Project Number WR11R002

CLIMATE CHANGE IMPACTS ON STREAM TEMPERATURE AND FLOW: CONSEQUENCES FOR GREAT LAKES FISH MIGRATIONS

Peter McIntyre
Center for Limnology
University of Wisconsin-Madison

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Climate change impacts on stream temperature and flow: consequences for Great Lakes fish migrations

WRI Completion Report

Submitted by Dr. Peter McIntyre, UW-Madison Center for Limnology

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Project Summary

Title: Climate change impacts on stream temperature and flow: consequences for Great Lakes fish migrations

Project ID: WR11R002

Investigator: Peter McIntyre, Assistant Professor, Center for Limnology; Evan Childress, PhD student, Freshwater & Marine Sciences

Period of Contract: March 1, 2011 through February 29, 2016

Background/Need: Having achieved consensus that Wisconsin's air and water are warming under global climate change (http://www.wicci.wisc.edu/), a key challenge now is to understand the breadth of ecological impacts. Wisconsin citizens benefit greatly from the services provided by water resources, and fisheries have particular cultural importance. Present understanding of climate warming impacts on fish is based largely on thermal tolerances; effects on breeding behavior and success are poorly known. Many important fish species migrate from the Great Lakes into tributaries to breed every year, and potential cues for these migrations (temperature, flow) are being altered by climate change. However, historical rates of change in migration timing are unknown, the abiotic triggers of migrations remain uncertain, and ecosystem responses to fish migrations have not been determined. *This project addresses needs for both scientific and public understanding of climate-driven shifts in the timing of Great Lakes fish migrations, and their ecological implications.*

Objectives: *Objective 1*: Quantify the historical timing of Great Lakes fish migrations into Wisconsin tributaries. *Objective 2*: Monitor the current migration timing along a latitudinal gradient of Wisconsin tributaries to identify threshold temperature and flow levels that trigger the onset of migrations. *Objective 3*: Predict how the timing of migrations is likely to shift with future climate change, and evaluate the implications from species to ecosystems.

Methods: To assess long-term trend in the timing of fish migrations across decades for a large number of US tributaries of the Great Lakes, we mined the US Fish and Wildlife Service's sea lamprey electric barrier data for the period 1950-2011. These data include daily (or nearly) records during the spring season for ~150 watersheds. However, few observation sets extend >20 years in a single watershed. To take advantage of the spatial extent of these data while minimizing the limitations arising from short time series per site, we developed a flexible Bayesian hierarchical spatial regression model that quantifies spatial and temporal trends. The model has two levels: a lower one that models the temporal trend in migration at each tributary, and an upper one that models the spatial variation in the trends, thereby accounting for spatial autocorrelation. The Julian day on which the maximum number of fish was observed provides an index of timing, and we analyzed the anomaly from the long-term average for each stream. Our work to date has focused on migratory species: white sucker and sea lamprey.

To understand the cues triggering migrations, we worked with Wisconsin DNR to identify 12 local citizens who recorded the arrival of suckers by checking a road crossing daily at a single stream in 2011 and 2012. We measured daily temperature and discharge in each stream, enabling us to analyze migration timing with respect to latitude, temperature, and discharge.

We planned to combine ecosystem monitoring and projections of stream flow and temperature to assess the future timing and significance of migrations. Unfortunately, our USGS partners lost funding for projections. To understand ecosystem responses to migrations, we conducted detailed studies of migration dynamics, nutrient inputs, stream metabolism, and larval export.

Results and Discussion: We found that the timing of fish migrations into Great Lakes tributaries is highly sensitive to water temperature, supporting the possibility that warming waters has and will shift spring migrations toward earlier calendar dates. However, historical migration data reveal more complex phenological shifts. For both suckers and lamprey, some locations are seeing later migrations, while fish are moving earlier in others. Such variability contrasts with general warming of the lake surface near every study stream from 1994-2011. Historical records of stream temperatures during the spring are not available for most streams, making it difficult to resolve the basis for complex shifts in timing. However, parallel work on lake-spawning species also indicates variable effects on reproductive phenology.

Our citizen science network provided evidence that tributary temperature, not flow or lake temperature, is the salient migration cue for suckers. The observed offset of migrations by ~10 days between southern and northern Wisconsin echoes differences in spring warming of streams. Since stream temperatures track air temperatures, this form of cue has likely shifted across the region by days-to-weeks over the last century. Equally importantly, our work offers the first proof that citizen science can yield useful data on fish migration phenology.

We found strong evidence that migrations are key events in tributary ecosystem dynamics. As thousands of suckers spawn and leave during a month-long run, they provide nitrogen and phosphorus. These nutrients boost primary productivity, benefitting all stream biota. Larval suckers pour out of river mouths in synchrony, creating a major food resource for predatory fishes. Thus, these migrations play a key role in the annual productivity cycle of the ecosystem.

Implications: Though the timing of spawning migrations is changing in the Great Lakes, the direction and magnitude of shifts is complex. Changes are expected to continue into the future, potentially decoupling critical ecosystem processes that were previously synchronized. Such phenological decoupling is a subtle yet profound threat to fisheries and ecosystem sustainability.

Related Publications:

Childress E & McIntyre PB. 2016. Life history traits modulate ecosystem-level effects of nutrient subsidies from fish migrations. *Ecosphere*, in press.

Childress ES, Papke R, & McIntyre PB. 2016. Reproductive success and early life history of suckers in Great Lakes tributaries. *Ecology of Freshwater Fish*, in press.

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Key Words: phenology, sucker, subsidy, nutrients, potamodromous, metabolism

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INTRODUCTION

Having achieved consensus that Wisconsin's air and water are warming under global climate change (http://www.wicci.wisc.edu/), a key challenge for scientists now is to understand the breadth of ecological impacts of climate change. Wisconsin citizens benefit greatly from the numerous services provided by our water resources, and fisheries have particular cultural importance. Present understanding of the likely effects of climate warming on fish ecology and fisheries productivity is based largely on studies of thermal tolerances; little attention has been directed toward impacts on the breeding behavior and success of important fish species. Many of the key sportfish and non-game fishes of Wisconsin migrate from lakes and large rivers into tributaries to breed every year. These migrations are triggered by temperature or flow cues whose reliability and timing are being altered by climate change. Several initiatives are underway to forecast shifts in these abiotic conditions, but the implications for the future of fish migrations and the host of ecological and economic processes they support are unknown. Moreover, the public at large struggles to understand the value of research on the physicochemical effects of climate change. The abiotic-biotic coupling underlying fish migrations offers an ideal opportunity for outreach that leverages broad public interest in fish and fisheries. *Thus, this project addressed needs for both scientific and public understanding of the ecological impacts of climate-driven shifts in water temperature and flow using the timing of Great Lakes fish migrations as a case study.*

PROCEDURES AND METHODS

<u>Objective 1</u>*: To obtain a historical context for the timing of fish migrations, and to assess long term trends across decades for a large number of US tributary rivers*. The US Fish and Wildlife Service collected a unique data set as part of their lamprey control program that included data for multiple migratory species over a period of six decades. Our initial analyses indicated that 8 of 13 species showed earlier peak spring migration dates through time. Earlier migration timing is consistent with the hypothesis that ever-warmer spring temperatures are advancing fish spawning phenology. However, this pilot analysis suffered from low sample size at most sites.

To make best use of the incomplete matrix of observations across sites and years, we developed a flexible Bayesian hierarchical statistical model to quantify shifts in migration timing simultaneously across sites. This approach draws strength from the breadth and duration of observations to inform inferences at any one site even in the absence of direct data. Our analyses span a total of 182 tributaries from 1950–2011, though few observation sets extend >20 years in a single watershed. The model has two levels: a lower one that models the temporal trend in migration at each tributary, and an upper one that models the spatial variation in the trends, thereby accounting for spatial autocorrelation. Initial model development focused on the date of the first fish observation, but we discovered that this appears to be biased by variation in when observations began each year. Thus, we focused solely on the timing of maximum migrant densities for white suckers and sea lamprey, the two most abundant species in the dataset. We used the anomaly from the long-term average for each stream to standardize observations across sites before analysis.

Rather than relying on a single lake surface temperature measurement to identify the migration cue, we defined the cue temperature regime based on the average temperature during 15 days prior to the first migration day. We extracted that information for white suckers in every stream for years where remote sensing data allowed it, then used functional data analysis to identify the time period in every year of fish observations that most closely resemble the typical temperature regime to trigger a migration. The final day of that period was designated as the estimated Julian date of cue temperature.

<u>Objective 2</u>*: To identify the cues that trigger fish migrations using data derived from a citizen science network of observers in Wisconsin.* Citizen science is an effective way to engage citizens and educate them about the local impacts of climate change. Additionally, it provides a mechanism for collecting data simultaneously across a broad geographic range. We established a volunteer monitoring network to observe the sucker migration along the Wisconsin shore of Lake Michigan to determine the current migration phenology and evaluate migration cues. Suckers were chosen because they are ubiquitous, abundant, and easily identifiable.
We collaborated with the WDNR and UW Extension volunteer monitoring program to identify and contact potential volunteers. The USGS provided stream gauges that were installed in each stream along with a temperature logger. Each volunteer was trained in fish identification, and an observation site was chosen to maximize visibility and convenience.

In 2011, 20 volunteers monitored sucker arrival, temperature, and flow levels in 15 tributaries spanning over 200 miles of Lake Michigan shoreline. In 2012, volunteers were again prepared to monitor, but unfortunately the fish arrived two months prior to the 2011 arrival date. Thus, our citizen monitoring had not yet been initiated when most migrations began, and we were unable replicate the 2011 results. Nonetheless, data on phenology were collected opportunistically at a few northern Wisconsin streams where the migration had not yet begun, and in Green Bay through others project within our broader research team. We did not attempt to reinstate citizen science monitoring in 2013 due to the need to pursue other project elements.

<u>Objective 3</u>*: To predict how the timing of migrations is likely to shift with future climate change, and evaluate the implications from species to ecosystems.* This project element was envisioned to include collaboration with USGS researchers on projecting future stream flow and temperature patterns, as well as field research to quantify ecosystem responses to spring fish migrations. Projections were not possible due to funding cuts to our colleagues at the USGS Wisconsin Water Science Center, therefore we focused on measuring ecosystem dynamics during migrations to understand the broader effects of shifting phenologies.

During the spring migrations in 2012 and 2013, we conducted a series of detailed studies on stream metabolism (measured using time series of oxygen dynamics), nutrient inputs (measured using water samples), algal growth limitation by light and nutrients (using nutrient diffusing substrates), and larval sucker production (using drift nets).

RESULTS AND DISCUSSION

Historical phenologies

Based on lake surface temperature data, the cue temperature regime moved to earlier dates throughout the period from 1995-2011 in most streams, suggesting that fish should be shifting to earlier migration timing across the Great Lakes. However, the actual migration data indicate both positive and negative trends in peak migration timing from 1950-2011 for both white suckers and sea lamprey (Figure 1). There are geographic patterns evident, though they defy simple summary.

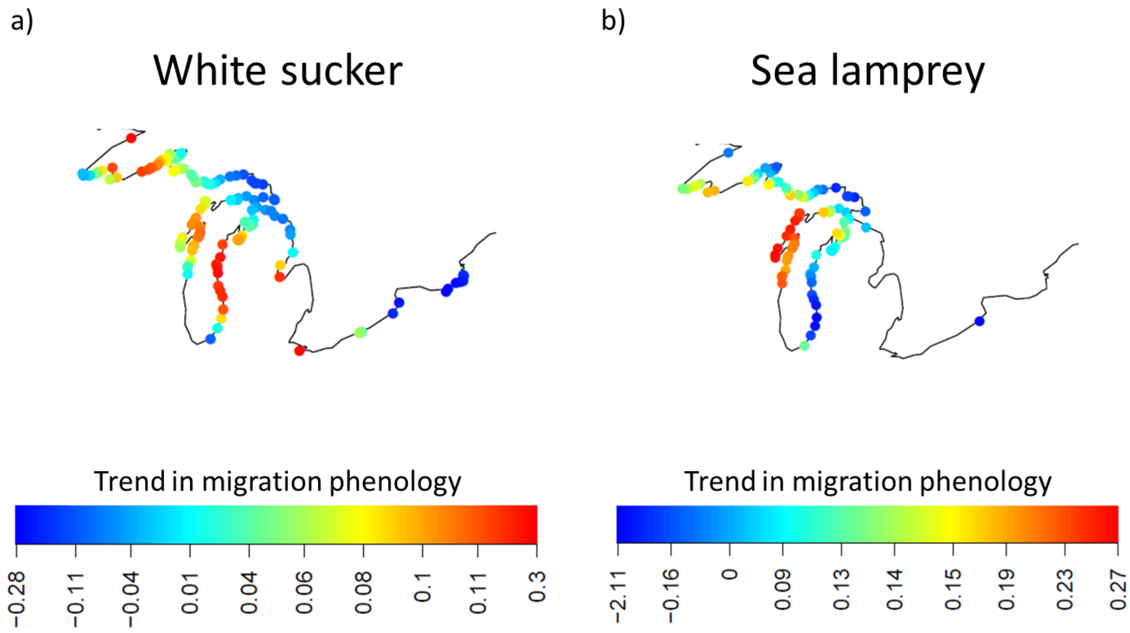

Figure 1. Spatial variation in the trend of migration timing for both species. The colour of each location reflects how many days per year the migration is changing. On a decadal scale, a coefficient of 0.3 indicates a change of 3 days per decade. Negative numbers in blue indicate a trend toward earlier migrations, while positive numbers in red indicate a trend toward later migrations.

Our statistical model, the most complete and sophisticated to date, suggests extensive heterogeneity in fish responses to climate change. Specifically, it is noteworthy that suckers and lamprey in some regions appear to show strong shifts to later spring migrations, despite consistent warming of lake temperatures (Figure 2). Further analyses are ongoing, therefore we consider the current patterns to be preliminary.

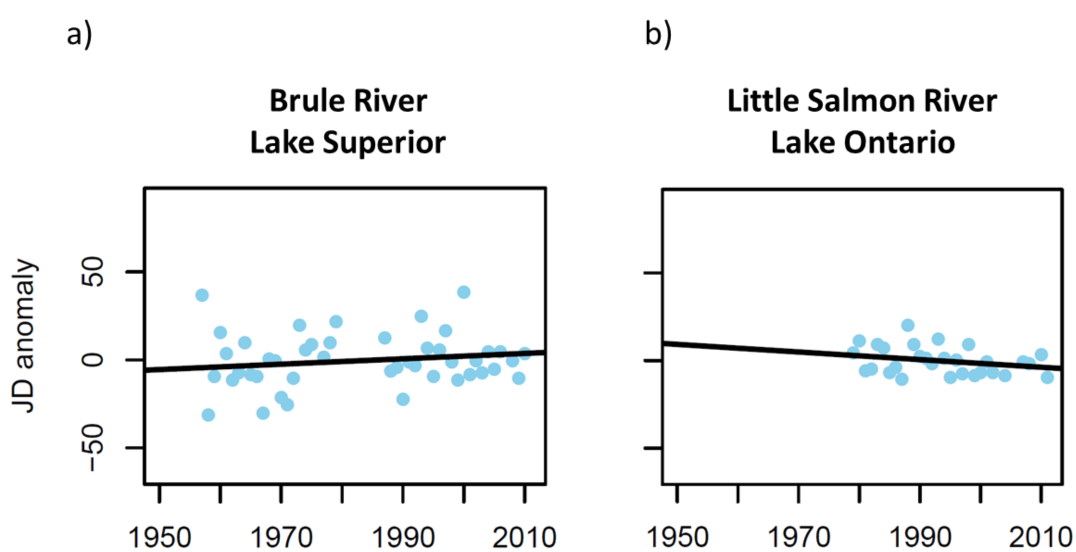

Figure 2. Scatter plots of Julian Day of the peak of migration at two rivers, each showing distinctive temporal trends. Brule Rive is located toward the western edge of Lake Superior, while the Little Salmon River on Lake Ontario is located on the eastern shores of the lake in New York.

The disparity between lake temperature trends fish migration timing underscores the need for better stream temperature data. We have recently received four stream temperature records (1950s to present) from USGS that we were unaware of, and we will couple these with the century-long record from the outlet of Lake Superior at Sault St. Marie to assess whether this heterogeneity derives from stream temperature shifts that diverge from lake temperature shifts. Our Bayesian hierarchical model will then enable us to draw upon the space-time mosaic of migration observations while also accounting for spatially variable shifts in stream temperatures. We have not completed these analyses yet, but they will provide a state of the art perspective on rates of change in fish migration timing. If the approach is successful for white suckers and sea lampreys, we will repeat it for all other species in the database (e.g. walleye).

Migration cue determination through citizen science

Our citizen science results from 2011 indicated that sucker arrival timing was closely linked with temperature but showed no clear pattern relative to flow. Mean temperature on the day of the first pulse of fish was 7.6˚ C (SD = 0.6) (e.g., Fig. 3). Despite the variability among sites in the start date of the migration, water temperatures at the start of the migration were highly consistent. In contrast, fish arrival was not associated with any particular hydrograph component. In some streams, fish arrived during high flows, but in others they arrived after long periods of declining flows (Fig. 4). This indicates that migration timing depends primarily on water temperature.

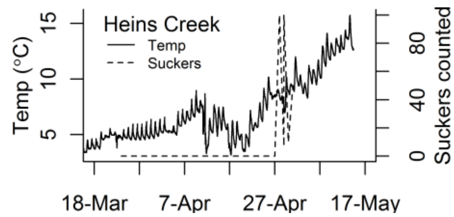

Figure 3. *Example of the timing of sucker migrations relative to stream temperature in 2011.*

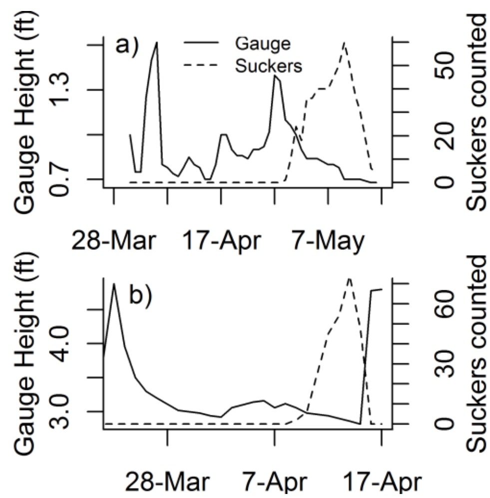

Figure 4. Examples of the timing of sucker migrations relative to stream discharge in (a) Fish Creek and (b) Oak Creek in 2011.

Ecosystem effects of sucker migrations

We found strong evidence that migrations are key events in tributary ecosystem dynamics. As many as 12,000 suckers may spawn in a single small stream, though there is extensive variation among watersheds. The size of runs does not accord clearly with watershed area or tributary discharge, and we also observed moderate interannual variation. The reasons for these differences remain unknown.

As thousands of suckers spawn and leave during a month-long run, they significantly elevate stream nitrogen concentrations (Figure 5). Interestingly, we calculate that phosphorus must be provided as well, but concentration data show little consistent evidence of boosted availability of phosphorus.

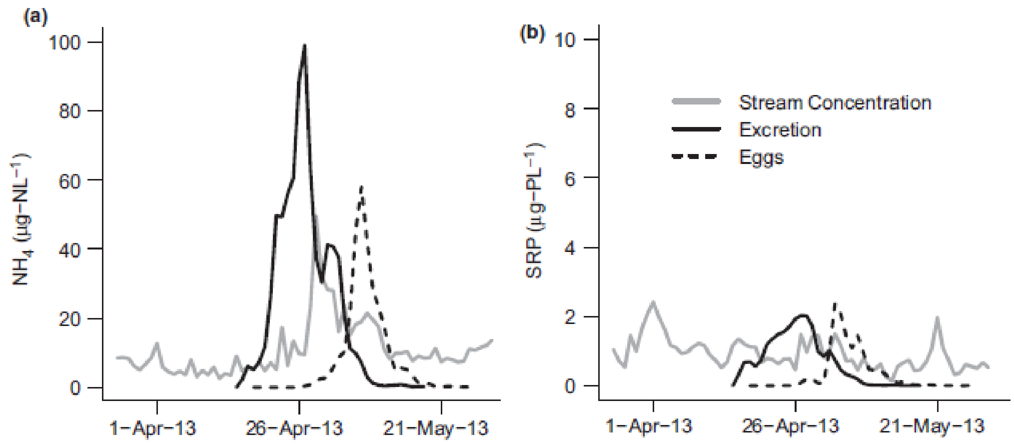

Figure 5. Dynamics of nutrient inputs via nutrient excretion (black line) and eggs (dashed line) relative to observed stream concentrations of nitrogen (a) and phosphorus (b). Stream concentrations of nitrogen and phosphorus remained unchanged in a reference stream with no fish migration.

Our nutrient diffusing substrate experiments indicate that algal growth is enhanced primarily by added phosphorus, sometimes with secondary benefits of adding nitrogen (Figure 6). This experiment indicates that fish migrations are likely to boost ecosystem productivity to the degree that they provide a source of phosphorus in bioavailable chemical form.

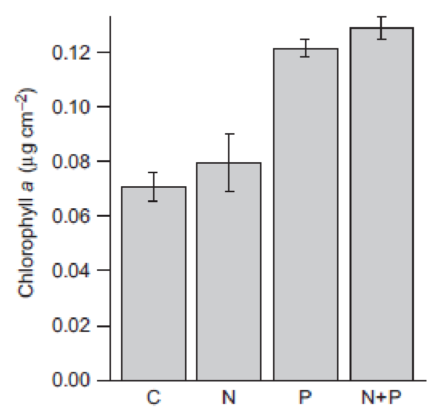

Figure 6. Response of algae to experimental additions of nitrogen only (N), phosphorus only (P), both N and P, or no nutrients (C).

Monitoring of whole-ecosystem metabolism confirms that large sucker runs enhance the productivity of the entire stream (Figure 7). This is the first strong demonstration of an ecosystem-level response to nutrients from a repeat-spawning fish species. Our results compliment those from salmon, but differ in important ways. Salmon both die after spawning and excavate large patches of substrate before laying eggs. Both factors elevate the breakdown of organic matter in the stream, and suppress algal growth. Thus, salmon streams typically see a decrease in ecosystem primary productivity during the migration, whereas we find that suckers boost gross primary productivity. Conversely, salmon enhance ecosystem respiration, whereas suckers cause only slight increases in respiration during their migration.

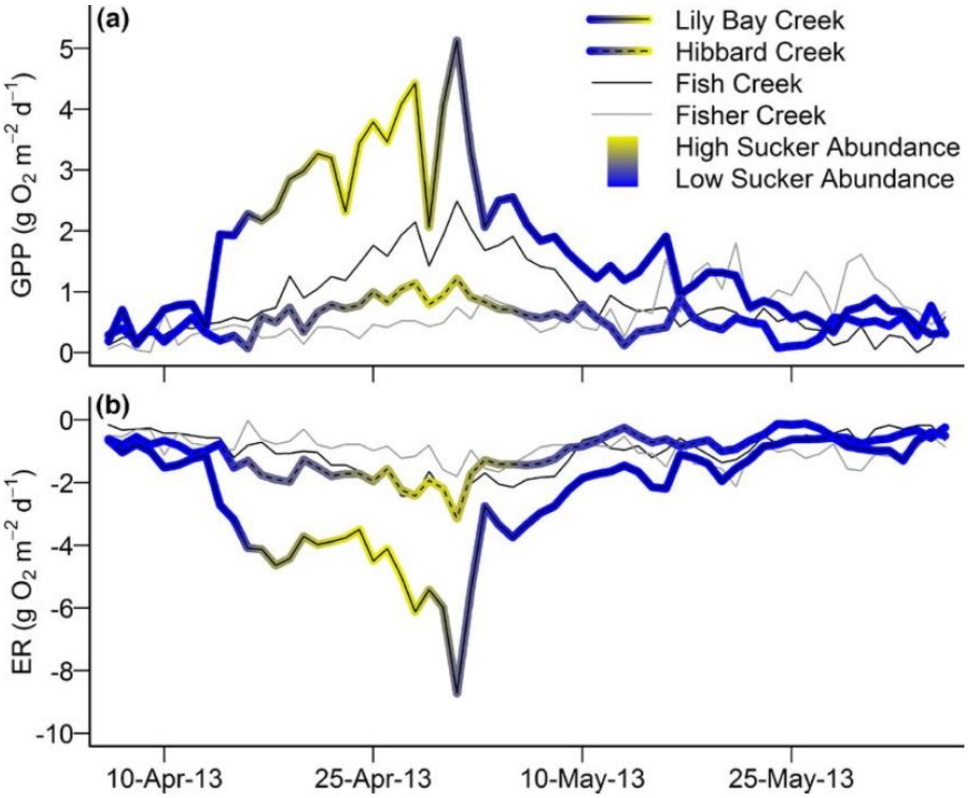

Figure 7. Ecosystem metabolism patterns in four streams in 2013. Colored lines indicate streams where migratory suckers were spawning. Grey lines indicate streams where fish could not gain access. Line color indicates the abundance of fish measured in each stream, from high (yellow) to low (blue).

The boost to ecosystem productivity arising from sucker migrations is likely to benefit all stream biota. We observed juvenile rainbow trout gorging on sucker eggs in 2012, but our attempt to study that relationship in 2013 was prevented by mass mortality of trout during the hot summer of 2012. After hatching, larval suckers pour out of river mouths in synchrony, entering the Great Lakes in enormous numbers. These emigrating larvae represent just a tiny fraction of the eggs laid, yet are still abundant enough to provide a major food resource for predatory fishes (Figure 8). Indeed, every year we would observe rock bass, creek chubs, yellow perch, and other species gather at stream mouths to take advantage of this resource pulse. Taken together, our findings indicate that migrations of native fishes into tributaries play a key role in the annual productivity cycle of both the streams and the Great Lakes.

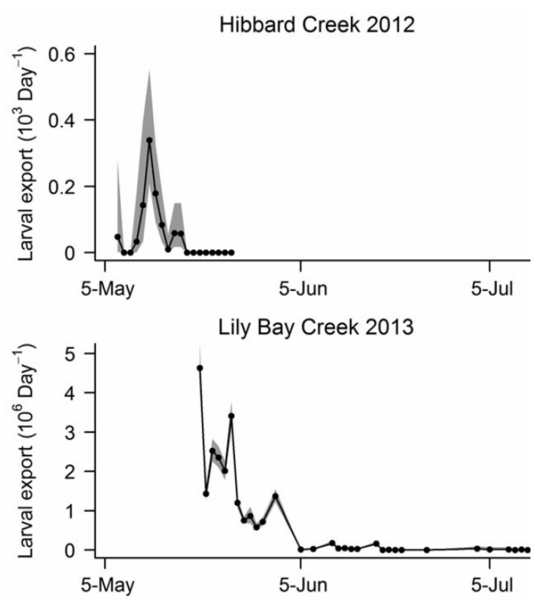

Figure 8. Emigration of sucker larvae from study streams in Door County through time. Lines represent observed dynamics; grey areas are confidence intervals estimated by bootstrapping.

CONCLUSIONS AND RECOMMENDATIONS

Though the timing of spawning migrations is changing in the Great Lakes, the direction and magnitude of shifts is complex. This complexity is quite different from reported patterns in the handful of other freshwater ecosystems where migration timing has been studied. In all other published cases, fish are moving earlier in the spring or later in the fall, in keeping with expectations from warming patterns and temperature-cued migrations. We observed that lake-based temperature cue regimes are indeed shifting forward in the spring, but fish appear to be responding in complex ways.

With continued or accelerating warming in the future, there is reason for concern about how changes in the timing of inputs of nutrients and larvae could affect ecosystem dynamics. If the growth of algae and insects shifts at the same pace as the timing of fish migrations, the effects may be minimal. However, as fish-associated nutrient inputs become earlier in the year, the amount of light energy available to support algal growth will be reduced because day length is independent of thermal regimes. Moreover, the shading of streams by budburst of trees is expected to shift with climate warming, but responding to a very different set of cues than tributary-spawning fishes. Similarly, the migratory birds that depend on the emergence of stream insects to refuel as they move northward in the spring may well arrive out of sync with their prey. These examples of phenotypic decoupling are troubling, though much more research is required to assess their likelihood and expected effects.

Groundwater resources will play a special role in future patterns of fish migration phenology. Groundwater flows and temperatures are far less influenced by air temperature than surface flows. Thus, groundwater inputs to tributary streams has a unique capacity to buffer them against climate change, at least over the short term. Great Lakes tributaries vary widely in the proportion of their flow derived from groundwater, which may be part of the explanation for the spatial heterogeneity that we observed in rates of change of migration timing. Should groundwater flows be reduced, rates of stream warming would almost certainly increase, leading to even earlier spring fish migrations.

This project has also served as a pilot exploration for developing a citizen science network to monitor migratory fish phenology in the Great Lakes region. We learned that this approach can yield high-quality data, but requires sufficient staff support to maintain intensive communication with the network of volunteers. In addition, our failure in 2012 to cover the migration season arose from the time lag involved in launching volunteer monitoring efforts anew each year. These lessons will be incorporated into plans for a much larger, sustained citizen-based phenology monitoring network being co-developed by Shedd Aquarium and UW-Madison Center for Limnology. Only citizen scientists can offer sufficiently broad coverage of Great Lakes watersheds to enable robust inferences about spatial patterns in migration timing. As we begin to seek funding to launch this new effort, the experience gained under this project will be invaluable.

APPENDIX A

Publications accepted

Childress E & McIntyre PB. 2016. Life history traits modulate ecosystem-level effects of nutrient subsidies from fish migrations. *Ecosphere*, in press.

Childress ES, Papke R, & McIntyre PB. 2016. Reproductive success and early life history of suckers in Great Lakes tributaries. *Ecology of Freshwater Fish*, in press.

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McIntyre PB, Reidy Liermann C, Childress E, Hamann EJ, Hogan J, Januchowski-Hartley SR, Koning AA, Neeson TM, Oele DL, & Pracheil BM. 2015. Conservation of migratory fishes in freshwater ecosystems. In Closs G, Krkosek M, & Olden JD: *Conservation of Freshwater Fishes*. Cambridge University Press, Cambridge, UK.

Publications in review or preparation

Mason LA, Riseng CM, Gronewold AD, Rutherford ES, Wang J, Clites A, Smith SDP, & **McIntyre PB**. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change*, in review.

Moerke A, David S, Childress E & McIntyre PB. Dynamics of spring fish migrations in northern Lake Michigan. *Freshwater Science*, in preparation.

David S, Moerke A, Herbert M, Khoury M, Moody A, Neeson T & McIntyre PB. Phylogenetic and ecological diversity of Great Lakes migratory fishes. *Journal of Great Lakes Research*, in preparation.

Research training

Evan Childress – PhD student, Freshwater & Marine Sciences, UW-Madison – *evan.childress@gmail.com* Evan completed his PhD, and is now a post-doc at the Conte Anadromous Fish Research Station in Massachusetts. During the course of his work, three undergraduates received research internships assisting with our field studies.

Ben Stewart-Koster – post-doctoral researcher – *b.stewart-koster@griffith.edu.au* – Ben has collaborated on this project to construct statistical models of historical timing of migration phenology. He is now a staff scientist at Griffith University, Australia.

Solomon David – post-doctoral researcher – *solomon.r.david@gmail.com* – Solomon was a post-doc at the Shedd Aquarium, and collaborated on this project by synthesizing available data on Great Lakes migration timing across dozens of fish species. He is now a staff scientist at the USGS Great Lakes Science Center.

Impact summary

Our work is boosting awareness of shifts in timing of Great Lakes fish migrations, and their role in tributary ecosystem dynamics. From an ecosystem management perspective, our findings provide new impetus to maximize access of migratory fishes to tributary ecosystems by removing barriers such as dams and impassable road culverts. Doing so can restore natural nutrient inputs, boosting production of the stream insects that feed birds and bats as well as fish that are preyed upon by bears and eagles. From a fisheries standpoint, we have shown that many favored species (walleye, pike, steelhead) will benefit from both restored spawning ground access and the annual pulse of prey fish derived from migrations of non-game fishes. Along with revealing the complexity of phenological shifts, this project has demonstrated the potential for citizen scientists to aid in documenting the timing of fish migrations at broader spatial scales than researchers alone can achieve. We are now planning a joint initiative between the Shedd Aquarium and UW-Madison Center for Limnology to develop a larger citizen science network for Great Lakes fish migrations that would interface with the USA National Phenology Network (https://www.usanpn.org/) and state agency staff to sustain monitoring of fish migration timing.

In addition to our ongoing collaboration with the Shedd Aquarium, we have worked on two other important outreach initiatives. First, we co-organized a major outreach event at the Shedd Aquarium to publicize Great Lakes fish migrations on the first World Fish Migration Day in May 2014. We talked with ~11,000 visitors as they entered and experienced the aquarium, including providing children with a migratory fish 'passport' and setting up science show-and-tell tables to talk about methods to track migrations. This event was a huge success, and we just completed the second World Fish Migration Day on May 21, 2014, with equal impact. Both Shedd and UW personnel benefit from this opportunity to leverage our respective resources and talents in the service of public awareness of migrations.

Second, we developed a daily program educating the public about fish migrations, sucker life history, and the impacts of climate change was at the Crossroads at Big Creek Nature Center in spring-summer 2011 and 2012. We prepared a brief lecture for the staff to present to visitors, after which visitors would observe sucker spawning in a local creek on the Center grounds. Brief lectures were given to two volunteer groups about fish migration ecology and climate change. This outreach effort was featured in newsletters for multiple citizen groups, as well as on the WRI Press Room website in August 2011 (http://wri.wisc.edu/pressroom/Details.aspx?PostID=1138).