinook salmon from the Green River, WA population, the original source of eggs for salmon stocked in Lake Michigan and Lake Huron, remain in coastal waters and move primarily northwards during spring and summer. Movement patterns found in our study also were similar to those movements of individuals from the Green River population.

In summary, our results describing distribution and movements increase our understanding of Chinook salmon populations and provide valuable information on recreational fisheries. We believe that Chinook salmon tend to be located high in the water column and in areas during spring because of warmer water temperatures that coincidently have a higher concentration of prey. From May to July, fish in the nearshore move north following the warming of surface water. During July and August, fish start to move away from the coast into deeper waters as nearshore and surface waters warm and prey distribution changes. The results suggest that minor changes in weather conditions can have an impact on the recreational fisheries by altering the distribution of Chinook salmon. Assuming Chinook salmon distributions respond to lake conditions, a rapid warming of a specific area of the lake is likely to precipitate a rapid decline in fishery catch rates as fish move offshore and become less densely aggregated in the water column.

Insights from this study have management implications relative to stocking locations and the fishing opportunities that they provide. Since Chinook salmon distribution seems determined by movements that can be affected by temperature and

forage conditions, the number of fish released in a stocking area will mainly contribute to the seasonal fall fishery in the same area when fish return to spawn. Because the lake-wide fishery is not directly linked to site-specific stocking rates, but more likely to the movement patterns described herein, managers should consider survival of smolts associated with stocking sites as the most important criteria for stocking strategies. Also, if Chinook salmon distributions are determined by forage conditions, as abundance of alewives is declining (Riley et al. 2008), it is possible that a shift in the prey base could result in changes in population distribution becoming less available for the recreational fisheries. This suggests that it is important for management to focus more effort in studying prey fish populations. Further, our results of extensive Chinook salmon movements in lakes Michigan and Huron support management based on a single-stock hypothesis; although further work is needed to determine population structure and gene flow of wild salmon and also to refine our study of movements.

Table 1 . Total number of recoverable Chinook salmon marked with coded-wire tags (adjusted by tag retention, MDNR unpublished data) by statistical district in Michigan waters of Lake Michigan and Lake Huron (Michigan Department of Natural Resources Coded-Wire Tag Database). No fish were marked after 1994 in Lake Michigan.

| Year | Statistical districts | | | | | |
|------|------|------|------|------|------|------|
| | *Lake Michigan* | | | | | |
| | MM3 | MM4 | MM6 | MM7 | MM8 | Total |
| 1990 | 98,393 | | 295,361 | 187,724 | | 581,478 |
| 1991 | 105,647 | 95,487 | 288,107 | 295,436 | 99,555 | 884,592 |
| 1992 | 100,302 | 97,458 | 288,583 | 279,027 | 97,266 | 862,636 |
| 1993 | 86,102 | 81,724 | 282,625 | 283,871 | 82,392 | 816,714 |
| 1994 | 84,577 | 90,756 | 256,390 | 274,030 | 98,281 | 804,034 |
| Total | 475,021 | 365,425 | 1,411,066 | 1,320,088 | 377,494 | 3,953,278 |
| | *Lake Huron* | | | | | |
| | MH1 | MH3 | MH4 | MH5 | MH6 | Total |
| 1991 | 215,617 | 246,842 | | | | 462,459 |
| 1992 | 208,052 | 150,910 | | | | 358,956 |
| 1993 | 200,100 | 201,640 | | 100,000 | | 501,740 |
| 1994 | 200,128 | 200,130 | | 100,080 | | 500,338 |
| 1995 | 102,000 | 205,805 | | 207,943 | | 515,748 |
| 1996 | 103,140 | 196,356 | | 205,877 | | 505,373 |
| 1997 | 102,354 | 203,990 | | 206,242 | | 512,586 |
| 1998 | 101,287 | | 176,391 | 204,143 | | 481,821 |
| 1999 | 102,277 | | 167,367 | | | 269,644 |
| 2000 | 101,731 | 104,339 | 225,940 | | 162,800 | 594,810 |
| Total | 1,436,686 | 1,510,012 | 569,698 | 1,024,295 | 162,800 | 4,703,481 |

Table 2. Numbers of Chinook salmon marked with coded-wire tags, recovered by selected recovery sources in the recreational fishery along management areas of State of Michigan waters and between May and October. Tagged fish were released and recovered in Michigan waters of Lake Michigan between 1993 and 1999 and recovered in Lake Huron between 1993 and 2001. Sources selected for the analysis include CBT (reported by charter captains), CCK (creel clerk interviews), HHB (headhunter sampled from charter fisheries), and HHR (headhunter sampled from non-charter fisheries).

| | Source of recovery | | | |
|---|---|---|---|---|
| Statistical district | CBT | CCK | HHB | HHR |
| *Lake Michigan* | | | | |
| MM4 | 4 | 37 | 0 | 0 |
| MM5 | 17 | 41 | 9 | 11 |
| MM6 | 318 | 119 | 63 | 144 |
| MM7 | 512 | 90 | 167 | 144 |
| MM8 | 28 | 109 | 68 | 106 |
| May | 139 | 54 | 112 | 90 |
| June | 116 | 52 | 83 | 92 |
| July | 140 | 79 | 42 | 87 |
| August | 266 | 106 | 59 | 73 |
| September | 176 | 154 | 11 | 23 |
| *Lake Huron* | | | | |
| MH1 | 18 | 136 | 1 | 330 |
| MH2 | 32 | 263 | 17 | 507 |
| MH3 | 146 | 515 | 12 | 292 |
| MH4 | 140 | 86 | 58 | 178 |
| MH5 | 84 | 89 | 7 | 173 |
| MH6 | 16 | 43 | 3 | 218 |
| May | 33 | 36 | 11 | 259 |
| June | 49 | 100 | 15 | 185 |
| July | 108 | 225 | 35 | 574 |
| August | 124 | 330 | 34 | 509 |
| September | 109 | 332 | 2 | 126 |
| October | 10 | 94 | 0 | 6 |

Table 3. Analysis of Deviance for main effects GLM of tag recovery rates of Chinook salmon in recreational fisheries of Michigan waters of lakes Michigan and Huron, and coefficients for source of recovery. Recoveries are from May to September 1993 to 1999 and statistical districts MM-4 to MM-8 for Lake Michigan, and from May to October 1993 to 2001 and from statistical districts MH-1 to MH-6 for Lake Huron. Source of recovery coefficients are in logit link scale and estimated using a contrast treatment matrix with charterboat captains reporting tags as reference level.

| Terms | df | Deviance | Residual Deviance | Pr(Chi) |
|---|---|---|---|---|
| *Lake Michigan* | | | | |
| NULL | 532 | 4050.7 | | |
| Source of recovery | 3 | 669.5 | 3381 | <0.0001 |
| Year | 6 | 875.8 | 2505 | <0.0001 |
| Statistical district | 4 | 674.6 | 1831 | <0.0001 |
| Month | 4 | 137.1 | 1694 | <0.0001 |
| | | | | |
| *Lake Huron* | | | | |
| NULL | 898 | 6341 | | |
| Source of recovery | 3 | 1732 | 4608 | <0.0001 |
| Year | 8 | 764 | 3843 | <0.0001 |
| Statistical District | 5 | 235 | 3608 | <0.0001 |
| Month | 5 | 242 | 3366 | <0.0001 |

| Coefficients | Value (logit scale) | Standard Error | t-value |
|---|---|---|---|
| *Lake Michigan* | | | |
| Charter self-reported | -3.867 | 0.059 | -18.5187 |
| Non-charter creel | -0.431 | 0.073 | -5.8399 |
| Charter headhunter | 1.611 | 0.076 | 20.9503 |
| Non-charter headhunter | 0.473 | 0.070 | 6.7338 |
| *Lake Huron* | | | |
| Charter self-reported | -5.770 | 0.141 | -40.8673 |
| Non-charter creel | -0.395 | 0.059 | -6.6570 |
| Charter headhunter | 1.884 | 0.128 | 14.7673 |
| Non-charter headhunter | 1.421 | 0.056 | 25.2789 |

Table 4. Location of release and recovery of coded-wire tag recoveries from Chinook salmon released and recovered in Michigan and Wisconsin waters of Lake Michigan and in Lake Huron for all years in the study from all recovery sources (recreational fishing including pier, shore, volunteer returns, and non-recreational sources). ONT corresponds to Canadian districts OH-1 to OH-5 in Figure 1.

| Recovered | Released in Lake Michigan | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Michigan waters | | | | | Wisconsin waters | | |
| | MM3 | MM4 | MM6 | MM7 | MM8 | WM3 | WM4 | Total |
| *In Michigan waters* | | | | | | | | |
| MM1 | 9 | 8 | 3 | 4 | 4 | 0 | 0 | 28 |
| MM2 | 10 | 2 | 0 | 0 | 0 | 23 | 2 | 37 |
| MM3 | 697 | 33 | 5 | 6 | 2 | 4 | 1 | 748 |
| MM4 | 173 | 453 | 13 | 8 | 3 | 4 | 4 | 658 |
| MM5 | 612 | 145 | 65 | 24 | 8 | 52 | 9 | 915 |
| MM6 | 267 | 131 | 2417 | 267 | 73 | 164 | 21 | 3,340 |
| MM7 | 154 | 86 | 199 | 469 | 75 | 106 | 19 | 1,108 |
| MM8 | 66 | 23 | 86 | 87 | 124 | 69 | 14 | 469 |
| *In Wisconsin waters* | | | | | | | | |
| WM1 | 17 | 23 | 13 | 26 | 8 | - | - | 87 |
| WM2 | 8 | 6 | 4 | 10 | 6 | - | - | 34 |
| WM3 | 33 | 15 | 28 | 25 | 11 | - | - | 112 |
| WM5 | 22 | 14 | 13 | 40 | 17 | - | - | 106 |
| WM6 | 2 | 3 | 3 | 7 | 2 | - | - | 17 |
| *In Lake Huron* | | | | | | | | |
| All areas | 77 | 103 | 35 | 30 | 11 | 49 | 4 | 309 |
| | | | | | | | | |
| Total | 2,147 | 1045 | 2,884 | 1003 | 344 | 471 | 74 | 7,968 |

| Recovered | Released in Lake Huron | | | | | | |
|---|---|---|---|---|---|---|---|
| | Michigan waters | | | | | Ontario waters | |
| | MH1 | MH3 | MH4 | MH5 | MH6 | ONT | Total |
| *In Lake Huron Michigan waters* | | | | | | | |
| MH1 | 3,160 | 293 | 34 | 88 | 15 | 64 | 3,654 |
| MH2 | 619 | 404 | 24 | 106 | 9 | 121 | 1,283 |
| MH3 | 423 | 1,597 | 54 | 162 | 12 | 63 | 2,311 |
| MH4 | 181 | 244 | 107 | 110 | 16 | 44 | 702 |
| MH5 | 172 | 202 | 21 | 678 | 16 | 36 | 1,125 |
| MH6 | 165 | 197 | 30 | 149 | 28 | 59 | 628 |
| *In Lake Huron Canadian waters* | | | | | | | |
| Ontario | 67 | 48 | 0 | 10 | 0 | - | 125 |
| *In Lake Michigan* | | | | | | | |
| All areas | 462 | 100 | 15 | 25 | 6 | 2 | 610 |

| Total | 5,250 | 3,085 | 285 | 1,328 | 102 | | 389 | 10,438 |
|---|---|---|---|---|---|---|---|---|

## REFERENCES

Adlerstein, S., E. Rutherford, S. C. Riley, R. Haas, M. Thomas, D. Fielder, J. Johnson, J. He, and **Ll. Mohr. 2008.** .Evaluation of Integrated Long-Term Catch Data from Routine Surveys for Fish Population Assessments in Lake Huron, 1973-2004. Great Lakes Fishery Commission. 37 pp.

Adlerstein, S. A., E. S. Rutherford, D. F. Clapp, J. A. Clevenger, and J. E. Johnson. 2007a. 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 27:792-803.

Adlerstein, S. A., E. S. Rutherford, J. A. Clevenger, J. E. Johnson, D. F. Clapp, and A. P. Woldt. 2007b. Lake Trout Movements in US Waters of Lake Huron Interpreted from Coded Wire Tag Recoveries in Recreational Fisheries. Journal of Great Lakes Research 33:186-201.

Argyle, R. L. 1982. Alewives and rainbow smelt in Lake Huron: midwater and bottom aggregations and estimates of standing stocks. Transactions of the American Fisheries Society 111: 267-285.

Aultman, D. C., and J.M. Haynes. 1993. Spring thermal fronts and salmonine sport catches in Lake Ontario. North American Journal of Fisheries Management 13:502-510.

Becker, R. A., J. M. Chambers, and A. R. Wilks. 1988. The new S language. A programming environment for data analysis and graphics. Wadsworth & Brooks/Cole Advanced Books & Software, Pacific Grove, CA.

Bence, J. R., and K. D. Smith. 1999. An overview of recreational fisheries of the Great Lakes. Pages 259-306 *in* W. W. Taylor and C. P. Ferreri, editors. Great Lakes fisheries and policy management: a binational perspective. Michigan State University Press, East Lansing, MI.

Benjamin, D. M., and J. R. Bence. 2003. Spatial and temporal changes in the Lake Michigan Chinook salmon fishery, 1985-1996. Michigan Department of Natural Resources, Fisheries Research Report 2065, Ann Arbor, MI. Available: www.michigandnr.com/PUBLICATIONS/PDFS/ifr/ifrlibra/research/reports/2065rr.pdf

Brandt, S. B., D. M. Mason, E. V. Patrick, R. L. Argyle, L. Wells, P. A. Unger, and D. J. Stewart. 1991. Acoustic measures of the abundance and size of pelagic planktivores in Lake Michigan. Canadian Journal of Fisheries and Aquatic Research 48: 894-908.

Brown, E. H. 1972. Population biology of alewives, *Alosa pseudoharengus*, in Lake Michigan, 1949-70. Journal of the Fisheries Research Board of Canada 29: 477-500.

Diana, J. S. 1990. Food habits of angler-caught salmonines in Western Lake Huron. Journal of Great Lakes Research 16: 271-278.

Dobiesz, N. E., D. A. McLeish, R. L. Eshenroder, J. R. Bence, L. C. Mohr, M. P. Ebener, T. F. Nalepa, A. P. Woldt, J. E. Johnson, R. L. Argyle, and. J. C. Makarewicz. 2003. Ecology of the Lake Huron fish community, 1970–1999. Canadian Journal of Fisheries and Aquatic Sciences 62: 1432–1451.

Elliot, R. F. 1993. Feeding habits of chinook salmon in eastern Lake Michigan. Michigan State University. Department of Fisheries and Wildlife. M.S. Thesis. 108 pp.

Great Lakes Fishery Commission. 2006. Great Lakes fish stocking database. Available: www.glfc.org/fishstocking/ index.htm. (April 2006).

Hale, R. S., and J. H. Gray. 1998. Retention and detection of coded wire tags and elastomer tags in trout. North American Journal of Fisheries Management 18:197–201.

Haynes, J. M., and C. J. Keleher. 1986. Movements of Pacific Salmon in Lake Ontario in spring and summer: evidence for wide dispersal. Journal of Freshwater Ecology 3: 289 –297.

Haynes, J. M., D. C. Nettles, K. M. Parnell, M. P. Voiland, R. A. Olson, and J. D. Winter. 1986. Movements of rainbow steelhead trout (Salmo gairdneri) in Lake Ontario and a hypothesis for the influence of spring thermal structure. Journal of Great Lakes Research 12 (4): 304–313.

Healey, M. C., and C. Groot. 1987. Marine migration and orientation of ocean-type Chinook and sockeye salmon. Pages 298–312 in M. J. Dadswell, R. J. Klauda, C. M. Moffitt, R. L. Saunders, R. A. Rulifson, and J. E. Cooper, editors. Common strategies of anadromous and catadromous fishes. American Fisheries Society, Symposium 1, Bethesda, Maryland.

Henderson, B. A., and S. J. Nepszy. 1992.  Comparison of catches in mono- and multifilament gill nets in Lake Erie.  North American Journal of Fisheries Management 12:618-624.

Hilborn, R. 1990. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. Canadian Journal of Fisheries and Aquatic Sciences 47: 635-643.

Hinke, J. T., G. M. Watters, G. W. Boehlert and P. Zedonis. 2005. Ocean habitat use in autumn by Chinook salmon in coastal waters of Oregon and California. Marine Ecology Progress Series 285:181-192.

Holey M. E., R. F. Elliott, S. V. Marcquenski, J. G. Hnath, and K. D. Smith. 1998. Chinook Salmon epizootics in Lake Michigan: possible contributing factors and management Implications. Journal of Aquatic Animal Health 1998 10:202–210.

Höök, T. O., E. S. Rutherford, S. J. Brines, D. J. Schwab, and J. McCormick. 2004. Relationship between surface water temperature and steelhead distributions in Lake Michigan. North American Journal of Fisheries Management 24: 211–221.

Johnson, J. E., and 13 co-authors. 2005. Analysis of the Chinook salmon populations of Lakes Huron and Michigan, 1985-2004. Report of the 2005 Great Lakes Fishery Commission Upper Lake Meetings. Available: http://www.michigan.gov/documents/Report_Red_Flags_Huron_Michigan_1_1225 84_7.pdf

Keller, M., K. D Smith, and R. W. Rybicki, editors. 1990. Review of salmon and trout management in Lake Michigan. Fisheries Special Report No.14. Michigan Department of Natural Resources, Charlevoix Fisheries Station, Charlevoix, MI.

Kitchell, J. F., and L. B. Crowder 1986. Predator-prey interactions in Lake Michigan: model predictions and recent dynamics. Environmental Biology of Fishes 16:205-211.

Madenjian, C. P.,G. K. Fahnenstiel, T. H. Nalepa, H. A. Vanderploeg, G. W. Fleischer, P. J. Schneeberger, D. M. Benjamin, E. B. Smith, J. R. Bence, E. S. Rutherford, D. S. Lavis, D. M. Robertson, D. J. Jude and M. P. Ebener. 2002. Dynamics of the Lake Michigan food web, 1970-2000. Canadian Journal of Fisheries and Aquatic Sciences. 59(4): 736-753.

McCullagh, P., and J. A. Nelder. 1989. Generalized Linear Models. Chapman & Hall, London. 509 pp.

Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grant, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 2005. Status review of Chinook salmon from Washington, Idaho, Oregon, and California. NOAA Technical Memorandum NMFS-NWFSC-35.

Nelson, D.D., and J. G. Hnath. 1990. Lake Michigan chinook salmon mortality- 1989. Michigan Department of Natural Resources Technical Report 90-4. Ann Arbor. MI.

Nettles, D. C., J. M. Haynes, R. A. Olson, and J. D. Winter. 1987. Seasonal movements of brown trout (*Salmo trutta*) in south-central Lake Ontario. Journal of Great Lakes Research 13(2):168–177.

Olson, R. A., J. D. Winter, D. C. Nettles, and J. M. Haynes. 1988. Resource partitioning in summer by salmonids in south-central Lake Ontario. Transactions of the American Fisheries Society 117:552–559.

Riley, S., E., Roseman, J. Nichols, T. O'Brien, C. Kiley, J. Shaeffer. 2008. Deepwater Demersal Fish Community Collapse in Lake Huron. Transactions of the American Fisheries Society 137:1879–1890.

Rutherford, E. S. 1997. Evaluation of natural reproduction, stocking rates, and fishing regulations for steelhead Oncorhychus mykiss, Chinook salmon O. tschawystscha, and coho salmon O. kisutch in Lake Michigan. Federal Aid in Sport Fish Restoration, Project F-35-R-22, Final Report, Michigan Department of Natural Resources, Ann Arbor MI.

Rybicki R., and D. F. Clapp. 1996. Diet of Chinook salmon in Eastern Lake Michigan 1991-1993. Michigan Department of Natural Resources, Research Report 2027. Lansing, MI. Available: www.michigandnr.com/PUBLICATIONS/PDFS/ifr/ifrlibra/research/reports/2027rr.pdf

Schmalz, P. J., M. J. Hansen, M. E Holey, P. C McKee, and M. Toneys. 2002. Lake trout movements in Northwestern Lake Michigan. North American Journal of Fisheries Management 22: 737-749.

Schneeberger, P., M. Toneys, R. Elliott, J. Jonas, D. Clapp, R. Hess, and D. Passino-Reader. 2001. Lakewide assessment plan for Lake Michigan fish communities. Great Lake Fisheries Commission Special Report 1-64. Available: www.glfc.org/pubs/SpecialPubs/lwassess01.pdf.

Stewart, D. J., and M. Ibarra. 1991. Predation and production by salmonine fishes in Lake Michigan, 1978-1988. Canadian Journal of Fisheries and Aquatic Sciences 48:909-922.

Tody, W. H., and H. A. Tanner. 1966. Coho salmon for the Great Lakes. Fish Management Report No. 1. Michigan Department of Natural Resources. Lansing, MI.

Walker, R. V., K. W. Myers, N. D. Davis, K. Y. Aydin, K. D. Friedland, H. R. Carlson, G. W. Boehlert, S. Urawa, Y. Ueno, and G. Amna. 2000. Diurnal variation in thermal environment experienced by salmonids in the North Pacific as indicated by data storage tags. Fisheries Oceanography 9: 171-186.

Warner, D. M., R. M. Claramunt, and C. S. Faul. 2006. Status of pelagic prey fishes in Lake Michigan, 1992-2005. Annual report to the Great Lakes Fishery Commission, Ann Arbor, MI. Available: http://www.glsc.usgs.gov/_files/reports/2005LakeMichiganPreyfishReport.pdf

Wurster, C. M., W. P. Patterson, D. J. Stewart, J. N. Bowlby, and T. J. Stewart. 2005. Thermal histories, stress, and metabolic rates of Chinook salmon (Oncorhynchus tshawytsha) in Lake Ontario: evidence from intra-otolith stable isotope analyses. Canadian Journal of Fisheries and Aquatic Sciences 62:700-713.
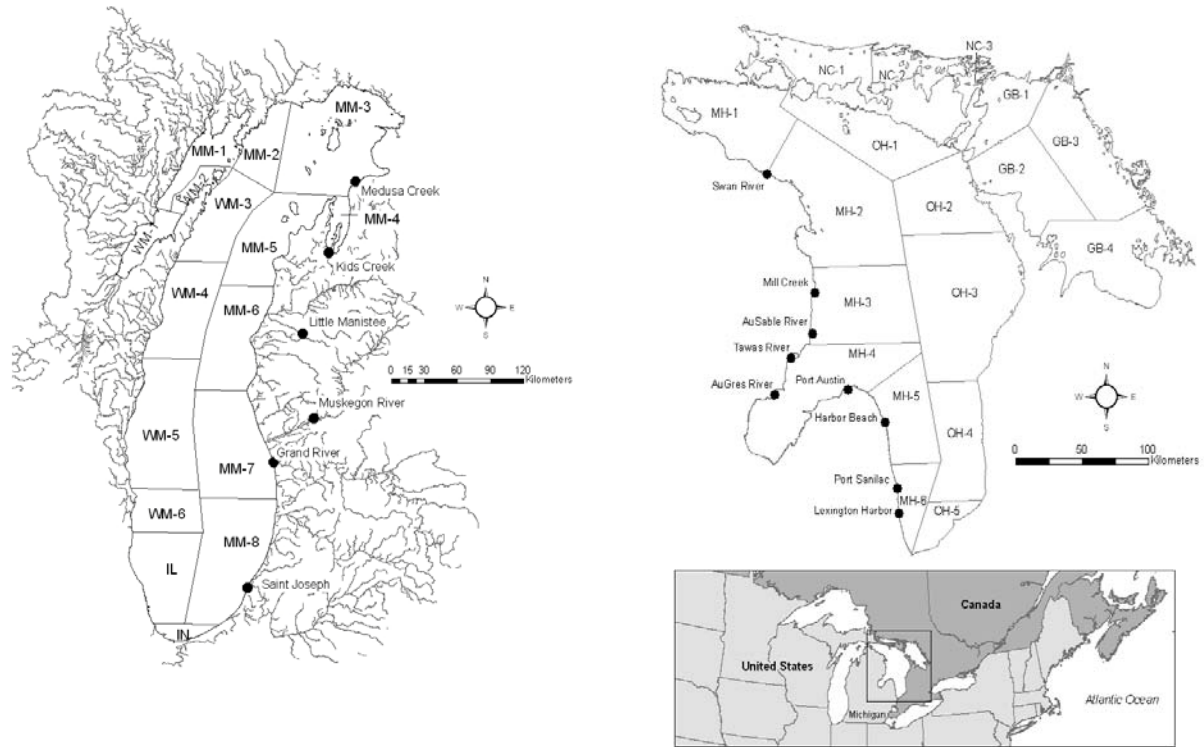
Figure 1. Maps of Lake Michigan and Lake Huron showing statistical districts and Chinook salmon release locations. In Lake Huron, statistical districts MH-1 to MH-6 are located within U.S. waters and other districts are in Canadian waters.
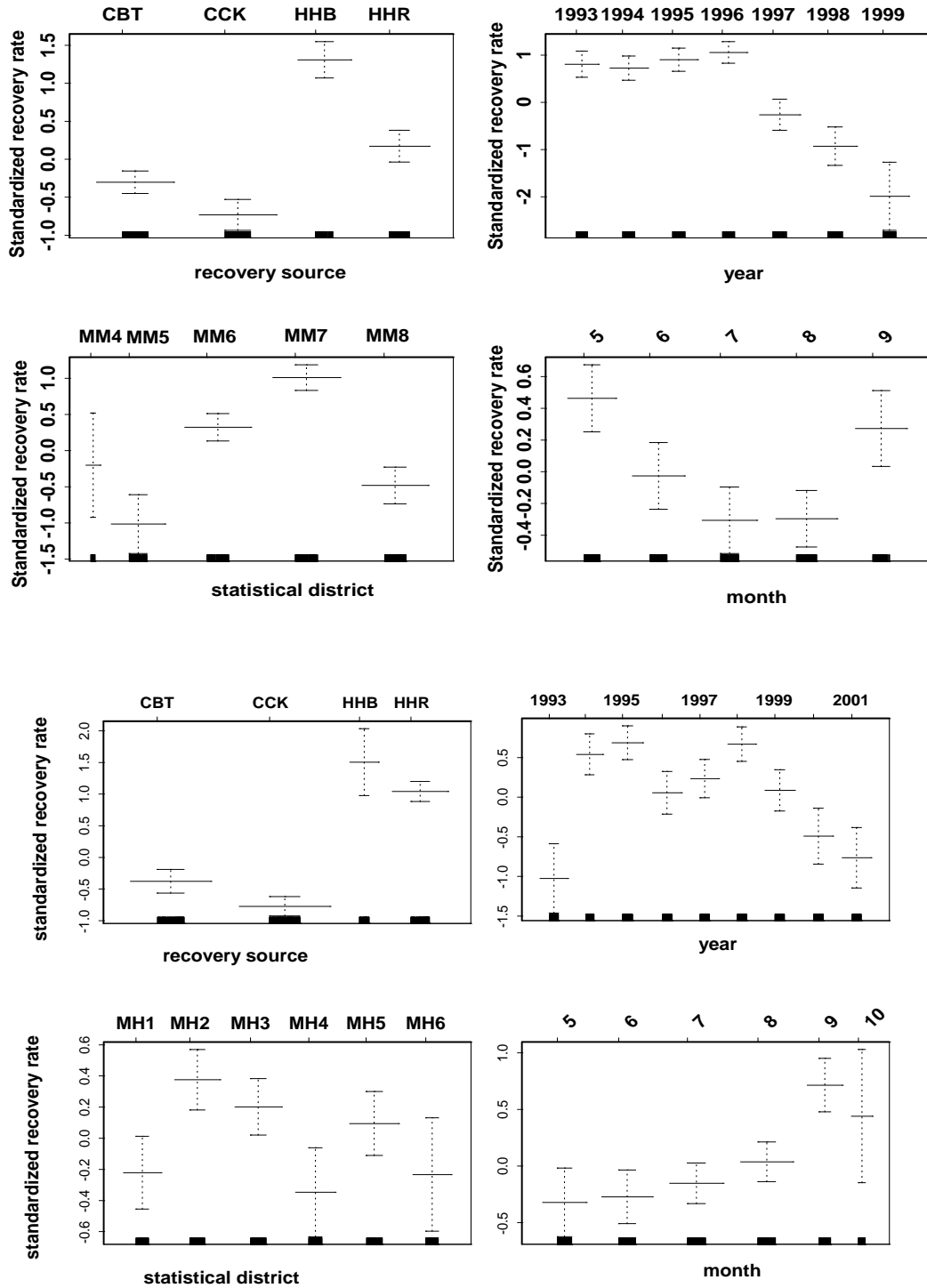
Figure 2. Main effects from generalized linear models of recovery rates of coded-wire-tagged Chinook salmon released in State of Michigan waters of Lake Michigan (MM4 – MM6) and U.S. waters of Lake Huron (MH1-MH6). Recovery sources: CCK=clerks from non-chartered trips, CBT=reported from chartered trips, HHR=headhunters (CWT collection specialists) from non-chartered trips, HHB=headhunters from chartered trips. Brackets represent 95% confidence intervals and y-axes are standardized so zero corresponds to mean recovery rates.
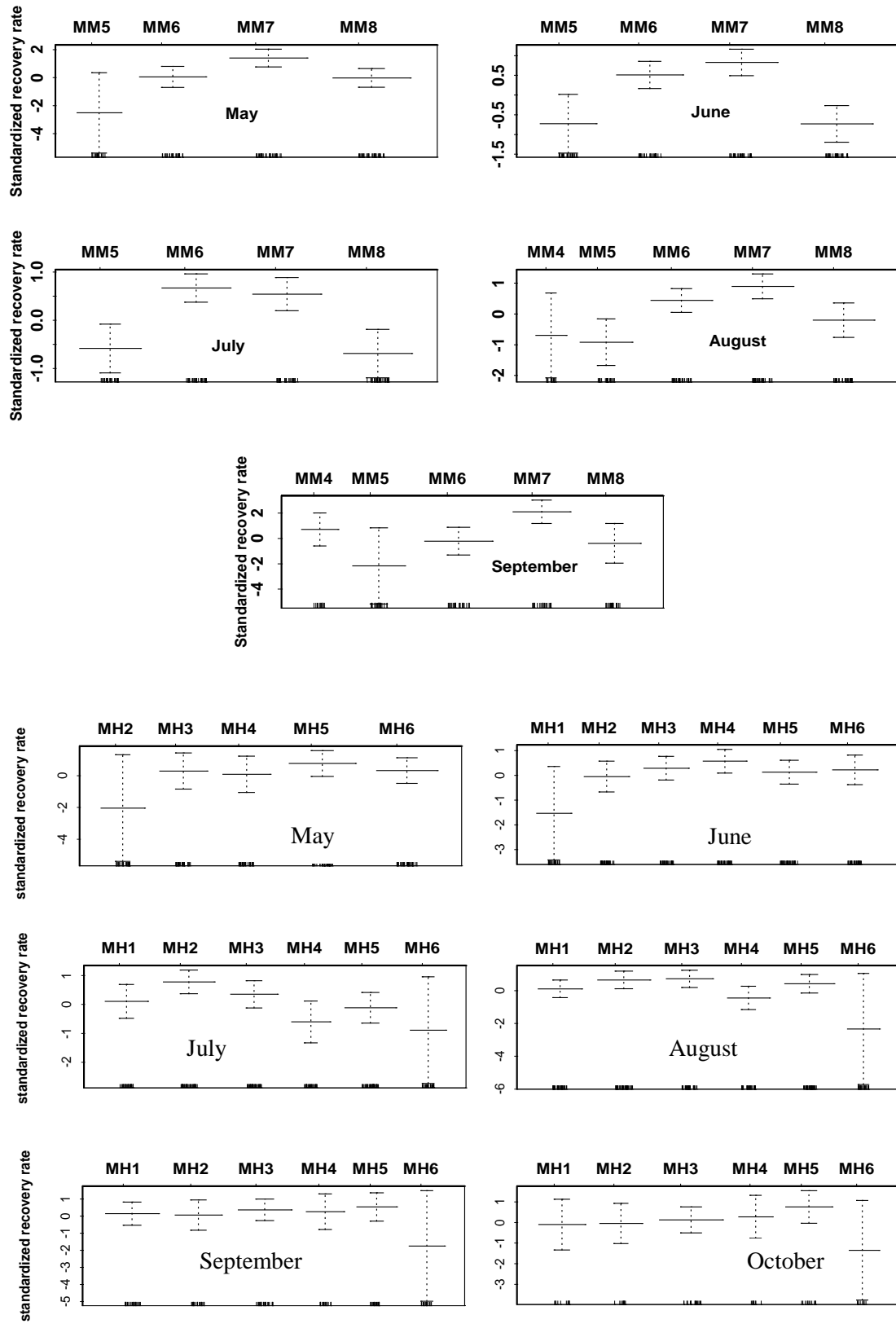
Figure 3. Fitted GLM effects for CWT recoveries of Chinook salmon by months as a function of statistical district. Other descriptions are as in Figure 2.
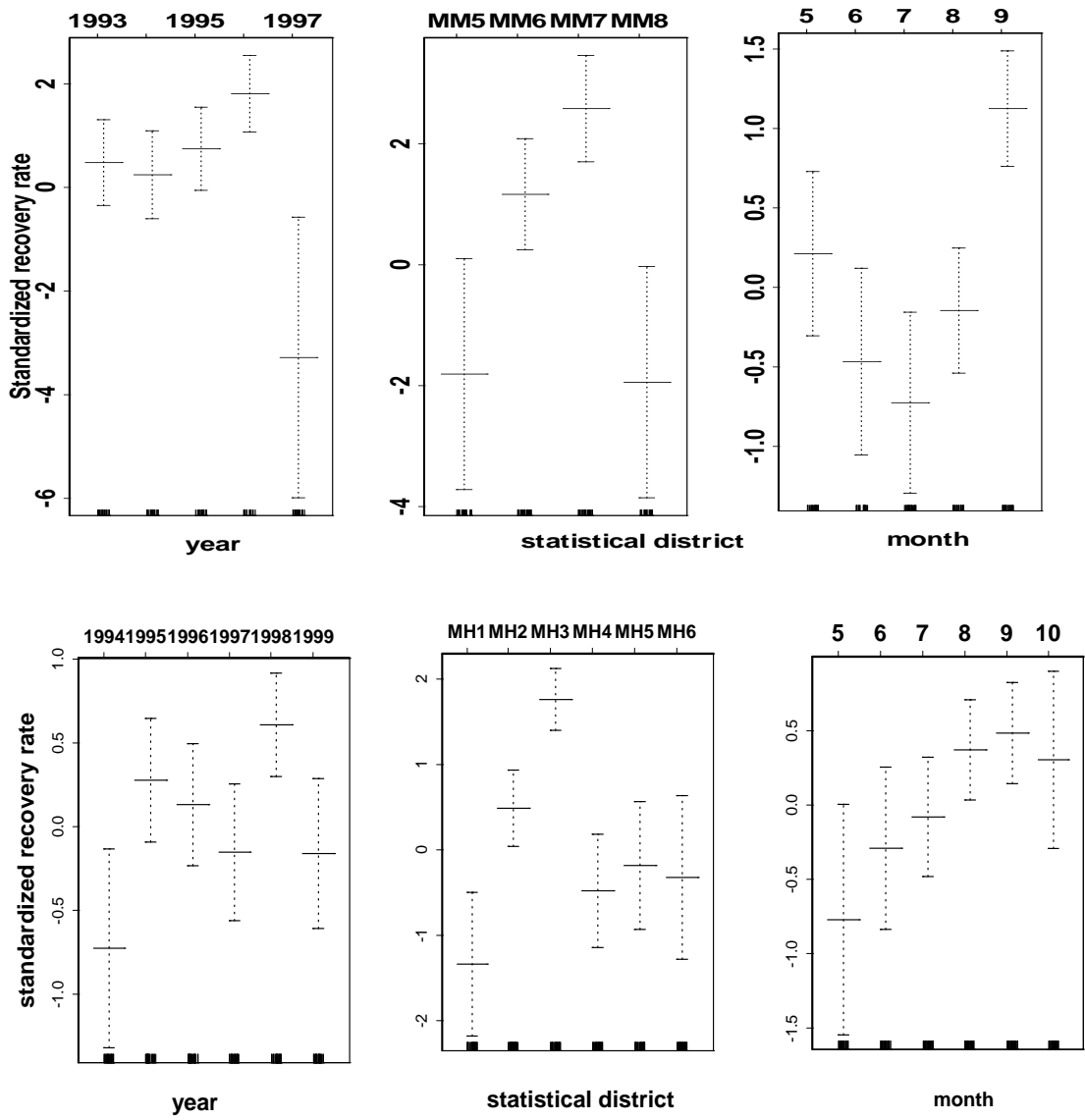
Figure 4. Effects of year, statistical district, and month of recovery from generalized linear models of tagged Chinook salmon recoveries by trip in recreational fisheries within the study period, from fish released in one statistical district among lakes Michigan and Huron. Additional information is similar to that in Figure 2.
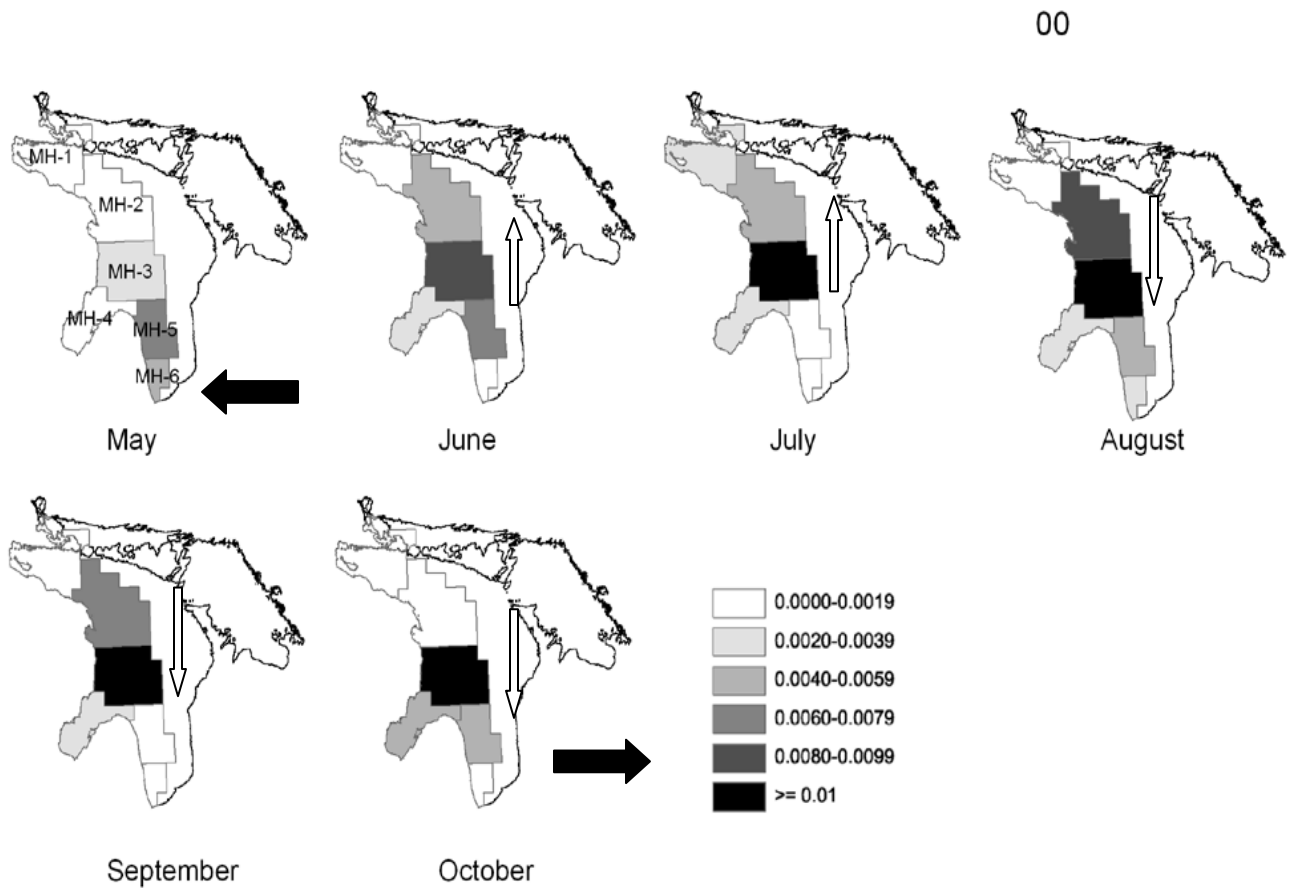
Figure 5. Generalized linear model predictions of the monthly distribution of coded-wire-tagged Chinook salmon based on standardized recoveries by trip of fish released in statistical district MH3 recovered from 1994 to 1999.
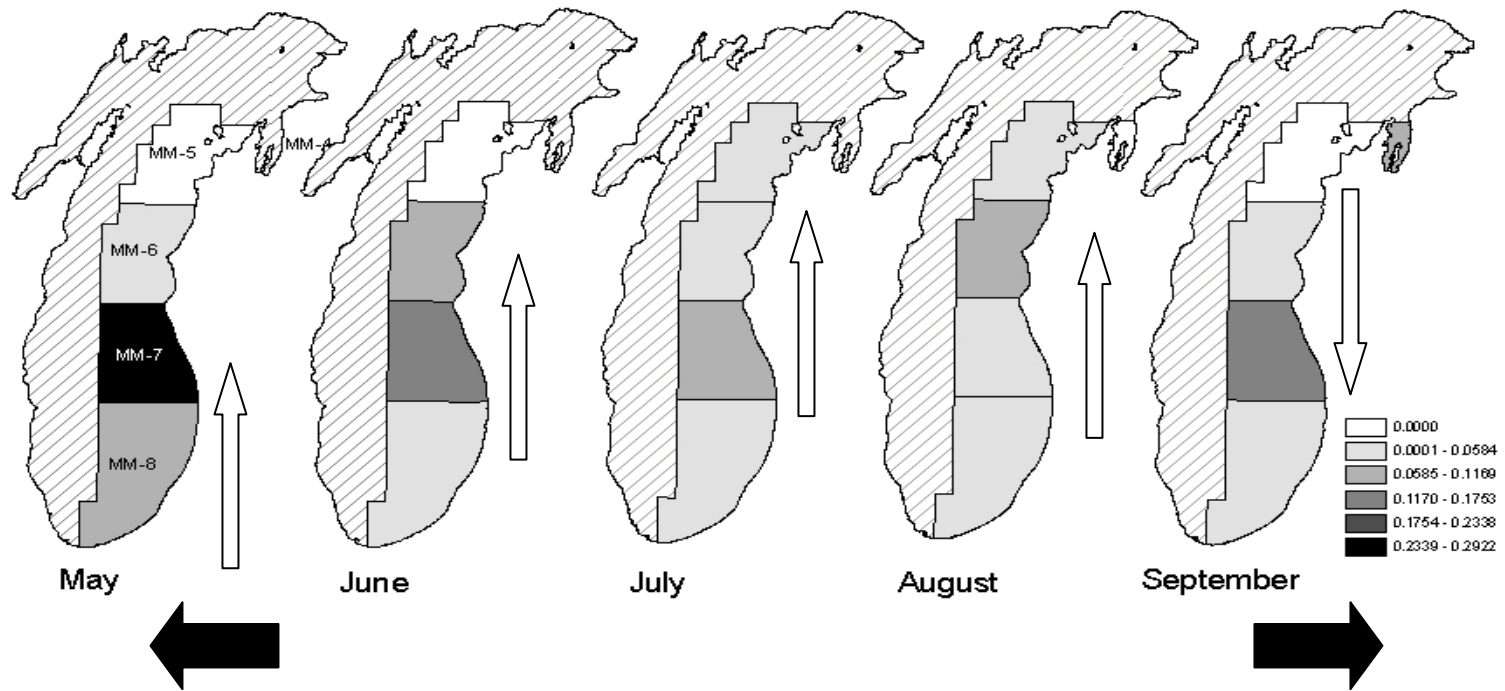
Figure 6. Generalized linear model predictions of the monthly distribution of coded-wire-tagged Chinook salmon based on standardized recoveries by trip.  Patterns are the same as for predictions for fish released in statistical district MM7.