Journal of Great Lakes Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Otolith microchemistry reveals spatio-temporal heterogeneity of natal sources and inter-basin migrations of Chinook salmon in Lake Huron

Stephen A.C. Marklevitz [a,*], Brian J. Fryer [b], James Johnson [c,1], David Gonder [d], Yolanda E. Morbey [a]

[a] Department of Biology, Western University, 1151 Richmond St., London, Ontario N6A 5B7, Canada
[b] Great Lakes Institute for Environmental Research, University of Windsor, 401 Sunset Ave., Windsor, Ontario N9B 3P4, Canada
[c] Alpena Fisheries Research Station, Michigan Department of Natural Resources, 160 East Fletcher St., Alpena, MI 49707-2344, USA
[d] Upper Great Lakes Management Unit, Ontario Ministry of Natural Resources and Forestry, 1450 Seventh Ave. East, Owen Sound, Ontario N4K 2Z1, Canada

ARTICLE INFO

Article history:
Received 19 September 2015
Accepted 1 March 2016
Available online xxxx

Communicated by Stephen Charles Riley

Index words:
Stock composition
Mixed fishery
Inter-basin movements
Strontium isotopes
Pacific salmon
Natural reproduction

ABSTRACT

The Chinook salmon fishery in Lake Huron is comprised of approximately 20% hatchery-reared fish and 80% fish from wild populations. However, finer-scale stock composition remains poorly understood because of the lack of lake-wide research and monitoring of this species and logistical constraints of mass-marking wild fish. This lack of information has resulted in a common assumption made by management agencies and used in fisheries models of a homogeneous mixture of hatchery and wild populations in the fishery. Using otolith microchemistry (multi-element concentrations and $^{87}Sr/^{86}Sr$ isotopic ratios), we identified natal sources of Chinook salmon opportunistically sampled through space and time in the 2008 and 2010 recreational fisheries. Our findings demonstrated extensive spatio-temporal variability in sample composition, providing the first direct evidence of heterogeneous mixing of hatchery and wild populations in the fishery. Our data also suggest that >90% of all fish in the recreational fishery originate in rivers and hatcheries in Southern Georgian Bay (46%) and Northern Lake Huron (46%). The majority of wild fish appear to originate from rivers in Southern Georgian Bay (55%) and Northern Lake Huron (35%); whereas the majority (67%) of hatchery fish appear to originate from Michigan hatcheries. Analysis of $^{87}Sr/^{86}Sr$ ratios suggests that <1% of the fish originated from Canadian Shield rivers east of the St. Marys River. Our results fill in critical knowledge gaps for fisheries management of introduced Pacific salmonids in Lake Huron and other Laurentian Great Lakes.

Introduction

Chinook salmon (*Oncorhynchus tshawytscha*) were introduced into the Laurentian Great Lakes to convert nuisance levels of invasive alewife (*Alosa pseudoharengus*) into recreational fishing opportunities (Kocik and Jones, 1999). Since the late 1960s, intensive stocking programs have maintained the abundance of Chinook salmon throughout several Great Lakes, but naturalized (wild) populations have become established (Claramunt et al., 2013; Crawford, 2001). Since the early 2000s, wild fish have been contributing over 80% of the Chinook salmon harvested by the Lake Huron recreational fishery (Claramunt et al., 2013; Johnson et al., 2010). Despite the prevalence of wild Chinook salmon in Lake Huron, coordinated lake-wide research and monitoring of this species has been limited. The lack of information about Chinook salmon limits our understanding of their basic ecology, including how different hatcheries or wild populations contribute to the fishery. The objective of our study was to use otolith microchemistry to identify natal sources of Chinook salmon in Lake Huron and test the common assumption of a mixed-stock fishery.

Wild populations of Chinook salmon were first discovered in Lake Huron during the 1980s in several Southern Georgian Bay rivers and shoal spawning was reported in the North Channel (Carl, 1982; Kerr and Perron, 1986; Kerr, 1987; Powell and Miller, 1990). More recently, wild populations have been documented in seventeen rivers; however, the sizes of these populations and their contributions to the lake-wide fishery are unknown (Johnson et al., 2010; Marklevitz et al., 2011). Hatchery supplementation has continued despite establishment of wild populations. Hatchery programs collect gametes annually from hatchery and wild origin fish returning to collection weirs. From 1968 to 2010, 111 million Chinook salmon were reared in hatcheries and stocked into the lake, with the majority released along the Michigan coast (FWS/GLFC, 2010). The fishery is therefore composed of fish with different juvenile-rearing histories (hatchery versus wild) originating from different natal locations.

Understanding the spatial and temporal variability in stock composition is basic information about population ecology, critical for proper fisheries management. Spatio-temporal variation in biotic and abiotic conditions can affect growth, body condition, age at maturation, and survival of Chinook salmon (Wells et al., 2006, 2007, 2008, 2012). In

* Corresponding author at: Lake Erie Management Unit, Ontario Ministry of Natural Resources, 320 Milo Rd., Wheatley, Ontario N0P 2P0, Canada. Tel.: +1 519 825 4075.
E-mail address: stephen.marklevitz@ontario.ca (S.A.C. Marklevitz).
[1] Retired.

http://dx.doi.org/10.1016/j.jglr.2016.03.007
0380-1330/

Lake Huron, interactions between prey availability and Chinook salmon density could influence intraspecific competition or interspecific competition with native lake trout (*Salvelinus namaycush*) (Riley et al., 2008; Roseman and Riley, 2009). With multi-agency management of the fishery, there are differing intensities of stocking and fishing pressure throughout the lake (Claramunt et al., 2013). For example, while Chinook salmon are predominately targeted by anglers in a multimillion dollar recreational fishery, in northern US waters they are also targeted in a small commercial gill net fishery. Furthermore, the intensity of the recreational fishery is a function of access to the fishing grounds and proximity to population centers. Some areas of Lake Huron have almost no access sites, especially in Ontario. Migration of Chinook salmon throughout the lake therefore exposes fish to different factors that can influence growth and survival rates among populations. To date, lack of information has forced fisheries management agencies of Lake Huron to make some general assumptions of stock composition including a homogeneously mixed fishery; lack of immigration or emigration from the Main Basin to other basins (i.e., Lake Michigan and Georgian Bay); constant age-specific selectivity and natural mortality rates; and survival rates independent of rearing origin (Adlerstein et al., 2007; Brenden et al., 2012).

In their native range, Chinook salmon migrate thousands of km from natal rivers to foraging areas in the ocean before returning to natal rivers to spawn (Quinn, 2005). Populations from similar geographic regions have similar oceanic distributions, which appear to be consistent over time (Weitkamp, 2010). In foraging areas at sea, populations of varying sizes co-mingle to form "mixed stock fisheries". Chinook salmon remain in mixed stock fisheries for 2–3 years before homing back to natal rivers (Dittman and Quinn, 1996; Quinn, 2005). The spatial precision of natal homing by Chinook salmon is extraordinary. One study showed over 99% of fish surviving to maturity returning to their natal river system (e.g. Columbia River system) with >98% returning to their precise natal river (e.g. Cowlitz River) (Quinn and Fresh, 1984). Beyond some basic knowledge of oceanic distributions, much of the at-sea ecology of Chinook salmon remains unknown. Logistical challenges also mean that most of our knowledge about at-sea salmonid ecology is derived from marked hatchery fish re-captured in fisheries (Quinn, 2005; Quinn et al., 2011; Weitkamp, 2010).

Similar to Chinook salmon in their native range, most of our ecological knowledge of Chinook salmon in Lake Huron is based on mark-recapture studies of hatchery fish. For example, comparing capture rates of marked to unmarked fish revealed increasing captures of presumably wild fish from 15% of the fishery in 1991–1995 to >80% in 2000–2010 (Adlerstein et al., 2007; Brenden et al., 2012; Johnson et al., 2010). Recaptures of Michigan-stocked fish also revealed long-distance movements by Chinook salmon within the Main Basin of Lake Huron (Adlerstein et al., 2007). Recaptures primarily along the Michigan coast suggest that Chinook salmon move northwards from May to July and southwards from August to October, when some presumably return to natal rivers or stocking sites to spawn. These extensive movements support the assumption that the Chinook salmon fishery in Lake Huron is a single management unit or stock (Adlerstein et al., 2007). On the other hand, spatial variability in the percentage of wild fish suggests otherwise (Johnson et al., 2010).

Basing our ecological knowledge of Chinook salmon in Lake Huron on hatchery fish has two major limitations. First, the majority of research and monitoring occurs along the Michigan coast which is also where the majority of stocking occurs (e.g. Adlerstein et al., 2007; Bence et al., 2008; Diana, 1990; Johnson et al., 2007). This means that the eastern coast of the Main Basin, the North Channel, and Georgian Bay, where the majority of wild populations are located, has been excluded from most research and monitoring programs (Marklevitz et al., 2011). Second, hatchery rearing and stocking locations may influence migration routes and timing via non-adaptive phenotypic plasticity. Timing of juvenile out-migration from rivers, homing rates and arrival timing of adults to spawning sites, and spatial distributions of spawning fish often differ between hatchery and wild fish (Daugherty et al., 2003; Dittman et al., 2010; Hoffnagle et al., 2008). While mass marking of wild Chinook salmon to study movements and distributions within Lake Huron is possible, such studies pose significant financial and logistical challenges.

Analysis of population-specific markers can reduce the dependence on mass marking to identify origins of fish. Microsatellite DNA variation is one type of natural marker used to identify natal locations of salmonids (Beacham et al., 2008; Seeb et al., 2004; Tucker et al., 2009). However, microsatellite analysis of Chinook salmon in Lake Huron would be minimally useful because of limited genetic divergence and an inability to differentiate among many of the wild populations (Suk et al., 2012). Otolith microchemistry has also been used to identify the natal locations of Chinook salmon (Barnett-Johnson et al., 2007, 2010; Brennan et al., 2015; Miller et al., 2010), including within the Great Lakes (Marklevitz et al., 2011). As otoliths grow, they permanently and chronologically incorporate major, minor, and microchemical (trace element) impurities at environmentally-representative concentrations into the calcium carbonate structure (Campana, 1999; Campana and Thorrold, 2001). Not only can elements vary in their concentration, the isotopes of some elements can vary relative to other isotopes of the same element. For example, strontium and sulfur isotope ratios have been used to discriminate marine versus freshwater environments or diets in salmonid fishes (e.g., Kennedy et al., 2000, Weber et al., 2002; Bacon et al., 2004). Strontium isotopes ($^{87}Sr/^{86}Sr$) are also known to vary with geological features and can be used to delineate natal origins (Brennan et al., 2015; Hodell et al., 1989; Wadleigh et al., 1985). We therefore should be able to predict the natal source of adult fish by comparing the microchemistry (i.e. elemental concentrations and $^{87}Sr/^{86}Sr$ isotopic ratios) in the juvenile section of adult otoliths to otoliths from juveniles collected from known natal sources.

The objective of our study was to use otolith microchemistry to identify natal sources of Chinook salmon captured throughout the Lake Huron fishery. Within the Lake Huron watershed, juvenile salmon occupy rivers in regions with different bedrock and surficial geology. Previous research found, this led to highly structured variation in multi-element concentrations in the otoliths of juveniles caught in natal rivers and to hatcheries, and to the ability to classify natal sources based on otolith microchemistry with high (87%) accuracy (Marklevitz et al., 2011). The presence of some natal sources on the Canadian Shield means that analyses of $^{87}Sr/^{86}Sr$ ratios in juveniles and adults could help further discriminate fish from this Precambrian geological region, and regions containing younger surficial geology (Bacon et al., 2004; Hodell et al., 1989). In the current study, we collected otoliths from adult Chinook salmon sampled opportunistically from Lake Huron recreational fisheries in 2008 and 2010. We identified natal sources based on otolith microchemistry comprising both multi-element concentrations and $^{87}Sr/^{86}Sr$ ratios, and evaluated the contributions of different hatcheries and wild populations to the lake-wide fishery. By identifying the natal source of individuals, we were able to examine spatial and temporal variability in sample composition to assess the assumption of a homogeneously mixed fishery.

Methods

Sample collection

In 2008 and 2010, adult Chinook salmon were collected through established Lake Huron fisheries assessment programs. Sampling was performed by Western University (Canada), Ontario Ministry of Natural Resources and Forestry (OMNRF), and Michigan Department of Natural Resources personnel. Although we attempted to stratify collections of fish from the lake though space and time, we could only opportunistically sample the in-lake fishery. The majority ($n = 464$) of fish were solicited from anglers through recreational angler (creel) survey and at fishing derby weigh stations. A few additional fish ($n = 17$) were