NSF Water Sustainability and Climate (WSC) project EAR-1209402

REACH (REsilience under Accelerated CHange)

Year 5 Progress Report for 2016–2017

Lead PI: Efi Foufoula-Georgiou (University of Minnesota)

Other PIs at the University of Minnesota: Jacques Finlay, Karen Gran, and Gillian Roehrig

1. ACCOMPLISHMENTS – What was done? What was learned?

1.1. What are the major goals of the project?

The overarching goal of our Water Sustainability and Climate project (called REACH: REsilience under Accelerated CHange) is to develop a framework within which the vulnerabilities of a natural-human system can be assessed to guide decision-making towards eco-hydrologic sustainability and resilience. A unique element of the developed framework is identifying and focusing on places, times, and processes of accelerated or amplified change. One specific hypothesis to be tested is that of Human Amplified Natural Change (HANC), which states that areas of the landscape that are most susceptible to human, climatic, and other external changes are those that are undergoing the highest natural rates of change. To test the HANC hypothesis and turn it into a useful paradigm for enabling water sustainability studies, a predictive understanding of the cascade of changes and local amplifications between climatic, human, hydrologic, geomorphologic, and biologic processes are being developed to identify "hot spots" of sensitivity to change and inform mitigation activities. The developed framework is being tested in the Minnesota River Basin (MRB) where geological history, climate variability, and intensive agriculture are affecting changes in water quantity, water quality, and ecosystem health.

1.2. What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

1.2.1. Major activities:

(1) Research integration, collaboration, and dissemination

1. A 3-day annual collaboration meeting was held in August 8-10, 2016 at the University of Minnesota in Minneapolis, MN, to bring PIs and their research groups together to discuss science integration and action plans for the next year.
2. 40 Presentations were given this past year at local, regional, national, and international conferences including: annual meetings of the American Geophysical Union, European Geosciences Union, National Association of Research in Science Teaching, American

Meteorological Society, Japan Geophysical Union, Community Surface Dynamics Modeling System, Green School Conference and Expo, River Flow – International Conference on Fluvial Hydraulics, IUGG Conference on Mathematical Geophysics, Institute on the Environment Sustainability Symposium, Upper Midwest Stream Restoration Symposium, Minnesota Quaternary Science meeting, Workshop on Information Theory and the Earth Sciences, Geology department at the University of Illinois, Waseca County Farmer Forum, Association for Science Teacher Education, International Conference on Higher Education Advances

(2) Educational activities

The fifth year of the "The River Run: Professional Development with a Splash of Technology" has progressed toward the project's goals of continued research and development. "The River Run" is an effort to promote awareness in secondary science classrooms about issues related to the Minnesota River and its watershed for the communities in which the classrooms exist. On-going work is exploring the development of an interactive, online computer-simulation tool that allows students to explore the impact of land-management practices on nitrate levels. The basis for this computer-simulation tool is the research of REACH members. A full high school curriculum unit centered on this simulation has been developed and piloted in one of our partner teacher's classrooms. Additionally, we are reworking scientific articles related to the WSC scientific research into formats accessible for students and classroom use. Examples of developed curricula can be found on the project site at this link (http://stem-projects.umn.edu/riverrun/test-page/).

(3) Stakeholder meetings

Stakeholder meetings have continued from last year and provide a venue for disseminating results from research on the REACH project directly to federal, state, and county agency staff; growers associations; citizen activist groups; farmers; and other university and extension agency researchers. Stakeholder meetings was held by multiple REACH PIs through the Collaboration for Sediment Source Reduction (CSSR) during January 2016 and Summer 2016 in Mankato, MN. Attendees (~20-40 people) came from Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, Minnesota Corn Growers Association, Minnesota Agricultural Water Resource Center, Blue Earth County, Greater Blue Earth River Basin Alliance, Minnesota Soybean Growers Association, University of Minnesota Extension Agency, University of Minnesota, Johns Hopkins University, Utah State University, North Dakota State University, and several farmers.

By working with the Management Option Simulation Model (MOSM) and investigating various scenarios, the stakeholder group was able to reach a consensus at the final meeting on March 7, 2017, regarding an approach to sediment management that included three main points: 1) Ravines that are large local sources of sediment can be targeted. Investment in stabilizing these ravines is worthwhile, but not sufficient to reduce sediment loading to meet water quality standards. 2) Eroding bluffs that threaten infrastructure and produce exceptionally large amounts of sediment can be targeted. Investment in stabilizing these bluffs is worthwhile, but bluff stabilization is not the most effective solution for long-term reduction in sediment loading across the watershed. 3) Achieving water quality standards will require priority investment in more temporary water storage to reduce high river flows and bluff erosion. This is a critical component of a strategy to reduce sediment in the Minnesota River.

1.2.2. Specific Objectives:

The project has four main objectives, on which significant progress has been made over the past 4 years, as described in the next section and the attached pdf document:

(1) Determine the extent to which current high rates of sediment production, amplified by land-use, hydrologic, and climate changes, are affected by the underlying geology and geomorphic history of the basin, guiding a topography-based predictive framework of sediment sourcing and budgeting in a dynamic landscape.

(2) Quantify how climate and land-use driven hydrologic change, amplifies and accelerates environmental and ecological change in the basin, and how nonlinearities and amplifications can be quantified and upscaled across basins of different size;

(3) Understand the interactions of the river network physical structure and biological processes, including the role of wetlands, lakes and riparian zones, in nutrient transport and cycling, phosphorous-sediment budgeting, and food web structure towards a predictive framework in highly dynamic agricultural landscapes;

(4) Propose conservation management strategies, including sediment and nutrient reduction, to sustain ecological health and species biodiversity while promoting economic development and agricultural productivity.

1.2.3. Significant results:

During 2016-2017, our research has been integrative along five major topical areas (*see attached pdf for a brief summary of these research topics*):

Integrated watershed-scale modeling to address multiple objectives: demonstration in the Le Sueur and Minnesota River Basins for effective conservation management options

Research informing the integrated multi-objective modeling framework is summarized as:

1. Sediment sourcing and cycling in a coupled human-natural landscape
1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns
1.2. Sediment connectivity and dynamics on river networks
1.3. Quantifying historical landscape changes that impact current erosional hotspots and legacy sediments
1.4. Incorporating near channel sediment into the watershed scale modeling framework

2. Cascade of climate and land use/land cover change to eco-hydrologic change
2.1. Reducing aggregation bias of water and solute travel time distributions in heterogeneous catchments
2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics

3. Quantifying nutrient and phosphorus cycling in intensively managed landscapes
3.1. Anthropogenic and environmental controls on nutrient inputs and export
3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics
3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes
3.4. Nitrogen, phosphorus and suspended algal biomass in an agricultural watershed of the Upper Midwestern USA

3.5. Patterns in resource use by aquatic consumers in agricultural streams of the Minnesota River Basin

4. The role of wetlands and water-retention structures in environmental restoration and tradeoffs

4.1. Network structure nitrate removal efficiency
4.2. Valuing Water Quality Improvements in Midwestern Ecosystems: Spatial Variability, Validity and Extent of the Market for Total Value
4.3. Evaluation of trade-offs associated with wetland interventions
4.4. Spatial optimization of wetland restoration using spatial ownership constraints and a real options analysis for Le Sueur River Watershed
4.5. Including additional ecosystem services in models of cost-efficient water quality improvements
4.6. Integrating the Management Options Simulation Model (MOSM) into optimization and tradeoff analysis
4.7. Integrated Le Sueur modeling

5. Engaging and educating the public

5.1. Socio-scientific issues
5.2. Curriculum development and classroom implementation
5.3. Development of a consensus strategy for sediment reduction through stakeholder-driven model development and scenario investigations

1.2.4. Key outcomes or other achievements:

The WSC REACH project is in synergy with two other projects: the new Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) and the Collaborative for Sediment Source Reduction (CSSR).

Intensively Managed Landscapes Critical Zone Observatory (IML-CZO)

The Minnesota River Basin (MRB), which is the focus of our REACH project, became in 2013 part of the Intensively Managed Landscapes-Critical Zone Observatory (IML-CZO), led by REACH PI Praveen Kumar at the University of Illinois. The IML-CZO aims to understand the present-day dynamics of intensively managed landscapes in the context of long-term natural coevolution of the landscape, soil, and biota under significant land-use change mainly due to agriculture. The IML-CZO will enable us to assess the short- and long-term resilience of the crucial ecological, hydrological, and climatic "services" provided by the Critical Zone, the "skin" of the Earth that extends from the treetops to the bedrock. An observational network of three sites in Illinois, Iowa, and Minnesota that capture the geological diversity of the low-relief, post-glaciated, and tile-drained landscape will allow for novel scientific and technological advances in understanding the Critical Zone. The IML-CZO also provides leadership in developing the next generation of scientists and practitioners and in advancing management strategies aimed at reducing the vulnerability of the system to present and emerging trends in human activities. The IML-CZO Program is a joint effort by a growing team of faculty and scientists from several institutions, including the University of Illinois at Urbana-Champaign, the University of Iowa, Purdue University, Northwestern University, Pennsylvania State University, the University of Minnesota, Utah State University, the University of Tennessee, the Illinois State Water Survey, the Illinois State Geological Survey, and the U.S. Geological Survey.

Collaborative for Sediment Source Reduction (CSSR)

Several REACH PIs (Wilcock, Belmont, Gran) have initiated a science-stakeholder collaborative for developing an implementation strategy for sediment reduction in the Blue Earth watershed, which is the largest sediment source to the MRB. This work involves extrapolating our sediment budget from the Le

Sueur watershed (a sub-basin of the Blue Earth watershed) and building a simulation model and decision support system with local stakeholders. This is a significant leveraging and knowledge-transfer opportunity because we will be directly collaborating with public and private decision makers in the most dynamic (amplified) portions of the watershed. This project has established a tight network of collaboration with Federal and State agencies and stakeholders to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions. Additionally, the CSSR has established a stakeholder group that meets semiannually to implement a strategy for reducing fine sediment loading in the Greater Blue Earth River Basin.

Supplement to extend study to evaluation of trade-offs associated with wetland interventions

A supplement funding to our project was approved. It aspires to lay the foundation in advancing a FEW systems-level thinking for agricultural landscapes by focusing on identifying and quantifying the challenging links between policy, markets, climate drivers, land and water management actions, and the cascade of environmental implications. We aim to achieve two goals: (1) assess the benefits and costs of alternative futures for the MRB, including impacts to ecosystem services across spatial and temporal scales and (2) incorporate these impacts into a generalizable framework that links policy, markets, and climate drivers, to land and water management actions, to the nonlinear cascade of environmental implications, to a socio-economic valuation of changes in ecosystems, back to potential policies, payments or incentive schemes needed to shift underlying drivers of behavior and resilience of the FEW system.

1.3. What opportunities for training and professional development has the project provided?

This past year the project has resulted in training of 2 research associates, 4 post-docs, 11 graduate students, and 6 undergraduate students at the University of Minnesota Twin Cities and Duluth campuses. Post-docs being supported directly by this grant are being mentored by multiple PIs on the grant, allowing for more interdisciplinary growth and interactions. These post-docs are also given the opportunity to help mentor graduate students, write proposals and publications, and attend conferences. Post-docs and graduate students are also given the opportunity to attend our annual collaboration meetings and present their research. In 2017 our fifth annual collaboration meeting will be held at the University of Minnesota in Minneapolis, MN. This grant is also providing training opportunities for 6 K-12 educators through our River Run initiative.

1.4. How have the results been disseminated to communities of interest?

Results are being disseminated through presentations at scientific conferences; through meetings with stakeholders in Minnesota as part of the Collaborative for Sediment Source Reduction (CSSR), an effort by multiple REACH PIs; through the IML-CZO outreach efforts; and through educational efforts with K-12 teachers from communities within the MRB involved in the River Run project.

1.5. What do you plan to do during the next reporting period to accomplish the goals?

In the final year of our WSC project, effort will be placed on (1). the synthesis and integration towards the main four objectives of the REACH project, and (2) leveraging the biophysical modeling and empirical data collected as part of the WSC grant to account the impact of potential actions on multiple ecosystem services (supplement).

(1) The main four objectives of the REACH project, which in short evolve around: (1) Sediment budgets: sources, pathways, and sinks of sediment and particulates; (2) Non-linear cascade of change: from climate and land-use change to hydro-ecological change; (3) Integrated nutrient and biological transport on river

networks and water bodies; and (4) Conservation management strategies to promote economic development and ecological integrity.

The educational component will involve continued collaboration and support for the River Run Team educators. Curriculum development and classroom implementation will continue, with formative and summative evaluations of the curricula in the classroom, and revisions throughout the year as classroom implementations occur. Continue familiarizing participating teachers with the on-line collaborative space, facilitating development of a "Community of Practice" among the educators and students. On-going work is exploring the development of an interactive, online computer-simulation tool, grounded in process-based fundamentals elucidated by REACH project members, that allows students to explore the impact of land-management practices on nitrate levels. Additionally, we are reworking scientific articles related to the WSC scientific research into formats accessible for students and classroom use. Lastly, continue to collect and display student-created digital media related to socio-scientific issues explored within the MRB for the public.

Community and stakeholder involvement will continue, primarily through an additional stakeholder meeting run by the CSSR team. Now that our collaboration's website has been launched, this will allow for more data dissemination and knowledge transfer. The collaboration's website will be linked with the web-based GIS server to allow more easy dissemination of derived spatial datasets to stakeholders, collaborators, and the community at large.

(2). The supplement aims to leverage the biophysical modeling and empirical data collected as part of the WSC grant to account the impact of potential actions on multiple ecosystem services (ES). The integrative work requires two steps: 1) identifying a set of ecosystem services and defining ecological production functions that regulate their supply, 2) developing valuation functions at the landscape scale that account for social and economic demand for each service. This integrated approach will allow us to evaluate any portfolio of actions that affects biophysical supply of ecosystem services and the associated social-based valuation.

We have identified and developed ecosystem service models for water quality and quantity, recreation (boating, fishing and swimming), and infrastructure. Several of these are adaptations of existing models (N and P functions), while the sediment functions have been developed explicitly for this project. These functions translate the biophysical outputs from the hydrological models to impacts on ecosystem services. In order to limit the number of objectives that the genetic algorithm needs to deal with, they have been combined into two ES indices, a health-related index, and a recreation index.

Once the valuation functions are complete, we will integrate them into the genetic algorithm decision optimization process. To that end, in addition to developing and testing the ecosystem service models, we are also developing an integrated software implementation to contribute to the multi-objective optimization. This translation will consist of wrappers to call our Python ES functions from C++, or re-implementations of our functions in C++ for increased performance and interoperability with the GA.

Supporting Files

PRODUCTS – What has the project produced?

Books:

Book Chapters:

Peer-Reviewed Journal Articles:

Belmont, P., J.R. Stevens, J.A. Czuba, K. Kumarasamy, S.A. Kelly (2016), Comment on "Climate and agricultural land use change impacts on streamflow in the upper midwestern United States" by Satish C. Gupta et al., *Water Resources Research*, *52*(9), 7523-7528, doi: 10.1002/2015WR018476.

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Danesh-Yazdi, M., A. Tejedor, and E. Foufoula-Georgiou (2017), Self-Dissimilar Landscapes: Revealing the Signature of Geologic Constraints on Landscape Dissection via Topologic and Multi-Scale Analysis, In Review.

Dolph, C.L., Hansen A.T., Finlay J.C. (2017), Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter in an agricultural river network of the Minnesota River Basin, USA. *Hydrobiologia,* 785(1): 127-147, doi: 10.1007/s10750-016-2911-7.

Dolph CL, Hansen AT & Finlay JC (in review) Patterns in resource use by aquatic consumers in agricultural streams of the Minnesota River Basin, *Freshwater Biology*.

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Foufoula-Georgiou, E., P. Belmont, P. Wilcock, K. Gran, J. C. Finlay, P. Kumar, J. A. Czuba, J. Schwenk, and Z. Takbiri (2016), Comment on "Climate and agricultural land use change impacts on streamflow in the upper midwestern United States" by Satish C. Gupta et al., *Water Resources Research*, 52, 7536–7539, doi:10.1002/2015WR018494.

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Hansen, A.T., J.A. Czuba, J. Schwenk, A. Longjas, M. Danesh-Yazdi, D. Hornbach, and E. Foufoula-Georgiou (2016), "Coupling freshwater mussel ecology and river dynamics using a simplified dynamic interaction model", *Freshwater Science*, *35*(1), 200-215, doi:10.1086/684223.

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Dissertations:

Czuba, J. A. (2016), A Network-Based Framework for Hydro-Geomorphic Modeling and Decision Support with Application to Space-Time Sediment Dynamics, Identifying Vulnerabilities, and Hotspots of Change, PhD. Dissertation, University of Minnesota, pp. 172.

Schwenk, J. (2016), Meandering rivers: interpreting dynamics from planform geometry and the secret lives of migrating meanders, PhD. Dissertation, University of Minnesota.

Danesh-Yazdi, M. (2017), Inferring the Impacts of Anthropogenic Changes and Catchment Spatial Heterogeneity on the Water Cycle Dynamics and Transport Time Scales, PhD. Dissertation, University of Minnesota.

Thesis:

Boardman, E. (2016), Nutrient dynamics in Minnesota watersheds, M.S. Thesis, University of Minnesota.

Batts, V. (2017), Effects of vegetation-sediment interactions in the morphological evolution of coarse-bedded rivers: Results from flume experiments, M.S. Thesis, University of Minnesota Duluth, 75 p.

Targos, C.A. (2016), Changes in channel geometry through the Holocene in the Le Sueur River, south-central Minnesota, USA. M.S. Thesis: University of Minnesota Duluth, 90 p.

Conference Papers and Presentations:

Andzenge, S., Koenig, W., & Loiselle, E. (April, 2016). Outdoor Classroom: Connecting Learners and Community through Environmental Science and Service Learning. Paper presentation at the annual meeting of the Green School Conference and Expo, Pittsburgh, PA.

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2016), Modeling bed-material sediment transport on a river network, River Flow 2016 – Eighth International Conference on Fluvial Hydraulics, St. Louis, Missouri, 12-15 July.

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Czuba, J.A., and E. Foufoula-Georgiou (2016), Guiding stream restoration from a watershed-scale perspective: A first-order approach for understanding environmental dynamics on river networks, Upper Midwest Stream Restoration Symposium, Milwaukee, Wisconsin, 7-10 February.

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Danesh-Yazdi, M., E. Foufoula-Georgiou and G. Botter (2016), "Accounting for catchment spatial heterogeneity via a time-variant Lagrangian transport formulation in estimating water and solute travel time distributions", B32A-04, AGU Fall Meeting, San Francisco.

Foufoula-Georgiou, E. (2016), "Climate and Humans as Amplifiers of Hydro-Ecologic Change: Science and Policy Implications for Intensively Managed Landscapes", Robert E. Horton Lecture, AMS Annual Meeting, New Orleans, Louisiana, 10-14 Jan. **[AWARDEE]**

Foufoula-Georgiou, E., and M. Ebtehaj (2016), "Resolving extreme rainfall from space: a new class of algorithms for precipitation retrieval over radiometrically complex terrain and coastal areas", EGU2016-18518, EGU General Assembly, Vienna, Austria, 17-22 April. **[SOLICITED]**

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Ghalichi, N. and Roehrig, G.H. (2017), Refracting environment-related educational curriculum through Gaian lens. Paper presented at the International Meeting of the Association for Science Teacher Education in Des Moines, IA

Ghalichi, N. and Roehrig, G.H. (2017), The Role of Coherent Research-Based Curricular Unit in Mediating Students' Integrated Vision of Human Impact on the Environment. Paper presented at the Third International Conference on Higher Education Advances in Valencia, Spain.

Gran, K.B., Cho, S.J., Hobbs, B., Belmont, P., Wilcock, P., Kumarasamy, K., Heitkamp, B., Marr, J., February 8, 2016, Prioritization of restoration actions using real-time reduced complexity modeling in a large agricultural watershed. Talk presented at the 2016 Upper Midwest Stream Restoration Symposium, Milwaukee, WI.

Gran, K.B., January 15, 2016, Sediment source reduction at a watershed scale: Incorporating geomorphic history into watershed management. Talk given at the Minnesota Quaternary Science meeting, sponsored by the Minnesota Geological Survey.

Gran, K.B., March 3, 2016, Cleaning up the muddy Minnesota River: Incorporating geomorphic history into watershed management. Geology department seminar at the University of Illinois, Urbana-Champaign.

Gran, K.B., March 9, 2016, Targeting water storage to maintain productive land and restore clean water. Talk given to the Waseca County Farmer Forum.

Guala, M., A. Singh, E. Wong, and E. Foufoula-Georgiou (2016), "Scaling and normalization of river bathymetry spectra and bedform velocity" EP53E-1031, AGU Fall Meeting, San Francisco.

Karahan, E. & Roehrig, G.H. (April, 2016). Case Studies of Secondary School Science Teachers Designing Technology Rich SSI-Based Instruction. Paper presentation at the annual regional meeting of the National Association for Research in Science Teaching, Baltimore, MD.

Karahan, E., and Roehrig, G.H. (2017), A Case Study of a Science and a Social Studies Teachers' Experiences of Co-teaching SSI-based Environmental Ethics Class. Paper presented at the National Association for Research in Science Teaching in San Antonio, TX

Longjas, A., A. Tejedor, and E. Foufoula-Georgiou (2016), "An entropy-based quantification of channel network complexity", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.

Marra, W.A., A. Tejedor, E. A. Addink, E. Foufoula-Georgiou, and M. G. Kleinhans (2016), "Connectivity of Multi-Channel Fluvial Systems: A Comparison of Topology Metrics for Braided Rivers and Delta Networks" EP53A-0930, AGU Fall Meeting, San Francisco.

Papalexiou, S.M., A. AghaKouchak, and E. Foufoula-Georgiou (2016), "A global assessment of changes in extreme daily maximum temperature", GC11B-1150, AGU Fall Meeting, San Francisco.

Papalexiou, S.M., E. Foufoula-Georgiou, and A. AghaKouchack (2017), "Watch the tail! A story on extreme hourly precipitation", EGU2017-10444-1, EGU General Assembly, Vienna, Austria.

Schwenk, S., A. Khandelwal, M. Fratkin, V. Kumar, and E. Foufoula-Georgiou (2016), "The Secret Lives of Migrating Rivers" EP51A-0882, AGU Fall Meeting, San Francisco.

Schwenk, J., A. Khandelwal, M. Fratkin, V. Kumar, and E. Foufoula-Georgiou (2017), "River morphodynamics from space: the Landsat frontier", EGU2017-11858, EGU General Assembly, Vienna, Austria.

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Singh, A., A. Tejedor, A. Densmore, and E. Foufoula-Georgiou (2016), "Landscape response to climate change: quantifying a regime shift in transport processes at the onset of re-organization", EGU2016-10233, EGU General Assembly, Vienna, Austria, 17-22 April.

Singh, A., A. Tejedor, J.-L. Grimaud, and E. Foufoula-Georgiou (2016), "Experimental investigation of the effect of climate change and tectonic anisotropy on landscape evolution", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.

Singh, A., A. Tejedor, C. Keylock, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Landscape evolution and re-organization under steady and transient states: results from an experimental investigation", 31st IUGG Conference on Mathematical Geophysics, Paris, 6-10 June.

Singh, A., A. Tejedor, J.-L. Grimaud, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Quantifying the scale- and process- dependent reorganization of landscape under climatic change: inferences from an experimental landscape" EP32A-08, AGU Fall Meeting, San Francisco.

Singh A., A. Tejedor, J.-L. Grimaud, and Efi Foufoula-Georgiou (2017), "Experimental evidence of landscape reorganization under changing external forcing: implications to climate-driven knickpoints", EGU2017-17359-1, EGU General Assembly, Vienna, Austria.
Takbiri, Z., A. Ebtehaj, and E. Foufoula-Georgiou (2016), "Inundation Retrieval Using Passive Microwave Observations", H23F-1624, AGU Fall Meeting, San Francisco.
Tejedor, A., A. Longjas, R. Caldwell, D. Edmonds, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Moving beyond the Galloway diagrams for delta classification: A graph-theoretic approach", EGU General Assembly, Vienna, Austria, 17-22 April.
Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2016), "An entropy-based quantification of delta channel network complexity", Workshop on Information Theory and the Earth Sciences, Schneefernerhaus, Germany, 25-27 April.
Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2016), "Quantifying delta complexity toward inference and classification", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.
Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2016), "A graph-theoretic approach to infer process from form in deltaic systems", 31st IUGG Conference on Mathematical Geophysics, Paris, 6-10 June.
Tejedor, A, A. Longjas, and E. Foufoula-Georgiou (2016), "River delta self-organization via entropy rate analysis" EP53A-0931, AGU Fall Meeting, San Francisco.
Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2017), "Is there a self-organization principle of river deltas?", EGU2017-11531, EGU General Assembly, Vienna, Austria.
Wu, Z., E. Foufoula-Georgiou, M. Guala, X. Fu, and G. Wang (2016), "A New Lagrangian Formulation of Bedload Transport Guided by Ensemble Statistics of Particle Velocities and Accelerations", EP53E-1018, AGU Fall Meeting, San Francisco.
Wu, Z., E. Foufoula-Georgiou, G. Parker, A. Singh, X. Fu, and G. Wang (2017), "Burial effects on bedload tracer transport", EGU2017-2677, EGU General Assembly, Vienna, Austria.

Websites:

(1) The River Run team has created, supported, and maintained a publicly viewable Word Press website since September 2013. The website can be found at (http://stem-projects.umn.edu/riverrun/). The website contains information that outlines the project's purpose, researcher bios, and location of participating schools and teachers. The primary use of the website thus far has been the accumulation of curriculum, resources, and data collection protocol for participating teachers. The site serves as a central hub for the dissemination of digital media to teachers and students (as well as the public) involved in the River Run. This site also contains updated information and articles pertinent to the project.

Future developments will focus on creating a digital space for student-created digital media (videos, projects, etc.) along with providing a virtual space for teachers to communicate. The goal is to give students a platform to showcase projects they've worked on in science classrooms located within the MRB while also getting participating teachers to use the website as a more central aspect of their teaching when teaching units involving the MRB. These efforts will be a major focus of interest for the research team and participating teachers/students in the upcoming year.

(2) The REACH website officially launched in August 2014. The website is hosted on the University of Minnesota STEM projects server and linked with the education and outreach webpage. (http://stem-projects.umn.edu/reach/)

Other products, such as data or databases, physical collections, audio or video products, software or NetWare, models, educational aids or curricula, instruments, or equipment:

Database:

A web-based GIS site has been developed for data exchange between collaborators and stakeholders. This site is currently set up only for internal data sharing, but specific files will be made public as they become available for sharing with stakeholders and the scientific community at large. Datasets that will become available include inventories and associated characteristics of erosional hot spot landforms in the Greater Blue Earth River basin; channel delineations from modern and historic aerial photographs; and spatial derivatives of high-resolution LiDAR topographic data for the MRB. These files will be made available once datasets are finalized.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS – Who has been involved?

1. What individuals have worked on the project?

Efi Foufoula-Georgiou (PI)

Jacques C Finlay (PI)

Karen B Gran (PI)

Gillian H Roehrig (PI)

Bonnie Keeler (PI)

Peter Hawthorne (Senior Scientist)

Eric Lonsdorf (Lead Scientist)

Brent Dalzell (research associate)

Amy Hansen (research associate)

Anthony Longjas (post-doc)

Alejandro Tejedor (post-doc)

Christy Dolph (post-doc)

Ben Janke (post-doc)

Jonathan Czuba (graduate student)

Mohammad Danesh-Yazdi (graduate student)

Jon Schwenk (graduate student)

Zeinab Takbiri (graduate student)

Evelyn Boardman (graduate student)

Sarah Winikoff (graduate student)

Anika Bratt (graduate student)

Anna Baker (graduate student)

Ian Treat (graduate student)

Narmin Ghalichi (graduate student)

Katie Kemmit (undergraduate student)

Mulu Fratkin (undergraduate student)

Se Jong Cho (predoctoral research associate)

Tessa Belo (undergraduate student)

Walter Atkins (undergraduate student)

Austin Cavallin (undergraduate student)

Kate Thompson (research assistant)

2. What other organizations have been involved as partners?

Utah State University

Johns Hopkins University

University of Illinois Urbana-Champaign

Iowa State University

University of Washington

Other collaborators and stakeholder groups:

Minnesota Pollution Control Agency

St. Croix Watershed Research Station

Gustavus Adolphus College

Minnesota Department of Natural Resources

Minnesota Corn Growers Association

Minnesota Agricultural Water Resource Center

Blue Earth County

Greater Blue Earth River Basin Alliance

Minnesota Soybean Growers Association

University of Minnesota Extension Agency

Minnesota Department of Agriculture

3. Have other collaborators or contacts been involved?

Yes.

<u>IMPACT</u> – What is the impact of the project? How has it contributed?

What is the impact on the development of the principal discipline(s) of the project?

The specific goal of the REACH project to understand the chain of events from precipitation to streamflow, to sediment, to stream biological activity change, and integrate this knowledge with socio-economic factors towards a science-informed decision making framework for water sustainability.

The project involves PIs that are experts in hydrology, geomorphology, river morpho-dynamics, hydro-informatics, biology, ecology, socio-economics, and education/public outreach. The work also combines field monitoring, theoretical work, and coupled hydrologic, biologic, geomorphic, and economic modeling of watersheds and their response to change geared towards informing management and policy decisions. While important discoveries are made in each of these fields (see reports of each PI for more details), it is the synthesis of these developments and the across-disciplines advances that will contribute to the integrated framework that REACH aims to develop for using the best science for management decisions in the Minnesota River Basin.

What is the impact on other disciplines?

The project is by definition interdisciplinary requiring expertise from several fields; hydrology, ecology, biology, geomorphology, engineering, river morphodynamics, socio-economic sciences, and education/public outreach. At the same time, advances made in one field are spread into other fields growing the holistic knowledge required for management of natural resources including water sustainability.

The involvement of stakeholders and state-government agencies in our project is also a unique element that promises implementation of the science to decisions that matter. Three of our REACH PIs (Wilcock, Belmont, Gran) are involved in a collaborative project that meets with stakeholders in the Greater Blue Earth River basin on a semiannual basis. This forum provides a strong venue for knowledge transfer and iterative interactions with state and local agencies responsible for managing water resources in the MRB.

What is the impact on the development of human resources?

The project funds several graduate students and post-docs (see list of participants), for whom opportunities for mentoring (co-supervised by more than one project PIs), and involvement in interdisciplinary research are greatly enhancing their ability to learn and grow as young professionals. These students and post-docs are invited in the annual project meetings to present their work.

The University of Minnesota leads an REU grant on Environmental Sustainability which hosts undergraduate students (mostly from diverse minority groups) every summer to be involved in environmental and earth surface dynamics research. The REACH annual meeting this 2017 is scheduled in late June to coincide with the REU group such that mentoring and interaction can take place. Several of the REU students are also given projects led by REACH PIs which involve field work and laboratory experiments, including research at the Outdoor StreamLab developed jointly by the NSF Science and Technology Center (NCED: National Center for Earth surface Dynamics) and the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. Also, our project is synergistic with the Summer Institute on Earth surface Dynamics (SIESD), offered every summer and attracting 30 plus top graduate students and young professional from all over the world.

The REACH project also includes a teacher training and curriculum development component in environmental sciences and restoration. This year, 6 K-12 teachers continue to be part of the River Run Team that has worked to develop and integrate new curricula on socio-science issues in the MRB.

What is the impact on physical resources that form infrastructure?

Our project relies on innovative combination of theory, numerical modeling, laboratory experiments, and field work. Laboratory experiments (to test river morphodynamics, sediment/tracer dispersal in rivers, and biological response to change) are performed at the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. SAFL is a world-renown experimental laboratory on fluid and environmental dynamics and is currently renovated by NSF funds (under the Advanced Research Infrastructure Renovation Grant). Advances in our project are leveraged and leverage advances in this laboratory which are then benefitting the national community of researchers in Earth-surface dynamics.

Our project is also leveraged by a rich dataset that has been generated by Federal and State agencies, including 1-3 m resolution LIDAR data covering the entire MRB (an investment in excess of $2 million); temperature, precipitation, and streamflow data; and extensive water quality and biological monitoring by the Minnesota Pollution Control Agency; multiple flow, nutrient, and sediment gages on tile drains; multiple edge of field samplers and agricultural ‘demonstration’ sites, maintained in our study area by the Minnesota Department of Agriculture; multiple gages on the mainstem Minnesota River tributaries maintained by the US Geological Survey, HSPF and GSSHA model outputs from MPCA and Army Corps of Engineers, respectively, for the entire study area.

What is the impact on institutional resources that form infrastructure?

REACH PIs initiated and established the Summer Institute on Earth Surface Dynamics (SIESD) which is offered every year and attracts 30 young investigators from around the world. REACH PIs contribute annually to the projects of the REU students at the University of Minnesota, contributing to attracting them to STEM fields.

What is the impact on information resources that form infrastructure?

The data of our project will be preserved by a collaborative agreement with SEAD, Sustainable Environment through Actionable Data, an NSF-funded DataNet project. We have begun uploading and sharing our data on the SEAD server. Through our involvement with SEAD we have suggested some changes and updates to the system that are being incorporated to help ourselves as well as future users of the system.

What is the impact on technology transfer?

In the state of Minnesota, funding for large scale watershed restoration and monitoring will be available over the next 25 years through the Clean Water Legacy Amendment of the State of Minnesota. This Constitutional Amendment assigns funds from a new sales tax ($300 million per year over the next 25 years) exclusively to actions to improve water quality in the State. *Broad scale management actions will be taken, providing the opportunity for a large- scale experiment in integrative, science-based management actions.* The understanding and models that will be developed from our project are certain to influence decisions at the management and policy levels of the State to ensure that the best science is used to restore healthy ecosystem functioning of streams in the state.

Our project has established a tight network of collaboration with Federal and State agencies and stakeholders (who provided enthusiastic support letters in the proposal development stage) to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions. This transfer is strengthened through the Collaborative for Sediment Source Reduction, which has established a stakeholder group that meets semiannually to implement a strategy for reducing fine sediment loading in the Greater Blue Earth River Basin.

What is the impact on society beyond science and technology?

Several PIs (Wilcock, Belmont, Gran) have initiated a science-stakeholder collaborative for developing an implementation strategy for sediment reduction in the Blue Earth watershed, which is the largest sediment source to the MRB. This work will involve extrapolating our sediment budget from the Le Sueur watershed (a component of the Blue Earth system) and building a simulation model and decision support system with local stakeholders. This is a significant leveraging and knowledge-transfer opportunity because we will be directly collaborating with public and private decision makers in the most dynamic (amplified) portions of the watershed.

Our project has established a tight network of collaboration with Federal and State agencies and stakeholders (who provided enthusiastic support letters in the proposal development stage) to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions.

CHANGES/PROBLEMS

Notifications and Request

Changes in approach and reasons for change

None

Actual or Anticipated problems or delays and actions or plans to resolve them

None

Changes that have significant impact on expenditures

None

Significant changes in use or care of human subjects

None

Significant changes in use or care of vertebrate animals

None

Significant changes in use or care of biohazards

None

NSF Water Sustainability and Climate (WSC) project EAR-1209402

REACH (REsilience under Accelerated CHange)

Year 5 Progress Report for 2016–2017

University of Minnesota

Efi Foufoula-Georgiou, Jacques Finlay, Karen Gran, Gillian Roehrig, Bonnie Keeler

Overarching Project Goals and Objectives

The overall goal of our Water Sustainability and Climate project (called REACH: REsilience under Accelerated CHange) is to develop a framework within which the vulnerabilities of a natural-human system can be assessed to guide decision-making towards eco-hydrologic sustainability and resilience. A unique element of the developed framework is identifying and focusing on places, times, and processes of accelerated or amplified change. One specific hypothesis to be tested is that of Human Amplified Natural Change (HANC), which states that areas of the landscape that are most susceptible to human, climatic, and other external changes are those that are undergoing the highest natural rates of change. To test the HANC hypothesis and turn it into a useful paradigm for enabling water sustainability studies, a predictive understanding of the cascade of changes and local amplifications between climatic, human, hydrologic, geomorphologic, and biologic processes are being developed to identify "hot spots" of sensitivity to change and inform mitigation activities.

The developed framework is being tested in the Minnesota River Basin (MRB) where geological history, climate variability, and intensive agriculture are affecting changes in water quantity, water quality, and ecosystem health.

The project has four main objectives:

(1) Determine the extent to which current high rates of sediment production, amplified by land-use, hydrologic, and climate changes, are affected by the underlying geology and geomorphic history of the basin, guiding a topography-based predictive framework of sediment sourcing and budgeting in a dynamic landscape.

(2) Quantify how climate and land-use driven hydrologic change, amplifies and accelerates environmental and ecological change in the basin, and how nonlinearities and amplifications can be quantified and upscaled across basins of different size.

(3) Understand the interactions of the river network physical structure and biological processes, including the role of wetlands, lakes, and riparian zones in nutrient transport and cycling, phosphorous-sediment budgeting, and food web structure towards a predictive framework in highly dynamic agricultural landscapes.

(4) Propose conservation management strategies, including sediment and nutrient reduction, to sustain ecological health and species biodiversity while promoting economic development and agricultural productivity.

University of Minnesota Research Summary

During 2016-2017, our research has focused on synthesizing our findings into an integrated multi-objective modeling framework that can guide management decisions by closing the loop between social and economic drivers of system change and the biophysical and economic consequences of those changes as informed by detailed analysis of the hydrology, sediment, nitrogen and phosphorus components of the intensively managed agricultural watersheds under study.

Convergent research:

Integrated watershed-scale modeling to address multiple objectives: demonstration in the Le Sueur and Minnesota River Basins for effective conservation management options

Research informing the integrated multi-objective modeling framework is summarized as:

1. Sediment sourcing and cycling in a coupled human-natural landscape

1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns
1.2. Sediment connectivity and dynamics on river networks
1.3. Quantifying historical landscape changes that impact current erosional hotspots and legacy sediments
1.4. Incorporating near channel sediment into the watershed scale modeling framework

2. Cascade of climate and land use/land cover change to eco-hydrologic change

2.1. Reducing aggregation bias of water and solute travel time distributions in heterogeneous catchments
2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics

3. Quantifying nutrient and phosphorus cycling in intensively managed landscapes

3.1. Anthropogenic and environmental controls on nutrient inputs and export
3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics
3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes
3.4. Nitrogen, phosphorus and suspended algal biomass in an agricultural watershed of the Upper Midwestern USA
3.5. Patterns in resource use by aquatic consumers in agricultural streams of the Minnesota River Basin

4. The role of wetlands and water-retention structures in environmental restoration and tradeoffs

4.1. Network structure nitrate removal efficiency
4.2. Valuing Water Quality Improvements in Midwestern Ecosystems: Spatial Variability, Validity and Extent of the Market for Total Value
4.3. Evaluation of trade-offs associated with wetland interventions
4.4. Spatial optimization of wetland restoration using spatial ownership constraints and a real options analysis for Le Sueur River Watershed
4.5. Including additional ecosystem services in models of cost-efficient water quality improvements
4.6. Integrating the Management Options Simulation Model (MOSM) into optimization and tradeoff analysis
4.7. Integrated Le Sueur modeling

5. Engaging and educating the public

5.1. Socio-scientific issues
5.2. Curriculum development and classroom implementation
5.3. Development of a consensus strategy for sediment reduction through stakeholder-driven model development and scenario investigations

INTEGRATED WATERSHED-SCALE MODELING TO ADDRESS MULTIPLE OBJECTIVES: Demonstration in the Le Sueur and Minnesota River Basins for effective conservation management options

Efi Foufoula-Georgiou (lead PI), Christy Dolph and Amy Hansen (post-doctoral fellows) --project synthesis coordinators

Collaborators: Brent Dalzell, Se Jong Cho, Jon Czuba, Sergey Rabotyagov, Todd Campbell, Christian Brauderick, Karthik Kumarasamy, Phil Gassman, Anna Baker, Peter Hawthorne, Eric Lonsdorf, Kate Thompson, Bonnie Keeler, Peter Wilcock, Patrick Belmont, Cathy Kling, Jacques Finlay, Karen Gran

Overview

At the heart of the WSC REACH project has been the dual imperative to 1) develop biophysical models that can capture the cascade of water quality changes arising from interactions between geologic history, human land use, and climate change in the Minnesota River Basin (MRB), and 2) inform real-time water quality management decisions in the MRB with the best science available (*Belmont and Foufoula-Georgiou*, 2017). During the final year of the project, the REACH group has addressed this imperative by pursuing two integrated modeling approach efforts at two different spatial scales (the Le Sueur River Basin and MRB scales, described below). Models at the two scales differ in accuracy and spatial resolution of some modeled components (higher for the Le Sueur River Basin model, where we have greater field data available to 'drive' the model) and in applicability to a broader suite of ecosystem benefits that are important to society (higher for the MRB scale, e.g., lake recreation values, drinking water quality, etc). The two modeling approaches are bridged by a third model with the scale of the smaller Le Sueur basin model but the coarser resolution and simplified biophysical processes of the larger MRB model. By developing these models in parallel, we will address key questions regarding how best to manage landscapes for local and external water quality while also advancing the science of landscape modeling. Specifically, this effort will enable us to 1) determine how the 'optimal landscape' depends on the scale or resolution at which landscapes are represented and 2) gain insight into the minimum biophysical complexity required to accurately assess water quality response to landscape interventions.

The Le Sueur River Basin Multi-Objective Model

The first integrated modeling effort is targeted at developing a multi-objective model for the Le Sueur River Basin (LSRB). The LSRB is one of the major sub-basins of the MRB, and one of the largest contributors to the total MRB pollutant load (*Belmont et al*., 2011). Previous water quality interventions in the LSRB have not been successful in attaining water quality targets. Approximately $7 million has been spent in the LSRB between 2008-2015, with no observed decreases in sediment, phosphorus, or nitrogen leaving the basin (*MPCA*, 2016). Our modeling effort is tackling this seemingly intractable problem through a watershed-based approach that addresses trade-offs and capitalizes on synergies between multiple key pollutants, including nitrogen, phosphorus, and sediment. This effort integrates the considerable model development work and data collection efforts that have been conducted in the LSRB under the auspices of REACH. Specifically, the Le Sueur model integrates a Soil and Water Assessment Tool (SWAT) model (*Kumarasary et al*., in prep) together with a data-driven sediment storage and delivery model (Management Option Simulation Model; MOSM; *Cho et al*., in prep) and a process-based nitrogen routing model developed to capture the effect of denitrification and hydrology on NO3 transport and uptake (Nitrogen Network Model; NNM; *Czuba et al*., in prep). The latter two models capture dynamics in sediment and nutrient transport that are not well accounted for in existing SWAT-based approaches. Independent efforts to characterize P response to land use in the LSRB are also being pursued by members of the group (Finlay, Dalzell).

Previous work by our group investigating responses of single pollutants to landscape or fluvial interventions in the LSRB have found that substantial reductions of sediment and nitrate loads can be achieved by restoring wetland cover to the landscape. However, the optimal configuration of restored wetlands for improved water quality appears different depending on the pollutant in question. For example, *Hansen et al*. (in prep) found that nitrate was reduced more efficiently by wetlands located directly on the river network (i.e., in channel wetlands) compared to wetlands located in isolated upland basins. River sediment loads, by contrast, appear to be reduced more efficiently via the storage of water in isolated upland wetlands. By intercepting water during precipitation events, these isolated wetlands ultimately decrease peak discharge in downstream river networks, and thereby reduce the amount of sediment lost from the incised portion of river networks via channel shear stress (*Cho et al*., in prep). These initial findings are suggestive of trade-offs in management strategies for the mitigation of specific pollutants (i.e., nitrate vs sediment), and will likely affect the optimal conservation landscape that must be managed for multiple pollutants simultaneously.

Our culminating modeling effort in the LSRB will integrate these multiple lines of evidence, and evaluate the effectiveness of candidate conservation scenarios in the LSRB for reducing peak hydrology, sediment load, nitrate load and phosphorus load (Table 1). Model outputs from this integrated approach are also being compared to a parallel stand-alone SWAT model for the LSRB, to evaluate how a more complete accounting of biophysical processes can affect model outputs. Evaluation of the trade-offs across multiple candidate conservation scenarios in the LSRB are being conducted using evolutionary computation (e.g., *Rabotyagov et al*., 2010), at the Iowa State Center for Agricultural and Rural Development (CARD).

Table 1. Conservation management options included in the Le Sueur and MRB scale integrated models.

Cover crops
Isolated wetlands, water retention ponds
Reservoirs, flow-through wetlands
Buffer strip management
Land retirement
Fertilizer management
Tillage management: conventional, reduced, conservation tillage
Near channel sediment management (bluff stabilization, toe protection)
Ravine management

Minnesota River Basin Integrated Model

The second integrative modeling effort pursued by REACH seeks to identify the costs and benefits of addressing water quality goals at the scale of the entire Minnesota River Basin. This effort is highly relevant and of great interest to stakeholders in the basin, who are concerned about the cost and impact of ongoing and prospective conservation efforts to improve water quality in the Minnesota River and downstream water bodies. This effort includes the modeling of key biophysical processes that have been identified by REACH and overlooked in previous modeling efforts; namely, the explicit accounting of near-channel sediment loads driven by changes in hydrology (*Cho et al*., in prep), and the critical role of wetlands in watershed-scale nitrate removal (*Hansen et al*., in prep). The MRB model has been built in SWAT by Brent Dalzell at the University of Minnesota. Modifications to SWAT capture inputs of near-channel sediment from major watersheds across the MRB; these inputs have been estimated in a collaborative effort by Se Jong Cho (UMN), Christian Brauderick (Utah State), Peter Wilcock (Utah State), Christy Dolph (UMN), Patrick Belmont (Utah State), Karen Gran (University of Minnesota-Duluth). SWAT source code has also been modified to capture the removal of nitrate by in-channel wetlands; nitrate removal functions were developed by Amy Hansen, Jon Czuba and Efi Foufoula-Georgiou.

The MRB scale model is being optimized over multiple water quality endpoints (N, P, and TSS) for multiple targets, including local water bodies (i.e., in-state rivers and lakes) and downstream water bodies (i.e., Lake Pepin, the Gulf of Mexico). The optimization of conservation management options (Table 1) will also ultimately include an accounting of total ecosystem benefits, which has rarely been attempted anywhere (*Keeler et al.,* 2012). This is an additional technological challenge, that requires adding 'ecosystem benefit functions' (i.e., relationships that describe the link between nutrients/sediment and various ecosystem benefits) to the existing model optimization infrastructure.

Developing multi-criteria objective functions

Defining the ecosystem benefit functions is the current focus of the NatCap team at UMN's Institute on the Environment (Peter Hawthorne, Eric Lonsdorf, Kate Thompson, Bonnie Keeler). We will link valuation assessments to the modeled changes in the MRB. Specifically, we have identified a suite of ecosystem service metrics relevant to the management inputs of the MRB that explicitly defines water quality. At the scale of management, i.e. HUC 12, we have gathered data to create ecosystem service indices related to recreation (e.g. fishing, swimming, boating), drinking water (e.g. number of supply areas), nutrients (nitrogen and phosphorous export), infrastructure (bridge scour, reservoir dredging rate). By combining these metrics into an ecosystem service index using multi-criteria analysis, we can rank the importance of each HUC 12 in the overall evaluation of in-field and wetland management options in the MRB. Over the next several months, we will finalize the multi-criteria objective function and integrate it into the genetic algorithm used to identify best management actions for the MRB. This integrated analysis will help close the loop between social and economic drivers of system change and the biophysical and economic consequences of those changes.

We will the pursue the combined biophysical and socio-economic modeling with an evolutionary computation approach designed by Sergey Rabotyagov (University of Washington), Cathy Kling (Iowa State), Todd Campbell (Iowa State, Center for Agricultural and Rural Development), and Phil Gassman (Iowa State CARD).

RESEARCH RESULTS INFORMING THE INTEGRATED WATERSHED MODELING FRAMEWORK

1. Predictive framework of sediment sourcing and cycling in a coupled human-natural landscape

1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns

J. Schwenk and E. Foufoula-Georgiou

Meandering river planform evolution is driven by the interaction of local nonlinear hydro-morphodynamic processes and by threshold-type nonlinear dynamics via cutoffs. Understanding if and how these "process or dynamic nonlinearities" show up in the static geometry of river planforms ("form nonlinearity") is important as it can provide the basis of inferring dynamics from static images, and deciphering changes in forcing (natural or anthropogenic) by observing changes in planforms. But *are dynamic nonlinearities encoded in the static meander planform geometries?* Previous attempts have found at most a weak signature of these dynamic nonlinearities in static meander planform morphologies. Using powerful analysis and detection methodologies, our work has unambiguously showed that the spatial structure of meandering centerlines does indeed encode dynamic nonlinearities (see Figure 1). We demonstrated this finding both in numerically simulated meandering rivers and in three natural rivers. Cutoffs were found to obscure the imprint of the dynamic nonlinearities of the governing morphodynamic processes, but they were also shown to act as a local source of nonlinearity themselves by rearranging the meander train and introducing small scales into the centerline. The degree of nonlinearity (DNL) was measured for two meandering rivers in the Minnesota River Basin. Both the Watonwan and Blue Earth Rivers saw an overall decline in DNL from 1938 to 2008, reflecting a shift in the driving dynamics (i.e., climate and land use changes), direct channel modifications such as channel straightening, and the occurrence of 36 cutoffs over the time period (*Schwenk et al*., 2016).

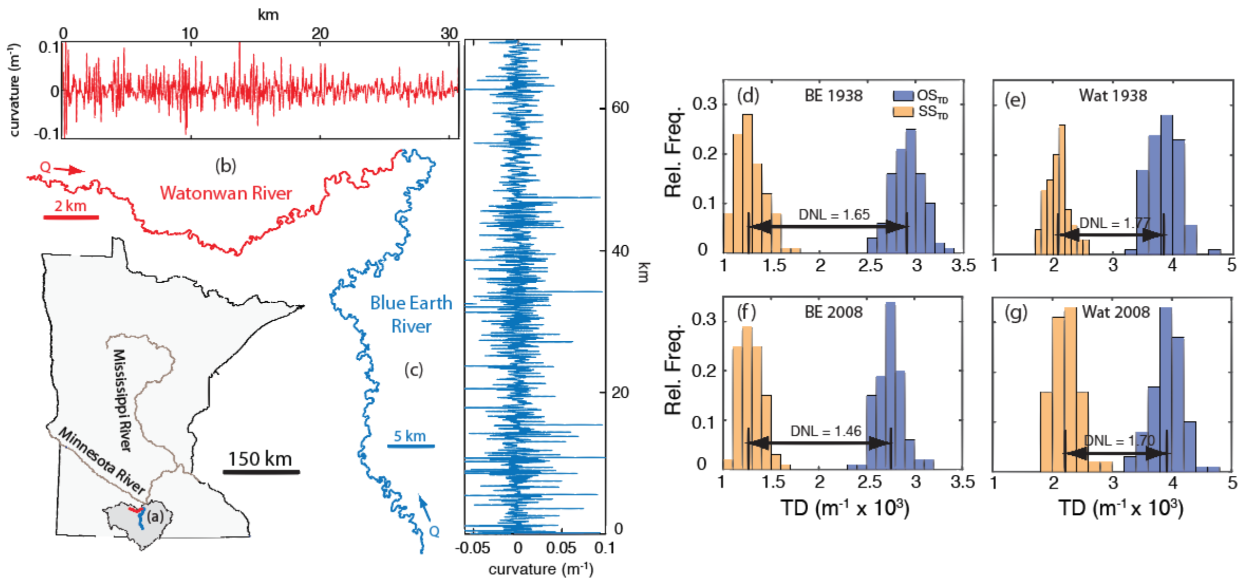


Figure 1. Left panel: the locations of the Blue Earth (in red) and Watonwan (in blue) rivers are shown within the Greater Blue Earth Basin (a) in Minnesota, USA. In (c) and (d), the 2008 Watonwan River and 2008 Blue Earth centerlines are shown in more detail along with their curvature series. As shown, both rivers flow to the same location but note the different scales for each. Right panel: the degree of nonlinearity (DNL) is shown for each river in 1938 and 2008. The degree of nonlinearity (DNL) is defined as the distance between the means (vertical black lines) of the OS_{TD} and SS_{TD} distributions. See *Schwenk and Foufoula-Georgiou* (2017) for the formulation of the DNL.

The need to monitor the ever-changing meandering rivers at high spatio-temporal resolutions is imperative in the quest to understand the role of climatic and human influences on planform adjustments. This was not possible before based on sparse areal photographs or field surveys, but becomes feasible now with the ability to observe landscapes from space. *However, efficiently extracting meandering river planform changes over large spatial domains and with high enough temporal resolution from satellite images, now available globally, presents multiple challenges*. Our work addressed these challenges using Landsat imagery and introduced a set of innovate and efficient methods to map and measure spatial and temporal planform changes including local and average widths, centerline migrated areas and rates, erosion and accretion, and cutoffs (*Schwenk et al*., 2017). The methods have been assembled in a freely-available, comprehensive toolbox called River Morphodynamics from Analysis of Planforms (RivMAP). As a proof-of-concept, the RivMAP toolbox was applied to over 1,300 km of the actively-migrating and predominately meandering Ucayali River in Peru (see Figure 2).

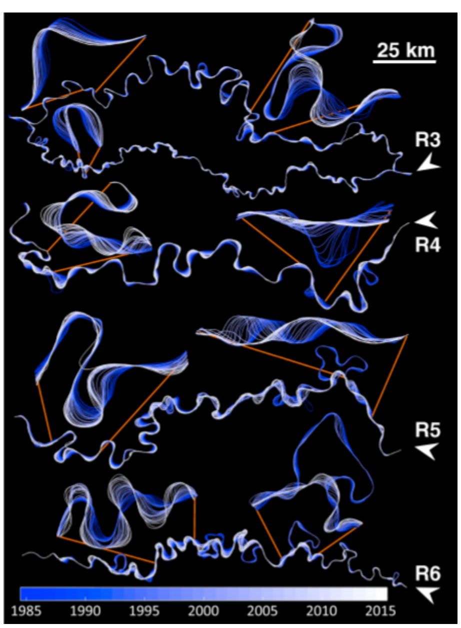


Figure 2. Centerlines obtained from Landsat-derived single-thread channel masks using RivMAP are shown for the study regions of the Ucayali. North arrows also indicate the direction of flow which travels from R6 to R3. Zoom views highlight some of the complex migration patterns and cutoffs along the Ucayali River. The total centerline length each year is approximately 1500 km including both branches in R3. Flow travels from R6 to R3.

Landsat 5 and 7 images collected from 1985-2015 were classified with a supervised classifier, and annual composite images were created that are shown to resolve bankfull channel and bar morphologies. We found that sediment flux, cutoffs, and climate simultaneously act as controls on migration rates and cannot be parsed without the high spatiotemporal analysis performed by this research. We also analyzed 13 meander cutoffs and found that cutoffs perturb river morphodynamics by accelerating migration rates (11/13 cutoffs) and widening the channel (8/13) both up- and downstream of the cutoff (*Schwenk and Foufoula-Georgiou*, 2016). The downstream distance of accelerated migration was found to scale with the length of river removed due to cutoff, presenting new challenges in modeling and prediction of rivers' self-adjustments to perturbations with implications for river and floodplain management.

1.2. Sediment connectivity and dynamics on river networks

J. Czuba, E. Foufoula-Georgiou, K. Gran, P. Belmont (Utah State University), and P. Wilcock (Utah State University)

High-resolution topography provides a basis for accurately mapping sediment sources, identifying pathways by which sediment moves through a watershed, and quantifying the physiographic characteristics of river channels and floodplains. *We take advantage of this information for quantifying sediment dynamics not only within a river reach but within an entire watershed*. Our work developed a network-based model for bed-material sediment that combines spatially-explicit sediment sourcing with in-channel transport and storage dynamics on a river network (*Czuba et al*., 2017a; see Fig. 3). Specifically, we presented spatiotemporal changes in bed-sediment thickness along an entire river network to elucidate how river networks organize and process sediment supply. The model was used to simulate the transport and storage of bed-material sand over a 600-year time period in the Greater Blue Earth River Basin in Minnesota. Using both analytical solutions (under independent Poisson arrival process) and via simulation (under more general conditions including in-channel storage) the probability distribution of bed-sediment thickness for each link of the river network was derived and used to understand the dynamics on the network in propagating, altering, and amalgamating sediment inputs in sometimes unexpected ways. One key insight gleaned from the model was that there can be a small fraction of reaches with relatively low transport capacity within a non-equilibrium river network acting as "bottlenecks" that control sediment to downstream reaches, whereby fluctuations in bed elevation can dissociate from signals in sediment supply.

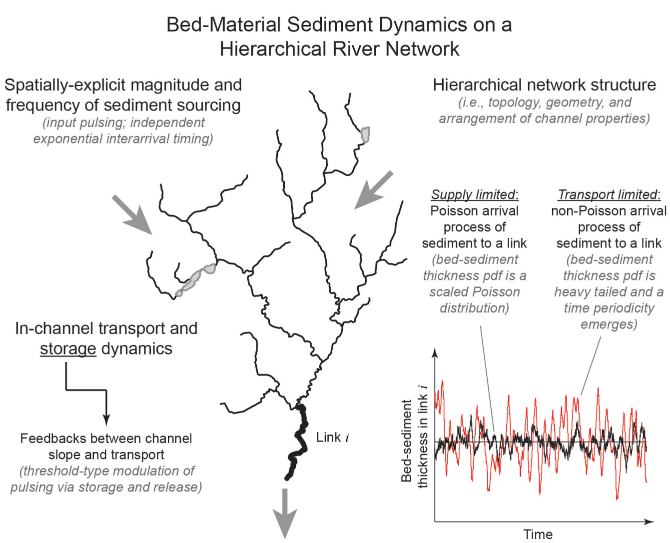


Figure 3. Conceptual overview of bed-material sediment dynamics on a hierarchical river network. The combination of spatially-explicit magnitude and frequency of sediment sourcing, hierarchal network structure, and in-channel transport and storage dynamics creates a temporal variability in bed-sediment thickness. Under supply-limited conditions, the bed-sediment thickness probability distribution function (pdf) is a scaled Poisson distribution, which is directly related to the Poisson arrival structure of the inputs. Under transport-limited conditions, the bed-sediment thickness pdf is heavy tailed and the temporal dynamics exhibit a characteristic timescale (periodicity).

Along the same lines, we investigated how punctuated sediment pulses, triggered in a watershed through a variety of mechanisms, from landslides to land-use change, *can propagate in a system and create hotspots of change*. We used a reduced-complexity network routing model that simulates the movement of bed material through a river basin and run this model in the Greater Blue Earth River (GBER) basin in Minnesota, USA, first with spatially uniform inputs and then with inputs constrained by a detailed sediment budget (*Gran and Czuba*, 2017). Results indicate (Figure 4) that pulses able to translate downstream disperse in place upon arriving at over-capacity reaches as sediment goes into storage. In the GBER basin, these zones occur just upstream of a knickpoint that is propagating upstream through all mainstem channels. As the pulses get caught in these sediment "bottlenecks," there is a decoupling of the original pulse of sediment and the resulting bed material wave. *These results show that the network structure, both in terms of network geometry and the spatial pattern of transport capacity, can play a dominant role in sediment connectivity and should be considered in predictive modeling of sediment pulse behavior at the watershed scale*.

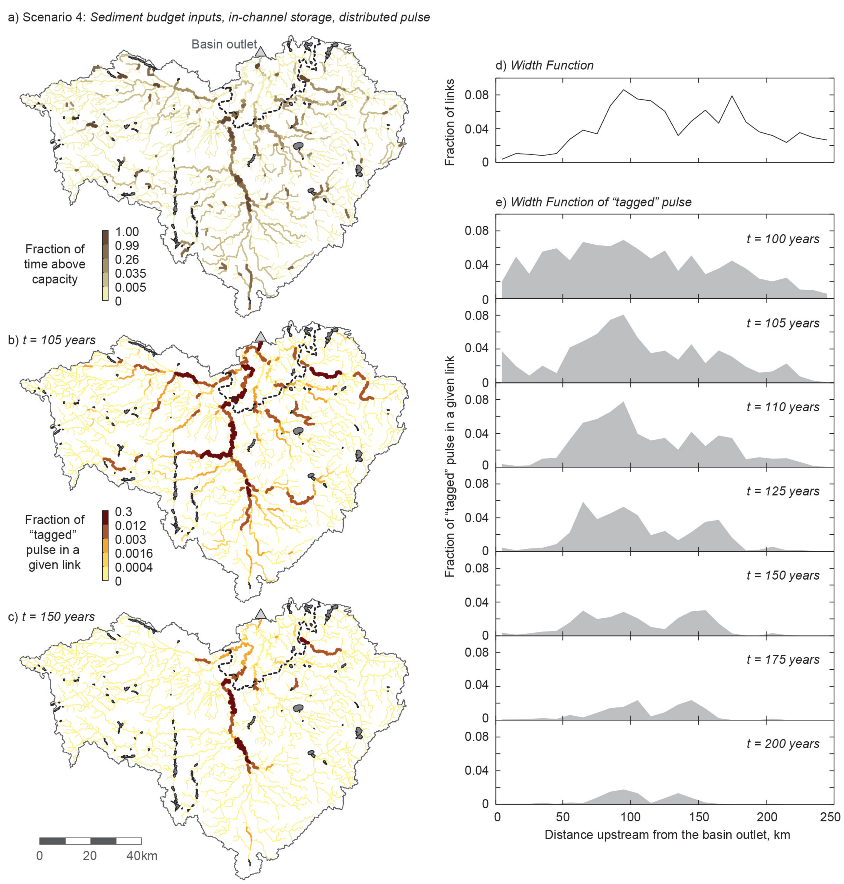


Figure 4. Response of the Greater Blue Earth River Basin to a distributed sediment pulse input for scenario 4. (a) Map of the Greater Blue Earth River Basin showing the fraction of time a given link was above capacity for a period of 500 years after pulse input. The color breaks are at the 0.99, 0.95, 0.90, and 0.75 quantile. The approximate extent of the knickzone is shown as a dashed line. Map of the fraction of the "tagged" pulse throughout the network at (b) 105 years and (c) 150 years. (d) Network width function describing the fraction of links a given distance from the basin outlet. The width function maps a two-dimensional network onto a one-dimensional space. (e) Network width function of the "tagged" pulse at various times showing where the dispersed sediment pulse is located with respect to distance from the basin outlet. The knickpoint is located approximately 45–65 km upstream from the outlet.

1.3. Quantifying landscape changes associated with the onset of Western settlement that impact current erosional hotspots and legacy sediments

K. Gran, I. Treat, C. Targos

The Minnesota River basin is fundamentally tied to its geomorphic history, as incision of the river valley over 13,000 years ago led to the deeply incised mainstem and tributary valleys seen today. Migrating knickpoints up all major tributaries have led to deeply-incised lower valleys with high bluffs and steep ravines, leading to abundant sediment loading. Previous research by *Gran et al*. (2013) quantified the incisional history of the Le Sueur River basin through numerical modeling constrained by lidar topographic analyses and depositional ages of river terrace sediments. This allowed *Gran et al*. to determine the sediment flux out of the basin associated with valley incision and widening before Western settlement-driven changes in land use and land cover. This background "Holocene" sediment budget indicated that fine sediment (silt and clay) loading per year was 4-5 times lower than modern sediment loads (225,000 Mg/yr from 2000-2010).

Two research efforts over the past few years led by M.S. students Courtney Targos and Ian Treat focused on understanding how additional aspects of basin hydrology and sediment loading changed during Western settlement including 1) river discharge, and 2) ravine erosion. *Targos* (2017) used ground-penetrating radar (GPR) coupled with subsurface stratigraphy to identify and map paleochannels preserved on terraces in the Le Sueur River valley. These terraces were dated using optically-stimulated luminescence (OSL). Paleochannel cross-sectional area was converted into paleodischarge via roughness calculations and compared with modern bankfull discharge rates. Major results indicated that paleodischarge values showed no systematic changes over the course of the Holocene with the limited sample size (n=4), but were all 3-10 times lower than modern bankfull discharge (Fig. 5). This compares well with a flood frequency analysis for the Le Sueur showing that $Q_{1.5}$ and Q_2 values have increased over the past 73 years (Table 1), coincident with increasing land drainage and ongoing climate change.

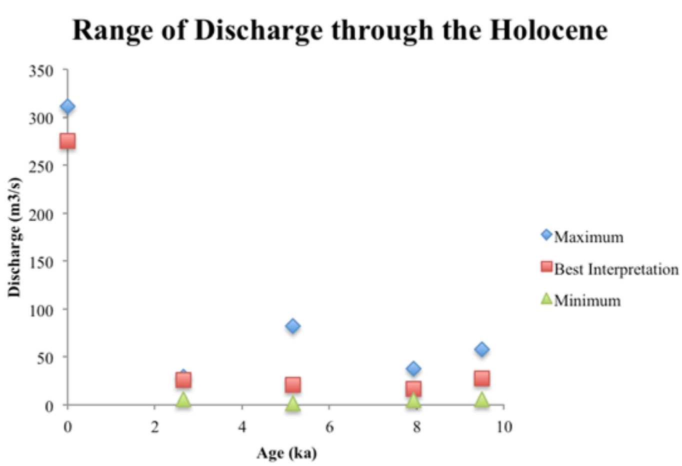


Figure 5. Bankfull discharge on the mainstem Le Sueur River as reconstructed from GPR paleogeometry data using modern roughness values. Modern bankfull discharge rates were calculated the same way, using modern channel geometry, slope, and roughness (*Targos*, 2017).

Table 1. Flood frequency for Le Sueur River gage at Red Jacket (05320500) using standard Bulletin 17B technique on 30 year datasets (*Targos*, 2017).

Increment of record	1.5 year flood (m^3/s)	2 year flood (m^3/s)
1940-1970	62	121
1950-1980	66	117
1960-1990	80	129
1970-2000	84	122
1980-2013	102	154

Ravines, steep first-order ephemeral channels, were the focus of the second effort into the impact of Western settlement in the Le Sueur River basin. Previous REACH research by *Belmont et al.*, (2011) show minimal changes in ravine contributions to the sediment load in the Le Sueur River Basin (LSRB) from pre-settlement to modern times despite basin-wide land use clearing and hydrologic change. The pre-settlement erosion rates were fairly unconstrained, however, determined only through a simple “volume lost” analysis of high-resolution lidar data (*Gran et al.*, 2009). Ravines have unique sediment storage capabilities that should record the history of deposition (and thus erosion) from these channels over time, allowing us to determine how ravine erosion has changed in the past 200 years as compared with Holocene deposition rates. As mainstem rivers migrate across incised valleys, ravines are often left disconnected from the main channel. These disconnected ravines build alluvial fans on terraces, forming one of the few sediment archives within the basin. Research by *Treat* (in prep.) used fly ash from coal combustion as an in-situ stratigraphic marker for post-settlement alluvium from six fans in the LSRB. Fly ash (Fig. 6) was found at depths exceeding two-meters on many of the ravine fans studied. Post-settlement rates on studied alluvial fans conservatively estimate deposition rates at 2.0 cm yr^{-1} compared to average Holocene fan depositional rates of 0.2 cm yr^{-1} (preliminary values). In many cases, increased deposition was followed by channel incision into ravines, indicating a shift from an overabundance of sediment to an increase in flows moving through ravines.

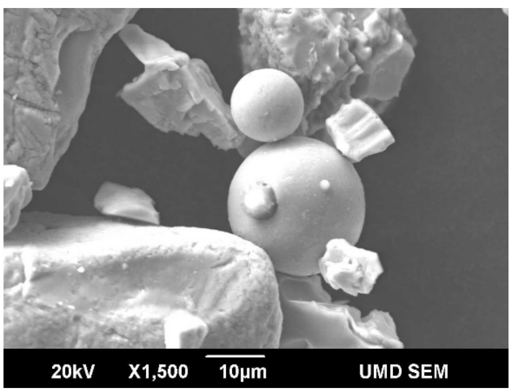


Figure 6. Fly ash contains spherical particles easily identifiable by their morphology and chemical signature. Fly ash serves as a marker of the arrival of coal combustion (generally from power plants and railroads) and thus mark the arrival of Western settlement in the Midwest (*Grimley et al.*, 2017).

1.4. Incorporating near channel sediment into the watershed scale modeling framework

B. Dalzell, S. Cho, K. Gran, P. Wilcox, P. Belmont, J. Finlay

In order to develop a more comprehensive framework with which to evaluate the impacts of alternative agricultural management practices on flow and sediment flux from Minnesota River Basin tributaries, we are incorporating empirical flow-sediment relationships in the what watershed-scale SWAT modeling framework. While the SWAT model contains routines to allow simulation of stream channel downcutting and widening, the processes simulated by the model are not representative of the ravines and large bluffs that are important sediment sources in the Minnesota River Basin (*Belmont et al.*, 2011).

In order to account for near channel sources of sediment, we are relying on area-normalized relationships between upland water yield and contribution of sediment from near channel sources to the stream channel downstream of the knickpoint. Initial efforts are focused on the Le Sueur River Basin because of the availability of monitoring data at gauges located both upstream and downstream of the knickpoint. This work by Se Jon Cho has resulted in a rating curve that correlates daily flow values to daily near channel sediment loading (after accounting for length of incised stream channel). We employed this rating curve by taking SWAT-derived values of daily stream flow and then computing daily contributions of near channel sediment. This information is formatted into a data file that the model treats as a point source and adds it to the stream network at the point of the knick zone (Fig. 7).

This modified modeling framework is important because changes to agricultural management practices, cropping patterns, and landscape drainage have all been shown to change the water yield of agricultural lands from the field to the watershed scale (*Dalzell and Mulla*, in review; *Kelly et al*., 2016; *Randall and Iragavarapu*, 1995; *Schilling et al*., 2008; *Schilling et al*., 2010; *Schilling et al*., 2013; *Schottler et al*., 2013). In order to have a model that can reasonably reflect changes in near channel sources of sediment as a result of changes to upland agricultural management in the Minnesota River Basin, it is important to ensure that the model incorporates the linkage between upland water yield and sediment that originates from near channel sources.

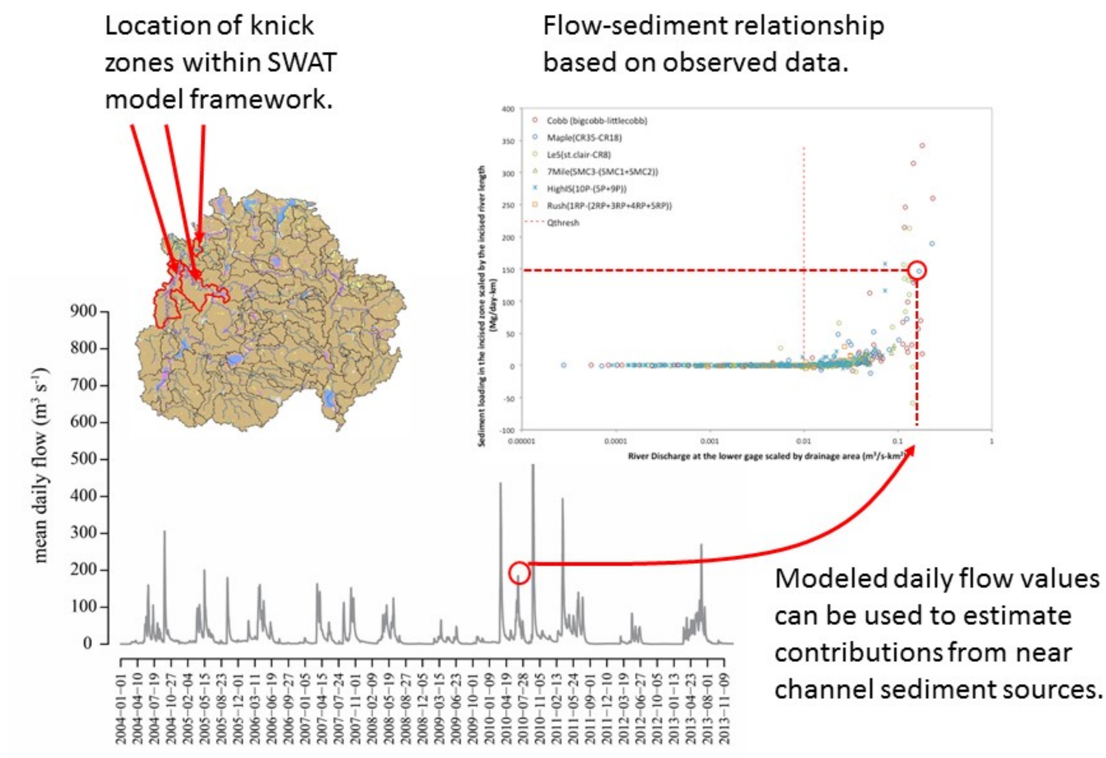


Figure 7. Schematic showing how modeled values of daily flow are combined with observed flow-sediment relationship in order to account for sediments originating from near channel sources within the SWAT model.

2. Cascade of climate and land use/land cover change to eco-hydrologic change

2.1. Reducing Aggregation Bias of Water and Solute Travel Times in Heterogeneous Catchments via a Time-Variant Lagrangian Transport Formulation

M. Danesh-Yazdi, G. Botter, and E. Foufoula-Georgiou

Anthropogenic changes in land cover and land use in the Midwestern U.S. since the 1970's have imposed contrasting spatial heterogeneities that are impacting in complex ways the residence and travel time of water in catchments (*Danesh-Yazdi et al*., 2016). Although detailed transport models with a large number of parameters might explain some physical processes of interest at the field scale, provided that enough observations are available for attribution of cause and effect, they are infeasible at the large watershed scale. The absence of rigorous data and theories for extrapolating information from the field to the larger scales necessitates developing reduced-complexity frameworks that are still able to explain the spatial heterogeneity and process complexity in real-world catchments. *In this study, we examined the ability of the lumped stochastic Lagrangian formulation for water and solute transport in providing reliable estimates of the mean travel time (MTT) in spatially heterogeneous catchments* (*Danesh-Yazdi et al*., 2017).

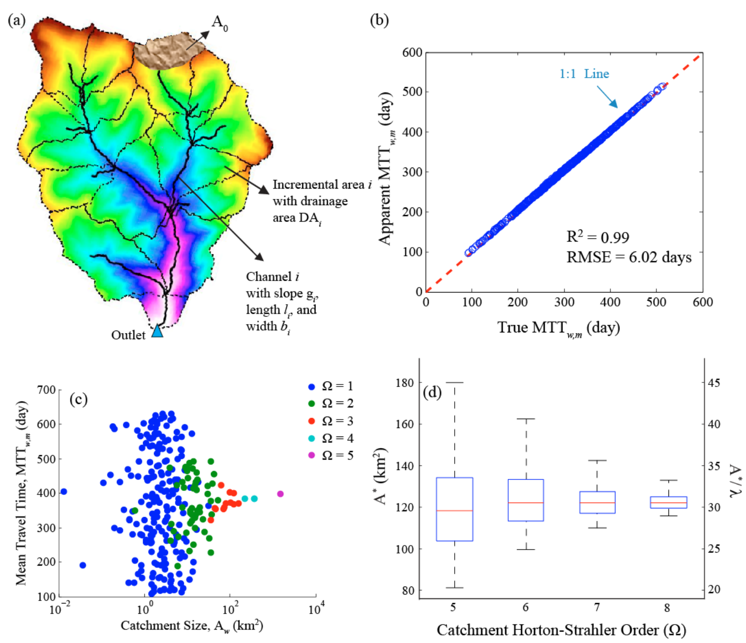


Figure 8. Effect of spatial heterogeneity on the scale of the aggregated time-variant travel time distribution (TTD). (a) Schematic of a catchment decomposition into incremental areas (IAs), each IA represented by a single storage model. (b) Comparison of the apparent MTT (computed using the aggregated fluxes of the catchment and a time-varying lumped Langrangian formulation) with the true MTT (computed using the fluxes of the individual IAs) in a two reservoir system under the random age sampling assumption. (c) Emergence of a characteristic scale (A^*) at which the aggregation effects of spatial heterogeneity vanish. (d) A^* versus catchment maximum Horton-Strahler order (Ω) for 1000 realizations of Tokunaga trees with parameters a = 1.1, c = 2, and mean incremental area λ = 3 km^2. The median of A^*/λ, i.e., A^*_{med}/λ, takes place at almost the same magnitude in catchments with different orders, while its variance decreases as the catchment's order increases.

Via numerical simulations of heterogeneous catchments, *we showed that a time-varying travel time distribution (TTD) formulation results in MTTs that are not significantly biased to the aggregation of spatial heterogeneity under different age sampling assumptions*. This finding reinforces the importance of such a time-variant lumped formalism to appropriately predict the catchment's mean transport time scales without the need to explicitly characterize and embed the small-scale spatial heterogeneity. *Although significant variability of MTT exists at small spatial scales, we showed that there exists a characteristic spatial scale (A^*) above which the MTT converges to a constant value not influenced by the aggregation of spatial heterogeneity*. *The ratio between the characteristic scale A^* and the mean incremental area of the basin was also shown to be on average independent of the river network topology and spatial arrangement of incremental areas*. The above findings have practical implications pertaining to data measurements in the field and inferences that can be made on transport time scales and mixing processes across spatial scales. Specifically, if the interest is to understand the functioning of a large catchment, collecting data at scales smaller than A^* does not allow extrapolation to estimate the MTT at larger scales. However, the MTT estimated via a time-variant Lagrangian transport formulation and for scales comparable to A^* is not significantly influenced by aggregation effects, allowing thus reliable interpretation and inference at the catchment scale.

2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics

V. Batts, K. Gran, and C. Lenhart

Previous REACH research investigating historic changes in flows on the Minnesota River *found that point bars are remaining submerged for greater periods of time during the recruitment window of dominant riparian species*. Over time, this shift can lead to more open point bars with less riparian vegetation established which may have important implications on point bar dynamics, including changes in the trapping efficiency for suspended sediment. *These observations and potential implications motivated a series of experiments to investigate the interplay between riparian vegetation, suspended sediment, and floodplain dynamics*.

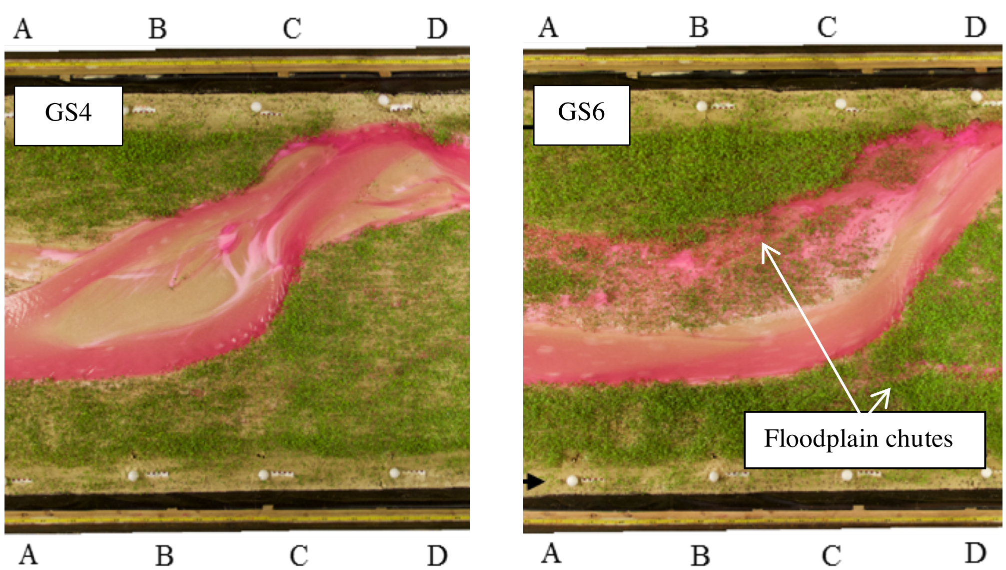


Figure 9. Vegetation growth on point bars (shown here comparing growth stage 4 and growth stage 6) narrows the channel and encourages meander migration. Vegetation on the cutbank side slows migration rates. In experiment 2, suspended sediment was able to go overbank into floodplain chutes and channels, filling them in and allowing for the floodplain to evolve along with the channel (*Batts*, 2017).

Coupled experiments were conducted in a 1.5 x 5 m flume at the University of Minnesota, Duluth to observe how floodplains respond to vegetation colonization with and without suspended sediment present. In each experiment, we imposed a two-stage hydrograph, with floods lasting for four hours, followed by 6 days of low flow in which the flume was seeded with vegetation (*Medicago sativa*). Experiments lasted for up to 9 cycles of flood followed by growth. One experiment used only bedload, while the second had a mix of bedload and suspended load. Results mirror those from previous experiments in documenting the role of vegetation in corralling the flow into fewer, narrower, deeper channels and slowing channel migration rates (Figure 9, 10).

Further, these experiments demonstrated that overbank flows rich in suspended sediment allowed the floodplain to adjust to changes in channel transport capacity associated with the growth and encroachment of riparian vegetation. Through time, suspended sediment filled in floodplain topographic lows and channel cutoffs (Figure 9), allowing for the floodplain to evolve with the channel. The experiments show that both vegetation and suspended sediment are important in maintaining meandering and allowing the floodplain to evolve in conjunction with the channel.

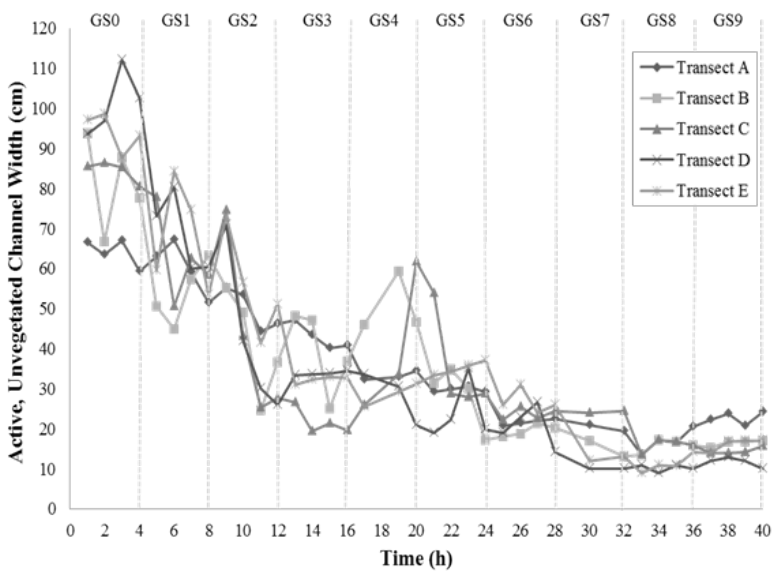


Figure 10. Channel narrowing over time with increasing vegetation density. Experiment 2 shown here. Each growth stage (GS) represents a flood cycle followed by vegetation growth. (*Batts*, 2017)

3. Quantifying nutrient and phosphorus cycling in intensively managed landscapes

3.1. Anthropogenic and environmental controls on nutrient inputs and export

E. Boardman, J. Finlay, M. Danesh-Yazdi, and E. Foufoula-Georgiou

We are exploring environmental controls and sources of watershed nitrogen (N) and phosphorus (P) losses across agricultural regions of Minnesota. We estimated Net Anthropogenic N and P Inputs (NANI and NAPI) for 62 watersheds based on modification of existing methods. Our approach takes into account atmospheric deposition, inorganic fertilizer inputs, and net food and feed inputs (including manure, crop N fixation, animal requirements, and human requirements). We considered watersheds larger than 150 km^2 due to the resolution of the input data, which is generally at the county-level scale. Our results show that N and P fertilizer inputs are the largest factors contributing to nutrient losses in agricultural watersheds. Responses are often nonlinear and are linked to legacy of agricultural fertilization, and modified by climate, inputs from permitted discharges, and landscape features such as wetlands and lakes (which trap nutrients) and bluffs (which accelerate P inputs).

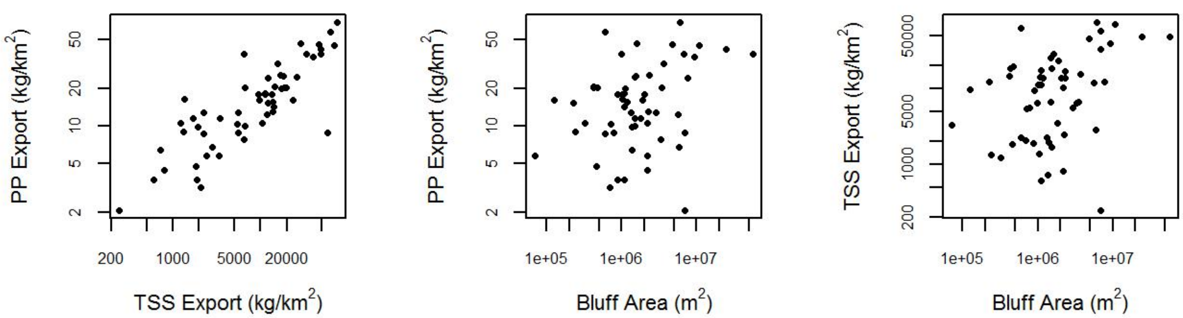
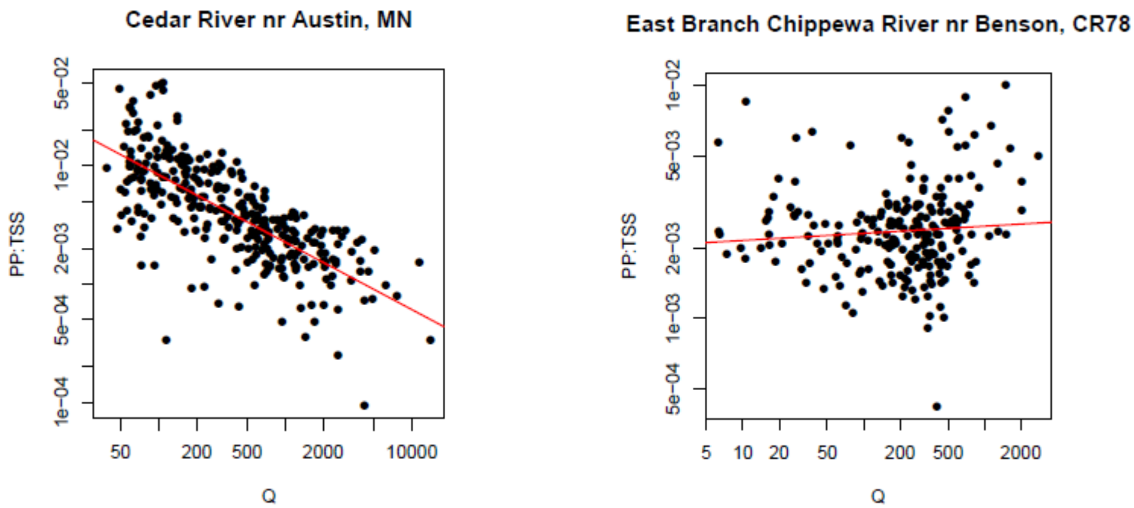


Figure 11. Relationships between annual particulate P and TSS yields (left), PP and bluff area (center) and TSS yield and bluff area (right) for watersheds across MN.

We are examining hydrologic controls on N and P export in support of efforts to tie together our knowledge of the hydrology, sediment transport, geomorphology, and nutrients in agricultural watersheds. We are using analyses of data for >100 sites with greater than 50% agricultural land cover, as well as some sites with low and moderate agricultural land cover to under the contribution of phosphorus to rivers in response to interactive effects of climate, hydrology, P inputs, and geomorphology. Notable findings thus far include the prevalence of concentrating relationships (i.e. higher flows drive increasing concentrations of N and P) for most watersheds and the observation that flow sensitivity varies amongst watersheds in accordance with landscape features (lakes, bluffs) and, for a minority of sites, human point source pollution from waste water treatment plants. *This suggests flow reduction BMPs may be more effective in watersheds where nutrient concentrations are more closely related to discharge.*

Our recent analyses explore the relationship between sediment generation and P mobilization within watersheds. Most agricultural watersheds show reduced P relative to total suspended sediment (TSS), indicative of mobilization of P poor soils from stream banks and bluffs. These relationships are strongest in the presence of extensive bluff areas, and weaker in flatter landscapes with abundant lakes (Figures 11 and 12).

a)



b)

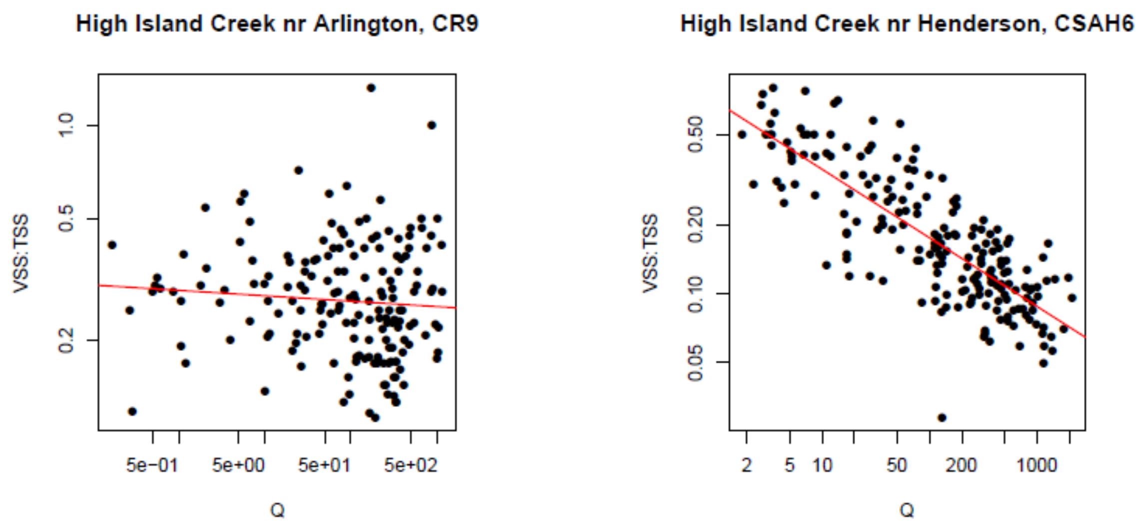


Figure 12. Sample plots showing (a) the ratio of PP to TSS decreasing with increasing discharge most typically observed in MN (left plot) and a relationship with no significant trend in PP:TSS with discharge in a lake rich watershed, and (b) an upstream (left plot) to downstream (right) continuum in which the downstream site has higher bluff area. VSS:TSS switches from no significant response across a range of discharge in the upstream, flatter part of the watershed to a strong decreasing trend with discharge in the downstream site. Untransformed data are plotted in log-log space.

The dominant form of P in rivers is highly sensitive to human inputs and the presence of actively eroding bluffs (Figure 11). Fertilizer P inputs increase the levels of dissolved phosphorus in rivers relative to particulate P. However the presence of bluff again modifies relationships where high sediment inputs from erosion drives down dissolved:particulate ratios (Figure 13).

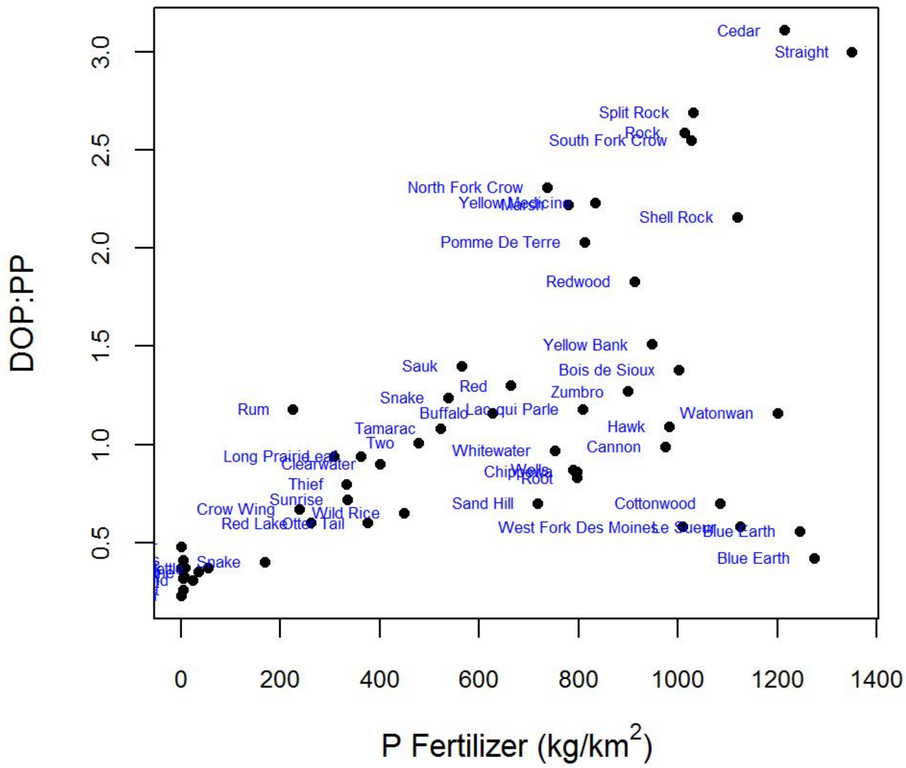


Figure 13. Relationship between P fertilizer inputs to watersheds and the ratio between annual dissolved phosphorus and particulate phosphorus yields across MN. Fertilizer stimulates DOP losses relative to PP except in watersheds with extensive eroding bluffs such as the Blue Earth and Le Sueur watersheds.

3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics

A. Baker, J. Finlay, and K. Gran

Sediment is a known driver of phosphorus loading to rivers and receiving waters worldwide, and thus, incorporating source-sediment phosphorus concentrations into predictive models for management practice selection and placement can improve our ability to manage the landscape for multiple benefits. *We are exploring phosphorus export and retention as a function of sediment geochemistry and sorptive capacity across a geomorphic gradient via the development of a sediment-associated phosphorus budget and experimental sorption testing*. This sediment-phosphorus budget is tightly coupled to the sediment budget developed by project PIs (K. Gran, P. Belmont (Utah State University), and P. Wilcock (Utah State University)). Primary sources of sediment to the basin, including till bluffs, alluvial stream banks, ravines, and agricultural fields, have been sampled to represent potential variability in texture and phosphorus content, and measurement of phosphorus chemistry and sorptive capacity of these sediments is underway. Total- (TP) and dissolved-phosphorus (DP) associated with these source sediments are being applied to the sediment budget to estimate the contributions of sediment to water column phosphorus loads. Comparison of preliminary load estimates derived from this sediment-phosphorus budget to loads measured by the Minnesota Pollution Control Agency suggest that as little as 24% of TP and less than 1% of DP exported from the watershed can be directly attributed to source sediment. These findings reaffirm the importance of investigating dissolved phosphorus sources and process that govern movement between dissolved and particulate pools throughout the basin, and point toward the potential significance of interactions between dissolved phosphorus and sediment in transport.

Exploration of TSS, DP and particulate phosphorus (PP) data collected at gages above and below knickpoints on the Le Sueur, Maple and Cobb Rivers supports the importance of sediment to phosphorus behavior and elucidates process that effect phosphorus export along the stream corridor. Plots of these constituents at the upper versus lower gage on the Maple River suggest distinct processes governing DP and PP export (Figure 14). Dissolved-P yield skews toward the upper part of the basin, suggesting that upland processing and release of DP dominates watershed-wide export. Particulate-P, on the other hand, shows a shift in dominant part of the basin as yield increases, with low PP yields generated by upland watershed processes and high yields generated by the incised zone. The same relationship is observed in TSS yields, and in both cases the shift corresponds to the crossing of a flow threshold identified by *Cho* (2017), beyond which rapid increase in sediment loading in the incised zone occurs.

To further explore the role of sediment in driving these spatial variability in phosphorus fractionation between dissolved and particulate phase, sorption tests are being carried out to uncover the equilibrium phosphorus concentration at zero sorption, which provides insight into the role of sediment as source or sink for phosphorus based on ambient dissolved phosphorus load conditions. These experiments also provide data describing sorptive capacity of sediments, which may be incorporated into the budget to describe movement of dissolved phosphorus between dissolved and particulate pools along the channel corridor from connected uplands to incised lower valley of the Le Sueur. Results of these analyses will be incorporated into the sediment-phosphorus budget to help understand the effect of sediment from distinct sources upon phosphorus bioavailability, export, and retention along the river network.

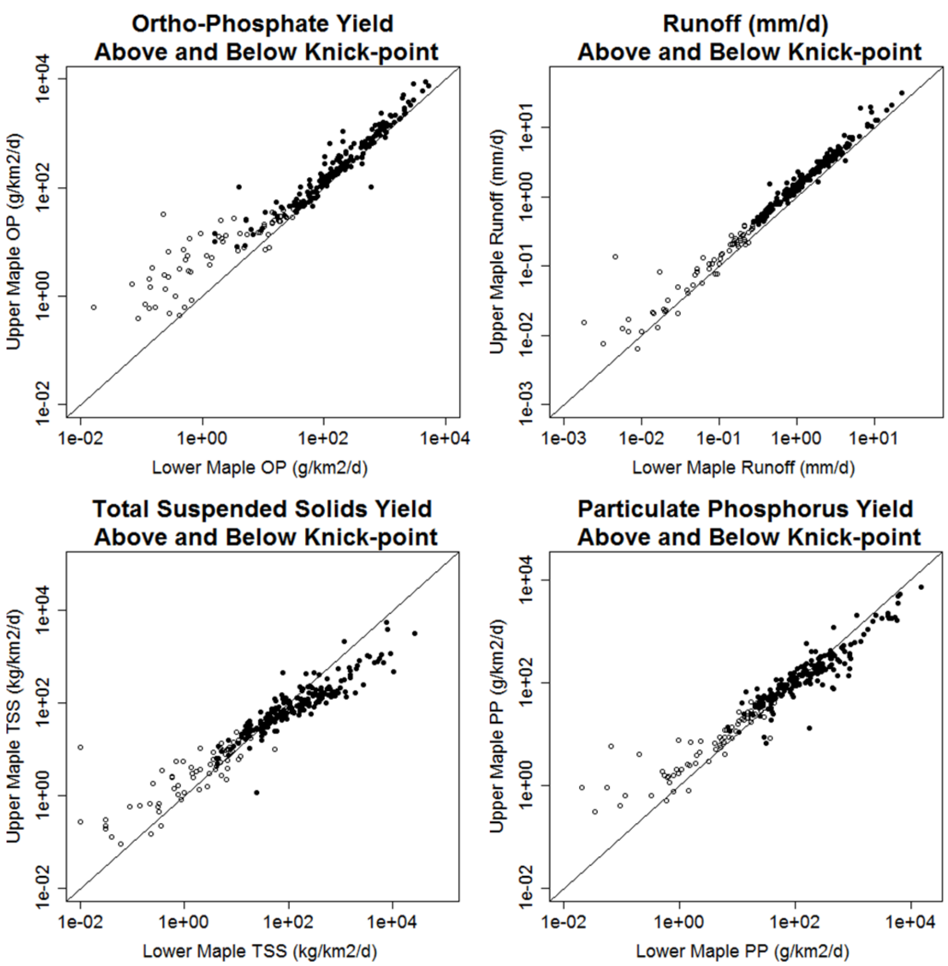


Figure 14. Yield of dissolved phosphorus, water, particulate phosphorus, and total suspended solids at the upper versus lower gage on the Maple River. Filled circles are samples collected above the flow threshold corresponding to the initiation of near channel erosion in the incised zone, while open circles are below that threshold.

3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes

A. Hansen, C. Dolph, E. Foufoula-Georgiou, and J. Finlay

Intensively managed row crop agriculture has fundamentally changed nitrogen processes within the Mississippi River basin through large scale alterations of land cover, hydrology and reactive nitrogen availability. These changes have created leaky landscapes where excess agriculturally derived nitrate enters the fluvial network and degrades water quality at local, regional, and continental scales. Individually, wetlands are known to remove nitrate at often high rates but the conditions under which multiple wetlands meaningfully reduce riverine nitrate concentrations has not been established. One region of the Mississippi River basin still contains the necessary combination of variable wetland cover in watersheds under intensive agriculture management to empirically address this question, i.e. the Minnesota River basin (MRB, Figure 15). We combined high-resolution land cover data with repeat spatially extensive water sampling data in the MRB to show that the effect of wetlands on riverine nitrate is highly coupled to spatial positioning, streamflow condition and crop cover (*Hansen et al*., 2017). We isolate the effect of wetlands from cropland and show that, under moderate to high streamflow, the reduction of riverine nitrate in response to increases in wetland cover is five times greater than to decreases in crop cover of the same area. *Our analysis indicated that ephemeral wetlands contributed to watershed nitrate removal, but only under the highest streamflow conditions. Wetland connectivity and spatial patterning within the watershed explained much of the remaining variation in relationships between wetland cover and riverine nitrate.*

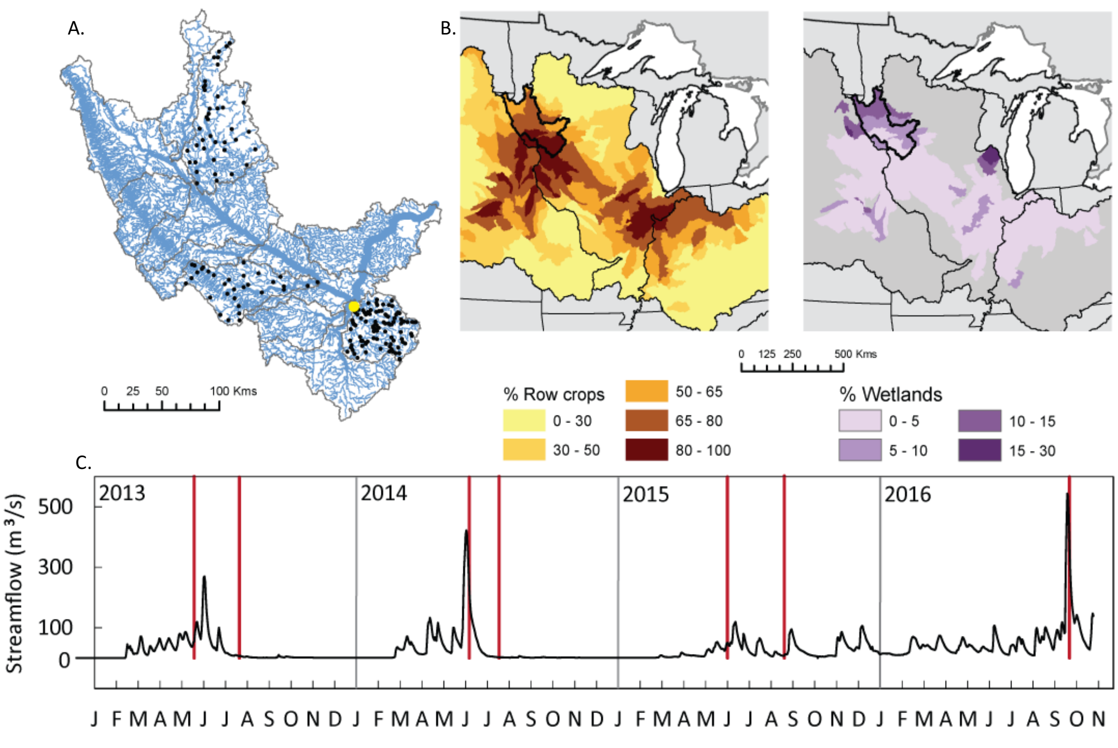


Figure 15. Land use and streamflow. Nitrate concentrations were observed at > 200 sample sites within the Minnesota River Basin (MRB, panel A, black markers). Sites were chosen to span a large range in drainage areas (0.253 km^2 to 5,239 km^2) and in in land use (% crop land cover between 30% - 95%, % lentic cover between 0.0 to 58%). Row crop cover and wetland cover (wetlands + lakes) in basins with over 50% row crop cover for the Ohio, Upper Mississippi and Missouri River basins, aggregated by HUC-8 sub-basins (Panel B). The MRB is outlined in black. Hydrograph from USGS gaging station 05320500 located at the Le Sueur River outlet (yellow marker in panel A). Seven sampling events, shown as red vertical lines, captured the range in hydrologic conditions within the four year study period (panel C).

To isolate the effect of wetland presence from crop absence on riverine nitrate under moderate to high streamflow, we analyzed the response of nitrate to wetland cover within eight subsets of the data for which crop cover was approximately constant. *We observed statistically significant linear relationships between nitrate and wetland cover for seven of the eight data subsets* (Fig. 16C). The slopes of the regression lines between nitrate and wetland cover increased with increasing crop cover, indicating that increases in wetland cover have a proportionately greater effect on nitrate in watersheds where crop cover is greater (Fig 16E). For example, the reduction in nitrate concentration would be twice as great in a landscape with > 80% cropland as in a landscape with 65 – 80 % cropland, and four times greater than in a landscape with 50 – 65 % cropland for the same area converted to wetlands (Fig. 16E). We applied the same method to isolate the effect of crop cover under moderate to high streamflow, by evaluating relationships between nitrate and crop cover for five subsets of the data where wetland cover was approximately constant. *We observed significant linear relationships between nitrate and crop cover within three of the five wetland cover subsets* (Fig. 16D). Unlike wetlands, the slopes of the regression lines between nitrate and crop cover did not change across wetland cover, indicating that the dependency of nitrate on crop cover was functionally the same regardless of wetland cover (Fig. 16F). *Taken together, the asymmetry in the rate of nitrate reduction per increment of additional wetland area versus per increment of reduction in crop area likely occurs because wetlands intercept runoff from a greater land area than they occupy, unlike changes in field based management strategies which only effect the area on which they are implemented.*

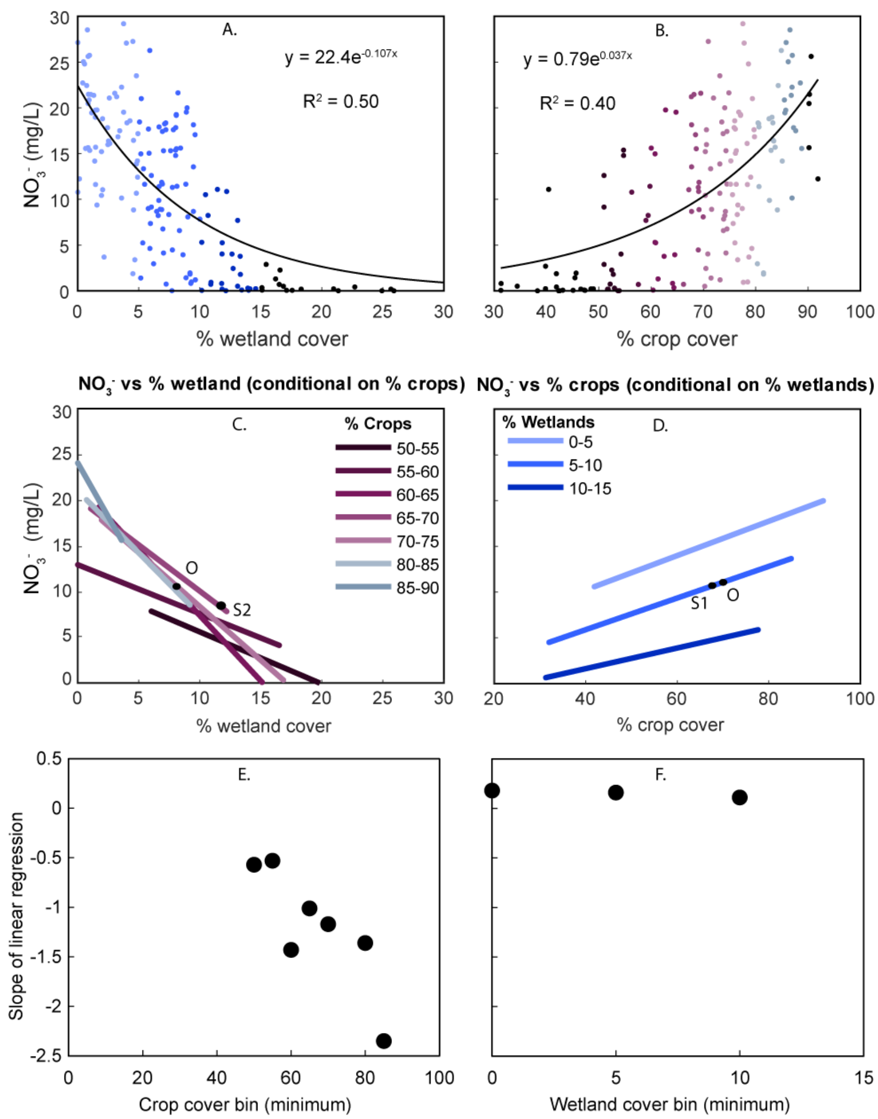


Figure 16. Effect of wetland cover and crop cover on riverine nitrate. Riverine nitrate decreased exponentially with wetland cover (panel A) and increased with crop cover (panel B) across the four sampling events occurring under moderate to high streamflow. To isolate the effect of wetland cover on nitrate, data was conditioned on crop cover using bins of 5% (panel C) and conversely, the effect of crop cover was conditioned on wetland cover again with bins of 5% (panel D). Black markers illustrate two restoration scenarios and the original land use (S1, S2, and “O”, panels C and D). The rate of decrease in nitrate with increase in wetland cover increased with crop cover (panel E) while the rate of increase in nitrate with increase in crop cover was independent of wetland cover (panel F).

Individual wetlands are known to be effective sinks for nitrate. In addition to reducing nitrate in situ, wetlands may have impacts on water quality and temperature dynamics that extend beyond the confines of the wetlands themselves. Non-saturating nitrate concentrations enhanced organic carbon effluxes and altered temperature dynamics could all potentially enhance denitrification rates within a stream network, thus extending water quality benefits beyond the wetland boundary. *We investigated the effect of wetlands on water chemistry, water temperature and benthic denitrification rates in downstream agricultural ditches through a field measurement campaign over the open water season*. We found that, although ditches located downstream of wetlands had lower NO_3^- and higher DOC, ditch denitrification rate was not significantly altered by the presence of upstream wetlands. Rather, wetlands indirectly effected denitrification within ditches by strongly influencing the stoichiometry of the two limiting resources, NO_3^- and organic carbon. Peak denitrification rates were observed when DOC and NO_3^- supplies were approximately balanced i.e. at DOC: NO_3^- ratios that were near the microbial requirement for denitrification. NO_3^- limitation occurred primarily at sites with > 3.5% wetland cover, and in the fall at all sites, and DOC limitation occurred primarily at sites with < 1% wetland cover (*Hansen et al*., 2016). Temperature was found to be a secondary control, only important when NO_3^- and DOC resources were balanced. *Our results suggest that wetland restoration and construction targeting nitrate reduction within intensively agriculturally managed basins should be implemented in a way that promotes balanced resource availability throughout fluvial networks. Wetlands are an important regulator of resource availability and thus could be used to create conditions that maximize denitrification in* NO_3^- *enriched watersheds*.

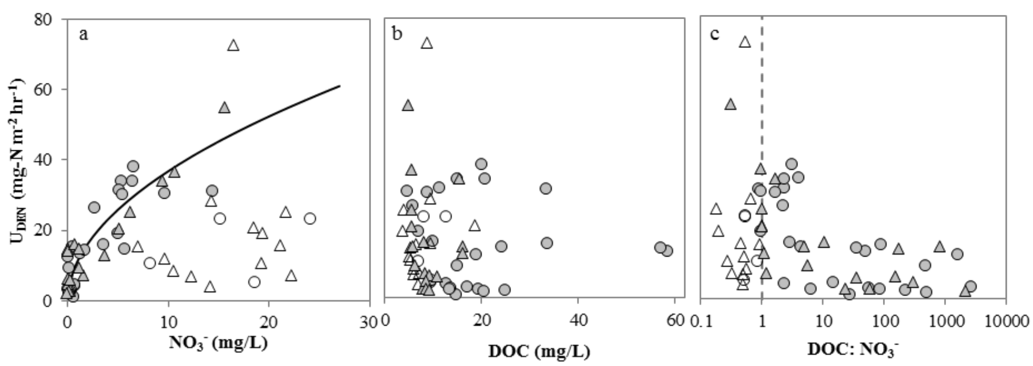


Figure 17. Denitrification rate (U_{DEN}) was determined to be limited by either NO_3^- or DOC. Observations from sites with high wetland influence are shown with circles and from sites with minimal wetland influence are shown with triangles. In panel a, samples that fit a NO_3^- limitation model are shown in gray and all other samples are hollow symbols. The upper limit on U_{DEN} was constrained by NO_3^- availability and could be modeled using a previously published model of denitrification by *Mulholland et al*. (2008) and extended by *Bohlke et al*. (2009) (solid line, panel a). Grey symbols are observations that are well described by the NO_3^- limitation model and open symbols are the observations not well described by the model. We did not find a predictive relationship between U_{DEN} and DOC (panel b) although when U_{DEN} was plotted against the ratio of DOC: NO_3^- data that did not fit the NO_3^- limited model was found to group together and have DOC: NO_3^- < 1, likely indicating insufficient organic carbon (panel c).

3.4. Nitrogen, phosphorus and suspended algal biomass in an agricultural watershed of the Upper Midwestern USA

C. Dolph, A. Hansen, A. Baker, J. Finlay

Algal growth in freshwater systems is widely considered to be limited primarily by ambient phosphorus rather than nitrogen concentrations. However, considerable evidence suggests that phytoplankton in lakes, as well as benthic algae in streams, can be controlled by both N and P, and that eutrophication mitigation efforts may thus need to target both nutrients. To date, it is largely unknown whether phytoplankton (i.e., suspended algal biomass) in streams and rivers can be limited by nitrogen as well as phosphorus. As we have recently shown, suspended algal biomass can be quite high in nutrient-rich streams and rivers draining agricultural landscapes, suggesting that phytoplankton may play an important role in nutrient cycling in these systems. Here, we evaluated relationships between suspended chlorophyll a (Chla; as a proxy for algal biomass), nitrogen (N) and phosphorus (P) concentrations across 92 stream and river sites draining an intensively managed agricultural watershed in the upper Midwestern USA. We sampled these sites repeatedly over multiple years and under various flow conditions. We found that, during most sampling dates, ratios of total N: total P in the water column greatly exceeded the Redfield ratio of 16:1 across most sites, suggesting that algal growth would likely be primarily phosphorus-limited. Indeed, suspended Chla was significantly related to total phosphorus during more than half of all sampling occasions.

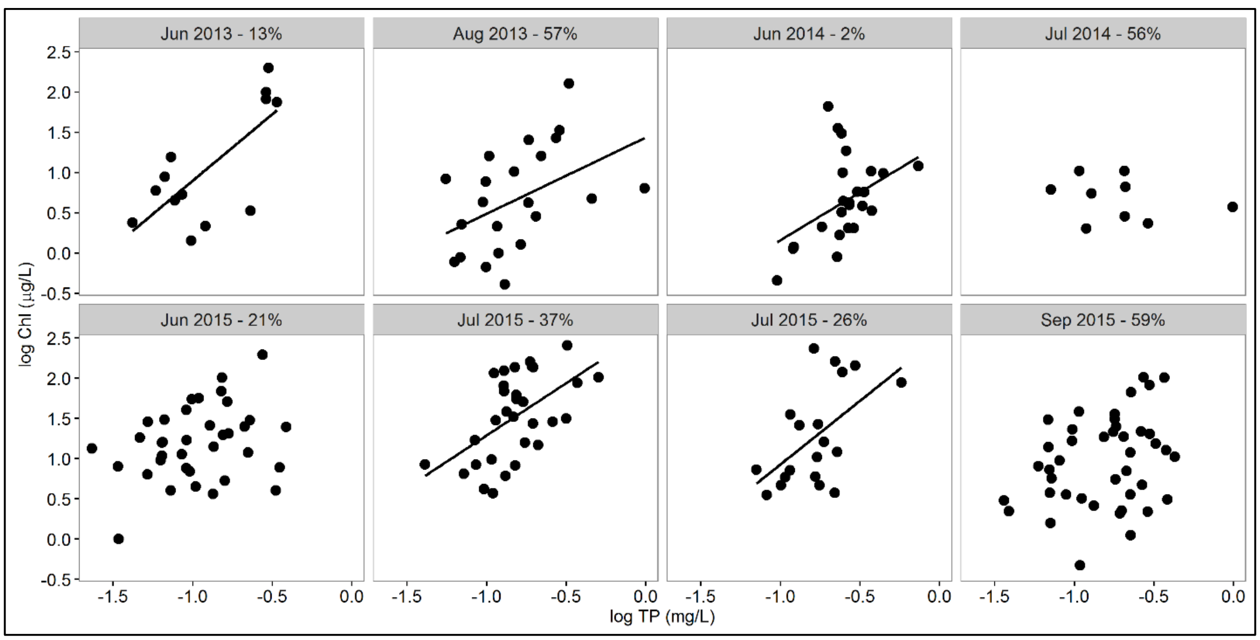


Figure 18. Chla in relation to TP across study sites sampled during each event. Lines indicate statistically significant linear regression relationships.

However, on two sampling dates (in early and late summer of 2015, respectively), Chla was also positively related to total nitrogen. Our findings suggest that the growth of suspended algal biomass in agricultural streams may be limited primarily by nitrogen or phosphorus, depending on seasonal and/or flow conditions. Moreover, we found that, across all sampling dates, increasing N appeared to support increased algal growth up to a N:P = 35:1, a ratio considerably higher than the Redfield ratio.

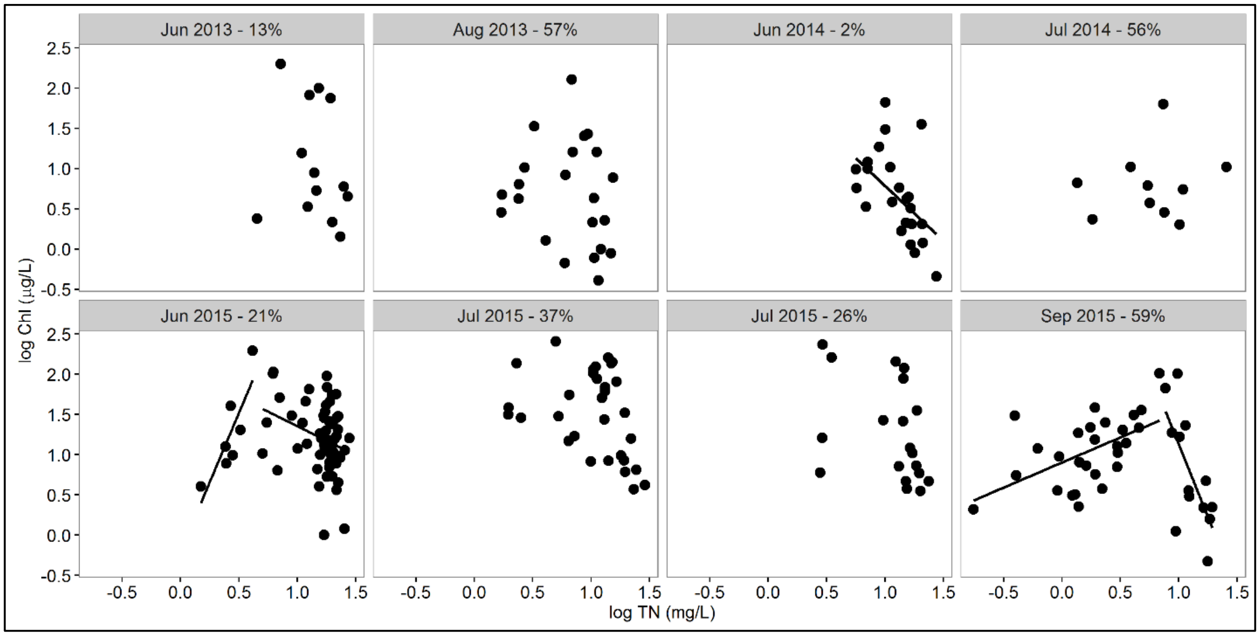


Figure 19. Chla in relation to TN across study sites sampled during each event. Lines indicate statistically significant simple linear regression or breakpoint regression relationships.

Finally, we estimated that, on average across all sites and dates, suspended algal biomass accounted for approximately 30% and 10% of PP and TP concentrations, respectively. This finding suggests that suspended algal biomass plays an important role in the assimilation and transport of phosphorus in agricultural river networks.

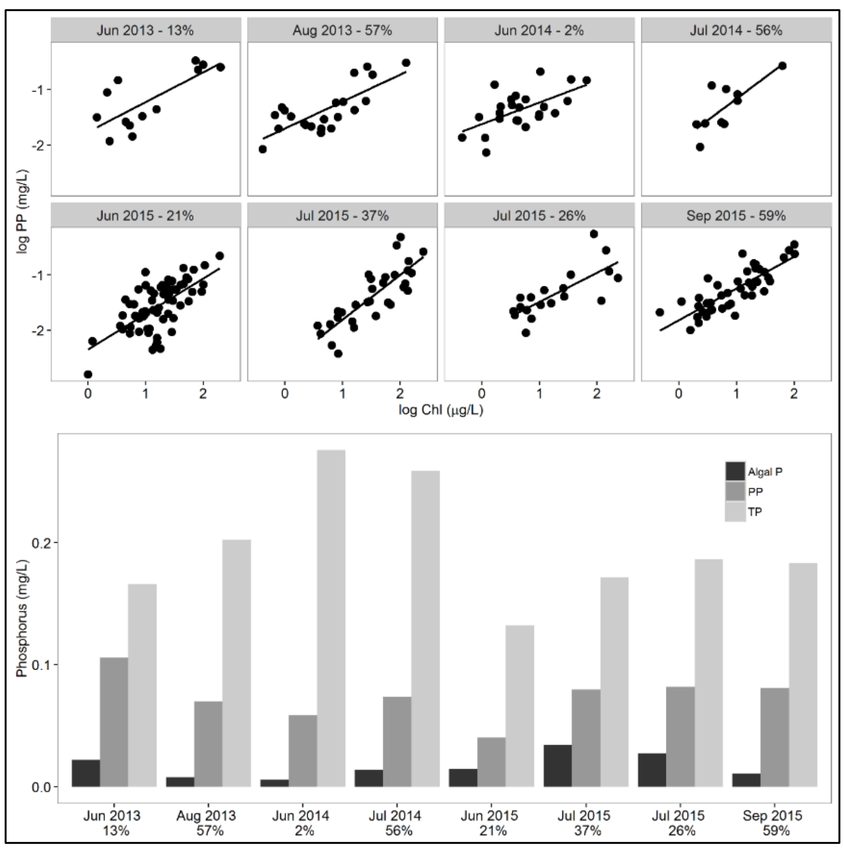


Figure 20. PP in relation to suspended Chla across sites during each sampling event (log-log scale; top) and mean concentrations of phosphorus contributed by algal biomass, particulate and total phosphorus, across study sites for each sampling event (bottom).

3.5. Patterns in resource use by aquatic consumers in agricultural streams of the Minnesota River Basin

C. Dolph, A. Hansen, J. Finlay

Food webs and organic matter cycling in agricultural streams are not well understood, despite the global ubiquity of agricultural land use, and its strong influence on environmental conditions. In this study, we used carbon and nitrogen stable isotope values ($\delta^{13}C$, $\delta^{15}N$) of basal resources and macroinvertebrate consumers to understand patterns in allochthonous and autochthonous resource consumption among macroinvertebrate functional feeding groups collected from four small to mid-size agricultural streams in the Minnesota River Basin, USA. Basal resources and consumer tissue were collected from these sites six times during the growing seasons of 2014 and 2015, to account for temporal variation in resource and consumer isotope values. Proportional contributions of food sources to macroinvertebrate feeding groups were estimated using MixSIAR.

Macroinvertebrate consumers at an open canopy prairie/grassland site used autochthonous resources more heavily than their counterparts at sites with more forested riparian canopies. However, estimates for macroinvertebrate diets at all sites indicated substantial reliance (~30-80%, depending on site and feeding group) on terrestrially-sourced materials. Moreover, although suspended chlorophyll concentrations at all sites sometimes reached levels high enough to be considered eutrophic, analysis of seston also indicated that suspended particulate matter is often terrestrial in nature. These findings are consistent with high erosion rates exhibited by streams in the region, which, together with low availability of stable substrate, may limit the transfer of algal resources to higher trophic levels, despite the high potential for authochthonous support of food web production in these systems.

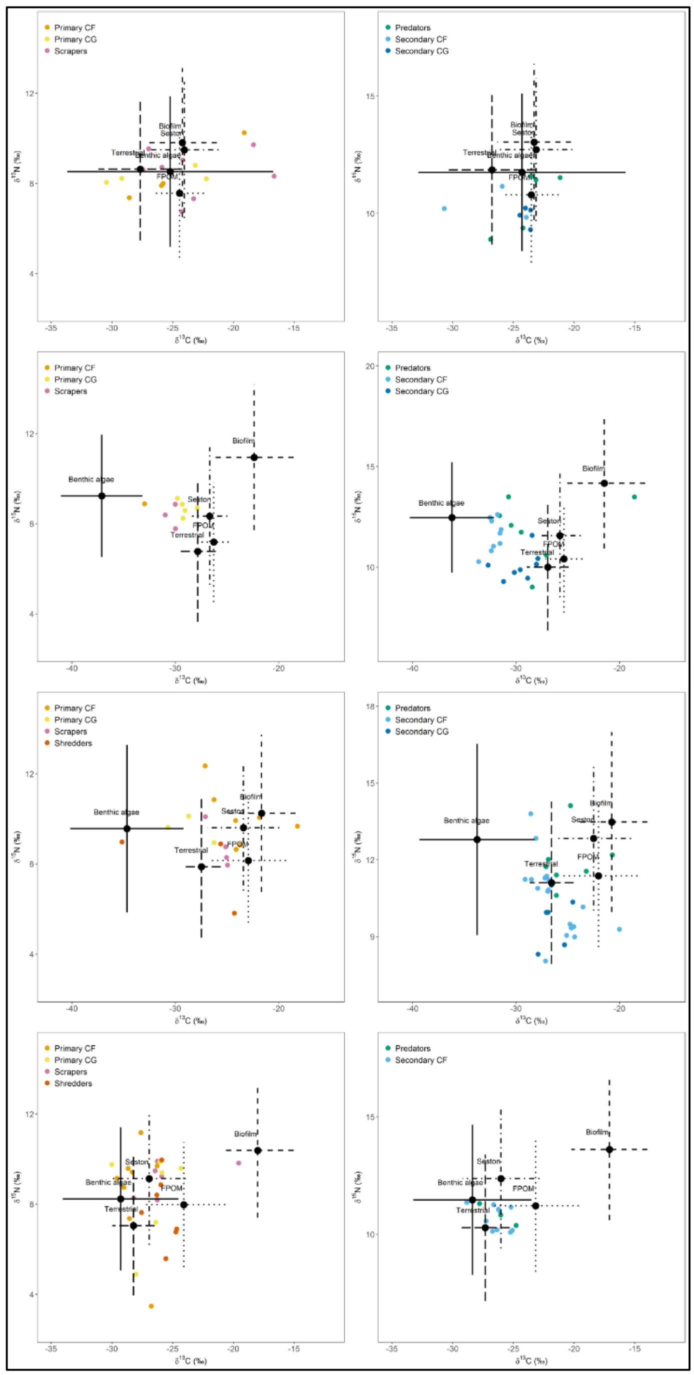


Figure 21. Stable isotope biplots of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of consumers (individual samples) and food sources (means), collected across all sampling dates at sites 1-4. Left and right panels show primary and secondary consumers for each site, respectively. Sources values have been corrected for primary or secondary consumer TEFs, as appropriate.

4. The role of wetlands and water-retention structures in environmental restoration of intensively managed landscapes

4.1. Network structure nitrate removal efficiency

J. Czuba, A. Hansen, E. Foufoula-Georgiou, and J. Finlay

Many agricultural landscapes of the Midwest, including the Minnesota River Basin, were once dominated by tall-grass prairie and dotted with poorly drained wetlands. Beginning in the late 1800s, these wetlands were drained for agriculture with the construction of surface ditches and installation of subsurface drain tiles. Only remnants of these wetlands remain today. However, where they do exist, they are important sources, sinks, and transformers of important macronutrients of carbon, nitrogen, and phosphorous. Specifically, the research by REACH members described in section 3 shows that wetlands (at least seasonally) are (1) a carbon source to downstream reaches, (2) decease nitrate possibly through assimilation or denitrification, and (3) are important locations of phosphorous storage and transformation between dissolved and particulate forms. *Thus, where these wetlands are located in the landscape has important implications for understanding downstream water quality*. We have developed a watershed-scale, network-based model (validated with field observations) of nitrate-nitrogen and organic carbon concentration through the wetland and river network complex of the 2,800 km^2 agricultural Le Sueur Basin in southern Minnesota (*Czuba et al*., 2017b). Using the model, we show that the capacity of denitrification to reduce river nitrate shifts between biogeochemical (denitrification reaction rates) and hydrologic (residence time) controls depending on flow discharge and proximity to wetlands. We also show that the spatial context of wetland restorations plays a key role in determining outcomes because nonlinearities in the network can lead to unexpected changes.

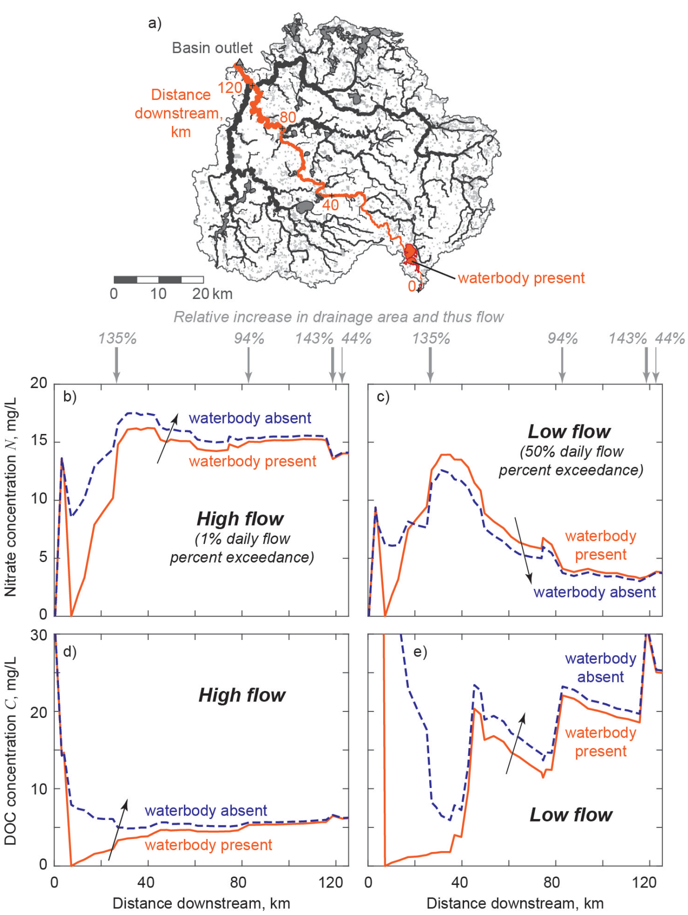


Figure 22. Conditions under which removing (or conversely) adding a waterbody to the network could give rise to unexpected behavior: when the removal of a lake downstream of a wetland can reduce downstream nitrate concentrations. (a) Highlighted pathway through the wetland and river network complex in the Le Sueur Basin along which further results are shown: (b, c) Nitrate concentration N and (d, e) organic carbon concentration C at the (b, d) 1% (high flow) and (c, e) 50% (low flow) daily flow percent exceedance. Conditions with the waterbody (lake) present (roughly 5 km downstream along the profile) are shown with a solid orange line whereas with the waterbody absent are shown with a dashed blue line.

For instance, we consider a case of removing a lake downstream of a wetland and the resulting downstream effects on nitrate and dissolved organic carbon concentrations (Fig. 22). In the absence of the lake (blue lines, Fig. 22), downstream nitrate concentrations increase at the high flow (Fig. 22b) because of the associated reduction in nitrate removal due to lower denitrification, as expected. However, at low flow (Fig. 22c) nitrate concentrations downstream unexpectedly decrease. This occurs because in the absence of the lake, higher organic carbon concentrations can propagate downstream, thereby increasing denitrification rates in these regions, and thus reducing downstream nitrate concentrations. This example illustrates how efforts to reduce watershed-scale nitrate concentrations and loads by restoring wetlands need to carefully consider the cascade of biogeochemical changes that propagate through the network in response to the spatial positioning of the suite of restored wetlands. The ultimate goal of this research is to identify where to target management actions, in terms of creating wetlands, in order to improve water quality.

4.2. Valuing Water Quality Improvements in Midwestern Ecosystems: Spatial Variability, Validity and Extent of the Market for Total Value

C. Dolph, J. Finlay, C. Kling, D. Keiser, D. Phaneuf, C. Vossler, J. Zhao

This project represents an outgrowth of the REACH project, and is an U.S. EPA-funded collaboration with Iowa State University (Cathy Kling & Dave Keiser), University of Minnesota (Jacques Finlay & Christy Dolph), University of Wisconsin (Daniel Phaneuf), University of Tennessee (Christian Vossler), & Michigan State University (Jinhua Zhao).

This project is seeking to define the total economic value the public assigns to improvements in water quality. A particular focus of this work is understanding the economic value people might assign to intangible or 'non-use' aspects of aquatic systems, such as 'biological integrity'. Biological integrity is often a goal of watershed management efforts, and considerable resources have been allocated in Minnesota to monitoring and improving the biological condition of streams and rivers. Measures of biological integrity may also represent an important proxy for the safety of streams and rivers for human use -- if stream and rivers are healthy enough for insect and fish communities to thrive, they will likely be clean enough for people to swim in, fish from, etc. However, there have been few efforts to understand what biological integrity is 'worth' to members of society. In other words, how much economic value do people assign to the conservation of stream integrity, whether or not they benefit from it directly? A major focus of the EPA-funded project is a state-of-the art survey, developed and administered by a team of economists from multiple research universities, that will seek to understand the economic value that members of the public associate with improvements in water quality in general, and with improvements in biological integrity in particular. These economic value estimates can then be fed back into the WSC REACH collaboration, as a way to evaluate the costs and benefits of improvements in water quality against all other environmental costs and benefits associated with human land use in the Minnesota River Basin.

Before survey work can be implemented however, we needed to address several questions:

1) What is the best way to measure biological integrity in our study region?
2) What is the state of biological integrity across our study region?
3) How can biological integrity be conveyed to the public?
4) What improvements in biological integrity can we expect with improvements in pollutants like nitrogen, phosphorus, and sediment?

1) Defining stream and river ecosystem condition (the Biological Condition Gradient)

The first step in connecting water quality drivers like nutrient pollution to the value of ecosystem integrity was to select or generate a water quality indicator that could be used to represent overall stream condition in a way that was both holistic and relatable to a general audience and that could be modeled in relation to water quality parameters like concentrations of nitrogen, phosphorus, and sediment. In the fields of economics and ecology, many different approaches have been taken to try and define ecosystem 'integrity', and to summarize how water quality changes with changes human influence. However, these previous approaches typically have a number of shortcomings, i.e., they fail to capture important aspects of stream systems, such as biodiversity, or they are too specific and not generalizable (i.e., designed for specific regions and not applicable across state boundaries).

We conducted a review of the available water quality ladders and approaches that have been previously developed in the U.S. and abroad. From this review, it became apparent that the concept of 'biological integrity' or ecological status should be central to a water quality indicator. 'Biological integrity' is a goal specifically stated in the Clean Water Act. To that end, state and federal agencies have invested considerable resources in developing methods to assess biological integrity. Biological integrity is also an important aspect of understanding the intangible aspects of conservation, as it is often not directly 'used', even by active users. For example, one might still swim in a lake with a somewhat degraded biological community, but presumably we might value the lake both because we can swim in it and because of the habitat it provides to a healthy aquatic community. Over the last several decades, scientists and managers have developed a number of approaches by which to assess the biological integrity of streams and rivers. Based upon our research, we decided to use the **Biological Condition Gradient** (described below) as our measure of biological condition.

What is the Biological Condition Gradient (BCG)?

Starting in the 1980s and '90s, the U.S. Environmental Protection Agency (EPA) and state partners started to move away from emphasizing regulation of purely chemical measures of water quality to including more 'holistic' measures of 'biological integrity' (*Karr*, 1999). Similar developments occurred in Europe over a similar time period (e.g., *Hime et al.,* 2009). The upshot of this change was a hodgepodge of state-based efforts to measure biological condition – all U.S. states now incorporate some measure of biological integrity into their water quality assessment programs. However, these approaches emphasize different ecological aspects, depending on the state in question. For example, some measures of biological integrity emphasize species loss, while others emphasize particular metrics that correlate with disturbance. One critique of these different approaches is that they may detect disturbance, but they may or may not actually capture 'ecological integrity', because the concept in itself may not be well defined.

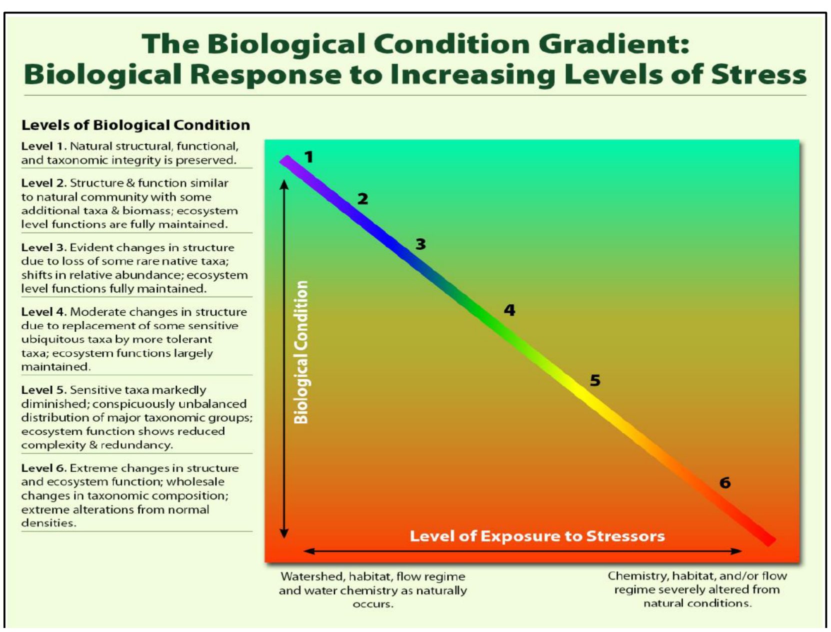


Figure 23. The Biological Condition Gradient – expected changes in biological community with changes in stress. Adapted from *Davies and Jackson* (2006).

The BCG is an attempt by EPA, together with many prominent stream ecologists from academia and state management agencies, to create a conceptual framework for ecological integrity that can be used to unify all these efforts:

- It creates a systematic, predictive conceptual framework for biological changes you would expect to see with human influence
- It allows for assessment of incremental progress, not just a binary view of impaired or not impaired.
- It provides a common interpretative framework to assist in comparability of results across states/programs.
- EPA emphasizes that it's useful in communicating current water quality conditions and expected changes (with reference to biological integrity)

The BCG describes biological changes (in fish, macroinvertebrate and/or algae populations) that are expected to occur with disturbance (e.g., nutrient enrichment; Figure 23). It uses fish/invertebrate/algal population information as the ultimate comprehensive sign of ecological status – with the view that those populations should be integrating everything else that's happening in the stream or river, including changes in habitat, water quality, flows, etc. The BCG has levels from '1' (pristine systems) to '6' (severely degraded). Each level is associated with decreases or increases in particular aquatic species or populations. For example, as you move from pristine to more degraded conditions, streams may exhibit the loss of sensitive species like brook trout, and an increase in tolerant or invasive species, such as common carp.

EPA has recently released a new (in 2016) practitioner's guide to the BCG: https://www.epa.gov/wqc/practitioners-guide-biological-condition-gradient-framework-describe-incremental-change-aquatic, which is a useful resource for understanding how the measure can be developed for new study regions.

2) Biological Condition Gradient datasets compiled for entire study region (together with landscape, habitat and water chemistry data).

Once we had defined the BCG as our measure of ecosystem integrity, our next step was to assemble a BCG dataset for our study region. Minnesota was one of the first states to develop a BCG for streams and rivers, and originally we had planned to focus primarily on a Minnesota dataset for our analysis relating water quality drivers to biological condition. In the past year or so, however, several other states in the Upper Midwest have developed BCGs for their stream and rivers. Thus, upon initiation of our project we realized that we had a unique opportunity to compile a much larger dataset that would be useful more broadly to scientists and managers throughout our study region (Figure 24). Assembling this dataset involved making contact with relevant state agency partners and environmental consulting firms in Iowa, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, Virginia and West Virginia. Thus, data assembly took longer than we had

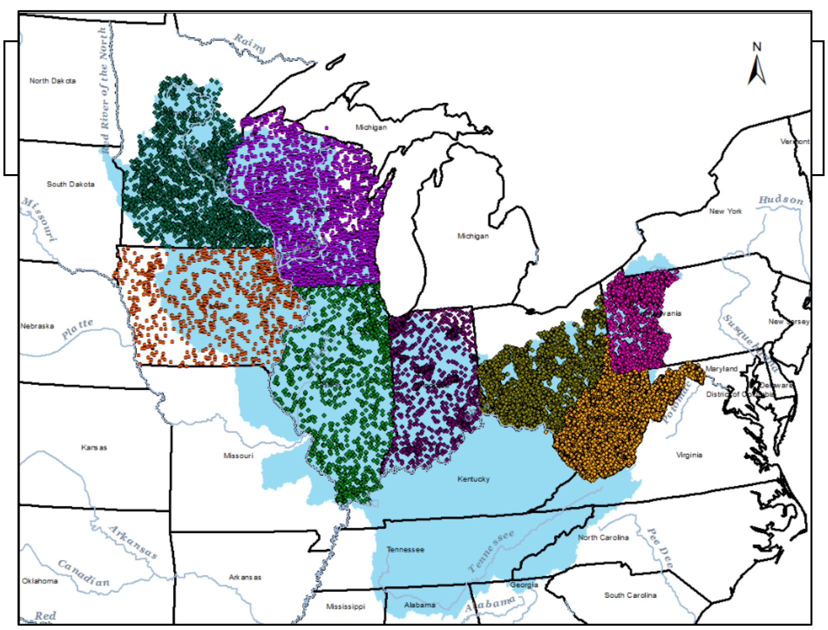


Figure 24. Locations of study sites for which biological integrity data has been compiled across the Upper Mississippi and Ohio-Tennessee River Basins (shown in light blue).

initially expected; however, we believe the development of this cross-boundary dataset will be invaluable not just to our project, but to related efforts going forward.

The assembled dataset consists of raw taxonomic data (for fish and/or invertebrates), biological condition scores, plus habitat and landscape information for ~31,000 stream samples in the Upper Mississippi and Ohio-Tennessee River Basins.

3) Conveying ecosystem health to lay audiences

The development of visual aids and other materials that will be used to assist the lay public in understanding differences in biological condition are in progress. This work is a key component of the surveys under design by our economist collaborators. Before we can ask respondents about how much they value change in ecological condition, they first need a clear picture of the water quality changes they are being asked to evaluate.

Work accomplished under this objective included:

- Creating maps of BCG Levels in sub-regions where surveys will be applied (see Twin Cities metro area example – Figure 25).

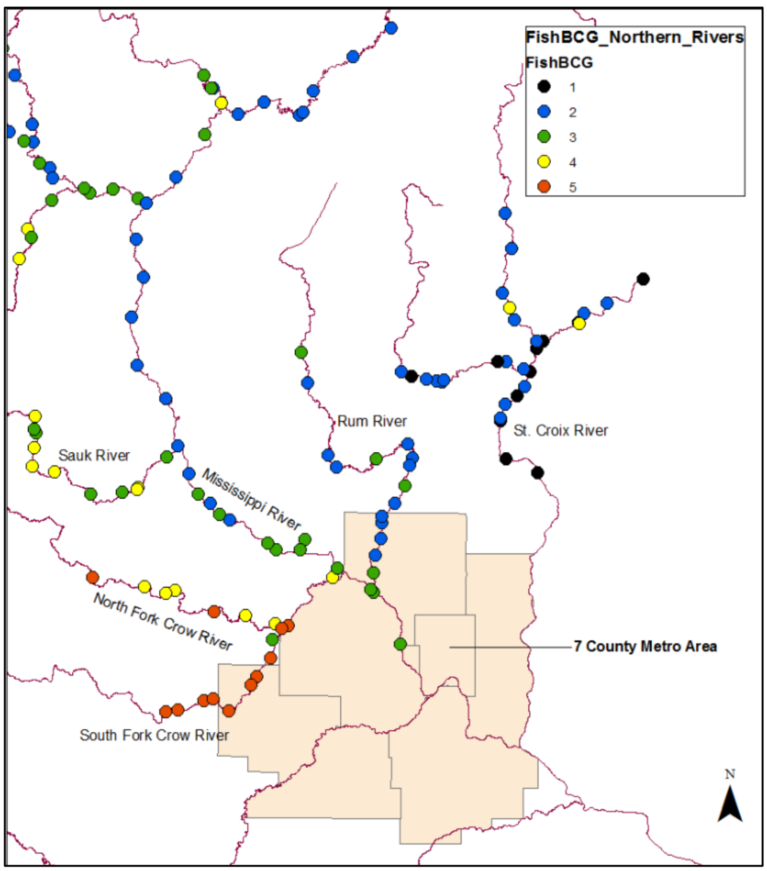


Figure 25. BCG Levels for Northern Rivers, draining to the Twin Cities Metro Area (note: there are no Northern Rivers rated as level 6 in Minnesota).

- Visualizing example sites in each BCG level for a region (see example for Minnesota streams -- Figure 26);

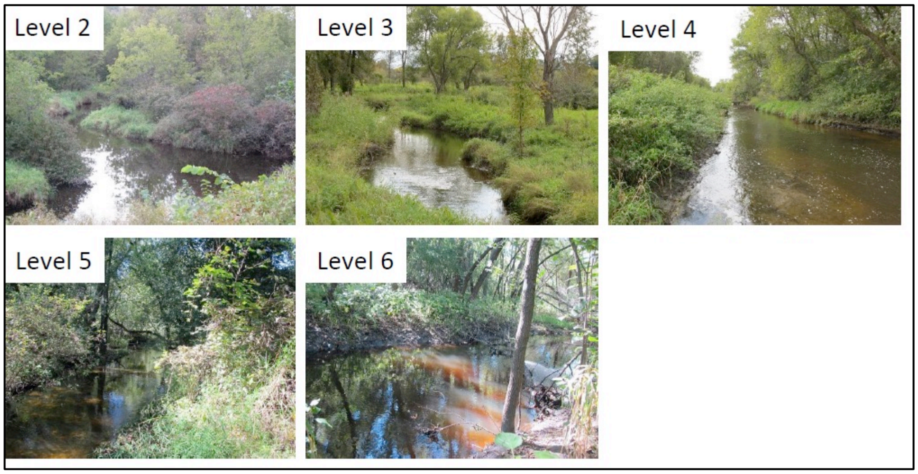


Figure 26. Examples of Minnesota streams at different BCG levels. No Level 1 sites are pictured.

- Summarizing riparian habitat, instream habitat, and water clarity info for sites in each BCG level;
- Identifying potential language describing taxonomic changes at each BCG level for a lay audience (Table 2).

Table 2. Potential language describing characteristics of biological communities at each BCG Level.

BCG Level	Descriptive language
1	Near pristine, historical, pre-European settlement
2	Earliest changes, slight elevation in stress (increased temps or nutrients), slight increases in populations of some tolerant taxa
3	Detectable decreases in species that are sensitive to pollution (e.g., most stoneflies, brook trout) and increases in opportunist, intermediate tolerant species (e.g., filter-feeding caddisflies, many midges, many minnow species)
4	Substantial reduction of sensitive groups (e.g., most stoneflies, brook trout, brook lamprey, many mayflies, many darter fish species), replacement by more tolerant species (filter-feeding caddisflies, many midges, many minnow species, tubificid worms, black bullhead). Sensitive species are reduce but still maintain viable populations. Many states put their aquatic life use attainment goal here.
5	Individual animals show signs of physical stress (increased mortality, less reproductive success, increased tumors and deformities on the body); Often top predators are almost gone; tolerant non-native taxa may dominate (e.g., common carp); most sensitive species are gone.
6	Severe degradation, low diversity, small number of species may dominate (be extremely abundant).

4) Models to link ecosystem condition to biophysical stressors (nitrogen, phosphorus, sediment) completed

During the WSC REACH project, our research group has successfully developed models linking water quality drivers (i.e., land cover and land use) to water quality pollutants (i.e., nitrate). These models are being used to inform our effort to optimize conservation management practices on the landscape to maximize improvements in water quality in the Minnesota River Basin. For example, we used extensive field observations collected over a range of streamflow conditions, together with land use data for the Minnesota River Basin, to evaluate the

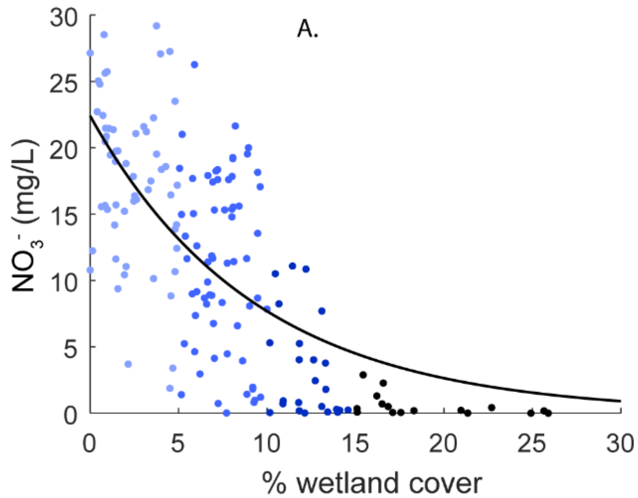


Figure 27. Effect of wetland cover on in-stream nitrate concentration, for sites in the Minnesota River Basin.

effectiveness of wetlands in reducing agricultural nitrogen (*Hansen et al*., in prep). In a comparative analyses of common management strategies for nitrate reduction, wetland restoration on agricultural land was found to be five times more effective at reducing nitrate concentrations than other strategies. Our analysis quantifies the critical role wetlands can play in strategically balancing agricultural production while meeting water quality goals in intensively managed landscapes.

Finally, we have completed preliminary analysis, using available water chemistry datasets together with BCG scores, to establish thresholds in nitrogen, phosphorus and sediment that are associated with each BCG level. Expanding this analysis to our larger dataset (across the Upper Midwest) with a more extensive water chemistry dataset will be a major focus of our continuing work funded under the EPA project.

4.3. Evaluation of trade-offs associated with wetland interventions

B. Keeler, P. Hawthorne, S. Polasky, E. Foufoula-Georgiou, P. Belmont, A. Hansen, and J. Czuba

Our WSC-REACH project, focused in the Minnesota River Basin, has made breakthrough discoveries in monitoring and modeling the effects of climate and land-use change on the water cycle, river channel and floodplain dynamics, water quality, and aquatic life. It also has exposed our fundamental knowledge gaps on how the interconnected system of Food-Energy-Water (FEW) works and the need for such an understanding to drive sustainable environmental and economic outcomes. *This research is part of a supplement to our project that aspires to lay the foundation in advancing a FEW systems-level thinking for agricultural landscapes by focusing on identifying and quantifying the challenging links between policy, markets, climate drivers, land and water management actions, and the cascade of environmental implications*. We aim to achieve two goals: (1) assess the benefits and costs of alternative futures for the MRB, including impacts to ecosystem services across spatial and temporal scales and (2) incorporate these impacts into a generalizable framework that links policy, markets, and climate drivers, to land and water management actions, to the nonlinear cascade of environmental implications, to a socio-economic valuation of changes in ecosystems, back to potential policies, payments or incentive schemes needed to shift underlying drivers of behavior and resilience of the FEW system (Figure 28).

The economic benefits of sediment reduction and other wetland services are poorly quantified. In general, there is a lack of guidance in the ecosystem services literature on how to do sediment valuation well. Most researchers rely on benefits transfer or willingness to pay studies to estimate sediment value. *We are initiating a full cost accounting of sediment costs and benefits*. Our work will focus on the MRB, but include a broader review and interpretation of sediment-related costs. We will review the literature on sediment value and costs, interview experts in the MRB and elsewhere about the biophysical and economic assumptions needed to estimate costs, and propose a comprehensive framework for the accounting of sediment value. The outcome of this work will be a “go-to” reference for sediment valuation that updates and expands the scope of previous literature. Our focus will not be on generating sediment values specific to the MRB, but rather producing a synthetic and comprehensive reference that will make a useful and needed contribution to the ecosystem services literature.

The second part of this effort will result in a visualization of trade-offs. Models developed by the REACH team can evaluate how wetland interventions will affect a variety of objectives of interest to stakeholders such as nitrate removal, sediment, DOC, mussels, peak flow, etc. How do these various objectives trade off? How much of one objective do you have to give up to get more of another objective? For example, if you prioritize wetlands for denitrification how much sediment retention (via high flow reduction) do you lose? What are the opportunities for win-wins and where are there tradeoffs? How do we prioritize wetlands that maximize benefits at minimal costs? How can we engage stakeholders in prioritizing some objectives over others and expressing values or weights? What does an optimal scenario of wetland restoration for multiple objectives look like? We are leveraging methods already developed in our group on visualizing tradeoffs to multiple objectives and developing optimized portfolios of restoration interventions. We will apply this optimization approach to the outputs of REACH models to generate efficiency frontiers that visualize how different objectives (water quality, carbon, habitat, peak flow, etc) tradeoff with each other. These frontiers can be useful in assigning weights to different objectives and then generating "optimal" landscapes that maximize objectives given user-defined constraints (budget, area, etc). The outcome of this work will be efficiency frontiers and optimized wetland intervention portfolios (aggregated by subwatershed, HUC, or other unit of interest). These biophysical results can be combined with cost data and agricultural production value to assess how different scenarios affect the distribution of private vs. public benefits.

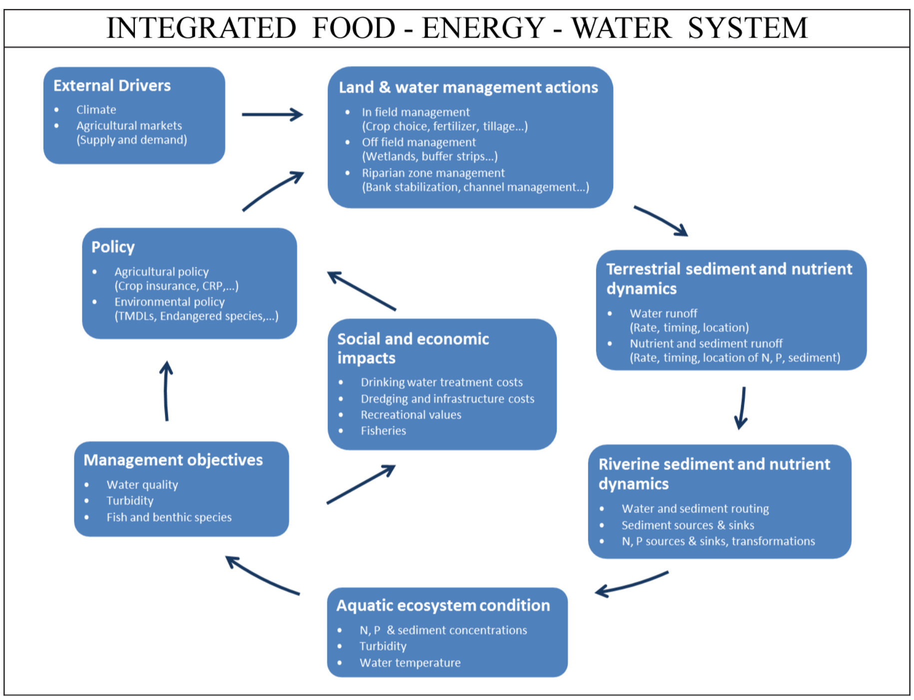


Figure 28. Our framework for studying the integrated FEW system of agricultural landscapes.

Supplement

The supplement aims to leverage the biophysical modeling and empirical data collected as part of the WSC grant to account the impact of potential actions on multiple ecosystem services (ES). The integrative work requires two steps: 1) identifying a set of ecosystem services and defining ecological production functions that regulate their supply, 2) developing valuation functions at the landscape scale that account for social and economic demand for each service. This integrated approach will allow us to evaluate any portfolio of actions that affects biophysical supply of ecosystem services and the associated social-based valuation.

We have identified and developed ecosystem service models for water quality and quantity, recreation (boating, fishing and swimming), and infrastructure. Several of these are adaptations of existing models (N and P functions), while the sediment functions have been developed explicitly for this project. These functions translate the biophysical outputs from the hydrological models to impacts on ecosystem services. In order to limit the number of objectives that the genetic algorithm needs to deal with, they have been combined into two ES indices, a health-related index, and a recreation index.

Once the valuation functions are complete, we will integrate them into the genetic algorithm decision optimization process. To that end, in addition to developing and testing the ecosystem service models, we are also developing an integrated software implementation to contribute to the multi-objective optimization. This translation will consist of wrappers to call our Python ES functions from C++, or re-implementations of our functions in C++ for increased performance and interoperability with the GA.

4.4. Spatial optimization of wetland restoration using spatial ownership constraints and a real options analysis for LeSueur River Watershed

S. Rabotyagov and others (University of Washington)

The Le Sueur Watershed in South Minnesota is one of the 12 major watersheds in the Minnesota River Basin. It is the heaviest contributor of sediment for Minnesota River, delivering as much as 30% of the Minnesota River's annual sediment load, although it drains only 6% of the basin area. For the purpose of reducing peak flows and sediment loading rates for MRB, Mitchell (2015) has shown that restored wetlands can be effective. The study showed that wetland restoration can reduce peak flows and sediment loading rates in the Le Sueur watershed and also found the effects vary significantly between different spatial scenarios. These various effects potentially indicate an opportunity for cost-effectiveness analysis and spatial optimization. The key three components of this work are (1) Sediment coefficient estimation, where a meta-modeling approach was used to develop simplified relationships between wetland placement scenarios and sediment loading rates; (2) Economic costs estimation, where we develop a wetland restoration cost model based on published USDA-ERS research by augmenting it with a real options analysis to estimate critical land payment. Critical payments represent the minimal easement payment at which signing contract for wetland restoration is preferred to agricultural cultivation by the farmers facing uncertainty; and (3) Spatial optimization model, in which we take into account the ownership structure in the watershed which induces interdependence in wetland restoration decisions. Specifically, we create restoration clusters by grouping the potential restoration sites belonging to the same landowners, and then build the spatial optimization model which reduces overall costs by selecting wetland candidate sites owned by the same landowner in order to reduce transactions costs. Results indicate that introducing uncertainty into the model of farmer decision-making has the predicted effect of increasing the likely minimum costs of conservation, and that recognizing spatial interdependence induced by land ownership pattern results in a different spatial pattern of optimal wetland restoration, as compared with results from optimization without considering land ownership and transactions costs.

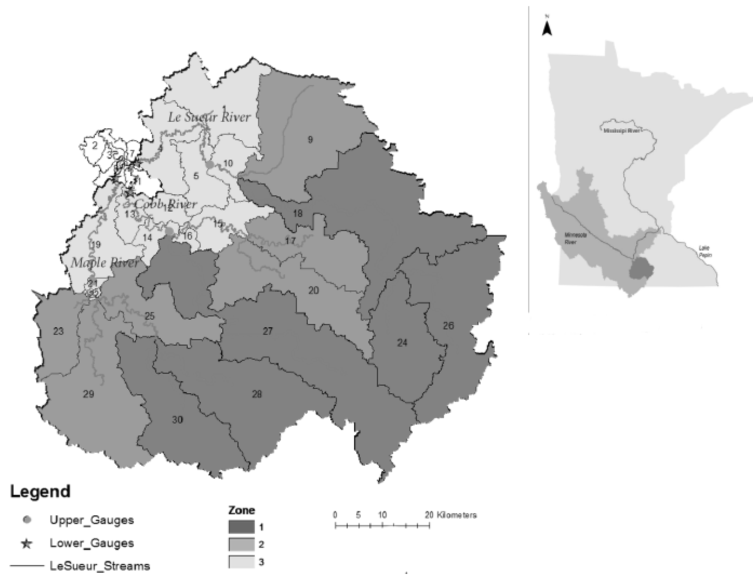


Figure 29. WRS Placement Zones in the Le Sueur River Watershed.

4.5. Including additional ecosystem services in models of cost-efficient water quality improvements
S. Rabotyagov and others (University of Washington)

Wetlands provide a number of important ecosystem services that are sometimes difficult to quantify. The goal of this project is to analyze the ecosystem services that wetlands will provide under different levels of restoration in the Le Sueur Watershed in South Minnesota. To achieve this goal we built a mixed integer mathematical program that integrates management and environmental goals. The results obtained from this experiment allow the assessment of tradeoffs among the objectives. These data will also be used in the analysis of the solutions' robustness. Wetland ecosystems are key elements in water quality and quantity control. Many wetlands have been drained and converted into agricultural fields, and so these ecosystem services are no longer provided. Water quality and quantity issues caused by land conversion to agriculture are acute in Le Sueur Watershed in South Minnesota and are of concern to the stakeholders. Previous research (*Mitchell*, 2015) has shown that wetland restoration will increase water storage and decrease sediment loading rates in the lake, where the watershed drains. We build an optimization model that incorporates the ecological objectives to analyze potential changes in the ecosystem services in the watershed.

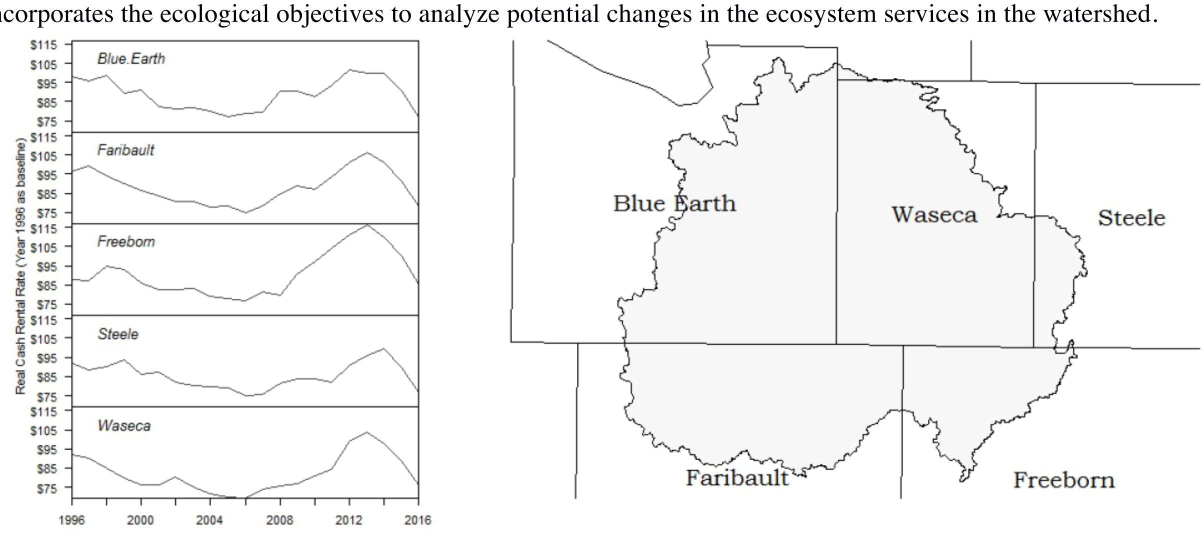


Figure 30. Cash rental rates, dollars per acre (1996-2016, adjusted for inflation)

The model includes the following objectives:

Sediment loading. We obtained the sediment loading rates for each potential restoration site in the area. The rates show the *reduction* in sediment load under different restoration scenarios compared to the current level. There are eight unique restoration scenarios that differ in depth and hydraulic conductivity. We calculate the total reduction in the watershed as a result of restoration efforts. An important feature of the model is that we include all restoration scenarios simultaneously. Thus, the model defines which scenario is the most beneficial for each potential restoration site.

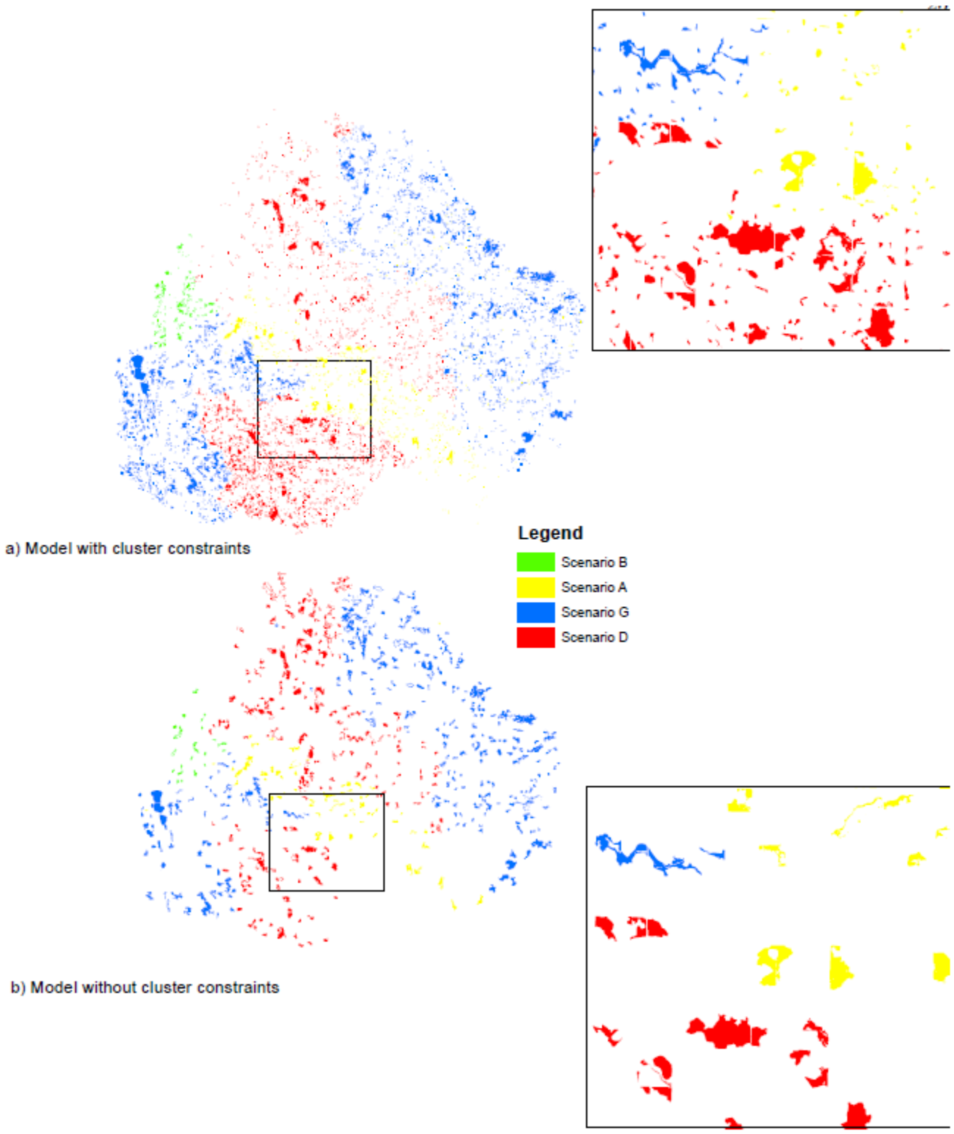


Figure 31. Examples of the spatial distribution of the restored WRS.

Waterfowl habitat. Wetlands are an important habitat for duck species, and the decrease in wetlands has caused a decrease in their populations. Restoration of the wetlands will positively affect the species; therefore, we include the area restored as an objective. We calculate the total area restored and maximize it. We will estimate the number of hatchlings new wetlands can produce using the model's output and the area specific model from *Hansen et al*. (2015). We also consulted wildlife scientists regarding the parameters that the model should account for and potential challenges using the specified model.

Costs of the wetland restoration. Costs are associated with the restoration of each potential site. The cost is two-fold. The direct cost reflects the restoration expenses, while the transaction cost is included to reflect the negotiation with the landowner regarding giving up part of the property for the wetlands. The transaction cost is incurred once for each landowner but not for each potential site.

The decision variables of our mixed integer objective model are binary. They represent the decisions on whether the potential site is chosen for restoration under one of the eight scenarios or not. The solutions of the model are spatially explicit management plans. The next step in this project is the analysis of the solution's robustness. We understand that there is uncertainty associated with the coefficients used in the model. Our goal is to analyze whether the solutions stay Pareto optimal if the coefficients change. We will use the range of the possible values in the analysis. We will adopt the method used in *Hadka et al*. (2015) for the robustness analysis.

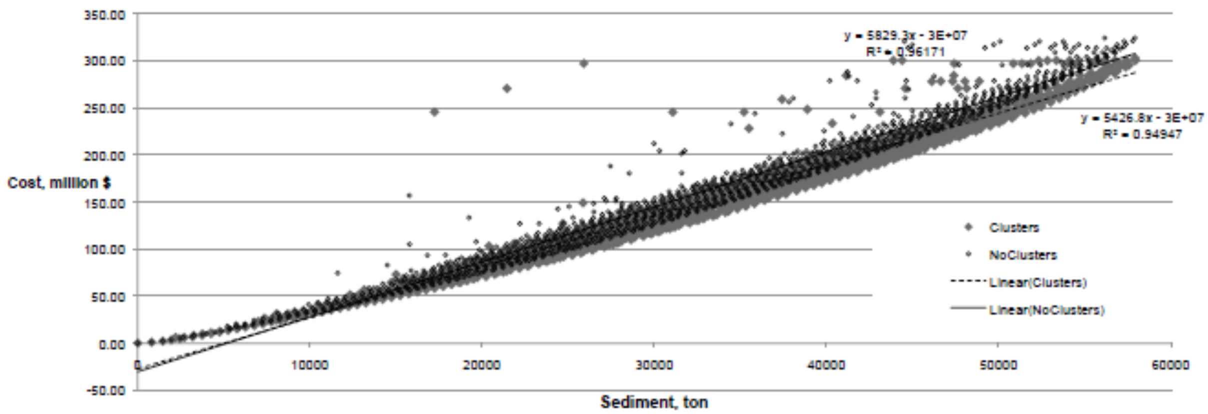


Figure 32. Tradeoffs between total cost of restoration and sediment reduction.

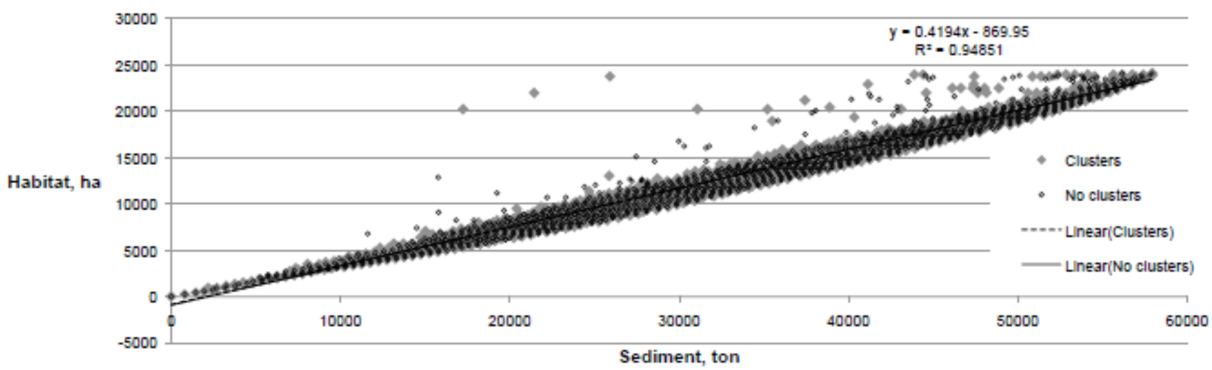
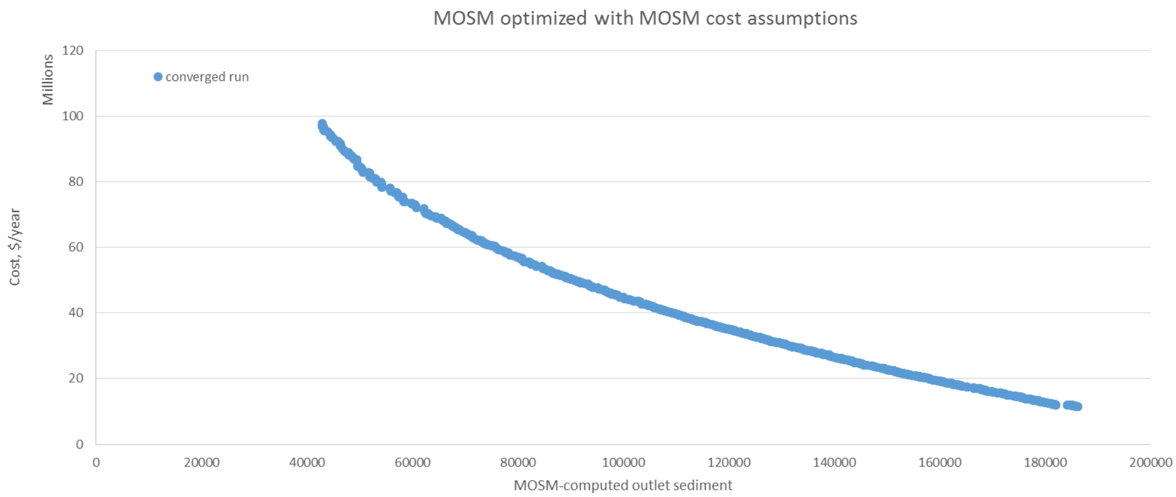


Figure 33. Synergy between sediment reduction and habitat protection.

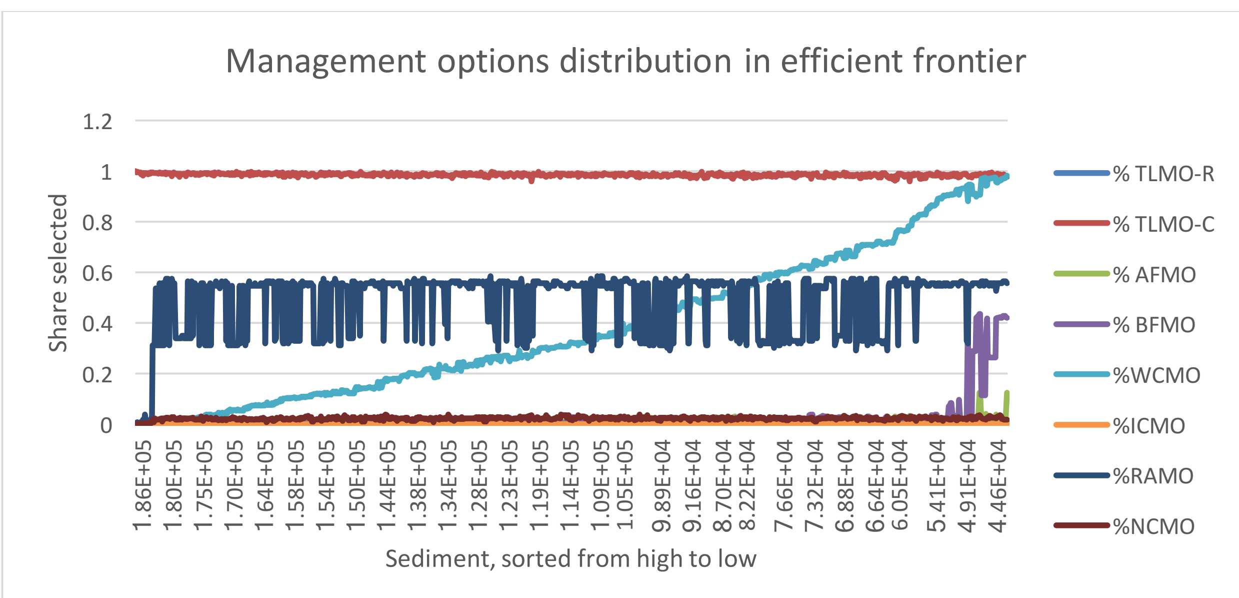
4.6. Integrating the Management Options Simulation Model (MOSM) into optimization and tradeoff analysis

S. Rabotyagov, Se Jong Cho, P. Wilcock, others

The MOSM model includes additional management options in addition to wetland restoration, including riparian buffers, grassed waterways, reduced and conservation tillage, and in- and near-channel management options. Several of those options involve retiring land from agricultural production and they often cross land ownership boundaries. We incorporate the MOSM model structure into spatial optimization and utilize our land retirement cost estimates (real options model) as well as the spatial landownership information into the evolutionary optimization algorithm. As a result, we not only can characterize the nature of tradeoffs between sediment and cost of management options, but explore the mix of management options selected under a range of different sediment reduction targets.



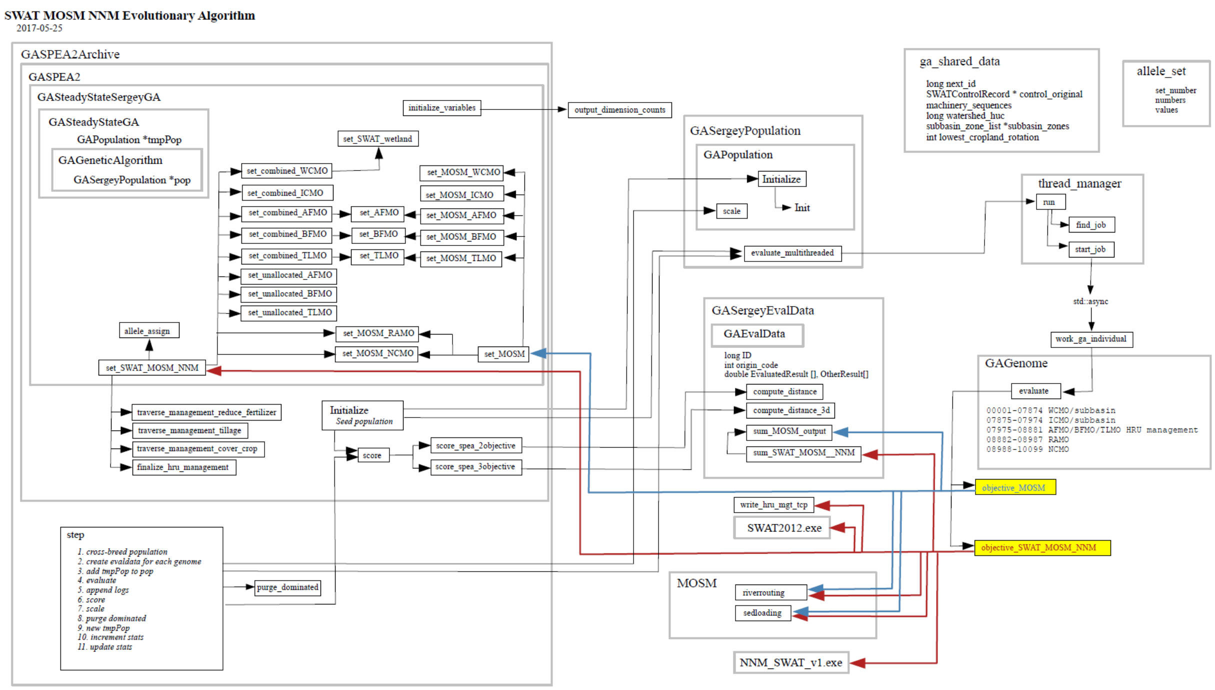
Results indicate that under the assumption of very low cost of conservation tillage (baseline scenario in the MOSM model), tillage management options are selected by the algorithm (TLMO). Ravine stabilization efforts (RAMO) are used extensively throughout the range of sediment reduction targets. However, the main result is that once meaningful sediment reduction goals are being modeled, wetland restoration (WCMO) becomes the dominant cost-effective means of attaining those targets, with the share of available restoration sites rising almost in a linear proportion to the sediment reduction goals. Further, riparian buffers do not enter the optimal solution until the algorithm explores solutions capable of attaining very large (and very costly) sediment reduction levels.



4.7. Integrated LeSueur modeling

S. Rabotyagov and others

As a part of the 2016 PI meeting, a consensus emerged that multiple models need to be brought together in a tightly coupled fashion in order to a) assess model performance and b) increase confidence in the relevance of modeling and optimization results in terms of their ability to represent the main features of the studied system. In addition, the structure of the model inputs and outputs affords the integration across different disciplines and investigator groups. The effort is ongoing, but major components of model integration have been completed. The integrated model brings together the following main components: 1) SWAT model of LeSueur watershed; 2) the MOSM model; 3) the Nitrate Network Model (NNM); 4) real options cost model; 5) spatial landownership cluster model; and 6) the evolutionary algorithm optimization and tradeoff analysis framework.



5. Engaging and educating the public

5.1. Socio-scientific issues

G. Roehrig, E. Karahan, S. Andzenge, and N. Ghalichi

Our curriculum development and associated research has focused on socio-scientific issues (SSIs) to promote teaching and learning of environmental science in the context of the Minnesota River Basin. One of the essential outcomes of K-12 science education is to enable students to use their understanding of science to contribute to public debate and make informed decisions about SSIs that impact their lives. Students need to be able to assess the risks and benefits of alternative solutions, pose questions, and evaluate the integrity of evidence and counter evidence in order to make well-informed decisions. Science is a discipline that relies on empirical evidence and formal reasoning that depends on logical and mathematical concepts and the processes of induction or deduction. However, SSIs are interpreted in a creative fashion and variations in scientific reasoning are not fully able to explain conclusions reached because the explanation lies in a reality, which is much less objective. Moreover, the decision-making processes in SSIs are different and more complicated from those involved in reaching conclusions regarding purely scientific questions.

Research in SSI-based interventions is relatively new, and there is a need for understanding more about the effects of SSI-based learning environments. Despite the growing body of literature in SSI, only a few researchers have gathered empirical data on the effects of SSI-based learning environments. In response to this need, we have developed SSI-based curriculum in collaboration with local environmental science teachers and our research has explored how students respond to teachers' practices of teaching SSI. Our results working in four different high school environmental science classrooms show that in order to actively participate in an SSI-based investigation and decision-making processes, students needed to utilize multiple reasoning modes and interdisciplinary thinking (*Karahan and Roehrig*, 2016a). Students, who were exposed to more traditional data-driven SSI instruction, mostly reasoned scientifically about the sediment load issues in the Minnesota River. In contrast, students who experienced SSI instruction with the inclusion of social domains, such as ethics and economics, and student-driven community involvement projects showed multiple reasoning modes, including scientific, social-economic, ethical, and ecological reasoning modes, in their decision-making about the sediment load issue in the river. Comprehensive, semester-long SSI content integration that incorporates social and ethical domains resulted in higher-level socio-scientific reasoning for students which is critical when considering the need to increase scientific literacy and public engagement in scientific issues such as sediment load (*Karahan, Andzenge, and Roehrig*, 2016).

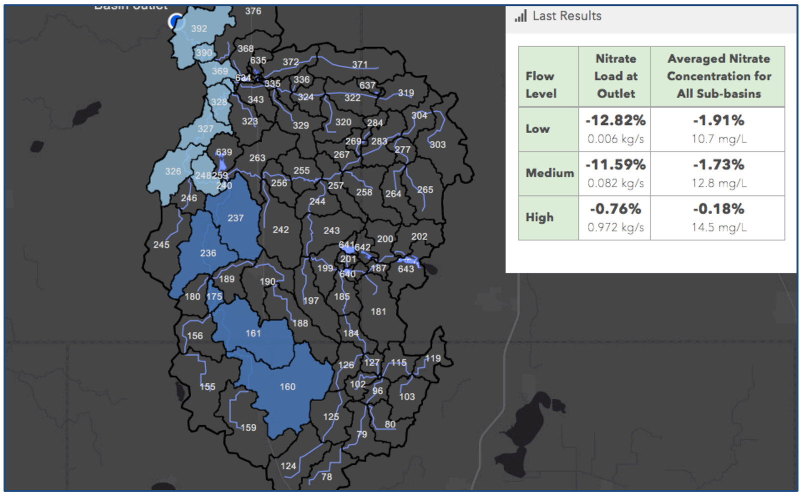
Associated research has explored how a SSI-based environmental science class can be structured for promoting the agency of the students (*Karahan and Roehrig*, 2016b). Agency is defined as purposeful actions taken by a student in their own interest or capacity to make choices and act on these choices in a way that makes a difference. Our goal here was to empower students to act on their learning around issues within the Minnesota River Basin. Teachers who used the multifaceted and interdisciplinary nature of a SSI were able to empower their students to select and act on environmental issues based on their personal interests. As a result, the students were more motivated and encouraged to make differences in the society they lived in by using the community-based projects for improving the quality of the environment surrounding them.

The current phase of our work is focused on teachers' classroom practices that promote students' development of socio-scientific reasoning. The co-teaching case of a science and social science teacher shows the benefits of bringing different epistemological perspectives into the classroom (*Karahan and Roehrig*, 2017). An exploration across all four teacher cases shows the pedagogical strategies that support students' learning, as well as particular curricular activities and structures (*Karahan and Roehrig*, in review).

5.2. Curriculum development and classroom implementation

G. Roehrig, S. Andzenge, N. Ghalichi, A. Hansen, and J. Czuba

On-going work is exploring the development of an interactive, online computer-simulation tool that allows students to explore the impact of land-management practices on nitrate levels.



The figure above is a screen shot from the simulation that allows students to explore the mitigation of farm lands to wetland on nitrate loads. A full high school curriculum unit centered on this simulation has been developed and piloted in one of our partner teacher's classrooms. Preliminary curriculum results have been presented (*Ghalichi & Roehrig*, 2017a and b). Full results are forthcoming in Narmin Ghalichi's dissertation (projected December 2017).

5.3. Development of a consensus strategy for sediment reduction through stakeholder-driven model development and scenario investigations

S.J. Cho, K. Gran, M. Bevis, and N. Mitchell (with collaborators REACH PI: P. Wilcock (Utah State University), REACH PI: P. Belmont (Utah State University), B. Hobbs (Johns Hopkins University))

The Greater Blue Earth River Basin (GBERB), encompassing the Blue Earth, Le Sueur, and Watonwan Rivers, is a major source of fine sediment loading to the mainstem Minnesota River. For the past five years, we have been involved in an effort to develop a consensus strategy for managing the GBERB to reduce fine sediment loading. The GBERB is geomorphically-primed to produce high sediment loads (*Belmont et al*., 2011), but sediment loading has increased by a factor of 4.5 following Western settlement and land clearing for agriculture (*Gran et al*., 2013). Sediment loading is driven by a combination of land cover changes as well as hydrologic changes within the watershed, and management strategies must include a range of approaches from tillage management to bluff stabilization to hydrology management. This project was funded primarily through a series of grants from Minnesota state agencies and agricultural research groups, but the REACH project has benefited from the science undertaken through CSSR (Collaborative for Sediment Source Reduction), and there has been significant synergy between the two projects.

Over the past five years, we have met with a group of stakeholders covering a range of interests including local, state, and federal agency staff; producers and agricultural interest groups; and academics. With their input, we developed a reduced complexity hydrologic model for the GBERB that simulates water and sediment movement throughout the watershed and allows for investigation of different management actions to reduce sediment loading directly or indirectly (through hydrology management). This model is known as the Management Option Simulation Model (MOSM).

By working with the model and investigating various scenarios, the stakeholder group was able to reach a consensus at the final meeting on March 7, 2017, regarding an approach to sediment management that included three main points: 1) Ravines that are large local sources of sediment can be targeted. Investment in stabilizing these ravines is worthwhile, but not sufficient to reduce sediment loading to meet water quality standards. 2) Eroding bluffs that threaten infrastructure and produce exceptionally large amounts of sediment can be targeted. Investment in stabilizing these bluffs is worthwhile, but bluff stabilization is not the most effective solution for long-term reduction in sediment loading across the watershed. 3) Achieving water quality standards will require priority investment in more temporary water storage to reduce high river flows and bluff erosion. This is a critical component of a strategy to reduce sediment in the Minnesota River. A short consensus document was produced that is now being circulated among local, state, and federal agency staff and agricultural interest groups. In addition, we have two papers in preparation focusing on 1) the Topofilter algorithm used to evaluate spatially-distributed sediment delivery ratios across the watershed, linking small-scale erosional processes to watershed-scale observations of landform development and sediment transport (*Cho et al.,* in prep. a), and 2) how a purpose-built watershed simulation model is developed through a stakeholder meeting process in order to reach a consensus on mitigation plans to address agricultural nonpoint source sediment pollution (*Cho et al*., in prep. b). The MOSM model and user manual will be archived at the University of Minnesota Digital Conservancy following final edits.

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