Third NPAFC-IYS Virtual Workshop on Linkages between Pacific Salmon Production and Environmental Changes

Technical Editors: Jeongseok Park, William Stanbury, and MacKenzie Kermoade

Vancouver, Canada, 2021
Third NPAFC-IYS Virtual Workshop on *Linkages between Pacific Salmon Production and Environmental Changes*

*May 25–27, 2021 in Canada and USA  
May 26–28, 2021 in Japan, Korea, and Russia*

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Third NPAFC-IYS Virtual Workshop on Linkages between Pacific Salmon Production and Environmental Changes

May 25–27, 2021 (Canada and USA)
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Technical Editors: Jeongseok Park, William Stanbury, and MacKenzie Kermoade

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Preface

The International Year of the Salmon (IYS; https://yearofthesalmon.org) is an international framework for collaborative outreach and research, and seeks to increase understanding and raise awareness of the challenges facing salmon and the measures to support their conservation and restoration against increasing environmental variability. The overarching theme of the IYS is “Salmon and People in a Changing World,” and the proposed research themes are (1) status of salmon; (2) salmon in a changing salmosphere; (3) new frontiers; (4) human dimension; and (5) information systems. These five research themes are integrated into the current NPAFC Science Plan (2016–2022), whose goal is to understand variations in Pacific salmon production in a changing climate (https://npafc.org/science-plan/). The North Pacific Anadromous Fish Commission (NPAFC), with support by several partners—Fisheries Agency of Japan, Hokkaido Research Organization, Hokkaido Salmon Propagation Association, Japan Fisheries Research and Education Agency, Japan Salmon and Trout Resources Enhancement Association, North Pacific Marine Science Organization (PICES), and Tohoku Ecosystem-Associated Marine Sciences (TEAM)—hosted the Third NPAFC-IYS Virtual Workshop on “Linkages between Pacific Salmon Production and Environmental Changes” on May 25–27, 2021 (PST).

About 300 salmon experts and scientists from around the world registered for the virtual workshop. Not only were there 29 pre-recorded presentations and 32 e-posters, but also 13 keynote and 15 oral presentations. Summary and discussions also took place during three days of live sessions addressing the following topics (and sub-theme) related to the IYS research themes:

- Salmon production in changing environments (status and trends of key salmon populations and their environments; effects of freshwater habitats changes on salmon production; survival mechanism of juvenile salmon in changing ocean environments; winter ocean ecology and survival of Pacific salmon; linkages between salmon production and climate/ocean changes)
- New technologies/integrated information systems for salmon research and management (new technologies; integrated information and management systems)
- (Special Session) Resilience for salmon and people: lesson from the Great East Japan Earthquake in 2011 (restoration of ecosystems and human society in the coastal zone systems; research for retrieval and sustainable management of salmon populations; risk management and sustainability for the coastal zone systems and salmon production)

The Workshop Science Committee consisted of Jun Aoyama (International Coastal Research Center, Atmosphere and Ocean Research Institute, Univ. Tokyo, Japan), Ed Farley, Jr. (Auke Bay Laboratories, NMFS, USA), Jim Irvine (Pacific Biological Station, DFO, Canada), Ju Kyoung Kim (Aquatic Living Resources Center, FIRA, Korea), Svetlana Naydenko (Pacific Branch of VNIRO (TINRO), Russia), Mark Saunders (IYS North Pacific Steering Committee, Canada), Shigehiko Urawa (Chairperson; Fisheries Resources Institute, FRA, Japan), and Jeongseok Park (NPAFC Secretariat, Canada).

On behalf of the Workshop Science Committee, we thank all presenters and participants for sharing information and addressing the topics related to the IYS research themes at the workshop and for submitting materials for this volume. We also thank Aidan Schubert (IYS Coordinator) for facilitating the live sessions of the workshop. Live and pre-recorded oral and poster presentations given at the workshop are also available for educational purposes at https://npafc.org/workshop-presentations-2021.

Technical Report No.17 is a compilation of extended abstracts submitted by workshop presenters. Material in this report has not been peer-reviewed and does not necessarily reflect the views of NPAFC member countries, or authors’ agencies. I appreciate William Stanbury (NPAFC Web/Publication Manager) and MacKenzie Kermoade (2021 NPAFC Intern) for their help in editing the extended abstracts. Abstracts have been edited for clarity and publication purposes.

Jeongseok Park
Deputy Director, NPAFC
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Resilience for Salmon and People—Lessons learned from the Great East Japan Earthquake in 2011: Summary and Discussion
Jun Aoyama, Shigehiko Urawa, and Masahide Kaeriyama
State of Canadian Pacific Salmon in 2019 and 2020: Responses to Changing Climate and Habitat

Sue C.H. Grant¹, Bronwyn L. MacDonald¹, Dawn Lewis², Niki Wilson³, Jennifer L. Boldt², David A. Patterson⁴, Kendra A. Robinson⁴, Ian Perry⁵, Jackie King², Chrys M. Neville², and Dan T. Selbie⁶

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Keywords: salmon, productivity, climate change, habitat change, abundance, trends, Pacific, status, marine, freshwater, ecosystems

Global climate change is the overarching driver of Canadian Pacific salmon trends (Grant et al. 2019). Average land-ocean temperature has risen by 1°C over the last century (IPCC 2018), and the last six years were the warmest on record (Fig. 1; NOAA 2020). This trend is accelerating, emphasizing the need to dramatically reduce greenhouse gas emissions globally (IPCC 2014; White et al. 2016; Holsman et al. 2018; Bush and Lemmen 2019).

Pacific salmon productivity and growth are impacted by global climate warming through changes in their freshwater and marine environments (Holsman et al. 2018; IPBES 2018; Bush and Lemmen 2019; Grant et al. 2019; Boldt et al. 2020). Other factors that contribute to salmon trends like habitat changes, disease, contaminants, hatcheries and fisheries are embedded within this global climate change context.

Rising air temperatures are warming freshwater ecosystems where salmon spend the first part of their lives incubating as eggs in their spawning gravel, and rearing as juveniles for up to two years. In British Columbia (BC), spring and summer months were notably warmer than average from 2016 to 2019, with the exception of summer 2019, which was more variable (PCIC 2019). Air temperature anomalies have been even greater in the Yukon than BC, due to its more northern location (Fig. 2; Bush and Lemmen 2019).

Increasing temperatures are compounded by heat waves, which are expected to become more frequent and longer lasting (IPCC 2014). In BC in June 2021, an unprecedented heat wave set all time high air temperature records in multiple locations across the province, and broke the highest temperature ever recorded in Canada by greater than 1°C on two consecutive days (Environment & Climate Change Canada 2021).

Warming temperatures in spring months contribute to earlier onset of snowmelt. In 2016, 2018, and 2019, early snowmelt in most regions of BC resulted in below-average snowpacks by the second week of May, which in 2016 set record lows relative to the ~30-year time series. In 2017, the onset of snowmelt began several weeks later than normal, though extreme hot temperatures led to rapid snow melt in the second half of May. By June 2017,
snowpacks were anomalously low in northern latitudes. Early loss of snowpack reduces the cool water inputs into rivers and lakes from snowmelt in warmer summer months.

Fig. 2. Canadian gridded temperature and precipitation anomalies (CANGRD) from the Government of Canada: https://climate-change.canada.ca/climate-data/#/historical-gridded-data. Temperatures from 2016 to 2018 coincide with the freshwater residence period of 2021 salmon returns with the exception of pinks that also used freshwater habitats in 2019. These data are interpolated from adjusted and homogenized climate station data at a 50 km resolution. Anomalies represent the departure from a mean reference period (1961–1990). Temperature anomalies are expressed as degree Celsius (°C).

Correspondingly, river temperatures in a number of systems have been warmer. For example, summer river temperatures have increasingly exceeded the optimal temperature ranges of some salmon populations, particularly adult sockeye that migrated to their upstream spawning grounds in the Fraser watershed from 2016–2018 (DFO 2021). River temperatures above 18°C can result in decreased adult salmon swimming performance, and above 20°C can increase adult mortality, adult disease, egg viability, and legacy effects that have negative impacts on juvenile condition (Tierney et al. 2009; Burt et al. 2011; Eliason et al. 2011; Sopinka et al. 2016).

High in-river spawning and incubation temperatures can have population-specific negative effects on fertilization success and embryo survival, affect timing of hatch (Whitney et al. 2014), emergence (Macdonald et al. 1998), and reduce swimming endurance and impair swimming behavior of fry (Burt et al. 2012). For juveniles that rear in freshwater, warmer temperatures can improve juvenile growth rates when prey are not limiting (Brett 1971, Edmundson and Mazumder 2001), and also increase the length of the growing season in some areas (Schindler et al. 2005). The specific freshwater conditions each salmon population is exposed to will vary by system; however, as temperatures continue to increase, the net effect on salmon populations is expected to be negative (Crozier et al. 2019, 2021).

In addition to rising temperatures, global climate change affects patterns in precipitation. Record summer droughts have affected BC in recent years, including 2015, 2017, and 2018. The most significant of these occurred in 2017, during which records were set for the driest season, with almost no rain falling in southern BC from June to late October. In 2018, BC experienced extensive dry conditions from July to November due to a lack of precipitation during this period, and an early spring heatwave that depleted snowpacks early. In 2019, a spring heatwave created dry conditions across the province, and drove down streamflows. Heavy rains in July relieved the drought, and by October most of the province had returned to normal. Increasing frequency of drought in recent years has lowered river flows, potentially blocking access to spawning habitat, stranding salmon, and increasing their exposure to predators.

Profound changes are also occurring in the marine ecosystems, where Canadian Pacific Salmon spend the latter parts of their lives rearing as juveniles for one or more years before they return to freshwater to spawn. Water temperatures have been warmer than average in the Northeast Pacific Ocean in recent decades, and were unusually warm from 2014–2020 (Fig. 3; Boldt et al. 2020). Marine temperature records were set throughout this period (Leising and Bograd 2021). Most concerning is that oceans are not just warming in surface waters but throughout the water column. Even if air temperatures were stabilized within this century through significant reductions in greenhouse gas emissions, the ocean will continue to warm (Cheng et al. 2020).

The notable warm Blob heat wave in the Northeast Pacific Ocean was present from the latter half of 2013 to the fall of 2016 (Bond et al. 2015), occurring prior to the ocean entry of most of the salmon that will return in 2021. This marine heat wave was characterized by sea-surface-temperatures (SST) that were 3–5°C above seasonal averages and extended down to depths of 100 m (Bond et al. 2015). A strong El Niño event occurred in late 2015 to early 2016 (Ross 2017), further increasing temperatures to the hottest observed throughout the 137-year time-series (Chandler et al. 2017).
Fig. 3. Annual average sea-surface-temperature anomalies from Fisheries & Oceans Canada lighthouse stations: https://www.dfo-mpo.gc.ca/science/data-donnees/lightstations-phares/index-eng.html. The 2018 and 2019 temperatures at the end of the time series coincide with the marine residence period of some sockeye, chum and Chinook salmon returning in 2021. Note there are gaps in the 2019 data points for these sites. Anomalies represent the departure from a mean reference period (1961–1990). Temperature anomalies are expressed as degree Celsius (°C).

There was a return to near-average temperatures in 2017 and 2018, likely due to the cooling effect of the La Niña that persisted until the second half of 2018 (Ross and Robert 2018, 2019). In 2017, warmer than normal temperatures persisted below 100 m, then returned near normal in 2018. New heatwaves were observed in the late summer and fall of 2018 through 2020 (Hannah et al. 2019; Ross and Robert 2020; Leising and Bograd 2021). The 2019 MHW was the third largest and longest on record, and warmer than normal subsurface temperatures were observed once more at about 100m. The 2020 marine heatwave formed in May 2020 and peaked in size in September 2020 as the second largest MHW recorded since 1982 (Leising and Bograd 2021). This MHW fell below the size requirements of MHW classification in early April 2021; however, in late April another large MHW began to form and is continuing to expand as of July 2021 (Leising and Bograd 2021).

Warm ocean temperatures may be harmful to salmon through their effect on zooplankton community composition, near the base of the salmon food web (Mackas et al. 2007). In warm Blob years in the Northeast Pacific Ocean, zooplankton communities shifted towards a greater abundance of smaller lipid-poor southern copepod species. These species are considered less nutritious for animals feeding on them. Concurrently during this period, there was a decrease in larger, more nutritious, lipid-rich zooplankton species (Mackas et al. 2007; Young et al. 2018; Galbraith and Young 2020).

Fig. 4. Commercial, recreational and Indigenous subsistence catch of Canadian pink, chum, sockeye, coho and Chinook Salmon (Grant et al. 2019; NPAFC statistics: https://npafc.org/statistics/). Average catch from 1925–1993 was 24.2 million, and from 1994–2017 was 11.6 million. Returns in the last two years were extremely low at 1.9 million in 2019 and 3.1 million in 2020.

Salmon productivity and abundances are generally declining in response to these large changes in their ecosystems. Catch for all five Fisheries & Oceans Canada managed Pacific Salmon species has declined in the past
decade (Fig. 4; Grant et al. 2019; NPAFC statistics: https://npafc.org/statistics/). This is due to both declines in target salmon population abundances, and constraints placed on mixed-stock fisheries to protect co-migrating salmon populations in poor status. Catch has dropped from an average of 24 million between 1927 and 1993, down to 12 million in recent decades. The last six years, catch averaged 4 million, and was particularly low in 2019 and 2020 at 1.9 million and 3.1 million, respectively (Fig. 4).

Despite large reductions in catch, numbers of fish reaching the spawning grounds have continued to generally decline for many Canadian Pacific Salmon populations. Though there are exceptions among all species, where particular populations are not exhibiting declining trends.

Total escapements of Chinook in 2019 and 2020 were poor, which continued the recent trend of generally low abundances (Grant et al. 2019). There are some exceptions to these trends, particularly for populations on the east coast of Vancouver Island. Chinook have generally been declining throughout their range from Oregon up to Alaska (Sharma et al. 2013; Kilduff et al. 2014; Dorner et al. 2018). They are not just declining in abundances, but are also returning at younger ages and smaller sizes, and are producing fewer eggs-per-female (Ohlberger 2013; Ohlberger et al. 2018; Xu et al. 2020). A number of these populations are facing an imminent threat of extinction (COSEWIC 2020).

Sockeye returns in 2019 and 2020 were also poor, continuing the low abundance trends observed for this species in recent years, particularly in central to southern latitudes of BC (Grant et al. 2019; Hyatt et al. 2021). Fraser River sockeye returns reached record low numbers in 2019 of 486,000, and hit a new record low again in 2020 of 292,000; compared to a long term average of 7.2 million returns (1950–2020). A number of these populations are facing an imminent threat of extinction (COSEWIC 2017). Populations in the Taku River of the Northern BC-Alaska transboundary region were exceptions to the sockeye trend in 2020.

Coho marine survival remained low relative to the 1980s. Returns in 2019 and 2020 were generally below average, though there were some populations that had returns that were closer to average. Several new survival/escapement coho indicators are in development, including for Cowichan and Sakinaw.

Pink salmon returns in 2020 were mixed but generally better than other species. Chum salmon generally exhibited poor returns in 2019 and 2020, in contrast with their recent positive trend for most populations (Grant et al. 2019).

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Patterns of Growth of the Pink Salmon *Oncorhynchus gorbuscha* in Year-Classes with Different Survival Rates during the Marine Life-history Phase

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**Keywords:** Sakhalin Island, pink salmon, growth rate, variation in size composition, skewness of size structure, survival rate during marine life-history phase

Catches of pink salmon *Oncorhynchus gorbuscha* off the eastern Sakhalin Island decreased almost threefold, from 93,181 metric tonnes (on average for 2001–2014) to 33,328 metric tonnes (on average for 2015–2019). This decrease became particularly pronounced in the dominant line of odd-numbered years: from 134,971 to 19,911 metric tonnes. A poor harvest did not meet the pre-season forecast and left fishermen disappointed. The search for the causes of a sharp pink salmon stock decline have become an urgent issue. First, it was found that pink salmon abundance decline could be caused by typhoons which led to spawning area destruction by floods and to high mortality of juvenile salmon entering the sea during storms (Kaev 2018). Then it was shown that the early temporal form of pink salmon abundance declined first, and this can serve as a precursor to the general reduction in pink salmon stocks (Kaev 2019). In this study, we analyze the growth patterns of pink salmon as one of the most important indicators of species’ response to changes in habitat conditions. It was previously believed that a study of growth helps to predict fish abundance variations (Dementyeva 1976).

Despite their high importance, the number of fish growth studies decreased (Reshetnikov et al. 2013), although scale measurement technique improvements allowed expanding the range of method applications for constructing fish scale patterns (Dgebuadze and Chernova 2009). This is particularly true for Pacific salmon: there have only been a few articles in which growth was considered as an attribute of stock dynamics. In recent years, the interest in growth pattern studies in Pacific salmon has increased in light of the critical size hypothesis suggesting that juvenile salmon must reach some minimum critical size to survive their first winter at sea (Beamish and Mahnken 2001; Howard et al. 2016). The problem of size-selective mortality has become widely discussed (Beacham et al. 2018).

The objective of this article is to evaluate the significance of pink salmon growth in its stock dynamics based on a retrospective assessment of growth patterns in year-classes with different survival rates at sea. Pink salmon return to the southeastern coast of Sakhalin Island from 2005–2020 is studied. This stock is the most abundant in the Sakhalin and has the longest data series on inter-circuli distances on scales. The survival rate of each year class is estimated as a percentage of the adult fish that returned to spawn from the number of juveniles that migrated from rivers (return rate, RR). The run size is calculated as a sum of the number of salmon in commercial fishing (the catch biomass divided by mean salmon weight) and escaped to spawn (from visual counts in several control rivers). The abundance of downstream migrants is estimated from the number of spawners in all rivers on the coast multiplied by the downstream migration index obtained annually in two or three control rivers (Kaev and Klovach 2014; Kaev and Irvine 2016).

Inter-circuli distances on scales were measured along the greater radius, starting from the 2nd circulus. The 1st circulus (central plate in the scale focus) was not measured due to errors that may arise from different degrees of scale focus deformation, being typical to all salmon at the final stages of spawning migration. The fish body length by the time of first circulus formation was assumed to be 0.133 of adult fork length (Kaev 2015b). The growth rate analysis was carried out starting from the second circulus. Body length of juveniles with the specified number of circuli is assumed to be the sum of the length that increases during their formation, except for the central plate in the scale focus.

The growth study was carried out for pink salmon females only. Furthermore, we used samples collected only during the mass migration of the late-run pink salmon (on average, 85% of catches) to exclude any impact of morphological and biological differences between seasonal forms. The growth patterns of 1,556 females (from 44 to 240 annually) from 45 samples (from two to six annually) were studied. The distance to the median of five adjacent circuli inclusive with the smallest sum of inter-circuli distances was assumed to be the first year of scale growth; then the number of circuli in the first annual zone was normalized to 23 circuli (Kaev 2015a). The number of circuli of the second year of growth was not normalized, since only the first five circuli measurements were used.
The data were tested for normality of distribution (by the χ² test) using the Statistical software package. The analysis showed that 361 of 405 empirical size-frequency distributions did not differ significantly from the normal distribution (χ² values varied in the range of 0.46–18.88 at p—from 0.997 to 0.052). In 35 distributions, a difference from the normal distribution exceeded the first statistical level of significance (χ² from 6.19 to 19.19, p—from 0.011 to 0.049). In nine cases, it proved to be higher than the second statistical level of significance (χ² from 11.66 to 26.02, p—from 0.002 to 0.009), which is acceptable for biological studies (Plokhinsky 1970). Statistical analysis was carried out using the MS Office Excel package.

**Table 1.** Survival rate of pink salmon during the marine phase with the year-classes divided into groups with low, medium, and high return rate (RR) values.

<table>
<thead>
<tr>
<th>Year of return</th>
<th>Low RR, %</th>
<th>Year of return</th>
<th>Medium RR, %</th>
<th>Year of return</th>
<th>High RR, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>0.87</td>
<td>2005</td>
<td>7.65</td>
<td>2009</td>
<td>10.32</td>
</tr>
<tr>
<td>2017</td>
<td>1.49</td>
<td>2007</td>
<td>6.53</td>
<td>2011</td>
<td>10.40</td>
</tr>
<tr>
<td>2019</td>
<td>1.81</td>
<td>2012</td>
<td>8.77</td>
<td>2013</td>
<td>15.09</td>
</tr>
<tr>
<td>2008</td>
<td>4.20</td>
<td></td>
<td></td>
<td>2006</td>
<td>18.02</td>
</tr>
<tr>
<td>2016</td>
<td>4.49</td>
<td></td>
<td></td>
<td>2010</td>
<td>12.99</td>
</tr>
<tr>
<td>2018</td>
<td>2.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>1.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pink salmon year-classes were arranged into three groups: with low, medium, and high survival rates during the marine phase (Table 1). The range of RR variations did not differ much between odd- and even-numbered year-classes which made it possible to consider them together in a relatively short observation series. The year-class returned in 2014 (RR 13.99%) was removed from the analysis since its unexpectedly high abundance was partly caused by straying of salmon of Kuril Islands origin (Kaev and Zhivotovsky 2017).

Comparing pink salmon survival rate with its growth rate (Fig. 1), we pay attention first to the period of inshore residence (before the formation of the 5th–6th circuli), which is a decisive time for the strength of year-class formation (Kaev and Irvine 2016). This agrees quite well with a study of the marine growth of juvenile pink salmon and their survival rate in the northern Gulf of Alaska, which indicates a decrease in predation mortality after juveniles’ migration offshore (Malick et al. 2011). In the southeastern Sakhalin, the pink salmon year-class returned in 2013 with the fastest growth in coastal waters were referred to the group with high survival rates, and the year-class returned in 2016 with the slowest growth were referred to the group with low survival rates. However, the
survival rate of the former year-class was not record-breaking high, while that of the latter was the highest in its group with a low survival rate.

The variance (CV) and configuration (As) of the obtained length-frequency distributions were analyzed at the time of 2 (conditional onset of marine growth in the coastal area), 7 (after its completion), and 23 circuli (overwintering) formation (Table 2). First, there is a reduction in variability with growth that becomes especially pronounced for the period of first circuli formation. CV value averaged for all year classes reduced from 13.7 to 11.2% during salmon growth between the 2nd and 7th circuli formation. This reduction further occurred during salmon growth to the 23rd circulus, down to 7.5%, but its rate per circulus slowed down twofold. For juveniles’ body length, there is a larger variance within the group of year-classes with a high survival rate at the 2nd circulus; the differences in the variance within groups decrease until it levels out completely.

Table 2. Body length (FL), variability (CV), and skewness (As) of size-frequency distribution for pink salmon females with 2, 7, and 23 circuli on scales from year-classes with high, medium, and low survival rates during the marine phase.

<table>
<thead>
<tr>
<th>Year of return</th>
<th>FL, cm</th>
<th>CV, %</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1.24</td>
<td>6.67</td>
<td>26.4</td>
</tr>
<tr>
<td>2011</td>
<td>1.07</td>
<td>6.26</td>
<td>23.3</td>
</tr>
<tr>
<td>2013</td>
<td>1.31</td>
<td>7.22</td>
<td>26.8</td>
</tr>
<tr>
<td>2006</td>
<td>1.13</td>
<td>6.32</td>
<td>24.3</td>
</tr>
<tr>
<td>2010</td>
<td>1.15</td>
<td>6.25</td>
<td>24.3</td>
</tr>
<tr>
<td>Mean</td>
<td>1.18</td>
<td>6.54</td>
<td>25.0</td>
</tr>
<tr>
<td>2005</td>
<td>1.09</td>
<td>6.12</td>
<td>23.7</td>
</tr>
<tr>
<td>2007</td>
<td>1.09</td>
<td>6.03</td>
<td>24.1</td>
</tr>
<tr>
<td>2012</td>
<td>1.06</td>
<td>5.82</td>
<td>21.9</td>
</tr>
<tr>
<td>Mean</td>
<td>1.08</td>
<td>5.99</td>
<td>23.2</td>
</tr>
<tr>
<td>2015</td>
<td>1.07</td>
<td>6.35</td>
<td>24.3</td>
</tr>
<tr>
<td>2017</td>
<td>1.11</td>
<td>6.58</td>
<td>26.2</td>
</tr>
<tr>
<td>2019</td>
<td>1.20</td>
<td>6.90</td>
<td>19.0</td>
</tr>
<tr>
<td>2008</td>
<td>1.10</td>
<td>6.13</td>
<td>24.2</td>
</tr>
<tr>
<td>2016</td>
<td>0.97</td>
<td>6.04</td>
<td>23.8</td>
</tr>
<tr>
<td>2018</td>
<td>1.06</td>
<td>6.39</td>
<td>24.6</td>
</tr>
<tr>
<td>2020</td>
<td>1.06</td>
<td>5.62</td>
<td>24.4</td>
</tr>
<tr>
<td>Mean</td>
<td>1.08</td>
<td>6.29</td>
<td>23.8</td>
</tr>
</tbody>
</table>

A comparison of skewness As of the length-frequency distributions between groups with different survival rates does not provide such a well-defined trend as obtained with CV. However, it is worth noting that a large difference appears between As values within the groups at the time of comparison. The greatest difference is observed within the group with a low survival rate.

Below we consider how the size-frequency distribution of juveniles in different groups changed between the time of formation of circuli 2 and 7, i.e., during their inshore residence. Due to the significant difference in salmon body size, data on their body lengths is presented as percentage proportions of the mean values in samples for each year-class, which were then arranged into groups with low, medium, and high survival rates (Fig. 2). During the inshore residence, the proportion of modal size groups increased while proportions of small- and large-sized fish
decreased. A decrease in the proportion of small-sized fish prevailed, especially in the group with low survival rates. In length classes of 60–80% from average, the percentage decreased by 6.4%. In the groups with medium and high survival rates, the percentage decrease was 3.3 and 2.5%, respectively. The percentage of large-sized fish also decreased, but not as significantly.

**Fig. 2.** Size structure (in % relative to mean size) of pink salmon with two (1) and seven (2) circuli on scales, averaged for the year-classes with low (a), medium (b), and high (c) survival rates during the marine life-history phase.

In all three groups of year-classes with different survival rates, the positive skewness in the length-frequency distribution decreased during inshore residence (Fig. 3). In groups with high and medium survival rates, this process was relatively short, especially in the first group, while in the low survival rate group it was the most profound and

**Fig. 3.** Body length increase in pink salmon underyearlings during the formation of respective circuli and variations in skewness of size-frequency distribution, averaged for the year-classes with high (1), medium (2), and low (3) survival rates during the marine phase.
prolonged. Patterns of skewness variations in length-frequency distribution of groups with high and medium survival rates were similar, but different in the group with a low survival rate.

At first glance, the data on the growth rate of pink salmon in the early marine phase is consistent with the opinion that fast-growing juveniles typically manifest a higher survival rate (Cross et al. 2008). From the other side, there is a non-significant correlation between the growth increase during the formation of the first four circuli (from 2nd to 5th) and the survival rate of the respective year classes \( (r = 0.32; p > 0.05). \) In our opinion, a direct strong relationship of survival rate with growth rate is unlikely. This relationship is determined not only by fish feeding success but also by many other factors, such as predators. The mentioned relationship was mostly strengthened by the contribution of three-year-classes (two with the fastest and one with the slowest growth) while growth graphs for the rest of the year-class are located quite compactly for the time of inshore residence (see Fig. 1) and interspersed among three groups with different survival rates. Thus, in our case, the growth rate of juveniles does not certainly increase the survival rate of pink salmon year classes under consideration.

After downstream migration, juvenile pink and chum salmon show a sharp increase in size variability, which is determined by rapid growth due to the transition to external feeding and by the timing of their sea entry. New smaller migrants join the already grown-up juveniles in inshore waters (Kaev and Romasenko 2002). Chum salmon year-classes in inshore bays that are initially characterized by a strongly pronounced positive skewness in the size structure manifest a low survival rate. For pink salmon, such a pattern could not be identified clearly, apparently due to earlier seaward migrations. Some pink salmon, mainly the largest individuals, might leave the survey area before observations (Kaev 2003). There is an opinion that reduction of size variability as juveniles grow in marine waters is a common phenomenon associated with a higher mortality of smaller fish (Beacham et al. 2018). It could be agreed upon, but a similar size variability reduction is observed among survivors considered separately (Table 2).

In general, survived adult fish had a larger size at the beginning of the marine phase compared to the body length distribution in the entire juvenile population previously observed inshore (Moss et al. 2005; Cross et al. 2009; Claiborne et al. 2011). Nevertheless, it is rather possible that captured juveniles did not characterize the entire population. The proportion of larger juvenile individuals that could leave the sampling area was underestimated, and as a result, the impact of size-selective mortality was overestimated (Beacham et al. 2018). Growth patterns identified in survived fish may cause additional uncertainty on this issue. A predominant reduction in smaller fish numbers, which is especially pronounced in year-classes with a low survival rate (see Fig. 2), fully meet the criteria for size-selective mortality. This is also consistent with variations in the skewness of length-frequency distributions towards negative asymmetry during inshore residence that mean a reduction in smaller fish proportion and are also pronounced in year-classes with a low survival rate (Fig. 3). This effect was observed in juvenile chum salmon when they were caught in the coastal zone off Iturup Island before and after the storm. In latter samples, the proportion of smaller juveniles reduced, probably due to their increased mortality in extreme weather conditions. Grown-up juveniles have a higher swimming ability which is very important for surviving at early life stages. Salmon fry that recently migrate from rivers also become slow-moving under storm conditions, aggregating in dense schools (Kaev 1992).

In offshore waters, trends in skewness of length-frequency distributions remained similar between the pink salmon year-classes with high and medium survival rates (Fig. 3). Pink salmon underyearlings spend summer–autumn feeding season mainly in the deep-water Sea of Okhotsk (Shuntov and Temnykh 2008), where the highest amount of macrozooplankton per unit of nekton biomass is recorded (Shuntov 2001; Dulepova 2002). Despite an almost three-fold fluctuation in macrozooplankton biomass there in different years (Volkov 2008), no food deficiency for young salmon have been reported. If a certain food shortage sometimes occurred in semi-enclosed inshore bays, it could affect the growth rate of salmon and their distribution, but there is no reliable evidence of any strict limitation of their abundance by the food factor obtained to date (Volkov 2016; Shuntov et al. 2010a, b, 2017, 2019). Variations in the growth of pink salmon during the offshore period are likely not significant for survival. This is evidenced by two year-classes with an abnormally low growth rate in open waters of the Sea of Okhotsk (see Fig. 1): one of them which returned in 2011 is in the group with a high survival rate, and the other returned in 2012 is in the group with average survival rate.

Excess mortality among slow-growing pink salmon during the winter-spring period in the ocean was shown by a comparison of inter-circuli distances within groups of circuli in underyearlings that completed their feeding season in the Sea of Okhotsk and in two-year-old salmon that migrated towards the Sea of Okhotsk in the following year (Zavolokin and Strezhneva 2013). These results should be considered with great caution since the proportions of fish of different origin in samples taken are unknown. In fact, circuli diagrams significantly differ between fish from different parts of the Sakhalin–Kuril region (Kaev 2015a), and even more on the interregional level (Temnykh
It should also be considered that the growth rate is influenced by a multitude of factors, e.g., water temperature, which accelerates or slows down the metabolic processes in poikilothermic organisms.

The anomalous decline in growth rates in the year-classes 2011 and 2012 was associated with temperature conditions, rather than with the transition to feeding on secondary forage organisms (Kaev 2015b), which is fully consistent with the opinion of V.P. Shuntov considering the lack of density-dependent factors’ effect on salmon in offshore waters. The emergence of such year-classes suggests that mortality rates during overwintering, related to fish size, are not decisive in the formation of pink salmon year-class strength. No reliable evidence has been obtained to date to confirm the hypothesis of a “critical size” for juvenile salmon that, if not reached by the end of the summer-autumn feeding season, substantially decreases chances to survive the wintertime (Beacham et al. 2017, 2018).

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Recent Trend in Variability of Chum Salmon Stock and its Potential Mechanism in Hokkaido, Japan

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Keywords: chum salmon, ocean condition, sea surface temperature, age at maturity, growth rate

Chum salmon stock in Hokkaido has been declining since its peak in 2004. In 2017, its stock level reached the lowest level over the past 30 years. In addition, we observed that the stock levels were lower than what we predicted using the sibling regression method. In such a situation, both improving hatchery programs and enhancing the accuracy of the pre-season forecast are essential to managing the chum salmon stock in Hokkaido. We explored factors affecting the variability in-stock level and precision of the pre-season forecast.

We calculated the number of chum salmon caught in Hokkaido as the sum of the number of fish caught by the coastal fishery and the number of fish caught in rivers over the period 1986–2020. The number of salmon caught by the coastal fishery is based on data published by the Hokkaido Prefectural Government, and the number of salmon caught in rivers is based on data published by the Hokkaido salmon enhancement association, a public interest incorporated foundation. The return rates of salmon were calculated for 1983–2015 brood years, which were caught during 1986–2020 as three- to five-year-old fish in Hokkaido, using the number of fish released and the number of fish caught described above. The return rates were calculated only for the Pacific coast area, which has had a significant impact on the stock variations of chum salmon in Hokkaido. In order to clarify the relationship between the return rates and coastal sea surface temperatures (SSTs), we conducted regression analyses between monthly average sea surface temperatures from April to June, when chum salmon juveniles enter the ocean and grow in coastal areas (Irie 1990; Seki 2005), at the Pacific coastal areas and return rate of salmon at the Pacific coast. For the calculation of the monthly average sea surface temperatures, we used SSTs for ten areas along the Pacific coast published by the Japan Meteorological Agency (Available at https://www.data.jma.go.jp/gmd/kaiyou/data/db/SP/dbindex_SP.html).

Our analyses revealed that the return rate of chum salmon is positively correlated with coastal sea surface temperature (SST) at ocean entry timing. This suggests that the SST during the ocean entry timing of chum salmon juveniles would be a major driver in controlling the year-class abundance and that the decline of the stock level would be caused by the “cold-spring” SST phase around Hokkaido. In 2016, the ocean regime around Hokkaido changed to a warmer condition; however, the 4-year-old fish abundance of the 2015 year-class has not recovered, and a deviation between pre-season forecast and actual abundance has increased, as well.

We found that the deviations between pre-season forecast and actual abundance were mainly caused by overestimating the abundance of 4-year-old fish. We analyzed the relationships between age at maturity of year classes and the ratio of 4-year-old fish to 3-year-old fish abundance, known as sibling relationship, to identify the factors affecting these overestimations. Our analyses revealed that the age at maturity had decreased in most areas, and it would affect the sibling relationships.

These results suggest that the decline of chum salmon stock levels in Hokkaido would have been mainly caused by cold ocean conditions during spring. In addition, the analysis for the 2015 year-class, which matched favorable ocean conditions in the coastal area, suggests that the survival rate in the Okhotsk Sea and/or farther area might be recently decreasing. The decline of the age at maturity, which affects the sibling relationship, suggests that the survival rate of fish with a slower growth rate might be decreasing.

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Keywords: Long monitoring survey, summer Bering Sea, Japanese chum salmon abundance, genetic stock identification

Asian chum salmon (Oncorhynchus keta), including Japanese stocks, are mainly distributed in the Bering Sea during summer to feed on abundant prey (Urawa et al. 2018). Since 2007, Japanese salmon research cruises have been annually conducted by R/V Hokko maru in the summer Bering Sea in order to monitor the abundance, growth and feeding of chum salmon, and their habitat (e.g., Honda et al. 2021). In this study, we estimated stock-specific abundance of chum salmon using a genetic stock identification (GSI) method. Our monitoring research has been carried out at 17 stations in the central Bering Sea (52°30’N–58°33’N, 174°49’E–174°49’W) using a surface trawl net. The average number of chum salmon caught was 2,885 fish (range: 2,653–3,308 fish) between 2007–2013 except for 2010 (no survey), while it was 2,068 fish (range: 1,532–3,058 fish) between 2014–2019. A total of 21,779 adipose fin samples were collected and DNA was extracted from these samples in the laboratory. Stock compositions (Japan, Russia, and North America) of immature chum salmon were estimated using a conditional likelihood using an SNP baseline dataset from 186 populations in the Pacific Rim (Seeb et al. 2011; Sato et al. 2014).

The estimated GSI compositions were 26.1±1.0–38.7±1.3% (mean ± standard deviation) Japanese, 58.6±1.5–69.4±1.2% Russian, and 2.6±0.7–4.0±0.9% North American stocks during the 2007–2013 seasons. On the other hand, the stock compositions were 15.8±1.1–25.9±1.4% Japanese, 65.3±1.6–73.1±1.6% Russian, and 7.0±1.1–14.7±1.3% North American during 2014–2019. Stock-specific CPUE (catch per unit effort) of chum salmon in the summer Bering Sea suggests that the abundances of Japanese and Russian stocks in 2007–2013 were higher than that in the 2014–2019 seasons. Particularly, the abundance of Japanese stocks decreased dramatically in 2014 and continued at a low level during the following years (2015–2019). Why has Japanese chum salmon abundance decreased in the summer Bering Sea since 2014? The brood year strength of Japanese chum salmon is determined in the early life stage during the coastal and offshore migrations to the Okhotsk Sea (Urawa et al. 2018; Urawa and Bugaev 2021). Relationships between the abundance of juvenile Japanese chum salmon in the autumn Okhotsk Sea and ocean age (OA)-1 fish in the Bering Sea in the following summer showed significant positive correlations (unpublished data). This result indicates that recruitment of Japanese stocks in the summer Bering Sea may already be decided in the autumn Okhotsk Sea of the previous year. Furthermore, the estimated abundance of Japanese hatchery juvenile fish in the Okhotsk Sea in the fall has decreased since 2013 (Urawa et al. 2018; Urawa and Bugaev 2021). Low numbers of juvenile chum salmon migrating from Japan to the Okhotsk Sea since 2013 may have affected (decreased) the abundance of Japanese chum salmon in the summer Bering Sea since 2014.

To contribute to a stock assessment of Japanese chum salmon, a correlation between the abundance of Japanese stocks in the summer Bering Sea and their adult return was evaluated. For the same brood year fish, relationships between mean CPUE of OA-2 Japanese stocks in the summer Bering Sea and total numbers of adult fish (OA1–4) returning to Japan showed significant positive correlations. This result shows that the CPUE of OA-2 Japanese stocks in the summer Bering Sea may reflect a total abundance of Japanese stocks of the same brood year. In addition, there was a significant positive correlation between the mean CPUE of OA-2 Japanese stocks in the Bering Sea and the numbers of OA-3 fish returning to Japan in the following year. This result indicates a possibility that the number of OA-3 fish returning to Japan can be estimated using the OA-2 CPUE of Japanese stocks in the summer Bering Sea of the previous year. Our results suggest that long monitoring survey data in the summer Bering Sea may be useful for stock assessment of Japanese chum salmon.

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Moving Targets: Assessing Fraser River Pink Salmon Run Size during a Period of Change and Uncertainty

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Keywords: Fraser River, pink salmon, Pacific Salmon Commission, stock assessment, run reconstruction

The Pacific Salmon Commission (PSC) is a regional fisheries management organization established in 1985 by Canada and the United States as the body responsible for upholding the terms of the Pacific Salmon Treaty (PSC 2019a). The mandate of the Treaty is to ensure the two Parties share responsibility for the management, research, and enhancement of salmon stocks of mutual concern to maximize optimal production and to allocate harvests relative to the production of salmon in each country. The PSC Secretariat helps administrate the implementation of Treaty obligations and supports the intense in-season management schedules for Fraser River sockeye (Oncorhynchus nerka) and pink (Oncorhynchus gorbuscha) salmon (https://www.psc.org). Biological staff manage test fisheries, collect and analyze DNA samples for stock identification, operate a hydroacoustic program in the lower Fraser River (e.g., PSC 2021; Fig. 1), and update stock assessments throughout the fishing season. Despite representing one of the most data-rich and most intensely managed salmon fisheries in the Pacific, accurately estimating the return of pink salmon, in a timely manner for making fisheries management decisions, continues to be a challenge. Recent changes to the productivity (DFO 2021) and migration behaviour (Folkes et al. 2018) of the pink salmon run has confounded in-season assessments, leading biologists to review and update their traditional suite of stock assessment tools with the aim of improving the accuracy of run size and timing estimates.

Pink salmon return to the Fraser River on an odd-year cycle (Heard 1991), typically with peak arrival timing in marine approach fisheries at the southern and northern ends of Vancouver Island (Fig. 1) occurring in the third week of August (PSC 2021). Many of the assessment tools originally developed for sockeye salmon do not perform well for pink salmon due to slower and more variable migration speeds. In addition to small and highly variable catchability coefficients associated with pink salmon catches in marine test fisheries, bias in assumed marine timing, migration behaviour, and run size priors have also contributed more frequently to assessment errors in recent years.

Similar to many other Pacific salmon populations (Dorner et al. 2008; Kovach et al. 2012), Fraser River pink salmon have demonstrated both non-stationarity and/or increased variability in both productivity (DFO 2021) and migration behaviour (Fig. 2) over the last 20 years. These changes are not surprising considering the observed...
trends in several oceanographic variables (e.g., sea surface temperature (SST), Pacific decadal oscillation (PDO), North Pacific gyre oscillation (NPGO)) over the same time frame (e.g., Agha et al. 2021; Crozier et al. 2021; Litzow et al. 2018), and a recognition that characteristics of Pacific salmon returns will often co-vary with environmental data (Beamish et al. 1999; Peterman and Dorner 2012; Connors et al. 2020). As a result, there is greater uncertainty in pre-season assumptions and priors that are used to parameterize in-season stock assessment tools. In response, both DFO and PSC biologists have recently revised their data sources and models used for both pre-season forecasts and in-season assessments of Fraser River pink salmon.

Two approaches have been explored to improve the information in pink salmon pre-season priors. The first approach constrains the historical dataset to a reduced number of years, both for model fitting and for generating prior distributions. Given the non-stationarity in the time series of timing and northern diversion (the percentage of the return anticipated to migrate around the northern tip of Vancouver Island en route to the Strait of Georgia; Folkes et al. 2018), initial pre-season estimates provided to fisheries managers in 2021 were based on a reduced subset of historical data from 2001–2019 (Fig. 2). Other salmon scientists have noted correlations between environmental regime shifts and aspects of salmon biology (e.g., Beamish et al. 1999) and acknowledge that older historical data may not be representative of current conditions.

The second method used to improve pre-season forecasts identifies environmental covariates which could explain the underlying non-stationarities in salmon abundance or behaviour. For example, DFO forecasts timing and northern diversion rates of Fraser River sockeye and pink salmon using oceanographic covariates associated with conditions experienced by returning adults during marine approach (Folkes et al. 2018). While the actual models are more complex, a simple linear regression illustrates the significant relationship between summer water temperature and the arrival timing of pink salmon to marine test fisheries (Fig. 3). DFO also incorporated
environmental covariates into their pink salmon stock recruit model to forecast the 2021 return (DFO 2021). A simple log-linear regression between regional spring SST during the ocean entry year illustrates the potential influence of a single environmental covariate, particularly when temperatures are higher than average (Fig. 4). Restricting the historical time series greatly improved model fit and significance due to the increased frequency and magnitude of extreme sea surface temperatures, and SST anomalies, in recent years. At lower temperatures, the relationships illustrated in Fig. 3 and Fig. 4 are no longer significant. Non-linear relationships between environmental variables and salmon survival or behaviour are not unusual (Munsch et al. 2020; Eliason et al. 2010), and some variables will only become informative predictors once a certain threshold has been exceeded (Munsch et al. 2020; Satterthwaite et al. 2020). In addition, it is important to select oceanographic covariates for which a biological mechanism can be identified. Such considerations will improve the predictive capacity of the approach and reduce the probability of reliance on models for which the relationship breaks down over time (Gosselin et al. 2021).

![Fig. 4. The relationship between mean sea surface temperature (SST, °C) in May of the out-migrating year at Pine Island and run size. The shaded region is the 95% confidence interval.](image)

More accurate pre-season forecasts also improve the performance of in-season stock assessment tools. For example, pre-season estimates of run size, timing, and northern diversion are used as priors in Bayesian time-density models which generate estimates of total salmon abundance and arrival timing (Michielsens and Cave 2018). The priors are updated using in-season CPUE data from marine area purse seine test fisheries to produce daily estimates of fish abundance. However, even with improved prior assumptions, low and highly variable historical catchability estimates also contribute to uncertain and/or biased in-season run sizes. For example, in 2013, an in-season run size estimate of 26 million pink salmon derived from test fishery CPUE and historical catchability estimates was later revised to an estimate of 16 million post-season—a bias of 78% (PSC 2019b). Hydroacoustic estimates produced at a facility in the lower Fraser River (near Mission, BC, Fig. 1) provide a much more accurate assessment of daily run size, but unlike the 6–8 day migration time between marine test fisheries and the river exhibited by sockeye salmon (Michielsens and Cave 2018), pink salmon swim more slowly resulting in a two–three week offset between marine approach areas and river entry (White 1998). As a result, hydroacoustic estimates of pink salmon abundance cannot be incorporated into run reconstruction models to update test fishery catchability, or into time-density models to update estimates of total run size (Michielsens and Cave 2018) in time to inform management decisions.

Given the uncertainty in pink salmon catchability, one alternative is to adopt a simplified approach using a direct relationship between CPUE and run size. There is a significant log-linear relationship ($R^2 = 59\%$) between three-day average test fishery CPUE early in the run and total pink salmon run size (Fig. 5). This simple tool can be used to provide an early indication of whether the strength of the run is likely to deviate from the pre-season forecast. Alternatively, when available, commercial fishing CPUE data have also been used to estimate pink salmon abundance through the U.S. approach (PSC 2016). While data are limited, historical run reconstructions suggest that U.S. purse seine fisheries operating in the San Juan Islands (Fig. 1) have a much lower, and less variable, catchability than the seaward purse seine test fisheries (PSC 2016). When available, the commercial data can be incorporated into existing run reconstruction models and used to update the estimate of test fishery catchability. However, modelers must still use caution when the commercial fishing effort is low and/or there are few days of commercial openings as incorrect migration rate assumptions can still introduce errors into the run reconstructions.
Changing environmental conditions and concurrent changes to productivity and migration behaviour of Fraser River pink salmon necessitates a re-evaluation of traditional stock assessment approaches. Updated model parameterization and use of environmental data to better predict annual timing and abundance of returns may help improve in-season assessments and increase the probability of achieving fisheries management objectives. In addition to improving prior estimates of run size and timing using environmental data, application of a suite of alternative in-season stock assessment tools and data sources are also required for developing robust estimates of pink salmon return. Modelling approaches should be iteratively re-evaluated in a retrospective framework, particularly until causal relationships between environmental covariates and salmon biology are better understood.

REFERENCES


Temporal and Spatial Variations in Body Size of Chum Salmon in Hokkaido

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Keywords: body size, chum salmon, condition factor

In Hokkaido, chum salmon (Oncorhynchus keta) is one of the most commercially important species. A decline in body size of Hokkaido chum salmon has been reported over the last century, and density-dependent growth had been suggested as a possible cause (Ishida et al. 1993; Kaeriyama 1998). Changes in body size relate to both behavioral and physiological traits such as survival, number of eggs per body, and mating success in many marine fish species. These changes may cause fisheries problems, one example being a reduction of recruitment. The coastal catch of chum salmon in Hokkaido has been decreasing in recent years, however, trends and geographic variation of decline are uncertain. To understand the biological condition deeply, we analyzed the changes in body size of chum salmon in Hokkaido.

To measure changes in chum salmon body size we collected data from 18 rivers in Hokkaido: the Tokushibetsu, Tokoro, Abashiri, Shari, Shibetsu, Nishibetsu, Kushiro, Tokachi, Utabetsu, Shizunai, Shikiu, Yurappu, Moheji, Shiriuchi, Toshibetsu, Chitose, Shikanetsu, and Teshio. From 2000–2018, fork lengths and body weights were measured, and 100 scale samples were taken (50 fishes per sex) once every 10 days during spawning season. Fulton’s condition factor was estimated (K = BW (kg) / FL (cm)³ × 10⁶, BW: body weight, FL: fork length). After outliers were removed by Smirnov-Grubbs' test (p < 0.05), over 400,000 individual data were used for the following analysis. Age- and sex-specific means in one sampling of each river were weighted by the number of catches in the river and the estimated mean size of the year. Ages were estimated using scales. Linear regressions between each length, weight, and condition factor with year were examined in each river. From this size-year regression, regression coefficients with significant slope (p < 0.05) were used for the examination of the size-dependent decline of body size. The regression coefficient and mean body length, or weight of 18 years in each river, were used for linear regression. For clustering analysis, condition factors in each river were scaled and analyzed using Ward’s method.

Fig. 1. Linear regression of mean body size in age-4 chum salmon in Chitose River. Panel shows (a) body weight, (b) fork length, and (c) condition factor. Condition factors were estimated by the relationship between body weight and fork length.

Declines in body weight and condition factor were detected among 17 rivers and fork length was found to have decreased among 16 rivers (Fig. 1). The average weight loss of age-3 (i.e., 0.2 in the European system), age-4
and age-5 fish were 0.029kg, 0.036kg, and 0.052kg per year, respectively. The average loss of condition factor was 0.058–0.060 per year in chum salmon aged 3–5. The slopes of the regression line for 18 years were negatively correlated with average body weight, which might mean a size-dependent decline of body size (Fig. 2). Using Ward’s hierarchical cluster analysis, indefinite groups were constructed among rivers according to temporal variation of each fork length and body weight. Compared to length and weight, variation in condition factor uncovered two more distinct groups in both sexes, southern and northern groups. The southern group contained populations in the Northeastern and Northwestern Pacific Ocean areas and the Nishibetsu River. The northern group consisted of the Okhotsk Sea area, the northern Japan sea area, and the Shibetsu River.

**Fig. 2.** Relationship between average body weight and slope of regression line for 18 years.

Because any further analysis using environmental or ecological data did not proceed this study, the reason for body size decline has not been uncovered. Both the individual and population size of chum salmon in Hokkaido during the last century was negatively correlated with an increase in fish releases (Kaeriyama 1998; Ishida et al. 1993) and density-dependent competition was suggested as one of the causes. Recently, however, the number of releases from Hokkaido have been stable and commercial catches have been decreasing. Decreasing return rate suggests intraspecific competition is not the major cause of the recent decrease in body size.

**REFERENCES**


Microevolution of Asian Sockeye Salmon *Oncorhynchus nerka* and Its Link to Modern Diversity of Populations

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**Keywords:** sockeye salmon, *Oncorhynchus nerka*, mtDNA, phylogeography, microevolution, postglacial expansion

Sockeye salmon are one of the most economically valuable species in the North Pacific. Among all the Pacific salmon it is distinguished by the most pronounced philopatry and, accordingly, the temporary stability of local populations. This biological feature significantly hinders gene flow between populations and contributes to the maintenance of sophisticated intraspecific organization. The study of current diversity formation patterns and the history of sockeye salmon populations is the key point of insight into extremely complex population structures common to pacific salmon. Phylogeography and reconstruction of paleo expansion of the species against the backdrop of global climatic oscillations in the Late Pleistocene allow us to clarify the origin of sockeye salmon populations and the diversification of intrapopulation units. MtDNA is still the marker of choice for estimation of population diversity and genetic divergence, as well as for the study of the pathways of species expansion and reconstruction of the sequence of colonization of new areas in the postglacial periods. We performed an analysis of the contemporary phylogeography of sockeye salmon and considered possible scenarios for microevolution in their Asian range using mtDNA control region (D-loop) sequencing.
One hundred seventy-two sockeye salmon from 20 samples were analyzed. Fin tissue samples were collected from 2003–2017 in the watersheds of the Chukotka Autonomous Region (Chukotka), Kamchatka peninsula (Kamchatka), continental coast of the Sea of Okhotsk, and the Kuril Islands (Fig. 1). Primers HN20 and Tpro2 (Brunner et al. 2001) were used for amplification and sequencing of 1025 bp mtDNA fragments (the entire D-loop). After multiple alignments of the sequences, 16 polymorphic sites were identified (Table 1). Most of the substitutions were detected in the first and last quarter of the D-loop sequence, as well as one insertion that was registered in the poly-T region in the middle of the sequence. Two mass haplotypes (hap_1 and hap_2) were revealed; they were present in most samples and differed by three substitutions and two indels.

Table 1. Haplotypes of the Asian sockeye salmon mtDNA control region and their nucleotide sequences.

<table>
<thead>
<tr>
<th>Haplotype</th>
<th>Substitution position</th>
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<tbody>
<tr>
<td>Hap_1_10T</td>
<td>GTAATCC-ATTCAGC</td>
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<td>Hap_14</td>
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In the geographical distribution of the haplotypes of sockeye salmon mtDNA, some patterns can be traced (Fig. 1). Along the Asian coast of the Pacific Ocean the frequencies of the haplotypes are distributed evenly rather than a mosaic, there is no pronounced clinal character in the change in frequencies. However, the presence of both haplogroups in most populations in approximately equal proportions indicates that the entire Asian portion of sockeye range is a zone of secondary contact. The star-shaped topology of the haplotype network (Fig. 2) indicates a fast and significant increase in the diversity of groups, assuming a rapid expansion of the species after a decrease in its number due to the climatic oscillations of the Pleistocene. The genealogy of Asian sockeye D-loop haplotypes showed that all sequence variants were distributed among the two haplogroups: in the first one the central haplotype was Hap_1_10T, in the second one—Hap_2_13T; unique haplotypes differed from central ones mostly in one substitution or indel (Fig. 2). Recent demographic expansion from small founder populations was also revealed by mismatch distributions analysis (Figs. 3a, b). A good fit of both the sudden population expansion model and spatial

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Fig. 2. Genealogical networks of sockeye salmon D-loop haplotypes, built on the base of the minimum number of nucleotide substitutions (MST-tree): a—excluding indels, b—including indels. The size of the circles and the area of the sectors are proportional to the frequency of the haplotype in the corresponding samples.
expansion model was observed for both haplotypic lineages. All the results point to a rapid postglacial expansion event in the Asian part of the range. The time at which the event took place was dated by the Bayesian skyline plot analysis (Fig. 4) and indicated rapid abundance growth in the Early Holocene. In fact, during periods of the Late Pleistocene glaciations, significant areas of sockeye salmon range were covered with ice. Our results confirm the previously stated hypothesis (Brykov et al. 2005) about the relatively young historical age of most populations of Asiatic sockeye salmon, which we attributed to the beginning of the Holocene transgression (~11,700 years ago). The exception, apparently, are sockeye salmon from the Kamchatka River basin, where in addition to the two main haplotypes, 12 derivatives were found: 11 of them belong to the first haplogroup, and one to the second (Hap_6 endemic for this basin). Certainly, the haplotypic diversity in populations that underwent cover glaciation will be less than in populations inhabiting the territories of former refugia (Hewitt 1996). We have every reason to believe that the vast paleobasin in the middle and upper reaches of the Kamchatka River (a deep lake in the Kamakovskaya Lowland and its tributaries) was one of the refugia in the Asian part of sockeye salmon range (Braitseva and Evtueeva 1968), where, from the time of the Sangamon (Eemian) interglacial period (130–115 thousand years ago) and throughout the last glaciation, a large population existed.

Fig. 3. Mismatch distribution analysis of the two phylogenetic lineages of sockeye salmon: a—haplogroup 1, b—haplogroup 2. The solid lines represent the expected distributions under a sudden expansion model (Model 1), the dashed line—the expected distributions under a spatial expansion model (Model 2), dots—the frequencies of the observed pairwise differences.

Fig. 4. Bayesian skyline plot for Asian sockeye salmon. The central bold line represents the median value for the relative effective population size, and the solid area denotes the 95% upper and lower credible limits.

Literature and our results (Brykov et al. 2005; Bachevskaya et al. 2013, 2015; Khrustaleva 2016) allow us to present a scenario of the modern diversification of sockeye salmon mtDNA haplotype formation, implying recurrent colonization of Asia by this species. The Hap_2_13T haplotype seems to have a more ancient origin (Fig. 5) associated with the American continent. The hypothesis of the North American origin of the Hap_2_13T haplotype is supported by its predominance in the sockeye salmon populations of the northwest coast of the Bering Sea (northeastern Kamchatka and Chukotka), east Kamchatka (Khrustaleva 2016), and its low polymorphism in Asian populations. It is possible the first wave of sockeye migration into Asia which followed the Middle Pleistocene, the Illinoian Stage (the Riss glaciation) (240–140 thousand years ago), led to the spread of the Hap_2_13T haplotype along the entire Asian-Pacific coast up to the northern islands of the Japanese archipelago. Most likely, the Hap_1_10T formed later, probably in Asia, because almost all transitional haplotypes (Hap_8, 9, 10) between
haplogroups are found in the Iturup Island populations. The existence of a refugium in the Hokkaido Island region (Hokkaido and some surrounding islands) is evidenced by the presence of relict isolated populations of kokanee and freshwater ichthyofauna there and on Iturup Island (Gritsenko et al. 2012). The migration of fauna and flora of a modern composition to the southern Kuril Islands from Hokkaido Island occurred in the upper Pleistocene when there were no straits between the islands (Geologiya SSSR 1964). However, the upper Pleistocene climatic oscillations again led to fragmentation of sockeye salmon range, isolation of individual populations in several refugia, and their divergence due to local adaptation and haplotype frequency shifts under the influence of the genetic drift (population bottleneck). We suppose that the beginning of the Holocene transgression marked the extremely rapid (explosive) distribution of this species throughout their entire modern range, and watersheds were colonized simultaneously by individuals from different geographical areas, both northern (Alaska or the Beringia region) and southern (Japan and the South Kuril Islands), in parallel with the irradiation of a Hap_1_10T haplotype from the Central Kamchatka refugium. Most likely, the southernmost Asian populations (the Japanese archipelago and the South Kuril Islands), which can be considered relict, escaped secondary contact.

Fig. 5. Bayesian tree of D-loop haplotypes of sockeye salmon. Posterior probabilities are given in the nodes.

In conclusion, we would like to emphasize that our inferences are preliminary and require further experimental confirmation. However, the data obtained allow us to consider a scenario for the formation of the modern diversity of sockeye salmon mtDNA haplotypes, which implies the repeated colonization of the Asian coast by this species during the periods of sea transgression after the Pleistocene glaciations. Moreover, it is important to take into consideration the origin of Asian sockeye stocks when analyzing its population structure.

REFERENCES


Molecular Characterization and Expression of Synaptic Plasticity-related Genes in the Olfactory Organ and Brain of Chum and Pink Salmon during Seaward and Homeward Migration

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Keywords: Anadromous, Homing, Imprinting, Olfaction, Neuroplasticity

Homeward migration of anadromous Pacific salmon (Genus *Oncorhynchus*) depends on the imprinted memory of odorants from their natal streams prior to seaward migration. Previous studies suggested the importance of synaptic plasticity in the olfactory imprinting of salmon. Although some neurotransmitters and receptors suggested its regulatory function in the olfactory imprinting by salmon, the relationship between pre-synapse molecules and olfactory imprinting was not revealed. A soluble N-ethylmaleimide-sensitive factor attachment protein receptor (Snare) complex mediates vesicle exocytosis in pre-synapse and regulates synaptic transmission and neuroplasticity (Fig. 1). In this study, three Snare component genes; snap25, stx1, and vamp2 were isolated from the olfactory center (olfactory bulb [OB] and telencephalon) of both chum salmon (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*) and the expressions in the olfactory nervous system during migrations of these salmon were analyzed by molecular biological techniques.

Molecular characterization of cDNA encoding salmon Snap25 indicated that alternative splicing produced both salmon Snap25a and Snap25b, as known in high vertebrate species. Two Syntaxin isoforms, stx1a and stx1b, were isolated as single-copy genes according to expectation. Salmon Vamp2 (110 residues) was shorter than that of high vertebrate species (115 residues) while the SNARE motif was highly conserved.

![Fig. 1.](image-url)
amino- and carboxyl-terminal SNARE motif in Snap25s, H3 domain including SNARE motif in Stx1s, and R-SNARE motif in Vamp2 between chum, pink, and the other vertebrates. Their phylogenies showed similarities of molecular evolution of Snare deduced amino acids between salmonids and other vertebrates.

Through quantitative-PCR analyses of the chum salmon olfactory organ (olfactory rosette: OR) and brain, these SNAREs mRNA (snares) showed similar expression patterns in each brain region as seen in other vertebrate species. In chum salmon, snares mRNA in the OR expressed significantly more during seaward migration than in adult life stages, including feeding and homeward migration. High snares mRNA expressions in a juvenile’s OR reflected the development of the olfactory nervous system. Snare mRNA in the OB (primarily olfactory center) showed the highest expression levels during seaward migration of juveniles. Snap25b and stx1s in the telencephalon (including higher olfactory center) increased not only during the seaward period but also in the homeward adult. Vamp2 in the telencephalon decreased in adults as in the OB.

In pink salmon, snares mRNA expression levels remained higher in the OR during homeward migration and decreased during upriver migration. These profiles were related closer to two adjacent periods, the development of the olfactory nervous system and homeward migration, than in chum salmon. In pink salmon, the developmental period of the olfactory nervous system and sexual maturation are adjacent to each other, therefore snares mRNA levels remained higher during the early phase of homeward migration. In the OB, snap25b increased while stx1b and vamp2 decreased. In the telencephalon, snap25s and stx1a increased in adults while vamp2 decreased as in chum salmon.

In these two Pacific salmon species snares mRNA was regulated similarly (Fig. 1). That pattern was upregulation during seaward migration and temporal upregulation during homeward migration. However, snares regulation in adults showed differences between the two salmon species. This is possibly related to sexual maturation age in each species: mainly three–five years in chum, compared with two years in pink salmon. In addition, migration patterns and dependence on the river for reproduction are known to differ between chum and pink salmon (Fig. 2).

This study evaluated neuronal development and plasticity status of the olfactory nervous system in two Pacific salmon species that have different migratory and maturation features. Imprinting probability is deeply related to reproduction success and enlargement of distribution. In summary, it was suggested that salmon snares mRNA expressions reflected neuronal development in the peripheral OR, possibly associated with primary projection into the OB and related with higher neural regulation in the telencephalon. In future studies, snares genes will be useful molecular markers to evaluate neuronal development and activity in salmon, coping with changing environment in the Pacific area.
An Overview of the Recent Salmon Returns in Japan: Poor Returns of Chum and Pink Salmon

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Keywords: adult returns, catch timing, chum salmon, coastal sea surface temperature, oceanic current, Okhotsk coast, Pacific coast, pink salmon

All seven species of anadromous Pacific salmon listed in the NPAFC Convention—chum salmon, Oncorhynchus keta; coho salmon, O. kisutch; pink salmon, O. gorbuscha; sockeye salmon, O. nerka; Chinook salmon, O. Tshawytscha; cherry (masu) salmon, O. masou; and steelhead trout, O. mykiss—are caught every year by coastal fisheries in northern Japan. Of these, chum and pink salmon are most commonly caught; for example, chum and pink salmon comprised more than 97% (93.5% and 3.7% by weight, respectively) of the total catch in 2019, followed by masu salmon (2.7%) (Ministry of Agriculture, Forestry and Fisheries, Japan 2021). However, chum and pink salmon catches have either declined or been variable in recent years. This study assessed the status of current stocks of Japanese chum and pink salmon and the environmental anomalies that may be affecting salmon stocks.

Fig. 1. Coastal catch (□), in-river catch (■) and number of released fry (—) for pink salmon in Japan (1970–2020).

The number of pink salmon released annually from hatcheries in Hokkaido increased markedly in the early 1980s. From the late 1980s to 2012, releases were relatively constant, with an average of 141 million fry released from 1988 to 2012 (Fig. 1). However, from 2013 to the present, the number of fry released has declined to approximately 120 million due to poor adult returns (i.e., coastal catch + in-river catch), which resulted in the lack of broodstock in rivers. Adult returns have also fluctuated markedly since the 1990s, with the relative abundance of pink salmon adult returns shifting occasionally from odd- to even-numbered years and vice versa from 1970 to 2020. From 1970 to 1991, odd-numbered-year lines were generally more abundant than even-numbered-year lines, but the latter were more numerous than the former during 1992–2002. Pink salmon adult returns in odd-numbered years exceeded those in even-numbered years during the period from 2003 to 2015, but the abundance has shifted once again from odd- to even-numbered years from 2016 to the present. From 2003 to 2020, the average number of adult returns of pink salmon in even-numbered years has been relatively stable at 6.6 million fish, except for extremely poor returns in 2012 and 2014 when 2.2 million and 1.6 million fish adults returned, respectively. However, adult returns in odd-numbered years have declined continuously from 14.9 million in 2007 to 1.1 million in 2019. Catch timing of pink salmon in coastal waters, i.e., the 25th, 50th, and 75th percentiles of the cumulative coastal annual catch, typically occurred earlier in odd-numbered years than in even-numbered years from 1989 to 2020. The 50th percentile of the coastal catch timing has been occurring earlier in both odd- and even-numbered years over the same period (Spearman’s rank correlation, [odd-numbered years] $\rho = -0.67, p < 0.001, n = 16$; [even-numbered years] $\rho = -0.68, p < 0.001, n = 16$). Japanese pink salmon return to coastal waters around August when the coastal sea surface temperature (SST) is at its highest. In the coastal waters of the Sea of Okhotsk (44°–46°N, 142°–147°E), the SST anomalies (mgd_sst_pac_T provided by the Japan Meteorological Agency) increased from 1989 to 2019 (Spearman’s rank correlation, $\rho = 0.07, p < 0.05, n = 1116$ [36 of 10-day average SST/year × 31 years]), and it appears that the earlier catch timing of pink salmon observed in the last three decades may be
associated with warmer SST conditions along the Okhotsk coast (e.g., Kovach et al. 2012). In addition, it is also possible that the intensive selection for earlier migrants of Japanese pink salmon that occurred by Hokkaido salmon hatcheries during the 1980s and up to the mid-1990s may have influenced this change in catch timing (Saito et al. 2016).

The number of chum salmon released annually increased sharply in the 1970s, but it has remained relatively constant since the early 1980s (Fig. 2). The adult returns of chum salmon peaked in 1996, with 89 million fish caught around northern Japan. However, returns of adult chum salmon started declining gradually after the mid-2000s, and then more markedly from 2010 to 2015, before being severely reduced to levels last seen in the late 1970s to early 1980s in the last five years (2016 to 2020). The declines observed in adult chum salmon returns have been particularly severe along the Pacific coasts of Hokkaido and Honshu islands (Saito and Miyakoshi 2018). When coastal SSTs increase along the Pacific coasts during March to May, the brood year stocks of chum salmon that experience these warm coastal SST conditions during the early period of their marine lifecycle tend to show better early survival, which results in improved year-class strength as adults (Saito and Nagasawa 2009; Saito and Miyakoshi 2018). The 2012 and 2013 brood years, which experienced cold coastal SSTs during March to May of 2013–2014 followed by higher SSTs during June to July in the same years, showed very poor adult returns during 2016 to 2018 along the Pacific coast (Saito and Miyakoshi 2018). Such abrupt changes in coastal SSTs, from negative anomalies to positive anomalies during March to July of 2013–2014, were believed to have been responsible for the poor adult returns in these brood years (Saito and Miyakoshi 2018). Although abrupt changes in SST were still observed in the spring of 2015 to the early summer, the coastal SSTs along the Pacific coast were higher during March to July in 2016. Given the coastal SST conditions in 2016 and considering the previous findings, the 2015 brood year could have been expected to show better year-class strength as adults. However, adult returns from the 2015 brood year were similar to, or lower than, those of the 2012 and 2013 brood years along the Pacific coast. In particular, the adult returns of the 2015 brood year along the Pacific side of Honshu were extremely low at 12.4% and 15.6% of the poor adult returns for the 2012 and 2013 brood years, respectively. During the spring to early summer of 2016, the intensity of the cold Oyashio Current (OC) that flows southward along the Pacific coast off Japan weakened considerably. Unlike the OC, the Tsugaru Warm Current, which originates from the Tsushima Warm Current (TWC) and flows from the Sea of Japan to the Pacific Ocean through the Tsugaru Strait between Hokkaido and Honshu, intensified during the same period. Wagawa et al. (2016) demonstrated that adult return rates of chum salmon in Iwate Prefecture, where the chum salmon catches are typically the highest on the Pacific side of Honshu, were negatively correlated with the ratio of warm (TWC) to cold (OC) water when the chum salmon would have been at the juvenile stage. Although the underlying mechanisms of how the relative ratio of warm to cold water affects juvenile survival in coastal waters are unknown, the extremely poor adult returns of the 2015 brood year may be related to the intensities of the OC and TWC in 2016. Since the trend of a weaker OC and a stronger TWC have continued to some extent from 2016 to the present, there is some concern about the future adult returns of chum salmon along the Pacific coast of northern Japan.

REFERENCES
Analysis of Temperature Tolerance in Juvenile Chum Salmon (*Oncorhynchus keta*)

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Keywords: chum salmon, temperature tolerance, heat shock protein, collagen

An increase in seawater temperature as a consequence of global climate change will inevitably adversely affect aquatic organisms. The impact may be severe for stenothermal species with a limited temperature range inhabiting cold-water environments, such as salmonids. In this study, we analyzed the temperature tolerance of early-return and late-return chum salmon in Iwate Prefecture, Japan (Fig. 1). The early-return chum salmon initiate their return migration to natal rivers in late September to early October, when the sea surface temperature (SST) is around 20°C, and most late-return populations come back in December when the SST is lower than 16°C. Thus, temperature tolerance may differ between those two groups. At the cellular level, heat stress may result in protein unfolding and thus impact biochemical functions. Heat-impacted cells may respond in two non-exclusive ways: proteolysis or protein degradation by proteasomes, and/or protein re-folding by chaperone proteins such as heat shock proteins (HSPs) (Iwama et al. 1999). HSPs are chaperone proteins that are produced by cells as a reaction to stressors. While their main function is the refolding of damaged proteins, some HSPs also play important roles incorrectly folding newly synthesized proteins (Ito and Nagata 2019). Thus, the HSPs are critical components for survival during physiological stress. To analyze the difference in the temperature tolerance between the populations of early- and late-returning chum salmon, we compared survival rates and transcript levels of HSPs among the different populations of chum salmon exposed to elevated temperatures.

Fig 1. Locations of rivers where juvenile chum salmon were obtained. Fertilized eggs of chum salmon were obtained from a hatchery on each river and then hatched in the laboratory tank. (A) Tsugaruishi River, (B) Katagishi River, (C) Satetsu River.

Fig 2. HSP47 mRNA levels in muscle tissues of Satetsu and Katagishi juvenile chum salmon kept at different temperatures: (A) 11°C, (B) 18°C, and (C) 23°C. Muscle samples were collected at six hours, and one, three, seven, and 14 days.
The first experiment was conducted using juvenile chum salmon from the Tsugaruishi River. The juvenile salmon were first kept in a tank with a temperature of 12°C at day 0 of the experiment and these served as controls. The water temperatures were then gradually increased up to 20, 21, 22, 23, 24, or 25°C using six separate tanks, and the fish were kept at these new temperatures for 42 days. Muscle tissues were collected on days seven, 14, 28, and 42.

The second experiment was conducted on juvenile chum salmon from the Satetsu River (early returns) and the Katagishi River (late returns). The juvenile salmon were first kept in a tank at a controlled temperature (11°C) on day 0 of the experiment. The fish were then maintained for 14 days in separate tanks at 11°C, 18°C, and 23°C. Muscle tissues were collected at six hours, and one, three, seven, and 14 days of the experiment.

![Fig. 3](image-url) Collagen mRNA levels in muscle tissues of Satetsu and Katagishi juvenile chum salmon kept at different temperatures: (A) 11°C–COL1A1, (B) 18°C–COL1A1, (C) 23°C–COL1A1, (D) 11°C–COL1A2, (E) 18°C–COL1A2 and (F) 23°C–COL1A2. Muscle samples were collected at six hours, and one, three, seven, and 14 days.

We measured the transcript levels of HSP16, HSP30, HSP47, HSP60, HSP90a, HSP90b, and HSC70 in muscle samples by quantitative real-time PCR. The results of the first experiment showed that both early- and late-return Tsugaruishi River fish struggled to survive at water temperatures above 22°C, but the survival rates of the early returns were higher than those of the late returns. Although the HSP transcripts tended to increase at elevated temperatures, there were no obvious differences in most of the HSP transcript levels between the early and late returns. However, the HSP47 transcript levels of the early returns exposed to elevated temperatures were consistently and significantly higher than those of the late returns. Similar results were obtained for HSP47 transcript levels in the second experiment. The HSP47 levels in the early-return population of Satetsu River tended to be higher than those in the late-return population of Katagishi River. Transcript levels of HSP47 were low at the control temperature of 11°C in both populations, whereas Satetsu River fish exposed to temperatures of 18°C and 23°C showed increases in HSP47 transcripts on day 3 and 7 (Fig. 2). HSP47 interacts with collagens and is regarded as a collagen-specific protein (Ito and Nagata 2017). Therefore, we measured transcript levels of two subtypes of collagen type I: collagen I α1 (COL1A1) and collagen I α2 (COL1A2). Collagen transcript levels of both COL1A1 and COL1A2 were significantly higher in the fish from the Satetsu River compared to Katagishi River fish (Fig. 3). We also measured total collagen protein levels in muscle tissues of Satetsu and Katagishi River fish. Based on the HSP47 transcript data, we compared total collagen levels from the day three samples. The basal total muscle collagen levels of Satetsu River fish were significantly higher than those of the Katagishi River fish.
Total collagen levels in Satetsu River fish at 18°C were also significantly higher than those of Katagishi River fish (Fig. 4).

![Fig. 4. Total collagen levels in muscle tissues of juvenile chum salmon kept at 11°C, 18°C, and 23°C. Values are the means ± SE. Differences in transcript levels between sampling points were analyzed using one-way ANOVA. Values not sharing a letter are significantly different by Tukey’s HSD (p < 0.05).](image)

Together, the data reveals some differences in temperature tolerance between the different groups of chum salmon. While most of the HSPs transcript levels were not significantly different between early-return and late-return populations, the transcript levels of HSP47 were consistently higher in early-returns than those in the late-returns, indicating that this collagen specific chaperone may be important for temperature tolerance due to its role in repairing and generating collagens. These results suggest that the HSP47 and collagen may be key factors influencing temperature tolerance in chum salmon.

REFERENCES


The Ecological Context of Aerobic Scope in Cost of Transport for Chum Salmon Migrating Upriver

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Keywords: metabolic rate, aerobic scope, cost of transport, thermal adaptation

Ectotherms adjust their thermal performances to various thermal ranges by altering their metabolic rates (Angilletta 2009). Exploring the relationship between thermal niche and the performance of metabolic traits is a controversial topic in the thermal adaptation of ectotherms. Aerobic scope (AS), the difference between resting metabolic rate (RMR) and maximum (aerobic) metabolic rate (MMR), has been proposed as a functional metric for thermal performance (Pörtner and Farrell 2008). The thermal sensitivity of AS is described by the thermal performance curve, where AS increases with temperature up to a peak (which is defined as the optimum temperature of aerobic scope, $T_{opt}$), and declines thereafter (Payne et al. 2016). Sub-optimal temperatures are known as pejus temperatures ($T_{pej}$). It has been reported that some salmonid species exhibit a variety of thermal profiles for AS curves, and the thermal performance curve of each species or population roughly corresponds to their temperature regime (Lee et al. 2003; Eliason et al. 2011; Clark et al. 2011; Eliason et al. 2013; Raby et al. 2016). Although the intra- or inter-specific adaptation of AS has been shown, however, the degree of correspondence between the thermal performance curves and temperature regimes varies in species or populations. For instance, the peaks of thermal performance curves in some populations do not always correspond with the mode of historically experienced temperatures (Clark et al. 2011; Eliason et al. 2013; Raby et al. 2016; Abe et al. 2019). While the studies of thermal performance curves of AS in Pacific salmonids indicated AS is an ecologically relevant trait, the ecological contexts of AS are not fully understood.

In order to explore the ecological meaning of thermal performance for AS, we used the framework of cost of transport ($COT$) with aerobic power constraint. This model incorporates the effect of maximum sustained speed (critical swim speed, $U_{crit}$) and the recovery time on $COT$ by assuming the constraint of metabolic power supply (critical power $P_{crit}$) (Martin et al. 2015). The $COT$ model, in other words, enables us to discuss the cost of resting and the time limitation of exercise in high-intensity swimming of salmon, which the existing $COT$ model could not access.

$$COT (J\cdot m^{-1}\cdot kg^{-1}) \text{ is generally expressed as the amount of energy consumption per unit distance travelled:}$$

$$COT = \frac{P_{travel}}{U_{swim} - U_{flow}}, \quad (1)$$

where, $P_{travel}$ is total power spent on travel ($J\cdot kg^{-1}\cdot s^{-1}$). $U_{swim}$ and $U_{flow}$ are the swim speed of fish ($m\cdot s^{-1}$) and the flow speed against fish swimming direction ($m\cdot s^{-1}$), respectively. Thus, $U_{swim} - U_{flow}$ is considered as substantial migration speed. $COT$ assumes a U-shaped relationship with $U_{swim}$ and then, the optimum swim speed $U_{opt}$ is estimated from the $COT$ curve as the swim speed, where the $COT$ was minimized ($COT_{min}$).

$P_{total}$ is the sum of the power requirements of maintenance metabolism $P_{meth}$ and of swimming $P_{swim}$:

$$P_{total} = P_{meth} + P_{swim}, \quad (2)$$

$P_{total}$ is equal to $P_{travel}$ in the $COT$ model without aerobic power constraint but not always equal to $P_{travel}$ in the $COT$ model with the power constraint. In the $COT$ model of the present study, critical power $P_{crit}$ was assumed, which is defined by the maximum rate of aerobic energy supply and $U_{crit}$ was also assumed as the swim speed, where $P_{total}$ is equal to $P_{crit}$. Demand for power exceeding $P_{crit}$ is supplied from anaerobic metabolism, which has a finite capacity. Thus, in the case that fish swim over $P_{crit}$, the time duration of swimming was limited and the fish needed rest after exhausting anaerobic metabolism.

When fish swim under the intensity of $P_{crit}$, the total power requirement, $P_{travel}$, of migrating fish is equal to $P_{total}$. Meanwhile, in the case that fish swim over $P_{crit}$, the additional costs should be added to $P_{travel}$. Therefore, the $COT$ model is considered as follows,
$$COT = \begin{cases} \frac{P_{total}}{U_{swim} - U_{flow}} & (P_{total} \leq P_{crit}) \\ \frac{P_{total} + P_{metb} \left( \frac{y_r(P_{total} - P_{crit})}{P_{crit} - P_{metb}} \right) + (y_r - 1)(P_{total} - P_{crit})}{U_{swim} - U_{flow}} & (P_{total} > P_{crit}) \end{cases},$$

where, $y_r$ is the recovery yield to restore substrate of anaerobic metabolism. $P_{metb}[y_r(P_{total} - P_{crit})/(P_{crit} - P_{metb})]$ is the energy expenditure during the resting period and $(y_r - 1)(P_{total} - P_{crit})$ is the overhead cost to convert a substrate, such as amino acid or lipid, to the substrate of anaerobic metabolism (e.g., glycogen). The parameters in the $COT$ model were used from published respiration data sets (Abe et al. 2019) and estimated parameters (Martin et al. 2015).

This $COT$ model was applied to chum salmon ($Oncorhynchus keta$) migrating upriver in the Kitakami River because their population has a measured performance of AS and the salmon experienced temperatures below $T_{optAS}$ throughout most of their upriver migration (Abe et al. 2019) (Fig. 1). In the $COT$ model, fish minimize $COT$ by swimming more rapidly through higher flow speed (Fig. 2A). The predicted behavioral response of fish to intermediate flow speed is to cap swimming speed so that power requirements do not exceed $U_{crit}$, but under high flow speed, $U_{opt}$ is higher than $U_{crit}$ (Fig. 2B). To evaluate the validity of the predicted behavior, we compared the swimming behavior of tagged chum salmon with accelerometers to the predicted behavior. The swimming behavior of tagged chum salmon altered while migrating upriver (Fig. 3). The fish continuously swam in the lower basin, where flow speed was low, but the fish started to rest occasionally after narrowing, where flow speed starts to increase (Fig. 3B). The fraction of time spent at high swim speed also increased (Fig. 3C).

In order to examine the temperature range for minimizing $COT$, minimum $COT$($COT_{min}$) was calculated for different temperature and flow speed conditions. In the case of a warmer temperature than $T_{optAS}$, $COT_{min}$ were higher than $T_{optAS}$ in any flow speed (Fig. 4A). $COT_{min}$ sharply increased at high flow speed and warm temperature further magnified the effect of flow speed (Fig. 4A). In contrast, the simulation in lower temperature than $T_{optAS}$ suggested the temperature minimizing $COT_{min}$($T_{COTmin}$) was not always the lowest temperature and $T_{COTmin}$ depended on flow speed (Fig. 4B).

Fig. 1. Aerobic scope of chum salmon in the Kitakami River and environmental temperature. Solid line represents a thermal performance curve fitted for salmon captured in the Kitakami River. The dashed vertical line represents the optimal temperature of AS ($T_{optAS}$). The histogram shows the distribution of river temperature from 2013 to 2017 in October, the seasonal timing of chum salmon return in the river.

Fig. 2. Swimming model and simulation and predicted optimal swimming behavior. (A) $COT$ as a function of the speed the fish swims at $T_{optAS}$. The color indicates flow velocity. Filled circles denote the $COT$ minimizing swim speed at each flow velocity. (B) Estimated $U_{opt}$ and time proportion of resting under as a function of flow speed.
The relationship between $COT_{\text{min}}$ and water temperature for each velocity condition showed that the slower the flow speed condition, the lower $T_{COT_{\text{min}}}$ (Fig. 5). $T_{COT_{\text{min}}}$ approached optimal temperature as flow speed increased but did not exceed $T_{optAS}$ in low flow speeds ($< 0.9 \text{ m·s}^{-1}$) (Fig. 5). At high flow speed ($\geq 1.0 \text{ m·s}^{-1}$), however, $T_{COT_{\text{min}}}$ switched to moving away from $T_{optAS}$. Interestingly, from intermediate flow speeds ($\geq 0.7 \text{ m·s}^{-1}$), $COT_{\text{min}}$ decreased with the temperature when approaching $T_{optAS}$, but increased sharply after $T_{optAS}$. The sharp increase in $COT_{\text{min}}$ became more remarkable with higher flow speed (Fig. 5). This is because the swim speed minimizing $COT_{\text{min}}$ becomes higher than $U_{crit}$ under high flow speed and chum salmon would have to spend a large fraction of its time resting. The simulation suggested that the temperature slightly below $T_{optAS}$ minimized $COT$ under high flow speed, that is, the temperature range is better to save $COT$ for salmon migrating upriver. In addition, the temperature range minimizing $COT_{\text{min}}$ corresponded to the empirical temperature of tagged chum salmon migrating upriver (Fig. 5). Our results provided a new perspective on the ecological meaning of aerobic scope. Further quantitative study is needed to better understand the metabolic adaptation of fish to thermal regimes.

Fig. 3. Study map, the distributions of flow velocity, and the swimming behavior of tagged salmon migrating upriver. (A) Study map of the tracking survey. Filled yellow and black circles represent the release point of tagged fish and the point positioned by VHF tracking, respectively. The time-series data retrieved from the attached accelerometer was classified with six sections divided by the positions. (B) The measurement of flow speed was performed at four bridges (Chitose, Hanafuji, Maiya, and Tome represented in (A)). The colors represent flow velocity and the filled circles indicate the measured values with a flow meter. Colored meshes were created using two-dimensional linear interpolation. (C) Time proportion of time occupied by high-intensity swimming inactive phase (red) and time proportion of time occupied by total time (grey) in each section.

Fig. 4. Minimum $COT$ ($COT_{\text{min}}$) as a function of flow speed. The upper (A) and lower (B) figures represent the predictions of $COT_{\text{min}}$ over and under $T_{optAS}$, respectively. The colored lines indicate predicted $COT_{\text{min}}$ in each temperature. The black lines denote predicted $COT_{\text{min}}$ at $T_{optAS}$. 
**Fig. 5.** Minimum $COT (COT_{\text{min}})$ as a function of temperature. Colored lines indicate predicted $COT_{\text{min}}$ in each flow speed. Filled circles denote the $COT_{\text{min}}$ minimizing temperature ($T_{\text{COT\text{min}}}$) at each flow speed. The vertical black line represents $T_{\text{optAS}}$. The shaded area indicates the $T_{\text{pej}}$ range (sub-optimal temperature range). The grey lines indicate the temperatures at which AS becomes 80% of its maximum value. Box plot denotes the experienced temperatures of tagged salmon.

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Does Long-distance Downstream Migration Influence the Survival of Chum Salmon? Comparison of Adult Returns between the Upper and Lower Reaches Release Sites

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Keywords: chum salmon, river, downstream migration, mortality, adult returns

Mass mortalities are presumed to occur immediately after entry into the ocean in the early life stages of chum salmon, Oncorhynchus keta (Wertheimer and Thrower 2007). However, high levels of mortality in chum salmon fry have been observed in rivers (Kasugai et al. 2013, 2014; Morita et al. 2015). In the Nishibetsu River, located in eastern Hokkaido, northern Japan, chum salmon fry migrate downstream over a distance of approximately 100 km from the hatcheries in the upper reaches to the river mouth. Chum salmon fry released into the upper reaches in mid-April arrived at the lower reaches approximately two weeks later (Kasugai et al. 2013). The condition factors of fry caught in the lower reaches were lower than those of fry caught in the upper reaches (Kasugai unpublished data). In addition, glycogen, triglyceride and nutrient conditions of fry caught in the lower reaches were remarkably lower than those at the release sites (Mizuno and Misaka unpublished data). Thus, it was suggested that the condition of released fry becomes poor during downstream migration in the Nishibetsu River.

Fig. 1. Location of this study. Closed triangles indicate hatchery and recapture site in the river. Closed circles and open circles indicate survey sites in the littoral and nearshore areas, respectively.

To investigate the influence of long downstream migration on the survival of chum salmon, marked fry were released into the upper reaches (UR) and lower reaches (LR) of the Nishibetsu River on 24 April 2010, and adult returns of marked fish were compared. Surveys were carried out between late April and mid-July in 2010, to understand the migration of marked fish in the river and coastal areas (Fig. 1). In the Nishibetsu River, fry were recaptured using a rotary screw trap at a salmon weir. In Nemuro Bay, juveniles were captured with seine nets in the littoral zone and two-boat trawling in the nearshore areas. To evaluate the survival of marked fish, scales and otoliths for aging and mark confirmation were extracted from 400 adult fish caught in the Nishibetsu River at 10-day-intervals from late August to early December between 2012 and 2014. The number of marked fish found in the samples was expanded to estimate the total number of marked fish caught in the Nishibetsu River.

Upper reach fry recaptured at the salmon weir peaked on 3 May, and they migrated from the hatchery to the salmon weir in about 10 days on average. The condition factors of UR fry recaptured at the salmon weir were lower than those at the time of release. Appearance periods in the coastal area did not differ between UR juveniles and LR juveniles. In the littoral zone, UR juveniles were caught less frequently than LR juveniles, and the condition factors of UR juveniles were lower than those of LR juveniles. In the nearshore areas, the catch number of UR juveniles was almost the same as the catch number of LR juveniles. Adults of both marked fish were found before the parent
breeding period, and periods of upriver migration did not differ between UR adults and LR adults. The river return rate of UR adults was estimated to be approximately half that of LR adults. Our study suggests that the deterioration of nutritional conditions for fry during long-distance downstream migration could influence salmon survival.

REFERENCES


The Use of Spatial Stream Network Models to Evaluate the Effects of Varying Stream Temperatures on Wild Coho Life History Expression and Survival

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Keywords: coho salmon, jacks, climate change, forecasts, freshwater temperature, marine indicators

Climate change is affecting survival of Pacific salmon (Oncorhynchus spp.) stocks all along the west coast of North America. In this study, we evaluated survival of wild coho salmon (O. kisutch) measured at Bingham Creek in western Washington, where a full census trap has operated since 1982 (Fig. 1). Annually at the trapping site, all coho smolts were marked with a coded wire tag (CWT) and released. Returns of tagged precocious males (jacks) and recoveries of tagged adults in fisheries and returning to the trap were used to estimate marine survival. The relationship between jack and adult marine survival has been used as a management tool to forecast returns of wild coho throughout coastal watersheds for decades but has become increasingly unreliable. The goal of this study was to use environmental indicators to better account for variation in jack and adult marine survival and improve forecasting skills.

Wild coho jack rates for brood years 1980 to 2016 were evaluated over time and found to be increasing, especially after 2005, a year characterized by delayed upwelling and low productivity in the coastal environment (Brodeur et al. 2006; Schwing et al. 2006). Jacking is thought to be initiated by reaching a specific growth or body condition threshold by a certain point in the salmon life cycle (DeFilippo et al. 2019), although it is uncertain whether this occurs in freshwater or during the early marine stage. Freshwater rearing conditions can influence smolt characteristics such as emigration timing and body size, which in turn influence age-at-maturity (jack rates) in the marine environment. We hypothesized that jack rates were related to freshwater rearing conditions (e.g., streamflow, temperature) and that by accounting for variation in stream flow and temperature during critical life
history periods, we could better predict jack abundance and improve forecast model performance (Fig. 2). We also considered the role of ocean conditions during the first few months following freshwater emigration.

**Table 1.** Freshwater indicators used to predict coho salmon jack rate at the Bingham Creek trap (brood years 1996 to 2016). Indicators included spawner abundance (adults passed above the Bingham Creek trap) and cumulative, minimum, and maximum (cum., min., max.) stream flow during life history phases measured at the Satsop River (USGS 1203500). Stream temperatures for missing dates over the time series were derived from the relationship between stream flow and stream temperature measured at the Satsop River (Ecology 22G070) from 1960 to 1993.

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</table>

The freshwater dataset used to evaluate variation in jack rates through time (brood years 1996 to 2016) included spawner abundance, stream flow during spawning, incubation, summer rearing, overwinter periods, and stream temperature during the peak summer rearing period (Table 1). In addition, spatially continuous mean August stream temperature maps (“Thermalscapes”) were developed for current conditions and mid- (2040) and late-century (2080) stream temperature scenarios based on climate change projections (Winkowski et al. 2018; Winkowski and Zimmerman 2019). The spatial stream network (SSN) models used in this study fit temperature data measured at 123 new monitoring stations since 2014 in addition to the 36 sites used in the NorWeST summer stream temperature model (Isaak et al. 2014, 2017).

**Table 2.** Marine indicators used to predict jack rate and adult marine survival of coho salmon at the Bingham Creek trap (brood years 1996 to 2016). Indicators from the basin scale included thermal regime (cool = 1996 to 1999 plus La Niña years and warm = 2000 to 2016 plus El Niño years), North Pacific Gyre Oscillation (NPGO), Aleutian Low—Beaufort Sea Anticyclone (ALBSA), Pacific Decadal Oscillation (PDO), and Oceanic Niño Index (ONI). Regional indicators included timing of the physical spring transition from predominantly downwelling to upwelling conditions based on hydrography, sea surface temperature, deep salinity, zooplankton, and ichthyoplankton measurements off Newport, Oregon (fisheries.noaa.gov/west-coast/science-data/ocean-ecosystem-indicators-pacific-salmon-marine-survival-northern). The local indicator was Chehalis River flow (USGS 12027500) during smolt outmigration.

<table>
<thead>
<tr>
<th>Marine Indicators</th>
<th>Scale</th>
<th>Period</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Regime</td>
<td>Basin</td>
<td>Warm/Cool</td>
<td>Based on sibling relationships</td>
</tr>
<tr>
<td>NPGO</td>
<td>Basin</td>
<td>May–Sep</td>
<td>o3d.org/npgoenso.html</td>
</tr>
<tr>
<td>ALBSA</td>
<td>Basin</td>
<td>May–Sep</td>
<td>psl.noaa.gov/data/timeseries/ALBSA/</td>
</tr>
<tr>
<td>PDO</td>
<td>Basin</td>
<td>May–Sep</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>ONI</td>
<td>Basin</td>
<td>Jan–Jun</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>Physical Spring Transition</td>
<td>Regional</td>
<td>Spring</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>SST NDBC Buoys</td>
<td>Regional</td>
<td>May–Sep</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>Deep Salinity</td>
<td>Regional</td>
<td>May–Sep</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>Regional</td>
<td>May–Sep</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>Ichthyoplankton</td>
<td>Regional</td>
<td>Jan–Mar</td>
<td>NOAA Stoplight Table</td>
</tr>
<tr>
<td>Outmigration Flow</td>
<td>Local</td>
<td>Apr–Jun</td>
<td>waterdata.usgs.gov</td>
</tr>
</tbody>
</table>

Marine indicators used to evaluate jack and adult marine survival rates integrated environmental information across multiple spatial scales and included outmigration stream flow, timing of the spring transition from downwelling to upwelling conditions, sea surface temperature, salinity, zooplankton, ichthyoplankton, North Pacific Gyre Oscillation (NPGO), Aleutian Low—Beaufort Sea Anticyclone (ALBSA), Pacific Decadal Oscillation (PDO),
and Oceanic Niño Index (ONI) measurements during the early marine residence period (January through September of ocean entry year) for brood years 1996 to 2016 (Table 2). Generalized additive mixed models (GAMMs) were used to model jack and adult return rates over time and to model jack and adult marine survival as a function of environmental indicators using the R statistical package v.3.6.1 (R Core Team 2019) and mgcv package (Wood 2017).

All GAMMs were fitted with an autoregressive corAR1 error structure for correlation from one brood year to the next, a gaussian distribution with an identity link function, and included a fixed effect for thermal regime. Models were fitted with thin plate regression splines for parameter components, and the dimensions or degrees of freedom (i.e., knots, or degree of smoothing) were restricted for the fixed year parameters to a maximum of 5 to prevent overfitting. Support for candidate models was determined using AIC based on a full subsets approach (Sobocinski et al. 2021) where all covariates were assessed for collinearity and candidate models did not include covariates that were correlated with one another ($r > 0.28$). The predictive performance of the top-ranked model was assessed using a one-year ahead approach and compared to observed values with recent five-year model evaluation statistics.

Sibling relationships between jack and adult survival at Bingham Creek were not static through time and varied by thermal regime with lower jack-to-adult ratios observed in cool brood years (1980 to 1999 including La Niña years) compared to warm years (2000 to 2016 including El Niño years). Between brood years 1980 and 2016, coho jack rates ranged from 0.02 to 0.54% with a significant ($p < 0.01$, $R^2 = 0.31$, effective degrees of freedom [$EDF = 1.72$]) positive shift over time (Fig. 3). Overall, there was little support for the hypothesis that jack rates were affected by variation in freshwater during critical life history phases. However, the top performing GAMM ($R^2 = 0.56$) determined that jack rates were affected by the thermal regime (cool or warm), Chehalis River flow rates from April to June during outmigration ($k = 3$), El Niño conditions (ONI from January to June of ocean entry; $k = 3$), and timing of the physical spring transition from predominantly downwelling to upwelling conditions in the year of ocean entry ($k = 5$, Fig. 4). While thermal regime was a significant coefficient, it did not change the directional impacts of individual covariates. Jack rates were highest at extreme El Niño values (ONI greater than 0.5 or less than -0.5), when Chehalis River flows were $> 2000$ cfs ($56.6$ m$^3$ s$^{-1}$) during outmigration, and in years with an earlier spring transition date ($< June 1$).
Fig. 4. Top performing generalized additive mixed model predicting Bingham Creek jack rate as a function of thermal regime, the Oceanic Niño Index from January to June (ONIJJ), stream flow in the Chehalis River from April to June (Flow.AJ), and the physical Spring transition date based on hydrography (Phys.Trans.Hydro) in the year of ocean entry (brood years 1996 to 2016). Note that although significant, the regime coefficient did not lead to variation among the top covariates.

Covariates in the GAMM that best predicted ($R^2 = 0.80$) wild adult coho marine survival at Bingham Creek included timing of the physical spring transition from predominantly downwelling to upwelling conditions in the year of ocean entry ($k = 4$), wild coho jack rate from the same brood that returned to the trap the previous year ($k = 4$), and an indicator that integrated information about the North Pacific climate during the summer of ocean entry (ALBSA, $k = 4$), plus thermal regime (cool or warm, Fig. 5). Unlike the jack model, thermal regime significantly ($p < 0.01$) affected the directional response of the covariates. However, like jacks, higher adult coho marine survival was associated with earlier spring transition dates ($< June 1$), but also the ALBSA index, with higher survival observed during lower ALBSA index values ($< 50$). Adult survival was also strongly positively related to jack rate, but during warm regimes only.

Fig. 5. Top performing generalized additive mixed model predicting Bingham Creek adult marine survival as a function of thermal regime (cool on left and warm on right), the physical spring transition date based on hydrography (Phys.Trans.Hydro), jack rate, and the Aleutian-Low Beaufort Sea Anticyclone index from May through September (ALBSA.MS) in the year of ocean entry (brood years 1996 to 2016). Note that the thermal regime coefficient had varying directional effects on the top covariates.
Results of one-year ahead forecasting (Table 3) found that for the jack model, the GAMM slightly over-predicted abundance (MRE = -6.6%). For the adult model, the GAMM also slightly over-predicted abundance (MRE = -14.5%) but was within the acceptable range for forecasting adult returns. The adult model was particularly successful in 2019, a year when many forecasts over-predicted adult returns of wild coho.

**Table 3.** Statistics of fit for the one-year-ahead models predicting jack abundance and adult returns to Bingham Creek. Model evaluation statistics are mean raw error (MRE), mean absolute error (MAE), root mean square error (RMSE), mean percent error (MPE), and mean absolute percent error (MAPE).

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Jack Model</th>
<th>Adult Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRE</td>
<td>3.19</td>
<td>-88.4</td>
</tr>
<tr>
<td>MAE</td>
<td>11.33</td>
<td>126.52</td>
</tr>
<tr>
<td>RMSE</td>
<td>15.62</td>
<td>159.21</td>
</tr>
<tr>
<td>MPE</td>
<td>-6.6%</td>
<td>-14.5%</td>
</tr>
<tr>
<td>MAPE</td>
<td>24.8%</td>
<td>26.7%</td>
</tr>
</tbody>
</table>

The expression of the jack life history at Bingham Creek appeared to have two modes based on trade-offs in the coastal marine environment. Under the first mode, jack rates were positively related to flow during the outmigration window and negatively related to the timing of the spring transition. In those years, smolts carried out of the Chehalis River during strong flow regimes were more likely to return as jacks, rather than adults, when the timing of the physical spring transition occurred before June. Earlier spring transition dates are typically associated with higher prey availability, thereby allowing juveniles to reach the critical growth or lipid accumulation threshold required for jacking. However, jack rates also increased over the last decade and a half, and under this model, appeared to be the result of climate variation in the nearshore environment, with warmer periods, including El Niño years, producing more jacks. In those years, jack rates increased during poor ocean conditions and possibly emerged as a trade-off between remaining in an unfavorable ocean versus returning to freshwater to reproduce. Note that jack rates were highest at both high and low ONI values and increased during both favorable (cool, early onset of upwelling) and unfavorable (warm, delayed upwelling) conditions.

No freshwater indicators were identified as being important predictors of jack rate in Bingham Creek for brood years 1996 to 2016. This does not mean that environmental conditions experienced during the freshwater rearing period are not contributing to increased jack rates. There is certainly room to explore other temperature metrics that may not be correlated with mean August stream temperature but could influence behavior, growth, or ecology of juvenile salmon during the freshwater rearing period. By mid-century (2040), temperatures in Bingham Creek are expected to increase by 9% to 14.5°C and by late-century (2080) they will increase by 21% to 16.0°C. The main stem Chehalis and many of the major tributaries in the basin are projected to exceed 18°C in August by 2080 (Winkowski and Zimmerman 2019), approaching the upper limit of thermal tolerance for juvenile salmonids.

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Ontogeny of Critical Swimming Speeds for Juvenile Chum Salmon

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Keywords: metabolic rate, swimming performance, ontogeny, thermal sensitivity

Chum salmon (Oncorhynchus keta) is widely distributed over a large geographic range of the North Pacific Ocean (Augerot 2005). The Pacific side of Honshu Island, Japan, called the Sanriku coastal area, represents the southernmost range of the Asian population of chum salmon (Kaeriyama 1989). Chum salmon juveniles reside in the Sanriku coastal area for two months, a relatively short residence period compared to Alaskan juveniles (Irie 1990; Orsi et al. 2004). Juveniles reside in the coastal area where the sea surface temperature (SST) ranges from 5–13°C and in late May, they start their offshore migration to feeding grounds in the Okhotsk Sea (Irie 1990). Sanriku is located at a lower latitude than Hokkaido and is a long distance to the Okhotsk Sea. In addition, the offshore currents such as the Tsugaru Warmwater Current and the Chishima Current, flow in the opposite direction from which the juveniles migrate. Hence, high swimming performance is required for juveniles to overcome the offshore currents. Before offshore migration, the fork length (FL) of the chum salmon juveniles ranges from 3–8 cm, and soon after the migrations, FL reaches from 8–12 cm. It is possible that during their short coastal residence, the swimming performance may change. However, the swimming performance has not been measured across a wide body size range yet. Therefore, the effect of body size on the swimming performance of chum salmon remains unclear.

For measuring the swimming performance, the Blazka- or Brett-type swim tunnel respirometer (Loligo Systems, Denmark) was used. Chum salmon fries, juveniles, and adults originated from hatcheries and the wild. Fries, juveniles, and adults (n = 41; 3.58–71.7 cm FL) were reared in tanks at three temperature conditions (8, 12, and 20°C) in the International Coastal Research Center, the Atmosphere and Ocean Research Institute, University of Tokyo. Other juveniles (n = 7; FL: 14.4–19.0 cm FL) were reared at 22°C in the Iwate Fisheries Technology Center. The fries and juveniles were reared in a tank filled with seawater and were fed at approximate surplus food levels. The adults were reared in tanks filled with freshwater, and were not fed. After 12–72 hour fasts, individual fish were put into the respirometer, and their critical swimming speed: \( U_{\text{crit}} \) (cm·s\(^{-1}\)) and oxygen consumption rate: \( \dot{M}_{O_2} (\mu g \text{ } O_2 \cdot g^{-1} \cdot \text{min}^{-1}) \) were measured based on previous protocol (Abe et al. 2019).

First, the \( U_{\text{crit}} \) tended to increase with an increase in FL through the entire life history (Fig. 1). The effect of temperature on \( U_{\text{crit}} \) was not significant (\( t = 1.16, p = 0.25 \)). When the \( U_{\text{crit}} \) values only of the fries and the juveniles were fitted with a linear function of FL, the slope of the regression line was steeper than that in the entire life history (Fig. 1), indicating the \( U_{\text{crit}} \) increases five times as quickly as in the entire life history. In addition, the absolute value of \( U_{\text{crit}} \) in the early life stage was higher than the southward current (25 cm·s\(^{-1}\); Wagawa et al. 2016).
experienced by juveniles in Sanriku. Hence, it is possible the juveniles in Sanriku increase their body size, acquire the ability to swim at a higher speed than the southward currents and then, start their northward migration to the Okhotsk Sea.

In order for juveniles to increase their body size, surplus energy, the subtraction of respiration and excretion from total energy intake, should be allocated for somatic growth as much as possible. Surplus energy is largely affected by respiration. The energy decreases under high water temperature because of high respiration cost. It is possible that temperature has a profound effect on the respiration cost of chum salmon. However, little is known about the temperature effect on the respiration cost.

It is generally known that \( \dot{M}_{O_2} \) increases exponentially as swimming speed increases. Therefore, \( \dot{M}_{O_2} \) was fitted with an exponential function of swimming speed as follows (Dewar and Graham 1994):

\[
\dot{M}_{O_2} = SMR \cdot e^{(aU)},
\]

where \( SMR \) (standard metabolic rate) is the intercept for the \( \dot{M}_{O_2} \) when swimming speed is 0, \( a \) is the coefficient related to swimming speed \((U)\) of the function for \( \dot{M}_{O_2} \).

SMR is considered as a minimum respiration cost. To reveal the temperature effect on respiration cost during the early life stage, SMRs of juveniles \((n = 18, \text{body weight } < 15 \text{ g})\) were compared between different water temperatures.

![Fig. 2. SMR (Standard Metabolic Rate) across the temperature range from 5 to 20°C. The solid curve indicates the exponential function of temperature and SMR. The curve was extrapolated (broken line) to derive the SMR at 5°C. The green shaded area indicates the sea surface temperature ranges of the coastal area where the Japanese juveniles reside (Irie 1990).](image)

SMR was higher at a higher temperature, and the thermal sensitivity \((Q_{10})\) for SMR was estimated to be 2.13 (Fig. 2). In the Sanriku coastal area, the water temperatures (averaged from surface to 20 m depth) around 2010 increased more rapidly than around 1980 (1980s: 1.5–2.5°C month\(^{-1}\), 2008–2015: 2.4–3.0°C month\(^{-1}\); Kawashima et al. 2018). The \( Q_{10} \) value indicates that if the SST (5°C in March) increases to 14°C in June (3.0°C month\(^{-1}\)), the respiration cost at 14°C becomes twice as high as that at 5°C. Hence, the rapid increase of SST might decrease the energy for somatic growth of chum salmon juveniles more rapidly, leading to smaller body sizes before offshore migration, a decline of swimming performance, and consequently, lower survival rate.

The \( Q_{10} \) of chum salmon juveniles was lower than that of sockeye \((O. \text{nerka}: 2.36; \text{Beauchamp et al. 1989})\) and pink salmon adults \((O. \text{gorbuscha}: 2.36; \text{Beauchamp et al. 1989})\), while a little bit higher than that of coho \((O. \text{kisutch}: 1.98; \text{Stewart and Ibarra 1991})\) and Chinook salmon adults \((O. \text{tshawytscha}: 1.98; \text{Stewart and Ibarra 1991})\). However, one remaining question is what is the \( Q_{10} \) of other Pacific salmonids in their early life, such as fry and juveniles. Further study of \( Q_{10} \) differences among life stages or species may provide the physiological background for interspecific differences in the distribution range of Pacific salmonids.

REFERENCES


Prey Selectivity and Diet Partitioning of Juvenile Salmon in Coastal Waters in Relation to Prey Biomass and Implications for Salmon Early Marine Survival

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Keywords: trophic ecology, prey, diet overlap, selectivity, Chinook salmon, coho salmon, California Current

Feeding conditions for juvenile salmon during their early ocean residence have been shown to be critical to their growth and survival, although direct sampling of their food availability has been limited (Brodeur et al. 2011). Increased understanding of prey dynamics during the early marine period of juvenile salmon could help us to better understand when increased competition may be occurring between salmon that eat at similar trophic levels. Juvenile coho (Oncorhynchus kisutch) and Chinook (Oncorhynchus tshawytscha) salmon typically consume age-zero juvenile fish, crab larvae, krill, and amphipods during their early marine residence, many of which are difficult to quantitatively assess using typical plankton gear (Brodeur et al. 2011). In May 2017 and 2018, as part of the National Oceanic and Atmospheric Administration’s Juvenile Salmon Ocean and Ecosystem Survey (JSOES), we collected juvenile salmon and their prey concurrently in coastal waters off Washington, USA by adding a fine mesh liner to the surface trawl net that has previously been used to sample juvenile salmon. The primary focus of the JSOES survey is to better understand the early marine period of Endangered Species Act (ESA) listed salmon and how changes in ocean conditions may impact their marine survival (Daly et al. 2013; Burke et al. 2013; Crozier et al. 2021). The goal of our study was to specifically examine prey environment, diet overlap, and how salmon utilized the available prey in 2017 and 2018.

Ocean conditions during the winter and spring previous to juvenile salmon outmigration have been correlated with first summer salmon prey community and biomass, salmon diets, and salmon size, growth, body condition, and subsequent adult returns (Pearcy 1992; Daly and Brodeur 2015; Brodeur and Daly 2019). Sea surface ocean temperatures in 2017 were warm, and we observed low catches at every trophic level measured (Wells et al. 2017), resulting in a poor ocean productivity year for salmon. Ocean temperatures were cooler in 2018 than in 2017, although still above the long-term average, and numerous ecosystem indicators in 2018 suggested better conditions than 2017 (fair ocean condition year). Ocean ecosystem indicator rankings for 2017 and 2018 are available at https://www.fisheries.noaa.gov/west-coast/science-data/ocean-ecosystem-indicators-pacific-salmon-marine-survival-northern.

Non-metric multidimensional scaling ordination (NMDS) was used to visually compare the prey field biomass in 2017 and 2018, and the Analysis of similarities (ANOSIM) was used to test for significant differences between the years (Clarke 1993). The prey fields were significantly different from each other (ANOSIM, Global $r = 0.152; p = 0.002$), and the average prey biomass per km towed was higher in 2018 mostly due to increased catches of crab.
larvae (Fig. 1). The diversity of prey was also higher in 2018 (Shannon H’= 1.15) than in 2017 (H’ = 0.56). The biomasses of fish in the prey field were only slightly higher in 2018, but invertebrates were much more prevalent in 2018.

To compare the juvenile salmon diet composition to the prey fields, we calculated the diet composition on prey that were recently consumed (prey conditions of 3 or 4; see Brodeur et al. (2011) for methodology) and we averaged these diets across the juvenile salmon at each station. The prey field biomass at a sampling station was converted to percentage compositions for comparison to juvenile coho and Chinook salmon diets. Overall, the salmon diets were similar to each other in 2017 but not 2018. The salmon were selective on specific taxa that were rare in the environment, and also avoided consuming some common taxa found in the environment. Specifically, in 2017, Chinook and coho salmon ate similar diets to each other (ANOSIM; Global \( r = 0.041; p = 0.24 \)), yet the diets were significantly different from the prey composition in the environment (ANOSIM; Global \( r = 0.445; p = 0.001 \); Fig. 2). In 2018, the diets of the two species were significantly different from each other and also from the prey in the environment (ANOSIM; Global \( r = 0.474; p = 0.001 \); Fig. 2). Percent Similarity Index (PSI) was used to calculate how closely the diet and prey composition were to each other, with a resulting value > 60% indicating high overlap (Wallace and Ramsey 1983). Percent Similarity Index between average station diet and available prey composition was low for coho and Chinook salmon in both years (all values < 16%) as the salmon were consuming taxa that were rarely or not caught in the trawl or were rarely/not consuming taxa that were the dominant taxa caught in the environment.

By visually comparing the frequency of taxa occurring at a sampling station in the environment and the diets (Fig. 3), we observe that yearling coho and Chinook salmon infrequently fed upon fish such as juvenile smelts (Osmeridae), ronquils, and flatfishes. Juvenile smelt were present in the environment at almost all (2017) or all (2018) of the stations sampled, yet they were eaten only at around 20% of the stations for Chinook salmon and about 40% of the stations for coho salmon (Fig. 3). Juvenile flatfishes were also sampled in the environment at almost all of the stations, yet they were present in the diets of Chinook salmon at only a few stations in both years and were found not at all (2017) or rarely (2018) in coho salmon diets. Juvenile sculpins (Cottidae) were consistently selected and consumed by the salmon (eaten at > 60% of the stations sampled), yet they were rarely caught in the environment (2018) or not caught at all (2017; Fig. 3). For invertebrate prey, both salmon species increasingly ate Cancer spp. larvae and coho salmon shrimp larvae (Pandalidae) and hyperiid amphipods (Amphipoda) relative to the frequency of these taxa in the environment, although the fine mesh liner in the net may not be able to quantitatively retain such small taxa accurately. Overall, juvenile salmon diets had higher congruency with the prey in the environment in 2018 than in 2017, when there was both higher biomass and diversity of prey available.
While we observed differences in the salmon diets and the prey environment in 2017 and 2018, there was little difference in salmon marine survival based upon adult returns between the two years. Yearling Chinook salmon returned from ocean outmigration years 2017 and 2018 in extremely low numbers, and coho salmon returned in slightly higher numbers in 2018 than in 2017. Although any comparison involving only two years is insufficient to draw definitive conclusions, our results are consistent with an emerging hypothesis that diet partitioning may occur when food resources are plentiful, and interspecific competition for the same prey taxa may occur when food resources are scarcer. In the future, looking at prey fields of salmon and their feeding selectivity during more productive ocean conditions than were observed in 2017–2018 could help us to better understand the trophic dynamics and survival of juvenile salmon during their early marine period and contribute to forecasting subsequent salmon returns.

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REFERENCES


Return Rates of Chum Salmon are Affected by Different Timings of Juvenile Release

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Keywords: chum salmon, return rate, SST, release timing

Recently, there has been a decreasing trend in the return rate of late-run chum salmon juveniles released from hatcheries in southern Hokkaido. According to previous studies, return rates are critically affected by high mortality of juveniles along the coast (Healey 1982; Bax 1983; Fukuwaka and Suzuki 2005), which is related to coastal sea surface temperature (SST) and juvenile weight at release (Mayama and Ishida 2003). In the Hokkaido hatchery program, chum salmon are classified into three populations (early-, middle-, and late-run) depending on run timing. Their offspring are released in the corresponding order, and juveniles of each run population experience different coastal environments.

Fig. 1. The location of Moheji river.

We, therefore, hypothesized that coastal environmental conditions faced by late-run juveniles are not optimal. Verifying this hypothesis required analysis of return rates and the coastal environment for each run population. This study aimed to clarify the relationship of each run population’s return rate to release timing, weight of juveniles at release, and coastal SST.

To determine return rates, we compared the number of released juveniles and captured returned fish in the Moheji River from 2002 to 2014. We then examined the effects that mean juvenile weight at release, the halfway point of population release (the time at which the number of released fish reached half of the total), and the coastal SST of the Tsugaru Strait exerted on return rates for each run population.

There were no obvious changes in return rates for the early- and middle-run populations over the study period. However, for the late-run population, the return rate decreased. The halfway point of population release had a positive correlation with return rates for early and middle runs (early, $r = 0.62, p < 0.05$; middle, $r = 0.64, p < 0.05$). On the other hand, for the late run, the halfway point of population release and the coastal SST at that time showed a negative correlation with the return rate (halfway point of population release, $r = -0.75, p < 0.05$; coastal SST, $r = -0.68; p < 0.05$). Furthermore, the length of the period from the halfway point of population release to the time when the coastal SST exceeded $13^\circ$C (optimal coastal SST duration) was positively correlated with return rate ($r = 0.83, p < 0.05$). No correlation was observed between mean weight at release and return rate for any of the three runs.

This study shows that the return rates of late-run populations are affected by the timing of juvenile release and the duration of optimal coastal SST.

REFERENCES


Low Nutritional Status in the Freshwater Phase and Temperature at Seawater Entry Reduce Swimming Performance of Juvenile Chum Salmon

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Keywords: Chum salmon, early marine entry, nutritional status, $U_{crit}$

Chum salmon (*Oncorhynchus keta*) is an important commercial fish in Hokkaido and northeastern Japan, and its resources are maintained by stock enhancement programs (Nagata et al. 2012; Miyakoshi et al. 2013; Kitada 2014). Japanese chum salmon likely experience substantial mortality when entering the sea and reaching the Sea of Okhotsk; however, little is known about the causes of this early mortality. Following their release, juvenile chum salmon spend days to weeks in the river (Hasegawa and Takahashi 2013; Kasugai et al. 2013), and the nutritional condition of individuals decreases during this time (Shimizu et al. 2016). In the salmon of eastern Hokkaido, the adult return rate tends to be low when coastal water temperatures are low, during the early stages of marine life (Nagata et al. 2016). Thus, sea surface temperature (SST) has been implicated as a key factor in determining the distribution and outmigration of chum salmon along the coast. When juvenile chum salmon experience low water temperatures ($\leq 5°C$) in coastal waters, their movements are restricted and their growth ceases (Miyakoshi et al. 2007; Kasugai et al. 2012). However, it is unclear whether the nutritional conditions of freshwater and SST interact to affect the growth and swimming ability of juvenile chum salmon. The purpose of this study is to elucidate the combined effects of freshwater feeding status and seawater temperature on the swimming ability of juvenile chum salmon under laboratory conditions.

![Fig. 1. Design of rearing experiments. The experiment was conducted in April and May 2018. Salmon fry were reared in freshwater at feeding rates of 0, 1, and 3% for five days, followed by seawater rearing with sufficient food at 4, 7, and 10°C, respectively.](image)

Juveniles weighing approximately 1.0 g were categorized into the following three groups and reared in freshwater for five days at different feeding rates (FR): 0% (fasted), 1%, and 3% per body weight. Fish from each group were then acclimated for three days to seawater at low (5°C), medium (7°C), or high (10°C) temperatures, creating nine treatments (Fig.1). Fish were then reared for an additional five days in which they were fed to satiation. Critical swimming speed ($U_{crit}$, Brett 1964) was evaluated using a stamina tunnel as an indicator of swimming ability.

$U_{crit}$ was affected by both fasting experience in freshwater and seawater temperatures (Fig.2). $U_{crit}$ on the 5th day of seawater rearing was not affected by the feeding rate during freshwater rearing, but the effect of seawater temperature was observed and was significantly lower in the 5°C group. On the 10th day of seawater rearing, there was a significant difference in $U_{crit}$ between the FR 0% group and the FR 3% group. $U_{crit}$ was also significantly lower at lower water temperatures.

The results of this study indicate that low seawater temperatures reduce the swimming ability of juvenile chum salmon, and that relatively short periods of freshwater fasting affect swimming ability. The effect of water temperature on swimming ability is known in many salmonid fishes. However, the possibility that nutritional status during freshwater life affects swimming ability after the transition to seawater is a new finding. The improvement of nutritional status may contribute to the improvement of the survival rate of hatchery juvenile chum salmon after release.
Effects of feeding rate in freshwater and transfer to a different seawater temperature with feeding on critical swimming speed ($U_{\text{crit}}$) for juvenile chum salmon. Values are expressed as means ± SE ($n = 10$). The effect of feeding rate during freshwater rearing was tested by the Kruskal-Wallis test. Results of the experiment on days five and ten after seawater transfer were analyzed using a two-way ANOVA (feeding rate × temperature). A two-way analysis of variance showed no interaction between feeding rate and seawater temperature. Therefore, multiple comparison tests were performed using the Tukey-Kramer method, with the level of statistical significance taken as $p < 0.05$. Groups sharing the same letter are not significantly different.

REFERENCES


Survival of Japanese Chum Salmon during Early Ocean Life in 2011–2017

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Keywords: juvenile chum salmon, early ocean life, survival, Okhotsk Sea, otolith mark

Adult returns of Japanese chum salmon have shown a decreasing trend since a peak (76 million fish) in 2004, while falling to 19–31 million fish in recent years (2016–2020). For sustainable management, it is an urgent issue to understand where and why the survival of Japanese chum salmon is decreasing.

The Okhotsk Sea is the most important feeding area for juvenile chum salmon originating from Japan and the Russian Far East, except for the coastal area of the Bering Sea (Urawa et al. 2018). Juvenile chum salmon released from Japanese hatcheries migrate along the coastal shelf of northern Japan, heading for the Okhotsk Sea. Genetic and otolith mark studies have indicated that juvenile chum salmon of all regional populations in Japan are distributed in the Okhotsk Sea during their first summer and fall (Urawa et al. 1998, 2001, 2004, 2006, 2007; Chistyakova and Bugaev 2013, 2016).

A long-term trawl survey has been conducted by Russian research vessels to estimate the abundance of juvenile chum and pink salmon in the Okhotsk Sea during the fall season (mainly October). The occurrence of otolith-marked juvenile chum salmon caught in the Okhotsk Sea during the fall of 2011–2017 was reported by Bugaev et al. (2019). The abundance of juvenile chum salmon in the Okhotsk Sea was variable: 164–553 million fish in 2011–2017. A total of 9,870 juvenile chum salmon were examined for otolith marks, and 347 otolith-marked fish released from hatcheries in Japan were detected by using the NPAFC otolith mark release database (http://npafc.taglab.org). In the present study, the abundance of Japanese hatchery-released juvenile chum salmon in the Okhotsk Sea was estimated by using the NPAFC otolith mark release database and the recovery data reported by Bugaev et al. (2019).

![Fig. 1. Survival rates and adult returns of chum salmon released from Japanese hatcheries. The survival rates of juvenile fish were estimated from their abundance in the Okhotsk Sea.](image-url)
Fig. 2. Relationship between estimated abundance of Japanese hatchery chum salmon juveniles in the Okhotsk Sea and adult returns by brood year (BY) stock.

The estimated abundance of Japanese hatchery-released juvenile chum salmon was 122 million fish in 2011 (early survival rate of brood year 2010 fish from release sites to the Okhotsk Sea: 6.8%) and 247 million fish in 2012 (early survival rate of brood year 2011 fish: 15.0%), while it decreased to 21–66 million fish in 2013–2017 (early survival rate of brood year 2012–2016: 1.2–4.4%) (Fig. 1). There was a significant positive correlation ($R^2 = 0.850; p < 0.01$) between abundance of Japanese hatchery-released chum salmon juveniles in the Okhotsk Sea and adult returns (Fig. 2). This indicates the brood year strength of Japanese chum salmon is determined in the early life stage during the coastal and offshore migrations to the Okhotsk Sea.

A recent decrease in early ocean survival of juvenile chum salmon might be caused by size-dependent mortalities (Honda et al. 2021). To move from the Pacific coast to the Okhotsk Sea, juvenile chum salmon are forced to migrate against the ocean current with a strong swimming performance (Azumaya et al. 2021), which depends on body length (Iino et al. 2021). However, the growth of juvenile chum salmon is disturbed by a reduced period of favorable habitat (SST: 8–13°C) and nutrient-rich prey abundance in the Pacific coastal water due to climate warming and/or weaken cold currents (Nagasaka and Shimizu 2021; Saito 2021; Sato et al. 2021; Yamada et al. 2021). Further studies are required to clarify the survival mechanisms of juvenile chum salmon during their early ocean life for better management of Japanese populations

REFERENCES


Factors Affecting the Migration of Juvenile Chum Salmon (*Oncorhynchus keta*) from the Coast of Hokkaido to the Okhotsk Sea

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Keywords: juvenile chum salmon, migration model, swimming speed

Japanese juvenile chum salmon (*Oncorhynchus keta*) migrate from coastal waters to the Okhotsk Sea during late spring/early summer. The Oyashio current flows southwestward off the Pacific coast of Hokkaido, while the Tsushima warm current flows northward off the Japan Sea coast (Fig. 1a). Thus, the migration direction of juvenile chum salmon is along the current off the Japan Sea coast, but opposite the current off the Pacific coast. In this study, factors affecting the migration of juvenile chum salmon from the Japan Sea coast and the east Pacific coast of Hokkaido to the Okhotsk Sea were investigated using a juvenile salmon migration model.

The juvenile salmon migration model was driven by active swimming and passive transport by the currents which were the hydrodynamic model's outputs. In the migration model, particles were assumed to be juvenile chum salmon. The integrated period of the model was from March to August. Starting positions of the migration were in the Ishikari Bay along the Japan Sea coast of Hokkaido and the Pacific east coast of Hokkaido (Fig. 1a), and 44 particles from the coast of the Japan Sea and 134 particles from the Pacific east coast of Hokkaido were released every day during the model integration, respectively. The directions of active swimming and swimming speeds of juveniles were assumed to be opposite the current and the constant during the model integration. The migration routes and particle numbers that reached the Okhotsk Sea in 5cm/s swimming speed intervals from 5 cm/s to 100 cm/s were examined.

The juvenile chum salmon migration model reproduced the actual distribution of juvenile chum salmon off the Japan Sea coast of Hokkaido (Mayama and Ishida 2003) (Fig. 1b) (red lines). On the Japan Sea coast, juvenile
chum salmon reached the Okhotsk Sea with passive transportation by the Tsugaru warm current. On the Pacific coast, juvenile chum salmon reached the Okhotsk Sea by their active swimming (Fig. 1b) (green lines). Particles released during the period of suitable water temperature range (8–13°C) for juvenile chum salmon off the coast of the Japan Sea entered the Okhotsk Sea. As particles were released during the first half of the suitable water temperature period, particles experienced temperatures within the chum salmon habitat temperature range (2.7°C–15.6°C) from their release points to the Okhotsk Sea (Azumaya et al. 2007). Particles with a swimming speed of more than 35 cm/s, which were released from the Pacific east coast of Hokkaido, entered the Okhotsk Sea. With the increasing swimming speed, the number of particles that entered the Okhotsk Sea increased and the residence time became shorter (Fig. 2).

![Fig. 2. Number (blue bars) and residence time (green bars) of particles migrating from the east Pacific coast of Hokkaido to the Okhotsk Sea by swimming speed.](image)

Juvenile chum salmon migrate from the Japan Sea coast to the Okhotsk Sea by passive current transport without dependence on their active swimming speed. Meanwhile, the active swimming speed affects the migration of juvenile chum salmon from the Pacific coast to the Okhotsk Sea. The results suggest that an important factor for successful migration and survival of juvenile chum salmon is release timing off the Japan Sea coast and the body size of released fry on the Pacific coast.

REFERENCES


Characteristics of Prey Environment during the Early Ocean Life of Juvenile Chum Salmon in Two Coastal Areas around Hokkaido, Northern Japan

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Keywords: zooplankton community structure, coastal area, juvenile chum salmon

The early life stage of juvenile chum salmon in the ocean is a critical period in their life history. Their growth and survival in coastal waters are largely affected by physical factors, such as temperature, salinity, and ocean currents. Furthermore, since the quality and quantity of zooplankton as a prey source regulates juvenile growth, clarifying the characteristics of zooplankton used by juvenile chum salmon is important for growth and survival. To evaluate the prey environment during the early life stage of juvenile chum salmon in the ocean, we investigated the temporal dynamics of zooplankton community structure from spring to early summer in two coastal areas of Hokkaido, northern Japan. The first area was off Atsuta on the coast of the Sea of Japan, and the second was off Konbumori on the eastern Pacific coast.

Zooplankton sampling in the Atsuta area was conducted every ten days from late March to mid-June and weekly in the Konbumori area from June to July in 2006–2018. Four sampling stations were established in the Atsuta area (43°23′–24′N, 141°18′–25′E) at 0.5, 1.0, 2.0 and 10 km from the shore, and four stations were established in the Konbumori area (42°52′–56′N, 144°33′–35′E) at 0.4, 1.3, 3.5, and 7.8 km from the shore. Zooplankton samples were collected with a NORPAC net (0.45 m diameter, 0.33 mm mesh) using vertical tows from a depth of 20 m to the surface (if the water depth was less than 20 m, the net was towed from near the sea bottom to the surface). Water temperature and salinity were recorded at each sampling station using a CTD (RINKO-Profiler; JFE-Advantech Co. Ltd., Japan.) from the surface to the bottom at 1-m intervals. The analysis of zooplankton community structure was referred to Kaga et al. (2016). The zooplankton community data among stations in all years was ordinated by nonmetric multidimensional scaling based on the Morisita-Horn similarity index. Clustering was performed using the k-mean method, with the optimal number of clusters estimated using the Calinski criterion (Calinski and Harabasz 1974). In addition, indicator species analysis was performed to identify indicator species in each cluster (Dufrêne and Legendre 1997). These analyses were conducted using the vegan package (v.2.5-7, Oksanen et al. 2020) and labdsv package (v.2.0-1, David 2019) implemented in R statistical software (v.3.6.3, R Core Team 2020).

In both areas, zooplankton typically consisted of copepods, amphipods, euphausiids, cladocerans, hydrozoans, appendicularians, chaetognaths, and meroplanktonic larvae (organisms that are planktonic for only a part of their life cycle) such as gastropods, polychaetes, decapods, and echinoderms. Cluster analysis based on zooplankton abundance revealed that the zooplankton community structure in the Atsuta area could be classified into three groups: warm-water species of copepods and meroplankton dominated-group, cold-water species of copepods dominated-group and euphausiids and hydrozoans dominated-group. On the other hand, the community structure in the Konbumori area could be classified into two groups: cladocerans and warm-water species of copepods dominated-group, and cold-water species of copepods dominated-group. Zooplankton community structure in both areas generally varied as the season progressed, i.e., from cold-water species in spring to warm-water species in early summer. However, in recent years, warm-water species have tended to be dominant in the Konbumori area from early spring. In terms of body size, zooplankton in both areas tended to shift from large to smaller species as the water temperature increased. Cold-water zooplankton species are generally large and rich in energy (e.g., Hooff and Peterson 2006; Mackas et al. 2007), whereas the zooplankton in warm areas are typically smaller and nutritionally poor (e.g., Batten and Walne 2011). Bi et al. (2011) reported that the mean abundance of warm oceanic copepods was inversely related to the annual mean abundance of Chinook yearling and Chinook jack returns, suggesting that ocean conditions for Chinook salmon are unfavorable when these warm oceanic copepod species are abundant. Peterson et al. (2017) reported that the survival of Pacific salmon migrating to the sea from coastal streams and large rivers of the Pacific northwest is positively correlated with the availability of an abundant and lipid-rich food source when they first enter the ocean. Similarly, in our study areas of Atsuta and Konbumori, the stomach contents of juvenile chum salmon consisted primarily of large, cold-water zooplankton species (unpublished data). Thus, the earlier appearance and predominance of small, warm-water zooplankton species might not favor the growth and survival of juvenile chum salmon, which require large zooplankton prey for optimal growth in coastal areas.

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Stock Identification of Chum Salmon Overwintering in the Gulf of Alaska by Using a New SNP Baseline

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Keywords: chum salmon, Gulf of Alaska, winter, distribution, stock composition, SNP analysis

The Gulf of Alaska is an important winter habitat for chum salmon originating from both the continents of North America and Asia (Urawa et al. 1997, 2016; Beacham et al. 2009). There is, however, limited knowledge of their stock-specific distribution, abundance, and survival in winter.

An international cooperative expedition was conducted in the Gulf of Alaska between February 16 and March 18, 2019, onboard the Russian R/V Professor Kaganovskiy (Pakhomov et al. 2019). A total of 223 chum salmon were caught by a surface trawl, which was the most abundant catch among Pacific salmon. Although chum salmon were widely distributed in the survey area (47°–56°N, 137°–147°W), they were relatively abundant in southwestern warm waters. The SST of chum salmon habitats averaged 6.7°C, ranging between 5.0°C and 7.5°C.

The regional origin of individual fish was estimated by using a new Pacific-rim SNP baseline (545 SNPs, 400 populations) developed by the Pacific Biological Station. The SNP analysis confirmed that chum salmon in the Gulf of Alaska during winter were a mixture of various populations: 22.0% Japan, 20.2% Russia, 14.8% West Alaska, 5.1% Yukon River, 6.5% Central Alaska, 11.2% Southeast Alaska (SEAK), 16.5% British Columbia (BC), and 3.7% Washington. In ocean age (OA)-1 fish, SEAK and BC populations were dominant, and West Alaska, Yukon and Asian populations were not included. In OA-2 fish, all regional populations appeared in the Gulf of Alaska, and South BC and Japanese populations were predominant. In OA-3 fish, West Alaska, Russian and Japanese populations were dominant, each occupying 25%. The proportion of Asian (Russian and Japanese) populations increased with ocean age: 40% in OA-2, 50% in OA-3, and over 70% in OA-4 fish. Most populations except for central Alaska were more abundant in southern waters (south of 52°N).

A total of 28 otolith-marked chum salmon were found in the Gulf of Alaska. All of OA-1&2 marked fish were released from hatcheries in SEAK (n = 22). OA-3&4 marked fish were from Central Alaska (n = 3), SEAK (n = 2) and Japan (n = 3).

Skinny chum salmon were frequently observed during the expedition. Chum salmon showed skinny condition (Condition Factor < 0.9) in 15% of the sample, most of which were OA-2 or 3 fish. In particular, OA-2 fish had an apparent lower condition factor than other age groups. SNP analysis showed that skinny chum salmon originated in all regional populations except for West Alaska. In OA-2 chum salmon, occurrence of skinny fish was 70–75% in BC populations, and 30–50% in other populations. In OA-3 chum, the occurrence of skinny fish was 60% in the North & Central BC populations, and around 20% in Russian and Japanese populations. The commercial catch of chum salmon in BC was extremely low in 2019 and 2020 (Grant et al. 2021; Velez-Espino et al. 2021). High occurrence of skinny chum salmon in winter might be a cause of these poor returns in BC populations.

Chum salmon mainly fed on euphausiids, pteropods, and jellyfish, and their stomach content index (SCI) was lowest among the pink, chum, sockeye, and coho salmon caught during the winter expedition (personal communication from Anton Khleborodov, Russia).

From these observations we propose three hypotheses: 1) not only the first winter, but also following winters, are a critical time for the survival of chum salmon; 2) chum salmon have a survival strategy that while overwintering they feed less and depend more on their energy accumulated in the previous summer/fall season; and 3) the energy content level prior to winter season and the winter habitat temperatures affect the survival of chum salmon. To test the hypotheses, in addition to winter expeditions, high-seas surveys during summer and fall are indispensable to assess the feeding and trophic condition of salmon.

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Zooplankton Community Structure and Development during Late Winter 2019 and 2020 in the Northeastern Pacific Ocean

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Keywords: North Pacific, Gulf of Alaska, zooplankton, composition, distribution, density, International Year of the Salmon

The winter high seas habitat in the Gulf of Alaska is recognized to be critical for Pacific salmon survival, particularly during the first winter migration of all species. However, there is a general paucity of the baseline information for this ecosystem, which contributes to the uncertainty of current forecasts of salmon returns as well as fish foraging and behavior patterns in the changing North Pacific ecosystem. The limited understanding of the Gulf of Alaska pelagic system calls for basic ecological information about zooplankton that underlie the salmon potential prey fields, including its composition and density. Recent large-scale warming events in the North Pacific (e.g., the “Blob”) have highlighted the strong possibility of short- and long-term changes in the pelagic salmon habitat. Two winter expeditions were conducted in 2019 and 2020 as major contributions to the International Year of the Salmon announced in the fall of 2018. During 19 February–17 March 2019 and 12 March–7 April 2020, surveys of the Gulf of Alaska (GoA) were conducted to research the winter ecology of the North Pacific salmon ecosystem on board of R/V Professor Kaganovskiy and F/N Pacific Legacy No.1, respectively. Both surveys consisted of ~1 x 1-degree survey grids covering ~650,000–700,000 km², which mainly overlapped in their southern parts (Fig. 1).

Fig. 1. Station grid surveys during February–March 2019 (filled circles) and March–April 2020 (open triangles) in the Gulf of Alaska.

In total, over 100 stations were sampled. At each station, oceanographic profiles using CTD, zooplankton, and micronekton were collected. Zooplankton were sampled in the top 250 m water column vertically using a Bongo net with a mouth area of 0.5 m² and mesh size of 0.250 mm. Micronekton were sampled with pelagic trawls in the top 30 m of water: RT 80/396 trawl with 10 mm cod end mesh in 2019 and NPAFC 1142 research trawl with the 4 mm cod end mesh in 2020. Survey average zooplankton abundance was 173±100 ind.m⁻³ and 386±122 ind.m⁻³, while biomass was 6.4±1.7 mgDW.m⁻³ and 10.4±3.6 mgDW.m⁻³ in 2019 and 2020, respectively. Spatial distribution patterns were similar during both years with the highest densities of mesozooplankton observed in the
southern parts (below 50°N) of the surveys, which strongly negatively correlated to the densities of surface micronekton (Fig. 2).

During both years, copepods dominated mesozooplankton numerically and the smallest size fraction (< 5 mm) accounted for over 90% of total abundance (Fig. 3A). Chaetognaths were the second most abundant zooplankton group, mostly contributing to the largest (> 10 mm) size fraction, though this size class never exceeded 5% of total abundance (Fig. 3A). While insignificant in abundance, euphausiids, pteropods, jellyfish, and decapods were important in terms of biomass. The < 5 mm size fraction contributed most to total biomass (~ 50%, though slightly higher during 2020), followed by > 10 mm and 5–10 mm size fractions (Fig. 3B).
Preliminary analyses indicated that the period of observations coincided with the initiation of the phytoplankton bloom and copepod reproduction. Community analyses revealed rather uniform mesozooplankton assemblage composition across the sampling area. Taxonomically, however, zooplankton assemblages were different between years with a higher contribution of species of southern origin during 2020. Micronekton were characterized by jellyfish dominating in the northern and pelagic tunicates dominating in the southern parts of surveys. Overall, there was a noticeable difference in mesozooplankton and micronekton densities between years. Densities of both mesozooplankton and non-gelatinous micronekton in 2020 were almost double those in 2019. This can partially be attributed to the differences in the survey timing but more likely reflected the restructuring of the oceanographic setting between surveys.
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The International Year of the Salmon Pan-Pacific High Seas Expedition 2022

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Keywords: salmon, winter, high seas, North Pacific, expedition, international

Pacific salmon are an important cultural, commercial, and biological resource for countries of the North Pacific Rim. Salmon and the people that depend on them are faced with increasing uncertainty as climate and ecosystems undergo significant changes with serious social and ecological implications. As conditions become more variable and salmon returns become more unpredictable, the need to understand factors affecting salmon during all life history stages intensifies. Winter is the least studied and thus least understood period in the life history of Pacific salmon (Myers et al. 2016). As part of the International Year of the Salmon (IYS), the North Pacific Anadromous Fish Commission (NPAFC) with its five member countries (Canada, Japan, the Republic of Korea, the Russian Federation, and the United States) is planning a Pan-North Pacific high seas research expedition in late winter 2022 to build upon two related IYS international expeditions, which were conducted in the Gulf of Alaska during the winter of 2019 and 2020 (Pakhomov et al. 2019; Somov et al. 2020). Given the challenges of completing an international survey during the pandemic, the difficult decision was made to postpone the multi-vessel research expedition from early 2021 to the winter of 2022.

As many as five research vessels with researchers from five countries will concurrently survey the North Pacific in winter 2022 (Fig. 1). The overarching objective is: “To demonstrate the utility of an international pan-Pacific winter ecosystem survey to understand how increasingly extreme climate variability in the North Pacific Ocean and associated changes in the physical environment influence the abundance, distribution, migration, growth, fitness and survival of Pacific salmon and surrounding species.” We have been working with a group of scientists from around the North Pacific Rim to address a set of four sub-objectives: (1) determine species and stock-specific ocean distributions and relative abundances, and the condition of juvenile, immature/mature Pacific salmon within the study area, and factors/mechanisms controlling them; (2) document the spatial and temporal variation in physical and biological oceanographic conditions; (3) document the distribution, condition, and standing stocks of zooplankton and nekton that serve as the prey base for Pacific salmon and associated marine fishes; and (4)
demonstrate the ability to effectively collaborate across the five NPAFC parties and our partners to conduct integrated ecosystem research that will support the sustainable management of salmon in a rapidly changing North Pacific Ocean.

Fig. 1. The 2022 IYS Pan-Pacific Winter High Seas Expedition survey map. The expedition will cover five zones: zone 1 will tentatively be covered by a Russian vessel, zones 2 & 3 will be tentatively covered by a Russian charter vessel, zone 4 by a US vessel and zone 5 by a Canadian vessel.

Lead scientists from each country and experts in specific research areas are developing a cruise plan with research protocols that all ships involved will adhere to. This expedition will be novel for a number of reasons, including the data mobilization efforts and technologies that will be applied. All data collected on the 2022 Expedition will be made publicly available and adhere to international standards and the FAIR data principles, meaning that data are findable, accessible, interoperable, and reusable. Discussions are ongoing about the potential to utilize novel technologies and tools including real-time salmon stock identification at sea, environmental DNA (eDNA), genomic salmon health assessments, remote sensing technologies, and ocean gliders/Saildrones. We are also working on a comprehensive communications plan that will engage target audiences in this important work.

The novel technologies and tools applied as part of the 2022 Expedition will provide new salmon and environmental observations from across the North Pacific Ocean and facilitate their rapid synthesis. This will lay the foundation from which to design an international ocean monitoring and ocean research system required to inform fisheries management in a highly uncertain environment. This long-term monitoring system will improve forecasts and vulnerability assessments that will support effective responses to the increasingly unpredictable state of salmon stocks. It will also provide more accurate salmon distribution models to inform high seas enforcement activities. Furthermore, it will inform long-term investments in hatcheries and in-season strategies for releases by helping to understand the interactions of hatchery fish with native salmon stocks and the overall ecosystem. Finally, these efforts will provide baseline data to inform processes related to the implementation of BBNJ (Biodiversity Beyond National Jurisdictions) to help understand the future impacts of a growing ocean economy. The 2022 expedition will set the stage for this important work as salmon and their ecosystems face an unpredictable future.

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Trace Elements in Cherry Salmon (*Oncorhynchus masou*) in the Southwestern Part of the Sea of Okhotsk

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**Keywords:** Pacific salmon, cherry salmon, *Oncorhynchus masou*, trace elements, Sea of Okhotsk, southeast coast of Sakhalin

**Introduction**

The Far Eastern shores of Russia are washed by three large seas—the Bering, Okhotsk, and Sea of Japan—as well as the waters of the northwestern Pacific. Marine and oceanic waters of the western Pacific are exceptionally rich in aquatic biological resources—fish, sea animals, invertebrates, algae, and seagrasses. Concerning fish abundance, the main contribution is made by pelagic objects—pollock, herring, sardine-ivasi, and Pacific salmon.

Salmon of the west Pacific exist in many groups, each manifesting in places of wintering, feeding, and spawning. A special area during anadromous and catadromous migrations of salmon is the Kuril-Kamchatka region, which is known as an oceanic biogeochemical province, and as a highly productive water area used for feeding by many salmon groups. Passing through this geochemically impacted region, salmon, together with food (plankton), accumulate various chemical elements in their tissues significantly enriching their mineral composition. At the same time, a considerable number of salmon groups do not winter in the ocean, but spend their winters in the Sea of Japan without crossing the Kuril ridge and the Kuril-Kamchatka trench. Therefore, the study of the mineral composition of salmon tissues makes it possible to clarify the routes of their migration and the possible region of their ocean residency and feeding more definitively. In addition, knowledge of the levels of trace elements in the tissues of important food items, such as Pacific salmon, is also necessary from a sanitary and hygienic standpoint.

The Sakhalin-Kuril region is one of the main salmon-catching areas in the Russian Far East. The main objects of fishing and artificial breeding in the Sakhalin region are chum salmon (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*). Masu salmon (*Oncorhynchus masou*) are endemic to the Asian coast; however, the majority of their range is located in the Sea of Japan basin and the southern Sea of Okhotsk (South Kuril Islands, Sakhalin Island, Hokkaido and Honshu Islands, Amur River). The most numerous masu salmon populations live in the rivers of Primorye, the Tatar Strait, Sakhalin (especially the southwestern and southern coasts), Hokkaido, the northern part of Honshu, Sakhalin Bay (Amur and its tributaries), and western Kamchatka (Birman 1986; Bugaev et al. 2007; Omelchenko et al. 1991; Semenchenco 1989).

**Fig. 1.** Sampling locations on Sakhalin Island.
Spawners of both masu salmon and pink salmon came to spawn off the southeastern coast of Sakhalin and were caught in the mouths of the closely located Bakhura and Firsovka rivers flowing into the Gulf of Patience. The sampling locations are shown in Fig. 1.

**Materials and methods**

We collected the masu salmon specimens in the summer of 2017 at the mouth of the Bakhura River, pink salmon spawners in the fall of 2018 at the mouth of the Firsovka River. Ten individuals (five females and five males) were taken; muscle tissue, liver, and gonads were taken from all sampled individuals and frozen before delivery to Vladivostok for chemical analysis. All elements were determined in samples after acid mineralization, carried out in the laboratory microwave system MARS 6, according to National State Standard 26929-94 (National State Standard 2010). The analysis was performed on a Shimadzu AA 6800 atomic absorption spectrophotometer in the geochemical laboratory of the Pacific Geographical Institute of the Far Eastern Branch of the Russian Academy of Science: Zn, Cu, and Ni—in a flame; Pb and Cd—in a graphite furnace. The accuracy of determining the elemental composition, as well as possible contamination of the samples during analysis was controlled by a comparison with calibration solutions, including an empty (zero) solution. The accuracy and precision of the method used have been confirmed by regular analysis of the standard reference material SRM-1566a. The results of the analysis for the content of trace elements in the organs and tissues of fish are presented in μg / g wet weight and are shown in Fig. 2. The mean, standard deviation, and significance of the compared differences (using the Mann-Whitney U test) were calculated using SPSS Statistics 21 software for MacOSX.

**Results and discussion**

The results of the analysis are presented in Fig. 2, which shows the concentrations of trace elements in the organs and tissues of a masu salmon from the Bakhura River.
When deciding which elements to analyze, we chose elements that have a negative impact on the environment and organisms. It should be emphasized that Zn and Cu are, as a rule, indicators of the flow of household wastewater and discharge of bilge water from ships. Lead (Pb), Cd, and Ni are indicators of technogenic impact and the latter two elements, especially nickel, enter the marine environment mainly through the combustion of hydrocarbon fuels (Khristoforova et al. 2015; Khristoforova et al. 2019a; Khristoforova et al. 2019b). As you can see, zinc strongly prevails over other elements, and this is typical for the entire biosphere. Iron and zinc were the first and main chemical elements in the emerging microelement composition of the biota (Boychenko 1976). Copper, nickel, and lead are found in masu salmon in close and noticeable amounts, while cadmium is clearly a minor element. A comparison of the content of zinc, copper, and nickel in organs and tissues of fish of both species shows an obvious predominance of these elements in masu salmon (Fig. 3). The organs and tissues of pink salmon from the Firsovka River, on the other hand, are markedly dominated by the content of Pb and Cd (Fig. 4).

Differences in element concentrations could be explained by biological and environmental characteristics of masu salmon. *Oncorhynchus masou* is a species of Pacific salmon with a long freshwater period. Smoltilification and drift in the sea for most masu salmon occurs after one or two years of life in the river. In Japan, the southern part of Sakhalin, and the south of Primorye—the southern range of masu salmon—most juveniles migrate in the second year and return to spawn after one winter at sea. The marine part of the masu’s range, like the feeding area, is limited to Asian waters. Masu salmon is mainly a marine species (Atlas 2002; Masuda et al. 1984; Shuntov and Temnykh 2011). The juveniles of the Sea of Japan stocks mainly enter the waters of the southern basin of the Sea of Okhotsk for feeding (Shuntov and Temnykh 2008). Most of the salmon leave the Sea of Okhotsk during November.
and during winter and autumn-summer migrations, they are found throughout the water area of the Sea of Japan, where they intensively feed and consume small fish. Most of the mature individuals enter the Sea of Okhotsk through the La Perouse Strait and partially penetrate through the southern Kuril straits. Masu are mainly caught in May when they pass through the open waters of the southern part of the Russian economic zone in the Sea of Japan. Off the southwestern coast of Sakhalin, in catches by set nets, the fishing peak occurs at the end of May, and more rarely in the first half of June. By the mid-end of June, catches decline (Shuntov and Temnykh 2011).

Migration of masu to rivers, in general, occurs much earlier than other species of Pacific salmon. Its spawning grounds overlap little with other species and it ripens for two or three months before spawning (Semenchenko 1989). Thus, the masu caught by us could form a microelement composition that is more consistent with the technogenic and anthropogenic influence (Zn, Cu, Ni) from both, one–two years of life in the river (before downstream migration to the sea) and during a two–three month stay in a spawning river.

**Conclusion**

Finally, we came to understand the reasons for the differences in the microelement composition of masu salmon and pink salmon that spawn in the rivers of Southeastern Sakhalin. Pink salmon fed in the waters near the Kuril Islands of the northwestern part of the Pacific Ocean, having passed through the impact geochemical zone twice (first when entering the ocean for wintering, then during the return migration for spawning from the ocean to the rivers of the Sea of Okhotsk), accumulating noticeably greater amounts of elements such as Pb and Cd, supplied to the environment by volcanism and upwellings.

Masu salmon, being not oceanic but a marine species due to the peculiarities of its biology and ecology, during its life cycle accumulates microelements in organs and tissues, which are more consistent with technogenic and anthropogenic influences (Zn, Cu, Ni).

**REFERENCES**


Did Recent Marine Heatwaves and Record High Pink Salmon Abundance Lead to a Tipping Point that Caused Record Declines in North Pacific Salmon Abundance and Harvest in 2020?

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Keywords: Chinook salmon, trophic cascade, North Pacific ecosystem, competition, growth, survival, climate change, COVID-19 pandemic

Total abundance of Pacific salmon returning from the North Pacific Ocean increased following the 1977 ocean regime shift, peaking in 2018 when approximately 950 million pink, chum, and sockeye salmon returned from the ocean (Fig. 1). In 2019, salmon abundance remained exceptionally high (~854 million salmon). Together the 2018/2019 period was the highest two-year period of salmon abundance on record since 1925, nearly 20% greater than the previous two-year high in 2009/2010, and more than 3.2 times higher than average abundance during relatively low salmon production years from 1960 to 1975.

Pink salmon continue to dominate the abundance of Pacific salmon returning from the North Pacific, reaching approximately 700 million maturing fish in 2018 and nearly 640 million fish in 2019 (Fig. 1). The exceptional return in 2018 is highly unusual because pink salmon abundance is typically highest in odd-numbered years (Irvine et al. 2014). Approximately 88% and 68% of total pink salmon returned to Asia rather than North America in 2018 and 2019, respectively (Table 1). In contrast, peak abundance of pink salmon in North America occurred in 2013 and 2015 (more than 300 million fish per year). Overall, pink salmon represented approximately 74% of total salmon abundance in 2018/2019. Most pink salmon are of natural origin, but abundance of hatchery pink salmon during 2005 to 2015 was greater than abundance of wild chum salmon and approximately equal to abundance of wild sockeye salmon. Total chum and sockeye salmon represented only 14% and 12%, respectively, of total salmon abundance in 2018/2019. These values exclude Chinook and coho salmon, whose combined reported catch was 1.5% of total salmon catch from the North Pacific during 2018/2019 and approximately 5% of total salmon catch, on average, during 1925 to 2019 (NPAFC 2020).
Table 1. Total abundance of pink, chum, and sockeye salmon (catch plus spawning escapement) returning from the North Pacific Ocean to streams in Asia and North America, 2016 to 2020. These values extend the 1925 to 2015 salmon abundance database (Ruggerone and Irvine 2018; Irvine et al. 2021), primarily using Approach 3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Asia Pink</th>
<th>Chum</th>
<th>Sockeye</th>
<th>North America Pink</th>
<th>Chum</th>
<th>Sockeye</th>
<th>Total Pink</th>
<th>Chum</th>
<th>Sockeye</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>335</td>
<td>110</td>
<td>24</td>
<td>97</td>
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<td>79</td>
<td>432</td>
<td>150</td>
<td>104</td>
<td>686</td>
</tr>
<tr>
<td>2017</td>
<td>287</td>
<td>74</td>
<td>21</td>
<td>226</td>
<td>49</td>
<td>79</td>
<td>513</td>
<td>123</td>
<td>101</td>
<td>737</td>
</tr>
<tr>
<td>2018</td>
<td>614</td>
<td>98</td>
<td>23</td>
<td>87</td>
<td>42</td>
<td>86</td>
<td>701</td>
<td>140</td>
<td>109</td>
<td>950</td>
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<tr>
<td>2019</td>
<td>435</td>
<td>74</td>
<td>24</td>
<td>203</td>
<td>37</td>
<td>81</td>
<td>639</td>
<td>111</td>
<td>104</td>
<td>854</td>
</tr>
<tr>
<td>2020</td>
<td>205</td>
<td>68</td>
<td>17</td>
<td>110</td>
<td>23</td>
<td>71</td>
<td>315</td>
<td>92</td>
<td>87</td>
<td>494</td>
</tr>
</tbody>
</table>

Table 2. Revised abundance of sockeye salmon (millions of fish) returning to the Mainland and Islands region of Russia (M&I), as originally reported by Ruggerone and Irvine (2018). During the 2020 update of the salmon abundance database, we noticed that interceptions of sockeye salmon in the Kuril Islands that began in 2001 were not included in the database. The missing Kuril Islands sockeye catch led to very small increases in the M&I sockeye abundance values from 2001–2005 (<1%), increasing to 10% in 2006–2008, then to 60% in 2009 to 2013, and to 160% in 2014 and 2015. Inclusion of these intercepted sockeye salmon led to a maximum increase of 5% in sockeye abundance returning to Asia and 1% to North America and Asia combined (in 2015). Some of these sockeye salmon would have returned to Kamchatka, but we have assumed for simplicity that all returned to the Mainland and Islands region.

<table>
<thead>
<tr>
<th>Year</th>
<th>M&amp;I</th>
<th>Asia</th>
<th>North Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>0.5</td>
<td>8.5</td>
<td>65.6</td>
</tr>
<tr>
<td>2002</td>
<td>0.3</td>
<td>13.8</td>
<td>70.7</td>
</tr>
<tr>
<td>2003</td>
<td>0.2</td>
<td>9.8</td>
<td>73.6</td>
</tr>
<tr>
<td>2004</td>
<td>0.1</td>
<td>9.1</td>
<td>89.8</td>
</tr>
<tr>
<td>2005</td>
<td>0.7</td>
<td>13.0</td>
<td>87.2</td>
</tr>
<tr>
<td>2006</td>
<td>0.8</td>
<td>12.6</td>
<td>89.1</td>
</tr>
<tr>
<td>2007</td>
<td>0.5</td>
<td>18.3</td>
<td>84.8</td>
</tr>
<tr>
<td>2008</td>
<td>0.4</td>
<td>14.5</td>
<td>74.8</td>
</tr>
<tr>
<td>2009</td>
<td>0.5</td>
<td>14.8</td>
<td>75.5</td>
</tr>
<tr>
<td>2010</td>
<td>0.6</td>
<td>15.1</td>
<td>105.2</td>
</tr>
<tr>
<td>2011</td>
<td>1.0</td>
<td>17.3</td>
<td>83.0</td>
</tr>
<tr>
<td>2012</td>
<td>0.8</td>
<td>21.1</td>
<td>79.0</td>
</tr>
<tr>
<td>2013</td>
<td>0.9</td>
<td>22.4</td>
<td>74.3</td>
</tr>
<tr>
<td>2014</td>
<td>0.9</td>
<td>18.2</td>
<td>106.5</td>
</tr>
<tr>
<td>2015</td>
<td>1.7</td>
<td>21.9</td>
<td>110.2</td>
</tr>
</tbody>
</table>

Unexpectedly, the high abundance of Pacific salmon came to an abrupt end in 2020. Preliminary commercial catch statistics for all salmon species indicate Pacific salmon harvests, which provide an index of abundance, declined more in 2020 than in any other period on record since 1930 (Fig. 2). Commercial salmon harvests declined by approximately 187 million fish compared with average harvest during the previous 10 years (2010–2019; Fig. 2, NPAFC 2020). Although the COVID-19 pandemic may have reduced commercial harvests to some extent in some regions, most fishery reports and preliminary escapement estimates indicate low abundance rather than harvest impacts from the COVID-19 pandemic led to unusually low harvests of Pacific salmon in 2020.

Harvests of each species of Pacific salmon declined 35%, on average, in 2020 when compared with the previous 10-year average. This decline was greater than in any previous period. Harvests of Chinook salmon in 2020 were the lowest on record since 1925, declining 54% compared with the previous ten years. Chum salmon harvests in 2020 declined 42%, followed by pink (40%), coho (27%), and sockeye (10%). Sockeye salmon harvests declined relatively little because returns to Bristol Bay in the southeastern Bering Sea remained robust and offset the exceptionally low harvests of sockeye salmon in the Gulf of Alaska, British Columbia, Washington, and the Columbia River. Pink salmon returning to the Norton Sound region in northern Alaska in 2020 continued with relatively high returns that began in 2016 (J. Menard, jim.menard@alaska.gov, personal communication), providing evidence for the beneficial effects of the warming ocean on salmon in the extreme north.
We hypothesize that a tipping point was reached in the North Pacific Ocean, leading to the substantial decline of all five species of Pacific salmon in 2020. We infer that the tipping point was caused by the combined effects of unusually frequent marine heatwaves since 2014 (Krovnin et al. 2019; Gupta et al. 2020; Litzow et al. 2020) and exceptional back-to-back year abundances of pink salmon in 2018/2019 (Fig. 1). This hypothesis is partially supported by Connors et al. (2020), who reported the combined effects of sea surface temperature (SST) and pink salmon abundance on productivity (return per spawner) of 47 sockeye salmon populations (brood years 1976–2009) ranging from the Fraser River in British Columbia to Bristol Bay, Alaska. Investigators found that a 1.5°C increase in SST (1 standard deviation) was associated with a 23% increase in sockeye productivity in the Bering Sea, a 9% productivity increase in the Gulf of Alaska, but with a 12% decline in productivity in the southern region (British Columbia and Southeast Alaska). The frequent heatwaves following the period considered by Connors et al. (2020) likely contributed to the growing abundance of pink salmon in the north while also contributing to a northward shift in the adverse effects of high SST on production of other salmon species.

Connors et al. (2020), while simultaneously considering the influence of ocean warming, also reported that a 119 million increase in pink salmon abundance (i.e., 1 standard deviation) was historically associated with a 9% decline in sockeye productivity in the Bering Sea and the Gulf of Alaska, and a 21% decline in British Columbia (e.g., Fig. 3). This finding is consistent with the trophic cascade caused by abundant pink salmon (Batten et al. 2018) and other studies indicating adverse effects of pink salmon on the growth, age-at-maturation, survival, and abundance of sockeye salmon, Chinook salmon, coho salmon, chum salmon, marine fishes, seabirds, and potentially southern resident killer whales (Ruggerone and Nielsen 2004; Ruggerone et al. 2016a, 2019; Ruggerone and Irvine 2018). Support for the adverse interaction between pink salmon and other marine species is strengthened by biennial patterns in marine species that are consistent with the biennial pattern in pink salmon in most years; these biennial patterns cannot be explained by physical oceanography. The adverse effect of numerous pink salmon on vital rates of other salmon species is far-reaching because salmon are known to migrate 1,000s of kilometers at sea. For example, 11–38% of Chinook salmon sampled on the southeastern Bering Sea shelf during 2005–2010 originated from the west coast of the contiguous United States (Larson et al. 2013).
In summary, both pink salmon abundance and high SST were extreme leading up to the salmon decline in 2020, and more extreme than observed in the Connors et al. (2020) study, which ended with the 2009 sockeye salmon brood year. Furthermore, pink salmon abundance in 2018 did not decline as in past even-numbered years. We hypothesize that a tipping point was caused by the record-setting back-to-back-year abundances of pink salmon and unique ocean conditions leading up to the salmon decline in 2020. This hypothesis is consistent with research that has uncovered non-stationary effects of ocean temperatures on salmon catch in the Gulf of Alaska, including negative effects of recent heatwaves on catch (Litzow et al. 2020).

Preliminary 2021 commercial harvest data indicate at least some populations improved from the low numbers in 2020. Alaska and Russia pink salmon abundances appear to have rebounded to the exceptionally high values in 2019. Sockeye salmon returning to Bristol Bay, Alaska, set a new record high in 2021 (66 million fish (catch and escapement); T. Sands, ADF&G, personal communication), apparently in response to favorable early marine growth in the Bering Sea (e.g., Ruggerone et al. 2007) and relatively few maturing pink salmon in 2020 (Ruggerone et al. 2016b). In contrast, commercial harvests of Chinook, coho, chum, and sockeye salmon remain somewhat low in many regions of Alaska and Russia. Further evaluation of 2021 and 2022 harvests and returns of Chinook, coho, chum, pink, and sockeye salmon are needed to evaluate the validity of our tipping point hypothesis.

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The Ups and Downs of Far East Salmon Stocks During Recent Decades: Some Considerations and Possible Causes

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Keywords: East Kamchatka pink salmon, West Kamchatka pink salmon, odd and even-year generations, catch, heat content, ice cover

Over recent decades Far East pink salmon stocks have undergone considerable variations associated with the strengthening of short-term climate variability in the North Pacific. The last minimum of total pink salmon catch (147,500 metric tons) in 2014 was followed by its growth to a maximum of about 511,000 metric tonnes in 2018. This rise of catches was associated with an increase in heat content of surface waters in the northern North Pacific and Far East Seas in 2014–2019. This presumably created favorable environmental conditions for pink salmon stocks, especially for those spawning in Kamchatka rivers, during their marine period of life. The growth of catches was essentially caused by an unusual increase in catch of even-year generations of East Kamchatka (EK) pink salmon, which were not a dominant stock. From 2012 to 2018, this catch rose more than six times, from 16,730 metric tonnes up to 111,250 metric tonnes, respectively (Fig. 1). In 2018, the share of EK pink salmon in the total Russian pink salmon catch reached almost 22%.

In 2020, the situation changed. The total pink salmon catch was only 179,400 metric tonnes, 1.25 times lower than the expected volume of 222,800 metric tonnes. The maximal underfishing relative to the projected volume was noted near the East Kamchatka—20,700 metric tonnes and 82,700 metric tonnes, respectively. Thus, the catch constituted only ¼ of the expected value.

It may be supposed that a decrease in the total pink salmon catch in 2020 was associated with changes of abiotic conditions in the winter season of 2019–2020. The main purpose of this paper is an attempt to reveal the environmental factors which caused the decrease in pink salmon catches, and especially East Kamchatka pink salmon, in 2020.

The Kamchatka pink salmon catch statistics for 1978–2020 are available online from the NPAFC website (https://npafc.org). Heat content in the 0–100 m layer in the North Pacific region north of 40ºN was calculated using the EN4 dataset v.4.2.1 with a spatial resolution of 1° × 1° and temporal resolution of 1 month (Good et al. 2013). The calculations were made for each month from December to April during the 1978–2020 period. We suppose that the areas with the maximal absolute values of correlation coefficients between the catches and heat content coincide with the wintering areas of pink salmon or are located close to them. The length of time series under consideration is \( n = 21 \) years with the number of degrees of freedom \( \nu = 19 \). For \( \nu = 19 \), all correlation coefficients with absolute values equal to, or higher than, 0.43 are statistically significant at \( p \leq 0.05 \). The data on ice concentration for the 1979–2020 period were taken from Climate Data Record (CDR) NOAA/NSIDC (Meier et al. 2017, https://nsidc.org/data/G02135/versions/3).

Figure 1 shows the correlation pattern between the heat content in the upper 0–100 m water layer and catches of EK pink salmon in even years. In December, the area of maximal (positive) correlation coefficients exceeding...
0.50–0.60 is located north and south of the Aleutian Islands, with a center at 170° W (Fig. 2a). By February, this area is displaced northward and expands, covering almost the entire southern Bering Sea (Fig. 2b). In April, the area with correlation coefficients above 0.60 narrows (Fig. 2c). This allows for the suggestion that a considerable number of fish could winter in the southern Bering Sea, especially during the second half of the 2010s, when the anomalous warming was observed in the Northeast Pacific and southeastern Bering Sea.

Fig. 2. Correlation patterns between catches of EK pink salmon in even years and heat content in the upper 0–100 m water layer for December (a), February (b), and April (c) during 1978–2020.

The suggestion is confirmed by the high statistical relationship between the catches in even years and characteristics of the Bering Sea ice cover in the winter–spring period. As an example, Figure 3a shows changes in the latitude anomalies of the geographical center (centroid) of ice cover in the sea in February and anomalies of the even-year catches of EK pink salmon. Both time series in this Figure were normalized to the corresponding standard deviation. In 1978–2010, the relatively small fluctuations in both characteristics, not exceeding one standard deviation (± σ), were observed. Beginning from 2012, a northward shift of the geographical center of the ice cover, with a maximum in 2018, was noted. In the same years, there was an increase in the even-year catches of EK pink salmon, also with a maximal volume in 2018. In 2020, the extension of ice cover in the Bering Sea

Fig. 3. Normalized anomalies of EK pink salmon catches in even years and latitude of geographical center (centroid) of ice cover in the Bering Sea (a); latitudinal position of the ice edge at 175°W in February during the 1980–2020 period.
returned to the mean long-term situation. At the same time, the catches decreased significantly. The correlation coefficient between the time series under consideration for the entire period from 1978 to 2020 is 0.60 \( (p < 0.05) \). The correlation coefficient becomes even higher, if the latitudinal position of the ice edge at 175°W is used as a characteristic of the ice cover (Fig. 3b). In this case, its value reaches 0.84 \( (p < 0.01) \). The minimum area of ice cover and the extreme northern position of its edge in the Bering Sea were noted in 2018. In the same year, the record catch of EK pink salmon for even-year generations (111,250 metric tonnes) was obtained.

Thus, the growth of the even-year catches of EK pink salmon from 2014–2018 coincided with an anomalous decrease of ice cover area in the Bering Sea and shift of its margin far to the north. It should be noted that the positive relationship between catches and characteristics of ice cover can be interpreted in two ways. First, the extension of ice cover reflects the general thermal state of the sea: the higher heat content in the upper layer results in a lower intensity of ice formation, and vice versa. In this case, the ice cover is only an indicator of the thermal regime of the waters. Second, if the even-year generations of EK pink salmon really winter in the southern Bering Sea, then reduction of the ice cover area with a shift of its southern margin to the north, contributes to the expansion of the winter-feeding area and, therefore, a better survival of the corresponding generation. The opposite situation leads to a lower survival and, as a result, to decrease in catches. Thus, the return of thermal and ice conditions in the Bering Sea and the near-Aleutian region to the mean long-term level in the winter of 2019–2020 obviously contributed to the less favorable survival conditions for the 2018 East Kamchatka pink salmon generation and recovering of the “saw-shaped” variations of biomass observed during the recent decades and, as a result, the similar variations of catches, with their high volumes in odd years and low volumes in even years. It should be noted that the return of thermal and ice conditions in the Bering Sea to the mean long-term level is also confirmed by the results of the analysis given in the paper (Eisner 2020).

The positive relationship of catches with the winter heat content in the upper 0–100 m layer is observed for both even- and odd-year generations of EK pink salmon (Fig. 4). However, judging by the position of the domain with maximal correlations, the odd-year generations of EK pink salmon winter further west than the even-year generations, in the area of the western Subarctic Gyre between 160–170°E (Fig. 4a, b), and in the late winter they probably migrate eastward to the area of 180–170°W (Fig. 4c).
Fig. 5. Correlation patterns between catches of WK pink salmon in even years and heat content in the upper 0–100 m water layer for February (a) and April (b) during 1978–2020.

Fig. 6. Correlation patterns between catches of WK pink salmon in odd years and heat content in the upper 0–100 m water layer for December (a) and March (b) during 1979–2019.

The correlation relationship between the catches of the West Kamchatka (WK) pink salmon in even (dominant) years and heat content in the upper 100 m layer is less clear (Fig. 5). It can be supposed that their wintering area is located within the western Subarctic Gyre, between 150°E and 165°E. It should be noted also that there are not any significant correlations between both the even-year catches of WK pink salmon and odd-year catches of EK pink salmon with the above-noted characteristics of ice cover in the Bering Sea.

The correlation coefficients between the heat content and catches of WK pink salmon in odd (non-dominant) years were lower than for all other stocks discussed above (Fig. 6). Perhaps, this is associated with minor changes in catch volumes from 1979–2017. The only exception was 2019, when the catch amounted to 60,200 metric tonnes. From the analysis of Figure 6, it can be supposed that pink salmon of this stock winter in the eastern Subarctic Gyre. This is partly confirmed by the relatively low, but statistically significant, correlation coefficients between the odd-year catches of WK pink salmon and latitude of the ice cover centroid in February and March, which, equal to 0.49 and 0.52 ($p < 0.05$), respectively. In this case, the expansion of ice cover can be considered as an indicator of the
thermal state of waters in the Northeast Pacific and southern Bering Sea. The highest catch of WK pink salmon in odd years was obtained in 2019, when, as in 2018, the ice cover area in the Bering Sea was minimal.

Thus, the results of the analysis revealed a positive relationship between the thermal conditions of water during the wintering of all Kamchatka pink salmon stocks and their catches. However, their wintering areas differ. From 1978–2020, dominant odd-year generations of EK pink salmon and even-year generations of WK pink salmon were probably located within the western Subarctic Gyre, while odd-year generations of WK pink salmon were located in the eastern Subarctic Gyre, and even-year generations of EK pink salmon were mainly located in the southern Bering Sea.

**Conclusion**

1. The high heat content of surface waters in the North Pacific and Far Eastern seas in 2014–2019 contributed to the formation of favorable environmental conditions for salmon, and especially pink salmon spawning in the Kamchatka rivers, during the marine period of their life cycle.

2. The growth of catches of Far East pink salmon in 2014–2018 was largely associated with an unusual, rather sharp, increase in the catch of even generations of EK pink salmon which are not dominant for this stock. In 2018, its share in the total catch of Russian pink salmon reached almost 22%.

3. Based on the analysis of the correlation between catches and heat content in the upper 100 m layer of the North Pacific region in the winter months, it can be assumed that for the dominant odd-year generations of EK pink salmon from 1978–2020 and for WK pink salmon of even years, wintering areas are located within the western Subarctic Gyre; for odd-year generations of WK pink salmon in the eastern part of the gyre; and for even-year generations of EK pink salmon, mainly, in the southern Bering Sea.

4. The main factors resulting in growth of catches of the even-year generations of EK pink salmon from 2014–2018 was the high heat content of surface waters in the northern North Pacific and an anomalous decrease in ice cover area in the Bering Sea combined with the displacement of its southern margin far to the north. These factors led to a widening area of favorable conditions for wintering in the southern Bering Sea.

5. The return of climatic conditions in the Bering Sea to the “normal” state in winter 2019–2020 resulted in worse survival of EK pink salmon born in 2018 and recovery of “saw-tooth” changes in abundance characteristics of this stock observed during the last decades, with high catches in odd years and low catches in even years.

**REFERENCES**


Reported Occurrences of Pacific Salmon in the Canadian Arctic Continue to Increase Whereas Reports of Atlantic Salmon Sightings Remain Low

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Keywords: Pacific salmon, Atlantic Salmon, Arctic, range extension, climate change, subsistence fisheries

Environmental changes are affecting Pacific and Atlantic salmon production throughout their entire ranges (IUCN 2009; Grant et al. 2019). Warming water temperatures are influencing survival and abundances of salmon in freshwater habitats and are shifting optimal marine habitats northward (Abdul-Aziz et al. 2011; Yoon et al. 2015; Grant et al. 2019). Relatively high abundances of juvenile pink (Oncorhynchus gorbuscha) and chum (Oncorhynchus keta) salmon were caught in the Chukchi Sea in 2007 (Eisner et al. 2013) and immature chum salmon were found at higher latitudes in the Bering Sea in 2009 (Sato et al. 2012). Catches of larger juvenile pink salmon in a warmer Chukchi Sea suggest that the sub-Arctic marine environment may be becoming viable salmon habitat (Moss et al. 2009). Atlantic salmon may also be shifting their marine distribution northward with warming temperatures (Todd et al. 2011; Chittenden et al. 2013). In freshwater, warming temperatures may also be improving pink salmon production in rivers flowing into the northern Bering Sea (Farley et al. 2020). Further north, there has been a sharp increase in the geospatial and temporal distributions of vagrant adult Pacific salmon in the Canadian Arctic in recent years (Dunmall et al. 2013, 2018), and increases in Pacific salmon have also been observed along the Alaskan north slope (Carothers et al. 2019) and in Greenland (Nielsen et al. 2020). Vagrant Atlantic salmon (Salmo salar) are occasionally harvested in subsistence fisheries in Nunavut (Bilous and Dunmall 2020) and are expected to shift northward, possibly impacting southern populations of Arctic Char (Salvelinus alpinus) due to overlaps in tolerances and habitat requirements (Reist et al. 2006; Jonsson and Jonsson 2009; Bilous and Dunmall 2020). Beyond indicating changes in production and distributions in their current ranges, Pacific and Atlantic salmon are also reminding us of the connections among our oceans.

In the Canadian Arctic, salmon are increasingly harvested in subsistence fisheries targeting preferred Arctic fishes. Arctic Salmon is a community-based monitoring program that tracks the occurrences of salmon harvests and other unusual fishes in subsistence fisheries across the Canadian Arctic. Through this program, it is possible to detect and monitor widening geographic occurrences and increasing abundance trends of rare species in a vast, remote, and sparsely populated environment (Dunmall et al. 2013, 2018). Here, the objective is to update observed changes in Pacific salmon occurrence and harvest locations in subsistence harvests in the Canadian Arctic since previous reviews (Stephenson 2006; Nielsen et al. 2013; Dunmall et al. 2013, 2018), and relate these to a recent review of Atlantic salmon harvests in the Canadian Arctic (Bilous and Dunmall 2020). Reports of Pacific salmon harvested from 2018 to 2020, and provided to Fisheries and Oceans Canada through Arctic Salmon, are summarized by species and compared to previous reports of salmon from 2000 to 2017 (Dunmall et al. 2013, 2018), thus providing a 20-year record of salmon harvests in the Canadian Arctic. By continuing to document changing salmon distributions as a tangible example of biodiversity change, we can better understand the influence of rapid environmental change on Arctic ecosystems and its potential impact on cultures of northern Indigenous Peoples.

While following a generally increasing trend over the past 20 years, Pacific salmon harvests are becoming more variable in recent years in the Canadian Arctic, with the occasional years of extremely high harvests becoming more frequent and more extreme. Chum salmon remains the most abundant Pacific salmon species harvested across the Canadian Arctic, and is the only species harvested in the Mackenzie River consistently year after year. From 2016 to 2020, three years (2016, 2017, and 2019) have been documented with exceptionally high Chum Salmon harvests compared to only one year (2011) in the period 2010–2015. The number of salmon that may be present during these exceptional years also appears to be increasing (Fig. 1). Pink salmon harvests have shifted in recent years from higher harvests in even-numbered years to higher harvests in odd-numbered years (Fig. 1). Also, the geographic distribution of pink salmon harvests is increasing as they have now been reported in new locations, including near Cambridge Bay and Clyde River, Nunavut (McNicholl et al. in press), and upstream in the Mackenzie River to Fort Good Hope, Northwest Territories (Dunmall et al. unpublished data). Reported harvests of sockeye salmon have increased in recent years, from almost none prior to 2017 to over 400 in 2019, although harvests remain variable year to year (Fig. 1). Most of the sockeye salmon harvested in 2019 were caught in Sachs Harbour and Ulukhaktok, Northwest Territories. The number of Chumook salmon reported was variable from 2018 to 2020, from a low of zero to a high of 20 (Fig. 1). One coho salmon was reported harvested in the Canadian Arctic in 2019.
in 2019. The geographic distribution of chum, sockeye, Chinook, and coho salmon harvests did not expand from previous accounts (Dunmall et al. 2018).

![Graph showing salmon harvests from 2000 to 2020]

**Fig 1.** The number of each species of Pacific salmon reported to the Arctic Salmon community-based monitoring program from harvesters across the Canadian Arctic from 2000–2020. Only two coho salmon were reported during this period (in 2011 and 2019), thus they are not included.

Atlantic salmon harvests in the Canadian Arctic have been reported, although rarely, in 11 communities across Nunavut (reviewed in Bilous and Dunmall 2020). These sightings were summarized from Atlantic salmon occurrences and locations documented in Nunavut Coastal Resource Inventory (NCRI) reports (see https://www.gov.nu.ca/economic-development-and-transportation/information/nunavut-coastal-resource-inventory). These reports contain information obtained from interviews, maps, reports, research, and other resources and were completed by the Fisheries and Sealing Division of the Department of Environment (DOE), Government of Nunavut, in communities across Nunavut from 2007 to 2015. The information was intended to support assessment, management, and conservation opportunities, preserve Inuit Qaujimajatuqangit (IQ), and assist in preparing for environmental changes, particularly those that are induced by climate change (Government of Nunavut 2014). Most of the reported sightings were during summer months along the coast as well as in rivers and lakes; however, Atlantic salmon have also been occasionally sighted in freshwater during winter (Bilous and Dunmall 2020). Clyde River had the most reported sightings of Atlantic salmon (n = 14) compared to the other communities. While Pond Inlet reported the earliest harvests, in the 1950s, a specific timeframe for the Atlantic salmon observations in each community was only reported occasionally. As IQ is holistic and often based on a long time series of observations (Wenzel 2004), it is possible that sightings in other communities similarly span a long timeframe.

In conclusion, over the past 20 years, and particularly since 2011, almost all Pacific salmon species found in North America, with the exception of coho salmon, have increased in occurrence and geographic distribution in the Canadian Arctic. These species are also experiencing more extreme variations in harvests, with an increased frequency of exceptionally high harvests and a higher level of harvest during those exceptional years. A similar relative increase in occurrence, geographic spread, or extreme variation in harvests levels of Atlantic salmon in Nunavut has not been reported. While the difference in Pacific and Atlantic salmon harvests could be attributed to reporting frequency, the sharp contrast and consistency across almost all the communities in the Canadian Arctic suggests that there may be less Atlantic salmon than Pacific salmon species in coastal and freshwater environments in the Canadian Arctic. As distributions of Pacific and Atlantic salmon species are predicted to shift northward with environmental change (Reist et al. 2006; Abdul-Aziz et al. 2011; Todd et al. 2011; Chittenden et al. 2013), this difference in observations among species is an area for further investigation and could provide insight into the factors influencing northward distributional shifts in the marine environment. Within the reported Pacific salmon harvests, the extremes in variation and increases in salmon observed in recent years may be attributed in part to
differences in reporting frequency across years. It is also possible that fishing conditions influenced harvests of salmon, and salmon may have been present in low-level harvest years but were not harvested due to poor fishing conditions (Chila et al. in press). However, consistency in reports of an increasing trend in Pacific salmon across communities in the western Canadian Arctic suggests that more salmon have been present in the western Canadian Arctic in recent years. Also, Inuvialuit knowledge about Pacific salmon harvests across the six communities in the Inuvialuit Settlement Region similarly document an increasing trend of Pacific salmon harvested in subsistence fisheries, attributed to climate change (Chila et al. in press). Therefore, the trends suggest that the occurrences of chum, pink, sockeye, and Chinook salmon are generally increasing and becoming more variable in the Canadian Arctic. Sightings of Atlantic salmon in the eastern Canadian Arctic occur but are not new and this species may not be experiencing similar dramatic trends.

The Arctic Salmon community-based monitoring program has expanded in recent years from an original focus on the Northwest Territories to also include communities across Nunavut in order to facilitate the detection of Pacific and Atlantic salmon in subsistence fisheries across the Canadian Arctic. The Arctic Salmon program has also shifted from monitoring salmon to monitoring the harvest and/or occurrence of all “usual fish” across the Canadian Arctic, which also include other species found outside known distributions (McNicholl et al. in press). By developing a network of people interested in biodiversity change of fish across the Canadian Arctic, the Arctic Salmon program can connect individual sightings of usual harvests into a community-based monitoring program that effectively tracks changes in the biodiversity of fishes harvested in coastal and freshwater subsistence fisheries across a vast and remote area.

REFERENCES


Mechanisms, Impacts, and Mitigation for Thiamine Deficiency and Early Life Stage Mortality in California’s Central Valley Chinook Salmon

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Keywords: thiamine deficiency, Pacific salmon, early life stage mortality, mitigation measures

Thiamine Deficiency Complex (TDC) is a nutritional deficiency of thiamine (vitamin B1) recently linked with high mortality of early life stages of Chinook salmon (Oncorhynchus tshawytscha) in California’s Central Valley (CCV) hatcheries. Prior to 2020 TDC had never been diagnosed in California salmon, yet there is some evidence it had gone undetected in the past. In early 2020 hatched fry showed clinical signs of TDC that included loss of equilibrium, lethargy, abnormal swimming, and death between hatching and first feeding (Foott 2020). In spring 2020, we launched an interdisciplinary study to better understand the mechanisms, impacts, and mitigation measures for TDC and early life stage mortality in CCV Chinook salmon. We documented that excessive fry mortality was related to thiamine deficiency. We demonstrated that egg and fry thiamine baths recover ailing fry, and injection of pre-spawn females with thiamine prevented fry mortality and TDC (c.f., Futia et al. 2017). Consistent with previously published research, we confirmed TDC in symptomatic fry with egg thiamine measurements (Harder et al. 2018). Marine ecosystem surveys in the central part of the California Current Large Marine Ecosystem documented an unusually dominant population of Northern anchovy (Engraulis mordax) beginning in 2018 and persisting through 2020. Anchovy have thiaminase (Greig and Gnaedinger 1971; Tillitt unpublished), an enzyme that destroys or degrades thiamine in its consumers, and from published research diets high in clupeid species with thiaminase can result in low egg thiamine leading to TDC. Our gut content analysis found that Anchovy were the dominant prey item for Chinook salmon captured in fisheries off California’s central coast in 2020, making up 97% of the prey items by weight. Other work has documented low thiamine concentration in ocean water off Baja California (south of typical CCV Chinook salmon feeding areas) (Sañudo-Wilhelmy et al. 2012), but we do not yet know the significance of these published water data as it relates to CCV Chinook salmon TDC.

There are many unknowns linked with TDC in CCV Chinook salmon. For instance, we do not know what caused the rapid expansion, and record high biomass, in the Central California anchovy population and sharply reduced populations of other salmon prey items in this region (Thompson et al. 2019). We have no information on aqueous thiamine concentrations from the foraging or spawning and incubation areas for CCV Chinook salmon. We also do not know the extent of TDC and its impacts on naturally spawning CCV Chinook salmon populations. To
address thiamine deficiency at the top predator level, our work suggests investigating factors that affect thiamine synthesis, thiamine availability, food web transfer and causes of changes in species across the entire marine food web that includes CCV Chinook salmon.

This research suggests that the coastal marine ecosystem that CCV Chinook salmon are part of has been somehow out of balance, leading to high populations of Northern anchovy and much reduced availability of normal prey diversity. We now know that TDC has been affecting CCV Chinook salmon in recent years, we understand at least one factor (thiaminase) that can lead to TDC in CCV Chinook salmon, and we have developed effective treatment options for reducing TDC impacts on CCV Chinook salmon hatchery populations.

REFERENCES


Salmon Conservation Under Changing Conditions and with Freshwater-marine Carryover Effects

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Keywords: changing correlations, direct and indirect effects, environmental indices, life history stages, teleconnections

Conservation management of endangered salmon in regulated rivers requires an understanding of drivers across life stages in freshwater and marine systems. Clear relationships between survival and environmental drivers can be difficult to identify with certainty, especially while environmental conditions are shifting regionally and through time. We presented a series of papers that considered: 1) what shifting relationships among environmental indices can mean for predicting salmon responses (Gosselin et al. 2021a), and 2) the relative contributions of environmental, biological and anthropogenic drivers on smolt-to-adult survival (Gosselin et al. 2021b).

We first showed how correlations may be shifting in the last century across 42 freshwater, marine and climate indices in a study of 72 river sites where Chinook salmon (Oncorhynchus tshawytscha) and coho salmon (Oncorhynchus kisutch) occur in the western USA. We found regional differences in correlations among indices, which had relatively greater associations with teleconnections in the Northwest and within types of environmental indices in the Southwest (Gosselin et al. 2021a). We also found changes in correlations across 10-year windows of timeseries likely influenced by climate phases and their direct influence on freshwater temperature and precipitation. Stronger and weaker correlations may occur through time when superimposing influences from multiple teleconnections that are in- or out-of-phase.

![Fig. 1. A couple of different perspectives to consider when interpreting correlations of environmental indices.](image)

We shared two perspectives that can be important to consider when interpreting correlations between indices (Fig. 1). From a climate-centric perspective, the correlations can represent how teleconnections set up conditions that migratory salmonids will experience as they enter different habitats. There could be one or a few convenient large-scale marine/climate indices that represent multiple local conditions. From a fish-centric perspective, the correlations could represent carryover or cumulative biological effects. For example, a fish could repeatedly experience high temperatures in the egg, fry, smolt, subadult, and adult stages. These two perspectives are also not necessarily mutually exclusive.
We then presented results from an examination of smolt-to-adult survival across four life stages (juvenile downstream; estuary; ocean; and adult upstream) and compared direct and carryover effects for ~400,000 individually tagged, wild, Chinook salmon from the Snake River (Pacific Northwest, USA; 2001–2016). We identified the most important effects from over 20 relationships examined in a hierarchical Bayesian mark-recapture model (Gosselin et al. 2021b). By analyzing the covariates in a unified model, we evaluated their relationships to survival within and across life stages in a common currency.

![Fig. 2. Estimated regression coefficients ($\beta$) for direct and carryover effects on survival across three life stages. Thick horizontal lines represent medians, thin horizontal lines represent 90% credible intervals, and ends represent 99.8% credible intervals of posterior distributions (as Fig. 4 in Gosselin et al. 2021b).]

**Table 1.** Marginal effect size ($\Delta d_k$) of each predictor $k$ on survival in stage $d$, computed by varying the predictor over its observed range while holding all other predictors constant at their sample means. All estimates are reported as posterior median and 90% credible interval. Bold represents 90% credible interval that does not include 0 (modified from Table S2 in Gosselin et al. 2021b).

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Range observed</th>
<th>$\Delta d_k$</th>
<th>$\Delta d_k$</th>
<th>$\Delta d_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGR river temperature ($^\circ$C)</td>
<td>6.2–15.0</td>
<td>-0.66</td>
<td>-0.97</td>
<td>-</td>
</tr>
<tr>
<td>LGR River flow (kcfs)</td>
<td>26.8–188.8</td>
<td>0.81</td>
<td>(-0.01, 0.50)</td>
<td>-0.01</td>
</tr>
<tr>
<td>LGR water spilled (%)</td>
<td>0–58.2</td>
<td>-0.13</td>
<td>-0.12</td>
<td>-</td>
</tr>
<tr>
<td>LGR juvenile fork length (mm)</td>
<td>55–155</td>
<td>0.78</td>
<td>2.26</td>
<td>-</td>
</tr>
<tr>
<td>SWE (inches)</td>
<td>9.5–24.0</td>
<td>-0.11</td>
<td>0.91</td>
<td>-</td>
</tr>
<tr>
<td>PITPH (number of powerhouse)</td>
<td>1–4.7</td>
<td>-</td>
<td>-0.55</td>
<td>-</td>
</tr>
<tr>
<td>SSTarc (unitless)</td>
<td>-0.48–1.38</td>
<td>-</td>
<td>-1.67</td>
<td>-</td>
</tr>
<tr>
<td>BOA river temperature ($^\circ$C)</td>
<td>6.7–22.6</td>
<td>-</td>
<td>-</td>
<td>-0.38</td>
</tr>
<tr>
<td>BOA river flow (kcfs)</td>
<td>79.2–501.5</td>
<td>-</td>
<td>-</td>
<td>0.19</td>
</tr>
<tr>
<td>BOA water spilled (%)</td>
<td>0.6–65.2</td>
<td>-</td>
<td>-</td>
<td>-12</td>
</tr>
</tbody>
</table>
Across the direct effects examined in the juvenile downstream stage (Fig. 2a), the direct and carryover effects in the ocean stage (Fig. 2b), and the direct and carryover effects in the adult upstream stage (Fig. 2c; Table 1; modified from Gosselin et al. 2021b), the strongest marginal effect sizes indicated that marine conditions (i.e., sea surface temperature index, SSTarc) had a strong negative relationship with ocean survival. Yet, juvenile fish length in the river had comparable but positive marginal effect sizes with ocean survival (Fig. 2; Table 1; modified from Gosselin et al. 2021b). Fish length, river temperature, and the snow-water-equivalent (SWE) index had important direct and/or carryover associations to river and ocean survival. Furthermore, the freshwater index of dam powerhouse passage (PITPH) showed a negative but uncertain influence on ocean survival.

As conditions in freshwater and marine environments continue to change, it is important to continue existing monitoring programs, to understand underlying mechanisms, and to not rely only on correlations between environmental indices because they break down over time. These mechanisms will allow us to understand which relationships are relevant under certain climate phases and which mitigative strategies are likely to be robust under a changing climate. Furthermore, as the ocean continues to warm and exert relatively large impacts on salmonid survival (Crozier et al. 2021), it will be important to consider a diversity of mitigative options, including freshwater-marine carryover effects that may help increase ocean survival.

REFERENCES


Juvenile Yukon River Chinook Salmon in a Warming Arctic

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Keywords: northern Bering Sea, marine survival, maturity, diet, energy density

Recent changes in Arctic temperatures have important implications for coastal ecosystems of the northern Bering Sea (NBS) and Yukon River Chinook salmon (*Oncorhynchus tshawytscha*). The abundance of Yukon River Chinook salmon has declined significantly over the last 20 years, resulting in various levels of commercial fisheries closures, restrictions to subsistence fishing opportunities, and the inability to meet harvests necessary for subsistence in many years (Fall et al. 2020). Although causes of the decline of Yukon River Chinook salmon are unclear, their survival after their first summer at sea (September) has been relatively stable over the last 15 years (Murphy et al. 2017; Howard et al. 2020; Murphy et al. 2021). This emphasizes the importance of early life-history stages and Arctic ecosystems in the survival of Yukon River Chinook salmon.

Sea ice plays a key role in the NBS ecosystem. Arctic sea ice extent during the summer has been shrinking at a rate of approximately 13% per decade over the last three decades with notable impacts on Arctic ecosystems, coastal communities, and global temperatures (Moon et al. 2019). However, the extent of winter sea ice in the Bering Sea has been either relatively stable or has increased over this same time period (Jones et al. 2020). Climate models have predicted a long-term loss of 34% in winter sea ice extent in the Arctic; however, the significant loss of Bering Sea winter sea ice during 2018 and 2019 indicate that the loss of winter sea ice may occur at a faster rate than predicted by climate models (Jones 2020).

The Optimal Interpolation Sea Surface Temperature (OISSTv2.1) dataset (Huang et al. 2021, accessed by NOAA’s Coastwatch Westcoast Regional Node ERDDAP site) was selected for this analysis as it includes winter SST proxy values when sea ice is present. Proxy SST values vary between 0 and -1.8°C and are based on sea ice concentrations (ice cover and thickness) (Banzon et al. 2020).

Information on the abundance, stock origin, diet, and energetic condition of juvenile Chinook salmon has been routinely collected during the northern Bering Sea surface trawl and ecosystem survey. This survey has sampled coastal waters of the NBS, latitudes 60°N–65.5°N, since 2002 (Murphy et al. 2021). Early life-history survival of juvenile Chinook salmon can be approximated by the number of juveniles-per-spawner (J/S) for the Canadian-origin

**Fig. 1.** The number of juveniles-per-spawner (grey bars) and parent year spawner abundance (dashed line) for a) the Canadian-origin stock group within the Yukon River, and b) the total Yukon River stock group (b), 2003–2019. Error bars are the standard deviation of juveniles-per-spawner based on the variance of juvenile abundance.
and Total Yukon River stock groups (Fig. 1). Figure 2a shows the spatial correlation between monthly average OISST values and total Yukon River Chinook salmon juveniles-per-spawner. The area within the estuarine habitats (bottom depths < 20 m) just offshore of the Yukon River Delta was selected for this analysis (Delta OISST index) (Fig. 2a).

![Spatial and temporal correlations between OISST and the number of Canadian-origin Yukon River Chinook salmon juveniles-per-spawner (J/S), 2003–2019. OISST values are the average monthly values during the year of marine entry. The black ovals identify the spatial extent of the Delta OISST index. The purple lines in (a) are the 20 m depth contour. Correlation coefficients between the average monthly Delta OISST index and the number of Canadian-origin and Total Yukon River J/S are shown in b).](image)

**Table 1.** Pearson correlation coefficients between juvenile Chinook salmon and monthly OISST values within the nearshore habitats of the Yukon River Delta, 2003–2019. Correlations are included for the number of juveniles-per-spawner (J/S) for the Canadian-origin and Total Yukon River stock groups, stomach fullness index (SFI), the proportion of fish in the diet (piscivory), energy density (ED wet weight and dry weight), the proportion of Canadian-origin Chinook salmon maturing at Age 3 and 4 years (jack rate), and the proportion of non-Yukon River Chinook salmon stocks in the northern Bering Sea. Asterisks identify the significance of the correlation (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).**

<table>
<thead>
<tr>
<th>Month</th>
<th>Canadian-origin J/S</th>
<th>Total Yukon J/S</th>
<th>Stomach Fullness Index</th>
<th>Piscivory</th>
<th>ED (wet)</th>
<th>ED (dry)</th>
<th>Jack Rate</th>
<th>non-Yukon stocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec</td>
<td>0.63***</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>0.82***</td>
<td>0.8***</td>
<td>0.38</td>
<td>0.55</td>
<td>0.44</td>
<td>0.05</td>
<td>-0.16</td>
<td>-0.57*</td>
</tr>
<tr>
<td>Feb</td>
<td>0.28</td>
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<td>0.31</td>
<td>0.48</td>
<td>0.28</td>
<td>-0.39</td>
<td>-0.44</td>
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<tr>
<td>Mar</td>
<td>0.52</td>
<td>0.42</td>
<td>0.31</td>
<td>0.43</td>
<td>0.43</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>0.2</td>
<td>-0.06</td>
<td>-0.41</td>
<td>-0.18</td>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>0.1</td>
<td>0.02</td>
<td>-0.49</td>
<td>-0.57*</td>
<td>-0.12</td>
<td>0.48</td>
<td>0.34</td>
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</tr>
<tr>
<td>Jun</td>
<td>-0.04</td>
<td>-0.11</td>
<td>-0.67***</td>
<td>-0.54</td>
<td>-0.31</td>
<td>0.31</td>
<td>0.15</td>
<td>0.74**</td>
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<td>-0.25</td>
<td>-0.65*</td>
<td>-0.84***</td>
<td>-0.03</td>
<td>0.63*</td>
<td>0.62*</td>
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<tr>
<td>Aug</td>
<td>-0.15</td>
<td>-0.09</td>
<td>-0.6*</td>
<td>-0.62*</td>
<td>0.38</td>
<td>0.74**</td>
<td>0.65*</td>
<td>-0.01</td>
</tr>
<tr>
<td>Sep</td>
<td>-0.2</td>
<td>-0.15</td>
<td>-0.26</td>
<td>-0.55</td>
<td>0.04</td>
<td>0.15</td>
<td>0.12</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
The Canadian-origin and total Yukon River juveniles-per-spawner are both positively correlated with the winter Delta OISST index and therefore negatively correlated with winter sea ice concentrations in the nearshore habitats of the Yukon River Delta (Table 1, Fig. 2b). Similar correlations by both stock groups of Chinook salmon and the spatial scale of the correlation (Fig. 2a and Fig. 2b) indicate that this may reflect the importance of ecosystem processes within the nearshore habitat of the Yukon River Delta and the NBS to the survival of Chinook salmon. Although the correlation with temperature occurs before Chinook salmon enter marine habitats, winter sea ice concentrations could be impacting the productivity of the nearshore estuarine fish community. Chinook salmon may have a higher dependency on the estuarine fish community than other species of salmon due to the high level of piscivory within estuarine habitats (Miller et al. 2016), and the NBS (Farley et al. 2009; Cook and Sturdevant 2013; Garcia and Sewall 2021).

Fig. 3. Correlation coefficients between the Delta OISST index and a) stomach fullness (SFI) and piscivory, b) energy density (ED kJ/g) dry weight and wet weight, c) the proportion of early maturing males (Jack Rate), and d) the proportion of non-Yukon River Chinook salmon stocks in the northern Bering Sea. The Delta OISST index is the average monthly OISST values (Jan–Sep) within the nearshore (< 20 m) estuarine habitats of the Yukon River Delta.

Stomach fullness (ratio of stomach contents and body weight) and percent piscivory of juvenile Chinook salmon are both negatively correlated with the Delta OISST index during the summer (May–August) (Table 1, Fig. 3). This result is consistent with negative relationships observed between stomach fullness, piscivory, and the in-situ temperature data collected during the NBS survey (Garcia and Sewall 2021, Murphy et al. 2021). The decline in stomach fullness with increasing temperature likely represents a decline in prey availability (Garcia and Sewall 2021; Murphy et al. 2021); however, the impact of declining stomach fullness on the juvenile Chinook will require a more detailed look at the foraging ecology of Chinook salmon within a bioenergetics model framework.

The energy density (ED) dry weight of juvenile Chinook salmon was positively correlated with the Delta OISST index during the summer months (Fig. 3). Changes in the water content of juvenile Chinook salmon resulted in different correlation patterns between ED wet weight and ED dry weight. Energy allocation patterns of juvenile Chinook salmon in the NBS support a higher degree of adaptive resilience to overwinter conditions than lower latitude stocks of Chinook salmon (Moss et al. 2016) and juveniles may be conserving energy at the cost of growth. The increase in ED dry weight with temperature helps temper concerns over declining stomach fullness and piscivory (Garcia and Sewall 2021). However, the reduction in energy density with the record warm temperatures in 2019 may indicate that reduced stomach fullness in Chinook salmon is starting to negatively impact the ability of juvenile Chinook salmon to store energy (Murphy et al. 2021).

The proportion of early maturing (age 3 and age 4) Chinook salmon returning to the Yukon River is positively correlated with June and July temperatures (Delta OISST) (Fig. 3). Similar to the correlation with diet
and energy, this likely is the result of summer temperature correlations between the Delta and the NBS. Positive correlations have also been observed between juvenile size and maturation rates of Yukon River Chinook salmon (Howard et al. 2020). Siegel et al. (2017) found that male Yukon River Chinook salmon were more likely to mature at the youngest age (age 3) in warmer years, even after accounting for the effects of growth (measured with scales). This may reflect the influence of temperature on prey quality and lipid levels (energy density) of Chinook salmon that is not captured in estimates of fish length or scale growth.

The proportion of non-Yukon River Chinook salmon in the NBS is positively correlated with June and July Delta OI SST data (Fig. 3). This correlation likely reflects increased northward dispersal of stocks from the southern Bering Sea (SBS) into the NBS during warm summers. This pattern is consistent with increased northward dispersal of sockeye salmon and age-0 pollock with summer temperatures (Murphy et al. 2021). The Canadian-origin stock group has typically been the most abundant stock group of Chinook salmon in the NBS, with an average proportion of 47%. However, the record warm temperatures in 2019 resulted in the highest observed proportion of non-Yukon River Chinook salmon in the NBS (35%), which was greater than the proportion of Canadian-origin Chinook salmon (30%). Increased presence of non-Yukon River stocks in the NBS will confound efforts to connect the distribution, size, diet, and condition of juvenile Chinook salmon to Yukon River Chinook salmon.

Although it is unclear what ecological processes are contributing to the decline in abundance of juvenile Chinook salmon from the Yukon River, the combined impact of increased summer temperatures and increased winter sea ice concentrations in the estuarine habitats of the Yukon River Delta is concerning. The correlation between winter temperatures and juveniles-per-spawner may point to limiting factors within the estuarine habitats of the Yukon River Delta; however, additional research on the foraging ecology of juvenile Chinook salmon will be needed to provide an ecological context to this correlation. The decline in stomach fullness and piscivory with summer temperature primarily reflects a reduction in prey availability and prey quality with temperature. The increase in energy density of juvenile Chinook salmon with temperature tempers the negative impact of reduced stomach fullness and piscivory; however, energy density of juvenile Chinook salmon decreased with the record warm temperatures in 2019 and may indicate that the reduced stomach fullness could be negatively impacting the ability of Chinook salmon to store energy. The proportion of early maturing Chinook salmon is also positively correlated with summer temperatures, which is consistent with previous observations that maturity rates are positively correlated with temperature and growth of Chinook salmon (Siegel et al. 2017; Howard et al. 2020).

We thank the vessel captains, vessel crew members, and the many scientists who have supported these coastal surveys in Alaska. Research on Yukon River Chinook salmon is currently supported by the Alaska Fisheries Science Center, Alaska Department of Fish and Game, and through the National Oceanic and Atmospheric Administration’s Pacific Coastal Salmon Recovery Fund administered by the Alaska Department of Fish and Game’s Alaska Sustainable Salmon Fund (grant award NA19NMF4380229).

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Dynamics on Distribution, Production, and Biological Interactions of Pacific Salmon in the Changing Climate of the North Pacific Ocean

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Keywords: Pacific salmon, global warming, inter-specific interaction, intra-specific interaction, trophic level, population density-dependent effect

The global warming effect for the distribution of chum salmon based on the IPCC AR4 SRES-A1B scenario was already predicted (Kaeriyama 2008), and it was clarified that Japanese chum salmon were positively affected in the 1990s (Kaeriyama et al. 2012, 2014) and negatively influenced since the mid-2000s by global warming (Kaeriyama and Urabe 2018; Kaeriyama 2019). Global warming will have significant impacts on the distribution and migration of Pacific salmon in the North Pacific in this century. The objective of this paper is to evaluate the global warming effect on distribution, production, and inter- and intra-specific interactions of Pacific salmon in order to establish sustainable salmon conservation management. The COBE-SST database of the Japan Meteorological Agency was used to evaluate the SST in the North Pacific Ocean and Arctic Sea, the stable isotope analysis for evaluating the trophic level of Pacific salmon, and the Lotka-Volterra equations for evaluating the inter- and intra-specific interactions among pink, sockeye, and chum salmon. I also defined optimal (OGT) and allowable growth temperatures (AGT) of chum salmon as 8–12 °C and 5–7°C, respectively (Kaeriyama 2004; Kaeriyama and Urabe 2018).

Fig.1. Annual changes in catch of pink, chum, and sockeye salmon in 1925–2019 in the North Pacific Ocean (Data: NPAFC Catch Statistics).

Based on the NPAFC catch data of pink, chum, and sockeye salmon in the North Pacific Ocean (Fig. 1), the southern salmon catch has followed a decreasing trend in Japan since the mid-2000s and in British Columbia, Canada, since the 1990s. In contrast, northern salmon abundance has trended upwards in Russia since the mid-2000s and has been highly stable in Alaska since the 1990s. Temporal changes in areas of AGT and OGT of chum salmon in June and July from the 1920s to the 2010s in the North Pacific Ocean and the Arctic Sea indicate the following:

1) In June, the area of AGT has increased since the 1980s, and approached almost all coasts of Russia in the 2010s, coinciding with increased abundance and survival rate during the early ocean-life period of Russian chum.
and pink salmon (Figs. 1, 2). This suggests that Okhotsk and Bering Seas are favorable ecosystems for the survival of Russian chum and pink salmon since the mid-2000s (Kaeriyama 2019).

2) In July, the area of OGT showed a tendency to leave the coast in the Gulf of Alaska since the mid-1990s and from the waters near Japan in the 2010s. Each of these periods appeared to coincide with the decline of salmon abundance in British Columbia, Canada, and Japan, respectively (Figs. 1, 3). For Fraser River sockeye salmon, communicating uncertainty in fisheries management inputs is increasingly important with climate change, and as ecosystems and fish respond (Cohen 2012; Peterman and Dorner 2012; Grant et al. 2021). On the other hand, Japanese chum salmon would miss a migration route to the Okhotsk Sea and their survival rate has declined since the late-2000s (Kaeriyama and Urabe 2018).

Fig. 2. Temporal change in the allowable growth (AGT) and the optimal growth temperatures (OGT) of chum salmon in June during the 1920s–2010s in the North Pacific Ocean and the Arctic Sea.

Fig. 3. Temporal change in the allowable growth (AGT) and the optimal growth temperatures (OGT) of chum salmon in July during the 1920s–2010s in the North Pacific Ocean and the Arctic Sea.

Fig. 4. Mean and SD in $\delta^{13}$C and $\delta^{15}$N (A) and trophic levels (B) of Pacific salmon in the North Pacific Ocean. NB: off the St. Lawrence Island.
The relationship between $\delta^{13}$C and $\delta^{15}$N of Pacific salmon (Fig. 4A) showed parallel regression lines for the Gulf of Alaska, the Western Subarctic Gyre, the eastern Bering Sea, and the coastal sea around the Aleutian Islands in the North Pacific Ocean (ANCOVA; $F = 2.283, p = 0.059$), except for chum salmon off St. Lawrence Island, where they had maximum enrichment because of high nutrient abundance and low growth rate of phytoplankton under a cool climate and strong upwelling environment (Schell et al 1998; Qin and Kaeriyama 2016). These common slopes among four ecosystems indicate the kinetic isotope effect (Wada et al. 2013) in the North Pacific Ocean, suggesting that the dynamics of multiple metabolic chain systems are similar for Pacific salmon (Sugisaki et al. 2013). In Pacific salmon, Chinook salmon occupied the highest trophic level (4.3), followed by steelhead trout (4.1), sockeye and coho (3.9), and chum and pink salmon (3.5) (Fig. 4B; Qin and Kaeriyama 2016). The sockeye, chum, and pink salmon had lower trophic levels than other species, despite being more than 95% of the total catch of Pacific salmon in the North Pacific Ocean.

Fig. 5. Loka-Volterra equations of two species ($N_1$ and $N_2$). $K$: carrying capacity, $N$: population size, $\alpha$: competition coefficient, 1: species 1, 2: species 2.

* Convergence

Table 1. Inter- and intra-specific interaction among chum, pink and sockeye salmon based on the Loka-Volterra equation

I evaluated the inter- and intra-specific interaction of pink, chum, and sockeye salmon using the Lotka-Volterra equations (Fig. 5). I used 2010–2018 catch data as population size and 1993–2018 catch data as a carrying capacity for each country's population of the three species. In the three species, pink salmon was strongest, followed by sockeye and chum salmon. No consistent regularity was found for intraspecific interactions (Table 1). Temporal changes in body size and abundance of pink, sockeye, and chum salmon from 2000 to 2018 in the North Pacific Ocean are indicated as follows.

1) Pink and sockeye salmon decreased body sizes with an increase in their abundance, although chum salmon decreased their body size without a change in abundance.

2) Body sizes of the three species had significant negative correlations with the abundance of pink and sockeye salmon, despite no correlation between body sizes and abundance of chum salmon (Fig. 6).

That is to say, the abundance of pink and sockeye salmon would affect the density-dependent effect for three species as the inter- and intra-specific interaction except for chum salmon.
Fig. 6. Density-dependent effect for pink, sockeye, and chum salmon in the North Pacific Ocean. A: Temporal changes in abundance (N) and body size (BW). B: Relationship between abundance and body size for chum, pink and sockeye salmon since 2000. Data: NPAFC Catch Statistics

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Projected Impacts of Global Warming on Chum Salmon Stocks in Hokkaido, Japan

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Keywords: chum salmon, global warming, ocean entry period, duration of preferable sea surface temperature

In recent years, there has been a rapidly growing worldwide concern regarding the impacts of climate change on marine ecosystems. The Japan Meteorological Agency (JMA) reported that the sea surface temperature (SST) around Hokkaido has been increasing by 1°C per 100 years, and we are concerned about future impacts of increasing ocean temperature on the chum salmon stock in Hokkaido. Predicting the changes of ocean temperature conditions, and knowledge about how the change of ocean conditions could affect chum salmon stock, are essential if substantial measures are to be taken. To date, JMA published a long-term (100 year) forecast about trends in the variability of annual mean SST using a global climate model. However, there were issues with the forecast that were identified so that the prediction could be applied to salmon stock management in Hokkaido. The prediction is calculated as an annual mean SST, and the unit region for the prediction is larger than that used for chum salmon stock management.

We estimated the future variability of daily SST in six sea areas around Hokkaido using the JMA model (Yukimoto et al. 2012) that was developed based on the IPCC assessment report in the present study, which almost corresponds with the unit regions for chum salmon management. The estimations were targeted for 2016–2100 and were calculated based on four scenarios (RCP 2.6, 4.5, 6.0, 8.0). Using these estimations, we analyzed the future variability of the SST regime during the ocean entry period of chum salmon around Hokkaido coastal areas, and how the changes associated with climate change affect chum salmon stock in Hokkaido.

We analyzed the variabilities between start and end dates, and the duration of 8–13°C temperatures which is recognized as preferable SST for chum salmon juveniles in coastal areas of Hokkaido (Irie 1990, Seki 2005). Our analyses revealed that the starting and ending dates with the preferred SST were advanced and delayed in all six areas, respectively, but the variabilities of SST through the targeted period differed between areas and scenarios. The period of the preferred SST decreased in the Okhotsk and Nemuro areas and increased in the northern and southern Japan sea, as well as western Pacific areas, and no obvious change was found in the eastern Pacific area. These results suggest that while future changes of SST during the spring season due to climate change might negatively impact the early survival of chum salmon juveniles in the Okhotsk and Nemuro areas, it might positively affect their survival in the northern and southern Japan sea areas, as well as the western Pacific area.

REFERENCES


Recent Changes in the Spatial and Temporal Distribution of Salmon Habitat in the North Pacific

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Keywords: Pacific salmon, marine heat waves, primary production, mixed-layer properties

As the oceans warm, marine heat waves (MHW) have gained attention. The 2014–2016 MHW in the northeast Pacific, in particular, catalyzed increased interest in the causes and consequences of widespread, intense, and persistent warming. For a few decades now, researchers have recognized correlations between decadal-scale warming and cooling cycles and cycles of salmonid productivity. Generally, warming has negative impacts on salmon stocks from warmer parts of the North Pacific, and positive effects on stocks in colder regions. Thus, the 2014–2016 MHW in the northeast Pacific was an alarming event to fishery managers in the continental USA.

While statistical relationships between SST and salmon population variation are frequently observed, the mechanism linking them are less clear. Warming can impact salmon directly or indirectly. Direct impacts could include behavioral avoidance of temperatures beyond thermal preference and changes in metabolic rate affecting growth and maturation. Indirect effects could occur through impacts on salmon prey. Bottom-up effects of warming are likely dependent on the mechanism of warming and its ecosystem context, which influence the timing, magnitude, and composition of primary and secondary production. Winter mixing resupplies surface waters with nutrients, and spring stratification allows phytoplankton to deplete the nutrients. The cycle of mixing and stratification gives the ocean a memory that can drive intra- and inter-annual production variability in complex ways.

Fig. 1. Large marine ecosystems of the North Pacific, as defined by Longhurst (1998) on the basis of current boundaries and dynamics driving seasonal production regimes.

In this paper, we explore recent trends (2002–2020) in SST (Hadley 1°; Rayner et al. 2003), mixed layer depth (via Argo buoy data; Holte et al. 2017), and primary production (based on ocean color and temperature; Behrenfeld and Falkowski 1997) across ecosystems of the North Pacific; changes in the horizontal extent of thermally-suitable habitat for six species of Pacific salmonids (based on Hadley 1° SST and species-specific temperature criteria; Abdul-Aziz et al. 2011); and summarize recent changes in salmon production across the north Pacific that may be related to changes in ocean conditions. We summarize information by large marine ecosystems, as defined by Longhurst (1998) and as shown in Fig. 1.

North Pacific ecosystems have shown quite different patterns of variation in mixed layer properties and primary production over the past two decades (Fig. 2). The Bering Sea has exhibited low-frequency variation in SST, with generally warmer-than-average conditions from 2014–2020. From 2018–2020, mixed layer depth experienced episodes of deepening in the winter (January–March) while maintaining warmer-than-average SSTs. Primary production shows no obvious relationship to these changes. The eastern North Pacific Gyre experienced high SSTs in 2014–2016 and late 2018–2020, which followed a relatively cool period from 2006–2013. The warming began in the second half of 2013, with periods of mixed-layer shoaling through 2014, which also corresponded to periods of higher-than-normal primary production. The western portion of the North Pacific Gyre did not exhibit the same low-frequency variation in SST but did experience a period of warming in 2013 and 2014, with slight shoaling of the thermocline evident and little deviation of primary production from its usual seasonal pattern. Both the Alaskan Downwelling and California Current regions experienced warmer-than-usual SSTs in

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2014–2016 and 2019. As in the eastern Pacific Subarctic Gyre, the onset of the MHW in the California Current was associated with a shallower mixed layer depth, a pattern shared with the Alaskan Downwelling region to a lesser extent. In all three regions, the initial period of warming was associated with higher primary production, but while the warming persisted, the higher production did not. The Sea of Okhotsk, like the eastern subarctic Pacific, showed clear interdecadal variability, but of opposite sign, and has generally cooled over the past two decades.

We used convergent cross mapping (CCM) to evaluate whether physical variable anomalies (mixed layer depth, temperature, and salinity) cause anomalies in primary production. To address the causal relationship between
two time series, CCM reconstructs system states from the two time series variables and then quantifies the correspondence between them using nearest neighbor forecasting (Ye et al. 2015). If variable $X$ drives variable $Y$, then information about $X$ can be obtained from $Y$, establishing causality (Sugihara et al. 2012). Primary production anomalies were weakly to moderately coupled to anomalies in physical variables, with linkages most typically to adjacent regions at lags of several months. The California Current and North Pacific Transition Zone are exceptions: productivity is related to temperature in those areas nine months previously.

**Fig. 3.** Relationship between primary production and mixed layer properties. Color intensity indicates strength of relationship; number is the lag (in months) with the strongest relationship. Abbreviations: CCAL = California Current; NPPF = North Pacific Transition Zone; KURO = Kuroshio Current; PSAW = Pacific Subarctic Gyre (west); PSAE = Pacific Subarctic Gyre (east); BERS = Bering Sea; OKHS = Okhotsk Sea; ALSK = Alaskan Coastal Downwelling; PP = primary production; MLD = mixed layer depth; MLT = mixed layer temperature; MLS = mixed layer salinity. Ecoregion boundaries are defined by Longhurst (1998), but his BERS region is split into the Bering and Okhotsk seas.

![Physical Predictors](image)

**Fig. 4.** Anomalies in aerial extent of thermally suitable sea surface temperatures (in millions of km$^2$).

The marine heat waves in 2014–2016 and 2019 reduced the area of suitable SSTs in the north Pacific by up to $2 \times 10^6$ km$^2$ compared to average months for steelhead, Chinook, and sockeye salmon, and somewhat lesser amounts for other species (Fig. 4). During the summers of 2014–2016, suitable SSTs for Chinook were almost non-existent, limited to small portions of the Bering Sea and Sea of Okhotsk (Fig. 5). The Bering Sea remained hospitable for sockeye and steelhead in this period, although suitable areas in the eastern North Pacific subarctic gyre contracted towards the Aleutian Islands.
Table 1. Ocean temperatures and observations of unusual salmon fishery conditions aligned by ocean entry year for the dominant year classes of the affected species for all entries except 2014 US Fraser River Sockeye Fishery Disaster Determination. In that case, return year 2014 is aligned with marine heatwave year 2014 to reflect the impact of warm SSTs on the adult migration route. Russian pink salmon harvest data from npafc.org; Chignik harvest and escapement from adfg.alaska.gov; US Federal Fishery Disaster Determinations (FDDs) from https://www.fisheries.noaa.gov/national/funding-and-financial-services/fishery-disaster-determinations; BC fishery information from Pacific Salmon Commission Reports (psc.org). Positive responses are in dark green text and negative responses are in red text.

<table>
<thead>
<tr>
<th>Ocean Climate Year</th>
<th>Climate Conditions</th>
<th>Notable Salmon Observations in Years Following</th>
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</thead>
<tbody>
<tr>
<td>2014</td>
<td>Extreme warm SST anomalies in the Bering Sea and Gulf of Alaska and NE Pacific</td>
<td>Pink salmon harvest in Russia—368.7 million. Washington State coho and pink salmon, tribal fishery FDD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-historical high Bristol Bay sockeye harvest and returns (&gt; 50 million); Record high Prince William Sound pink salmon harvest (98 million). Extremely low Fraser River sockeye returns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-historical high Bristol Bay sockeye harvest and returns (&gt; 50 million). Extremely low Fraser River Sockeye run size; Extreme low steelhead returns to the Thompson and Chilcotin Rivers</td>
</tr>
<tr>
<td>2016</td>
<td>Extreme warm SST anomalies in the Bering Sea, warm in the Gulf of Alaska and western Subarctic North Pacific</td>
<td>2017 pink salmon harvest in Russia—353 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-historical high Bristol Bay sockeye harvest and returns (&gt; 50 million). Chignik sockeye FDD; many GoA sockeye stocks had poor returns; Fraser River “cycleyear” sockeye harvest and returns well below average</td>
</tr>
<tr>
<td>2017</td>
<td>Near normal SSTs in the Gulf of Alaska, warm in the Bering Sea</td>
<td>Record high pink salmon harvest in Russia—676 million. Lowest pink salmon returns to SE Alaska since 1980</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-historical high Bristol Bay sockeye harvest and returns (56.5 million wild sockeye). Chignik sockeye harvest below average, barely met escapement goals; 2019 Fraser River sockeye fishery closed; extreme low run-size (500,000)</td>
</tr>
<tr>
<td>2018</td>
<td>Extreme warm SST anomalies in northern Bering Sea and Chukchi Sea, warm throughout the Gulf of Alaska</td>
<td>High pink salmon harvest and returns to Russia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-historical high Bristol Bay sockeye harvest and returns (58.2 million wild sockeye). Extremely low Copper River sockeye run-size; Fraser River sockeye record-low run-size of 300,000</td>
</tr>
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</table>
Salmon stocks around the North Pacific have responded to the recent MHW in divergent ways (summarized in Table 1). Those originating from North America and entering the Gulf of Alaska (eastern Subarctic Gyre and Alaskan Downwelling regions) have fared poorly, while those utilizing the Bering Sea and Sea of Okhotsk have mostly seen increases. The general patterns are consistent with the idea of the effect of warming being dependent on its relation to thermal optima—warming above the optima is detrimental, while warming below it is beneficial. These effects can be modulated by food availability (although increased primary production in the first part of the 2014–2016 MHW apparently did not mitigate impact of warming on North American stocks) and other food web effects (redistribution and altered energetics of predators, an area in need of investigation).

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Physiological Tools for Evaluating Growth Status of Migrating Salmon

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Keywords: growth indices, Insulin-like growth factor (IGF)-I, IGF-binding proteins

Growth-dependent mortality of juvenile salmon during the early phase of their marine life has been an active area of research. Although the exact timing and the extent of growth-dependent mortality are not clear (Beacham et al. 2017), the general belief is that large and/or fast-growing juveniles have a better chance to survive and will be recruited to the stock (Beamish and Mahnken 2001). Monitoring growth status of out-migrating juveniles is therefore of particular importance. However, a direct measure of growth of individual fish requires marking and recapture of the same individuals, which is extremely difficult to conduct on free-swimming salmon. Instead, indirect methods are often used to evaluate/estimate growth. Among them, scales and otoliths are useful to reconstruct past growth patterns and habitats. However, they may not provide information on the recent/current growth rate. Biochemical growth indices such as muscle RNA/DNA ratio have been used to monitor recent/current growth, although their validity is somewhat incomplete (Johnson et al. 2002). Ideally, growth indices should be directly involved in the growth process and not a result of growth (Couture et al. 1998).

We focus on hormones and proteins involved in growth regulation to evaluate current growth status because they provide a semi-quantitative estimation of growth rate and mechanistic interpretation. The growth of vertebrates including salmon is mainly regulated by the growth hormone (GH) and insulin-like growth factor (IGF)-I system (Fig. 1). In this system, GH is secreted from the pituitary gland and can promote growth by directly acting on the target tissues such as muscle and bone, or indirectly through stimulating hepatic production of IGF-I. IGF-I is then secreted into the bloodstream, delivered to the target tissues and mediates the growth-promoting action of GH. Circulating IGF-I has been reported to be correlated with individual growth rate in salmon and proposed as an index of salmon growth (Beckman et al. 2004a, b; Beckman 2011).

Mechanistically, the activity of IGF-I is tightly regulated by IGF-binding proteins (IGFBPs). IGFBPs are capable of inhibiting and potentiating IGF-I action by controlling its availability to the receptor. Thus, IGFBPs are important components of the GH-IGF-I system. There are six types of IGFBPs, termed IGFBP 1 to 6, identified in mammals. In teleosts, two subtypes ("a" and "b") of each member of IGFBPs are generally present due to an extra round of whole genome duplication in this lineage.

In salmon circulation, at least three IGFBPs are detected. We have identified these three IGFBPs as IGFBP-1a, 1b, and 2b, respectively (Shimizu and Dickhoff 2017). Rearing experiments using post-smolt coho salmon held in freshwater revealed that circulating IGFBP-2b levels were high in well-fed fish and positively correlated with individual growth rate (Beckman et al. 2004a, b). These characteristics are similar to those of IGF-I and there is a positive correlation between circulating IGF-I and IGFBP-2b levels, suggesting that IGFBP-2b is a major carrier of circulating IGF-I. In contrast, IGFBP-1a and -1b are induced under catabolic conditions such as fasting and stress, and inversely correlated with individual growth rate (Shimizu et al. 2006, 2011; Kaneko et al. 2020). It is of note

Fig. 1. The growth hormone (GH)–insulin-like growth factor (IGF)-I–IGF-binding protein (IGFBP) system regulating fish growth.
that IGFBP-1b appears to be more sensitive to fasting than IGFBP-1a in masu salmon (Kawaguchi et al. 2013). These findings led us to propose that circulating IGF-I and IGFBP-1b are positive and inverse indices of salmon growth, respectively (Fig. 2).

We are currently working on chum salmon because of its importance in Japan and recent declines in return numbers. Rearing experiments using juvenile chum salmon held in seawater confirmed that circulating IGF-I and IGFBP-1b levels were positively and negatively correlated with individual growth rate, respectively (Kaneko et al. 2019b), confirming their applicability to salmonids in general. Using these physiological indices, we have been conducting field surveys through a collaboration with Hokkaido Research Organization and the Abashiri Fisheries Cooperative to evaluate growth status of out-migrating juvenile chum salmon in the Abashiri area, northeastern Hokkaido, Japan. Profiles of serum IGF-I and IGFBP-1b levels suggested that small, slow-growing juveniles stayed at the estuary throughout the out-migration season and might suffer growth-dependent mortality (Kaneko et al. 2015). On the other hand, serum IGF-I levels in fish in nearshore were high, suggesting that they were activating growth while moving to offshore.

In order to further assess the utility of the growth indices for free-swimming salmon, we conducted a "biological validation" by measuring plasma samples of young coho salmon caught at a region where growth retardation was expected (Kaneko et al. 2019a). Coho salmon plasma were obtained by a field survey conducted by Canadian and US researchers along the Strait of Georgia and surrounding waters, British Columbia, Canada (Journey et al. 2018). The Johnstone Strait is thought to be a poor feeding ground for salmon due to its strongly tidally mixed waters. Our assumption was that IGF-I and IGFBP-1b levels were low and high, respectively, in coho salmon in Johnstone Strait. However, plasma IGF-I levels in fish from the Johnstone Strait were not low, being comparable to those from other regions (Journey et al. 2018). It is possible that the fluctuation of environmental factors, such as water temperature, might disturb the growth-IGF-I relationship. On the other hand, plasma IGFBP-1b levels were highest at the Johnstone Strait as expected (Kaneko et al. 2019a). These results showed that responses to the growth indices are sometimes contradictory. However, when we calculated the molar ratio of IGF-I to IGFBP-1b, which is theoretically a fraction of IGF-I available for growth promotion, it was lowest in fish from Johnstone Strait (Kaneko et al. 2019a). Thus, combining multiple growth indices may stabilize the accuracy of growth evaluation. Although more validation for IGF-I and IGFBP-1b is necessary to utilize them as growth indices for migrating salmon, the results so far are supportive and warrant further research.

In summary, we propose that IGF-I and IGFBP-1b are useful physiological tools to assess the recent/current growth status of salmon and a good complement to other growth indices such as scales, otoliths, and RNA/DNA ratio. An advantage of these endocrine factors is that they provide a mechanistic basis of growth alteration. Rearing experiments using the physiological tools should help disentangle factors influencing growth and thus assess the timing and degree of the possible growth-dependent mortality of juvenile/young salmon.
REFERENCES


Environmental DNA survey of the Winter Salmonsphere in the Gulf of Alaska

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Keywords: environmental DNA, Gulf of Alaska, salmon, Northeast Pacific, winter

Environmental DNA (eDNA) is an emerging field to study the diversity and distribution of aquatic communities without the need to capture individuals. It utilizes sequencing of traces of DNA left behind in the environment by organisms to provide an unbiased account of species composition and distribution in an environment without the need for invasive sampling methods (Rees et al. 2014). The International Year of the Salmon (IYS) Gulf of Alaska (GoA) expeditions were launched in 2019 and 2020 to illuminate the factors influencing the survival of Pacific salmon in the open ocean. The winter months, when open-ocean conditions might critically impact ocean survival of first ocean-winter juvenile and subadult salmon, are the least understood but could largely determine stock performance (Beamish and Mahnken 2001; Naydenko et al. 2016; Shuntov et al. 2017; Nagasawa 2000; Ishida et al. 2000). Despite progress on salmon marine ecology during the winter, questions regarding the health and survival of salmon during this period remain unanswered, particularly in the open ocean. Specifically, the impact of predators and competitors has been notoriously difficult to assess due to the scarcity of data, in part due to the difficulty of catching large highly mobile predators of salmon in trawl surveys. Accordingly, we collected water samples during the GoA expeditions and performed an eDNA survey on the samples with the goal of describing the salmonsphere (i.e., the relative abundance and distribution of Pacific salmon, as well as their prey, competitors, and predators).

Water samples of 5 L were collected at 2–4 m below surface using a Niskin bottle at all oceanographic stations during the 2019 and 2020 GoA expeditions. Duplicate 2 L subsamples were filtered into 0.22 μm Sterivex cartridge filters and preserved at -80°C for transport back to the laboratory. All sampling equipment was cleaned with 1.6% sodium hypochlorite solution followed by rinsing with distilled water. In 2020, an additional step of 10% sodium thiosulfate rinse was added to neutralize any residual bleach from the system. Upon return from the field, DNA was extracted from the filter cartridges using the DNeasy extraction kit (Qiagen). To assess chordate and cephalopod species diversity we amplified conserved regions of mitochondrial 16S gene using primers designed by Deagle et al. (2009). To speciate salmonids we similarly targeted the cytochrome oxidase I (COI) gene of Pacific salmon (Thomas et al. 2017). The 16S and COI amplifications were normalized prior to library preparation using a normalization plate to standardize the input material and retrieve similar sequence levels across the different samples. Library preparation was performed using the KAPA Low Throughput Library Preparation kit for Illumina platforms, as per manufacturer’s instructions. The 16S and COI samples were pooled into nine libraries sequenced in single-end 300 bp on an Illumina MiSeq platform, with 7–18 barcoded libraries per run. Sequencing data were quality filtered, demultiplexed, and rarefied using the OBItools suite (https://git.metabarcoding.org/obitools/obitools/wikis/home). Next, unique reads were queried against the nr BLAST database using a standalone local BLAST algorithm (https://blast.ncbi.nlm.nih.gov/Blast.cgi) and results were assigned to the lowest taxonomic level using MEGAN (https://bio.tools/megan). A detailed description of the workflow can be found at https://github.com/bensutherland/eDNA_metabarcoding/. R was used for filtering and assigning species detections to samples and for statistical analysis and visualization of the data. Reads belonging to common contaminants (such as humans, pigs, chickens, and cows) were excluded from the analysis.
eDNA was able to detect all salmon species caught in 2019 except for Chinook, which had only three individuals captured. Salmon distributions detected by eDNA were in general similar to trawl catches, with the exception of pink salmon that showed a distinct distribution center in the northwest of the survey region where no pink salmon were caught in trawls, suggesting that trawl sampling might have missed a secondary distribution center (Fig. 1).

Fig. 1. Capture and eDNA detection location of pink salmon (*Oncorhynchus gorbuscha*) in the GoA in 2019 and the distribution density calculation based on the respective data.

Fig. 2. Capture and eDNA detection location of steelhead (*Oncorhynchus mykiss*) in the GoA in 2019.
In 2020, all salmon species captured by trawl were detected by eDNA and eDNA detections outnumbered trawl catches, presumably due to the increased detection sensitivity due to the addition of sodium thiosulfate to the sampling procedure. For instance, only one steelhead (Oncorhynchus mykiss) was captured in 2020, but steelhead DNA was detected at four stations during the survey (Fig. 2). The center of distribution for coho, sockeye, and pink salmon in the GoA in 2020 based on eDNA data was shifted to the west compared to trawl catches (Fig. 3). Given the half life of DNA in sea water, specifically in the winter environment, this could suggest eastward movement of these species towards the continental shelf in the study area during early spring of 2020. One main area of interest in eDNA data was the distribution and abundance of predators of salmon, as predators are notoriously difficult to assess in trawl surveys due to their low abundance and high motility. Only two potential predator species of salmon, North Pacific daggertooth (Anotopterus nikparini) and Pacific spiny dogfish (Squalus suckleyi), had been caught during the GoA expeditions. Indeed, these two species were also detected in the eDNA data. Additionally, salmon sharks (Lamna ditropis), presumed to be major predators of salmon in the open ocean, were detected during both years of the survey (Fig. 4) (Nagasawa 1998; Seitz et al. 2019). Other detections of potential predators of juvenile salmon were Dall’s porpoise (Phocoenoides dalli) as well as a number of predators of presumed lesser importance such as Orca (Orcinus orca), lancetfish (Alepisaurus ferox), and Steller sea lion (Eumetopias jubatus). Dall’s porpoise and salmon shark showed distribution patterns that aligned with the overall distribution of Pacific salmon in both years, suggesting that they might seek out high abundances of their prey species (Fig. 4). Specifically in 2020, where the majority of salmon appeared to be just west of the survey area, predator detections were most common on the westernmost stations (Fig. 4). Surprisingly, harbour seal (Phoca vitulina) DNA was also detected in the GoA, specifically in 2019, and seemed to show strong patterns of co-occurrence with salmon in their distribution. While this species is commonly thought to be restrained to the continental shelf, a visual observation from a crew member of the 2019 expeditions seems to confirm these unexpected detections (Brown and Mate 1983).
Many prey and competitor species of salmon in the open ocean, such as myctophids and cephalopods, perform diurnal vertical migrations which make an adequate assessment of their abundance and distribution by conventional surface trawl surveys challenging as they spend the daytime in deep waters. As DNA remains in the environment even after a species leaves, eDNA detections of vertically migrating species were only slightly affected by time of day in contrast to trawl catches that occurred almost exclusively at night (Table 1). For instance, the distribution of abundant species like Boreopacific armhook squid (*Gonatopsis borealis*) and California headlightfish (*Diaphus theta*) showed a much more even distribution in the eDNA data compared to trawl catch data (Fig. 5). The current dataset did also allow some insights into some species of salmon prey, specifically copepods. *Mesocallanus tenuicornis* and *Metridia pacifica* were the most abundant copepod species detected in 2019 and 2020, with *Mesocallanus tenuicornis* dominating in the south and *Metridia pacifica* being dominant in the north of the GoA.

![Fig. 4](image-url)

**Fig. 4.** eDNA detection location of salmon shark (*Lamna ditropis*) and Dall’s porpoise (*Phocoenoides dalli*) in the GoA in 2019 and 2020 overlayed the distribution density all salmon species (*Oncorhynchus* spp.) combined.

<table>
<thead>
<tr>
<th>Species</th>
<th>Time</th>
<th>eDNA</th>
<th>Trawl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squid</td>
<td>Day</td>
<td>52.7%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>43.7%</td>
<td>91%</td>
</tr>
<tr>
<td>Myctophids</td>
<td>Day</td>
<td>79.3%</td>
<td>8.6%</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>80%</td>
<td>86%</td>
</tr>
</tbody>
</table>

**Table 1.** Proportions of detections of diurnal vertically migrating prey and competitor groups of salmon.
Fig. 5. Capture and eDNA detection location of California headlightfish (*Diaphus theta*) in the GoA in 2019 and 2020 with the time sampling time indicated by color.

Together, eDNA surveys in combination with conventional trawl surveys allow for a more holistic impression of the open ocean environment in the GoA that salmon face during the ocean winter. Specifically, interactions with predators and competitors are becoming increasingly resolved—an unprecedented resolution due to the non-invasive and unbiased nature of eDNA sampling.

REFERENCES


Hokkaido-wide eDNA Monitoring for Sakhalin Taimen, Endangered Salmonid Species

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Keywords: Sakhalin taimen, environmental DNA, endangered species, distribution

Sakhalin taimen (Parahucho perryi) is one of the largest anadromous salmonid fish species in the world. While they are known as a keystone species in river ecosystems, they are currently listed as a critically endangered species on the IUCN Red List due to human disturbances which have caused habitat degradations (e.g., deforestation and river reconstruction) (Fukushima 2006; Rand 2006; Fukushima et al. 2007; Fukushima et al. 2011). For now, their distribution and population status are unclear because it is very difficult to find the organisms in natural environments—just like many other endangered species. In this study, we estimated their current distribution and biomass simultaneously in Hokkaido, Japan, using an environmental DNA (eDNA) species-specific detection system established in a previous study (Mizumoto et al. 2018). We collected eDNA samples from 120 river systems and applied this detection system to them. Our results suggest that distribution of Sakhalin taimen is quite limited and that they are at the brink of extinction for most of the river systems in Hokkaido. Furthermore, we found low levels of human disturbances, especially on river connectivity in two major river systems, where high eDNA concentrations of Sakhalin taimen were detected. These results suggest that eDNA methods play an important role in understanding the population status of endangered species in aquatic environments, and that river consecutiveness is critical for the sustainability of this long-living, precious anadromous fish species. See Mizumoto et al. (2020) for details.

REFERENCES


The Identification of Individuals with Hatchery and Natural Origin in a Mixed Sample of Amur River Chum Salmon by Otolith Microchemistry

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Keywords: otolith microchemistry, LA ICP-MS, chum salmon, identification of origin in a mixed sample, hatchery releases

Objective

This paper presents the results of using microchemical analysis of otoliths to identify chemical markers that are specific to juvenile fall chum salmon released from hatcheries in the Amur River basin, with their subsequent identification in otoliths of returning spawners. The implementation of this approach can be a methodological solution for detecting “hatchery-produced” and natural-origin fish in a mixed sample of chum salmon spawners.

It was hypothesised that the difference in the chemical composition of the edge zone of otoliths of hatchery-produced juveniles and natural-origin juvenile fish, in terms of strontium $^{88}$Sr to calcium $^{43}$Ca isotopic ratio, would make it possible to establish fish origin. Analysis of strontium content in the juvenile zone of an otolith’s thin section of an adult chum salmon was performed to test this hypothesis.

Materials and methods

This study used samples of juveniles and spawners of Amur River fall chum salmon.

Microchemical analysis was carried out at the Research Equipment Sharing Centre of the Geological Faculty of Perm State National Research University by laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS) using LSX-213 G2 laser ablation system and a Bruker Aurora M90—Quadrupole ICP-MS.
The concentration of strontium $^{88}\text{Sr}$ and calcium $^{43}\text{Ca}$ isotopes in the edge zone of the otolith of juvenile fish were analysed at a distance of 152 to 229 μm (on average 188.4 ± 1.95 μm) from the primordia zone. We analysed the chemical composition of the juvenile zone of the otolith’s thin section of adult fish at a distance of 159–205 μm (on average 183.2 ± 1.13 μm) from the primordia.

The obtained absolute values of the $^{88}\text{Sr}$ isotope concentration (ppm) were standardized relative to the $^{43}\text{Ca}$ isotope concentration (%) and presented as a ratio of molar masses.

**Results**

In most of the comparison pairs, fall chum salmon juveniles of artificial origin had high $^{88}\text{Sr}/^{43}\text{Ca}$ ratio values in the edge zone of otoliths compared with juvenile fish of natural origin. Pairwise, multiple comparisons of groups performed using the Tukey HSD test showed that juvenile fish of natural origin had significantly ($p < 0.001$) lower values of the studied indicator compared with juveniles collected at fish hatcheries; however, the sample taken from the Bidzhansky Hatchery in 2018 did not differ from juveniles sampled at the Gur River ($p = 0.999$) and the Anyui River in 2018 ($p = 0.163$), on 29 April 2020 ($p = 0.839$), and on 6 June 2020 ($p = 0.098$). Samples of juveniles of natural origin did not differ statistically from each other with the exception of one pair whose comparison with the $p$-value was close to the used significance level; juveniles from the Gur River had a higher $^{88}\text{Sr}/^{43}\text{Ca}$ ratio when compared with juveniles from the Anyui River, sampled on 17 June 2019 ($p = 0.029$). Among the hatchery-origin juveniles of fall chum salmon, the lowest $^{88}\text{Sr}/^{43}\text{Ca}$ ratio values were characteristic of the fish of the Bidzhansky Hatchery. Juveniles of the Gursky and Udinsky Hatcheries had the highest values of the analysed indicator which was shown at the most pairs of comparison following results of Tukey HSD test. Figure 2 shows box plot diagrams of the $^{88}\text{Sr}/^{43}\text{Ca}$ isotope ratio values of the edge zone of otoliths of juvenile fall chum salmon samples collected in 2018–2020 from hatcheries and the Gur and Anyui Rivers.

![Fig. 2. Values of the $^{88}\text{Sr}/^{43}\text{Ca}$ isotope ratio of the edge zone of otoliths of juvenile fall chum salmon from Bidzhansky Hatchery, Gursky Hatchery, Udinsky Hatchery, Anyuisky Hatchery, the Anyui River, and the Gur River.](image)

Fall chum salmon spawners collected at the Anyuisky Hatchery significantly differed from fish collected from catches at the main channel of the Amur River in terms of the $^{88}\text{Sr}/^{43}\text{Ca}$ isotope ratio value of the juvenile zone of otoliths (ANOVA, $F_{9.350} = 180$, $p < 0.001$). Both male and female fall chum salmon of the Anyuisky Hatchery had significantly higher values of the studied indicator in all comparison pairs, except for the sample collected at the mouth of the Amur River near Oremif Village ($p = 0.985$ for males, $p = 0.803$ for females). Among adult chum from the Amur River, the individuals captured at the start of spawning migration during 29 August–5 September had a higher $^{88}\text{Sr}/^{43}\text{Ca}$ isotope ratio value of the juvenile zone of otoliths in comparison to individuals sampled during the second half of September. The adults captured at the mouth of the Amur River near Oremif Village had higher values of the $^{88}\text{Sr}/^{43}\text{Ca}$ ratio in comparison with other fish collected in the Amur River main channel, the exception being fish captured near Nikolaevsk-on-Amur on 3 September ($p = 0.081$) and 5 September ($p = 0.106$). Figure 3 shows box plot diagrams of the $^{88}\text{Sr}/^{43}\text{Ca}$ isotope ratio values of the juvenile zone of otoliths of fall chum salmon spawners samples from the Anyuisky Hatchery and the Amur River collected in 2019.
Fig. 3. Values of the $^{88}\text{Sr}:{^{43}\text{Ca}}$ isotope ratio of the juvenile zone of otoliths of fall chum salmon spawners samples from the Anyuisky Hatchery and the Amur River collected in 2019.

Table 1. The proportion of fish with the $^{88}\text{Sr}:{^{43}\text{Ca}}$ molar ratio value higher than $1.7 \times 10^{-3}$ among samples of the Amur fall chum salmon spawners used in the study.

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Sampling date</th>
<th>Number of specimens processed by LA ICP-MS</th>
<th>Proportion of fish with the marker value higher than $1.7 \times 10^{-3}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anyuisky Hatchery (males)</td>
<td>30 Sep–5 Oct 2019</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>Anyuisky Hatchery (females)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Amur River, Oremif Village</td>
<td>29 Aug 2019</td>
<td>18</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>3 Sep 2019</td>
<td>26</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>5 Sep 2019</td>
<td>22</td>
<td>50</td>
</tr>
<tr>
<td>The Amur River, Nikolaevsk-on-Amur</td>
<td>16 Sep 2019</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>20 Sep 2019</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>The Amur River, Tyr Village</td>
<td>15 Sep 2019</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>The Amur River, Susarno Village</td>
<td>21 Sep 2019</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>The Amur River, Belgo Village</td>
<td>24 Sep 2019</td>
<td>29</td>
<td>31</td>
</tr>
</tbody>
</table>

Based on the consistently low marker value in juveniles of natural origin, we used the upper threshold value of the 95% confidence interval for the $^{88}\text{Sr}:{^{43}\text{Ca}}$ molar ratio of these samples, which is equal to $1.7 \times 10^{-3}$ mmol/mol, as a cut-off value to differentiate fish of artificial and natural origin. With this approach, the distribution of the studied adults over the variational series of values of the analysed marker allows us to assume the ratio of natural- and artificial-origin individuals among the studied spawners. Among fish from the Anyuisky Hatchery, most of the fish have marker values higher than the threshold level we have accepted. Moreover, the proportion of such fish is higher among females than males. Also, a comparatively high proportion of such fish was found among 18 specimens of fall chum salmon collected in late August at the mouth of the Amur River. Fish with high strontium content in the juvenile zone of otoliths were most rare in catches in the last 10 days of September (Table 1).

Table 2. The number of fish by age group of adult fall chum salmon from the Anyuisky Hatchery and the Amur River main channel with different values of the analysed isotopic ratio of the juvenile zone of the otolith.

<table>
<thead>
<tr>
<th>Age</th>
<th>Fish from the Amur River main channel</th>
<th>Anyuisky Hatchery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{88}\text{Sr}:{^{43}\text{Ca}} &lt; 1.7$ mmol/mol</td>
<td>$^{88}\text{Sr}:{^{43}\text{Ca}} &gt; 1.7$ mmol/mol</td>
</tr>
<tr>
<td>2+</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>3+</td>
<td>32</td>
<td>27</td>
</tr>
<tr>
<td>4+</td>
<td>62</td>
<td>40</td>
</tr>
<tr>
<td>5+</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
The age structure of fall chum salmon collected at the Amur River main channel differed from that at the Anyuisky Hatchery (Table 2). Among the Amur River individuals with a $^{88}\text{Sr}:^{43}\text{Ca}$ molar ratio value below $1.7\times10^{-3}$, fish aged 4+ were the largest proportion (63%) and fish aged 3+ had the lowest proportion (33%). Individuals with the chemical marker value higher than $1.7\times10$ mmol/mol were proportioned differently: 4+ fish was somewhat lower (59%) and 3+ fish was slightly higher (40%). Among the fish collected at the Anyuisky Hatchery with a $^{88}\text{Sr}:^{43}\text{Ca}$ marker value higher than $1.7\times10$ mmol/mol, 3+ individuals were numerically predominate. In a mixed-sex sample of fish, the proportion of individuals aged 3+ was 52%, the proportion of fish aged 4+ was 45%. Also, among the fish collected at the Anyuisky Hatchery, two fish aged 2+ were present, while the fish captured in the Amur River main channel such specimens were not found. The proportion of occurrence of fish aged 5+ was the highest (5%) among the Amur River individuals with a $^{88}\text{Sr}:^{43}\text{Ca}$ value below the threshold level we used.

Conclusion

The results of this study may indicate the applicability of our approach to the determination of artificial-origin fish in a mixed sample of Amur fall chum salmon. The following results may serve as evidence of the applicability of the method used for the stated purpose: the revealed ratio of artificial- and natural-origin fish among Anyuisky Hatchery fish, the proportion of “hatchery-produced” fish among females and males of fall chum salmon collected at the Anyuisky Hatchery, and age composition and phenological shift in spawning migration time of the fish classified as fish of artificial origin. Results similar to ours were obtained for the chum salmon of Alaska, Kamchatka, the Kuril Islands, and Hokkaido Island (Imai et al. 2007; Zaporozhets and Zaporozhets 2012; McConnell et al. 2018; Knudsen et al. 2021).

REFERENCES


Migration and Homing Behavior of Chum Salmon Tagged in the Okhotsk Sea, Eastern Hokkaido

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Keywords: archival tag, chum salmon, tagging, water temperature

Chum salmon is an important species for the commercial fishery in Hokkaido. Recently, coastal sea water temperatures in autumn have been higher than the historic mean. In years when these temperatures are high, the timing of the chum salmon return is delayed.

To elucidate the influence of sea water temperature on the migration behavior of chum salmon in coastal waters, we visually counted the number of swimming chum salmon from the research vessel and captured individuals by angling in early September 2016 and in late August in 2017, 2018 and 2019. We released the captured fish into the Okhotsk Sea after tagging them with archival tags.

After release, the tagged fish were recaptured in coastal waters or rivers. In 2016, 2017, 2018, and 2019, 14, 14, 10, and 25 chum salmon were tagged and released, respectively, with six, two, one, and 11 fish being recaptured. Many of the individuals tagged each year were recaptured along the Okhotsk coast of Hokkaido, except for those tagged in 2018. The tagged chum salmon released in late August showed clear diurnal vertical migration between the surface and a depth of 200 m and later showed vertical movement in water shallower than 50 m. In contrast, those released in early September 2016 did not show clear diurnal patterns, and just moved vertically in water shallower than 50 m. The tagged individuals released in late August preferred to remain in the 2°C sea water at 200 m depths during the daytime. This behaviour is considered to regulate their cavity temperature (Azumaya and Ishida 2005). In contrast, those released in early September preferred the 17°C sea water of the surface layer. At the release site, the sea surface temperature in late August 2017 and early September 2016 was 16.8°C and 17.2°C, respectively, but the swimming behaviour of the two groups of fish was different.

The difference in swimming behavior of fish with different release timing did not seem to be related to ambient water temperature at that time. We believe that differences in maturity and changes in water temperature before recapture may also have an effect.

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Tracking Radio-tagged Masu Salmon (Oncorhynchus masou) from the Sky by Use of Drone

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Keywords: bio telemetry, drone, masu salmon, Oncorhynchus masou, radio tag

In order to track the location and movement of salmonids in rivers and lakes, several types of external tags such as fin-clipped, ribbon, spaghetti, elastomer (Choe and Yamazaki 1996), etc. are traditionally used. However, it has been a problem that such tags should be checked visually by recapturing the released fish in various locations, as the tag detection rate largely depends on the sampling locations and procedures. In order to improve the recapture rate, fish collection procedures by use of net, trap, fishing rod, electric fisher, etc. have also been developed.

Recently, several types of remote tags such as Passive Integrated Transponder (PIT), acoustic, and radio tags have been devised. These tags are advantageous because they allow researchers to know the location and movement of experimental fish without recapturing them. In these systems, however, it is necessary to set stationary receivers—including antennas—along rivers or lakeshores and therefore the detection rates fundamentally depend on the number of receivers (antennas) and their reception range (Binder et al. 2017). As another option, the researcher can move along the rivers or lakeshores on foot or in a research vessel with a portable receiver. In a previous river experiment, researchers floated down the river in a research boat (Aarestrup et al. 1999). In our study, we walked up and down along the rivers (Munakata et al. unpublished data). In both cases, it is nearly inevitable to come across several types of barriers such as waterfalls, cliffs, or bushes, etc. In the case of lakes, researchers should move in wider ranges to detect and track experimental fishes.

In order to decrease study effort and improve detection efficiency, we developed a new tracking method for radio-tagged salmonids by using a flying drone. In this system, the biggest concern was to avoid radio disturbances by mechanical noises from the drone, so we developed a new receiver which is composed of a noise filter, amplifier, radio signal analyzer using micro processor, and a memory unit (micro-SD memory card). These parts were connected to a directional antenna and a portable lithium-ion battery and were attached to a drone (Phantom II, DJI Co., Ltd.) (Fig. 1). We used two types of radio tags (MCFT3 and nanotag NTF-3-1, Lotek Co., Ltd.) for which the frequency is 151.89 MHz. Based on the specific transmitting patterns, we could discriminate tag identification.

Data receptions (radio strength and ID) were analyzed and recorded on a micro-SD memory card with its location based on GPS data.

One of the difficulties of flying the drone over small streams is to avoid structures and barriers such as trees, cliffs, bridges, and electrical wires. In the case of lakes, it is also difficult to fly the drone with equal pitches. Thus, in this study, we programmed flight route and altitudes based on tridimensional survey flight data. Basically, we flew the drone at a higher and safer altitude and took still photos over the expected flight areas. Then the flight route and altitude were programmed using metashape (Agisoft LLC) and UgCS (GeoMetrics Inc.) software.

Fig. 1. A photograph of the radio receiving drone. All receivers, including directional antenna, are attached to the drone.
One of the advantages of radio tracking by a flying drone is to know the detection result in real-time. By doing so, the operation can be finished in the shortest time and with the least effort. To implement real-time radio tracking, we developed an additional system. When the receiver detects a radio tag, an LED lamp attached to the drone flashes (Munakata et al. unpublished data) allowing the operator to grab detection time and total number of radio tags through a camera installed on the drone—the information is then displayed on the remote-control panel. After the flight, detailed tracking data including flight route, tag ID, radio strength, and tag location can be downloaded from the micro-SD memory card.

![Fig. 2. A sample picture of the calibration test for the radio tag set underwater. Two types of white lines show the programmed flight course (lower) and actual flight course (upper). Yellow pins and numbers represent the detection points and radio strength. Smallest number indicates the highest radio strength.](image)

By use of such a receiving system, we calibrated the detection depth and radius for the radio tags in a lake. In the case of Lotek MCFT3 (Frequency 151.89 MHz, output 0.016 mW), maximum detection depth and radius were approximately 8 m and 15 m, respectively, when the drone flew at an altitude of 10 m (Munakata et al. unpublished data). The detection range tended to decrease in relation to the flight altitude, but we were able to mark 4 m depth and 10 m radius at an altitude of 30 m. In these trials, moreover, we could fly the drone at a constant pitch and altitude (see detail in Fig. 2).

In 2019, we demonstrated the radio tracking experiment on a Biwa salmon (Oncorhynchus masou subsp.) (Kuwahara and Iguchi 2007). On 9 November, five adult Biwa salmon were caught by set net near the mouth of Ado River flowing into Lake Biwa, Shiga prefecture, Japan. The five individuals were anesthetized, and a radio tag (MCFT3) was implanted into their abdominal cavities through a 1 cm incision made by a surgical blade. After the wound was stitched, the fish were reared in a plastic cage placed in the river for about one hour, and then the fish were released near the set net. Two hours after the release, and one to five days after the release, we attempted to detect the location of the experimental fish. One day later, we detected all the fish on the upstream side of the river (Munakata et al. unpublished data). Among five individuals, three fish moved approximately one to three kilometers upstream from the release point. On the other hand, radio signals from the other two fish were detected close to the release point so we attempted to visually locate these fish based on the radio signals. These two fish (a female and male) died but these fish seemed to have released a major part of their matured eggs and sperm. Five days after the release, on the other hand, one of three experimental fish was found approximately 7 km upstream from the release point. Thus, in this experiment, we could detect the location of all five tagged Biwa salmon adults along the river using the drone receiving system. During the experiment, we attached not only the radio tag, but also an external ribbon tag on the dorsal part of the fish. During the radio tracking, however, we could not visually locate the experimental fish except for the two dead fish. From these results, the drone receiving system was considered to be a highly efficient tracking method.

In response to this result, we also attempted to track the movement of Taiwan salmon (Oncorhynchus masou formosanus) (Hsu et al. 2010) in a steep mountain stream in Wuling, Taiwan. In November 2019, five Taiwan salmon which were caught by electro fisher were anesthetized and a radio tag (nano tag NTF-3-1) was implanted into the abdominal cavity of each fish. After the implantation, the fish were reared in a hatchery FRP tank overnight and then released near the sampling point. One and two days after the release, we attempted to detect the location of these fish. One day after the release, we found that two fish moved approximately 200 to 300 m upstream from the release point while three fish stayed near the release point (Munakata et al. unpublished data). Two days after the release, on the other hand, it was demonstrated that all five fish gathered within 50 m from the released point. In this case, we also tracked the location of five Taiwan salmon in a small mountain stream. Moreover, it is also noteworthy that we could discriminate tag identification with five experimental fish gathered in the same area.
Based on these results, it is indicated that the drone receiving system can be a useful tool for tracking the location and movement of radio-tagged salmonid in small streams and shallow lakes.

REFERENCES


The Salmon of Knowledge

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Keywords: knowledge graph, information technology, program management, decision support, salmon restoration, natural language processing

We developed a knowledge management system for salmon managers that is capable of dealing with the complexity of multi-agency salmon fisheries and habitat management programs, despite the dynamic nature and sheer volume of information involved. This enterprise IT system was designed, installed, loaded, and exercised by Fisheries and Oceans Canada (DFO). Features include advanced security, automated data-processing, and an extensible user-friendly interface.

Fig. 1. The Salmon of Knowledge is a large statue in Belfast, Ireland, that celebrates an ancient myth and the 1991 return of salmon to River Lagan after being absent since 1774.

The Salmon of Knowledge (Fig. 1) is a huge statue in Belfast that commemorates an ancient Irish myth. Each scale on the statue represents some of the knowledge required to re-establish Atlantic Salmon in River Lagan in 1991. The myth describes a magic salmon that possessed all of the knowledge in the world and how the first person to taste it would acquire that knowledge. Without spoiling a good story, let us take that magic as a metaphor1 to make us think about building and managing our knowledge about salmon, specifically in the context of the International Year of the Salmon (IYS).

IYS has an overarching goal for the future: Salmon are resilient. This means salmon populations can survive surprise from careless industrialization and global warming, in addition to unpredictable, natural, ecosystem dynamics. IYS elaborates: “to realize a shared future with salmon, an effort beyond the capacity of any one group or country is needed to raise awareness, address knowledge gaps, and devise new approaches to informing and taking decisions.” This echoes Holling (1973):

“A management approach based on resilience… would emphasize the need to keep options open, the need to view events in a regional rather than a local context, and the need to emphasize heterogeneity. Flowing from this would be not the presumption of sufficient knowledge, but the recognition of our ignorance; not the assumption that future events are expected, but that they will be unexpected. The resilience framework can accommodate this shift of perspective, for it does not require a precise capacity to predict the future,

1Any sufficiently developed technology is indistinguishable from magic (Clarke 1968).
but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take.”

Starting in 2017, we addressed this problem, devise resilience, from the perspective of knowledge management, collaboration, and decision support (Fig. 2). The problem posed to us by DFO in 2019 was knowledge assembly for a scenarios-based, fisheries-management decision: efficient discovery of who knows what we need to know to make a better decision? Note two meanings: (1) finding metrics for prescribed decision criteria that will be used to compare scenarios; and (2) discovering unrealized but important decision criteria that should be added to the decision process.

We hypothesize that part of the decision-support problem stems from how information is stored, managed, and inter-related within and between knowledge sources. The information sources in use today are lists and tables, structures which assume that knowledge units are static in form and relatively harmonized in terms of their structure—an approach that rapidly falls apart without a rigorous, top-down, structure for knowledge management. Because of the large number of heterogeneous information sources involved, our approach was to use graph database technology (neo4j.com) to cope with:

(a) the scope, diversity, and complexity of salmon ecosystems, including all aspects of human impacts and interests;
(b) the fluidity of projects, agencies, habitats, problems, and methods—both the content and the structure of salmon information are dynamic;
(c) the need for provenance of datasets and analysis results, thus defensible decisions;
(d) information discovery by following chains of indirect links; and
(e) epistemology: using a rich set of ideas to organize, navigate, and apply salmon information.

Essentially, this technology is more similar to how humans think, compared to a relational database. The ideas tabled in the NPAFC/IYS workshop International Salmon Data Laboratory (Akenhead et al. 2019) accelerated our thinking.
By March 2020 we were able to demonstrate how a salmon knowledge graph could manage the ideas involved in decision support (Fig. 3) as a means of organizing and discovering the knowledge required for fully informed and fully inclusive decisions.

**Fig. 4.** Adaptive management applies learning from experience (outcomes monitoring) to replace elements of a strategic plan. Enabling those replacements, available from science and technology, requires a decision process embedded in the strategic plan. Managing such a process—across many salmon-related agencies, programs, projects, and people—can be enabled by a knowledge graph.

A related problem was posed in 2021: program management for many salmon restoration projects conducted by many agencies in DFO’s Pacific Region. Our perspective on this problem is Adaptive Management (Holling 1978, Gunderson and Holling 2002; but see Walters 2007), which we see as convolving strategic planning and decision support (Fig. 4). Problems thwarting efficacious, multi-agency, program management include:

- **Too much information:** ~100,000s of projects, people, places, agencies, documents, datasets;
- **Too complicated:** many dimensions, each diverse: salmons’ lives; habitat metrics; observation and analysis methods; funding and management; economic, social, and cultural impacts;
- **Too dynamic:** churn of participants, obsolescence of information, crippling lags before updates;
- **Too hidden:** information is buried in technical reports, web pages, scattered, ad hoc, Excel files;
- **Too isolated:** important connections are missing, information is simply not shared.

**Fig. 5.** A query (Cypher, via Neo4j Browser) to display everything in the graph linked to salmon restoration projects linked to the Quesnel River Watershed. A user can review the information within a node and expand further links from a node to discover unrealized connections: new knowledge.
The 2021 project proceeded with an emphasis on tools and technology. We received a dataset (MS Excel) containing metadata for > 800 salmon restoration projects. This was converted to a knowledge graph by a combination of (a) code in Python and Cypher to dissect complicated Excel data into nodes and links; (b) natural language processing to extract key phrases and entities (Person, Place,); (c) base layers (~180,000 [total] of place names, postal codes, and First Nations agencies were loaded); and (d) artificial intelligence to automatically generate links such as “project has place,” “agency has place,”. The result, merely a Proof of Concept so far, was an unprecedented ability to visualize and traverse information in a process of knowledge discovery (Fig. 5).

Fig. 6. The knowledge graph system implemented by Fisheries and Oceans Canada was designed as cloud-based enterprise IT with appropriate cyber-security and CD/CI tools (continuous development, continuous integration). This system, Graphish, can be re-implemented quickly and safely by other agencies. Less demanding installations, including personal computers, will not incur license costs.

Connecting automated data-processing pipelines to the knowledge graph was an important achievement, stemming from the data extraction, loading and linking process. These pipelines promise radical efficiency in the near future, for updating the knowledge graph and delivering analyses including decision indicators. After initial coding, these pipelines are available to users as autonomous containers (Docker) held in a cloud-based, enterprise IT system (MS Azure, DevOps), as designed and implemented by DFO (Fig. 6). Rigorous attention to cyber-security was exacted. The Salmon Knowledge Graph is just one application of this system (Graphish); knowledge graphs for other communities of practice can be instantiated quickly and the technical design can be replicated safely by other organizations.

Fig. 7. The salmon knowledge graph schema was derived from a dataset of salmon restoration projects. Automated creation of links between nodes related to program management was facilitated by base layers of (left side) places in GeoNames.org, postal codes, and First Nations; and (center bottom) key phrases extracted by natural language processing.

The schema for the 2021 salmon knowledge graph (Fig. 7) was derived from the reported structure of the salmon restoration projects. This was an enlightening change in perspective from the preceding top-down design.
derived from ideas about decisions and planning. The schema (labels that index many instances of nodes and links) is the basis for navigating and applying the knowledge graph.

![Image of the prototype user interface]

**Fig. 8.** The prototype user interface allows exploration of the salmon knowledge graph by interactive Views, currently including maps, tables, and networks (graphs). Queries are constructed by picking from lists of node and link types and instances. Users who are not programmers can add and edit information with this interface, implying on-going, community-wide, improvement. New Views, that control and present automated data processing, are easily added as a means to new efficiencies. A four-minute demonstration: (https://drive.google.com/file/d/1jbDT-4r4CPmJ9URb5Vzoif6 KEzPSc00g).

By March 2021 we were able to demonstrate additional value from this technology in two ways:

1. We showed that sophisticated and penetrating questions, difficult to pose to a relational database (sequential joins), could be expressed quickly as knowledge graph queries. Examples include: changes in patterns of project ownership over time; identifying First Nations with interests in a watershed (spatial analysis) that are not linked to salmon restoration projects in that watershed; and

2. Skill barriers were lowered by user-friendly web forms that enabled information discovery and reports. This user interface (*Graphishuai*, via R and Shiny) presents various Views of the information (Fig. 8) such as GraphView (network) for both discovering and editing information, and MapView for realizing spatial patterns. This interface is a software platform that will support many further Views, each as a tool that might involve automatic or semi-automatic data processing, each delivering value from salmon knowledge management.

**REFERENCES**


Integrated Research on Olfactory and Geomagnetic Imprinting and Homing in Pacific Salmon

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Keywords: olfaction, geomagnetic map, imprinting, homing, natal river, navigation, migration

Pacific salmon are recognized for their amazing abilities to memorize their natal river information during a short-distance downstream migration, carry out a long-distance feeding migration in the ocean for many years for growth, and make a precise long-distance spawning migration from oceanic feeding habitat to their natal river for reproduction. Two different sensory mechanisms, olfaction, and magnetoreception, are involved in the imprinting and homing processes in Pacific salmon. It is believed that olfactory imprinting occurs from the spawning ground to the mouth of a natal river, and olfactory homing occurs from the vicinity of the river mouth to the spawning ground of a natal river (Ueda 2019, 2020); Geomagnetic imprinting is thought to occur as juveniles depart the mouth of their natal river to oceanic nursery habitat, and geomagnetic homing occurs from the oceanic feeding habitat back to the mouth of their natal river (Putman 2018, 2021) (Fig. 1). This report presents current findings on olfactory and geomagnetic imprinting and homing in Pacific salmon and proposes an international collaborative research project to test olfactory and geomagnetic imprinting and homing in Pacific salmon across the Pacific Ocean.

Salmon olfactory organs respond to a relatively narrow suite of dissolved chemical compounds, such as amino acids, steroids, bile acids, and prostaglandins (Hara 1994). Electrophysiological responses of the olfactory nerve in masu salmon to artificial stream water (ASW) based on the composition of dissolved free amino acid (DFAA) closely resembled responses elicited by the corresponding natural stream water (Shoji et al. 2000). In the Teshio River in Hokkaido, Japan, juvenile chum salmon undergo their downstream migration in spring, and adults undergo their upstream migration in autumn; there is an average four-year span between the juvenile downstream and adult upstream migration. The Teshio River water contained 15 DFAAs, and the concentrations of these DFAAs fluctuated greatly. However, the composition (mole %) of 5–7 DFAAs was stable between the spring and autumn samples within a four-year span. The same concentrations of DFAA as those found in the Teshio River during the time of juvenile imprinting in spring (jASW) and adult homing in autumn (aASW) were prepared after a four-year period. Behavioral experiments addressing upstream selective movement were conducted in a Y-maze. Four-year-old mature male chum salmon captured in the Teshio River showed a significant preference for either jASW or aASW over control water, but they did not display a preference between jASW and aASW, revealing that the long-term stability of the composition of DFAA in the natal stream is crucial for olfactory imprinting and homing in chum salmon (Yamamoto et al. 2013).
Geomagnetic navigation functions as a mechanism for salmon to reach distant, oceanic foraging grounds and returning to the vicinity of their natal river using the predictable gradients of Earth’s magnetic field as a kind of “map” (Putman 2018). Juvenile salmon appear to possess a magnetic map (orientation to spatial information in the magnetic field), but this ability appears to be disrupted if salmon are reared in a strongly variable magnetic field (Putman et al. 2014a). Finally, long-term spatiotemporal variability in the homing routes of salmon can be predicted by assuming specific values of magnetic field parameters imprint upon smolts as they enter seawater and use those values as navigational coordinates upon reaching maturity (Putman et al. 2014b). The use of ‘map-like’ information from the Earth’s magnetic field for orientation has been shown in diverse taxa, but questions remain regarding the function of such maps. A ‘magnetic displacement’ experiment was carried out to demonstrate that juvenile pink salmon use magnetic cues to orient. The experiment was designed to simultaneously explore whether their magnetic map is used to direct fish (i) homeward, (ii) toward the center of their broad oceanic range, or (iii) along their oceanic migratory route. The headings adopted by these navigationally naive fish coincided remarkably well with the direction of the juveniles’ migration inferred from historical tagging and catch data. This suggests that the largescale movements of pink salmon across the North Pacific may be driven largely by their innate use of geomagnetic map cues. Key aspects of the oceanic ecology of pink salmon and other marine migrants might therefore be predicted from magnetic displacement experiments (Putman et al. 2020).

Fig. 2. Schematic illustrations of olfactory imprinting in juvenile salmon (A) and olfactory homing in adult salmon (B). The initiation of the downstream migration of juveniles induces the expression of the brain-pituitary-thyroid (BPT) hormones, which then induce the upregulation of the NMDA receptor, inducing imprinting long-term potentiation (LTP), which enhances olfactory memory formation related to natal stream-specific odors. The initiation of the homing migration of adult salmon induces the activation of the brain-pituitary-gonad (BPG) hormones, which then induce the upregulation of NMDA receptor, inducing homing LTP, which enhances olfactory memory retrieval related to natal stream-specific odors.

The plasticity of the nervous system and synaptic plasticity are fundamental mechanisms for memory formation and retrieval in the brains of vertebrates. The plasticity of the nervous system results from the structural and functional changes of the nervous system that occur in response to stimuli from the outside environment. Synaptic plasticity promotes the ability of chemical synapses to change synaptic strength that is modified to encode memory formation. Long-term potentiation (LTP) is the persistent strengthening of synaptic activity that produces a long-lasting increase in the signal transmission between two neurons that is induced by the N-methyl-D-aspartate (NMDA) receptor (Martin et al. 2000). The NMDA receptor plays an important role in memory formation and retrieval and is composed of the essential NR1 subunit and the differentially expressed NR2A-D subunit (Shipton and Paulsen 2013). In hatchery-reared juvenile chum salmon, the environmental changes associated with the release into the river at the initiation of downstream migration induce the activation of the brain-pituitary-thyroid hormones,
which then stimulate the upregulation of NR1 and induce the induction of LTP, ultimately enhancing olfactory memory formation related to natal river-specific odors. In adult salmon, the salmon gonadotropin-releasing hormone neurons in the preoptic area must be involved in gonadal maturation, and those in the olfactory bulb and terminal nerve may have olfactory-related functions that are related to olfactory-guided homing migration. The initiation of homing migration in adult chum salmon induces the activation of the brain-pituitary-gonad hormones, which then stimulate the upregulation of NR1 and induce the induction of LTP, which subsequently improves olfactory memory retrieval related to natal river-specific odors (Ueda et al. 2016) (Fig. 2). The neural and hormonal mechanisms of geomagnetic imprinting and homing in salmon have not been investigated and should be clarified (Gould 2014).

With the International Year of the Salmon, we believe it fitting to definitively test the olfactory and geomagnetic imprinting and homing hypothesis in Pacific salmon. This can be achieved through careful manipulation of the DFAA and magnetic field during embryonic development and early rearing stages of salmon, thus allowing different groups to be “programmed” to return to specific coastal locations and natal rivers. Differential marking of groups and coordination with fishers allows for a clear test of predictions. Electronic tagging a subset of smolts and stable isotope analyses of returning fish would allow further inferences into the aspects of oceanic ecology influenced by magnetic navigation. This experiment would move salmon research towards process-based models to mechanistically understand and predict spatiotemporal variability in salmon returns (Putman et al. 2019).

REFERENCES

Effective Hatchery Releases to Increase Adult Returns of Chum Salmon in the Ishikari River, Hokkaido, Japan

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Keywords: chum salmon, coastal sea surface temperature, GAM, hatchery practices, Ishikari River, river temperature, size at release, timing of release

Hatchery practices have a marked effect on the size at, and timing of, ocean entry of hatchery-reared Pacific salmon (*Oncorhynchus* spp.) (Weitkamp et al. 2015). Because both of these factors play such a crucial role in the early survival and growth of hatchery-reared and wild salmon juveniles during the period of coastal residency (Quinn 2005), hatchery practices have a direct effect on the growth and survival of hatchery-reared fish. The relationship between juvenile releases and adult returns for salmon with otolith thermal marks is expected to provide insights into the causal effects of hatchery practices on differences in salmon survival. To test this hypothesis, the effects of release parameters (e.g., release numbers, release date, and size at release) and the water temperature of the release river (near the release point; hereafter, river water temperature (RWT) and at sea (near the river mouth; hereafter sea surface temperature (SST)) on adult returns to the Ishikari River were investigated in chum salmon released with thermal otolith marks.

The Ishikari River in Hokkaido, Japan, flows into the Sea of Japan. The river and its catchment area are the third longest and second largest in Japan at 268 km and 14,330 km², respectively. There is only one salmon hatchery, the Chitose Salmon Field Station (CSFS), on the Ishikari River. The CSFS produces approximately 30 million juvenile chum salmon annually for release into the river. In the 1998 brood year, a subpopulation of the hatchery-reared juveniles was subjected to otolith thermal marking; since the 2001 brood year, almost all released juveniles were marked using this method. During August to December of every year, adult chum salmon returning to the river are captured using a fish wheel installed approximately 10 km downstream from the CSFS. During the upriver migration season, a monitoring survey is conducted by CSFS staff at approximately 10-day intervals. At each survey, 100 fish are randomly selected and examined for body size, age (scales), and hatchery release group (otoliths); in this way, approximately 1,000–1,200 fish are sampled for monitoring purposes in the Ishikari River each year. Based on the findings, the number and age of hatchery-reared adults returning to the river can be estimated. In this study, release information and adult return numbers for fish aged two to five years old with 63 different otolith markings were used to compile a dataset of year class strength for each marking group over the period 2001–2014. These data were then analyzed using a general additive model (GAM) in which the adult return number for each otolith thermal marking cohort was used as a dependent variable, and the effect of brood year (as a categorical variable), release date (Julian date), size at release, RWT, and SST were treated as explanatory variables. These variables were used to examine the effects of hatchery release practices and water temperatures on adult return numbers for each thermally marked otolith cohort. In all the constructed models, the number of released juveniles was included as an offset variable, and models with different explanatory variables were ranked using Akaike’s Information Criterion (AIC). To avoid problems associated with multicollinearity, since the variables of release date, RWT, and SSTs were strongly correlated with each other (*r* = 0.81–0.86, *n* = 63, *p* < 0.0001), they were not used as explanatory variables in the same model runs.

Of 16 models examined in this study, the top four models with the lowest AIC scores showed small differences in the AIC (i.e., AIC* − AIC* min, where *i* indicates the *i*-th model, and *min* denotes the model having the lowest AIC for the 16 models) ranging from 0 to 1.82. The model with the lowest AIC used brood year effect, size at release, and SST as explanatory variables. Although the latter two variables were assumed to have been included as smooth terms, the effect of size at release on the dependent variable was fitted as a linear function. In the second and third models, release date and RWT were selected, respectively, instead of the SST of the first model. The fourth model consisted of the brood year effect and size at release. Based on the model findings, adult returns in the Ishikari River could potentially be increased by releasing juveniles with a mass ≥ 0.73 g after March 30, or when the RWT and SST are ≥ 4.6°C and ≥ 5.3°C, respectively.

Hatchery practices are expected to change gradually in response to the changes in river and/or coastal seawater temperatures brought about by climate change in the future. Consequently, the monitoring of fish that have been thermally marked, as demonstrated by the findings of this study, will be indispensable for developing robust and sustainable hatchery practices that will help to mitigate against future changes in the environment.
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Quantitative Estimation of the Ecosystem Services Supporting the Growth of Japanese Chum Salmon

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Keywords: Ecosystem services, Japanese chum salmon, bioenergetics model, lower trophic level ecosystem model

Japanese stocks of chum salmon (Oncorhynchus keta) are released in spring, spend several months near the coast of Japan, then migrate to the Okhotsk Sea, where they remain until late fall (Urawa 2000; Azumaya and Ishida 2004) (Fig. 1). The fish then migrate toward the western North Pacific, where they overwinter, then migrate into the Bering Sea by the following summer. In the fall, they move into the Gulf of Alaska in the eastern North Pacific, where they spend one winter. They repeat the migration track between the Bering Sea (summer) and the Gulf of Alaska (winter) 3–4 times, and then return to Japan when approaching maturity in the summer of their fourth to fifth year.

Salmon provide provisioning, culture, and supporting services for human populations. However, salmon are themselves also supported by the ecosystem services provided by their habitat, which are called “supporting services” or “habitat services” (TEEB 2010). The ecosystem providing the reproduction habitat for commercially valuable species provides an important so-called “nursery-service,” which is (economically) valued in its own right (TEEB 2010). However, it is difficult to evaluate the monetary value of supporting services from the ecosystem when they are not traded on the market. In this case, revealed preference or stated preference approaches are used, but both approaches have limitations (TEEB 2010). As for salmon, their growth and survival are dependent on the supply of appropriate prey and their habitat in the ocean, which we regard here as supporting services for salmon. However, a means for quantitatively estimating supporting services for salmon in oceans has yet to be developed.

In this study (Karasawa et al. 2020), we focused on the prey consumption, growth and survival of Japanese chum salmon, and developed a method that quantitatively estimates the supporting services for the growth of Japanese chum salmon using a bioenergetics model coupled with a lower trophic level ecosystem model (NEMURO: North Pacific Ecosystem Model for Understanding Regional Oceanography; Kishi et al. 2007). We estimated the prey biomass consumed by a cohort of Japanese chum salmon, defined as a group of Japanese chum salmon released in a single year. The phytoplankton biomass indirectly consumed by this cohort was also estimated (Fig. 2); this was considered to be the primary production supporting the fish. We also attempted to calculate the monetary value of supporting services for the growth of Japanese chum salmon.

Our model estimates showed that a cohort of Japanese chum salmon consumed in total ca. 4.2–4.7 × 10⁹ kg wet weight of zooplankton during Stages 1–9, and that the cohort indirectly consumed 2.0–2.2 × 10⁹ kg C of primary production, which amounted to 0.17–0.19% of primary production in the areas and periods through which the salmon migrated. Thus, a cohort of artificially released Japanese chum salmon was supported by 2.0–2.2 × 10⁹ kg C of primary production during Stages 1–9. This is the production that supports the human harvest of a cohort. Although we applied the model similarly to previous studies examining the impact of environmental variability on
the growth of Japanese chum salmon, including studies that predicted future scenarios (Kamezawa et al. 2007; Kishi et al. 2010; Yoon et al. 2015), this is the first attempt to estimate the supporting services for these fish.

**Fig. 2.** Diagram of the NEMURO model showing transfer paths of organic matter from PL (large phytoplankton) and PS (small phytoplankton) to ZP (predatory zooplankton). Arrow (1) indicates a direct path from PL to ZP, arrow (2) is a pathway from PL to ZP via ZL (large zooplankton), arrow (3) is a pathway from PS to ZP via ZL, arrow (4) is a pathway from PS to ZP via ZS and ZL, and arrow (5) is a pathway from PL to ZP via ZS. \( \alpha_{ZP}, \beta_{ZP}, \gamma_{ZP} \) and \( \alpha_{ZL}, \beta_{ZL}, \gamma_{ZL} \) are the ratios of prey consumed by ZP and ZL, respectively. Karasawa et al (2020).

It is possible to extend our new approach to briefly consider the monetary value of supporting services for the growth of Japanese chum salmon. As an example, we calculated the monetary value of ZP consumed by Japanese chum salmon assuming that the monetary value of ZP is equivalent to that of krill. Krill is an important component of ZP in NEMURO (Kishi et al. 2007), and it is also traded in the Japanese commercial market. We used the average price in the Tokyo Metropolitan Central Wholesale Market for the period 2002–2018 (http://www.shijou-tokei.metro.tokyo.jp/index.html), i.e., 476 Japanese yen kg\(^{-1}\) wet weight. Using the market price of krill, the total value of ZP consumed by Japanese chum salmon was estimated to be 2.0–2.2 × 10\(^{12}\) Japanese yen (0.1 × 10\(^{12}\), 0.2 × 10\(^{12}\), 1.0–1.1 × 10\(^{12}\), and 0.7–0.8 × 10\(^{12}\) Japanese yen in the Sea of Okhotsk, the western North Pacific, the Bering Sea and the Gulf of Alaska, respectively). These values were estimated considering the interannual variation in age composition (i.e., the percentage of fish returning to Japan at Stages 5 and 7 varied from 50% to 75%). The sum total (18–20 × 10\(^9\) US dollars based on the exchange rate in 2018) far exceeds the value of the Japanese chum salmon harvest (0.06 × 10\(^{12}\) Japanese yen or 0.5 × 10\(^9\) US dollars averaged over the period 2001–2017). Thus, the harvest of ca. 0.06 × 10\(^{12}\) Japanese yen was supported by a shadow cost (prey) of up to 2.0–2.2 × 10\(^{12}\) Japanese yen.

**REFERENCES**


Predicting the Port-catch Volume of Salmon at Eastern Hokkaido

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Keywords: estimations, LSTM, extended data, Fishery Volume

As we all know, freshness determines the value of aquatic products. The shorter the interval between the start of fishing and the sale, the greater the profit (Nicolae et al. 2015). Especially in the vast Hokkaido area, it is very necessary to make an effective and scientific transportation plan. In this process, the estimation of the port capture can greatly help the overall planning of the transportation system and improve transportation efficiency.

Deep learning methods are widely used in a variety of fields, including aquaculture (Benzer and Benzer 2015), fish identification (Monkman et al. 2019), and fishery catch prediction (Shiichi and Teruhisa 2000). Because of its ability to mine long-distance time series data, the Long Short-Term Memory Network (LSTM) (Hochreiter and Schmidhuber 1997), a machine learning method based on recurrent neural networks, has been widely employed in speech recognition, machine translation, data prediction, and other domains. Therefore, we use this method to forecast the port catch.

This experiment used the fishery catch in four ports (Nemuro, Ochiishi, Habomai, and Rausu), from 1 June 2005 to 30 November 2015 (Fig. 1). For water temperature data, we used satellite data from the NEAR-GOOS website and the same time interval (the temperature of 50 m). The data of the first 20 days beginning 1 June were used to predict the catch value for the next day.

In the experiment section, we propose a data enhancement method to address the issues of insufficient data and over-fitting of the network model. The model processes both the original and the added data, and the experimental results are compared.

Fig. 1. Position of ports in eastern Hokkaido.

Fig. 2. Extended data based on Poisson distribution.
Since Poisson distribution corresponds to discrete natural phenomena, it is often used in fishery resource analysis. Considering the problem of fish arriving at the fishing range of a port, this can be seen as a queuing problem, and thus the Poisson distribution can model this phenomenon very well.

To expand the training set, we used the Poisson model to generate extended data in the training set. We extracted data on port-catch volume in the training set, then assumed a fish had a weight of $w = 3$ kg and treat $K$ as the number of fish in one group of fish. To begin, the port-catch volume (tonnes) was converted into the number of shoals of fish, and the shoal data was fed into the Poisson distribution to generate extended data. Finally, the data were restored to tonnes (Fig. 2). The reason for changing the tonnage of the fish to shoals of fish is twofold: first, increasing the $\lambda$ of Poisson distribution will reduce the fluctuation of the Poisson distribution, thereby reducing the error and bringing the artificial data closer to the real data. Second, this method of data processing mimics the natural motion of fish.

Regarding the setting of the coefficient $N$ (the number of fish in each group), since the data scale of each fishing port is different, the size of the fish school is also different. Therefore, we calculated the average value of the catch data of each fishing port as a benchmark for $K$ value and observed the effect of the change in $K$ value on the experimental error to find the most suitable $K$ value.

![Error comparison between Raw and 10x data](image)

**Fig. 3.** Error of two situations.

According to the experimental results, we used the Root Mean Square Error (RMSE) to evaluate the experimental results, comparing the RMSE in different models and different training sets (Fig. 3).

For the experimental results, we can see that it is feasible to use the LSTM model in RNN to predict fishery catch data. Some processing methods for the original data also have a certain effect. By increasing the training set through experimental methods, the test error of the model can be increased to a certain extent, and the problem of model over-fitting on the original data set can be alleviated.

This research will help the use and maintenance of aquatic resources. Through the prediction of data and the efforts made to reduce the prediction error, we can use the forecast of fishing port capture to guide and support fishery logistics and transportation.

REFERENCES


Development of a Selection Method of Favorable Juvenile Fish by Egg Weight in Masu Salmon (Oncorhynchus masou)

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Keywords: egg weight, growth rate, masu salmon, Oncorhynchus masou, parr mark

Masu salmon (Oncorhynchus masou) is an important target for coastal fisheries in Japan (Hasegawa et al. 2021). However, the stock abundance of this salmon has been decreasing since the 1980’s (Miyakoshi 2014). As a countermeasure, attempts have been made to increase the stock abundance by discharging juveniles (HRO 2013), but the effectiveness is low. One solution to this problem is to improve the quality of discharging juveniles by a selection method without genetic or hormonal treatments. Previous studies in chinook salmon (O. tshawytscha) have revealed that differences in egg weight resulted in different properties, such as growth rate and migration timing (Cogliati et al. 2018). Hence, selection by egg weight may contribute to improving quality of discharging juveniles in other species.

In this study, we selected eggs obtained from single and multiple female masu salmon by wet weight. In experiment 1, we divided eggs into larger (> 0.089 g) and smaller (< 0.079 g) groups in December 2018. In experiment 2, we divided eggs into larger (> 0.084 g) and smaller (< 0.079 g) groups in December 2019. These eggs were reared in separate tanks of the same environment (Table 1). We selected 5 (exp. 1: Feb. to Sep. 2018), 10 (exp. 1: Oct. 2018 to Feb. 2019, exp. 2: Feb. to Sep. 2019), or 56 (exp. 2: Oct. 2019) juveniles from both groups, measured body weight (BW), and took photographs of left or both sides. Moreover, we measured standard length (SL), body surface and parr mark areas from the photographs by using "Image J" (Rasband 1997–2012), and calculated condition factor (CF: BW / SL³ × 100) and parr mark area index (PAI: total parr mark area/body surface area × 100). Significant differences between the two groups were verified by the student's t-test, and the significance level was less than 5% (p < 0.05).

Table 1. Rearing environment of masu salmon juveniles from multiple females (exp. 1) and a single female (exp. 2)

<table>
<thead>
<tr>
<th>Exp. 1</th>
<th>Exp. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish number</td>
<td>Larger egg group (80→64)</td>
</tr>
<tr>
<td>(beginning→final)</td>
<td>Smaller egg group (80→71)</td>
</tr>
<tr>
<td>Water temp. (°C)</td>
<td>18 (Jul.) to 10 (Dec.)</td>
</tr>
</tbody>
</table>

Fig. 1. Egg weight distribution and selection standard in exp. 1 (A) and exp. 2 (B). The dashed lines show selection standard of the larger and the smaller egg groups, and the numbers in figures are average weight (mean ± SD).
Mean egg weight ± SD were 0.102 ± 0.014 g and 0.070 ± 0.007 g (exp. 1), and 0.087 ± 0.002 g and 0.077 ± 0.002 g (exp. 2) in the larger and the smaller egg groups, respectively (Fig. 1). In both experiments, the larger egg groups tended to show higher SL and BW values than the smaller egg groups in the early period (exp. 1: Feb. to Apr. 2018, exp. 2: Feb. to Mar. 2019). On the other hand, the smaller egg groups tended to show higher SL and BW values in a later period (exp. 1: Oct. 2018 to Feb. 2019, exp. 2: Aug. to Oct. 2019). There was no difference in CF values between the larger and smaller egg groups in both experiments. In PAI, the larger egg group tended to show higher values than the smaller egg group during the early (exp. 1: Feb. to May 2018, exp. 2: Feb. to Mar. 2019) and later period (exp. 1: Oct. 2018 to Feb. 2019, exp. 2: Apr. to Oct. 2019) (Figs. 2 and 3).

As a result, the larger egg group tended to show higher SL and BW values in the early period, and the smaller egg group tended to show higher SL and BW values in the later period. The phenomenon observed in several salmonids suggested that individuals from large eggs showed larger body size than individuals from small eggs in the early life stage, and the body size difference disappeared with growth approximately 100 to 150 days after
hatching (Ohkuma 2005; Bromage et al. 1992). This phenomenon is thought to be caused by different metabolic rates between groups. In previous studies, the southern population of masu salmon had a smaller egg size than the northern population in natural rivers (Morita et al. 2009). Seppänen et al. (2009a, b) also reported that the southern population of Atlantic salmon (*Salmo salar*) showed a higher metabolic rate than individuals of the northern population under common rearing conditions. Yamamoto et al. (1998) revealed a positive relationship between metabolic rate and growth in masu salmon. Based on this information, it seems that the individuals from smaller eggs may have higher metabolic rates than the individuals from larger eggs. Thus, it is probable that the individuals from smaller eggs may show a higher growth rate than the individuals from larger eggs after discharging.

In PAI, the larger egg group tended to show higher values than the smaller egg groups throughout the experiment period (Figs. 2 and 3). The meaning and role of parr marks in salmonids are still unclear, except that it acts as a protective color (Donnelly 1985). It was reported that in river rainbow (*O. mykiss*) and cutthroat (*O. clarkii bouvieri*) trout resident juveniles have more parr marks than migrant juveniles (Northcote and Hartman 1988).

Therefore, the parr mark characteristics may be related to their migration characteristics, and individuals with high PAI (parr mark number × area) possibly have characteristics that allow them to remain in the river at a higher rate. Based on these results, egg weight selection may choose juveniles that are suitable for the purpose of various discharges, such as the discharging for increasing the stock of the migrant and the resident types.

**REFERENCES**


Development of Age Determination Technique Part 1: Neural-Network Based Prediction of Chum Salmon Age by Scale Images

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Keywords: salmon scale, age identification, automatic extraction, neural networks

Introduction
In recent years, the poor catch of chum salmon has continued in Japan, and the research aimed at monitoring the stock status and elucidating the factors that cause fluctuations in stock has been attracting attention. However, since it takes a lot of time to perform age assessment by hand, it is required to actively introduce information technology such as AI and ICT. Neural networks have been applied to predict or represent fisheries data, and many works in the field of fisheries have been presented (Hyun et al. 2005; Suryanarayana et al. 2008; Zhou 2003). In this study, we constructed an age-assessment system using neural networks to automate salmon age determination using scale images and verified its effectiveness. Salmon age determination was composed as the computational process by using neural networks with respect to the image classification. The age-assessment system will contribute to the analysis of salmon data in Hokkaido.

Salmon scale and age determination
Salmon scales have been corrected for use in the investigation of the age distribution of salmon returns. The data of 20,000 tails are summed in every year, and the scales are cleaned and transcribed onto a plastic plate as replica samples. The samples have been corrected for over 20 years. Three images of Fig. 1 present the press machine, a replica sample, and an extracted scale image, respectively. The enlarged images from the replica samples were used for age determination. The magnifying glass device provided a fine image of the salmon scale.

Circuli appear as curved and striped patterns arranged around the center of the scale. Each narrow pattern of circuli indicates a period of reduced scale growth each year. The age of a salmon is measured by counting the areas of narrow circuli, starting from the center of the scale and moving in a straight line to the edge. Each narrow pattern is considered one year of life, with the edge of the scale being considered a year as well. In Fig. 2, two scales are presented, and the left image is a scale with four years of growth, and the right image presents a scale with five years of growth. The yellow lines are the annuli determined by the expert Fisheries Institute staff. There are many types
of narrow patterns, and assessment work, supported by Fisheries Institute staff, takes a long time. A scale image is divided into two parts: the narrow annuli and the other. Such the annuli indicate the period during each year.

Neural networks have been used for various classification problems. Multilayer-type networks have often been called the multilayered perceptions for constructing the recognition procedure. In this study, we used two neural networks to extract the center and annuli from the scale. The annuli data consists of the training data indicating the year-period marks. The Fig. 2 (right) presented the data processing, binary filter, segmentation, detection process from the center of the scale and the annuli. The outputs by the two neural networks are used for evaluating salmon age.

Scale classification based on neural networks

Neural networks have been used for image or pattern recognition, data learning, and classification problems. Multilayer-structured neural networks are useful for various data-learning problems in engineering and scientific fields. Here, we focused on a simple classification problem for the salmon scale, and then used multilayer neural networks to solve this problem. There are two classifications for age determination: one is the center of the scale, and the other is the annuli. We introduced two neural networks for the center and year period detection procedures. We set a Type-1 network used for detecting the center from cropped partial images. A Type-2 network was for the annul according to the order of determination.

The structure of the Type-1 network is the four-layer feed-forward type, and two hidden layers were used. The size of the cropped images from scale were 200×68 pixels. The number denoted the image size and the number of input layer nodes of the Type-1 network was 13,600. The number of nodes in the hidden-layers was 1,500. A sigmoid type activation function was used for the output node. The output layer consists of one node for classifying two states, center or not. The structure of the Type-2 network was five layers of feed-forward neural net. Three hidden layers were used. The image size for classifying the annuli was 50×34 pixels. The number of input layer nodes of the Type-2 network was 1,700. The numbers of three hidden-layer nodes were 750, 1,500, and 750, respectively. The output layer with one node was used for classifying the annuli or not. The activation function of the output node was the same as the Type-1 network. Figure 3 presents the procedure for the age determination process: the data processing, binary filter, segmentation, and detection process from the center of the scale and the annuli. The outputs by the two neural networks are used for evaluating salmon age.

![Fig. 3. Schematic figure of the computational procedure using neural networks for extracting the center and annuli.](image)

The computational procedure for both neural networks was composed of Python 3.6 and Keras software. As concerning the optimizer for the data training procedure, we used Adam with a certain settled parameter set. About 500 iterations for the training process were required for Type-1 neural network. However, about 2000 iterations of the data training were required in Type-2 neural network. The performance for the untrained data set for the over-trained neural network is inferior to the optimal-trained network. We settled the training iterations for obtaining the optimal trained neural nets. The centers and annuli were obtained by the networks. The center and the arrangement of year periods were used as the count of each year. The annuli as the year-period marks were classified by a criterion using the nearest distance in the direction through the center.
Computational results and summary

The scale image with the year-period marks and center is presented in Fig 2. The yellow lines indicate the year-period marks by the fishery Institute staff. The detected marks by the neural network almost conformed to the lines. The accuracy ratios of the annuli for training and test data were 73.6% and 71.7%, respectively. In this study, we used only 60 tails of salmon obtained recently. Then, the reliability of the neural network should be developed using many samples. The stability in training was indicated by almost the same performance for the test and training data. The age-determination system with two neural networks provided the annuli and center from the salmon scale, and the system is helpful to realize the automatic age-assessment for the salmon returns in Hokkaido.

REFERENCES

Development of Age Determination Technique Part 2: Image Processing for Age Determination Based on the Annuli of a Chum Salmon Scale

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Keywords: salmon scale, age identification, Fourier transform, image processing

Introduction

In recent years, the poor catch of chum salmon has continued in Japan, and research aimed at monitoring the stock status and elucidating the factors that cause fluctuations in stock has been attracting attention. It takes a lot of time to perform age-assessment work by hand. Information technology has been developed and used for solving various problems in engineering and science fields. Previous work on computerized age-determination has been completed (Endo et al. 1997; Mitani et al. 1988); however, the automation process was not established, and we need to solve the problem associated with huge salmon samples. We constructed new age-assessment technology using advanced image processing to automate the work for scale samples in order to contribute to the investigation of salmon return data in Hokkaido.

Salmon scale data

The salmon scale has been corrected for the purpose of investigating the age distribution of salmon returns. The data of 20,000 tails of chum salmon are processed every year. The scales are cleaned and transcribed on a plastic plate, known as a replica sample. Three images in Fig. 1 present a chum salmon, the press machine, and a replica sample, respectively. The press machine has been used for making replica samples to produce an engraving print. The objective of using a print-type plate is the preservation of the salmon scale. The curved and striped annuli patterns are arranged around the center of the scale. The narrow annuli indicate a period in each year of slow growth, and the age of the salmon is determined by counting the number of narrow annuli patterns, starting from the center of the scale and moving in a straight line to the edge. The three images of Fig. 2 present the microscope images of scales from the replica samples. The left figure presents the microscope scale image without back noise. The contour of scale is clear, and it is easy to extract the scale from the whole image. The center and left figures present the scale images with the back noise. The noise is ascribable to the distorted plastic plate by the heat press. In the age determination of the salmon scale, the magnifying glass device is often used to extract the scale with the detailed annuli structure. In this case, the back noise of the replica samples does not affect the age determination. Concerning the computational work using the salmon scale, the contrivance to remove such back noise is helpful to obtain clear scale image data.

Age determination based on image processing

There are two factors important for the age assessment of chum salmon: one is to properly locate the center of the scale, and the other is the ability to find the narrow annuli. It is not easy to find all parts of the annuli on a scale.
Every year, 20,000 tails of chum salmon are caught for investigating the distribution of salmon returns in Hokkaido prefecture, Japan. Therefore, an automatic system for reading the age data from scales is helpful to shorten the work of the fishery-data research section. The back noise can be removed by a combination of the binary filters. An example of the segmentation is presented in Fig. 3. The shape of the scale is close to a half circle, and a vertical direction of the annuli is effective to find the center. However, the shape of the scale is not a half circle. Therefore, it is possible that a high density partial-region with multi-directional annuli includes the center. We introduced a new iterated procedure to obtain the maximum density region in each step.

![Original image of salmon scale and binary filter for the segmentation.](image)

Fig. 3. Original image of salmon scale and binary filter for the segmentation.

Figure 4 presents the new procedure that is used to find the center of a scale. The Fourier transform of a cropped region of the scale image was obtained. The Fourier intensity map indicated the vertical direction of the annuli. Then we obtain the many directions using the Fourier intensities of the scale. It is possible that the region with maximum density of directions is an estimated center. Establishing an accurate center, several iterations of the process with the Fourier transform were introduced. Figure 5 presents the process to have an accurate center of the scale with four-times iterations. By using the extracted center of the scale, the interval frequency of the line through the center indicates the annuli. The total frequency distribution of all lines through the center was presented in the right image in Fig. 6. The left image in Fig. 6 presents the obtained annuli with blue lines. The lines were almost correct as the annuli for the age determination.

![Center detection of salmon scale using the Fourier transform and maximum density of direction.](image)

Fig. 4. Center detection of salmon scale using the Fourier transform and maximum density of direction.
Summary

In age determination work, replica samples have been used. The samples are good for preserving the scale sample with primitive scale form. However, such plastic plate samples are not adequate to analyze the salmon scale. Therefore, we introduce the fundamental method to have a clear scale image and to obtain the center of the scale with the Fourier transform and maximization of the direction density. It is useful to perform the computational process of a scale analysis system. As a result, the annuli for the age assessment were successfully extracted, and the distribution of the salmon scale leads to the age. The development and refinement of the annuli system will be our future work for investigating the salmon returns in Hokkaido.

REFERENCES


Challenges to Improving the Chum Salmon Hatchery Program in Kitami Region, Hokkaido

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Keywords: chum salmon, hatchery program, Hokkaido, Okhotsk Sea

In the eastern region on the Okhotsk side of Hokkaido, the Kitami Salmon Enhancement Program Association produces and releases a total of approximately 180 million chum salmon fry every year. In the last 10 years, 6,893–19,144 thousand, with a mean of 12,224 thousand, chum salmon returned to this region; this quantity is equivalent to 33–48% of total return of chum salmon in Hokkaido and 28–42% in Japan. The number of chum salmon returning to the Kitami region peaked from 2003–2013 but has declined significantly since 2014. In Hokkaido, non-profit private salmon enhancement program associations established in nine regions produce and release juvenile chum salmon (Miyakoshi et al. 2013). The operating expenses of the enhancement programs are collected from fishery production; however, the recent decline in salmon catches has made the operation of the salmon enhancement associations even more difficult.

The hatchery techniques for chum salmon in Japan have been intensively developed for several decades until the 2000s (Nogawa 2010). To further raise the stocking effectiveness for chum salmon, the Kitami Salmon Enhancement Program Association continues to modify and improve hatchery procedures, which are not sticking to the conventional manual for hatchery programs. For example, at the alevin stage, fish density in the ponds is reduced and the amount of water supply is kept to a minimum, and at the fry stage, the depth of rearing ponds is deeper than the normal rearing ponds. The fish quality is checked by examining the development of gill structure repeatedly at each hatchery to evaluate the incubating and rearing conditions. Each procedure at our hatcheries is aimed to reduce stresses on fish at each life stage and improve fish quality by considering the habitat environments and ecology of chum salmon in the wild.

In addition, we are conducting our own research to improve hatchery techniques and stocking effectiveness, some of which are conducted in collaboration with national and prefectural research institutes. Specifically, buoys to observe sea water temperatures are installed in the coastal areas to decide the release timing. We are implementing releases of marked fish to evaluate the return rates by the differentiated release timing and effects of transplantation at the egg and fry stages. Furthermore, we have conducted assessments for naturally spawning chum salmon in some rivers by ourselves and have restocked chum salmon adults captured by weirs to enable them to spawn in the wild (Kitada 2014).

Because the chum salmon fishery is one of the most important ones in northern Japan, those involved in the salmon fishery and stock enhancement are eager to know the causes of the decline of chum salmon in recent years. Recent research indicates the reduction of fitness and genetic alterations by consecutive hatchery breeding of chum salmon in Japan (Kitada and Kishino 2020). Since the hatchery-based stock enhancement program has been, and will be a major management method for chum salmon in Japan, those involved in salmon fishery and stock enhancement expect that researchers will show the effective and viable measures for hatchery improvement to realize the recovery of salmon returns and a sustainable salmon fishery.

REFERENCES


Research and Development of a Supporting Information System for Optimization of Salmon Release Operations and Monitoring the Coastal Environment on the Okhotsk Coast, Japan

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Keywords: chum salmon, release, information system, satellite data, numerical forecast model

Introduction

Chum salmon (Oncorhynchus keta) is one of the important fishery resources in the North Pacific. Recently, under a changing climate, the return of chum salmon in Hokkaido has begun to decrease. More precise juvenile release operations are required for adapting to climatic changes, including warming sea temperature, and this can be accomplished by modifying the sea entry condition. It is necessary for this precise operation to predict the coastal marine environment in the release period and monitor short-term changes in coastal residency. Miyakoshi et al. (2007) applied satellite sea surface temperature data to compare the release timing of hatchery-reared juvenile chum salmon to spring coastal sea surface temperature during high and low survival periods. They demonstrated that satellite remote sensing and GIS (Geographic Information System) techniques are useful to identify optimum release timing for favorable coastal survival of chum salmon. The main objective of this study is to develop a supporting information system with WebGIS for optimization of salmon release operations and monitoring the coastal environment in the Okhotsk coast, Japan.

Materials and Methods

The salmon, which travelled to the sea from a river, feeds on zooplankton at a coastal region at a time when the water temperature is roughly 8–13°C; here the salmon grows until it begins its migration to offshore waters. The favorable water temperature of the area along the coast exists for a short period and when temperatures reach more than 13°C earlier, a juvenile salmon can only grow in a limited area along the shore (Miyakoshi 2018). It was recently pointed out that this is one of the factors driving the recent decrease in salmon resources. We expect that we can release juvenile salmon at a more appropriate time through the implementation of a system, which can predict the coastal water temperature before the release time.

We developed a supporting information system for the optimization of salmon release operations on the Okhotsk coast. This system was designed as a web-based visualization tool with two service sites, i.e., the monitoring of marine environment (marine site) and supporting of salmon release operation (release site) (Fig.1).

Fig. 1. Structure of prototype Web-GIS.
To predict the SST over the next three months, we employed an Auto Regression (AR) model in R package (https://www.econometrics-with-r.org/14-3-autoregressions.html) using the long term Satellite SST datasets, GHRSSST Level 4 MUR Global Foundation Sea surface Temperature analysis (v4.1) (https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1) from 2003 to 2020. We applied this AR model to estimate the days when water temperature reached 5–13°C, representing the coastal stay period (Kobayashi 1977). When we can estimate the days of favorable water temperature for release, we can estimate the final fork length at offshoring time with a chum salmon growth model with back-calculation method (Smale and Taylor 1987; Campana 1990). We include this estimation system as a simulator function in release site.

To display short term monitoring of the marine environment (sea temperature, salinity, current, and water masses in various layers), we employ the output of an eddy-resolving analysis model based on four-dimensional variational assimilation and a high (2 km) resolution forecast model covering Japanese coastal areas developed by the Japan Meteorological Agency (Sakamoto et al. 2019). The Soya warm current is a very important marine system occupying the coastal environment along the Okhotsk coast (Ohshima et al. 2017; Karaki et al. 2018). We applied the water mass classification definition (Takizawa 1982) to distinguish water mass, including Soya warm current, using the numerical forecast model output.

Results and Discussion

In the marine site (Fig.2), we employed the output of an eddy-resolving analysis model based on four-dimensional variational assimilation and a high (2 km) resolution forecast model covering Japanese coastal areas developed by the Japan Meteorological Agency. We also use GCOM-C satellite SGLI data, sea surface temperature (SST) and chlorophyll-a, with 250 m spatial resolution operated by JAXA.

Fig. 2. Example of marine site
in prototype Web-GIS.

Fig. 3. Example of release site
in prototype Web-GIS.
In the release site (Fig.3) there are two functions, one is the SST prediction function and the other is the salmon release simulation function. On the SST prediction page, we have obtained the next three months of SST predictions in each of 16 rivers along the Okhotsk coast. On the salmon release simulation page, when we input the number of the release operation, date, release fork length, and number of release salmon, we can then obtain the mean fork length, which is one of the indices of survival/return rate in the period of offshoreing from coastal residency. When we change the input parameters, we can turn the final offshoreing mean fork length as large as possible.

Concluding Remarks
To optimize the salmon release operation, we developed a prototype Web-GIS as a visualization tool that incorporates a salmon release simulation function. It might be useful during the preparation of release and a release date decision by using water temperature predictions over three months in advance. A prediction map of the marine environment from numerical model outputs, and a week ahead forecast of water temperature, can assist in the release timing during the short time of release operations. The release simulator function can help in risk management through a more accurate release operation.

We challenge to have a co-work, co-production, and co-design with Kitami Salmon Enhancement Program Association to develop information service for optimum salmon release operation in the Okhotsk coast, Hokkaido, Japan. We started to use the prototype system for the salmon release season in spring 2021 and further research and development can improve the chum salmon enhancement operation in the future.

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REFERENCES
Research Project of TEAMS for Restoration of Ecosystems and Human Society

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Keywords: 2011 Great East Japan Earthquake and Tsunami, restoration, ecosystems, human society, TEAMS

The Great East Japan Earthquake and Tsunami on March 11, 2011, caused immense damage to marine ecosystems, both nearshore and offshore, on the Pacific coast of northeastern Japan (the Tohoku region). Most fishing vessels and fishery related infrastructure were destroyed by the disaster. In the Tohoku region, salmon hatcheries have been common in many rivers, and every year, released chum salmon have returned to their own rivers. When the 2011 disaster occurred, a lot of juvenile chum salmon were reared in the hatcheries before being released into the sea. Therefore, the salmon production cycle in this region was also severely disrupted by the disaster.

In order to reconstruct the devastated human society, scientific investigation was essential to understand the effects of such strong disturbances on not only coastal land areas but marine ecosystems, and to monitor the process of their recovery. The research project of “Tohoku Ecosystem-Associated Marine Sciences (TEAMS)” was established under such circumstances by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) in 2011FY. The purpose of the TEAMS project is to clarify the impact of the earthquake and subsequent tsunami on marine-related ecosystems of the Tohoku coastal areas, highlight the restoration process of the ecosystems based on scientific research, and contribute to the reconstruction of fishery industries in the Tohoku region, including salmon production.

The TEAMS project was carried out for a period of 10 years—ranging from coastal to offshore seas and from surface to bottom in the Sanriku region—involving the cooperation and collaboration of a large number of researchers across Japan. Enormous research results obtained on the catastrophe of the earthquake and tsunami on the land and ocean ecosystems will contribute to future crisis management know-how not only in Japan but also overseas (TEAMS 2016). The background and results of this project will be a role model for disaster recovery as it included collaboration between different fields and regions and cooperation between researchers, fishermen, research institutes, and governments both local and national.

In addition, the results of this project will be useful for the monitoring and future prediction of marine ecosystem dynamics, the development of sustainable fisheries and aquaculture management, and the establishment of a new marine industry coexisting with marine environmental conservation and landscape (TEAMS 2020). We hope that they will be widely useful in various fields such as the education for conservation of marine ecosystems.

REFERENCES


Challenges to Make Salmon in Sanriku an Icon of the Region

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Keywords: recovery from the Great East Japan earthquake, Sanriku, chum salmon, local identity

Hokkaido and Iwate are major areas for salmon production in Japan as these regions have accounted for about 80% (Hokkaido) and 10–15% (Iwate) of total chum salmon annual catch in Japanese coastal waters (except recent years); Hokkaido has provided nearly 55% of chum juveniles for the stock enhancement program, while Iwate has provided 25%. The Great East Japan earthquake on 11 March 2011, struck off the northeastern coast of Japan causing a massive tsunami that severely damaged the Pacific coast of the Tohoku region. The coastal devastation was much more extensive in Iwate (the Sanriku region) where it is geographically characterized as a Ria—a deeply embayed coast with steadily increasing depth seaward—making the tsunami higher than in other areas. Important facilities for the salmon fishery, including hatcheries and processing plants as well as natural habitats for salmon, were destroyed or severely damaged by the tsunami. As part of the Tohoku Ecosystem-Associated Marine Sciences Program (TEAMS), subsidized by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Atmosphere and Ocean Research Institute, the University of Tokyo launched a project named “Project Grand Mailet” (PGM) to ascertain the impacts of the tsunami on the coastal ecosystem and to observe subsequent environmental or ecological transitions. This project involved research on salmon to help the reconstruction of fishery industries in the region affected by the disaster. Studies conducted by the project have revealed many specific ecological/physiological traits of salmon in Sanriku, presumably due to its particular environment for salmon reproduction; Sanriku has relatively warm water in rivers during the winter because of its latitude and oceanographic conditions and rich spring waters affect water composition (e.g., Aoyama 2017; Kitagawa et al. 2017; Abe et al. 2019; Nobata et al. 2019). These findings potentially provide a new insight into the stock enhancement techniques adapted to the local environment of Sanriku. However, the economic importance of salmon, which accounted for more than 20% of the total fishery production in Iwate in 2006, has declined sharply, to only about 6% in 2019 (Iwate Prefecture 2020). Furthermore, the number of fishery workers in the region has also been declining, particularly after the disaster (Iwate Prefecture 2020). These facts imply that an intensive salmon fishery approach for regional reconstruction contribute less to the whole local community and a much broader and more inclusive approach is required. The PGM has initiated a multidisciplinary approach to know the actual status of salmon in Sanriku to re-establish ecological, cultural, and commercial images of salmon in Japan, which has mostly relied on Hokkaido. A variety of studies conducted in the project revealed not only locally specific ecological characteristics, but also anthropological traits such as traditions or relationships between humans and salmon in Sanriku (e.g., Yoshimura and Aoyama 2019) which are different from the indigenous Ainu culture described from Hokkaido. These facts suggest that the salmon in Sanriku have ecologically adapted to the local environment and have established a long and good relationship with people in the area. The salmon in Sanriku are not only a fishery resource but could potentially be an icon of the region or a local identity that encourages the reconstruction of society from the disaster.

REFERENCES


Effects of the Great East Japan Earthquake and Tsunami on Fisheries and Salmon in Iwate Prefecture

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Keywords: The Great East Japan Earthquake, tsunami, chum salmon resources in Iwate

The 9.0-magnitude Great East Japan Earthquake (GEJE) occurred at 14:46 local time on 11 March 2011. The following tsunami swept away towns, buildings, cars, and even human lives on the Pacific coast of Iwate Prefecture. The tsunami reached the coast about 30 minutes after the earthquake occurred (Fig. 1a), and soon swept away buildings and cars (Fig. 1b). The fisheries in Iwate were also severely damaged and the hatchery enhancement program for chum salmon (*Oncorhynchus keta*), a most important fisheries resource in Iwate, was in a critical situation (Ogawa and Shimizu 2012; Goto 2018). The salmon fisheries yield occupies about 20% of all fisheries yield in Iwate Prefecture. Iwate has over 100 years of history for the hatchery enhancement program. The number of hatchery-released fry has increased gradually since 1971, and approximately 400 million fry are released annually since 1984 (Fig. 2). The number of salmon returns also increased with the increasing number of released fry, and it reached a peak (25 million fish) in 1996 (Fig. 2). The salmon resource depends on the hatchery enhancement program in Iwate. On the other hand, after the marked peak in 1996, it has been decreasing gradually, with notable decreases of 40% in 1998 and 60% in 2011, when compared to the average between 1983 and 2010 (Fig. 2). Why are adult returns decreasing? We estimate that a decreasing number of fry releases due to natural disasters, such as repeated earthquakes and typhoons, and changes of ocean environment have strong impacts on recent adult returns.

Fig. 1. Thirty minutes after the earthquake occurred the tsunami reached a cliff (a). Five minutes after image (a) the water level increased substantially (b).

Fig. 2. Annual change in chum salmon release and adult returns in Iwate, 1963–2020. The orange line indicates the number of released fry, the blue bars indicate the number of adult returns, the red circle indicates the GEJE in 2011, and the blue circle indicates a typhoon disaster in 2016.
In the spring of 2011, a total of 440 million chum salmon larvae were reared at hatcheries. Although some chum salmon fry were released before the disaster, the tsunami swept away most of them, including eggs, alevins and fry along with several hatchery facilities. The reconstruction of damaged hatchery facilities started several weeks after the disaster. First, a survey was conducted to confirm the contamination of saltwater in hatchery water supplies. Restoration of capture facilities, and removal and cleaning of rubble at hatcheries were performed gradually. All hatchery staff worked hard because they understood the importance of the hatchery program for the sustainable management of salmon resources in Iwate. In September 2011, only six months after the disaster, hatchery facilities had almost recovered to produce 320 million chum salmon fry. Instead of 28 hatchery facilities in 27 rivers before the disaster, now there are 20 facilities in 20 rivers, which can produce and release 400 million salmon fry.

![Graphs showing the number of adult chum salmon returns in the Tsugaruishi, Katagishi, and Orikasa rivers, from 2010–2019. Red and yellow bars indicate the first generation of the GEJE brood-year, and the second generation, respectively.]

Most of the hatchery-reared chum salmon were affected by the tsunami. After the disaster, we continued a long-term monitoring program to evaluate the effects of the disaster on adult returns in the Tsugaruishi, Katagishi and Orikasa rivers. In the Tsugaruishi and Katagishi rivers, where chum salmon fry could not be released in the year when the tsunami occurred, the average number of adult returns was about 30,000 fish in the Tsugaruishi River and about 16,000 fish in the Katagishi River between 2010 to 2013 (Fig. 3). In 2014 when the disaster brood-year (2010) adult salmon returned, it significantly decreased 10,577 fish in the Tsugaruishi River and 2,751 fish in the Katagishi River. On the other hand, in the Orikasa River, chum salmon fry could be released in the disaster year, because it was not directly damaged by the tsunami. However, because of the power outage that occurred the day after the tsunami, chum salmon fry were immediately released. The average number of adult returns was 7,600 fish before the disaster, while it was 9,255 fish in 2014 (Fig. 3). So, there seemed to be no effect on the number of adult returns in the Orikasa River. In addition, the number of 2010 brood-year adult chum salmon returns decreased from the middle of November in the Tsugaruishi River and late October in the Katagishi River, and they did not recover thereafter (Fig. 4). These observations suggest the survival of chum salmon fry directly damaged by the tsunami was quite low. On the other hand, about 400 million fry were released in the spring of 2015 (offspring of the 2010 brood-year which is called second generation). The number of adult returns in the fall of 2018 (2014 brood-year returned) was 44,822 fish in the Tsugaruishi River and 23,612 fish in the Katagishi River—these exceeded the average number of adult reruns between 2010 to 2013 (Figs. 3 and 4). These data indicate that the hatchery
enhancement program plays a major role in maintaining chum salmon resources in Iwate. In addition, our long-term monitoring data indicate that the effects of the GEJE had almost recovered in the second generation.

Fig. 4. The number of chum salmon returns in the Tsugaruishi (a), Katagishi (b), and Orikasa rivers at every ten-day term (c). Red and yellow bars indicate the first generation of the GEJE brood-year, and the second generation, respectively.

These days, the number of adult returns has been decreasing in Iwate. We have been monitoring SST (Sea Surface Temperature) and the density of juvenile chum salmon in the coastal water (SST: since 1966; the density of juveniles: since 2003). Our monitoring data shows that coastal SST is increasing between April and July (Fig. 5a)
and the duration of SST between 5 to 13°C, which is favorable for juvenile chum salmon (Saito and Nagasawa 2009), is decreasing (Fig. 5b). We observed a negative correlation between SST and the density of juvenile chum salmon in coastal waters (Fig. 6a) and a positive correlation between the density of juvenile chum salmon in coastal waters and adult returns (Fig. 6b). Therefore, we estimate that recent ocean environment changes have been affecting the survival of juvenile chum salmon, consequently decreasing the number of adult returns.

**Fig. 5.** Annual change in SST (a) and the duration between SST 5 to 13°C (b) along Iwate coast from 1974–2020.

**Fig. 6.** Relationships between SST and density of juvenile chum salmon in coastal water (a) or adult returns (b) in Iwate.

The critical damage done by the Great East Japan Earthquake and Tsunami and the following reconstruction procedure unexpectedly reconfirmed the importance of the hatchery enhancement program. Ten years after the earthquake the number of chum salmon returns is decreasing, possibly due to changes in the marine environment. In the future, in order to recover salmon resources in Iwate, it is necessary to continue the hatchery enhancement program with improved rearing and release methods.

**REFERENCES**


First Salmon Ceremony in the Southernmost Area of Salmon Habitat

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**Keywords:** first salmon ceremony, culture of salmon, importance of salmon in communities

Salmon inhabit the North Pacific Ocean and are an extremely important food source for people who live around the North Pacific rim. Salmon are not only important to people as a food resource there, but the capture and utilization are very important culturally. The first salmon ceremony is an important cultural event that takes place around the southernmost area of salmon habitat.

Gunther's research (1926, 1928) on salmon rituals in the North Pacific region, especially on the American continental side, hardly touches on the Japanese archipelago and the Far East, including Hokkaido. By comparing the beliefs and customs of the Ainu, the people of northern Honshu, the indigenous people of the Amur River basin, and the indigenous people of Sakhalin in relation to salmon hunting, Obayashi proposes that the salmon rituals from Amurland through Hokkaido to northern Honshu be viewed as a single continuum (Obayashi 1992, 1996). In addition, Suga (2000) and Suzuki (2004), among others, have conducted research on salmon rituals around the Tohoku region.

The objective of this study is to understand the status of salmon culture in the southern limit of salmon habitat. The target of the research is the MATABE ceremony, the first salmon ceremony in the Tsugaruishi district of Miyako City, Iwate Prefecture. We surveyed rituals related to the MATABE ceremony. The research was conducted by participating in the ritual, interviewing the people involved, and collecting historical data.

In this paper, the case study of the ceremony is the Tsugaruishi area, Iwate prefecture (Fig. 1). Tsugaruishi is one of the rivers with the highest salmon catch in the Tohoku region. The first salmon ceremony at Tsugaruishi, called MATABE ceremony, is one of the most distinctive and rare salmon ceremonies in Japan. In addition to the first salmon ritual, Tsugaruishi has various traditions and myths related to salmon.

Artificial hatching of salmon is also carried out in Tsugaruishi River, but the system is slightly different from others. In Japan, fishery cooperatives generally handle everything from salmon capture to artificial hatching. However, in Tsugaruishi, artificial hatching is carried out by fishery cooperatives while salmon capture is carried out by specialized organizations. The caught salmon are fertilized on the spot by the fishery cooperative’s staff. The used salmon is sold to general customers at the shop managed by the capture organization and the profits are used for operating expenses of the organization. Salmon capture organizations in Tsugaruishi have played a very important role in the management of local communities. For example, the cost of public activities in the district was...
paid by the capture organization, and salmon was distributed to the district members of Tsugaruishi. After the
earthquake in 2011, they handed relief money to residents. In this way, salmon play a very important economic role
in Tsugaruishi.

The “MATABE ceremony” is held at noon on 30 November every year. The ceremony is performed by a
salmon capture organization and is attended by those concerned with the district at Tsugaruishi. The feature of this
ceremony is to use a bifurcated straw doll named “MATABE” (Fig. 2). An old tradition in Tsugaruishi has it that a
man named MATABE once broke a salmon net to save people from starvation, but that action of breaking the
salmon net was a serious crime at that time and he was executed upside down. After the death of MATABE, salmon
no longer ran up the river. The villagers considered it the curse of MATABE and mourned him. After mourning,
the salmon started to run up the river again. Since then, people have performed this ritual at Tsugaruishi to mourn
MATABE and pray for a good catch of salmon. It is from this narrative that the people of Tsugaruishi worship
MATABE as a hero and now perform this ceremony. The shape of the doll imitates MATABE being killed upside
down. The use of a straw doll for salmon rituals is very characteristic of this region and this is the only place in
Japan where straw dolls are used in salmon rituals. Finally, during the ceremony the representative sprinkles water
drawn from the Tsugaruishi river on the MATABE doll (Fig. 3). I explained that straw dolls imitate the shape of a
person, but there is also a theory that they imitate the shape of a fish because the act of pouring water from the river
reminds people of salmon. We will omit it here, but there are other factors that are reminiscent of salmon from the
form of the old ritual. The ceremony finishes after this performance and the dolls are stored on the riverside until
around February, when the salmon fishing season on the river ends.

The first salmon ceremony is one of the ceremonies that pray for a big salmon catch. A ceremony marking the
event of the first salmon run of the season is practiced by many coastal Native groups on the North Pacific Coast
(Gunther 1926, 1928) and many of the ceremonial features are similar throughout the area. Many tribes on the coast
make salmon one of their principal foods. In most localities there are no salmon in streams during some seasons, or
if any are to be found the quality is so poor that Natives do not use them. Hence the coming of the first salmon is a
real event, for it means not only a change from a diet of dried meats and fish, but in many instances saves people
from imminent starvation. The first salmon ceremony tends to take place in the southern area of salmon habitat.
The commonalities between salmon ceremonies in northern Japan and the Northwest Coast have often been pointed
out (Obayashi 1992). Finally, we consider why the first salmon ceremony remains around the southernmost area of
salmon habitat.
When considering the factors behind these remaining first salmon ceremonies in the southern area of salmon habitat, we need to consider the position of salmon at a local level. So, we would like to point out the following three points: the monetization of salmon, timing of salmon run-up, and food importance of salmon.

(1) Monetization of salmon: As we mentioned earlier, when looking at the salmon hatching systems of Tsugaruishi, the economic contribution of salmon cannot be overlooked. The sales of salmon caught in the river are often used for the operation of the Tsugaruishi community. In other words, it is an area where salmon is indispensable for the operation of the local community. It has a history of at least 100 years and this operation system is still in place now.

(2) The timing of salmon run-up: Although it is related to the next point, the timing of salmon run-up is the off-season agricultural work that makes it possible to devote a lot of labor to fishing and securing food (Kodani 2002).

(3) Food importance of salmon: Since salmon migrate upstream from autumn to winter, they have been regarded as a valuable source of nutrition in winter. Salmon is a fish that is said to have no parts to throw away, has high nutritional value, and above all is a highly conserved food—an example being Aramakisake (dried salmon with salt; Fig. 4). Traditionally, a Japanese diet has depended on rice, and there is a proverb around northern Japan that states salmon can be captured in large numbers in a year when rice is poor. Therefore, some people value salmon as much as rice.

![Fig. 4. Aramakisake (dried, salted salmon).](image)

Note—First salmon ceremonies can be universally confirmed in northern Japan, where salmon rituals are widely practiced. Due to present difficulties, I cannot provide an in-depth look at the cultural role of salmon in North America, however it should be pointed out that salmon have a special meaning to several North American tribes. Eventually, this point needs to be considered in comparison with other rituals.

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Recovery from a Critical Disaster and Sustainable Conservation Management for Chum Salmon under a Warming Climate on the Sanriku Coast, Japan

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Keywords: chum salmon, GEJE, TEAMS, Salmon Café, global warming, Jomon period, Sanriku Coast

The 2011 Great East Japan Earthquake (GEJE) and tsunami caused immense damage to the Sanriku Coast in northeastern Honshu, Japan. After this catastrophic disaster, the Tohoku Ecosystem-Associated Marine Science (TEAMS) research program was formed. The objectives of this paper are to introduce valuable research results from TEAMS and to clarify the impact of global warming on chum salmon, which is a further threat after the GEJE. For the last ten years, a lot of researchers and scientists contributed to various salmon research fields, including salmon ecology and physiology, oceanology, genetics, the economy, and salmon ethnology for restoring salmon production, coastal and lower freshwater ecosystems, the fisheries industry, salmon hatchery programs, and regional-human communities (Table 1). Research results were immediately provided to the Salmon Café as outreach and published in the proceedings of Salmon Café every year since 2013 (Fig. 1).

Table 1. Main results of chum salmon research from the Tohoku Ecosystem-Associated Marine Science (TEAMS) program.

- Life-history strategy of juvenile chum salmon in rivers and sea of the Sanriku Coast
- Temporal-spatial change in the distribution of juvenile chum salmon eDNA on the Sanriku Coast
- Predation effect of seabirds on hatchery-stocked juvenile chum salmon
- Temperature tolerability and seawater adaptability of juvenile chum salmon
- Ontogeny and developmental stage of juvenile chum salmon
- Population dynamics of chum salmon returning to the Sanriku Coast
- Physiology and migration behavior of adult chum salmon
- Genetic population structure of Sanriku chum salmon
- Wild population and natural spawning of Sanriku chum salmon
- Oceanological characteristic of the Sanriku Coast using the WebGIS
- Salmon ethnology on the Sanriku Coast
- Fisheries industry and food processing of salmon
- Food processing of salmon
- Fish disease of chum salmon

Fig. 1. Sanriku Coast on northern Honshu Island, Japan (A), Salmon Café (B), and Proceedings of the Salmon Café (C).
First, we introduce some results of important salmon research. Qin et al. (2016) clarified the carbon and nitrogen stable isotope of juvenile chum salmon on the Sanriku Coast before and after the tsunami. The carbon stable isotope after the tsunami was higher than it was before, despite no difference in the nitrogen stable isotope. This result supports that 1) the tsunami caused carbon enrichment in the coastal ecosystem because of the churning of sludge, and that 2) juvenile chum salmon did not change their trophic level after the tsunami (Fig. 2). Minegishi et al. (2019) demonstrated the temporal-spatial change in the distribution of environmental DNA of juvenile chum salmon in the Otsuchi Bay. Juveniles were distributed throughout the bay from January to early June with two peaks (March and May) during periods of outmigration to other bays. On the Sanriku Coast, juvenile chum salmon dominantly fed on *Themisto japonica* during the offshore migration period (Kaeriyama 1986). Yamada et al. (2019) examined feeding ecology of juvenile chum salmon and clarified that 1) juveniles dominantly preyed on *Neocalanus plumchrus* and *Themisto japonica* from 2013–2015, however, 2) they fed primarily on decapod larvae in 2016 with very few *Themisto japonica* found in their stomachs. In the spring of 2016, the Oyashio cold current was very weak and left the Sanriku Coast in May.

Unfortunately, the return of chum salmon to the Sanriku Coast has continued to decline, even after the GEJE, despite damaged facilities and the salmon hatchery regime quickly recovering after the tsunami. After peaking in the 1990s, chum salmon return has been declining year-by-year and decreased to below a million individuals in 2019–2020 (Fig. 3). In this century, the sea surface temperature (SST) in spring showed an increasing trend (Fig. 4A) and in the recent quarter century, the SST increased 0.95°C in March, 1.13 °C in April, 1.40°C in May, and 1.58°C in June (Fig. 4B). Juvenile chum salmon stay on the Sanriku Coast from March until the SST reaches
12.5°C, before migrating offshore (Kaeriyama 1986); however, this stay-duration has been decreasing in recent years (Fig. 4C).

Chum salmon form a mark on their scales when juveniles migrate from the Sanriku Coast to offshore habitat at 8–14 cm in fork length (Fig. 5). Therefore, we can estimate the body size of a juvenile at offshore migration by measuring from the focus to the mark on the scale of an adult salmon, using the scale back-calculation. Figure 6 demonstrates the temporal changes in estimated fork length (FL) anomaly at offshore migration, return rate, and the duration of coastal stay for juvenile chum salmon on the Sanriku Coast. The FL, duration, and return rate showed declining trends over time. The relationship between FL and return rate, and the relationship between FL and duration indicated significant positive correlations ($p < 0.01$), respectively. These facts suggest that juvenile salmon could not grow sufficiently by the offshore migration period due to the shortened stay-duration year by year, resulting in a decline in return rate of the Sanriku salmon (Kaeriyama 2019). We revealed temporal changes in estimated FL at age-1 Ishikari and Tsugarushi River populations and return rates of Hokkaido and Iwate Prefecture chum salmon. Both FL and return rate increased after the 1980s, peaked in the late 1990s, and then began to decline after the early 2000s. The relationship between FL and return rate of both populations indicated significant correlations (Fig. 7). This suggests that global warming had a positive effect on Japanese chum salmon in the 1990s (Kaeriyama et al. 2014), but would have a negative impact on them since the mid-2000s.
In general, larger juveniles precede the offshore migration period. On the Sanriku Coast, large juveniles (10–14 cm in FL) migrate offshore in advance while taking an optimal foraging strategy in May. Small juveniles (8 cm in FL) passively migrate offshore after late May, so they escape from the warm current (Kaeriyama 1986). We define these migration patterns as the active migration (AM) and the passive migration (PM), respectively. The temporal change in the offshore migration pattern of juvenile chum salmon in the Sanriku Coast since the 2000s (Fig. 8) indicated the following:

1) The period of offshore-migration has been reduced; AM juveniles have decreased and have disappeared after June.

2) The PM juveniles tended to accelerate the time of offshore migration.
3) Dominant prey *Themisto japonica* also decreased or disappeared in the stomachs of juveniles after June. These results suggest that juvenile survival rate would decline because of a missing migration route to Hokkaido or the Okhotsk Sea, and a lack of sufficient growth due to global warming (Kaeriyama and Urabe 2018).

![Fig. 8](image1.png)

**Fig. 8.** Temporal change in the offshore migration pattern of juvenile chum salmon on the Sanriku Coast. ■: the offshore migration period of the large AM; ■: the offshore migration period of the small PM; T: the appearance period of dominant prey *Themisto japonica* in stomach of juvenile chum salmon.

![Fig. 9](image2.png)

**Fig. 9.** The distribution of chum salmon remains in the Jomon Period. A: From the Incipient to the Early periods (16–5.5 kyr BP) • Incipient Period (16–12 kyr BP): 3 remains; • Initial Period (12–7 kyr BP): 5 remains; • Early Period (7–5.5 kyr BP): 22 remains. B: From the Middle to the Last periods (5.5–2.8 kyr BP): 67 remains.

We examined more than 130 thousand reports of the Jomon archaeological site (https://sitereports.nabunken.go.jp/ja) in order to evaluate the historical distribution pattern of chum salmon in Japan. Chum salmon were widely distributed throughout northern Japan since the middle Jomon period (5.5–2.8 thousand years ago; 67 remains). In the Incipient Jomon period (16–12 thousand years ago), relics of chum salmon were discovered in Tokyo and Nagano Prefecture (three remains). On the other hand, in the Initial and Early Jomon periods (12–5.5 thousand years ago), chum salmon disappeared on the Pacific Ocean side of northern Honshu. However, contrary to the evidence (Ishida et al. 2001) so far, they were clearly distributed from Aomori to Toyama prefectures on the Japan Sea side (15 remains) as well as Hokkaido in these periods (Fig. 9). According to the historical change in the isotopic temperature of the ice core at the Dome Fuji of East Antarctica, since 350 thousand years ago the global temperature from the mid-Initial to the Early Jomon periods was about 2°C higher than at
present (Watanabe et al. 2003). The Kuroshio Current strongly flowed north without the meander. These periods were called the "Jomon transgression" (Yamada 2019). In the last century, the global mean temperature has already increased about one degree Celsius and the current situation of chum salmon is approaching that of the Jomon transgression period in Japan.

**Goals**

1. Conservation & Use
   - Conservation and recovery of wild salmon
   - Innovation of salmon fisheries & hatchery stocking
   - Zoning between wild and hatchery salmon

2. Research & Monitoring: Interaction between aquatic ecosystems & salmon
   - Climate change (e.g., Global warming, Regime-shift): sea & freshwater ecosystems
   - Change in aquatic ecosystem affecting the life history & population dynamics of salmon

3. Restoration & resilience for wild salmon and river ecosystem
   - Restoration for impoverished river ecosystem
   - Resilience of wild salmon

![Fig. 10. Sustainable conservation management for chum salmon in Japan under the warming climate.](image)

Under a changing climate we need to establish the “sustainable conservation management for chum salmon,” based on a “back-casting approach” in Japan (Fig. 10). We should (1) set the final goal based on a sufficient analysis of the current situation, and (2) step up to the goal with adaptive management and the precautionary principle. We have three final goals: (1) how to conserve and use salmon, (2) how to carry out the research and monitor for interaction between aquatic ecosystems and salmon, and (3) how to restore and resilience for wild salmon and river ecosystems.

**REFERENCES**


Wild Population and Natural Spawning of Chum Salmon in the Kozuchi River on the Sanriku Coast, Japan

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Keywords: chum salmon, hatchery-based stock enhancement, wild fish, natural spawning

An intensive hatchery-based stock enhancement program has been implemented since the late 1970s and has been generally believed to sustain the Japanese chum salmon stock (Kaeriyama 1999; Nogawa 2010). On the Sanriku Coast (the Pacific side of northern Japan’s mainland) the stock enhancement program has been intensively implemented in almost all major rivers and has resulted in the drastic increase of adult fish returning to this area. The Great East Japan Earthquake and subsequent tsunami occurring in 2011, however, severely damaged almost all the hatcheries on the coast (Ogawa and Shimizu 2012). In some rivers, stock enhancement programs involving adult catch and mass releases of juveniles have been suspended since the disaster. Therefore, it can be expected that wild chum salmon populations may exist on the Sanriku Coast.

The Kozuchi River, located in the middle part of the Sanriku Coast, had its stock enhancement program suspended after the disaster in 2011. Thus, all chum salmon adults coming back to this river have reproduced naturally since the suspension of the stocking program. In contrast to the Kozuchi River, the neighboring Otsuchi River—adjacent to the Kozuchi River at their mouths—stock enhancement program has been continuously operated since the disaster. In the Otsuchi River, adults are caught by a hatchery weir that is set close to the river mouth and about 10–20 million juveniles have been released annually from the hatchery (Iwate Salmon Stock Enhancement Association 2021).

To assess quantitatively the wild population and natural spawning in the Kozuchi River, a field survey has been conducted throughout whole seasons from 2017 to 2020. A survey was carried out one to three times a week from the end of August or the beginning of September to February or early March in the area of 1.0 to 4.0 km upstream from the river mouth of the Kozuchi River. Spawning redds were visually counted and their numbers and positions were recorded by GPS while walking gently and slowly along or in the survey reaches. Carcasses were collected to estimate the number of returning adults.

At least 186–363 spawning redds were observed over the study area in each season from 2017–2020. The main spawning ground in the Kozuchi River appeared to be in the range of 1.0 km, which is located about 1.0–2.0 km upstream from the river mouth. For the returning adults, a total of 898–2023 carcasses were collected in each season in the Kozuchi River while 1537–2787 adult fish were officially reported to be caught by hatchery weir in the neighboring Otsuchi River (Iwate Prefectural Government 2021). The Otsuchi River population was larger than the wild Kozuchi River population over the studied four seasons, but the returning adults tended to decline from 2017 to 2020 in both rivers. This suggests that wild chum salmon can be affected by the global and oceanographic conditions as well as hatchery fish and/or that the Kozuchi River population may contain some straying of hatchery fish.

The present study confirmed that the wild chum salmon population in the Kozuchi River was generated after the disaster in 2011 and has been sustained by natural reproduction since then. The comparison with the neighboring Otsuchi River with stock enhancement indicated that the Kozuchi River population appears not to be negligible without stock enhancement and thus the effect of the stock enhancement program implemented in the Otsuchi River should be re-evaluated carefully. On the Sanriku Coast, natural spawning and wild populations are possibly an alternative or additional key to sustaining the chum salmon stock in this region and thus their values should be reconsidered.

REFERENCES


Downstream Migration and Spatial Distribution of Juvenile Chum Salmon in the Otsuchi Bay, the Sanriku Coast of Iwate, Japan

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Keywords: chum salmon, juvenile, downstream migration, otolith Sr:Ca ratio, growth increment analysis, littoral zone

Chum salmon (Oncorhynchus keta) is one of the most commercially valuable species in Iwate prefecture, located on the Sanriku coast. However, the annual catch of adult chum salmon in Iwate has drastically decreased after a peak in the 1990s despite the massive effort of releasing hatchery fishes (Hokkaido National Fisheries Research Institute, Japan Fisheries Research and Education Agency 2021). This decreasing trend has continued in the last decade under a marked decline in the adult return rate. The mortality that occurred during their early marine life, which is influenced by coastal environment and juvenile condition, is suggested as a significant factor to regulate the adult return rate of Japanese chum salmon (Saito and Nagasawa 2009). Also, the Great East Japan Earthquake that occurred in 2011, which devastated the coastal environment and salmon hatchery, is supposed to be one of the causes of this decline (Watanabe et al. 2015). Therefore, there is an urgent need to clarify the linkage between early mortality of chum salmon and the coastal environment for enhancing the sustainable use of chum salmon resources in Iwate.

The Sanriku coast is characterized by the ria coast, which consisted of many enclosed small bays with relatively short and steep rivers. The oceanographic structure in this region is complex and highly variable, owing to the mixing of Kuroshio and Oyashio currents. A previous study reported that chum salmon juveniles spend a couple of months in bays before they start their northward migration (Seki 1978). This finding implies that the match/mismatch to a suitable coastal environment within the bay is crucial for the survival of the juveniles and finally, to determine the year-class strength. Therefore, the timing of downstream migration and distribution after sea entry is essential information to understand their early mortality.

This study aimed to outline the phenology of downstream migration and spatial distribution of chum salmon juveniles in the Otsuchi Bay. Describing the presence of wild juveniles was also a goal because recent studies highlighted that wild fish originating from natural spawning can contribute to increasing chum salmon resources and enhance the resilience of their population, although Japanese chum salmon is considered to be sustained mainly by hatchery fish (Morita and Ohkuma 2015).

The phenology of downstream migration was investigated in the Kozuchi and Otsuchi rivers from January to May 2017. Juveniles in the Kozuchi River are solely composed of wild fish because hatchery release was suspended in this river after the Great East Japan Earthquake in 2011 (Minegishi et al. 2021). On the other hand, juveniles in the Otsuchi River are a mixed stock of hatchery and wild fish. Therefore, juveniles caught in the Otsuchi River had their origin differentiated by fork length (FL in mm) by finite Gaussian mixture modeling fitted via the EM algorithm, assuming the significant differences in body size between origins.

Continuous investigations suggested that downstream migration of wild juveniles occurred from late January to middle May in the Kozuchi River. Their FL was 41 ± 3 mm (mean ± SD), suggesting that they migrated downstream shortly after emergence. A significant correlation was found between FL and collection date, suggesting that the juveniles migrated into the sea at a larger size as the migration period progressed (Spearman’s rank correlation, $\rho = 0.296$, $p < 0.05$). The reason why the body size of migration increased at the later season is unclear, but it can be speculated that the juveniles that emerged later stay longer or grew faster in the river.

In the Otsuchi River, migrating juveniles were caught from February to May. Hatchery fish dominated the juveniles, but wild fish were concurrently collected through the migration period. The FL of wild fish (41 ± 2 mm) was equivalent to that in the Kozuchi River, while hatchery fish migrated into the sea with a larger FL (56 ± 6 mm). These results suggested that even in the Otsuchi River, where the hatchery program was conducted, wild juveniles are produced by natural spawning.

Subsequently, the spatial distribution after sea entry was investigated during March and May 2017. The collection was conducted in the Otsuchi Bay in three habitats (surf zone, sandy beach, and offshore) using three different fishing gears (surf zone net, dragnet, and seine net, respectively). The FL at sea-entry and growth in the

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sea were further estimated for collected juveniles based on otolith Sr:Ca ratio which was measured by an electron probe microanalyzer (EPMA) and growth increment analysis.

The FL composition of juveniles apparently indicated a habitat shift with growth. In the surf zone, juveniles were the smallest among three habitats, and their FL was almost identical to that of the wild fish at downstream migration (38 ± 3 mm). The FL of juveniles significantly increased as the distance from the shore increased (47 ± 5 mm in the sandy beach and 52 ± 4 mm in offshore (Steel–Dwass test, \( p < 0.05 \)).

Additional otolith analysis suggested that the differences in FL among habitats may be derived from different FL at sea entry and the amount of body growth in the sea. FL at sea entry of juveniles collected in the surf zone and offshore were almost equivalent to the FL at downstream migration of wild fish (35 ± 4 mm and 43 ± 5 mm, respectively). However, the FL at sea entry of juveniles collected in the sandy beach was significantly larger than the other two habitats (48 ± 3 mm, Steel–Dwass test, \( p < 0.05 \)). Body growth after sea entry showed a similar significant trend; while almost no growth was found in the surf zone (0.2 ± 0.4 mm), it was significantly smaller in the sandy beach and offshore site (6.7 ± 4.3 mm in the sandy beach and 3.0 ± 2.3 mm in offshore, Steel–Dwass test, \( p < 0.05 \)). Although this result should be considered a preliminary one due to the small number of juveniles analyzed, it could be expected that habitat preferences may differ depending on body size, and surf zone is a temporal habitat used by small juveniles immediately after sea entry.

This study suggested that chum salmon juveniles in the Otsuchi Bay consisted of multiple origins and may contain various movement patterns depending on body size. Because downstream migration of juveniles lasts about four months, it is expected that the phenological mismatch between the timing of sea entry and the preferable coastal environment such as water temperature, prey availability, and predation risk is crucial to understand their mortality. The early marine life of chum salmon in the Sanriku region should be scrutinized concerning phenological environmental changes to optimize hatchery release strategy and manage wild salmon resources appropriately.

REFERENCES


Spawning Environment of Chum Salmon in the Coastal Rivers on the Pacific Side of Northern Japan

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Keywords: chum salmon, wild fish, natural spawning, spawning redds, environment

The environment in the spawning redds such as water temperature and dissolved oxygen is important for the growth and survival of chum salmon (Oncorhynchus keta) during their early life stages (Bjornn and Reiser 1991; Bloomer 2016). However, little attention has been paid to natural spawning and the spawning habitat of chum salmon on the Pacific side of northern Japan (the Sanriku Coast), which constitutes the southern edge of the specific range. This is because most adults returning to Japanese waters, including the Sanriku Coast, have been considered to be hatchery-origin due to the intensive implementation of the stock enhancement program. Recently, the possible importance of the wild population for the entire Japanese stock has been reported (Morita et al. 2013; Aruga et al. 2014). Moreover, the natural spawning of chum salmon on the Sanriku Coast has been observed after Great East Japan Earthquake occurred in 2011 (Aoyama 2017; Minegishi et al. 2021). We investigated, as the first step, the spawning environment of chum salmon in the Kozuchi and Unozumai Rivers on the Sanriku Coast, Japan.

The study area was a range of about 230 m in both rivers, where the spawning redds of chum salmon were observed most abundantly during the spawning season in each river. The field surveys were carried out in the Kozuchi River on 24 and 25 December 2019, and in the Unozumai River on 19 December 2019. Water temperature, dissolved oxygen (DO), and electric conductivity (EC) in the riverbed and surface water were measured at 18 and 10 spawning redds and 12 and 10 non-spawning sites in the former and latter rivers, respectively. Vertical hydraulic gradient (VHG) was simultaneously measured with a piezometer. Gravel size was visually described following the Udden-Wentworth grain size scale.

In the Kozuchi River, the median water temperature, DO, EC and VHG in the spawning redds were 10.0 (9.1–11.1)°C, 8.0 (5.8–10.1) mg/L, 81.9 (71.6–98.1) mS/cm, 0.018 (0.006–0.020), while those in the Unozumai River were 10.5 (7.4–11.6)°C, 7.6 (6.7–10.2) mg/L, 91.5 (85.4–96.9) mS/cm, 0.013 (0.000–0.028), respectively. The spawning redds were placed predominantly in the 2–60 mm size gravel beds in both rivers. No statistically significant difference was observed in the environmental parameters for the spawning redds between the two rivers. At the non-spawning sites, however, the temperatures of the surface water (8.8°C) and the riverbeds (10.7°C) of the Kozuchi River were significantly higher than the Unozumai River (5.5°C for surface and 8.5°C for the riverbeds), while DO of the riverbeds in the Kozuchi River (5.2 mg/L) was significantly lower than the Unozumai River (7.4 mg/L). As the groundwater is generally characterized by lower DO compared to the surface water (Malard and Hervant 1999), the upwelling of groundwater was suggested to be more abundant in the Kozuchi River than in the Unozumai River. In the Kozuchi River, the DO and EC in the spawning redds were significantly higher and lower than those in the non-spawning sites, respectively, which suggests that the groundwater upwells more abundant in the non-spawning sites than in the spawning redds. On the other hand, in the Unozumai River, no statistically significant differences were observed in any environmental parameters between the spawning redds and non-spawning sites.

The present study revealed the environment of the spawning redds in the rivers on the Sanriku Coast: water temperature and DO in the spawning redds were about 10°C and 8.0 mg/L, respectively. In the Kozuchi River, it was found that the rich upwellings of the groundwater distribute patchily in the survey area. In contrast, in the Unozumai River, although the abundance of the groundwater upwelling appeared to be relatively less compared to the Kozuchi River, the groundwater upwells uniformly over the study area. So, chum salmon adults selectively spawn at the oxygen-rich sites where the groundwater upwells moderately in the Kozuchi River, while no selectivity is exhibited relative to the groundwater upwelling in the Unozumai River. The present study suggests that, in the Sanriku coastal rivers, the water temperature is a primary factor for chum salmon adults to select appropriate spawning sites, but the upwelling of the groundwater is likely less important when a suitable water temperature is available.
REFERENCES


The Utilization of Cold-water Zooplankton as Prey for Chum Salmon Fry in Yamada Bay, Iwate, Pacific Coast of Northern Japan

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Keywords: chum salmon fry, feeding habits, food environment, zooplankton, Neocalanus plumchrus, Themisto japonica, Oyashio

After migrating into the sea from rivers, chum salmon fry stay in coastal areas during spring to early summer, subsequently migrating to the northern North Pacific Ocean (Seki 2005). The availability of prey organisms in this early marine period is one of the most important factors affecting growth and survival of salmon fry (Terazaki and Iwata 1983; Ban et al. 1996; Seki 2005). The magnitude of the Oyashio Current significantly affects the zooplankton community structure in nearshore waters during this period (Terazaki 1980; Kotani et al. 1988; Nishibe et al. 2016). Therefore, we expect that feeding habits and prey selectivity of chum fry might vary in response to fluctuations in coastal environmental conditions. In order to clarify these relationships, we analyzed the stomach contents composition of chum salmon fry and in situ zooplankton community structure during their coastal residence period using samples collected at the Sanriku coastal area for four years. Our ultimate goal is to clarify the relationship between the nearshore environment of chum fry and the adult return rate, and to subsequently develop a salmon fry release strategy to improve returns of adult salmon.

We collected 1,252 salmon fry over a four-year period (2013–2016) at 12 sampling sites in Yamada Bay (Fig. 1) using a purse seine. At the time that we collected the fry, we also collected zooplankton samples using a surface plankton net (mouth diameter 30 cm, mesh size 0.33 mm). We dissected preserved stomachs to remove their contents and all ingested organisms were counted and identified into 17 different taxa. We measured wet weight for...
each taxon identified to 0.01 mg with an electronic balance. Zooplankton samples were also identified into 17 taxonomic groups, and the total wet weight of each taxonomic group was measured using the same methods we used with stomach contents.

Fig. 2. Yearly comparison in stomach content composition of chum salmon fry (A) and environmental zooplankton community (B) in April and May. Total contents (upper panel) and percentage composition of each taxon group (lower panel) were shown by gravimetric terms.

The mean water temperatures during the study period were low in 2013 and 2014 (8.3 and 6.7°C, respectively), and high in 2015 and 2016 (9.4 and 11.1°C, respectively). In particular, the water temperature was extremely high in 2016 throughout the study period (min; 9.2°C, max; 14.5°C).
Neocalanus plumchrus (copepod) and Themisto japonica (amphipod) are typical cold-water zooplankton that dominated the stomach contents of chum fry, except for 2016 (Fig. 2A); however, these zooplankton were not necessarily the most dominant in the water column (Fig. 2B). In 2016, zooplankton communities in the water column were mostly dominated by cnidarians and decapod larvae, and chum fry preyed primarily on decapod larvae (Fig. 2B). Based on the results of stomach content composition of chum fry and field zooplankton community structure, we calculated Ivlev’s elective values (EV, Ivlev 1961). The EV for Themisto japonica and Neocalanus plumchrus was always positive, suggesting that chum fry selectively preyed upon these cold-water zooplankters (Fig. 3). Decapod larvae were hardly preyed upon during 2013 to 2015; however, they were markedly preyed upon in 2016. Among small copepods, the EV for Acartia spp. and Pseudocalanus spp. were always negative, whereas the EV for harpacticoids was always positive.

Condition factor (K-value), as an indicator of somatic nutritional status for chum fry (Azuma et al. 1998) were higher in cold-water years than those of warm-water years (Fig. 4). Because these two cold-water zooplankton species are typically abundant in the Oyashio Current, the magnitude of Oyashio inflow into the coastal area may affect prey availability for chum salmon fry and their nutritional status.
Table 1. Comparisons of mean water temperature and mean biomass of cold-water zooplankters (Neocalanus plumchrus + Themisto japonica) in the water column of each study period, and adult return rate after three years in the entire coastal area of Iwate Prefecture.

<table>
<thead>
<tr>
<th>Costal retention year</th>
<th>Mean water temp. (°C)</th>
<th>Neocalanus+ Themisto biomass (mg m⁻³)</th>
<th>Adult return rate after 3 years (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>8.3</td>
<td>98.5</td>
<td>0.9</td>
</tr>
<tr>
<td>2014</td>
<td>6.7</td>
<td>606.9</td>
<td>0.6</td>
</tr>
<tr>
<td>2015</td>
<td>9.4</td>
<td>10.7</td>
<td>0.9</td>
</tr>
<tr>
<td>2016</td>
<td>11.1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The adult return rate of chum salmon that spent their fry period during this study varied from 0.6 to 0.9% between 2016 and 2018, with an extremely low value (0.2%) in 2019 (Table 1). Most of the adults returning in 2019 spent their coastal residence period in 2016 when cold water zooplanktons were very low. These results suggest that food availability during the coastal retention period affects the survival rate of salmon fry, and is one of the important factors influencing the return rate of adult salmon. Detailed studies are needed to elucidate the relationship between environmental conditions during the coastal residence periods and the adult return rates.

REFERENCES


Fine-scale Genetic Population Structure of Chum Salmon on the Iwate Coast, Northern Japan

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Keywords: fine-scale genetic population analysis, chum salmon, Iwate coastal rivers

Background and Objectives

Chum salmon (Oncorhynchus keta), with a wide natural range from the Far East to North America and high commercial importance in North Pacific fisheries (Salo 1991), is also an important fishery species in northern Japan. However, the chum salmon catch, or homing number, has been decreasing for nearly two decades on the coast of Iwate Prefecture or the Sanriku-region—the exact reason for such a decrease remains obscure. For effective conservation and management of a species, an accurate description of the genetic population structure is necessary (Spruell et al. 1999) to help provide a clear understanding of what constitutes a population and how population boundaries vary among different watersheds (DeHaan et al. 2014). Two salmon homing peaks are known in Iwate: an early-run from September to the end of October, and late-run from November to February. For conservation and fisheries management of chum salmon in Iwate, the temporal fine-scale genetic population structure was examined using fish collected from the Tsugaruishi River (TGI, predominantly late-run) and Akka River (AKA, predominantly early-run) through the entire homing season.

Materials and Methods

Dorsal fin samples from a total of 2,089 fish (TGI: 10 collections 902 individuals, AKA: 12 collections 1,187 individuals) were collected during the homing seasons, September 2018 to January 2019 (see Fig. 1 for locations). The samples were coded every ten days in each month: 1 to 10 as early (E), 11 to 20 as middle (M), and 21 to the end of the month as late (L). All fin samples were fixed in 85% ethanol and stored at room temperature until DNA extraction. Total genomic DNA was extracted with the Gentra Puregene Tissue Kit (QIAGEN) following the manufacturer’s protocol.

For the genetic analyses, 14 polymorphic microsatellite (ms) DNA loci (Tsukagoshi et al. 2015, partially unpublished) were used. To estimate genetic variability, the number of alleles (Na), allelic richness (Ar), and the expected (He) and observed heterozygosities (Ho) were calculated with the FSTAT (Goudet 2003) and Arlequin ver. 3.5 (Excoffier and Lischer 2010) programs. For genetic population structure, pairwise FST estimate, STRUCTURE, Principal Coordinate Analysis (PCoA), molecular phylogenetic Neighbor-joining (NJ) tree using CSE genetic distances (Cavalli-Sforza and Edwards 1967), and AMOVA were performed using the above Arlequin ver. 3.5,
AMOVA, STRUCTURE 2.3.4 (Pritchard et al. 2000), GenAlex 6.51b2 (Peakall and Smouse 2012), and PHYLIP (Felsenstein 2004) programs.

Results

The mean $N_a$ per collection for TGI and AKA was 14.14 (10L) to 15.42 (11M), and 14.64 (11E) to 15.92 (9E and 9L), respectively, and the value of early-run in AKA was higher than in the late-run (Mann-Whitney U test, $p < 0.01$). The mean $A_r$ per collection for TGI and AKA was found to be from 13.40 (12L) to 15.07 (10E), and 13.60 (11E) to 14.95 (9E), respectively, and the value of early-run in AKA was higher than in the late-run (Mann-Whitney U test, $p < 0.01$). The mean $H_e$ per collection for TGI and AKA was 0.835 (12L) to 0.859 (10E), and 0.834 (11E) to 0.859 (9E and 9M), respectively, and the Mann-Whitney U test between early-run and late-run was not significant in both TGI and AKA ($p > 0.05$). The mean $H_o$ per collection for TGI and AKA was 0.818 (12L) to 0.859 (10E), and 0.824 (12E) to 0.855 (10L), respectively, and the Mann-Whitney U test between early-run and late-run was significant in AKA ($p < 0.05$) but not in TGI ($p > 0.05$). A statistically significant deviation from HWE was not observed in all collections at 14 msDNA loci with Bonferroni corrections ($p > 0.05/14 = 0.00357$).

Pairwise $F_{ST}$ estimates (Table 1) suggested a significant difference between the early-run and late-run in both TGI and AKA, within rivers and also between rivers, after Bonferroni corrections ($p < 0.01$) and AMOVA ($p < 0.001$). In addition, moderate gene flow estimated by pairwise $F_{ST}$ was inferred within the early-run and the late-run groups of TGI and the late-run group of AKA.

![Fig. 2.](image) NJ tree for TGI (a) and AKA (b). Early-run collections in italic.

NJ trees (Fig. 2) also suggested genetic differentiation between early- and late-run with 100% support, and a closer kinship between the neighboring than the distant collections in both early- and late-runs of TGI and AKA. Such differentiation between early- and late-run collections in both rivers was favored by the results of STRUCTURE with $\Delta K$ ($K=2$) and PCoA (not shown).

Conclusions

The present study showed temporal genetic differentiation and structure using 14 msDNA loci in two representative rivers with different homing peaks, TGI and AKA, in Iwate. The obtained findings suggest distinct temporal reproductive isolation between the early- and late-run of chum salmon in both rivers. A moderate gene flow inferred within temporal homing groups in each river may indicate past anthropogenic activity such as artificial transplantation between rivers. The present findings suggest the usefulness of temporal fine-scale analysis through the entire season for unraveling complex salmon homing dynamics. Further studies will provide the basic information for conservation and management for sustainable use of chum salmon resources in Iwate.

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Table 1. The results of $F_{ST}$ analysis (*: $p < 0.05$ after Bonferroni correction). Early-run collections in italic.

<table>
<thead>
<tr>
<th>TG1</th>
<th>TGI</th>
<th>AK1</th>
<th>AKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10E18</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10M18</td>
<td>0.00189</td>
<td>-</td>
<td>-</td>
</tr>
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<td>10L18</td>
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Building Salmon Resilience: Lessons Learned from The Great East Japan Earthquake (GEJE) and Other Ecological Disasters

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Keywords: GEJE, salmon, tsunami, resilience, disaster management, hazard mitigation, genetic diversity

Introduction

Ecological disasters that occur throughout the world can be natural (e.g., earthquakes, tsunamis), anthropogenic (a consequence of human activity e.g., dam breaching, pollution), or sometimes a hybrid (e.g., some landslides). Disaster risk management plans lay out the goals and means to reduce disaster risks, often guided by the Sendai Framework (United Nations Office for Disaster Reduction 2015). Among other things, this Framework identified that national governments have the primary responsibility of reducing disaster risk, but that responsibility should be shared with local governments, the private sector, and other stakeholders.

Ecological disaster literature often focuses on resiliency, first defined by Holling (1973) as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” Climate change and major anthropogenic modifications to salmon ecosystems can compromise the resilience of salmon populations to major disturbances (Waples et al. 2009). The importance of maintaining habitat, ecosystem and genetic heterogeneity to maintain resiliency and hence, conserve salmon populations, is well-documented (e.g., Bottom et al. 2009). Identifying who is responsible for the mitigation of harmful effects of ecological disasters on salmon and how this is best achieved is vitally important.

It has been ten years since the Great East Japan Earthquake (GEJE) and tsunami of 11 March 2011 resulted in horrendous damage to local marine ecosystems of northeast Honshu, Japan. This region of Japan is not unique in experiencing earthquake generated tsunamis that cause catastrophic damage. In the six years preceding the GEJE, the 2005 Sumatra, 2006 Java, 2009 Samoa, 2010 Chile and 2010 Mentawai tsunamis each caused significant damage (Kontar et al. 2014). Not surprisingly, the overriding response to protect human lives often results in inadequate consideration of the environment, although increasingly balanced approaches to protect and restore coastal ecosystems are becoming more common (Santiago-Fandiño et al. 2014).

The decade long multi-disciplinary GEJE Tohoku Ecosystem-Associated Marine Science (TEAMS) project, established soon after the GEJE, was completed earlier in 2021. TEAMS sponsored numerous scientific events, created a website (http://www.jamstec.go.jp/i-teams/e/index.html) and database, and supported the publication of > 120 documents, including findings relevant to salmon, some of which are described in other papers in this session.

We suggest that application of lessons learned from Japan’s response to the GEJE, augmented by knowledge gained elsewhere, can mitigate future large-scale ecological disturbance effects on this and other coastal ecosystems supporting salmon. Our objective is to describe strategies (lessons learned) that can be used to build resilience within coastal salmonid ecosystems in order to facilitate recovery from ecological disasters, especially those pertaining to tsunami effects on the coastal ecosystem and anadromous salmon. We define resilience as the ability of the aquatic ecosystem to recover from major environmental disturbances.

Building Resilience

Many ecological disasters are foreseeable, although rarely does one know when such an event will happen. Japan, because it lies across several tectonic plates, is earthquake prone. The GEJE was the largest disaster in this region, but not the first, nor the last. The maximum height for the 2011 tsunami was 40.1 m; earlier major earthquake generated tsunamis occurred in 1611 (20 m), 1896 (38.2 m), 1933 (28.7 m), and 1960 (28.7 m). Building resilience is extremely challenging when the timing and scale of the next event are unknown.

Major hazard planning processes have a Planning phase intended to precede a major ecological event that is followed by Immediate Response, Longer Term Recovery and Mitigation phases (Fig. 1). These steps are iterative and repeating because natural disasters repeat themselves.

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We describe these phases to build resilience within coastal salmonid and other ecosystems subjected to major ecological disturbances such as an earthquake-generated tsunami:

1. Planning (Build Resilience)
   During the Planning phase, a hazard mitigation plan is developed with the primary goal of minimizing disaster impacts (e.g., https://www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf; p. 55). The plan should identify risks and vulnerabilities in the region of focus (e.g., the Sanriku region of Northeast Honshu). After identifying these risks, long-term strategies are developed to protect people, natural resources (e.g., salmon), and property from similar events:
   a. Map ecologically sensitive areas vulnerable to future inundation
   b. Manage salmon facilities (e.g., net pens, hatcheries) within the inundation zone
      i. Encourage tsunami resistant designs for existing facilities
      ii. Limit new developments within the flood zone and consider relocating existing facilities above the maximum historical inundation level
   c. Improve public and stakeholder awareness
   d. Identify and understand inter-sectoral roles and responsibilities that will include broad participation (local government, public, stakeholders, and knowledgeable experts)
   e. Identify effective communication approaches including how to get information to decision-makers quickly immediately following a disaster
   f. Identify actions to be carried out during the recovery and mitigation phases, which are intended to reduce environmental and economic losses. These might include:
      i. rebuilding or constructing appropriate physical structures (levees, dikes) with large setbacks,
      ii. rebuilding or constructing suitable enhancement facilities outside the potential impact zone, and
      iii. developing realistic plans to restore and maintain habitat and ecosystem diversity and connectivity, necessary for the replenishment and maintenance of genetic and phenotypic diversity. With respect to the GEJE, this would likely include creating and maintaining suitable habitat for natural salmon spawning upstream of the 2011 tsunami impact zone and ensuring these areas are adequately seeded by mature salmon in future years.

2. Immediate post-disaster response
   Because of the often enormous scale of damage caused by major ecological disasters, the immediate response understandably focuses on human health and safety. Regardless of the specific focus of the response, it is necessary to:
   a. Establish effective communication
   b. Inventory the spatial scale and scope of the damage
   c. Develop initial recovery goals with a timeline

3. Longer-term recovery and mitigation
   Depending on the magnitude of the event, this can take many years. During this period, it will be necessary to:
   a. Maintain effective communication among participants
   b. Reach consensus on roles and responsibilities
   c. Carry out a thorough assessment of damage and update recovery goals and timelines
d. Review and update as necessary strategies identified in the hazard mitigation plan

e. Decide on action steps, secure funding, and implement activities for the restoration and adaptive management of habitat, ecosystems and facilities undertaken, many of which should have been identified during the preparedness phase.

The GEJE Case Study

TEAMS had a broad mandate that included, “restoration of fishery grounds and marine resources necessary through reconstruction of seedling production systems for salmon and trout…” (http://www.jamstec.go.jp/i-teams/e/index.html). A multi-disciplinary team was established soon after the GEJE that included ~200 marine researchers. Work on several project areas was initiated (ecological succession in coastal fisheries, factors controlling coastal and open ocean ecosystem processes, data sharing, publication, and outreach) and five task groups were established. TEAMS sponsored numerous scientific events (including this third NPAFC-IYS workshop), created a website and database, and supported the publication of > 120 publications as well as many posters and presentations.

As a result of TEAMS, relationships among government agencies and academic institutions, and regulations and policies pertaining to disaster management were strengthened.

Recovery and mitigation phase activities included: (1) construction of a 400 km seawall, (2) development of coastal dikes, (3) reconstruction of destroyed salmon hatcheries, and (4) tidal gates. However, the ecological effects of some approaches designed to protect people remain uncertain.

Long-term effects of the GEJE are still being revealed but early indications are that the marine ecosystem is being re-established, some local fisheries are rebuilding, and more natural chum salmon spawning than expected is occurring. Nevertheless, the rebuilding of local chum salmon populations is proving difficult. Recent survivals of chum salmon in other areas of Japan have also been poor; research is needed to disentangle the effects of GEJE from those affecting all Japanese chum salmon.

TEAMS researchers worked hard to better understand ecological effects from the GEJE. Time will tell whether the resiliency of the salmon and other aquatic resources have been restored. We encourage government agencies, academic researchers, and others to focus on updating and revising their hazard mitigation plans before the next inevitable disaster hits. To build resilience, plans should include restoring and maintaining habitat and ecosystem diversity and connectivity, necessary for the replenishment and maintenance of genetic and phenotypic diversity.

Summary

Lessons learned from Japan’s response to the GEJE were augmented by relevant knowledge gained elsewhere. We described strategies to facilitate ecosystem recovery resulting from ecological disasters, especially those pertaining to tsunami effects on the coastal ecosystem and anadromous salmon. To prepare for natural disasters that tend to repeat themselves, a disaster management cycle that includes hazard mitigation plans should include: (1) a good understanding of inter-sectoral roles and responsibilities, (2) broad participation (public, stakeholders, and knowledgeable experts), (3) effective communication approaches, (4) appropriate physical structures (levees, dikes) with large setbacks, (5) suitable enhancement facilities outside the potential impact zone, and (6) realistic plans for restoring and maintaining habitat and ecosystem diversity and connectivity, necessary for the replenishment and maintenance of genetic and phenotypic diversity. After a disaster, there should be an immediate post-disaster response phase where the spatial extent of damage is determined as well as recovery goals with a timeline. Strategies identified in the preparedness phase need to be updated as necessary and implemented during longer-term recovery and mitigation phases before the cycle repeats itself with the preparation of the next hazard mitigation plan.

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Legacies of the Tohoku Earthquake and Tsunami Impacting the
Northern California Current in the Eastern North Pacific Ocean

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Keywords: marine debris, invasive marine species, Northeast Pacific Ocean, radioecology, radiocesium in marine foodwebs

On 11 March 2011, a devastating 9.0 magnitude earthquake struck off the coast of eastern Japan and a 38.38 m tsunami followed, inundating the west coast of Japan. In addition to the tragic toll on human life and devastating destruction of property and infrastructure, an estimated 1.5 million metric tonnes of natural and man-made debris were carried into the coastal ecosystem off Japan. Possibly 30% of this debris mass floated away into the North Pacific. Many items of this floating Japanese Tsunami Marine Debris (JTMD) crossed the North Pacific and landed on North American shores. The JTMD ranged in size from small particles to whole docks and carried substantial numbers of living marine organisms (invertebrates, algae, cyanobacteria, and fish) that had the potential for establishing on the North American coast. The fate of the debris and associated fauna and flora has been followed since 2011 and a summary of our findings is reported below.

An international collaboration of scientists examined > 600 JTMD items that landed in North America and the Hawaiian Archipelago and identified nearly 300 taxa that traveled across the Pacific Ocean on these rafts, which were primarily anthropogenic in origin and included docks, buoys, and vessels (Carlton et al. 2017). More than 50% of these taxa had not been previously observed in the landing regions and could present an invasion risk. For example, the mussel Mytilus galloprovincialis, which is a species from the Mediterranean that previously invaded Japan, was present on > 50% of the tsunami debris items. The size, reproduction, and growth of this filter-feeder was quantified to improve our understanding of long-distance rafting of this coastal species (Miller et al. 2018a). The majority of mussels (79%) had developing or mature gametes upon arrival in North America and displayed relatively high average growth rates (0.075 ± 0.018 SE mm/day). Information on the environmental and life history traits for many of the species that survived the transoceanic crossing was collated to examine trait variation in those transported species with and without prior invasion history to determine if there were shared characteristics, or an “invader profile,” that could contribute to risk analysis efforts (Miller et al. 2018b). Species with known invasion histories were more common in fouling and flotsam habitats, on artificial and hardpan substrates, in temperate reef systems, and at subtropical and tropical temperatures, and also displayed higher salinity tolerance than species with no prior invasion history. Among the most remarkable examples of transport were the multiple occurrences of a fish species, the barred knifejaw, Oplegnathus fasciatus, which were found alive in at least two ship hulls and in the wild at locations from Washington to California (Ta et al. 2018). These studies shed light on how so many species and individuals survived such a long-distance (> 5,000 km) and long-term (> four year) oceanic transit and contributed to our understanding of debris as an ocean transport vector for invasive species.

More than 80 species of marine algae were identified on 42 of the larger JTMD that came ashore in Washington and Oregon (Hansen et al. 2018). Molecular sequencing was used to confirm the algal checklist. Of these species, 85% were found to be fertile and actively releasing spores or gametes. A large portion of these were ephemeral or opportunistic species capable of reproducing multiple times in a single year and of quickly colonizing new habitats. These life history features appeared to be important in ensuring the survival of the species while at sea and were reflected in the global distribution of the species: 63% were globally widespread ephemeral and/or opportunistic species, 6% were restricted to only the NE and NW Pacific, 15% were endemic to Asia, and 16% were Asian species that have been exported globally by human activities (Hansen et al. 2019). The latter group included three species thought to be the most highly invasive algal species in Europe: Undaria pinnatifida, Codium fragile subsp. fragile, and Grateloupia turuturu.

Although the risk of colonization of Pacific North American shores by the algae seemed high, 61% of the JTMD algal species were found to already occur along the coast (Washington to Mexico) before the tsunami, including eight recently introduced Asian species. However, even for these, a genetic risk was present since the
JTMD and American populations were slightly different haplotypes. Although 80% of the fouled debris from the tsunami landed on Oregon and Washington shores, the prompt and nearly complete removal of the debris appears to have been effective in ameliorating most of the invasion risk (Hansen et al. 2019). To date, no new colonization by the debris algal species has been discovered in this area.

Systematic sampling (> 1,000 collections) of anthropogenic marine debris from the 12.5 km length Leadbetter Beach, Washington, between 15 June 2012 and March 2021 (Russ Lewis, Ocean Park, WA, unpublished data) yielded 68.6 metric tonnes of marine debris for an average of 1.7 kg/km/day. The fractions of JTMD were distinguished from other debris on several of these collections (Fig. 1). Possibly 24% but no more than 43% of all debris objects were JTMD. The decline of JTMD relative to all other debris between May 2015 and March 2021 was no less than 4.2% per month and more likely 6.4% per month or greater. Extrapolation of JTMD landings on Leadbetter Beach to the North American coast (Dutch Harbor Alaska to southern Oregon), where nearly all JTMD has been observed, indicates that no more than 0.8%, and more likely around 0.4% of the estimated initial JTMD mass had arrived by 2021, for a total estimated 32,946 metric tonnes. The dramatic 2012–2016 pulses of marine debris were primarily of non-JTMD objects and were more likely due to altered wind and ocean circulation patterns than to the overall quantities of floating debris in the North Pacific. Non-JTMD is the source of most debris on North American shores and, except possibly for the winter of 2013, most trash landing on North American beaches originated from North America. Although these debris continue to arrive (two JTMD boats washed up in Oregon and Washington in March 2021), no surviving reproductive JTMD species have been found in North America and nearly all debris landings since 2013 have been from other sources than JTMD.

A secondary effect of the earthquake was the explosions of nuclear reactors at the Fukushima Dai-ichi nuclear power plant which interjected enormous concentrations of radionuclides into the atmosphere and nearby ocean many orders of magnitude above pre-existing conditions. Surveys in the region off Japan have recorded elevated levels of harmful radionuclides in the water and biota in the month following the accident, and up to 600 km offshore of the release site (Buesseler et al. 2012). Since the time of the release, most of the radionuclides have either decayed away due to short half-lives or were present in small quantities to begin with. Two of these, $^{134}$Cs and $^{137}$Cs, remain at detectable levels in contaminated regions of the Pacific (Kaeriyama et al. 2014). Although some radionuclides can reach across the Pacific Ocean through atmospheric deposition and oceanic transport, another likely vector of trans-Pacific transport are fish and other organisms that make long-distance migrations during their lifetimes (Madigan et al. 2012). Sampling off Oregon in the years after the accident documented $^{137}$Cs in albacore which migrate across the Pacific from spawning grounds off Japan and most likely carried radioactivity with them (Neville et al. 2014).
Fig. 2. Concentrations of \(^{137}\text{Cs}\) (milli-Becquerels per kilogram wet weight) in pelagic taxa collected off the coast of Oregon and Washington from 2013–2015. Levels from multiple samples for individual albacore were from the muscle tissue only whereas all other measurements were on whole animals. Values with orange bars were below the Minimum Detectable Activity (MDA) levels for the spectrometer.

Table 1. Summary of \(^{137}\text{Cs}\) concentrations (milli-Becquerels per kilogram wet weight) found in selected nekton and macrozooplankton from collections off Oregon and Washington. Uncertainties in count rates, mass, geometry-altered efficiency, and chemical yield (using the IAEA-414 standards) were propagated for the presented error bars.

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<td>Salmon shark</td>
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<td>Pacific albacore</td>
<td><em>Thunnus alalunga</em></td>
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<td>Pacific herring</td>
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<td>Surf smelt</td>
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<td>84</td>
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<td>Pacific sardine</td>
<td><em>Sardinops sagax</em></td>
<td>38</td>
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<tr>
<td>Fried egg jelly</td>
<td><em>Phacellophora camtschatica</em></td>
<td>14</td>
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<td>Pacific sea nettle</td>
<td><em>Chrysaora fusceccens</em></td>
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In the years since the Fukushima release, water and biological samples have been collected from various cruises along the US West Coast for the analysis of radioactivity levels. Macroplankton and fishes were sampled primarily with surface or midwater trawls along much of the Oregon and Washington coasts over multiple years. Samples were dried to a constant weight at 100°C, then ash-dried at 450°C. Each sample, packed into a plastic jar with known counting efficiency, was counted for 24 h on a high-purity Germanium \(\gamma\) spectrometer with a relative efficiency of 70%. Methods were certified using IAEA-414 freeze-dried fish tissue standards. A total of 28 taxa ranging from gelatinous zooplankton to micronektonic shrimp, squid and fishes, and several large pelagic fishes and elasmobranchs were analyzed. Results from select taxa show low levels for the gelatinous taxa, intermediate levels for forage fishes, and high levels for highly migratory top predators, and apparently show a bioaccumulation with increasing trophic level (Table 1). In general, all individuals of albacore examined had higher levels than the non-elasmobranch nekton (Fig. 2), but all the levels were on the order of milli-Becquerels per kilogram wet weight. Similar analyses on salmon and several groundfish species off the West Coast of Canada showed barely detectable concentrations of \(^{134}\text{Cs}\) and \(^{137}\text{Cs}\) (Chen et al. 2015). All these levels are well below the minimum safety levels for seafood set by the US Food and Drug Administration and the dose exposures to humans are lower than many natural or other human sources of radioisotopes (Fisher et al. 2013). Therefore, it is highly unlikely there would have been any ecological effect or food safety concerns from the radioactivity in the samples we examined.

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The Challenge of Reconstruction Faced by the Domestic Salmon Industry after the Great East Japan Earthquake and Tsunami in 2011

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Keywords: Great East Japan Earthquake, domestic chum salmon, Sanriku region, tsunami, seafood processing firms, recovery speed

Rich fishery resources have economically supported many industries in the Sanriku coastal areas of the Tohoku region. The main fishery resources were chum salmon, saury, bonito, sea urchin, scallop, oyster, and wakame seaweed. Domestic chum salmon and farmed coho salmon were the most relevant fisheries products in Sanriku. A salmon industry cluster was formed in Hokkaido and Tohoku regions by hatchery enhancement, a set net fishery, seafood processing and distribution of domestic chum salmon (Fig. 1). However, that industry was closed down by the gigantic earthquake and subsequent tsunami that struck in northeastern Japan on 11 March 2011 (Shimizu et al. 2012).

Salmon hatcheries, seafood firms, fishing boats, fishing gears, houses and citizens in coastal communities were wiped off the map in the Pacific Ocean facing Tohoku region by the destructive power of the tsunami (Shimizu 2012). The total damage amounted to 300 billion dollars (Fisheries Agency of Japan 2012). Twenty thousand people were reported missing or dead. Three hundred and twenty-three seafood processing companies were destroyed (of 439) in Miyagi Prefecture and 59 of 178 were destroyed in Iwate Prefecture. A cluster of

Fig. 1. A cluster of chum salmon industry in Hokkaido and Tohoku regions. The salmon industry is formed by a cluster of enhancement, fishery, processing and distribution of chum salmon. Salmon hatcheries are mainly funded by the tax for enhancement from set net fisheries in Hokkaido region, and by the tax for enhancement and government funds in the Tohoku region. The global market of Japanese domestic salmon has recently reduced because salmon export from Japan to China has decreased due to the reduction of domestic salmon return.

Fig. 2. Seafood processing firms which grounds were inundated by the tsunami in Kesennuma, Miyagi Prefecture. This photo was taken by I. Shimizu in October 2011.

Fig. 3. Seafood processing complex destroyed by tsunami in Ohfunato, Iwate Prefecture. This photo was taken by I. Shimizu in October 2011.
enhancement, fishery, processing and distribution of domestic chum salmon was destroyed by the tsunami (Fig. 2).

The grounds of seafood processing firms were inundated by the earthquake and tsunami (Fig. 3). However, the salmon industry immediately began to rebuild after the major disaster struck the coastal area (Shimizu 2013).

For example, container freezers were prepared to encourage fish landing on fishing ports (Fig. 4) and chum salmon caught by the set net fishery was landed to fish markets in Miyagi and Iwate Prefectures. Salmon that returned to their original rivers were under maturing in each hatchery and salmon processing companies were reconstructed in their relative periods in Miyagi Prefecture. Aramaki-sake, matured-salted salmon, were processed by seafood companies in Iwate Prefecture (Fig. 5).

However, there were different conditions in recovery speed in the process of reconstruction after the salmon industry was closed down. Some seafood firms and several processing communities could rebuild rapidly, but on the other hand, some needed a lot of time for recovery (Shimizu 2011). What factors made the difference in recovery speed of seafood processing firms? Our objective was to clarify the causes of the different recovery speeds of seafood processing complexes and individual seafood companies. We conducted research in the affected area by the earthquake and tsunami in the Sanriku region (Fig. 6). We were studying the process of reconstruction with interviews between October 2011 and December 2014. The factors that affected recovery speed were analyzed.
based on a total of 74 results of interviews with the salmon industry. The characteristics of the factors were
categorized into slow speed recovery and fast speedy recovery.

The causes of slow speed recovery of seafood processing firms were as follows: (1) the scale of subsidence
was greater than the initial estimate and the flooded area by the tsunami was larger; (2) the size of the processing
complex was larger before the disaster struck; (3) there was a necessary delay for preparing a master plan to rebuild
a whole destroyed area; and (4) it was necessary to form a bottom-up type consensus among the participants for
reconstruction. A bottom-up consensus needed a lot of time to agree on several points for reconstruction.

On the other hand, the causes of fast speed recovery of seafood processing firms were as follows: (1)
employers were not victims themselves and were highly motivated to rebuild their business; (2) recovery plans were
launched immediately after the disaster struck to coincide with the salmon fishery season start; (3) information using
emergency government funds was gathered quickly after the disaster; (4) a lot of support was forthcoming from
business dealings, relations, groups, and buyers, or consumers; (5) the loss of raw materials and products inventory
were avoided by diversification of management risk. Raw materials for processing were able to avoid washing
away by the tsunami because the materials were stocked at height in storage areas; and (6) seafood companies were
reconstructed speedily by top-down leadership. Necessary returns of salmon resources were especially one of the
biggest motivations of reconstruction for the salmon industry.

Annual salmon harvest had been 25,000 metric tonnes level until the tsunami in the Sanriku region. We
estimated salmon processing capacity due to the results of interviews with seafood processing firms. The salmon
processing capacity has been restored to a level of 19,000 metric tonnes by the reconstruction of seafood firms. We
are concerned about the slow recovery of the lost share of Tohoku products in the Japanese seafood markets after the
disaster (Criddle and Shimizu 2014). However, the share of Sanriku seafood products has improved in the domestic
market in Japan. The seafood industry in the Sanriku region continues to develop a new domestic market for the
own future. However, salmon fishery production has decreased to 12,000 metric tonnes level since 2011 in Sanriku
region (Ogawa 2014). The shortage of raw materials caused by the reconstruction of processing capacity concerns
seafood processing firms. They need raw salmon materials proportionate to the increased processing capacity.
Therefore, new projects of salmon aquaculture and land-based farms have started in several areas in the Sanriku
region. We hope for an innovative new fishery complex in the reconstructed Sanriku region.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Slow speed recovery</th>
<th>Fast speed recovery</th>
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<tbody>
<tr>
<td>Scale of flooded area by tsunami</td>
<td>Larger</td>
<td>Not victims</td>
</tr>
<tr>
<td>Size of processing complex</td>
<td>Greater</td>
<td></td>
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<tr>
<td>Diversification of risk</td>
<td></td>
<td>Avoidance of the loss of materials</td>
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<td>A master plan to rebuild a whole area</td>
<td>Necessary delay for preparing</td>
<td>Conducted quickly by emergency funds</td>
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<td>Presence of support</td>
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<td>Motivation for reconstruction</td>
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<td>Consensus among the participants</td>
<td>Bottom-up form</td>
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In summary, the difference in recovery speed of salmon processing firms was clarified in Table 1. The factors
of difference were flooded area by the tsunami, size of processing complex, diversification of risk, a master plan to
rebuild whole area, presence of support, motivation for reconstruction, and consensus among the participants. First,
the main causes of slow speed recovery were as follows: flooded area by the tsunami was larger, size of processing
complex was greater, necessary delay for preparing a master plan, necessary to form a bottom-up consensus among
the participants. Second, the main causes of fast speed recovery were as follows: they were not victims of the
tsunami, diversification of risk was avoidance of material loss, a master plan was conducted quickly by emergency
funds, support was forthcoming from business groups, motivation for reconstruction was salmon return certainty in
autumn, a consensus was formed by top-down leadership.

The root cause of fast speed recovery of seafood processing firms was the motivation by expected salmon
returns in the autumn season. The contribution of certain salmon returns every autumn increased the motivation for
the reconstruction of seafood processing firms. They decided to reconstruct their salmon processing firms by
predicting the chum salmon fishery season. Chum salmon is not just ecologically, but socio-economically one of the
most precious resources reproducing in a natural environment.
REFERENCES


Farmed Non-native Coho Salmon in Sanriku Region Affected by Recent Intense Natural Disasters

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Keywords: escaped farmed salmon, Oncorhynchus kisutch, masu salmon, hybridization

Coho salmon farming is an economically important activity in the Sanriku region, which has recently experienced unprecedented natural disasters, including the Great East Japan Earthquake (GEJE), and the direct impacts of large typhoons. Each of these events was associated with a large number of farmed coho salmon escaping from hatcheries or net pens. As a result, there is considerable concern about the impact of these escapes on the ecosystem, especially on native masu salmon which occupy a similar ecological niche to coho salmon. Furthermore, coho salmon can hybridize with masu salmon (Ito et al. 2006), and hybridization is widely considered to have deleterious effects on native salmonid populations (Allendorf et al. 2001; Muhlfeld et al. 2009).

At the time of the GEJE in March 2011, five million farmed adult (1 yr+) coho salmon escaped into the ocean off the Sanriku coast, and in the fall of the same year, they migrated up several rivers in the region (Fig. 1). In addition to the presence of mature individuals among the returning coho salmon, spawning behavior was also observed. We, therefore, conducted a survey and performed genetic analyses to test for the presence of hybrids among sea-run masu salmon caught along the coast. The results revealed that there was no evidence of hybridization and that there has been no decrease in the number of masu salmon along the Sanriku coast since the GEJE.

Fig. 1. Two farmed adult coho salmon (top) and a chum salmon (larger fish at bottom) that had migrated upstream in rivers of the Sanriku region in October 2011.

Fig. 2. Farmed juvenile coho salmon that escaped into a natural river in Japan.
In August 2016, due to flooding caused by a typhoon, 500 thousand farmed juvenile (0 yr+) coho salmon escaped into a river in the Sanriku region (Fig. 2). A monitoring survey of population density in the river revealed that the number of coho salmon decreased over time. Since smolts were observed, one of the reasons for the decrease appeared to be due to seaward migration, but no individuals have returned to spawn in the river. Therefore, escaped coho salmon may be unable to establish viable populations in the Sanriku region.

These findings imply that the genetic impact of coho salmon on masu salmon population may not be serious. However, the impact of the escaped coho salmon on the ecosystem is still unclear. Non-native salmonids can change the population and community structure of native species, including salmonids, not only through hybridization but also through predation and interspecific competition. In the Sanriku region, Age-2 coho salmon that have managed to escape from net-pens are caught every year, and escapement from fish farms into rivers also frequently occurs. It has been reported that continued introduction increases the likelihood of establishment (Fausch 2007). Given that the quantities of farmed salmon will increase in the future, we need to be aware of two things. First, in ordinary times, advances in techniques for preventing farmed salmon from escaping are necessary. Second, as a pre-emptive measure for mitigating against the risk of a large-scale disaster, a monitoring system for assessing the impact of escapement on the natural environment should be developed.

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Radioactive Cesium in the North Pacific after the Fukushima Dai-ichi Nuclear Power Plant Accident

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Keywords: radioactive cesium, Fukushima Dai-ichi Nuclear Power Plant accident, surface dispersion, mode water

The Great East Japan Earthquake and consequent giant tsunami on 11 March 2011 resulted in serious damage to the Fukushima Dai-ichi Nuclear Power Plant (FNPP). Radioactive cesium ($^{134}$Cs and $^{137}$Cs) was then released into the ocean through atmospheric deposition and as direct releases. As is a concern for the fisheries community, the contamination level of fisheries products is the most important issue. The monitoring of the concentration of radioactive materials (mostly radioactive cesium and iodine) in fisheries products started immediately after the accident. The standard limit, 100 Bq kg$^{-1}$ for the sum of radioactive cesium ($^{134}$Cs + $^{137}$Cs), was set as the safe limit for food (https://www.mhlw.go.jp/english/topics/2011eq/dl/new_standard.pdf). This standard limit ensures that the lifetime effect of radioactive materials in fish is sufficiently low as to be safe even when a person continues to eat the fish—one milli-sievert or less per year. The monitoring results of radioactive cesium for fisheries products are published on the Fisheries Agency Japan website (https://www.jfa.maff.go.jp/e/inspection/index.html). Soon after the accident, ~40% of tested samples exceeded the standard limit. After that, the concentrations of radioactive cesium in fisheries products decreased rapidly, and very limited samples (< 10%) have exceeded the standard limit since FY2012. More recently, only 0.01% of inspected samples recorded more than 100 Bq kg$^{-1}$ during FY2019 and FY2020. Such a rapid decrease of radioactive cesium in marine organisms is reflected by the presence of radioactive cesium in the environment they inhabit, such as seawater and seabed sediment. Generally, cesium is a conservative element and mostly occurs in the dissolved phase in the marine environment. The distribution of radioactive cesium as a dissolved phase is fundamentally important to assess how the FNPP accident affects the oceanic environment.

![Fig. 1. Spatial distribution of $^{137}$Cs in surface seawater in the western and central North Pacific in June 2011. Closed circles indicate the sampling stations. The color of the closed circles indicates the concentration of $^{137}$Cs in the surface seawater. Gray arrows indicate the estimated velocity vectors from SSH data.](image)

To understand the entire context of the impact of the FNPP accident on the ocean, the total amount of release and dispersion pattern of radioactive cesium is important. Based on the field data and simulation models, the total amount of radioactive cesium released into the ocean was already estimated (c.f. Aoyama et al. 2016). Atmospheric deposition is the largest source of radioactive cesium from the FNPP. The total deposition of $^{137}$Cs was estimated as 12–15 PBq (PBq = 10$^{15}$Bq) onto the surface seawater in the North Pacific via atmospheric deposition (Aoyama et al. 2016), and 3.5 PBq was directly released as heavily contaminated water between March and April 2011 (Tsumune et al. 2012). The direct observation of radioactive cesium in the seawater had been conducted widely in the North Pacific. The spatial and temporal changes of radioactive cesium in the surface seawater in the North Pacific and
adjacent seas such as the Japan Sea, East China Sea, and the Bering Sea are also well documented (c.f. Kaeriyama et al. 2015). In summary, the Fukushima-derived radioactive cesium rapidly spread eastward in the northern part of the Kuroshio Extension in the North Pacific (Fig. 1; Kaeriyama et al. 2013; Kaeriyama 2017) and reached the western coast of the US and Canada in 2014 (Smith et al. 2014). The Fukushima-derived radioactive cesium was also found in subsurface water in the subtropical region in the western North Pacific, which intruded into the ocean interior as subtropical mode water during the first two years (Kaeriyama et al. 2014). A total of 15.5–18.5 PBq of Fukushima derived $^{137}$Cs exists in the North Pacific, half still exists in surface water (Inomata et al. 2018), and the rest have already been transported into the ocean interior as mode waters (Kaeriyama et al. 2016; Inomata et al. 2018) (Fig. 2).

Fig. 2. Mass balance of the Fukushima-derived $^{137}$Cs in North Pacific after 2012. STMW: subtropical mode water, CMW: central mode water.

In the near coastal area off FNPP, the concentration of radioactive cesium had been considerably elevated soon after the accident (Fig. 3). The concentration of radioactive cesium had rapidly decreased during half of the year in 2011 and slow but clear decreasing trends continued until 2015 (Kaeriyama 2017). Weekly monitoring of radioactive cesium in the coastal water off Onahama, about 35 km south of FNPP, revealed a continuous decrease of $^{137}$Cs from May 2012 to January 2020 with an effective half-life of 2.4 years.

Fig. 3. (a) The coastal monitoring locations for radioactive cesium near the FNPP site and (b) temporal change in $^{137}$Cs concentration in seawater. Modified from Kaeriyama (2017).

Since the FNPP accident 10 years ago, the dispersion patterns and spatiotemporal changes in radioactive cesium in the North Pacific have been well monitored, fisheries products are well monitored, and inspection results are published on the web. The rumor that fisheries in the Fukushima prefectures are still struggling is without scientific facts. To overcome reputational damage, the continuous monitoring of radionuclides is essential and scientific findings should be published widely in the future.
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Resilience for Salmon and People—Lessons learned from the Great East Japan Earthquake in 2011: Summary and Discussion

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Keywords: ecosystem service, disaster risk management, ecosystem resilience

Since ancient times, people on the Sanriku Coast (Pacific coast of northern Honshu) have frequently experienced tragedies caused by earthquakes and tsunamis: the Jogan-Sanriku in 869, the Keicho-Sanriku in 1611, the Enhou in 1677, the Hoei in 1707, the Kansei in 1793, the Ansei-Tokai in 1854, the Meiji-Sanriku in 1896, the Showa-Sanriku in 1933, and the Chile Earthquake in 1960 (e.g., Yoshimura 1984; COGJ 2005; ERIUT 2011). They have known the most fear of tsunamis in Japan and have developed empirically excellent risk management strategies for tsunamis. Nevertheless, an unexpectedly large tsunami struck people within 30 minutes of the Great East Japan Earthquake (GEJE; Magnitude 9.0) on 11 March 2011, leaving approximately 18.5 thousand people killed or missing.

In the face of productive but threatening nature, the Japanese people have cultivated wisdom and views of adaptation and symbiosis, with a reverent view towards nature. After World War II, rapid economic and population growth progressed land development and urbanization, greatly damaging the biodiversity in terrestrial and aquatic ecosystems. In addition, people lived on lands vulnerable to natural disasters. Based on the experience of the GEJE, we are progressing to construct a regional community and to recover the ecosystem, on the premises that “human life is first” and that there is “no upper limit to disasters.” In the future, extreme meteorological phenomena and large earthquakes are predicted under a changing climate. So, it is necessary to consider disaster prevention on the premise of unexpected natural phenomena.

Fig. 1. Linkages between ecosystem services and human well-being for establishing the ecosystem-based disaster risk reduction (modified MEA 2005).

Our lives are supported by ecosystem services, which are provided by biodiversity-based ecosystems (Fig. 1). The strength of linkages between categories of ecosystem services and components of human well-being are commonly encountered, including indications of the extent to which it is possible for socioeconomic factors to mediate the linkage (MEA 2005). In order to ensure safe and productive lives, we should rebuild the interaction between people and nature, and establish the Ecosystem-based Disaster Risk Reduction (Eco-DRR). The Eco-DRR actively utilizes the disaster prevention and mitigation functions of a healthy ecosystem to propose disaster risks.
such as green infrastructure. The disaster risk consists of functions as a hazard, exposure, and vulnerability (ADRC 2005). To diminish the disaster risk, it is important to reduce the level of vulnerability and to keep exposure as far away from hazards as possible by relocating populations and property. The reduction of vulnerability can be achieved through such measures as mitigation and preparedness (Fig. 2).

![Disaster risk management (ADRC 2005)](image)

In the last decade, we have achieved material reconstruction (Grey Project) in Sanriku. However, depopulation has not been resolved, and the economy and industries have not fully recovered. People have deep trauma caused by the GEJE. Masayuki Komatsu (The Tokyo Foundation for Policy Research, personal communication) argues that “final disaster reconstruction should be from the Grey Project to Green Project.” As the next step, therefore, we need to transform from the Grey Project to the "Green Ecosystem Project," which will conduce to human welfare with high biodiversity and rich ecosystem services (Fig. 3).

![Final disaster reconstruction from the Grey Project (B) to the Green Ecosystem Project (C) in Takada City, Sanriku. A: The tsunami destroyed Matsubara Natural Park and town in Takada City on 11 March 2011.](image)
Chum salmon on the Sanriku coast are facing not only disasters caused by the earthquake and tsunami, but also the warming climate. In a changing climate, we need to launch the “Sustainable conservation management for chum salmon,” based on the “back-casting approach.” This management should include several goals based on sufficient analyses of the current situation, and steps toward the goals with adaptive management and the precautionary principle (Kaeriyama et al. 2021). The goals for the sustainable management of chum salmon are:

1. Conservation and utilization of wild and hatchery salmon
   - Recovery and conservation of salmon
   - Innovation for sustainable salmon production and fisheries
   - Coexistence of wild and hatchery populations

2. Long-term research and monitoring for interaction between aquatic ecosystems and salmon
   - Climate change (e.g., global warming, regime-shift), and freshwater and ocean ecosystems
   - Change in aquatic ecosystems affecting the life history and population dynamics of salmon

3. Restoration and resilience for salmon and river ecosystems
   - Restoration for impoverished river ecosystems
   - Rebuilding and sustaining resilience of salmon

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