SECTION 1. ADMINISTRATIVE INFORMATION

Project title: Characterization of Spatial and Temporal Variability in Fishes in Response to Climate Change

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Actual cost: $139,162.72

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SECTION 2. PUBLIC SUMMARY

The number of fish collected in routine monitoring surveys often varies from year to year, from lake to lake, and from location to location within a lake. Although some variability in fish catches is expected across factors such as location and season, we know less about how large-scale disturbances like climate change will influence population variability. The Laurentian Great Lakes in North America are the largest group of freshwater lakes in the world, and they have experienced major changes due to fluctuations in pollution and nutrient loadings, exploitation of natural resources, introductions of non-native species, and shifting climatic patterns. In this project, we analyzed established long-term data about important fish populations from across the Great Lakes basin, including from Oneida Lake in NY, Lake Michigan, and the Bay of Quinte in Lake Ontario. Our objective was to evaluate spatial and temporal variation in fish catches from large freshwater lakes that have experienced large-scale changing conditions. We evaluated analytical approaches with the potential to disentangle sources of variability in standardized monitoring data. Specifically, we considered 1) how the decomposition of spatial and temporal variation in fish catches can be used to measure a response to perturbation; 2) how truncation of population age structure can alter population oscillations which may shift how a population is affected by environmental fluctuations; and 3) how the composition of a fish community may respond to a suite of environmental drivers through time. Using long-term gill-net data for walleye, we found that average catch and variance structure differed before and after large-scale perturbations. More generally, our results suggest that fish population responses to changing environments can be complex, but that long-term monitoring combined with modeling approaches can allow for detection of quantifiable changes.

SECTION 3. PROJECT SUMMARY

Predicting population responses to climate change requires consideration of how population dynamics vary over space and time. For instance, fish catch rates may vary among repeated samples from a single site, from site to site within a lake, from lake to lake, and over time. Although variability has historically been viewed as an impediment to understanding population responses to ecological changes, it can provide an important signal, rather than just being viewed as noise. In this project, we built upon recently completed analyses of fish population data in the Great Lakes basin to consider how spatial and temporal variation in fish populations may respond to climate change and other important drivers. This was a collaborative project, involving partners from around the Great Lakes region, and it relied on established data sets of fish catches, including from Oneida Lake in NY, Lake Michigan, and the Bay of Quinte in Lake Ontario. A PhD student's dissertation was supported through this project. Analyses included 1) an evaluation of the potential for source components of variability to serve as statistical indicators of responses to ecosystem-level perturbation (walleye in Oneida Lake), 2) an evaluation of the influence of the loss of older age classes in an important prey fish population related to environmental fluctuations (alewife in Lake Michigan), and 3) an evaluation of a suite of environmental signals on the composition of a fish community (the Bay of Quinte, Lake Ontario). The composition of spatial and temporal variability in walleye catches from Oneida Lake differed between two time periods associated with ecosystem changes. More broadly, our research helps elucidate the extent to which quantifiable responses in spatial and temporal variability occur in fish population data, which can help managers develop adaptation strategies to prepare for decisions about monitoring and management of dynamic ecological systems.

SECTION 4. REPORT BODY

Purpose and Objectives

There remains uncertainty regarding how climate change will influence the spatial and temporal variability of populations or other ecosystem attributes. A challenge is that climate change may have direct effects on some species (e.g., reduction of thermal habitat, changes in metabolism or reproductive processes) or have indirect influences through food web effects (e.g., a disruption of the synchrony between prey availability and predator demands; Winder and Schindler 2004). Climate change may also shift ecosystem conditions to be increasingly favorable for invasive species, which can in turn have detrimental effects on native species. Thus, in order to improve our current understanding of population responses to large-scale change and our ability to forecast effects of climate change on populations, there is a need to explicitly account for the role of variability in system dynamics and trophic interactions. There is a growing body of literature related to detection or prediction of ecological regime shifts, including attempts to identify reliable signals associated with approaching system transition points. Increased variability may be one such indicator (Brock and Carpenter 2006; Scheffer et al. 2009; Carpenter et al. 2011; but see Burthe et al. 2016). Analyses of long-term data can contribute to an improved understanding of how ecosystems can be sensitive to disturbance, and understanding how patterns or influences can change over time could contribute to more effective monitoring and management of dynamic ecological systems. We proposed to build upon previous analyses of fish population data in the Great Lakes basin to help predict how spatial and temporal variation in fish populations may respond to climate change and other important drivers. We recognized that shifting variance structure could have implications for ecological monitoring programs, and we hypothesized that shifting variance structure could be indicative of population-level responses to climate change.

Organization and Approach

This project was intended to contribute to management needs in three areas:

1) Advancing analytical methodology for quantifying responses to climate change;
2) Providing broad applicability across ecosystem types; and
3) Training new students and building capacity.

More specifically, in the 2012 project proposal, we proposed the following steps:

1) Extend the analytical framework developed by Irwin et al. (2013) to quantify spatial and temporal variability of fish populations to detect population responses to large-scale perturbation (see Figure 1);
2) Apply analytical approaches that are not restricted to assumptions of linear relationships; and
3) Provide management implications related to the findings of steps 1 and 2, with an emphasis on the ability to detect or predict impacts of climate change on fish populations, the potential consequences for monitoring programs, and the ability to communicate scientific uncertainties in ways that are useful to decision makers.

Most of the requested funding supported a PhD student, consistent with the NECSC's emphasis on knowledge transfer, capacity building, and providing opportunities for young researchers. The general approach to implementing the proposed ideas was to work with researchers and scientists within the Great Lakes basin to identify hypotheses or questions related to potential fish population responses to large-scale disturbance along with available data sources. Reflecting these discussions, the PhD student's dissertation (Vidal 2017) was organized around the following questions:

1) Can spatial and temporal components of variability in fish catch data be used as an indicator of response to perturbation? (Vidal 2017, Chapter 2, walleye in Oneida Lake, NY);

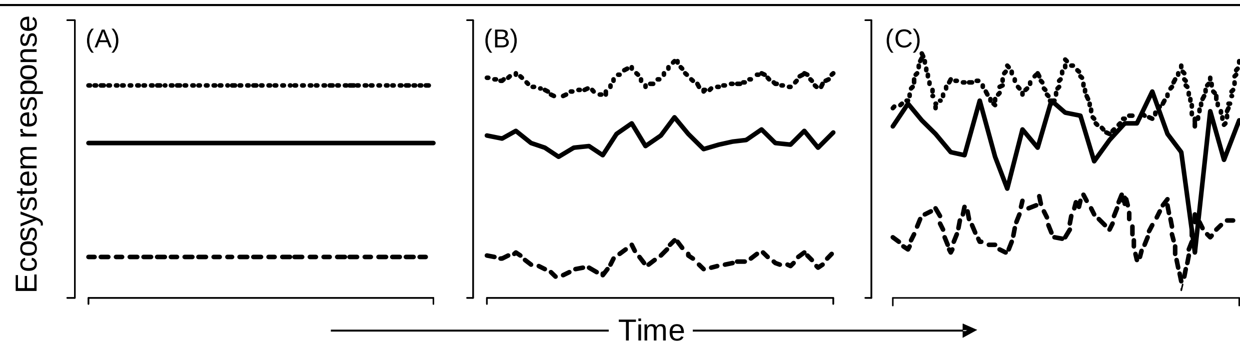

Fig. 1. Illustration of (A) spatial variation, as if this were the only source of variability, so that three sample sites (as dashed and solid lines) have different means but no temporal variability; (B) added coherent temporal variation to the spatial variation; and (C) added ephemeral temporal variation. Modified from Irwin et al. 2013.

2) Have changes to the age-structure of a prey fish population (alewife) in Lake Michigan changed the population's response to environmental signals? (Vidal 2017, Chapter 3); and
3) Are environmental drivers influencing the fish community of the Bay of Quinte in Lake Ontario, and if so, are there thresholds along gradients of the environmental variables that are important in structuring the community? (Vidal 2017, Chapter 4).

Project funds were managed through a Cooperative Research Unit Research Work Order, which is predicated on providing for graduate student training opportunities. This project was originally assigned a start date of 1 Sept. 2012. Recruitment of a qualified graduate student lasted into 2013, resulting in an enrollment date of Aug. 2013. Project funds were issued in FY2012 and FY2013, and the duration of the project was extended beyond these fiscal years to allow for the time needed to support a PhD student to completion of a degree, which was achieved prior to the project end data (Aug. 2017). The University of Georgia waived the graduate student's tuition while the graduate student was supported through a research assistantship on the project. Associated conference abstracts and journal publications received USGS IPDS numbers.

Project Results, Analysis and Findings

This project contributed to graduate student education (e.g., Vidal 2017) and professional training, built capacity (e.g., Vidal hired by MA Division of Marine Fisheries), and produced products (see below). Here, we provide a brief summary related to the project's proposed steps; however, more specific details about questions, hypotheses, data, and analyses are available in some of the project's products, namely Vidal (2017) and Vidal et al. (2017).

Additional summaries are provided below, in regards to the project's proposed steps:

1) Extend the analytical framework developed by Irwin et al. (2013) to quantify spatial and temporal variability of fish populations to detect population responses to large-scale perturbation;

    Vidal's dissertation, *Understanding the Role of Variability in Fish Population and Community Response to Changing Environmental Conditions*, highlights tools and approaches to disentangle variability in fish catch data. The analytical methods of Vidal (2017) included use of mixed-effect models, age-structured matrices, and random forest analyses. For instance, Vidal (2017) evaluated demographic changes, such as losses of older individuals from a population, to test a hypothesis that selective predation can induce similar effects as fishing. Vidal et al. (2017) used a negative binomial mixed model to partition variability and demonstrated that spatial and temporal components of variability can be responsive to major perturbation (e.g., establishment of an invasive species). Examining several decades of fish catch data, Vidal et al. (2017) found that the minimum, mean, and maximum catch of walleye were lower after perturbation in Oneida Lake, NY. Concurrent with the decline in catch, a reduction in site-to-site variability was observed, suggesting some spatial homogenization in terms of relative catches. In particular, high catches at individual sampling sites became less frequent. These results provide support for the idea that variance structure can be responsive to large-scale perturbation; therefore, variance components may be useful statistical indicators of response to a changing environment more broadly.

2) Apply analytical approaches that are not restricted to assumptions of linear relationships;

    Wagner et al. (2016) focused on detecting temporal "patterns" of change that went beyond estimation of a simple long-term trend by asking does a particular location exhibit an unusual trend in comparison to an overall lake-wide trend. This contribution describes such differences and methods for detecting them. More specifically, Wagner et al. (2016) applied a Bayesian model selection approach to established long-term catch data for yellow perch from fifteen sampling sites in Oneida Lake, NY. On average, catches declined over time. Nine sampling sites exhibited similarity to a common temporal pattern whereas six other sites had more distinct temporal dynamics. Further, "inconsistent" sites may appear unusual for different reasons, such as because of a difference in either the timing or severity of change. More generally, the detection of "unique" sites could be informative to decisions related to prioritizing locations for restoration or other management interventions.

3) Provide management implications related to the findings of steps 1 and 2, with an emphasis on the ability to detect or predict impacts of climate change on fish populations, the potential consequences for monitoring programs, and the ability to communicate scientific uncertainties in ways that are useful to decision makers.

    Understanding how populations respond to changing conditions is important to designing effective monitoring programs and management strategies. Our approach could be used to help elucidate the extent to which quantifiable responses in spatial and temporal variability occur in different forms of population data or determine if changing patterns are shared across locations or mostly unique to particular areas. Although this project focused on data from important fish populations in the Great Lakes basin, questions about how ecosystem structure and function respond to disturbance and analytical approaches for quantifying large-scale change are of much broader interest. Likewise, the modeling framework described in Vidal et al. (2017) has broader management implications because 1) count data are pervasive in ecological monitoring and 2) the importance of spatial and temporal variation in driving long-term population dynamics is not restricted to freshwater fish populations. In addition, we contributed to the training of the next generation of quantitative scientists and promoted skills necessary to synthesize across scientific disciplines and across spatial and temporal scales. Several presentations and seminars were provided and included illustrations of how variability and uncertainty can be influential in the context of decision making.

Conclusions and Recommendations

The Laurentian Great Lakes hold a massive amount of Earth's surface freshwater. These lakes are widely important because of their water quantity and quality, and because they support fisheries and provide other ecosystem services. Even with their great size and value, these ecosystems have experienced large-scale changing conditions due to alternations or fluctuations in multiple influential factors such as pollution and nutrient loadings, exploitation of resources, climatic patterns, and introductions of non-native species (e.g., Mills et al. 1993; Bence and Smith 1999; Casselman 2002; Holeck et al. 2004). How disturbance affects ecosystem structure and function is a continuing fundamental interest of ecologists, conservationists, and natural resource managers; long-term study of large, complex, dynamic ecological systems are critical for addressing meaningful hypotheses and questions at relevant timescales (Callahan 1984).

This was a collaborative project involving partners from across the Great Lakes basin, including multiple US states and the Canadian Province of Ontario. The analyses of Vidal (2017) and Vidal et al. (2017) make use of data from established long-term monitoring programs and contribute insights about how ecosystems can be sensitive to disturbance. Her research findings indicate that spatial and temporal variability can be responsive to perturbation, which can then offer finer-scale information about ecological reorganization than a mean response or total variability alone. The potential use of variance structure as an indicator of population-level responses to climate change is not restricted to Great Lakes fisheries. Vidal (2017) also begins to address shifting importance of environmental versus biological influences on fish populations over time. Likewise, detection of "unique" sites may be particularly informative to decision makers when developing adaptation strategies and facing choices about prioritization of resources for monitoring or management (Wagner et al. 2016). In total, this project led to a completed PhD dissertation, and it contributed to peer-reviewed publications, several professional presentations, and multiple continuing-education opportunities.

A recent special issue of *Fisheries* (see Paukert et al. 2016a) discusses potential climate-related impacts on North American inland fishes through four themes: 1) responses of individuals (e.g., physiology, growth), 2) population- and assemblage-level responses (e.g., range shifts), 3) human dimensions (e.g., angler values), and 4) management and adaptation (e.g., riparian planting). Few studies have directly assessed effects of climate change on freshwater fishes, but population responses to climate change could include shifting distributions, alteration of demographic processes, or possibly genetic changes (Lynch et al. 2016). It can be difficult to detect links (e.g., correlative relationships) between environmental signals and changing population attributes, which emphasizes the importance of maintaining data collection over the long term. Some of the analyses of Vidal (2017) likely would not have been possible with shorter-term data sets or less consistent data collection. Similarly, consistent collection of information on other covariates (e.g., water clarity and temperature) can be beneficial for explaining variation in fish catches. Next steps could include consideration of alternative variance structures when attempting to forecast fish population dynamics through alternative future climate scenarios.

Outreach and Products

The items in this list were identified in the proposal as anticipated deliverables – with some additional notes provided here on progress and products.

- Several project meetings and webinars – several interactions occurred involving PI(s) and the PhD student as well as meeting with data providers (see 'Other Communications' below). These meetings were sometimes in-person and sometimes conducted over phone or virtual conferencing. A project webinar was provided (see 'Presentations' below). A second project webinar has been invited for early 2018.
- a student thesis – a PhD dissertation was completed (see 'Student Training' below).
- a final project closeout report – this document.
- a presentation at professional society meeting – several professional presentations, including society conferences and university seminars, were provided during the project (see 'Presentations' below).
- article(s) intended for submission as peer-reviewed publication(s) – to date, two articles have been published acknowledging support from the NECSC (see 'Articles & Reports' below). The student-led publication (Vidal et al. 2017) was selected as a "Featured Paper" by the journal.
- flexible and adaptable coding for applying a negative binomial mixed model – discussions are ongoing about how to extend the approach of Vidal et al. (2017) to a focus on multiple systems (see 'Other Communications' below).

Student Training

- Vidal attended a workshop on Automatic Differentiation Model Builder focusing on fisheries modeling and stock assessment approaches using the software program.
- Additional professional development included Vidal contributing to workshops related to analysis and visualization of fish population data:
  - Introduction to R for Fisheries Scientists (2015): Full-day workshop, taught at the Southern Division meeting of the American Fisheries Society, Savannah, GA (50 participants)
  - Introduction to R & statistical refresher for GA DNR (2016): 2-day workshop, taught at Coastal Resources Division, Brunswick, GA (30 participants)
  - Introduction to R & statistical refresher for GA DNR (2016): 2-day workshop, taught at Charlie Elliot Wildlife Center, Mansfield, GA (20 participants)
  - An Introduction to Graphing and Modeling using R & RStudio (2017): Full-day workshop, taught at the Southern Division meeting of the American Fisheries Society, Oklahoma City, OK (9 participants)
- Vidal was hired as a Stock Assessment Scientist, Massachusetts Division of Marine Fisheries.
- Vidal was nominated (November 2017; pending) for a 2018 *Excellence in Research by Graduate Students Award* from The Graduate School at The University of Georgia

Articles & Reports

- Wagner, T., S. R. Midway, T. Vidal, B. J. Irwin, and J. R. Jackson. 2016. Detecting unusual temporal patterns in fisheries time series data. Transactions of the American Fisheries Society 145:786-794. DOI: 10.1080/00028487.2016.1150879 [IP-069825]
- Vidal T. E., B. J. Irwin, T. Wagner, L. G. Rudstam, J. R. Jackson, J. R. Bence. 2017. Using variance structure to quantify responses to perturbation in fish catches. Transactions of the American Fisheries Society 146:583-594 [FEATURED PAPER]. DOI: 10.1080/00028487.2017.1301992 [IP-068926]
- Vidal, T., 2017. Understanding the role of variability in fish population and community response to changing environmental conditions. PhD dissertation, University of Georgia, Athens, Georgia.
- NECSC progress reports 2013, 2014, 2015, 2016, 2017

Presentations

- Irwin, B.J., and T. Wagner. 2013. Using mixed models to quantify variability in fish populations. GA Chapter meeting of the American Fisheries Society, Jekyll Island, GA. [IP-043540]
- Irwin, B.J., and T. Wagner. 2013. Shifting variance structure as a potential indicator of fish-population responses to large-scale perturbation. Southern Division meeting of the American Fisheries Society, Nashville, TN. [IP-043541]
- Irwin, B. J., T. Vidal, T. Wagner, J. R. Bence, J. R. Jackson, L. G. Rudstam, and W. W. Fetzer. 2014. Shifting variance structure as an indicator of large-scale ecological change. Annual meeting of the Ecological Society of America, Sacramento, CA. [IP-054829]
- Vidal, T., C. Jansch, B. J. Irwin, T. Wagner, J. R. Bence, J. R. Jackson, L. G. Rudstam, and W. W. Fetzer. 2014. Using variance structure as statistical indicators of large scale ecological change. Annual meeting of the American Fisheries Society, Québec City, Québec, Canada. [IP-054828]

- Vidal, T. E., B. J. Irwin, and C. P. Madenjian. 2016. Disentangling exogenous drivers of Alewife population dynamics in Lake Michigan. Joint meeting of the GA-AL chapters of the American Fisheries Society, Columbus, GA. [IP-071298]
- Irwin. B. 2016. Analyzing data from gillnet monitoring programs: the Oneida Lake example. Cornell University Biological Field Station, Bridgeport, NY. [Invited poster (no abstract)]
- Irwin. B., T. Vidal, B. Crawford, T. Gancos Crawford, and C. Moore. 2016. Quantitative consideration of uncertainty and variability in decision analysis for conservation and management of ecological systems. Annual meeting of the Ecological Society of America, Fort. Lauderdale, FL. [IP-073549]
- Vidal, T. E., B. J. Irwin, and C. P. Madenjian. 2017. Demographic structure influences how environmental forcing affects Alewife recruitment in Lake Michigan. Meeting of the Southern Division of the American Fisheries Society, Oklahoma City, OK. [IP-081363]
- Irwin, B. J. 2017. Viewing fisheries from a decision-analytic perspective. Northeast Climate Science Center Regional Science Meeting, Amherst, MA. [Invited (no abstract)]
- Irwin, B. J. 2017. Spatial and temporal variability in fish populations. Northeast Climate Science Center Regional Science Meeting, Amherst, MA. [Invited (no abstract)]

Invited Seminars

- Irwin, B. 2014. Variance structure and ecological change. Computational Ecology and Epidemiology Study Group Seminar Series, University of Georgia, Athens, GA.
- Irwin, B. 2014. Quantifying variance to inform decision making. Cornell University Biological Field Station Summer Seminar Series, Bridgeport, NY.
- Irwin. B. 2014. Using quantitative models to support decision making. School of Fisheries, Aquaculture and Aquatic Science. Auburn University, Auburn, AL.
- Irwin. B. 2014. Using uncertain information in conservation decision making – Great Lakes fisheries management. North Carolina State University – Southeast Climate Science Center Global Change Fellows Seminar. North Carolina State University, Raleigh, NC.
- Irwin, B., and T. Vidal. 2015. Accounting for variability & uncertainty when informing natural resource management. NE Climate Science Center webinar, University of Massachusetts, Amherst, MA.

Other Outreach and Communications

- Cornell University Biological Field Station (CBFS) – We collaborated with CBFS researchers (e.g., Lars Rudstam, Randy Jackson) related to long-term data collected from Oneida Lake, NY. Data were instrumental for Wagner et al. (2016), chapter 2 of Vidal (2017), Vidal et al. (2017), and several of the presentations highlighted above. For related information on this system, also see Rudstam and Jackson (2015), Jackson et al. (2016), and Rudstam et al. (2016).
- USGS Great Lakes Science Center – We collaborated with Chuck Madenjian on analyses of Alewife in Lake Michigan. Data were used in chapter 3 of Vidal (2017) and in professional presentations. For related information on this system also see Madenjian et al. (2014).
- Ontario Ministry of Natural Resources – We collaborated with Jeremy Holden, Mike Yuille, and Jim Hoyle on analyses of the fish community of the Bay of Quinte in Lake Ontario. Data were

used in chapter 4 of Vidal (2017). For related information on this system also see Hoyle et al. (2012) and Hoyle and Yuille (2016).

- During this project period, PI Irwin participated in an expert workshop hosted and funded by the U.S. Geological Survey's (USGS) National Climate Change and Wildlife Science Center, and the Missouri Cooperative Fish and Wildlife Research Unit. This workshop was held at the USGS Northern Rocky Mountain Science Center (Bozeman, Montana) in June 2015, and resulted in a special issue of the American Fisheries Society journal Fisheries (2017, vol. 42, issue 7), titled *Effects of Climate Change on North American Inland Fishes*, which included Paukert et al. (2016b).
- Although not explicitly linked to this project, the project PIs have been invited to author chapters in the planned 2nd edition of the American Fisheries Society's book *Analysis and Interpretation of Freshwater Fisheries Data*. This invitation was extended, in part, because the type of analytical work and training conducted through this project are seen as broadly valuable to the profession.
- Minnesota – Late in the project, following the 2017 NE CSC Regional Science Meeting, we collaborated with Gretchen Hansen (Minnesota Department of Natural Resources), Sam Truesdell (Michigan State University), and Ellen Cheng (University of Georgia) about extending some of analyses developed through this project to several inland lakes in Minnesota. Related to these analyses, a project meeting was held on the campus of the University of Georgia in August 2017.

SECTION 5. REFERENCES

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