PROJECT ABSTRACT

Title: Conservation of native fish communities in tributaries to the Great Lakes: Predicting the impacts of contaminants delivered by spawning Pacific Salmon

Abstract body: Our project determined the most important factors for contaminant transfer from migratory Pacific Salmon (*Oncorhynchus* spp.) to stream-resident fish in upper Great Lakes tributaries. Pacific Salmon are considered an important sport fish in the Great Lakes fishery while the Great Lakes are replete with contaminants, especially persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs), and heavy metals, such as mercury. Moreover, the process of contaminant *biotransport*, although widely recognized, is less well understood than contaminant *bioaccumulation*, especially for individual fish species and different pollutants. More specifically, we wanted to identify what aspects of the environmental context (i.e., the physical, chemical, and biological characteristics of tributaries where salmon spawn) influence transfer of POPs and mercury, as has already been shown for nutrients delivered by salmon during their spawning migrations. Several approaches were used in the project that balanced realism and rigor and occurred at different scales. First, a broad survey of streams throughout the state of Michigan where fish were sampled for contaminant analyses while a suite of biological, physical, and chemical parameters were measured. Multivariate statistical approaches, including generalized linear mixed models, permutational multivariate analysis of variance, and non-metric multi-dimensional scaling, were used to identify which covariates explained the extent of contaminant transfer from salmon, the putative source, to stream-resident fish, including game fish, such as Brook Trout (*Salvelinus fontinalis*), and non-game fish, such as Mottled Sculpin (*Cottus bairdi*). Second, experiments, including a whole-stream manipulation, were used to establish empirically the extent and pathway of contaminant transfer to stream-resident Brook Trout and Brown Trout (*Salmo trutta*). Finally, a custom-built bioenergetics-bioaccumulation model was used to project contaminant transfer to stream-resident fish under different scenarios. From the survey, biological factors were found to be the most important influence on salmon-mediated contaminant transfer, including the flux of contaminant supplied by salmon spawners and species of the stream-resident fish. In addition, there were significant differences between pollutants, PCBs being most influenced by salmon contaminant biotransport whereas mercury was not. Experiments were consistent with the survey, with strong evidence of transfer of salmon-mediated POP but not mercury. We also found that the type of tissue consumed by stream-resident fish was an important determinant of contaminant burden in fish; salmon eggs were more contaminated with POPs while muscle tissue was most contaminated with mercury. Our modeling efforts suggest that variation in stream-resident fish POP concentrations could result from differences in salmon egg consumption, modulated by salmon run dynamics, individual fish behavior, and growth. Major conclusions include, first, that a limited number of factors influence transfer of POPs, but not mercury, from salmon to stream-resident fish. Second, at the watershed-level, biological context appears to be more important than physical or chemical context with respect to contaminant biotransport. Third, at the basin-level, the most important factor is the degree of contamination within the lakes because of how this then influences the salmon contaminant flux. Fourth, large variation in contaminant burden among stream-resident fish highlights the importance of diet, growth, and behavior. Overall, our results highlight that the environmental context can determine contaminant biotransport at scales that range from the basin to individuals. Our research has broader implications for several important issues in the Great Lakes, including managing contaminant exposure, maintaining sport fisheries, and restoring ecosystem connectivity through dam removal.

FINAL NARRATIVE REPORT

- **Project Title:** Conservation of native fish communities in tributaries to the Great Lakes: Predicting the impacts of contaminants delivered by spawning Pacific Salmon
- **Grantee Organization**

  University of Notre Dame

  Lake Superior State University

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- **Grant Amount** $222,115
- **Start and End Dates** January 1, 2013 to June 30, 2016
- **Key Search Words** Pacific Salmon, Brook Trout, Brown Trout, Mottled Sculpin, Contaminant Biotransport, Heavy Metals, Mercury, Persistent Organic Pollutants, PCBs, PBDEs, DDEs, Great Lakes, Ecosystem Linkages.

Background/Overview

1. For our Great Lakes Fishery Trust (GLFT) project, we proposed to assess the relationship between contaminant burden of stream fish and contaminant biotransport by migratory Pacific Salmon in the upper Great Lakes. More specifically, we proposed to conduct basin-wide surveys of upper Great Lakes tributaries, to establish persistent organic pollutant and total mercury contaminant concentrations in salmon and stream-resident fish, along with various physical, biological, and chemical components of the environmental context. The intent was to use that information to then establish factors important in determining the extent of contaminant burden of stream-resident fish with respect to salmon-mediated contaminant biotransport. Data generated would also be used to parameterize a contaminant bioaccumulation model from which contaminant burdens of stream-resident fish could be projected for a given stream receiving salmon spawners. Our broader intent was to use the projections in a mapping tool that would enable fisheries managers to identify locations where salmon-mediated contaminant transport might be especially problematic, which in turn would help guide future stocking with Pacific Salmon.

2. *Significant changes to the original proposal and funded plan of work* included a change in the modeling approach and analytical methods, addition of experiments, and elimination of

the risk assessment portion of the proposal. We originally proposed using the BASS model framework (Barber 1996) but for reasons of efficiency and flexibility a custom-built version of the bioaccumulation-bioenergetics model was used instead. More specifically, the current version of BASS, as configured, would not allow assessment of whether fluxes of contaminants supplied by spawning salmon influence bioaccumulation in stream-resident fish, and was unstable and unreliable in our computing environment. Our custom-built time dynamic model was parameterized using existing model formulations by Hanson et al. (1997) and Arnot and Gobas (2004); both have been cited more than 275 times for diverse applications in fish ecology and ecotoxicology. Our model, similar to BASS, makes predictions about growth and contaminant accumulation for different species, among scenarios that differ in salmon influence (e.g., proportion of salmon in diet, duration consumed) while using modeled daily rates of consumption, respiration, egestion, excretion, and contaminant exposure. Second, we originally proposed using cold-atomic adsorption spectroscopy to measure mercury concentrations in fish but due to instrument malfunctions, we switched to a direct mercury analyzer to measure total mercury. This change simplified our methods and resulted in data with improved recovery rates (Mean=100%, SD=7%). Mercury can occur in different elemental forms but in fish and predatory invertebrates more than 95% of mercury is methylated, and thus total mercury concentrations can be considered equivalent to methylated mercury concentrations (Mason et al. 2000). Third, we added experiments, including a whole-stream manipulation where salmon carcass and egg material were added to a stream in which salmon had never spawned. The movement of salmon-derived contaminants was then tracked through the system and ultimately into stream-resident fish. We decided to pursue these experiments because data were needed to parameterize our models but a complementary bridge was also needed between our survey and modeling efforts. Fourth, we decided not to proceed with the final step of using our model to generate contaminant burden estimates for stream-resident fish in Michigan watersheds. This was, in part, due to the large variability in fish contaminant burden, within and among watersheds where salmon spawn. Hence, much larger sample sizes than collected for this project would be needed to adequately characterize the distribution of contaminants in stream-resident fish. In addition, while a strong relationship was found between stream-resident fish POP concentrations and salmon biomass, the paucity of data for salmon run dynamics would limit the value of such projections for managers.

Outcomes

3. With respect to *advancing scientific knowledge*, our research project has advanced our overall understanding of the role of context in determining the degree of contaminant biotransport by migratory fish. This knowledge is especially relevant to upper Great Lakes tributaries, and the associated stream-resident fish communities. More specifically, ***first***, our basin-wide survey found the extent of contaminant biotransport is dependent upon the contaminant considered. With stream-resident fish, persistent organic pollutants (POPs) but not mercury, reflected salmon influence (Fig. 1). This contrast is surprising given that anadromous fish have been found to increase mercury concentrations in stream-resident fish and birds (Morrissey et al. 2011, Swanson and Kidd 2010, Zhang et al. 2001). Within the non-native range, spawning salmon in a Lake Ontario tributary increased both total and methyl mercury in invertebrates 25-fold, and in stream water by 10% (Sarica et al. 2004). Our results suggest that in the upper Great Lakes background sources of mercury may have a

larger influence on stream-resident fish mercury burden than that of salmon or that direct consumption of carcass material is *not* an important contaminant source to stream-resident fish. Our finding of a significant POP effect of salmon is consistent with previous work (Giesy et al. 1994, Janetski et al. 2012, Merna 1986) in which fish in stream reaches with salmon spawners had higher POP concentrations than fish in stream reaches without salmon.

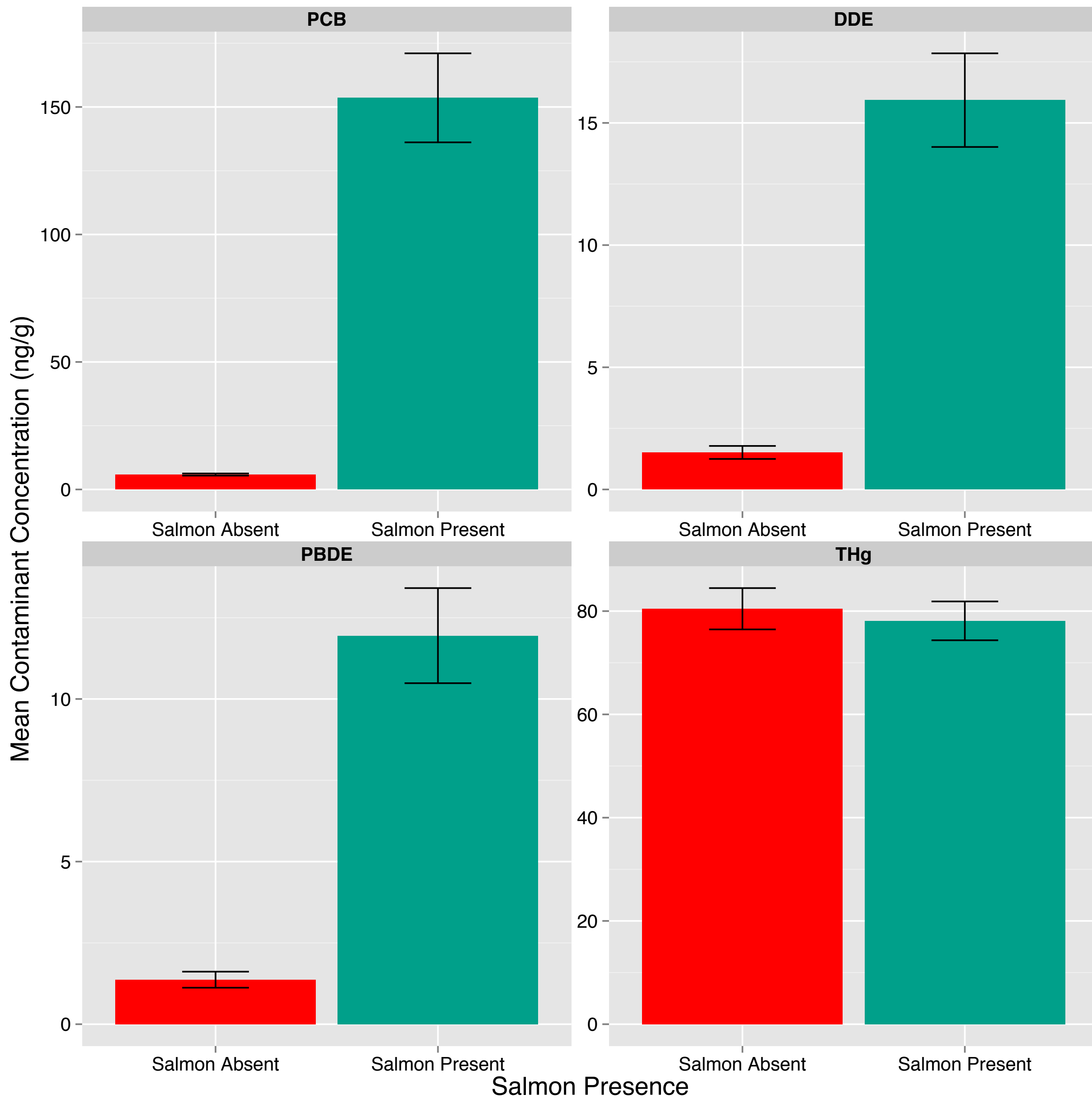

Figure 1. Mean contaminant concentrations (± SE) of stream-resident fish sampled from reaches with and without salmon spawners in 15 watersheds throughout the upper Great Lakes. Salmon strongly influence persistent organic pollutant concentrations but not total mercury concentrations in stream-resident fish.

Second, we found that species identity was an important aspect of the biological context influencing contaminant bioaccumulation and the magnitude of salmon contaminant biotransport (Fig. 2). For POPs, we found that Brown Trout exhibited the strongest relationship with salmon POP flux, followed by Brook Trout, with Mottled Sculpin having the weakest relationship. Species-specific differences in POP concentrations are likely driven by differences in diet, growth patterns, and degree of exposure to salmon material, such as

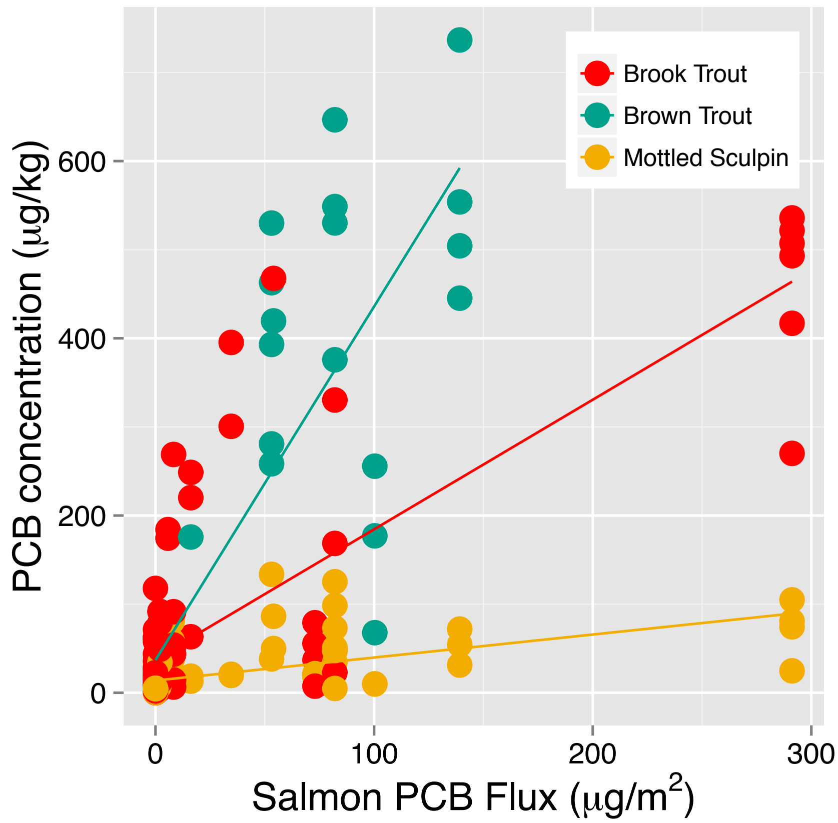

Figure 2. Relationship between PCB concentrations in stream resident fish and the flux of PCB supplied by spawning salmon from 15 watersheds sampled throughout the Upper Great Lakes. PCB flux calculated from visual abundance estimates, biometric data, and mean PCB concentration of salmon from a given watershed. Species-specific slopes indicate differential rates of bioaccumulation, with high levels of variation in fish collected from the same stream reach highlight individual responses to salmon derived contaminants.

through salmon egg consumption. Previous research from the native range has shown that growth and isotopic differentiation in resident trout, including Rainbow Trout (*Oncorhynchus mykiss*) is driven by salmon egg consumption (Armstrong et al. 2013, Moore et al. 2008, Scheuerell et al. 2007). We suspect egg consumption also drives POP accumulation in stream-resident fish in Great Lakes tributaries. Previously, a strong linear relationship has been found between POP concentrations and number of salmon eggs consumed by Brown and Rainbow Trout (Merna 1986). That Mottled Sculpin exhibited the weakest relationship with salmon POP flux is consistent with what is known about their biology (Scott and Crossman 1973, Swain et al. 2013). Freshwater sculpin are small benthic fish with a relatively large gape that forage on salmon material, including eggs, when available (Scott and Crossman 1973, Swain et al. 2013). However, their benthic preferences may result in their displacement to sub-optimal habitat when salmon spawn, reducing access to salmon material, especially eggs (Merna 1986). Furthermore, sculpin may also lack the dietary plasticity or gut capacity that allows gorging on salmon eggs, in contrast to trout (Armstrong and Schindler 2013). Another important factor is likely to be differences in physiology among species, specifically how organic contaminants are broken down. A related freshwater species, Deepwater Sculpin (*Myoxocephalus thompsonii*) can metabolize PCBs, decreasing contaminant burden (Stapleton et al. 2001), which has not been observed in salmonids. Although Mottled Sculpin exhibited the lowest PCB concentrations, their total mercury concentrations were higher than co-occurring trout, suggesting that diet along with growth efficiency may, in part, explain observed patterns. Overall, the differences observed among species suggest that bioaccumulation occurs at different rates as a function of individual diet, trophic position, and physiology (Kiljunen et al. 2008, Stapleton et al. 2001, Svendsen et al. 2009).

Third, we demonstrated that large-scale regional factors were important (Fig. 3). More specifically, broad-scale factors associated with lake basin were more important than small-scale factors associated with instream or watershed condition. The broader regional context likely reflects the gradient of PCB concentrations among lake basins due to differences in industrial development and historical contamination. Such a gradient was evident from the POP congener patterns (Gerig et al. 2015) and concentrations (Janetski et al. 2012). Lake

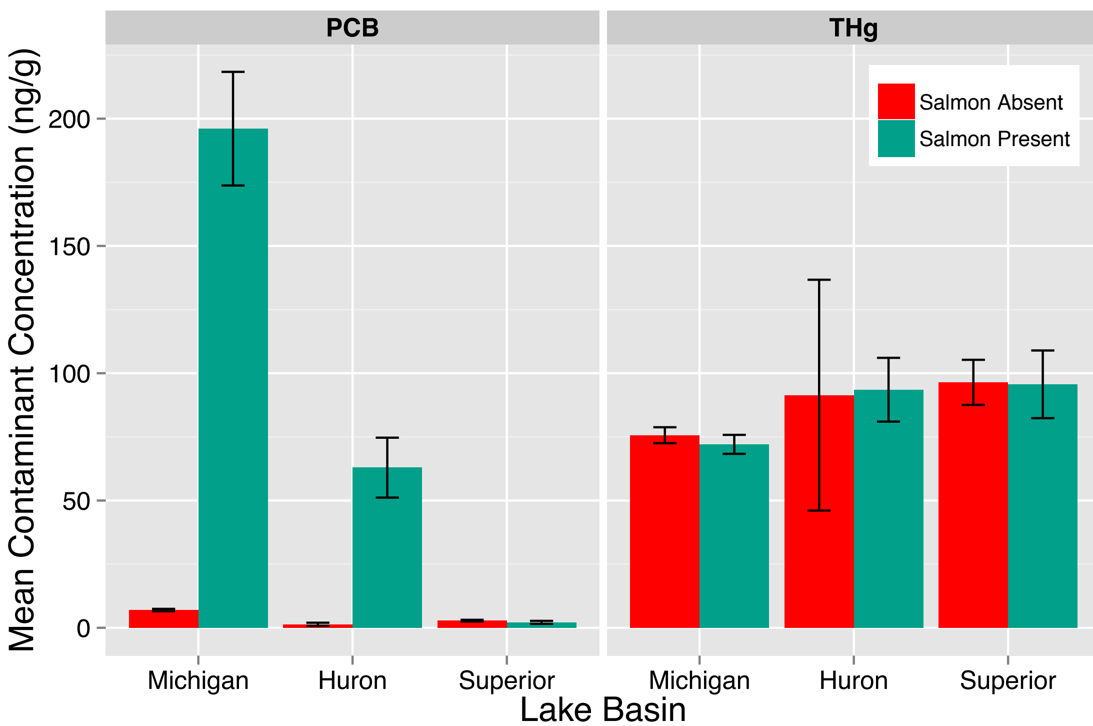

Figure 3. Mean contaminant concentrations (± SE) of stream resident fish in reaches with and without salmon spawners across the upper Great Lake basin. The magnitude of PCB contaminant biotransport by salmon varied by tributary receiving lake basin. For PCBs, relationship is likely driven by historical legacy of contamination and salmon population sizes; Lake Michigan exhibits highest pollution levels and larger salmon populations. For total mercury, no evidence of salmon mediated biotransport was observed given that there was no increase in the presence of salmon spawners.

Michigan is more developed and has an extensive industrial legacy compared with Lakes Superior or Huron (Hornbuckle et al. 2006, Venier et al. 2014). In contrast to POPs, total mercury concentrations were higher in the tributaries draining into Lake Superior. Differences among basins for mercury may reflect differences in watershed area, mercury availability, or productivity (Drevnick et al. 2007). Overall, the magnitude of basin-differences was much smaller for total mercury when compared to POPs (Fig. 3). For total mercury, the smaller differences among lake basins reflect atmospheric deposition being a key source, which is distributed relatively homogenously across the Upper Great Lakes. That bioaccumulation didn't appear to be influenced by watershed level factors, perhaps because our sites did not provide a sufficiently large gradient. For instance, for some variables such as pH (mean=8.4, SD=0.1), or temperature (mean=16.8 °C, SD=0.7°C), which have been shown to be important with respect to bioaccumulation (Ponce and Bloom 1991, Ng and Gray 2011), only small variation was evident among our study sites. Consequently, the magnitude of difference explained by biological context, including species identity and salmon pollutant flux, overwhelmed the influence of other variables that may explain patterns of POP concentrations in streams that salmon do not spawn in.

Fourth, previous research has suggested that variation in PCB concentrations of Pacific Salmon in Lake Michigan can be explained by differences in diet and growth efficiency among individuals (Madenjian et al. 1994, Madenjian 2011). A similar pattern likely regulates contaminant accumulation in stream-resident fish, especially through consumption of salmon eggs. Our work and others (Ivan et al. 2011, Moore et al. 2008, Scheuerell et al. 2007) indicates that salmon eggs represent an energetically dense food resource and a substantial source of POP contamination to stream-resident fish. Our empirical data highlights that eggs are enriched in POPs but depleted in mercury (Fig. 4). This pattern likely explains the strong evidence for POP but not mercury salmon biotransport. Hence, fish that consume eggs likely accumulate substantial contaminant burdens but may also benefit through improved growth. Our model demonstrated that variation in diet, ration size, and growth probably all interact and contribute to the observed variation in stream-resident fish contaminant burdens (Madenjian 1994), leading to the conclusion that physical or chemical variables are likely to be less important in mediating contaminant biotransport (Fig. 5). No evidence was found of physical habitat and instream features influencing stream-resident fish contaminant concentrations, but physical habitat may still be operating at a larger scale, given the differences evident among basins. Tributaries of the Great Lakes, particularly those within the Lake Michigan basin, are characterized by small substrates of glacial origin (Dorr and Eschman 1973). Such substrates are susceptible to disturbance, both from hydrological processes, such as floods, and ecosystem engineering, such as by salmon spawners (Janetski et al. 2009). In the Great Lakes, the disturbance effects of salmon can be magnified (Collins et al. 2011), reducing invertebrate abundance by 90% (Janetski et al. 2014). In addition, substrates prone to disturbance are also sensitive to redd superimposition that increases the availability of salmon eggs for consumption by fish (Moore et al. 2008). Thus, reduced invertebrate availability coupled with increased salmon egg availability, arguably, would facilitate rapid increases in POPs exposure through diet, consistent with large increases in POP concentrations in fish following salmon spawning that we found.

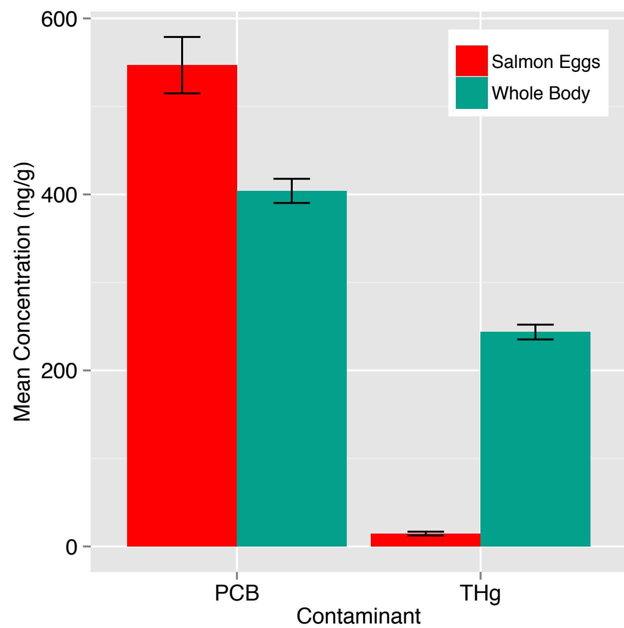

Figure 4. Mean contaminant concentrations (± SE) of two different types of salmon material. Whole salmon contains more mercury than eggs, whereas eggs contain more PCBs than whole salmon. This is evidence of the role of egg consumption in driving POP but not total mercury bioaccumulation in stream-resident fish.

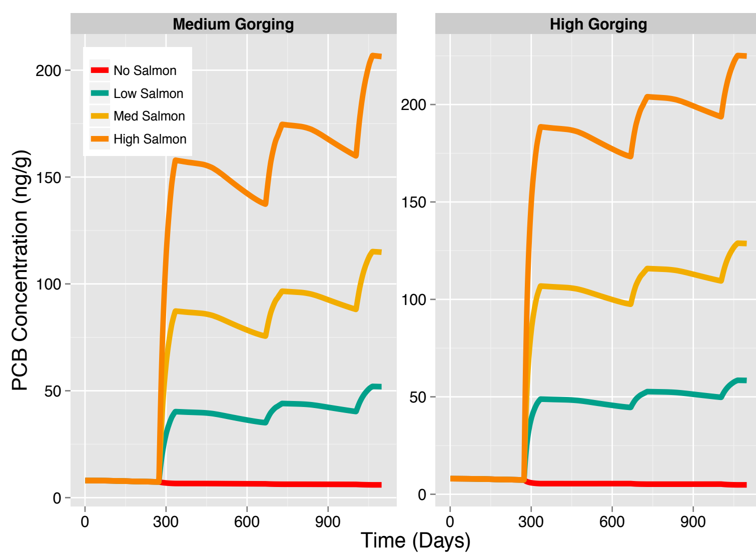

Figure 5. Simulated Brook Trout PCB concentrations with variable ration size and diet. Scenarios included diets with various proportions of salmon eggs (0, 10%, 50%, 100%) and also medium and high levels of gorging. Consumption was modeled as a function of fish weight and water temperature. Gorging scenarios represented an increase in food consumption above the base level by 100% for medium, and 300% for high scenarios. Increasing the proportion of salmon eggs led to increases in PCB concentrations under both scenarios. Similar concentrations were exhibited between medium and high gorge scenarios reflecting growth dilution; consumption of energetically dense salmon eggs increased fish growth of fish thereby reducing the concentration by diluting the mass of PCB in their body. Interaction between growth, diet proportion, and ration size produces PCB concentrations in the range of variability observed in our survey and experiments.

4. The project has provided numerous opportunities for the *education and advancement of graduate and undergraduate students focused on Great Lakes fishery*, either while pursuing their own research projects or while working as research technicians. Brandon Gerig, graduate student at the University of Notre Dame, is studying the role of context dependency in contaminant biotransport by introduced Pacific Salmon in the Laurentian Great Lakes. His work has already resulted in multiple presentations at regional and national meetings, as well as one publication. Gerig successfully defended his dissertation prospectus and became a PhD candidate in 2016, and is now well on his way to completing his PhD program in fall 2017 or spring 2018; we expect Gerig to complete and submit a further three manuscripts for publication during this period. Notre Dame undergraduates, Josephine Chau, Sean Cullen, Lea Lovin, Lillian McGill, Nick (David) Weber, Jack McClaren, and Andrew Wilson, and Lake Superior State University undergraduate students Ryan Cass, Brian Curell, and Kyle Urban, and Michigan State University graduate students Courtney Larson and Courtney Weatherbee, have all undertaken variety of research projects and supporting roles with respect to understanding the influence of Pacific Salmon on stream-resident fish in Great Lakes tributaries and bioaccumulation of mercury in Great Lakes food webs. This has included participating in stream surveys, conducting experiments, and undertaking modeling efforts. All research students have presented their research as posters or talks, at local, regional, and/or national meetings. Moreover, McGill and Cass have written Senior Theses based on their research, while Cullen and Urban will be writing their Senior Theses on their research during the next 12 months. McGill and Weber are currently developing manuscripts that will be submitted before the end of 2016, while both have been accepted to graduate programs this year, facilitated by their research experiences associated with this project.

5. The work undertaken for this projected helped us build many *new relationships with others in research or management communities*. First, through the implementation of the whole stream manipulation experiment at Hunt Creek we developed important relationships with personnel including retired station chief James Johnson, current station chief Dave Fielder, and research technician Bill Wellenkamp from the Michigan Department of Natural Resources (Michigan DNR) Alpena Fisheries Research Station. We also developed relationships with Michigan DNR personnel who manage state weirs from which salmon carcasses were obtained, including Scott Heintzelman and Joe Micevich of Little Manistee, Aaron Switzer of Platte River, and Pat Van Daele of Swan Creek. Another consequence of the Hunt Creek experiment was that Gerig participated in yearly stream population assessments on Hunt Creek with personnel from the Michigan DNR Charlevoix Fishery Research Station under the direction of Dave Clapp. Second, for the Hunt Creek Mesocosm experiment we had to establish professional relationships with James Aho, Michigan DNR Marquette State Fish Hatchery, and Dan Sampson, Michigan DNR Oden State Fish Hatchery, in order to obtain the young-of-year Brook and Brown Trout for the experiment. We also consulted with Roger Greil, manager of the Aquatic Research Laboratory, Lake Superior State University, on appropriate fish rearing techniques for Hunt Creek Mesocosm Experiment. In addition, we consulted with Troy Zorn, Michigan DNR Marquette Fishery Research Office, about the results of the experiment and their broader implications. That in turn led to pre-proposal being submitted to Great Lakes Fishery Trust in 2015. Third, the project has led us to study the potential impacts of other migratory fish as both a resource subsidy and vector for contaminant biotransport. Consequently we have had consultations

with Heather Hettinger, Michigan DNR biologist, Traverse City, MI, about the emerging Atlantic Salmon program in Torch Lake and Lake Michigan. Similarly, we developed a working relationship with Jory Jonas of the Michigan DNR, Charlevoix Research Station, after discussions at the Biennial State of the Lake Meeting in Traverse City, MI. We also developed an additional project studying mercury bioaccumulation in the Lake Michigan salmonine community after discussions with Matt Kornis and Chuck Bronte of US Fish and Wildlife Service (US FWS), Green Bay, WI, and Bo Bunnell and Chuck Madenjian from the US Geological Survey (US GS) Great Lakes Science Center, Ann Arbor, MI.

6. Our findings have *important implications for several issues facing fishery managers*. First, is with respect to managing non-traditional sources of contaminants to tributaries that support important populations of native stream-resident fish, such as the Brook Trout we studied. Biotransported pollutants present a difficult challenge for managers because they represent a diffuse source of pollutants across the landscape that requires different mitigation techniques then has been traditionally used to manage environmental contaminants. The results of our GLFT-funded research has defined the extent of the contaminant biotransport, highlighting the need for management to focus on tributaries open to migratory fish in the Lake Michigan basin. Our research points to salmon eggs as being a key source of contaminant transfer to resident fish from salmon, which is significant because the Great Lakes have over 50 species that exhibit a migratory life history, many of which deposit eggs in the process. The second issue confronting fishery managers for which are results are relevant is dam removal. Our results suggest that fishery managers should be involved in what is a balance between the trade-offs between ecosystem connectivity and ecosystem health. The effects of legacy contaminants and man-made dams on aquatic ecosystems are problems especially relevant to the Great Lakes and its associated fisheries given the number of dams, many of which are close to being obsolete, and the legacy of contamination in the region. Dam removal certainly provides ecological benefits but careful consideration and prioritization should be considered to minimize unintended consequences. Our research also suggests that there should be consideration of approaches used to control the spread of Sea Lamprey (*Petromyzon marinus*), such as temporary, seasonal barriers to minimize the impacts of contaminant biotransport by migratory fish. Our results are relevant to a third issue confronting fisheries managers, the influence of non-native species on stream ecosystems. More specifically, our experimental and modeling efforts have broader implications with respect to role that introduced migratory fish play as resource subsidies in Great Lakes tributaries. For example, our work has shown the importance of eggs over carcass material as a direct route by which salmon-derived resource subsidies influence stream ecosystems in the Great Lakes. This has implications for how managers perceive that non-native salmon provide an important resource subsidy to these systems, especially given that other studies have shown that the environmental context is an important factor in nature and extent of the ecological influence. Moreover, that because of the contrast in the environmental context between the non-native and native range of Pacific Salmon, those ecological effects are likely to be more negative disturbance than positive enrichment.

7. The *most important outcomes* of the project include, first, the complementary results from our basin-wide survey, manipulative experiments, and modeling. Together, these results that have conclusively shown that migratory Pacific Salmon increase the contaminant burden of

POPs, but not mercury, in several stream-resident fish species in tributaries of Great Lakes. This outcome is important because it gives the most concrete evidence, to date, of the extent of the problem despite many decades trying reduce the impact of legacy POPs on the Great Lakes ecosystems (Chapman and Anderson 2005, Gewurtz et al. 2011). Second, our project has shown that there are basin-scale differences in the extent of salmon contaminant biotransport, with important consequences for stream-resident fish. This outcome is important because this should enable management agencies to craft policies to minimize contaminant burdens in those Great Lakes basins where contaminant biotransport is likely to be the most pronounced; this would also minimize contaminant exposure to other organisms that consume those fish, including humans but also high profile fauna such as bears and predatory birds. Third, our project has shown the large variability in fish POP contaminant burden within the same stream highlights that individual fish behavior, diet, and growth likely interact to influence the magnitude of the salmon effect, which in turn has consequences for both establishing consumption advisories but also how contaminant biotransport is assessed and managed. More specifically, this information may mean that environmental managers have to issue widespread contaminant warnings for streams that receive salmon runs because small-scale monitoring may not adequately characterize the degree and extent of impact based upon the variation we observed in our broad-scale survey. Fourth, our project has shown that the flux of contaminants mediated by Pacific Salmon represents the most significant factor influencing stream-resident fish contaminant burden in streams where salmon spawn, while other more traditional aspects of environmental context such as instream habitat, land cover, water chemistry do not appear to be important. This outcome is important because it provides an easy and straightforward objective to mitigate contaminant biotransport: modify salmon stocking or institute preventative measures to reduce salmon spawner abundance so as to minimize contaminant biotransport.

Related Efforts

8. The project enabled Brandon Gerig to gain *additional funding* from the US Environmental Protection Agency through a STAR fellowship grant. This fellowship provided Gerig with tuition, stipend, and research expenses that have been primarily used to undertake the Hunt Creek whole-stream manipulation and conference attendance. In total, Gerig was awarded $84,000 over a two-year period from August 2015-August 2017.
9. There have been several *examples of spin off work* related to this project that we have undertaken. First, the whole-stream manipulation carcass addition and mesocsom experiments at Hunt Creek Fisheries Research Station were not a part of the original proposal. Theses experiments came about as a result of the 2013 Lake Superior State University Aquatic Research Laboratory meeting where Chaloner, Gerig, and project co-PI Ashley Moerke were able to meet with Jim Johnson, Michigan DNR research biologist, to discuss options for using the Hunt Creek Fisheries Research Station given its projected reduced use by Michigan DNR. This meeting translated into the experiments that provided considerable added value with little additional cost to the GLFT project. Second, Gerig was approached by Michigan DNR biologist, Jory Jonas, at the biennial State of the Lake meeting to discuss the implications of the GLFT funded research for future fish passage and dam removal. Specifically, Jonas was interested in this project could be leveraged to try and obtain additional funding to provide recommendations and risk assessment for the current Boardman River Dam removal project. The result of this meeting resulted in a pre-proposal

to the Great Lakes Fish and Wildlife Restoration Act Fund with respect to the consequences of dam removal and fish passage on contaminant movement in Great Lakes tributaries. While not funded, this proposal resulted in important insights and created an important future collaborator. Third, after listening to a webinar about the US FWS Mass Marking project (www.fws.gov/midwest/massmarking.htm), project co-PI Gary Lamberti along with Gerig and Chaloner, arranged a conference call with US FWS biologists Chuck Bronte and Matt Kornis. Consequently, Gerig worked with Mass Marking technicians to collect ~1600 tissue samples from members of the salmonine fish community around Lake Michigan, that will subject to both mercury and stable isotope analyses. This spin-off project will focus on determining factors how spatial patterns and food web structure influence mercury accumulation in the salmonine community. This in turn, through Mass Marking contacts, led to the establishment of a network of biologists from Lakes Ontario, Huron, and Superior to collect Chinook and Coho Salmon from each lake basin to augment the dataset generated for our GLFT project. This project will determine whether there are basin-scale differences in mercury accumulation by Pacific Salmon. Gerig also contacted US GS biologists, Bo Bunnell and Chuck Madenjian, about collect prey fish from Lake Michigan. This sampling effort resulted in the collection of 400 samples that are being used to characterize mercury concentrations in the prey fish community of Lake Michigan, and will be coupled to the salmonine research to explain how fish become contaminated while rearing in the Great Lakes, with consequences for their influence on Great Lakes tributaries. This activity also resulted in two proposals that were submitted to the Great Lakes Fishery Commission for consideration but were ultimately not successful.

Communication/Publication of Findings

10. This project has resulted in 9 publications, 25 presentations, and 1 website that have either been *presented, published, or are being planned.*

Publications

Cass, R. 2015. The effects of salmon carcasses on behavior and short-term growth of resident trout. Senior Thesis. Lake Superior State University, Sault Ste. Marie, MI.

Chaloner, D.T., B.S. Gerig, D.J. Janetski, C.P. Arango, A.H. Moerke, and G.A. Lamberti. Influence of Pacific Salmon spawners on stream ecosystems: Why context matters. Bioscience, in preparation.

Gerig, B.S., D.T. Chaloner, D.J. Janetski, R.A. Rediske, J.P. O'Keefe, A.H. Moerke, and G.A. Lamberti. 2016. Pacific Salmon are a source of persistent organic pollutants for stream-resident fish within Great Lakes tributaries. Environmental Science and Technology 50:554-563.

Gerig, B.S., D.T. Chaloner, R.R. Rediske, J. O'Keefe, A.H. Moerke, D. de Alwis Pitts, and G.A. Lamberti. Context modulates the role contaminant biotransport by Pacific Salmon in the Great Lakes. Ecological Applications, in preparation.

Gerig, B.S., D.T. Chaloner, S. Chernyak, S. Batterman, R.R. Rediske, A.H. Moerke, and G.A. Lamberti. Influence of an experimental Pacific salmon carcass and egg addition on food web structure and contaminant levels of stream-resident fish in a Michigan stream. Ecology, in preparation.

Gerig, B.S., D.T. Chaloner, and G.A. Lamberti. Ecological implications of Great Lakes salmonine introductions: predicting the effects of migratory salmonine spawning on resident fish growth and contaminant accumulation using bioenergetic-bioaccumulation models. Journal of Applied Ecology, in preparation.

Gerig, B.S., D.N. Weber, D.T. Chaloner, L. McGill, and G. A. Lamberti. 2016. Ecological Effects of Non-native Pacific Salmon and Brown Trout on Native Brook Trout in Great Lakes Tributaries. Canadian Journal of Fisheries and Aquatic Sciences, in preparation.

McGill, L. 2016. Use of an ecosystem-based model to predict the effects of non-native Pacific Salmon spawning on stream-resident fish in the Great Lakes basin. Glynn Family Honors Thesis. University of Notre Dame, Notre Dame, IN.

McGill, L., B.S. Gerig, D.T. Chaloner, and G. A. Lamberti. 2016. Use of an ecosystem-based model to predict the effects of non-native Pacific Salmon spawning on stream-resident fish in the Great Lakes basin. Ecological Modeling, in preparation.

Presentations

Cass, R. 2015. The effects of salmon carcasses on behavior and short-term growth of resident trout (Talk). Senior Thesis Symposium, Lake Superior State University (April), Sault Ste. Marie, MI.

Chaloner, D.T., D.J. Janetski, A.H. Moerke, R.R. Rediske, J.P. O'Keefe, B. Gerig, and G.A. Lamberti. 2012. The bad along with the good: contaminant transport to stream ecosystems by Pacific Salmon (Talk). 60th meeting of the Society of Freshwater Science (May), Louisville, KY.

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Weber, D.N., B. Gerig, L. McGill, L., D.T. Chaloner, and G. A. Lamberti. 2014. Ecological Effects of Non-native Pacific Salmon and Brown Trout on Native Brook Trout in Great Lakes Tributaries (Poster). College of Science - Fall Undergraduate Research Fair, University of Notre Dame (October), Notre Dame, IN.

Weber, D.N., B. Gerig, L. McGill, L., D.T. Chaloner, and G. A. Lamberti. 2016. Ecological Effects of Non-native Pacific Salmon and Brown Trout on Native Brook Trout in Great Lakes Tributaries (Poster). 76th Midwest Fish and Wildlife Conference (January), Grand Rapids, MI.

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Wilson, A.J., D.T. Chaloner, M.A. Brueseke, B.S. Gerig, and G.A. Lamberti. 2014. Patterns of Contaminant Transport by Pacific Salmon (*Oncorhynchus* spp.) into Great Lakes Tributaries (Poster). Notre Dame College of Science-Joint Annual Meeting, University of Notre Dame (May), Notre Dame, IN.

Project Website

Website: greatlakessalmoncontaminants.weebly.com/

11. We have *shared our findings with other agencies* through the many relationships we have established for this project, including with biologists at Michigan Department of Environmental Quality and Department of Natural Resources; tribal agencies, including the Little River Band and Little Traverse Band; and federal agencies, including the US Fish and

Wildlife Service and US Geological Survey. Second, we have presented the results of our project at local meetings, such as the Great Lakes Fish Health Committee Meeting and the Annual Meeting of the Aquatic Research Laboratory and Michigan Dept. of Natural Resources, which are attended by state biologists and managers. Third, we have presented out results at regional meetings including Midwest Fish and Wildlife Conference and Biennial State of the Lake, that are attended by state and federal agency scientists and managers. Fourth, we have presented results at national scientific meetings including annual meetings of the Society of Freshwater Science, American Fisheries Society, and Ecological Society of America, which are attended by state, federal, and academic biologists. Fifth, in the course of developing the project, we initiated a dialog with various agency scientists and managers, including discussions of potential ways in which monitoring of contaminant biotransport could be implemented through existing Department of Environmental Quality programs with Joe Bohr, biologist with Michigan DEQ, Lansing, MI; extent of contaminant biotransport in Michigan streams and implications for human health with Jennifer Gray, toxicologist with Michigan Department of Health and Human Services, Lansing, MI; implications of contaminant biotransport for salmon streams in the Pacific Northwest and Alaska with Nat Scholz, leader of the Ecotoxicology Unit, NOAA Northwest Fisheries Science Center, Seattle, WA, and future research involving interactions between endangered salmon and contaminant biotransport by invasive species in California with Thomas Williams, Fisheries Research biologist, NOAA Southwest Fisheries Science Center, San Cruz, CA. We are also planning a one page handout that will give the highlights of our GLFT project and which will be shared with government agencies and interested groups throughout the upper Great Lakes, using traditional mail and social media. We still plan to present the results of our project to the Great Lakes Fishery Commission within the next year and also hope to organize a special symposium at the annual meeting of the International Association for Great Lakes Research.

12. Not Applicable.
13. Please see uploaded pdf of Gerig, B.S., D.T. Chaloner, D.J. Janetski, R.A. Rediske, J.P. O'Keefe, A.H. Moerke, and G.A. Lamberti. 2016. Pacific Salmon are a source of persistent organic pollutants for stream-resident fish within Great Lakes tributaries. Environmental Science and Technology 50:554-563.
14. Not Applicable.

Discussion

Generalizations from project

Our project has shown that migratory fish, such as Pacific Salmon, can transport contaminants to tributaries of the Great Lakes and influence the contaminant burden of stream-resident fish. We found strong evidence of such contaminant biotransport and transfer with POPs, but not mercury, suggesting that not all contaminants are equal and that the pathway to contamination can be a significant determinant of impact. Also, environmental context does matter but only for a limited number of factors that directly influence the transfer of contaminants biotransported by Pacific Salmon to stream-resident fish. This result, particularly for POPs, reflects the fact that salmon supply a large flux of POPs to streams relative to much smaller atmospheric sources. In contrast, background sources of mercury appear to be a greater determinant of stream-resident fish mercury concentrations than salmon. Overall, species identity and spawning biomass appear to drive increases in stream-resident fish concentrations. High levels of variation likely reflect variation in diet, and species-specific physiology. What was also evident from this project was that the extent of contaminant biotransport differed at contrasting scales. However, the high levels of variation in individual fish POP concentration within the same stream likely reflected variation in diet and behavior which regulate the degree of salmon egg consumption. Within watersheds, locations with spawning salmon exhibited much higher POP concentrations and were more variable. This pattern of increased concentrations differed between lake basins, where Lake Michigan tributaries were the most while Lake Superior streams were the least contaminated. Our data found no evidence of biotransport in Lake Superior streams. Our whole-stream manipulation reinforced insights from our survey by showing that salmon increase both concentrations and variability in POP concentration. In addition, the experiment and modeling highlight that POP burdens accrued from a past run are retained over the course of a year. This carryover may also influence the level of variation observed in the survey; streams with inconsistent or variable salmon runs may have higher POP variation in stream-resident fish. Last, our modeling efforts provide a mechanistic explanation for the variation observed in the survey and manipulation; namely that variation in consumption rate and ration size of salmon eggs could regulate stream-resident fish POP concentrations.

Contrasts between specific components of project with other work

Survey

POP congener patterns revealed many insights about the relationship between the contaminant burden of salmon and that of stream-resident fish (see Gerig et al. 2015 for discussion). The first insight was the degree to which salmon spawners influence POP patterns of stream-resident fish. Second, that there is variation among basins reflecting regional differences in the extent and nature of contaminants in the environment. Third, similarity in salmon congener pattern between Lake Michigan and Huron indicates movement of fish from Lake Huron to Michigan to forage. Fish in Lake Michigan streams exhibited the clearest congener patterns. For example, Brook Trout in reaches with salmon had a congener pattern that overlapped with salmon but was distinct from locations without salmon but also distinct from that of sculpin. The strong contrasts in congener patterns between lakes Superior and Michigan likely reflect contrasts in historical pollution, and salmon abundance and species composition. For example, Lake Michigan received

15 times the direct input of PCBs compared with Lake Superior (Golden et al. 1993), and continues to receive larger atmospheric inputs of POPs (Li et al. 2009). Moreover, Lake Michigan still supports reasonable populations of both Chinook and Coho Salmon, although there are concerns about how long that will continue (Dettmers et al. 2012).

Our basin-wide survey generated insights about the environmental factors influencing stream-resident fish contaminant concentrations in the upper Great Lakes. First, the magnitude of contaminant biotransport by salmon to stream-resident fish was more significant with POPs than with mercury. This is surprising, given that salmon in the native and non-native range have been shown to increase mercury concentrations in stream consumers (Morrissey et al. 2011, Noel et al. 2014, Sarica et al. 2004, Zhang et al. 2001). Our results suggest background mercury sources can have a larger influence on stream-resident fish mercury burden than salmon. In addition, the inconsistent response of organisms to biotransported contaminants highlights that the extent of contaminant accumulation is significantly influenced by the trophic pathway and contaminant considered.

Contrasts between contaminants appear to reflect differences in the role of environmental context. First, biological factors, such as species identity, salmon presence, spawner biomass, and fish length were more important for contaminant burden than physical and chemical factors, such as the amount of course wood and water chemistry characteristics. Previous studies have found POPs concentrations in fish to vary with physical and chemical factors (King et al. 2004), but salmon may deliver such a large pollutant flux that other factors are swamped out. Second, large-scale regional factors, such as lake basin, were more important than small-scale, in-stream and watershed factors, reflecting contrasts in industrial development and historical contamination among the Great Lakes (Hornbuckle et al. 2006, Venier et al. 2014). Basin-scale variation in the extent of contamination sets the stage for basin-scale differences in POP concentrations in salmon, which in turn strongly influence risk of biotransport. The larger influence of biological over chemical or physical factors parallels recent research that considered how salmon spawners influence stable isotope composition of Sculpin (Swain et al. 2013), and juvenile Coho Salmon (Reisinger et al. 2013), in which the most important factor included salmon run size. Third, our results may indicate that POP burdens in resident fish are an integration of past salmon runs. The variability in stream-resident fish, particularly within Brook Trout, appear to exhibit a logarithmic relationship between salmon biomass and stream-resident fish contaminant burden suggests limits on uptake and incorporation of salmon-derived contaminants by resident fish; similar saturation patterns have been observed before with salmon-derived nutrients (e.g., Chaloner et al. 2002, Wipfli et al. 2003). Fourth, the large degree of variation suggests heterogeneous exposure to contaminants, such as through the clumped distribution of eggs but also variation in diet and growth efficiency (Madenjian et al. 1994, Madenjian 2011). Fifth, total mercury concentrations in Mottled Sculpin were higher than Brook or Brown Trout. This was surprising given that Sculpin are considered shorter-lived fish with a lower trophic level compared to trout but this may suggest that they grow inefficiently, needing to eat more food proportionally to grow, thereby increasing their dietary mercury exposure and increase their bioaccumulation rate (Madenjian et al. 1994, Madenjian et al. 2000). Last, the influence of landscape factors on PBDE and total mercury concentrations, in contrast to PCBs and DDE, can be explained by their predominant transport mechanism being atmospheric aerosol dust (Venier and Hites 2008); physical attributes of the environmental context may increase the interception and retention of PBDEs and mercury. For example, watershed area is directly correlated with mercury and PBDE concentrations (King et al. 2004), while forest cover has been shown to intercept mercury and facilitate its movement to the soil and streams (Tsui et al. 2009).

Experiments

The results of the whole-stream manipulation experiment were largely consistent with those of the survey. Results were also consistent with what has already been found about the influence of salmon contaminants on stream-resident fish, within and outside the native range of Pacific Salmon (Gregory-Eaves et al. 2007, Janetski et al. 2012, Merna 1986). However, our experiment was the first to show empirically that the contaminant burden of one organism can directly impact that of another organism. Key insights from the experiment include: First, the POP contaminant burden in resident fish increased rapidly after the salmon material addition, but dynamics differed between years and among contaminants, between POPs and mercury, as well as among types of POPs. The continued increase in DDE and PBDE, but not PCB concentrations in the second year of our salmon addition may result from resident fish not yet exhibiting equilibrium concentrations or related to variation in DDE and PBDE concentrations in salmon eggs. Second, eggs were higher in PCBs relative to salmon tissue whereas eggs are lower in mercury compared to salmon tissue; consumption of eggs could increase PCBs burden with no change in mercury concentrations. Previous research suggests that resident fish readily consume salmon eggs when available (Johnson and Ringler 1979, Ivan et al. 2011), while Rainbow Trout PCB and DDT concentrations increased with the number of salmon eggs ingested (Merna 1986). This evidence strongly suggests that eggs are a primary source of POPs to stream-resident fish.

Results of the mesocosm experiment, in conjunction with modeling, clarified the influence of salmon on stream-resident fish growth and mercury accumulation, especially the role of the type of salmon material. More specifically, consumption of salmon tissue did not enhance growth but led to large increases total mercury concentrations. We used our previously developed bioenergetics-bioaccumulation to show the consequences of salmon egg versus tissue consumption, with the former resulting in both improved growth and lower total mercury concentrations in Brook Trout. Given that we observed opposite patterns for Brook Trout total mercury concentrations in our large-scale survey and whole-stream experiment reaches, we suggest that Brook Trout do not consume large quantities of contaminated tissue, but rather are consuming large numbers of eggs. Our results contrast with the literature, especially from the native range of salmon (e.g., Bilby et al. 1998, Wipfli et al. 2003), which often implies that the major source nutrition from salmon is from carcass tissue, and hence the rationale for the addition of carcasses where salmon runs have been extirpated or much lower than they were historically (Cederholm et al. 1999). However, our results are consistent with more recent work that has emphasized the contrasting role of live spawners over dead carcasses in fertilizing stream ecosystems in the native range of salmon (e.g., Tiegs et al. 2011, Levi et al. 2013). Our data also suggest that mercury can be an effective tracer to assess diet and consumption rates in fish (cf., Ramos et al. 2013).

Modeling

The bioenergetic-bioaccumulation model provided insights that paralleled those from the survey and experiments. The range of modeled PCB concentrations corresponds to that of the empirical survey suggesting that individual variation in both the total amount of salmon consumed and individual ration size are important determinants of the extent to which fish incorporate certain salmon-derived contaminants. The model also highlights that fish are unable to reduce their PCB burden via metabolism or growth during a year. This insight may explain the amount of variation we have observed and suggests that interactions between growth rate, consumption rate, and contaminant concentrations in the diet can strongly influence the bioaccumulation rate. Moreover, these complexities may obscure the relationship between salmon contaminant flux and stream-resident fish contaminant burden, given that fish are likely integrating PCBs from multiple salmon runs.

Our bioenergetics-bioaccumulation model provided insights into the nature of contaminant biotransport and bioaccumulation. First, running the model without gorging lead to small increases in growth and intermediate increases in PCB concentration. These responses alone do not account for the range of concentrations observed in Brook Trout from our basin-wide survey. However, when simulating the effect of fish exhibiting gorging behavior, projected concentrations approximated the median of the observed field data. Recent research from the native range of Pacific Salmon highlights that dietary plasticity (e.g., consumption of salmon eggs) and ration size can influence growth outcomes (Armstrong et al. 2013, Armstrong and Bond 2013, Baldock et al. 2016, Jaecks et al. 2014). In both the native and non-native range of salmon resident fish exhibit 10-100 fold increases in energy intake through salmon egg consumption (Ivan et al. 2011, Jaecks et al. 2014) but this pattern is subject to considerable variation among individuals (Merna 1986). Moreover, Armstrong and Schindler (2013) highlight in a meta-analysis that piscine predators have the physiological capacity to effectively double or triple gut capacity in response to both spatial and temporally heterogeneous prey resources. Thus, stream-resident fish, such as trout, may be evolutionarily adapted to deal with feast or famine in resources. This adaptation, which allows use of temporally disjunct salmon subsidies, is likely responsible for regulating the bioaccumulation of contaminants in fish exposed to migratory fish runs. In addition, our model indicated that a significant proportion of the PCBs accumulated by Brook Trout from salmon eggs consumption are retained over the course of a year and carry over among years. This finding indicates that the contaminant burden within a fish can be an integration of multiple years worth of salmon runs. Variation in salmon run sizes known to occur among years then likely contributes to the overall variability we observe in our survey. Last, the influence of growth dilution is particularly apparent when we compare the growth trajectories and PCB concentrations between the medium gorging and high gorging scenarios. PCB concentrations are essentially equivalent between scenarios but the PCB mass of brook trout is ~2 times higher in the high gorge scenario. Thus, increased growth in the high gorge-high salmon scenario leads to significant growth dilution. Moreover, heterogeneity in stream temperature may facilitate either contaminant accumulation or dilution. This pattern has been shown to influence growth of juvenile Coho Salmon in Alaskan salmon streams (Armstrong et al. 2013). One broader implication of these results is that making stream or watershed projections about the level and risk of salmon biotransport may be challenging because of the high degree of uncertainty manifest in our simulations. More specifically, projecting the contaminant level of an individual fish in a specific stream with sufficient certainty will be challenging because of the absence of information about the location and abundance of salmon spawners. One recommendation for future work would be to work with agencies to identify those locations that are accessible by salmon spawners and where salmon are actively stocked because one important factor in contaminant burden of stream-resident fish is simply the presence of salmon.

Broader insights from project

Contaminant biotransport involves several different processes. This includes bioaccumulation of contaminants by an organism; movement of the organism and contaminant across an ecosystem boundary, and then the release of the contaminant into the recipient ecosystem (Blais 2005, Blais et al. 2007). The effects of contaminant biotransport are magnified when the mechanism of contaminant release into the recipient ecosystem is through direct consumption (Merna 1986, Janetski et al. 2012) or pollution to the base of the food web (Michuletti et al. 2010). Dramatic examples of contaminant biotransport include colonial nesting birds as well as migratory fish because both deliver a large pollutant flux to a relatively confined area over a short period of time as a result of their reproductive behavior (Blais 2005, Blais et al. 2007). Blais et al. (2007) proposed that semelparous fish represented a particular risk to aquatic systems because of their capacity to liberate large quantities of contaminated tissue because of senescence and death. In addition, Blais et al. (2007) suggest that iteroparous fish, such as widely distributed Arctic Char (*Salvelinus alpinus*), represent a reduced risk for contaminant transport because their life history meant the material delivered was largely limited to eggs. Our research suggests, however, that gametic tissue, such as eggs, may influence disproportionately the contaminant burden of stream-resident fish due to their nutritional value and contaminant content. Much like salmon, iteroparous fish, such as Steelhead (*Oncorhynchus mykiss*) and Atlantic Salmon (*Salmo salar*), migrate *en masse* and deliver eggs that are readily consumed by stream-resident fish (Johnson et al. 2016). Future research on contaminant biotransport should focus on assessing the flux of material deposited by *all* migratory fish, non-native and native, iteroparous and semelparous, to establish what members of the Great Lakes fish community present the greatest risk with respect to contaminant biotransport to tributaries.

Deeper understanding of the ecosystem and associated organisms that receive the biotransported contaminants could provide the best framework for understanding contaminant biotransport at broader spatial and temporal scales. Clements et al. (2012) proposed that bioaccumulation could vary in a theoretical aquatic food web due to (1) larger inputs of contaminants at the base of the food web; (2) longer food web length; or (3) altered rates of biomagnification. This conceptual framework conveniently lends itself to evaluate the food web implications of contaminant biotransport. In the context of contaminant biotransport in the Great Lakes, salmon lengthen the food web and circumvent the inefficiencies of bioaccumulation by allowing stream-resident fish to feed at a higher trophic level through consumption of salmon eggs that we have shown significantly influences POP bioaccumulation. Furthermore, in our survey we found strong evidence for the interaction between salmon biomass and species identity for POPs, suggesting species-specific biomagnification rates. Differing rates of bioaccumulations are likely due to the compounding effects of consumption (e.g., diet proportion, ration size) of contaminated tissue, habitat (e.g., depositional and spawning locations), and species-specific physiology (e.g., assimilation efficiency, growth rate). From our survey and experiment we found no evidence that salmon increased total mercury concentrations in stream-resident fish, and therefore conclude that other factors likely overwhelm the effect of salmon (cf., Baker et al. 2009). In our survey and experiment, we did not directly assess the influence of bottom-up, indirect processes. However, our results suggest that the effect of these processes would be much smaller than direct consumption of salmon eggs because of the relative inefficiency of food web bioaccumulation. For instance, direct consumption of salmon eggs represents food source 25 times more contaminated than other sources, such as aquatic invertebrates. In spite of eggs being a resource that is available for a short amount of time, widespread consumption could lead to sharp increases in POP levels.

Chemical tracers, such as stable isotopes, are commonly used in ecology to document the movement of material, including nutrients, energy, and contaminants, through ecosystems. In ecology and ecotoxicology, different tracers can be useful for tracking protein, lipid, or carbohydrates in order to establish more complete profiles of consumer resource use (Ramos et al. 2013). For instance, POPs generally track the lipid fraction of tissue, while heavy metals, such as mercury, are associated with the protein fraction (Mackay et al. 2000, Walters et al. 2008). Non-traditional tracers, such as POPs and their congeners, offer additional insight during the assessment of ecosystem linkages and resource use when isotopic differentiation is insufficient to identify prey items or when isotope data are unavailable (Ramos et al. 2013). This is particularly the case when the vector has a high contaminant burden relative to the recipient. Contaminants have been used to document the export of material from streams via emergent insects, material transport by colonial nesting birds, and to identify foraging areas used by Atlantic salmon (Walters et al. 2008). Similarly, our data suggest that POP congener patterns and contaminant burdens can be used to assess interactions between migratory salmon and resident fish. However, much like stable isotopes, many factors influence pollutant patterns, including habitat-specific foraging, location-specific contamination, individual physiology, and life-history attributes that can complicate interpretation of tracer data. Although not perfect, POPs contaminants do offer an additional tool for establishing pathways by which energy and nutrients move through and between ecosystems. In addition, POPs are routinely monitored by state and federal agencies to inform consumption advisories across broad geographical areas and river networks. Large pollutant datasets, such as by the US EPA Great Lakes Environmental Database (GLENDA, catalog.data.gov/dataset/great-lakes-environmentaldatabase-glenda), could be leveraged in ecological and ecotoxicological studies to evaluate factors that influence contaminant concentration and pattern (cf., Rasmussen et al. 2014). Such work would hopefully also allow a better understanding of the resource subsidies delivered by non-native migratory fish, such as Pacific Salmon. In particular, future studies should consider incorporating nontraditional tracers, such as POPs or heavy metals, with more traditional isotope approaches, to help elucidate the pathways of uptake and assimilation of such non-native resource subsidies. Such resource subsidies have already been shown to increase growth rates of stream-resident fish in the native range of salmon (cf., Bilby et al. 1998, Wipfli et al. 2003). Future research should evaluate this response empirically outside of the native range in the Great Lakes, such as by coupling short-term mark-recapture experiments (cf., Wipfli et al. 2003, 2008) with longer-term population monitoring to. Several studies in the Great Lakes have highlighted that resident fish can incorporate migratory fish eggs into their diet (Johnson and Ringler 1979, Merna 1986, Ivan et al. 2011, Johnson et al. 2016), increasing the energy intake as result (Ivan et al. 2011). However, no study has examined whether consumption of these resource subsidies are linked to increased population abundance or larger individual growth rates (ct., Bilby et al. 1998, Wipfli et al. 2003). Understanding whether migratory fish have a positive or negative on growth would inform future management of fish passage and contaminant biotransport in the Great Lakes.

Application of knowledge from project

Introduced Pacific Salmon populations are intensely managed in the Great Lakes for the economically important open-water and riverine recreational fishery. Non-native Pacific salmon were introduced in the mid-1960s with the intent of them acting as a biocontrol agent on invasive alewife while also helping to rehabilitate predator populations given that native Lake Trout (*Salvelinus namaycush*) had been decimated by invasive Sea Lamprey (Dettmers et al. 2012). Overall, this introduction was successful in terms of controlling alewife but also for maintaining the sport fishery, but negative impacts on native species and bioaccumulation of contaminants are now evident (Madenjian et al. 2008). Currently, whole lake ecosystem changes due to non-native mussels has shifted the trophic base of production away from the open water pelagic zone to the nearshore benthic zone, altering the available prey base for salmon in Lake Michigan (Bunnell et al. 2012). Lake Huron underwent similar changes beginning in 2004, and now only a small salmon fishery remains (Dettmers et al. 2012). The changing lake dynamics have altered how salmon are managed primarily through reductions in fish stocking. Reduced stocking sought to optimize the ratio of predators to prey in an effort to maintain the Chinook fishery in Lake Michigan (Tsehaye et al. 2014). Such changes in ecosystem dynamics, salmon populations, and fish stocking have implications for salmon-mediated contaminant biotransport in the Great Lakes. Reductions in overall population size and stocking rate will reduce the number of salmon spawners in streams, and consequently the overall flux of pollutants delivered by salmon. However, uncertainty remains in predicting contaminant biotransport impacts by salmon under these scenarios. For instance, more than half of the Chinook populations in Lake Michigan are believed to be of wild origin (Williams 2012). So one uncertainty is whether lower spawner densities will improve juvenile survival (i.e., compensatory response), allowing wild recruitment to increase, and in turn increasing the number of wild spawning salmon (Walters and Martell 2004). This could potentially lead to streams with the highest quality habitat for early life stages of salmon becoming 'hotspots' for contaminant biotransport relative to stream reaches with degraded or sub-optimal habitat. Thus, whether changing recruitment dynamics will result in a net reduction or increase in salmon mediated movement of contaminants is unknown.

Salmon mediated contaminant biotransport is at present not monitored or managed by state agencies. Our data for PCB concentrations of trout from 11 streams in Lake Michigan tributaries receiving salmon suggests that 8 had concentrations that would warrant consumption advisory for PCBs based on state and federal advisory levels. Moreover, many of these streams are considered to lack point sources of pollution and exhibit intact riparian corridors, little human development, and are often located in state or federal lands. However, in these areas spawning salmon can act as a predictable point source of pollution to streams with consequences for the fish communities within. To get a better sense of the scale of this problem, monitoring agencies could leverage the large quantity of data they already collect in order to better assess the extent of contaminant biotransport in streams receiving migratory fish. For instance, a relatively simple analysis using existing data on stream fish PCB concentrations and locations open to migratory fish could provide the insights needed to assess the potential magnitude of salmon-mediated contaminant biotransport at a regional level. In addition, future monitoring could focus on developing rapid ways to assess salmon spawner abundance in tributaries. We found, in general, that streams with larger salmon runs had higher contaminant burdens. Originally, we proposed to project which stream reaches were most as risk of biotransport. However, given the variability of concentrations observed within stream reaches it was apparent that it is not currently possible to make reliable projections of the contaminant concentrations of stream-resident fish in watershed across the Great Lakes. Shifting focus to a sampling regime that monitors the size and duration of runs would likely be the most fruitful avenue for prediction and management of salmon contaminant biotransport. Moreover, salmon are not considered a pollution source, in part, because they defy the conventional paradigm of pollution flowing from upstream to downstream with water flow. Our research should allow federal and state biologists and toxicologists to foster awareness of the issue of contaminant biotransport and develop science education material for the public. Such educational resources and outreach materials would ideally highlight stream reaches open to salmon and describe how contaminant biotransport occurs. This is especially important in Native American communities that are given special access to fish, for example having spearing fisheries for spawning fish, and consume larger quantities of Great Lakes fish than other components of the North American population.

Managers might consider how contaminant biotransport might be more actively managed. However, such pollutants present a difficult challenge for managers because they represent a diffuse source of pollutants across the landscape that requires different mitigation techniques then has been traditionally used to manage environmental contaminants (cf., Qi et al. 2014). Traditional techniques rely on engineering approaches to stop physiochemical non-point sources, such as removal of contaminated sediments or prevention of contaminated leachate loss. By contrast, contaminant biotransport represents a biological non-point source of pollution to streams that actually works against the usual physical movement of material (e.g. downstream transport). Literature concerned with managing non-point sources of nitrogen or phosphorus (Carpenter et al. 1998) and preventing the spread of invasive species while maintaining connectivity (Rahel 2013) is relevant to potential approaches to managing contaminant biotransport by migratory fish. Techniques for managing non-point sources of pollution have been effective at reducing transport of fertilizers to streams when threshold levels of nutrient levels are defined, source locations or "hot-spots" are delineated, and best management practices are implemented (Carpenter et al. 1998). Future management could minimize contaminant biotransport through selective stocking with salmon so that contamination of systems prioritized for fish conservation is avoided, or the implementation of seasonal barriers that limit contaminant influx to streams by spawning salmon. This has significant implications because the Great Lakes many species that exhibit a migratory life history, and where eggs are deposited in the process. Moreover, these species differ in many different ways, including the spawning modes (e.g., broadcast versus redd construction), size of individual (e.g., Lake Sturgeon versus Salmon versus Sucker), run size (e.g., very small (Lake Sturgeon), intermediate (Salmon, Steelhead), very large (Suckers)). Understanding the composition of migratory fish runs along with their contaminant levels in the Great Lakes by characterizing how the dynamics of migratory fish spawning runs vary by species and location would allow for a much more nuanced evaluation of which species in which locations posed the greatest risk with respect to contaminant biotransport. In addition, expanding research to quantify the extent to which resident, non-migratory fish utilize resources supplied by migratory fish would provide a more detailed understanding of the influence of such fish movements on stream-resident fish communities.

The effects of legacy contaminants and man-made dams on aquatic ecosystems are ecological problems relevant to the Great Lakes and its associated fisheries (Stanley and Doyle 2003). Migratory fish such as Pacific Salmon can impact stream-resident fish through (1) transport of contaminants accumulated in their bodies to spawning streams, where they can be assimilated by stream-resident fish; (2) shifts in diet and growth trajectories with the influx of high quality food items such as eggs; and (3) changes in fish community structure. Removal of obsolete dams can benefit tributaries by increasing sediment transport, restoring natural thermal and flow regimes, and extending migration corridors for fish (Poff et al. 1997). However, dam removal may have unintended consequences for Great Lakes tributaries by allowing colonization by invasive species as well as contaminant biotransport by migrating fish (Lanse et al. 2014, McLaughlin et al. 2013). Clearly dam removal can provide ecological benefits but careful consideration and prioritization should be considered to minimize risk of contaminant transfer given our results. Mitigating the impacts of salmon contaminant biotransport may be possible by using a combination of both modeling and on-the-ground approaches. For instance, a joint project between the Nature Conservancy and the University of Wisconsin-Madison has developed a barrier optimization tool where potential conservation gains (as indicated by miles opened up) can be balanced against the risk of Sea Lamprey colonization (greatlakesconnectivity.org/). This approach could be linked to our work on contaminant biotransport to provide insight into potential areas where the benefits of leaving barriers to mitigate against potential upstream impacts of contaminant biotransport outweigh those of restoring ecosystem connectivity. Similarly, an optimization approach may help establish allowable levels of contaminant transport to streams; Rahel (2013) argues that while the effects of reestablishing connectivity have lasting ecological effects for mobile organisms, those benefits must be prioritized in ways that balance against the downsides of connectivity. In addition, approaches used to control Sea Lamprey, such as temporary, seasonal barriers may be effective tools for minimizing upstream contaminant biotransport (Siefkes 2014). In other words, barriers could be erected at positions lower in watersheds to prevent salmon from obtaining access to areas upstream which have been identified as being important such as intact native fish communities, low background contaminant levels, or high angler use. This approach could be piloted using existing Sea Lamprey barriers and the success of the program evaluated. Another approach to consider involves a resistance board weir, which are commonly used to assess salmon runs in Alaska (Tobin 1994). The weir consists of a series of PVC pipes that create an impassable, floating fence across the river. Each individual PVC pipe is spaced a sufficient distance to allow movement of smaller resident trout, and non-game species, such as sculpin, while preventing movement of larger migratory species, such as salmon. This technique could be piloted in the Great Lakes in an effort to reduce biotransport risks associated with Pacific salmon while minimizing the impact of such an approach on smaller native fish species.

Challenges and benefits of project

Several challenges were encountered when conducting this project. One challenge was the variability among individual fish that complicated the relationship between salmon and stream-resident fish contaminant burdens. Contaminant concentrations in stream-resident fish, collected from the manipulative experiment (Brook Trout SD=109 ppb, Brown Trout SD=87 ppb) or survey (Brook Trout SD=159 ppb, Brown Trout SD=195 ppb) suggest very individual responses of fish. In addition, salmon exhibited large variation, both for whole fish (SD=174 ppb) and eggs (SD=172 ppb). Such variability makes predictions with an acceptable level of certainty across both space and time, very challenging. This variability also highlights that fish resident in streams with small salmon runs can still become contaminated due to individual behavior and circumstances, such as consumption of eggs or lack of growth dilution. Our data also highlighted that small-scale variation in physicochemical variables is likely to be unimportant in determining contaminant transfer. So while physicochemical variables can modulate bioaccumulation in streams, the significance of these factors is swamped out by the influence of salmon that may themselves increase concentrations in stream-resident fish by more than 20-fold. The second challenge was full characterizing salmon spawner abundance given constraints on travel and personnel. This inability to fully characterize the dynamics of the salmon run may account for some of the variation in the relationship between stream-resident fish contaminant burden and the salmon-mediated pollutant flux. Future research should focus on better understanding and characterization of salmon spawner dynamics in Great Lakes tributaries. Such data will be needed if managers are going to manage contaminant biotransport, not only with respect to salmon but also other migratory fish species. The third challenge was the declines in salmon population in the Great Lakes. Our study was conducted during a period when salmon runs were lower across much of the Great Lakes. This included in Lake Michigan tributaries where we thought that contaminant biotransport impacts would be most pronounced because of a combination of large salmon abundance and individual contaminant burden. Despite salmon populations changing because of altered energy pathways and stocking rates, our results showed that even in tributaries receiving smaller salmon runs, contaminant burdens in stream-resident fish could still be substantial.

Despite the challenges, there were several benefits from the project. First, was the complementary nature of the project, which combined broad-scale surveys, replicated experiments, and modeling (cf., Hilborn and Mangel 1997). The survey allowed the project to define the extent of contaminant biotransport to stream-resident fish in the Great Lakes. The experiment allowed identification of the important pathways by which stream-resident fish become contaminated by salmon. The modeling framework facilitated understanding how variability in contaminant accumulation is a function of growth, diet, and ration size. Overall, this nested project succeeded because of the realism of the survey, control in the experiment, and flexibility of the model. Taken together, these components provide the clearest picture to date of how contaminant biotransport mediated by migratory fish operates. The second benefit of our project was the use of two different contaminants types (i.e., POPs versus mercury). Specifically, use of multiple contaminants as a tracer allowed us to effectively identify salmon eggs as the likely pathway for contaminant uptake by stream fish. Moreover, the clear distinction between the burden of PCBs and mercury in eggs and salmon tissue highlight the utility of the approach of using contaminants as tracers of movement of material, especially from migratory fish species. Finally, another benefit of the project is that enabled us to interact with personnel from multiple state and federal agencies. These interactions helped raise the profile of issues related to salmon-mediated contaminant biotransport but also has potential help provide a more holistic evaluation of ecosystem health in tributaries of the Great Lakes.

Conclusions

Our research provides an increased understanding of the mechanisms and nuances surrounding the process of contaminant biotransport by Pacific Salmon into Great Lakes tributaries. Overall, our research has shown convincingly that salmon, at differing scales, levels of control, and frameworks, have a marked impact on stream-resident fish contaminant burden. However, salmon do not uniformly impact the stream-resident fish community and the magnitude of their effect appears tightly linked to the basin-scale extent of contamination, salmon spawner abundance, and stream-resident fish species identity. In addition, we found that salmon eggs are enriched in PCBs but depleted in mercury, which highlights that all tissues deposited by salmon are not the same with respect to their concentrations of different contaminants. Using our coupled bioenergetics-bioaccumulation model, we showed how high levels of variation in stream-resident fish contaminant levels could arise as a function of different diet proportions and ration size. These results highlight that contaminant biotransport is context dependent at scales from the regional to the individual. Furthermore, our research has implications for the stocking of non-native species and the emerging restoration tool of dam removal. Specifically, our research makes a strong case that the impacts of contaminant biotransport by salmon on stream-resident fish are most strongly influenced by egg consumption. Hence, being semelparous and producing large amounts of contaminated carcass material does not appear to be as large an influence on contaminant burden of stream resident fish as salmon eggs. This highlights the need to assess how both introduced and native migratory fish may act as a vector of contaminants into the tributaries of the Great Lakes.

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