Ecofore-Lake Erie Project Final Report

Report Title, Author, Organization, Grant Number, Date

Forecasting the Causes, Consequences and Remedies for Hypoxia in Lake Erie
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Organization: University of Michigan
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Executive Summary

Relieving excessive phosphorus loading is a key management tool for controlling Lake Erie eutrophication. During the 1960s and 1970s, excessive phosphorus inputs degraded water quality and reduced central basin hypolimnetic oxygen levels, which in turn, eliminated thermal habitat vital to cold-water organisms and contributed to the extirpation of important benthic macroinvertebrate prey species for fishes. In response to load reductions under the 1978 Great Lakes Water Quality Agreement (GLWQA) between the U.S. and Canada, Lake Erie responded quickly with reduced water-column phosphorus concentrations, phytoplankton biomass, and bottom-water hypoxia (dissolved oxygen < 2 mg/l). However, since the mid-1990s, cyanobacteria blooms increased and extensive hypoxia and excessive benthic algae returned.

We built and synthesized long term and recent trends in key nutrient loads and indicators of eutrophication, assessed their likely ecological impacts, and developed load response curves to guide revised hypoxia-based loading targets called for in the 2012 protocol amending the Great Lakes Water Quality Agreement.

Our results showed that reducing central basin hypoxic area to levels observed in the early 1990s (ca. 2,000 km^2) requires cutting total phosphorus loads by 46% from the 2003-2011 average or reducing dissolved reactive phosphorus loads by 78% from the 2005-2011 average. Reductions to these levels are also protective of fish habitat. We provide potential approaches for achieving those new loading targets under current and potential future climates, and suggest that recent load reduction recommendations focused on western basin cyanobacteria blooms may not be sufficient to reduce central basin hypoxia to $\leq$2,000 km^2.

Overarching goals and Objectives

In 2005, Ecofore-Lake Erie -- a multi-year, multi-institutional project supported by the National Oceanic and Atmospheric Administration -- began with the goal of developing a suite of management-directed models useful for exploring causes of changes in P loading, their impacts on central basin (CB) hypoxia, and how these changes might influence Lake Erie's highly valued recreational and commercial fisheries. The Ecofore-Lake Erie project focused on CB hypoxia because of uncertainty about the mechanisms underlying its return to levels commensurate with the height of eutrophication during the mid-20th century and because of its great potential to harm Lake Erie's valued fisheries.

The overall objective of this project was to create, test, and apply models to forecast how multiple stresses influence hypoxia formation and ecology of Lake Erie's Central Basin, with an emphasis on fish production potential. These models integrated the multiple factors that interact to create hypoxia in Lake Erie, such as surface water flow, phosphorus input, lake dynamics, climate variation, and fish movement patterns, biology, and physiology.

This project addressed two of NOAA Strategic Plan Goals: 1) to protect, restore, and manage use of coastal and ocean resources through ecosystem-based management, and 2) to understand climate variability and change to enhance society's ability to plan and respond.

Approach

Nutrient loading - Monthly and daily river export load series for the Raisin, Maumee, Sandusky, Vermilion, Cuyahoga, and Grand Rivers were completed for the period of record. Missing data have been filled in, and the complete time series has been posted to the project website (note: the website is being revised and turned into a permanent archive).

Daily Lake Erie nutrient loading estimates for CY2005 and CY2007 at 26 spatial nodes have been completed. CY1976 nutrient loads have been reconstructed from archived historical data. These are also available at the 26 spatial nodes in the Lake. All point source, atmospheric, and tributary data for 2003 - 2008 have been received. For Total Phosphorus (TP), additional annual load estimates have been completed for the water years (WY) 2003-2008. This updates the work of Dolan & McGunagle which included TP loads through WY 2002. These estimates have been provided to Steven Chapra at Tufts University for use with his TP mass balance model for the entire Great Lakes system to provide updated estimates of interlake loadings via the connecting channels including the St. Clair and Detroit Rivers.

P budgets - For all watersheds of the Lake Erie Basin in the U.S., historical P budgets were completed for agricultural census years from 1934 to 1974 at every decennial, and from 1974 to 2002 at every five years. Phosphorus budgets were estimated using an approach similar to the net anthropogenic N inputs approach (NANI). P budgets were constructed by quantifying all known anthropogenic P inputs (fertilizer, detergents, atmospheric deposition, imports of P in crop and animal products), outputs (exports of P in food and feed) as well as the net balances between inputs and outputs, resulting in an estimate of net anthropogenic P inputs (NAPI).

In addition, we developed relationships between watershed P inputs and river TP exports for the selected watersheds of the Lake Erie Basin (Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand in OH) for 5 agricultural census years from 1978 to 2002 to determine how the input: export relationship has changed over time and how the changes in relationships would be linked to the re-occurrence of the hypoxia in Lake Erie.

Watershed models - SWAT models have been developed, calibrated, and validated for the 6 major Lake Erie watersheds - Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand. Overall, the SWAT models' performance is strong when compared to observed stream discharge, sediment loads, and nutrient loads (total phosphorus, soluble reactive phosphorus, total nitrogen, and nitrate). These calibrated models were used to explore what best management practices (BMPs) and in what locations will provide the most effective load reduction strategies under current and potential future climates.

Multiple databases of land use, soil, digital elevation model (DEM), hydrography, and agricultural management practices were acquired, processed, and analyzed to develop dynamic input parameters for the Distributed Large-Basin Runoff Model (DLBRM) and the Revised Universal Soil Loss Equation (version 2) (RUSLE2) for the same 6 watersheds. We acquired and processed multiple databases of land use, soil, digital elevation model (DEM), and hydrography for the Grand River –Ontario. A computer program was written to spatially link the

Ontario soil attribute database with the polygon database for extracting the soil input parameters. Input parameters for the DLBRM were derived. We built basic model application databases (daily meteorology, land use, soils, elevation, and hydrography) for all 17 U.S. Lake Erie watersheds, and we completed DLBRM daily calibrations for five Lake Erie watersheds: Huron, Raisin, Maumee, Sandusky, and Grand (Ohio). Because of personnel changes and other limitations, this portion of the project was abandoned after the second year, and we focused exclusively on the SWAT modeling approach.

Hypoxia Models - Overall framework - The plan was to develop four levels of models, representing a range of complexity, intended to relate the attributes (magnitude, duration, spatial extent) of hypoxia in the central basin of Lake Erie to a range of stressors (physical conditions, external loadings of nutrients, and Dreissenid densities). The four models in order of increasing complexity were:

- Level 1 – one-dimensional model of the central basin with 1D thermal model and simple first-order deoxygenation rate in water column and zero-order SOD, forced by meteorological input alone;

- Level 2 – one-dimensional model of the central basin with 1D thermal model and simple phosphorus-chlorophyll-DO process model, forced by meteorological input and external phosphorus and organic carbon loading;

- Level 3a – Three-dimensional model composed of a 3D hydrodynamic – temperature model linked to the level two simple phosphorus-chlorophyll-DO process model, forced by hydrological and meteorological input and external phosphorus loading; and

- Level 3b -- Three-dimensional model composed of a 3D hydrodynamic – temperature model linked to an advanced eutrophication model (including Dreissenids and *Cladophora*), forced by hydrological and meteorological input, external nutrient and organic carbon loading, and *Dreissenid* density.

Due to limitations on data availability and other constraints, the level 3a model was built and underwent only minimal testing. The level 3b model was not developed.

Hydrodynamic Modeling - A three-dimensional, 2 km grid hydrodynamic model of Lake Erie was developed (based on the Princeton Ocean Model [POM]) to calculate lake-wide circulation and thermal structure. Daily inflows at 22 major tributaries and hourly meteorological data at 12 land stations and 3 meteorological buoys were assembled, edited and interpolated to create gridded forcing functions for the hydrodynamic model for 2004, 2005, 2007 and 1976. Complete 3D hydrodynamic model simulations were accomplished for all four years and results compared with observations. Alternative forcing functions (surface wind fields) were developed for 2004, 2005 and 2007 (not available for 1976). They are based on the 3-hourly output of the Canadian regional meteorological model GEM which employs 15 km grid and appear to be superior to mostly land-based meteorological observations normally used by POM in the Great Lakes. New model results (for 2004, 2005 and 2007) showed improvements in modeled thermocline shape and anti-cyclonic circulation pattern in the central basin.

The 1D hydrodynamic model was applied with scaled (relative to 1987-2007 period) air temperature for low change and high change scenarios, representing potential climates in mid and late 21st century. Results showed warmer lake temperatures with a somewhat shallower thermocline because of decreased wind stress (due to increased stability of atmospheric boundary layer).

Water Quality Modeling - The level 1 model was used to test whether weather/climate variability alone (i.e., changes in the mixing regime) could have produced the decline and then increase in hypoxia around the mid-1990s. Driving the model with year-specific mixing parameters demonstrated that the water column depletion rate had to decline and then increase to match the observations. This led to the need for explicit biogeochemical processes in the level 2 model.

The level 2 model was developed specifically for establishing the relationship between phosphorus loads and CB hypoxia. This model is driven by the one-dimensional hydrodynamic model that provides temperature and vertical mixing profiles. The biological portion of the model is a standard eutrophication model with a new formulation that adjusts the sediment oxygen demand (SOD) as a function of TP load, based on an empirical relationship between SOD and deposited organic carbon. The model was calibrated over 19 years (1987-2005) of chlorophyll, phosphorus, and DO concentration, and tested for corroboration with key process rates, such as oxygen depletion; organic matter production and sedimentation, estimates of hypoxic area by taking advantage of a new empirical relationship between bottom water DO and area (see below). It was validated with independent oxygen concentrations from the period 1960 through 1985.

The model was used to develop response curves for bottom water DO concentration, hypoxic-days (number of days per year with hypolimnetic DO below 2 mg/l), hypolimnetic depletion rates, and hypoxic area as a function of WB+CB TP and DRP loads. The response curves, incorporating the uncertainty associated with interannual variability in weather from the 19 calibration years, were used to explore implications for new loading targets. Dozens of combinations of loading scenarios and different climate scenarios were evaluated| with this model with the goal of developing a predictor of hypoxia, or hypoxic days, based on delivered total phosphorus and soluble reactive phosphorus loads to the lake.

Zhou et al. (2013) used geostatistical kriging and conditional realizations to provide quantitative estimates of the areal extent of summer CB hypoxia for 1987 through 2007, along with their associated uncertainties. Their geostatistical approach combines *in situ* DO measurements with ancillary data such as bathymetry and measurement locations to produce best estimates of bottom water DO and their uncertainties. Conditional realizations are then used to sample the uncertainty in the spatial DO distribution, leading to a probabilistic representation of hypoxic extent. They also developed a statistical relationship between bottom water DO concentration and hypoxic area, allowing our 1D hypoxia model output (concentration profile) to be converted to hypoxic area.

Modeling Impacts of Hypoxia on Lake Erie Fishes The Ecological Effects Team developed a suite of models to explore how hypolimnetic hypoxia impacts ecological interactions and fisheries production in the central basin of Lake Erie: 1) Empirical, statistical models; 2) Bioenergetics models (Growth rate potential models [GRP] and Individual-based models [IBM]); and 3) Foodweb models (Ecopath with Ecosim) and CASM [Comprehensive Aquatic Simulation Model]).

While empirical evidence points to a variety of taxa-specific negative and positive effects of hypoxia on fish feeding, growth, and production in Lake Erie, the magnitude of such potential effects and their population-level consequences remain open questions. Through the Ecofore-Lake Erie program, we explored such effects through a variety of models. Given the variety of pathways through which hypoxia may affect fish vital rates, models differ in their relative emphasis on diverse processes. Our simplest and most straightforward approach consisted of developing statistical relationships between measures of hypoxia and fish population metrics at the lake-basin scale, while other approaches seek more mechanistic relationships between hypoxia and fish habitat and population/community dynamics. These modeling approaches are described below.

Growth rate potential models - We developed bioenergetics growth rate potential models for emerald shiner, rainbow smelt, round goby, yellow perch, and walleye. We have applied these models 1) using physical, chemical and biological data collected during 2005/2007 IFYLE cruises in central Lake Erie and 2) using output from 1-dimensional hypoxia models. Our basic GRP model quantifies 1D fish habitat quality based on daily estimates of depth-specific temperature and oxygen concentration. This model was applied based on 1D hypoxia model output for the period of 1987-2005 (see Arend et al. 2011). In addition, this model was applied based on 1D hypoxia model output with increased temperatures (to simulate future climate warming) and with altered nutrient loadings. These latter simulations allowed us to quantify a change in fish habitat with proportional increases or decreases in phosphorous loading.

The GRP modeling approach has been extended to quantify fish habitat as a function of not only depth-specific temperature and oxygen, but also light and prey availability. The incorporation of prey availability is particularly important because while high nutrient loading may exacerbate hypoxic conditions, it may also contribute to increased overall system productivity which may counteract some of the potential negative effects on fish habitat. This modeling approach has relied on output from the level-2 hypoxia model. The hypoxia model readily allows for depth- and time-specific inclusion of temperature, oxygen and light. The hypoxia model also tracks settling of carbon to the benthos (which we use to model daily densities of chironomid prey) and three size classes of zooplankton (which we continuously redistribute in the water column based on rules designed to match field observations). The resulting environment is highly variable across both depths and time (e.g., between day and night). To capture this variability, the extended GRP model has been applied at 10 min intervals, and then combined to capture cumulative patterns across broader time scales. A manuscript is being developed which will present results of these models applied in hindcast (1987-2005) and forecast (warmer temperatures and increased loadings) modes.

Individual-based models- In addition to GRP bioenergetics models, we have also developed two types of individual based bioenergetics models: 1D and 3D. These models were intended to run from the output of 1D and 3D hypoxia models, respectively. While both model types have been developed, given that 3D hypoxia models were not fully parameterized, IBM applications have focused on the 1D version. This version uses the same environment as the extended GRP model, with depth-specific temperature, oxygen, light and prey updated at a fine (10 min) temporal scale. However, unlike the GRP model which tracks fish habitat, the IBM model tracks individual fish as they move, forage, grow and potentially die in the model environment. Specifically, the model simultaneously tracks a large number of different sizes and ages of walleye, yellow perch, rainbow smelt and emerald shiner. These simulated fishes can not only prey on model invertebrates (zooplankton and chironomids) but can also prey on each other (larger yellow perch and walleye potentially consuming smaller fishes of all four species), and by affecting vertical distributions hypoxia can mediate such foraging interactions. In addition, a density-dependent model term adjusts foraging success if simulated fish become concentrated in a narrow depth range.

The model initiates at the beginning of a growing season with a predetermined number and size/age distributions of fishes. However, differences in the model environment (temperature, oxygen, light, prey) throughout the growing season can affect growth and mortality rates and thereby determine the number and sizes of simulated fish alive at the end of the simulation. Two manuscripts are being developed which will present results of this model applied in hindcast (1987-2005) and forecast (warmer temperatures and increased loadings) modes and which will be compared to results of GRP models.

Foodweb models (CASM) - CASM is a bioenergetics-based foodweb model used to estimate ecological risks posed by various physical, chemical, or biological stressors in aquatic systems. Risks include direct impacts on individual modeled populations of primary producers or consumers, as well as indirect effects that result from alterations of grazing or predator-prey interactions. The foodweb in the CASM-LE consists of four broadly defined taxonomic groups of phytoplankton, six populations of herbivorous and carnivorous zooplankton, five benthic invertebrate populations (including Dreissenids), and 16 different taxonomically defined fish populations. Rainbow smelt, yellow perch, and walleye are represented by juvenile and adult populations. Various sources of data and information have been used to define foodweb interactions, initial population biomass values, bioenergetics parameters, and physio-chemical conditions in CASM-LE (e.g., physical, chemical and biological data from IFYLE; literature values; agency reports). Estimation of bioenergetic parameters in the CASM-LE is based in part on other bioenergetics work being performed as part of the Ecofore Project. The overall CASM-LE has a 3-layer vertical structure that permits certain invertebrate and fish populations to move vertically in relation to food availability and oxygen concentration.

Foodweb models(Ecopath with Ecosim; EwE) - Our Ecopath model focuses on the central basin of Lake Erie, and aims to evaluate the impacts of hypoxia on the lake ecosystem structure and function, and to explore water quality management and fisheries management scenarios. Our EwE team compiled and analyzed data since December 2008 to modify an existing Ecopath model for Lake Erie. We consulted lower trophic level experts regarding merging taxa into functional trophic groups in Ecopath. We estimated biomass of the lower trophic-level groups based on literature review and data sources including IFYLE field studies and the LEPAS (Lake Erie Plankton Abundance Study at Ohio State University). We modeled 41 age/size groups of fish: biomass estimated from IFYLE trawl and acoustic data, and from surveys by state and provincial agencies. We worked with Lake Erie fisheries managers to design relevant management simulations and to ensure the final EwE model is a useful management tool. The inputs of EwE have been carefully checked and verified and the team is drafting a manuscript on the model and findings.

Project management

Principal Investigator: Don Scavia (University of Michigan):

Investigators: J. David Allan, Dmitry Beletsky , Haejin Han,Thomas Johengen, Hongyan Zhang, Mary Anne Evans (University of Michigan); Tomas Höök (Purdue), Steven Bartell (E2, Inc.); Joseph DePinto (LimnoTech, Inc.); David Dolan (University of Wisconsin – Green Bay); Chansheng He (Western Michigan University); Roger Knight (Ohio DNR); Peter Richards (Heidelberg University); Stephen Brandt (Oregon State University); Stuart Ludsin (Ohio State University); Nate Bosch (Grace College), Doran Mason, Edward Rutherford, Steven Ruberg, David Schwab (NOAA)

Project management was accomplished through annual and semi-annual meetings and routine interactions among subgroups to ensure connectivity in time and space scales, and through regular and ongoing discussions with the management and policy communties.

Findings

The following synthesis paper summarizes the primary findings; it is in press in the *Journal of Great Lakes Research*.

WILL REPLACE WITH FINAL SYNTHESIS PAPER

Assessing and addressing the re-eutrophication of Lake Erie: Central Basin Hypoxia

END OF THE SYNTHESIS PAPER

If significant problems developed which resulted in less than satisfactory or negative results, they should be discussed.
There were only two unsatisfactory outcomes from this rather complicated, complex, and attempted comprehensive approach. We had two watershed modeling approaches that we hoped to compare (the Distributed Large-Basin Runoff Model [DLRBM] and the Soil and Water Assessment Tool [SWAT]). However, due to retirements of key DLRBM scientists and other personnel changes, we were not able to accomplish this comparison. While the comparison would have been interesting and useful, the SWAT models performed the desired function and, as such, there was no significant impact on the project.

The second shortcoming was our inability, given time and resource constraints, to accomplish the planned 3D ecological modeling portion of the project. We did complete the 3D hydrodynamic model, couple it with the level 2 simple ecology model, and provide preliminary output to the fish ecology group, but we were not able to complete a thorough analysis of the 3D results. This prevented the fish ecology group from testing 3D scenarios and the lake ecology group from building the more comprehensive model that would allow exploration of the Dreissinid effects. While this was disappointing, it did not inhibit use of our 1D model in both further scientific explorations and delivering outputs to the management community.

Description of need, if any, for additional work.
We would encourage further development and testing of the 3D model

Outputs - *New fundamental or applied knowledge*
The scope of this project revealed new information across a range of topics.

- We contributed substantively to answering the question of why, after decades of decline, DRP loads began increasing in the mid-1990s. The intersection of changed agricultural practices (e.g., fall broadcast application, no-till, etc.) with increased intensity and duration of spring storms are a likely cause.
- We developed the first capability for estimating the impact of changed loads directly on hypoxic area, an indicator of management concern, as opposed to oxygen concentrations and depletion rates that were done in the past.
- We demonstrated through laboratory, field, and modeling projects that increased hypoxia has the potential for negatively impacting a wide range of fish processes, including production and distribution.
- We identified for the first time where the watershed hot spots are for potential phosphorus load reductions and what impacts climate change may have on the effectiveness of proposed BMPs.

Outputs - *Scientific publications*

Arend, K.K., D. Beletsky, J.V. DePinto, S.A. Ludsin, J.J. Roberts, D.K. Rucinski, D. Scavia, D.J. Schwab, and T.O. Höök. Hypolimnetic hypoxia in the central basin of Lake Erie: understanding seasonal and interannual effects on habitat quality of important fish species. Freshwater Biology.

Arend, K.K., D. Beletsky, J.V. DePinto, S.A. Ludsin, J.J. Roberts, D.K. Rucinski, D. Scavia, D.J. Schwab, and T.O. Höök. 2011. Seasonal and interannual effects of hypoxia on fish habitat quality in central Lake Erie. Freshwater Biology, 56:366-383.

Beletsky, D., N. Hawley, Y.R. Rao. Modeling summer thermal structure and circulation in Lake Erie. *J. Geophys. Res. (in review).*

Beletsky, D., N. Hawley, Y.R. Rao, H. A. Vanderploeg, R. Beletsky, D. J. Schwab and S.A. Ruberg. 2012. Summer thermal structure and anticyclonic circulation of Lake Erie, *Geophys. Res. Lett.,* 39, L06605, doi:10.1029/2012GL051002.

Bosch N.S., J.D. Allan, J.P. Selegean, D. Scavia, 2013. Scenario-testing of agricultural best management practices in Lake Erie watersheds. *J. Great Lakes. Res.* http://dx.doi.org/10.1016/j.jglr.2013.06.004

Bosch, N.S., Allan, J.D., Dolan, D.M., Han, H., Richards, R.P., 2011. Application of the Soil and Water Assessment Tool for six watersheds of Lake Erie: Model parameterization and calibration. *J. Great Lakes Res*. 37, 263-71.

Bosch, N.S., M.A. Evans, D. Scavia, J.D. Allan (in revision) Interacting effects of climate change and agricultural BMPs on nutrient runoff, *J. Great Lakes Res.*

Brandt, S.B., M. Costantini, S.E. Kolesar, S.A. Ludsin, D.M. Mason, C.M. Rae, and H. Zhang. 2011. Does hypoxia reduce habitat quality for Lake Erie walleye (*Sander vitreus*)? A bioenergetics perspective. Canadian Journal of Fisheries and Aquatic Sciences. 68:857-879.

Croley II, T.E. and C. He. 2008. Ch.9. Spatially Distributed Watershed Model of Water and Materials Runoff. In: Ji, W. (ed). Wetland and Water Resource Modeling and Assessment: A Watershed Perspective. CRC Press, New York, p.99-112.

Croley, T. E., II, D. F. Raikow, C. He, and J. F. Atkinson, 2008. Hydrological Resource Sheds. Journal of Hydrologic Engineering (SCI) Vol.13 (9):873-885.

Croley, T. E., II, J. F. Atkinson, and D. F. Raikow, 2007. Hydrologic-hydraulic-ecologic resource sheds. Proceedings of Water Resources Management 2007 Conference, Honolulu, Hawaii, International Association of Science and Technology for Development, Calgary, Canada, August 20-22, 2007, 6 pp.

Daloğlu, I. 2013. An Integrated Social and Ecological Model: Impacts of Agricultural Conservation Practices on Water Quality, PhD Dissertation, University of Michigan, Ann Arbor, MI

Daloğlu, I., Cho, K. H., and Scavia, D. 2012 "Evaluating Causes of Trends in Long-Term Dissolved Reactive Phosphorus Loads to Lake Erie." *Environmental Science & Technology*, 46(19), 10660-10666.

Daloğlu, I., J.I. Nassauer, R.L. Riolo, D. Scavia (in review) An Integrated Social and Ecological Modeling Framework - Impacts of Agricultural Conservation Practices on Water Quality

DeMarchi, C., F. Xing, T. E. Croley, C. He, and Y. Wang. 2011. Application of a Distributed Large Basin Runoff Model to Lake Erie: Model Calibration and Analysis of Parameter Spatial Variation. Journal of Hydrological Engineering, 16(3): 193-202. Supported in part by NOAA CSCOR grant NA05NOS4781204 and Cooperative Institute for Limnology and Ecosystems Research's 2008 Great Lakes Summer Student Fellowship Program.

DeMarchi, C., T.E. Croley, C. He, and T.S. Hunter. 2009. Application of a distributed watershed hydrology and water quality model in the Great Lakes basin. Proceedings of the 7th

International Symposium on Ecohydraulics 2009, Concepcion, Chile, January 12-16, 2009.

Dolan, D. M. and K. P. McGunagle. 2005. Lake Erie total phosphorus loading analysis and update: 1996-2002. Journal of Great Lakes Research 31:11-22.

Dolan, DM. and S. C. Chapra. 2012. Great Lakes total phosphorus revisited: 1. Loading analysis and update (1994-2008). J. Great Lakes Res, 38:730-740

Goto, D., J.J. Roberts, S.A. Ludsin, S.A. Pothoven, H.A. Vanderploeg, S.B. Brandt, and T.O. Höök. (in revision) Seasonal bottom hypoxia affects demersal predator-prey size dynamics in a eutrophic system.

Goto, D., K. Lindelof, D.L. Fanslow, S.A. Ludsin, S.A. Pothoven, J.J. Roberts, H.A. Vanderploeg, A.E. Wilson, and T.O. Höök. 2012. Indirect consequences of hypolimentic hypoxia on freshwater zooplankton growth in a large eutrophic lake. Aquatic Biology. 16: 217–227.

Han, H., Allan, D.J., Bosch, N.S. 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. Journal of Great Lakes Research. 38: 289 – 298.

Han, H., N. Bosch, and J. D. Allan. Historical trends in phosphorus loading to watersheds of the Lake Erie and Lake Michigan basins. Journal for Great Lakes Research. In preparation.

Han, H., N. Bosch, and J.D. Allan. 2011. Spatial and Temporal variation in phosphorus budgets for 24 watersheds in the Lake Erie and Lake Michigan basins. Biogeochemistry, 102: 45-58. Supported by NOAA Center for Sponsored Coastal Ocean Research grant NA07OAR432000.

He, C. and T.E. Croley II. 2007. Application of a Distributed Large Basin Runoff Model in the Great Lakes Basin. Control Engineering Practice Vol. 15 (8): 1001-1011.

He, C. and T.E. Croley II. 2007. Integration of GIS and Visualization for Distributed Large Basin Runoff Modeling of the Great Lakes Watersheds. In: Scarpati and Jones (eds). Environmental Change and Rational Water Use. Orientación Gráfica Editora S.R.L., Buenos Aires, Argentina, pp. 247-260.

He, C. and T.E. Croley II. 2008. Ch.10. Estimating Nonpoint Source Pollution Loadings in the Great Lakes Watersheds. In: Ji, W. (ed). Wetland and Water Resource Modeling and Assessment: A Watershed Perspective. CRC Press, New York, p.115-127.

He, C. and T.E. Croley. 2010. Hydrological Resource Sheds and the U.S. Great Lakes Applications. Journal of Resources and Ecology, 1(1):1-6.

He, C. C. DeMarchi, and T.E. Croley II. 2008. Modeling Spatial Distributions of Nonpoint Source Pollution Loadings in the Great Lakes Watersheds by Using the Distributed Large Basin Runoff Model. Proc. Papers of American Water Resources Association GIS and Water Resources V, San Mateo, California, March 17-19.

He, C., and C. DeMarchi. 2010. Modeling Spatial Distributions of Point and Nonpoint Source Pollution Loadings in the Great Lakes Watersheds. International Journal of Science and Engineering 2(1):24-30.

Jarvie, H.P., C. Neal, P.J.A. Withers, D.B. Baker, R.P. Richards, and A.N. Sharpley. 2011. Quantifying Phosphorus Retention and Release in Rivers and Watersheds Using

Extended End-Member Mixing Analysis (E-EMMA). J. Environmental Quality 40(1): 1-13

Kidwell, D.M., A.J. Lewitus, E.B. Jewett, S. B. Brandt and D.M. Mason. 2009. Ecological impacts of hypoxia on living resources. Journal of Experimental Marine Biology and Ecology. 381:S1-S3.

Lewitus, A.J., D.M. Kidwell, E.B. Jewett, S. B. Brandt and D.M. Mason (Editors). 2009. Ecological Impacts of Hypoxia on Living Resources. Special Supplement of the Journal of Experimental Marine Biology and Ecology. 381: 215 pages.

Ludsin S.A., X.S. Zhang, S.B. Brandt, M.R. Roman, W.C. Boicourt, D.M. Mason, M. Costantini. 2009. Hypoxia-avoidance by planktivorous fish in Chesapeake Bay: implication for food web interactions and fish recruitment. Journal of Experimental Marine Biology and Ecology 381:S121-S131.

Ludsin, S. A., M. W. Kershner, K. A. Blocksom, R. L. Knight, and R. A. Stein. 2001. Life after death in Lake Erie: nutrient controls drive fish species richness, rehabilitation. Ecological Applications 11:731-746.

McCone, M. T.A. Endreny, J. Atkinson, J. DePinto, and J. Manno. 2006. "Role of International Policy and Science in Addressing Great Lakes Management and Lake Erie Eutrophication", in Hydrology and Water Law – Bridging the Gap, Edited by J. S. Wallace and P. Wouters, Title in the Water Law and Policy Series, Edited by P. Wouters and S. Vinogradov, International Water Association Publishing, London UK, pp. 78-107.

Michalak, A.M., E. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K.H. Cho, R. Confesor, I. Daloğlu, J. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T. Johengen, K.C. Kuo, E. Laporte, X. Liu, M. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme8, D.M. Wright, M.A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proc. Nat. Acad. Sci.* www.pnas.org/cgi/doi/10.1073/pnas.1216006110

Pothoven, S.A., H.A. Vanderploeg , S.A. Ludsin, T.O. Höök, and S.B. Brandt. 2009. Feeding ecology of emerald shiners and rainbow smelt in central Lake Erie. Journal of Great Lakes Research. 35:190-198.

Pothoven, S.A., H.A. Vanderploeg, T.O. Hook, S.A. Ludsin. 2012. Hyoxia modifies planktivore-zooplankton interactions in Lake Erie. Candian Journal of Fisheries and Aquatic Sciences 69(12):2018-2028.

Richards, R.P., I. Alameddine, J.D. Allan, D.B. Baker, N.S. Bosch, R. Confesor, J.V. DePinto, D.M. Dolan, J.M. Reutter, and D. Scavia. 2012. DISCUSSION: "Nutrient Inputs to the Laurentian Great Lakes by Source and Watershed Estimated Using SPARROW Watershed Models" by Dale M. Robertson and David A. Saad. *J. American Water Resources Association*. DOI 10.1111/jawr.12006.

Richards, R. P. 2006. Trends in sediment and nutrients in major Lake Erie tributaries, 1975–2004. *Lake Erie Lakewide Management Plan 2006 Update*, p. 10-22.

Richards, R.P., D.B. Baker, J.P. Crumrine, and A.M. Stearns. 2010. Unusually large loads in 2007 from the Maumee and Sandusky Rivers, tributaries to Lake Erie. Journal of Soil and Water Conservation 65(6): 450-462. Supported by NOAA CSCOR, the USDA CSREES, the USDA NRCS, Ohio DNR and Michigan DEQ.

Roberts, J.J. T.O. Höök, S.A. Ludsin, S.A. Pothoven, H.A. Vanderploeg, and S.B. Brandt. 2009. Effects of hypolimnetic hypoxia on foraging and distributions of Lake Erie yellow perch. Journal of Experimental Marine Biology and Ecology. 381: S132-S142.

Roberts, J.J., P.A. Grecay, S.A. Ludsin, S.A. Pothoven, H.A. Vanderploeg, and T.O. Höök. 2012. Evidence of hypoxic foraging forays by yellow perch (*Perca flavescens*) and potential consequences for prey consumption. Freshwater Biology. 57: 922-937.

Roberts, J.J., S.B. Brandt, D. Fanslow, S.A. Ludsin, S. Pothoven, D. Scavia, and T.O. Höök. Growth and condition of yellow perch in response to hypoxia: Synthesis of lab and field results. CJFAS.

Roberts, JJ., S.B. Brandt, D. Fanslow, S.A. Ludsin, S.A. Pothoven, D. Scavia, and T.O. Höök. 2011. Effects of hypoxia on consumption, growth, and RNA:DNA ratios of young yellow perch. Transactions of the American Fisheries Society. 40: 1574–1586.

Roberts, T. L. 2007. Right product, right rate, right time and right place…the foundation of best management practices for fertilizer. In Isherwood K. and Krauss A. eds. Fertilizer Best Management Practices: General Principles, Strategy for Their Adoption and Voluntary Initiatives vs Regulations: Papers Presented at the IFA International Workshop on Fertilizer Best Management Practices, 7-9 March 2007, Brussels, Belgium. International Fertilizer Industry Association, Paris, France. ISBN 2-9523139-2-X.".

Rucinski, D. K., D. Beletsky, J. V. DePinto, D. J. Schwab, and D. Scavia. 2010. A simple 1-dimensional, climate based dissolved oxygen model for the central basin of Lake Erie. Journal of Great Lakes Research 36:465-476.

Rucinski, D., D. Scavia**,** J. DePinto, D. Beletsky (in revision) Lake Erie's hypoxia response to nutrient loads and meteorological variability. *J Great Lakes Res.*

Schwab, D.J., D. Beletsky, J.V. DePinto, and D.M. Dolan. 2009. A hydrodynamic approach to modeling phosphorus distribution in Lake Erie. Journal of Great Lakes Research, 35(1):50-60.

Sharpley, A., P. Richards, S. Herron, D. Baker. 2012. Case study comparison between litigated and voluntary management strategies. J. Soil and Water Cons. 67:442-450

Vanderploeg, H.A., S.A. Ludsin, J.F. Cavaletto, T.O. Höök, S.A. Pothoven, S.B. Brandt, J.R. Liebig and G.A. Lang. 2009b. Hypoxic zones as habitat for zooplankton in Lake Erie: Refuges from predation or exclusion zones? Journal of Experimental Marine Biology and Ecology. 381:S108-S120.

Vanderploeg, H.A., S.A. Ludsin, S.A. Ruberg, T.O. Höök, S.A. Pothoven, S. B. Brandt, G.A. Lang, J.R. Liebig, and J.F. Cavaletto . 2009a. Hypoxia affects spatial distributions and overlap of pelagic fish, zooplankton and phytoplankton in Lake Erie. Journal of Experimental Marine Biology and Ecology. 381:S92-S107.

Wang, J., H. Hu, D. Schwab, G. Leshkevich, D. Beletsky, N Hawley, and A. Clites. 2010. Development of the Great Lakes Ice-circulation Model (GLIM): Application to Lake Erie in 2003-2004. Journal for Great Lakes Research, 36(3): 425-436.

Xing, F., C. DeMarchi, T. E. Croley, and Y. Wang. Application of Distributed Large Basin Runoff Model to Lake Erie: Model Calibration and Analysis of Parameter Spatial Variation. In review.

Zhang, H., Culver, D.A. and Boegman, L., 2008. A two-dimensional ecological model of Lake Erie: Application to estimate dreissenid impacts on large lake plankton populations. *Ecol.Model*. 214, 219-241.

Zhou, Y., D.R. Obenour, D. Scavia, T.H. Johengen, A.M. Michalak 2013. Spatial and temporal trends in Lake Erie hypoxia, 1987-2007, *Environmental Science & Technology*, 47, 899-905, dx.doi.org/10.102/es303401b.

Presentations at Conferences and Workshops

Allan, J.D., and H. Han. 2008. Phosphorus Loading to Lake Erie Watersheds: A Mass Balance Approach. 51st International Association for Great Lakes Research, May 19-23.

Arend, K., T. Höök, S. Ludsin, D. Rucinski, J. DePinto, and D. Scavia. 2008. Effects of hypoxia on yellow perch habitat suitability in the central basin of Lake Erie. Midwest Fish and Wildlife Conference, Columbus

Arend, K., T. Höök, S. Ludsin, D. Rucinski, J. DePinto, and D. Scavia. 2009. Evaluating and forecasting effects of hypoxia on yellow perch habitat suitability in central Lake Erie. Indiana American Fisheries Society Annual Meeting, Indianapolis

Arend, K.K., T.A. Höök, S.L. Ludsin, D. Rucinsky, D. Beletsky, J. DePinto, D. Scavia, D. Schwab. 2009. Comparing Effects of Hypolimnetic Hypoxia on Yellow Perch and Rainbow Smelt Habitat Suitability in Central Lake Erie. International Association for Great Lakes Research (IAGLR) 52nd Annual Conference on Great Lakes Research, Toledo, OH.

Arend, K., T. Höök, S. Ludsin, D. Rucinski, D. Beletsky, J. DePinto, D. Scavia, and D. Schwab. 2010. Seasonal and interannual effects of hypoxia on fish habitat quality in central Lake Erie. Michigan Chapter American Fisheries Society Annual Meeting.

Baker, D.B., Richards, R.P., and J.W. Kramer. 2010. Increasing trends in dissolved phosphorus in Lake Erie tributaries: the role of agricultural practices. International Association for Great Lakes Research 53rd Annual Conference on Great Lakes Research, Toronto, ON, May 17-21.

Beletsky, D., and D. Schwab. 2008. Modeling thermal structure in Lake Erie. IAGLR 2008. May 19-23, 2008, Peterborough, ON.

Beletsky, D., Schwab, D., Rao, R., Hawley, N., Vanderploeg, H., and R. Beletsky. 2010. Thermocline of Lake Erie. International Association for Great Lakes Research 53rd Annual Conference on Great Lakes Research, Toronto, ON, May 17-21.

Bosch, N.S. and J.D. Allan. 2008. An analysis of catchment nutrient inputs compared to riverine exports. International Joint Commission workshop – Loading from landscapes and coastal margin effects: Developing a framework to evaluate consequences of land management strategies. Oregon, OH.

Bosch, N.S., Allan, J.D., Han, H., and R.P. Richards. 2010. Using the Soil and Water Assessment Tool (SWAT) to Evaluate the Impact of Agricultural BMPs on Riverine

Nutrient Export to Lake Erie. International Association for Great Lakes Research 53rd Annual Conference on Great Lakes Research, Toronto, ON, May 17-21.

Bosch, N.S., H. Han, R.P. Richards, and J.D. Allan. 2009. Evaluating the impact of agricultural BMPs on riverine nutrient export to Lake Erie. North American Benthological Society, May 17-22.

Brandt, S., D. Schwab, and T. E. Croley II, 2007. Nearshore Water Quality: Linkages between Watersheds and Offshore Processes, International Joint Commission Workshop on 'Nearshore Processes,' Dearborn, Michigan, November 19-20.

Brandt, S.B., M. Costantini, S.A. Ludsin, D.M. Mason, and H.A. Vanderploeg. 2008. Spatially-explicit growth predictions to assess habitat quality of walleye during hypoxia in Lake Erie. Oral presentation at the International Association for Great Lakes Research 51st Annual Conference on Great Lakes Research, Peterborough, ON. May 20.

Croley, T. E., II, 2007. GLERL's Hydrology Program, GLERL-NCEP-NWS-NOS Meeting, Ann Arbor, Michigan, November 28.

Croley, T.E. Great Lakes Climate Change Thermodynamic Impacts Assessment. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Croley, T. E., II, 2008. Great Lakes Hydrologic Modeling, Hydrology Laboratory, NWS Office of Hydrology, Ann Arbor, Michigan, March 6.

Croley, T. E., II, and T. S. Hunter, 2007. Great Lakes Hydrology Modeling with the Advanced Hydrologic Prediction System, Michigan Technological Institute, Houghton, Michigan, October 8.

DeMarchi, C., T.E. Croley, T. Hunter., and C. He. 2009. Application of a Distributed Watershed Hydrology and Water Quality Model in the Great Lakes Basin. The International Conference on "Science and Information Technologies for Sustainable Management of Aquatic Ecosystems" (Heic2009): joint meeting of the 7th International Symposium on Ecohydraulics and the 8th International Conference on Hydroinformatics, Concepcion, Chile, January 12-16, 2009.

DePinto, J.V. "How does Lake Erie process the phosphorus loading it receives, and has the dreissenid invasion changed things?" invited presentation to the Lake Erie Phosphorus Task Force, Columbus, OH (October 1, 2008).

DePinto, J.V. "Nearshore phosphorus cycling and algal growth in the western basin of Lake Erie. 2009. Invited talk at the Western Lake Erie Basin Conference, Oregon, OH, (March 10-11, 2009).

DePinto, J.V. 2010. Recent Modeling in the Maumee Watershed and the Western Basin of Lake Erie. Invited presentation for the Lake Erie Millennium Network Conference, University of Windsor, April 27-29.

DePinto, J.V. 2011. Using the LMR-MB model to understand the 2011 *Microcystis* bloom in the Western Basin of Lake Erie. Invited talk at the Western Lake Erie Basin Partnership Leadership Team meeting, Perrysburg, OH. December 12, 2011.

DePinto, J.V., M.T. Auer, T.M. Redder, E. Verhamme. 2009. "Coupling the Great Lakes Cladophora Model (GLCM) with a whole lake Advanced Eutrophication Model (A2EM-

3D)." Presented at 53rd Annual Conference on Great Lakes Research, Toledo University, Toledo, OH (May 18-June 22, 2009).

DePinto, J.V., T.M. Redder, E. Verhamme. 2011. The Anatomy of an Algal Bloom: A 'Perfect Storm' in 2011. Invited talk at the Lake Erie Improvement Forum annual meeting, Camp Perry, OH. October 18, 2011.

DePinto, J.V., T.M. Redder, E. Verhamme. 2011. Use of spatial data for development and application of Great Lakes ecological models. Invited presentation, GIS Day 2011 Great Lakes Modeling Symposium, Notre Dame University, Notre Dame, IN. December 2, 2011.

DePinto, J.V.1, Vanderploeg, H.A.2, and AUER, M.T. 2008. Cladophora and open-water "desertification": Do Dreissenids play a role? Paper presented at the 51th Annual Conference on Great Lakes Research, Trent University, Peterborough, ON (May 19-June 23, 2008).

Dolan, D.M. and R.P. Richards. 2009. Spatially detailed nutrient load estimates for Lake Erie in 2005. 52nt Conference on Great Lakes Research. University of Toledo, Toledo, Ohio.

Dolan, D, R.P. Richards, and K. McGunagle. 2008. Total Phosphorus Loading to the Great Lakes. Landscapes and Loadings Workshop, Council of Great Lakes Governors, Maumee, OH, March 18. Presented by R. Peter Richards.

Dolan, D.M., R.P. Richards, and C.M. Piette. 2008. Updated Total Phosphorus Load Estimates for Lake Erie, 2005-2007. 51st Conference on Great Lakes Research May 19-23, 2008, Trent University, Peterborough, Ontario.

Dolan, D.M., Richards, R.P, and R.G. Kreis. 2010. Nutrient Load Estimates for Lake Erie in 2005. Invited presentation for the Lake Erie Millennium Network Conference, University of Windsor, April 27-29.

Dolan, D.M., Richards, R.P., Piette, C.M. Improved Spatial and Temporal Total Phosphorus Loads for Lake Erie Ecosystem Models, 2003-2005. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Dolan, D.M., Richards, R.P., Piette, C.M. Regression Analysis of Phosphorous Loading Data for the Maumee River, Water Years 2003-2005. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Goto, D., Rucinski, D.K., DePinto, J. V., Ludsin, S. A., Scavia, D., and Höök, T.O. 2010. Elucidating hypoxia effects on population dynamics of yellow perch and walleye in Lake Erie using a spatially explicit individual-based model. 71st Midwest Fish and Wildlife Conference. Minneapolis, Minnesota, December 12-15.

Goto, D., Rucinski, D.K., DePinto, J. V., Ludsin, S. A., Scavia, D., and Höök, T.O. 2011. Population-level consequences of hypolimnetic hypoxia in Lake Erie: Implications from a spatially explicit individual-based model. ASLO Aquatic Sciences Meeting. San Juan, Puerto Rico, February 13-18.

Han, H. and J.D. Allan. One hundred years of nutrient loading to Lake Michigan watershed. 2009. 57th North American Benthological Society. May 17-22.

He, C. and C. DeMarchi. 2009. Modeling Spatial Distributions of Point and Nonpoint Source Pollution Loadings in the Great Lakes Watersheds. Proceedings Paper of 2009 International Conference on Geographic Information Systems, World Academy of Science, Engineering and technology 54 (2009):795-801, Paris France, June 24-26, 2009.

He, C. and T. E. Croley. 2008. Resource Shed and Its Applications in the U.S. Great Lakes Watersheds. Lanzhou University, Lanzhou, P.R. China, Oct.29. 60 min.

He, C. and T. E. Croley. 2008. Resource Shed and Its Applications in the U.S. Great Lakes Watersheds. The Chinese Academy of Sciences Institute of Geodesy and Geophysics, Wuhan, Nov.3, 65 min.

He, C. and T. E. Croley. 2008. Resource Shed and Its Applications in the U.S. Great Lakes Watersheds. The Chinese Academy of Sciences Research Center for Eco-Environmental Sciences, Beijing, Nov.6, 65 min.

He, C. and T. E. Croley. 2009. Defining and Applying Hydrological Resource Shed in the Great Lakes Watersheds. Department of Geography, East Carolina University, Greenville, NC. Feb.18. 55 min.

He, C. and T. E. Croley. 2009. Hydrological Resource Sheds and Great Lakes Applications. Shanghai Jiaotong University, Dec.4, 2009, 70 min.

He, C., T.E. Croley, and C.. DeMarchi. 2007. Modeling spatial distribution of nonpoint source pollution loadings by using the Distributed Large Basin Runoff Model. 50th International Association for Great Lakes Research (IAGLR) Conference on Great Lakes Research, University Park, PA, 5/28-6/1/2007.

He, C., and T. E. Croley II, 2007. Integration of GIS and Distributed Large Basin Runoff Model for Modeling Nonpoint Source Loadings in the Great Lakes Watersheds, International Congress on Modelling and Simulation, Session 47: Nutrient Modeling Techniques to Support Water Quality Management, Christchurch, New Zealand, December 10-13.

He, C., T. E. Croley, and C. DeMarchi. 2008. Modeling Nonpoint Sources Pollution Loadings in the U.S. Great Lakes Basin. Shaanxi Normal University, Oct.24. 70 min.

He, C., T. E. Croley, and C. DeMarchi. 2008. Modeling Nonpoint Sources Pollution Loadings in the U.S. Great Lakes Basin. Research Institute for Protection of Yangtze Water Resources , Yangtze Water Resources Commission, Wuhan, Oct.31. 75 min.

He, C., T. E. Croley, and C. DeMarchi. 2008. Modeling Nonpoint Sources Pollution Loadings in the U.S. Great Lakes Basin. Research Institute for Protection of Yangtze Water Resources , Yangtze Water Resources Commission, Wuhan, Oct.31. 75 min.

He, C., T. E. Croley, and C. DeMarchi. 2009. Modeling Nonpoint Sources Pollution Loadings in the Great Lakes Watersheds. WMU Dept. of Civil and Construction Engineering CCE 4350 Hydrology class, Engineering College, Nov.19, 2009. 65 min.

He, C., T. E. Croley, C. DeMarchi. 2008. Modeling Spatial Distribution of Nonpoint Source Pollution in the Great Lakes Watersheds. The Association of American Geographers Annual Meeting, Boston, April 15-20.

He, C., T.E. Croley and C. DeMarchi. 2008. Climate Change and Nonpoint Source Pollution in the Great Lakes Basin: Opportunities and Challenges. Impact of Climate Change on the Great Lakes Ecosystem – A NOAA Science Needs Assessment Workshop to Meet Emerging Challenges. Ann Arbor, July 29-31.

He, C., T.E. Croley, and C. DeMarchi. 2008. Application of Distributed Large Basin Runoff Model and Resource Sheds in the U.S. Great Lakes Watersheds. (50 min presentation) The Chinese Academy of Sciences Research Center of Eco-Environmental Sciences, Beijing, Jan.5.

Impact of Climate Change on the Great Lakes Ecosystem – A NOAA Science Needs Assessment Workshop to Meet Emerging Challenges. Ann Arbor, July 29-31.

Jarvie, H. P., Neal, C., Withers, J.P., Baker, D.B., Richards, R.P. and A.N. Sharpley. 2011. Exploring Phosphorus Retention and Release in Rivers and Watersheds Using Extended Endmember Mixing Analysis. American Society of Limnology and Oceanography, San Juan, PR, February 18.

Kane, D. D., Conroy, J.D., Culver, D.A., Bridgeman, T.B., Chaffin, J.D., Bade, D.L., Edwards, W.J., McKay, R.M., Richards, R.P., and D.B. Baker. 2011. Re-eutrophication of Lake Erie: Insights from the Maumee and Sandusky Systems. American Society of Limnology and Oceanography, San Juan, PR, February 18.

Ludsin, S.A. 2007. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Department of Earth, Ecological, and Environmental Sciences, University of Toledo, Toledo, OH (invited seminar)

Ludsin, S.A. 2007. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Department of Biology, University of Akron, Akron, OH (invited seminar)

Ludsin, S.A. 2007. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Department of EEOB, OSU, Columbus (invited seminar).

Ludsin, S.A. 2007. Lake Erie hypoxia: history and management response. Ecological Impacts of Hypoxia on Living Resources Workshop Symposium, Bay St. Louis, MS. (invited presentation)

Ludsin, S.A. 2008. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Stone Laboratory Guest Lecture Series, Put-In-Bay, Ohio

Ludsin, S.A. 2008. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Department of Zoology, Southern Illinois University, Carbondale, IL

Ludsin, S.A. 2008. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. USGS Ohio Water Science Center, Columbus, OH

Ludsin, S.A. 2009. Exploration of hypoxia's effects on Lake Erie fisheries. Lake Erie Committee/State of the Lake Ecosystem Conference (SOLEC). Ypsilanti, MI (invited presentation).

Ludsin, S.A. 2009. Hypoxia effects on Lake Erie fisheries. State of Lake Erie Committee Meeting, Ypsilanti, Michigan

Ludsin, S.A. 2009. Hypoxia in Lake Erie: implications for food webs and fisheries. The Great Lakes: Adapting to a Wave of Change Conference, Michigan State University, East Lansing (invited presentation).

Ludsin, S.A. 2010. Hypoxia alters species distributions and interactions: implications for food webs and fisheries. Department of Biology, University of Waterloo (invited seminar).

Ludsin, S.A., and T.E. Croley II. 2008. Complexities of forecasting climate change effects on Great Lakes fisheries: an example with Lake Erie yellow perch. Climate Change in the Great Lakes Region Conference, Michigan State University, East Lansing, MI (invited presentation)

Ludsin, S.A., H.A. Vanderploeg, S.A. Pothoven, D.M. Mason, T. Höök, and S.A. Ruberg. 2007. Hypoxia effects on habitat and prey availability for rainbow smelt in central Lake Erie. International Association for Great Lakes Research, University Park, PA (contributed presentation)

Ludsin, S.A., T.O. Höök, D. Rucinski, J.V. DePinto and D. Scavia. 2008. Historical exploration of hypoxia effects on fish recruitment and production in Lake Erie. Oral presentation at the International Association for Great Lakes Research 51st Annual Conference on Great Lakes Research, Peterborough, ON. May 20.

Ludsin, S.A., Vanderploeg, H.A., Pothoven, S.A., Mason, D.M., Hook, T.O. and Ruberg, S.A. Hypoxia Effects on Habitat and Prey Availability for Rainbow Smelt in Central Lake Erie. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Modelling and Simulation, Session 47: Nutrient Modeling Techniques to Support Water Quality Management, Christchurch, New Zealand, December 10-13.

Pangle, K.L. , S. Pothoven, H.A. Vanderploeg, T.O. Höök, S.B. Brandt and S.A. Ludsin. Hypoxia's impact on pelagic fishes: a tale of two planktivores. Ecological Society of America. Pittsburgh, PA. August 1-6, 2010. abstract submitted.

Richards, R. P. 2008. Testimony on Lake Erie Phosphorus Loadings. U.S. House of Representatives Committee on Transportation and Infrastructure, Subcommittee on Water Resources and Environment. Port Huron, Michigan, May 12.

Richards, R. P. 2008. Food, Fertilizer, Fish, and Fouled Beaches: Water Quality in the Maumee River and the Western Basin of Lake Erie, 1975 to Present. Lake Erie Center, Maumee, OH, October 16.

Richards, R.P. 2008. Record Setting Phosphorus Loads from Agricultural Watersheds in Ohio. USDA Water Quality Conference, Sparks, NV, February 6.

Richards, R. P. 2009. Trends in sediment concentrations and loads in Northwest Ohio tributaries to Lake Erie, 1975-2008. Western Lake Erie Basin Conference, , Maumee Bay State Park, March 10.

Richards, R.P. 2009. Reduced loads of suspended solids and particulate phosphorus demonstrated by long-term monitoring. Briefing for Cameron Davis and Marcy Kaptur, U. Toledo, November 13

Richards, R.P. 2011. Lakes and Watersheds: A Quick Walk to the Limits of my Knowledge and Beyond. American Society of Limnology and Oceanography, San Juan, PR, February 19.

Richards, R.P. 2011. Maumee trends. Briefing for NRCS Chief and chief scientists, Oregon, OH. December 15, 2011.

Richards, R.P. 2011. Maumee trends. Maumee River Researchers' Meeting, Oregon, OH. December 1, 2011.

Richards, R.P. 2011. P and N Trends in the Maumee and Sandusky Rivers, Major Lake Erie Tributaries. International Association for Great Lakes Research, Duluth, MN. June 17, 2011.

Richards, R. P. and D.B. Baker. 2011. Increasing Trends in Dissolved Phosphorus in Lake Erie Tributaries: The Role of Agricultural Practices. American Society of Limnology and Oceanography, San Juan, PR, February 18,

Richards, R.P. and D.B. Baker. 2011. Chickasaw Creek nutrient and sediment export studies, 2009-2011 Water Years. Briefing for NRCS chief scientists, Celina, OH. December 16, 2011.

Richards, R.P., D.B. Baker, and J.P. Crumrine. 2007. Increased Dissolved Phosphorus Loading to Lake Erie from Agricultural Watersheds. Great Lakes Protection Fund Project Workshop, Tiffin, OH, December 18.

Richards, R.P., D.B. Baker, and J.P. Crumrine. 2008. Trends in Dissolved Reactive Phosphorus in Lake Erie Tributaries. Landscapes and Loadings Workshop, Council of Great Lakes Governors, Maumee, OH, March 19.

Richards, R.P, D.B. Baker, and J.P. Crumrine. 2008. Trends in Dissolved Reactive Phosphorus in Lake Erie Tributaries. Millennium Network Conference, Windsor, ON, April 29.

Richards, R.P., D.B. Baker, and J.P. Crumrine. 2008. Water Quality Trends in Lake Erie Watersheds. Western Lake Erie Basin Partnership Roundtable, Toledo, OH, February 20.

Richards, R.P., D.B. Baker, and J.W. Kramer. 2011. Loads and Concentrations in Rivers and Streams. EPA RARE Workshop, Celina, OH. July 26, 2011.

Richards, R.P. G. Hesse, R. Knight, K. Dinse, and D. Scavia. 2009. Lake Erie Hypoxia: Climate, Invasive Species, and Agricultural Loads. NOAA-CSCOR Regional Workshop, Silver Spring, MD, May 18-19.

Richards, R. P. and D. Scavia. 2011. The Great Lakes Watershed and Agriculture. Michigan Agriculture's Conference on the Environment, Lansing, MI, January 27,

Roberts, J.J., Höök, T.O., :Ludsin, S.A., Pothoven, S.A., Vanderploeg, H.A. and Nalepa, T. The ecological response of yellow perch to hypoxia in Lake Erie's central basin. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Roberts, J.J., T.O Höök, S.A. Ludsin, S.A. Pothoven, and H.A. Vanderploeg. 2008. Bioenergetics model to explore the effects of hypoxia on yellow perch habitat quality in Lake Erie's central basin. Oral presentation at the International Association for Great Lakes Research 51st Annual Conference on Great Lakes Research, Peterborough, ON. May 20.

Roberts, J.J., T.O. Höök, Paul A. Grecay, S.A. Ludsin, S.A. Pothoven, and H.A. Vanderploeg. 2009. Sub-daily behavioral consequences of hypoxia for yellow perch in Lake Erie's central basin. International Association for Great Lakes Research, Toledo, OH.

Roberts, J.J., T.O. Höök, S.A. Ludsin, and S.A. Pothoven. 2009. Growth and condition of yellow perch in response to hypoxia: synthesis of lab and field results. American Fisheries Society, Nashville, TN.

Roberts, J.J., T.O. Höök, S.A. Ludsin, S.A. Pothoven, and H.A. Vanderploeg. 2008. Response of yellow perch to hypoxia in Lake Erie's central basin: Spatial patterns. American Fisheries Society 138th Annual Conference, Ottawa, ON.

Roberts, J.J., T.O. Höök, S.A. Ludsin, S.A. Pothoven, and H.A. Vanderploeg. 2009. Implications of hypoxia for yellow perch habitat quality in Lake Erie's central basin: a spatially-explicit bioenergetics modeling approach. Oral presentation at the Michigan Chapter of the American Fisheries Society Annual Meeting, Dundee, MI.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia, D. Schwab. 2007. Model analysis of climate effects on dissolved oxygen in the central basin of Lake Erie. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia, D. Schwab. 2008. Development and Application of 1D Eutrophication Models for the Central Basin of Lake Erie. Oral presentation at the International Association for Great Lakes Research 51st Annual Conference on Great Lakes Research, Peterborough, Ont. May 20.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia, D. Schwab. Model analysis of climate effects on dissolved oxygen in the central basin of Lake Erie. Oral presentation at the International Association for Great Lakes Research 50th Annual Conference on Great Lakes Research, University Park, PA. June 1, 2007.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia, D. Schwab. 2008. Development and Application of 1D Eutrophication Models for the Central Basin of Lake Erie. Oral presentation at the International Association for Great Lakes Research 51th Annual Conference on Great Lakes Research, Peterborough, Ont. May 20.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia, D. Schwab. 2008. Long-Term Application of a Climate-Driven Dissolved Oxygen Model for the Central Basin of Lake Erie. Oral presentation at the International Association for Great Lakes Research 51st Annual Conference on Great Lakes Research, Peterborough, Ont. May 20.

Rucinski, D.K., D. Beletsky, J.V. DePinto, D. Scavia. 2009. "Application and comparison of 1D and 3D lower food web models for Lake Erie." Presented at 53rd Annual Conference on Great Lakes Research, Toledo University, Toledo, OH (May 18-June 22, 2009).

Rucinski, D.K., J.V. DePinto, D. Beletsky, D. Scavia, D.J. Schwab. Application and Comparison of 3D Eutrophication Models for Lake Erie. 54th Annual Conference on Great Lakes research. Duluth, MN. May 30, 2011.

Scavia, D. 2011. Agricultural and climate impacts on Lake Erie Hypoxia. Coastal Habitat Workshop, Ypsilanti MI. September 12, 2011

Scavia, D. 2011. Agricultural and climate impacts on Lake Erie Hypoxia. International Joint Commission Meeting, Detroit, MI. October 14, 2011

Scavia, D. 2011. Agricultural and climate impacts on Lake Erie Hypoxia. Great Lakes Commission Meeting, Detroit MI. October 15, 2011.

Scavia, D. 2012. Agricultural and climate impacts on Lake Erie HABs and Hypoxia. International Joint Commission Meeting, Ann Arbor, MI. March 27, 2012

Sellinger, C., and T. E. Croley II, 2008. GLERL's Hydrology Program, NOAA-USGS Committee on Hydrology Meeting, Silver Springs, Maryland, January 16.

Sharpley, Andrew and R. Peter Richards. 2008. Adaptive Management and Water Quality: Is there anything to be learnt from outside the U.K.. Agriculture, Water Management, and Climate Change, Bath, England, March 5.

Zhang, H., Rutherford, E., Mason, D., Johnson, T.B., Adamack, A.T., Zhu, X., and Scavia, D. 2010. Ecosytem Level Assessments of Hypoxia Impacts on the Food Web and Fisheries of Lake Erie. Poster. The 53rd annual international conference of the International Association for Great Lakes Research – lessons from the past, Solutions for the future. Toronto, ON, May 17-21.

Zhang, H., Rutherford, E., Mason, D., Johnson, T.B., Adamack, A.T., Zhu, X., and Scavia, D. 2010. Ecosystem Level Impacts of Hypoxia on the Food Web and Fisheries of Lake Erie. The 140th meeting of the American Fisheries Society. Pittsburg, PA, September 12-16.

Zhang, H., Rutherford, E.S., Mason, D.M., Adamack, A.T., Johnson, T., and Zhu, X. 2009. Ecopath with Ecosim and Ecospace: Hypoxia impacts on the fisheries of Lake Erie. Pre-Lake Erie Committee meeting. London, Ontario.

Management outcomes I: Management application or adoption of project results.

The vast majority of the research output from this project is being used by the International Joint Commission in their advice to the US and Canadian governments regarding additional nutrient management control for Lake Erie. Most of the hypoxia-related findings and recommendations in their report, "Lake Erie Ecosystem Priority: Scientific Findings and Policy Recommendations to Reduce Nutrient Loadings and Harmful Algal Blooms" (http://ijc.org/en_/leep/draft_report) were based on, and often drafted by, Ecofore investigators. The recommendations are incorporated in the synthesis paper provided above, and the key implications are repeated here:

Implications for Policy and Management Action

If an appropriate social/political process establishes "acceptable levels" (or goals) for hypoxia, the previously described response curves could be used to establish P loading targets. Given the emergence of DRP as a significant and increasing component of the total phosphorus load, we recommend considering both TP and DRP targets. In addition, because the results of management actions aimed at addressing non-point sources tend to occur on the scale of years to decades, potential impacts of a changing climate need to be taken into consideration. Most indications suggest that climate change will not only exacerbate existing problems, but also make reducing loads more difficult.

Whole-lake targets alone may no longer be appropriate due to differences in temporal and spatial scales of loading affecting hypoxia and other environmental stressors. For example, CB hypoxia evolves over a longer time frame in response to loads distributed over wider spatial and temporal scales than WB cyanobacteria blooms, which appear to be driven by relatively short-term loads of immediately available P. Thus, while a recent assessment demonstrated the Detroit River had little impact on the massive 2011 cyanobacteria bloom, it does not mean that the river is not an important driver for hypoxia; hypoxia development is a cumulative process that can be influenced by longer term loads of both immediately available DRP and P that is made available through internal recycling mechanisms over the summer. Thus, a new loading target aimed at reducing or eliminating cyanobacteria blooms might be insufficient in both magnitude and geographic proximity to reduce hypoxia. Even if whole-lake targets were appropriate, because the major components of the P load are now from non-point sources, and because resources available to address those sources will always be limited, management efforts need to be placed on sub-watersheds that deliver the most P. We now have the ability to identify not only the most important contributing watersheds (e.g., Detroit, Maumee, Sandusky), but also the regions within those tributary watersheds that release the most P. This knowledge should allow for more effective targeting of BMPs to high-load subwatersheds, assuming that the stakeholders (e.g., policy-makers, land developers, farmers) in those regions are open to adopting the newly proposed policies. For this reason, research that identifies factors that drive land-use decision-making behavior, and how these motivations and behaviors vary across the watershed, will be essential to helping policy-makers determine their ability to meet any newly developed loading targets through implementation of spatially-targeted BMPs.

For example, current farm policy is based on volunteer, incentive-based adoption of BMPs, and deliberations over the U.S. Farm Bill, including focus on special areas and replacing subsidies with revenue insurance, provide opportunities to employ more targeted approaches. However, farmer adoption of those practices will be paramount, and a recent analysis suggests revenue insurance uncoupled from conservation practices may have unintended consequences. Using a social-ecological-system modeling framework that synthesizes social, economic, and ecological aspects of landscape change under different agricultural policy scenarios, Daloğlu (2013) and Daloğlu et al. (in review) evaluated how different policies, land management preferences, and land ownership affect landscape pattern and subsequently downstream water quality. This framework linked an agent-based model of farmers' conservation practice adoption decisions with SWAT to simulate the influence of changing land tenure dynamics and the crop revenue insurance *in lieu* of commodity payments on water quality over 41 years (1970-2010) for the predominantly agricultural Sandusky River watershed. The results showed that non-operator owner involvement in land management decisions yielded the highest reduction in sediment and nutrient loads and that crop revenue insurance tended to create a homogeneous conservation landscape with slight increases in sediment and nutrient loads. However, it also suggested that linking crop insurance to conservation compliance and strengthening and expanding conservation compliance provisions could reduce nutrient loads.

Experiences in other large regions with nutrient problems (e.g., Chesapeake Bay, Gulf of Mexico/Mississippi River) have shown that significantly reducing non-point source loads is difficult. Not only are the sources spatially distributed, but the methods used are primarily voluntary and incentive based, and thus difficult to target and track. Reducing non-point inputs of sediments and nutrients is also difficult because the response time between action and result can be many years or longer, and the results can only be measured cumulatively in space and through time. For these reasons, we recommend use of an adaptive management approach that sets "directionally correct" interim targets, evaluates the results both in loads and lake response on appropriate time-scales (e.g., 3-year running averages), and then adjusting management actions or loading targets, if necessary. Such an approach also would allow for more effective testing and post-audits of the ability of models to project the ecosystem's response and thus improve subsequent assessments and projections. We see this iteration of research and analysis, management-focused model development and application, management action, and monitoring of results as a particularly effective way to manage large, spatially complex ecosystems. If the monitored results are not as anticipated, returning to research and model refinement establishes a learning cycle that can lead to better informed decisions and improved outcomes.

Management outcomes II: Societal condition improved.

While it is premature to assess this, we are confident that the impact of our work will be quite influential in setting the new GLWQA phosphorus loading targets, not only because our work became the center piece of the IJC LEEP Report (http://ijc.org/en_/leep/draft_report), but also because of the ongoing role many of the Ecofore investigators play in the GLWQA Task Force on setting those targets. Of course, once the targets are set (some time in 2014), it will take many years to observe changes in the environmental endpoint measures (e.g., loads and hypoxia)