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

REACH (REsilience under Accelerated CHange)

Final Progress Report for 2017–2018

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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) was 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 we tested was 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 were developed to identify "hot spots" of sensitivity to change and inform mitigation activities. The developed framework was 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. Weekly meetings were held across collaborating institutions and disciplines to advance completion of a biophysical modeling framework that captures the cascade of water quality changes arising from interactions between geologic history, human land use, and climate change, and mediated by biological, chemical and physical processes.
2. 36 presentations were given this past year at local, regional, national, and international conferences including: annual meetings of the Society for Freshwater Science, Minnesota Water Resources Science Conference, American Society of Civil Engineers (ASCE) World

Environmental and Water Resources Congress, National Association for Research in Science Teaching, Geological Society of America, American Geophysical Union, and European Geosciences Union.

3. REACH collaborators organized a forthcoming special issue of the journal Water Resources Research entitled, *Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology,* as a venue for culminating REACH project findings as well as related contributions from the global research community.

(2) 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. A number of stakeholder meetings in the past year have centered around REACH findings related to watershed scale impacts of wetlands, an issue of great interest to stakeholders across the region, and have included presentations and small group discussions with groups of wetlands experts from Minnesota Department of Natural Resources, Minnesota Pollution Control Agency, U.S. Fish and Wildlife Service, and U.S. Army Corps of Engineers, University of Minnesota – Duluth, St. Mary's University, and St. Croix Research Station. Amy Hansen (University of Minnesota) also conducted interviews with local, state and national media, related to recent published findings regarding the watershed scale impacts of wetlands on nitrate. We are also continuing to engage with stakeholders including The Nature Conservancy, Minnesota Pollution Control Agency, Board of Soil and Water Resources, the Corn Growers Association and the Minnesota Drainage Working group around concurrent efforts to plan restoration efforts in the Minnesota River Basin and beyond using the integrated modelling tools we have developed over the past year in REACH. Through a cooperative partnership with a concurrent funded project through the Environmental Protection Agency (*Valuing Water Quality Improvements in Midwestern Ecosystems: Spatial Variability, Validity and Extent of the Market for Total Value*), we have also convened focus groups on multiple college campuses to understand how our portrayal of stream and river services can affect how people value them. Findings from these focus groups are being used to design a much larger survey to quantify the economic value of total ecosystem benefits associated with water quality improvements.

1.2.2. Specific Objectives:

The project has four main objectives, on which significant progress has been made over the past 6 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 2017-2018, our research has been integrative along five major topical areas (*see attached pdf for a brief summary of these research topics*):

Convergent research:
Integrated watershed-scale modeling to address multiple objectives: Applying six years of interdisciplinary discovery to conservation decision making

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

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

1.1. Quantification of near-channel sediment supply across watersheds of the Minnesota River Basin

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

2.1. The influence of fertilizer, erosional hotspots and runoff on the form and transport of phosphorus in U.S. Midwestern rivers
2.2. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes
2.3. Incorporating new science into existing biophysical models

3. Biophysical interactions modify nutrient and phosphorus cycling in agricultural river networks

3.1. Characterizing phosphorus export across agricultural watersheds: biogeochemical processes and near channel sources modify hydrology driven export behavior
3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics

4. Optimizing conservation landscapes for multiple ecosystem services

4.1. Development of benefits transfer functions for additional ecosystem services: wildlife and pollinator conservation
4.2. Improving multi-objective spatial optimization results under epistasis with benefit to cost ratios
4.3. Tradeoffs in conservation modelling for diverse endpoints
4.4. Evaluating multiple policy mechanisms for cost effective agri-environment management schemes

5. Engaging and educating the public

5.1. Coherent systems learning using nitrogen and carbon cycling as subject matter

1.2.4. Key outcomes or other achievements:

The WSC REACH project has been in synergy with three other projects in the past year: the new Intensively Managed Landscapes Critical Zone Observatory (IML-CZO), the Collaborative for Sediment Source Reduction (CSSR) and a US EPA-funded interdisciplinary project aimed at valuing water quality improvements across the Upper Mississippi River Basin.

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) 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 are collaborating directly 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.

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

This project represents an outgrowth of the REACH, and is an U.S. EPA-funded collaboration with Cathy Kling (Cornell University), Iowa State University (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 interdisciplinary collaboration seeks 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.

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 and professional development for 4 research associates, 2 post-docs, 2 graduate students, and 3 undergraduate students at the University of Minnesota Twin Cities and Duluth campuses. Research associates have been empowered and supported by PIs to take on leadership roles in facilitating cross project interdisciplinary collaboration. Graduate students and 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.

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 centered around conservation and restoration planning; through the IML-CZO outreach efforts; and through interviews with local, state and national media.

Supporting Files

<u>PRODUCTS</u> – What has the project produced?

Books:

Book Chapters:

Peer-Reviewed Journal Articles:

*indicates published or in preparation in 2017-2018

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Dolph, C.L., Hansen. A.T., Rabotyagov, S., Foufoula-Georgiou, E., Belmont, P., Wilcock, P., Kling, C., Finlay, J., Gran, K., Dalzell, B., Cho, S.J., Campbell, T., Gassman, P., Czuba, J., Braudrick, C., Hawthorne, P., Lonsdorf, E., Thompson, K., Keeler, B., Baker, A., 2017. Resilience Under Accelerated Change (REACH): Modelling tradeoffs in water quality, ecosystem services and conservation in the Minnesota River Basin. October 18, 2017. Minnesota Water Resources Conference, St. Paul, Minnesota.

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Papalexiou, S.M., AghaKouchak, A., Trenberth, K.E., and Foufoula-Georgiou, E., 2018. Global, Regional, and Megacity Trends in the Highest Temperature of the Year, EGU2018-11975, EGU General Assembly, Vienna, Austria.

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Wilcock, P., Cho, S.J., Gran, K., Belmont, P., Hobbs, B.F., Heitkamp, B., Marr, J.D.G., 2017. Mud, Models, and managers: Reaching a consensus on a watershed strategy for sediment load reduction. AGU National meeting: December 15, 2017, New Orleans, LA.

Wu, Z., Furbish, D.J., and Foufoula-Georgiou, E., 2017. Two-regime distance-time scaling of bedload hops unifies disparate particle velocity distributions, EP41A-1813, AGU Fall Meeting, New Orleans.

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://mnriverrun.blogspot.com/). 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.

We are currently creating a digital space for student-created digital media (videos, projects, etc.) and curriculum, 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.

(2) The Intensively Managed Landscapes Critical Zone Observatory website highlights recent news, events and publications related research in the CZOs (including the Minnesota River Basin) and is available at http://criticalzone.org/iml/

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:

REACH collaborators have produced several original published field datasets, which are summarized in Gran et al., in prep (to be published in forthcoming special issue of Water Resources Research), and which are free and available to the public:

- **Characterization of streams and rivers in the Minnesota River Basin Critical Observatory: water chemistry and biological field collections, 2013-2016** (http://doi.org/10.1007/s10750-016-2911-7) - This dataset contains point locations, watershed areas and water quality information for 231 ditch, stream, river and wetland sites located in the Le Sueur River, Chippewa River, Cottonwood River, Cannon River, Wantonwan River and Blue Earth River basins of Minnesota (Dolph et al., 2017)
- Additional datasets including 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 is in preparation and will be published in summer of 2018.

Several modelling and educational tools (also summarized in Gran et al., in prep) have also been published and made publicly available:

- **Management Option Simulation Model (MOSM)** (http://hdl.handle.net/11299/191082) - simulates movement of water and sediment across a watershed and evaluates the effects of various management option scenarios on sediment loading (Cho et al., 2017).
- **RiverMUSE** (https://csdms.colorado.edu/wiki/Model:RiverMUSE) - Process-based model predicting mussel abundance described by Hansen et al., 2016a.
- **Sediment Routing model** (https://csdms.colorado.edu/wiki/Model:River_Network_Bed-Material_Sediment) - allows the user to analyze bed-material sediment dynamics in river networks under varying levels of complexity depending on the availability/knowledge of input data. These codes allow the user to reproduce the results from Czuba and Foufoula-Georgiou (2014, 2015), Czuba et al. (2017), and Gran and Czuba (2017).
- **Network Nitrate Model (NNM)** (https://csdms.colorado.edu/wiki/Model:Nitrate_Network_Model) - quantifies nitrate-nitrogen

and organic carbon concentrations through a wetland-river network and estimates nitrate export from the watershed (Czuba et al., 2018).

- **Interactive, online computer simulation of the Network Nitrate Model (**http://maps.umn.edu/le-sueur-nitrates/) - The network nitrate model (Czuba et al., 2018) was developed into an interactive, online computer-simulation tool. This tool was used in high school environmental science classrooms in the Minnesota River Basin for students to explore the impact of land-management practices on nitrate concentrations and loads. The tool focuses on a subbasin of the Le Sueur Basin, in order to make the interactive experience manageable.

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)

Peter Hawthorne (Senior Scientist)

Eric Lonsdorf (Lead Scientist)

Brent Dalzell (research associate)

Amy Hansen (research associate)

Christine Dolph (research associate)

Se Jong Cho (post doc)

Anthony Longjas (post-doc)

Alejandro Tejedor (post-doc)

Zeinab Takbiri (graduate student)

Anna Baker (graduate student)

Ian Treat (graduate student)

Narmin Ghalichi (graduate student)

Tessa Belo (undergraduate student)

Walter Atkins (undergraduate student)

Lizbeth Aguiree-Jaimes (undergraduate student)

Olivia Cacciatore (undergraduate student)

2. What other organizations have been involved as partners?

Utah State University

Johns Hopkins University

University of Illinois Urbana-Champaign

Iowa State University

Center for Agricultural and Rural Development, Iowa State University

University of Washington

Virginia Tech University

Other collaborators and stakeholder groups:

United States Army Corps of Engineers

United States Fish and Wildlife Service

Minnesota Pollution Control Agency

Minnesota Department of Natural Resources

Minnesota Department of Agriculture

Board of Soil and Water Resources

Minnesota Drainage Working Group

St. Croix Watershed Research Station

The Nature Conservancy

Gustavus Adolphus College

St. Mary's University

Minnesota Agricultural Water Resource Center

University of Minnesota Extension Agency

Minnesota Corn Growers Association

Minnesota Soybean Growers Association

Blue Earth County

Greater Blue Earth River Basin Alliance

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?

Over the past six years, REACH collaborators have created an interdisciplinary body of work that has highlighted the importance of specific places, times and processes in determining how human and climate induced changes to intensively managed agricultural landscapes propagate through river networks to result in downstream water quality impacts (Belmont and Foufoula-Georgiou 2017; Kumar et al., 2018). These advances are summarized in over 60 publications and manuscripts (see Project Publications), including a forthcoming special issue in the journal Water Resources Research entitled *Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology*. They have entailed the compilation and leveraging of large, existing publicly available datasets (e.g., Cho et al., in prep; Dolph et al., in prep; Vaughan et al., 2017) and the generation of large, unprecedented original field datasets (e.g., Kelly and Belmont, 2018; Dolph et al., 2017; Gran et al., in prep). Many contributions have focused on developing reduced complexity modelling approaches to highlight key processes (e.g., Czuba et al.,2014; Hansen et al., 2016a; Cho et al., in prep) while also grappling with integration of new knowledge into existing mechanistic modelling frameworks like SWAT (e.g., Hansen et al., in prep). They have involved understanding tradeoffs in ecosystem services derived from agricultural landscapes (e.g., Rabotyagov et al., 2016). They have involved forging new paths with stakeholders to incorporate science into decision making (Belmont and Foufoula-Geourgiou, 2017; Wilcock et al., in prep), and developing new educational approaches (Karahan and Roehrig, 2017a; 2017b). Many of our findings point to the role of altered hydrological regimes in driving pollutant outcomes (e.g., Foufoula-Georgiou et al., 2015; Kelly et al., 2017; Cho et al., in prep), the importance of hydrology-driven transport of near channel sediment sources and associated nutrients (Kelly and Belmont, 2018; Cho et al., in prep; Baker et al., in prep), and the ways in which biogeochemical processes can alter pollutant export behavior (e.g., Hansen et al., 2018; Czuba et al., 2018; Dolph et al., in prep). Scientific advancements in these areas have continued in this last year of the project, and are described in the attached research summary.

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. Considerable time and effort was invested into reconciling conflicting disciplinary perspectives and working collectively towards a truly interdisciplinary collaboration in which researchers from different fields understood the objectives and critiques of those from other disciplines. This work was not always easy, but was ultimately fruitful. According to a state agency staff partner, the scientific advancements made by the REACH group have done more to 'change the game' around water quality management in Minnesota than any other scientific collaboration. The involvement of stakeholders and state-government agencies in our project is also a unique element that has allowed us to influence policy decisions even as the science continues to advance.

What is the impact on the development of human resources?

The project has funded 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. In the final year of the project, post docs and research associates have been empowered to lead and facilitate the development of cross-disciplinary integrated models, which has provided the opportunity to grow a new generation of leaders in interdisciplinary research.

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. 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.

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). The findings from our project leverage advances in this laboratory and vice versa, and benefit 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?

We have cooperated with The Community Surface Dynamics Modeling System (CSDMS) to disseminate REACH models to a diverse community of experts in earth surface processes. We have also collaborated with the University of Minnesota Digital Conservancy to provide permanent, searchable doi links to original REACH-sponsored datasets.

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 developed from our project are influencing 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)

Final (Year 6) Progress Report for 2017–2018

University of Minnesota

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

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 the final year of this project (2017-2018), we have continued to advance the science under these four objectives, while integrating our findings into a multi-objective, coupled biophysical-economic modelling framework that explicitly links an array of spatially-targeted conservation management decisions on the landscape to outcomes in water quality and ecosystem services. This modelling framework integrates new information -- developed under the auspices of REACH over the life of the project -- regarding linkages between multiple terrestrial and aquatic processes that affect pollutant loads and ecosystem services in intensively managed agricultural landscapes.

Convergent research:

Integrated watershed-scale modeling to address multiple objectives: Applying six years of interdisciplinary discovery to conservation decision making

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

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

1.1. Quantification of near-channel sediment supply across watersheds of the Minnesota River Basin

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

2.1. The influence of fertilizer, erosional hotspots and runoff on the form and transport of phosphorus in U.S. Midwestern rivers

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

2.3. Incorporating new science into existing biophysical models

3. Biophysical interactions and near channel sources modify nutrient and phosphorus cycling in agricultural river networks

3.1. Characterizing phosphorus export across agricultural watersheds: biogeochemical processes and near channel sources modify hydrology driven export behavior

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

4. Optimizing conservation landscapes for multiple ecosystem services

4.1. Development of benefits transfer functions for additional ecosystem services: wildlife and pollinator conservation

4.2. Improving multi-objective spatial optimization results under epistasis with benefit to cost ratios

4.3. Tradeoffs in conservation modelling for diverse endpoints

4.4. Evaluating multiple policy mechanisms for cost effective agri-environment management schemes

5. Engaging and educating the public

5.1. Coherent systems learning using nitrogen and carbon cycling as subject matter

INTEGRATED WATERSHED-SCALE MODELING TO ADDRESS MULTIPLE OBJECTIVES: Applying six years of interdisciplinary discovery to conservation decision making

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

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

Overview

Over the past six years, REACH collaborators have created an interdisciplinary body of work that has highlighted the importance of specific places, times and processes in determining how human and climate induced changes to intensively managed agricultural landscapes propagate through river networks to result in downstream water quality impacts (Belmont and Foufoula-Georgiou 2017; Kumar et al., 2018). These advances are summarized in over 60 publications and manuscripts (see Project Publications, below), including a forthcoming special issue in the journal Water Resources Research entitled *Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology*. They have entailed the compilation and leveraging of large, existing publicly available datasets (e.g., Cho et al., in prep; Dolph et al., in prep; Vaughan et al., 2017) and the generation of large, unprecedented original field datasets (e.g., Kelly and Belmont, 2018; Dolph et al., 2017; Gran et al., in prep). Many contributions have focused on developing reduced complexity modelling approaches to highlight key processes (e.g., Czuba et al.,2014; Hansen et al., 2016a; Cho et al., in prep) while also grappling with integration of new knowledge into existing mechanistic modelling frameworks like SWAT (e.g., Hansen et al., in prep). They have involved understanding tradeoffs in ecosystem services derived from agricultural landscapes (e.g., Rabotyagov et al., 2016). They have involved forging new paths with stakeholders to incorporate science into decision making (Belmont and Foufoula-Geourgiou, 2017; Wilcock et al., in prep), and developing new educational approaches (Karahan and Roehrig, 2017a; 2017b). Time and effort was invested into reconciling conflicting disciplinary perspectives and working collectively towards a truly interdisciplinary collaboration in which researchers from different fields understood the objectives and critiques of those from other disciplines. This work was not always easy, but was ultimately fruitful. According to a state agency staff partner, the scientific advancements made by the REACH group have done more to 'change the game' around water quality management in Minnesota than any other scientific collaboration. Many of our findings point to the role of altered hydrological regimes in driving pollutant outcomes (e.g., Foufoula-Georgiou et al., 2015; Kelly et al., 2017; Cho et al., in prep), the importance of hydrology-driven transport of near channel sediment sources and associated nutrients (Kelly and Belmont, 2018; Cho et al., in prep; Baker et al., in prep), and the ways in which biogeochemical processes can alter pollutant export behavior (e.g., Hansen et al., 2018; Czuba et al., 2018; Dolph et al., in prep). Scientific advancements in these areas have continued in this last year of the project, and are described in sections 1 through 5 below.

From an interdisciplinary perspective, our collective efforts over the past year were directed towards the completion of a biophysical modeling framework that captures the cascade of water quality changes arising from interactions between geologic history, human land use, and climate change, and mediated by biological, chemical and physical processes. This approach integrates a Soil and Water Assessment Tool (SWAT) model (Kumarasamy and Belmont, 2017) 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 (Nitrogen Network Model; NNM; Czuba et al., 2018). The latter two models capture dynamics in sediment and nutrient transport that are not well accounted for in existing biophysical modelling approaches. Independent parallel efforts to characterize phosphorus sources and transport (Boardman et al., in prep; Baker et al., in prep; Dolph et al., in prep) have also been integrated into project findings.

Importantly, our approach has allowed for the accounting of wetland restoration effects on downstream water quality impacts, which is relevant to recent federal policy directives that have vastly underestimated the importance and value of wetlands (Boyle et al., 2017). Findings by the REACH collaboration have consistently highlighted the potential for wetlands to mitigate pollutant loads and transport at the watershed scale (Hansen et al., 2018; Mitchel et al., in review; Wilcock et al., in prep). However, wetland effects are typically omitted from most current conservation modelling approaches applied to agricultural landscapes.

Using our biophysical framework, we are evaluating costs and benefits associated with management of nitrate, phosphorus and suspended sediment in both the Le Sueur River basin – a subbasin of the Minnesota River Basin (MRB) which contributes disproportionately to pollutant loads in the region – and the larger MRB. 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).We consider a full suite of candidate management actions suites for reducing peak hydrology, sediment load, nitrate load and phosphorus loads (Table 1). Candidate landscapes are being evaluated using 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).

Table 1. Conservation management options included in the Le Sueur and Minnesota River Basin 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

Spatial patterns in management actions are being examined for general rules (i.e., of type, location and extent) that can meet nutrient reduction targets at least cost. This approach has allowed us to address how best to manage landscapes to protect water quality while also advancing the science of landscape modeling by exploring the role of spatial arrangement on management action efficiency. Our integrated modelling research over the past year has enabled the following key advancements:

- Understanding the importance of spatial targeting for conservation; significant gains in effectiveness of conservation management actions can be realized by optimizing (targeting) placement within a watershed due to non-linearities in aquatic biophysical processes, while disregarding non-linearities in biophysical processes results in a model that substantially underrepresents water quality benefits;
- Comparison of conservation actions that are both implemented within the river network (i.e., restoration of flow-through wetlands) and those that occur primarily on the landscape (i.e., cover crops)
- Identification of potential trade-offs for conservation landscapes that target sediment vs nitrate water quality goals

Methods innovations:

- Inclusion of multiple wetlands types and sizes in the suite of candidate management options
- Accounting for key biophysical processes and features that can modify watershed-scale water quality outcomes (near channel sediment generation, aquatic nitrate removal via denitrification)

- Advancements in deploying evolutionary algorithms to prohibitively large solutions spaces required for high resolution models in large landscapes

Using supplemental funding from NSF, the Natural Capital team at the University of Minnesota's Institute on the Environment has linked conservation landscapes to valuation of multiple ecosystem services (see sections 4.3 and 4.4) and is evaluating multiple policy mechanisms for implementing cost effective conservation landscapes to meet water quality targets and maximize ecosystem benefits.

RESEARCH RESULTS INFORMING THE INTEGRATED WATERSHED MODELING FRAMEWORK

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

1.1. *Quantification of near-channel sediment supply across watersheds of the Minnesota River Basin*

S. Cho, C. Braudrick, C. Dolph, K. Gran, P. Belmont and P. Wilcock

In the Upper Mississippi River basin, analysis of sediment core records from Lake Pepin -- a natural impoundment on the Mississippi River downstream of its confluence with the Minnesota River -- indicated a 10-fold increase in suspended sediment loading in the two hundred years since European settlement (Belmont et al., 2011; Kelley and Nater, 2000). While the Minnesota River Basin (MRB) only accounts for 25% of the flow into Lake Pepin, it is responsible for 88% of the sediment entering the lake (Engstrom, 2009). Geochemical fingerprinting of sediment cores of Lake Pepin and geomorphic analyses have demonstrated that the dominant source of sediment in the region has shifted in the last several decades from erosion of soil from agricultural fields to accelerated erosion of near channel sediment (e.g., streambanks, streamside gullies, and bluffs; Belmont et al., 2011). At the same time, the region has exhibited concurrent increases in peak stream flows, as the result of intensification of tile drainage together with increasing precipitation patterns in the region (Novotny and Stefan, 2007; Schottler et al., 2013; Foufoula-Georgiou et al., 2015), Given 1) the disproportionate impacts of sediment exported form the MRB to downstream water quality, 2) known increases in peak discharge in rivers throughout the basin, and 3) known increases in contributions from near channel sediment to suspended sediment loads the key challenge for sediment reduction in the Upper Mississippi is assessing the near channel sediment supply (NCSS) across the MRB in particular, and predicting how that supply changes as a function of river discharge.

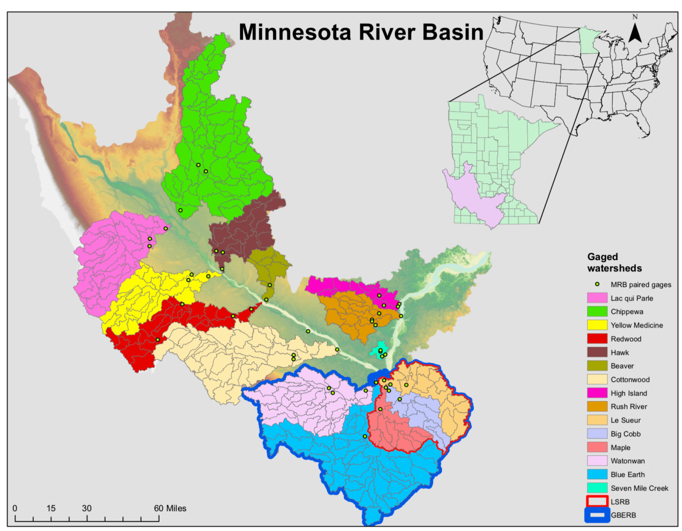


Figure 1: Watersheds with paired gages across the Minnesota River Basin are used in the evaluation of Near-Channel Sediment Supply (NCSS). Greater Blue Earth River Basin (GBERB) and Le Sueur River Basin (LSRB) (highlighted) have been the focus of previous studies examining NCSS contributions to suspended sediment loads.

Since the mid-2000s, the major tributaries to the Minnesota River have been extensively monitored for water chemistry including sediment load. Each major tributary has at least two gage locations for which continuous discharge measurements are coincident with repeated water quality sampling (Figure 1). We have used the available gage observations to develop a practical method for estimating dynamic Near Channel Sediment Supply (NCSS) – i.e., sediment derived from actively eroding portions of tributaries draining to the Minnesota River -- as a function of river discharge. Rather than estimating and cumulating local sources of sediment, our approach uses observations of sediment loading at paired stream gages bracketing the incising portion of multiple tributaries, to provide a measure of aggregate NCSS from those parts of the watershed with the largest near-channel sources (i.e., bluffs). By directly linking specific river discharge conditions to rates of near channel sediment loss, the NCSS model can be used to predict future climate impacts on sediment loading or to inform conservation-planning efforts aimed at reducing sediment export from the Minnesota River Basin.

We combined estimates of bluff extent and flood plain connectivity to understand the potential for basins across the MRB to contribute and intercept sediment from near channel sources. We then used two mathematical approaches to independently estimate the contribution of near channel sediments to total suspended sediment loads, as a function of discharge, in actively eroding portion (i.e., 'knickzone') of each gaged subbasin of the MRB. These analyses indicated NCSS increases with increasing discharge for 14 of the 15 basins we studied (Figure 2). Specifically, NCSS per river km increased with the square of the river discharge per unit area of the watershed, when the river discharge surpasses the 20% exceedance probability level. The predictive discharge-NCSS relationships developed here have been incorporated into the integrated MRB SWAT model as point sources (described above), and can be used to inform conservation planning efforts, particularly with regards to quantifying the expected impact of water conservation measures on water quality targets for sediment.

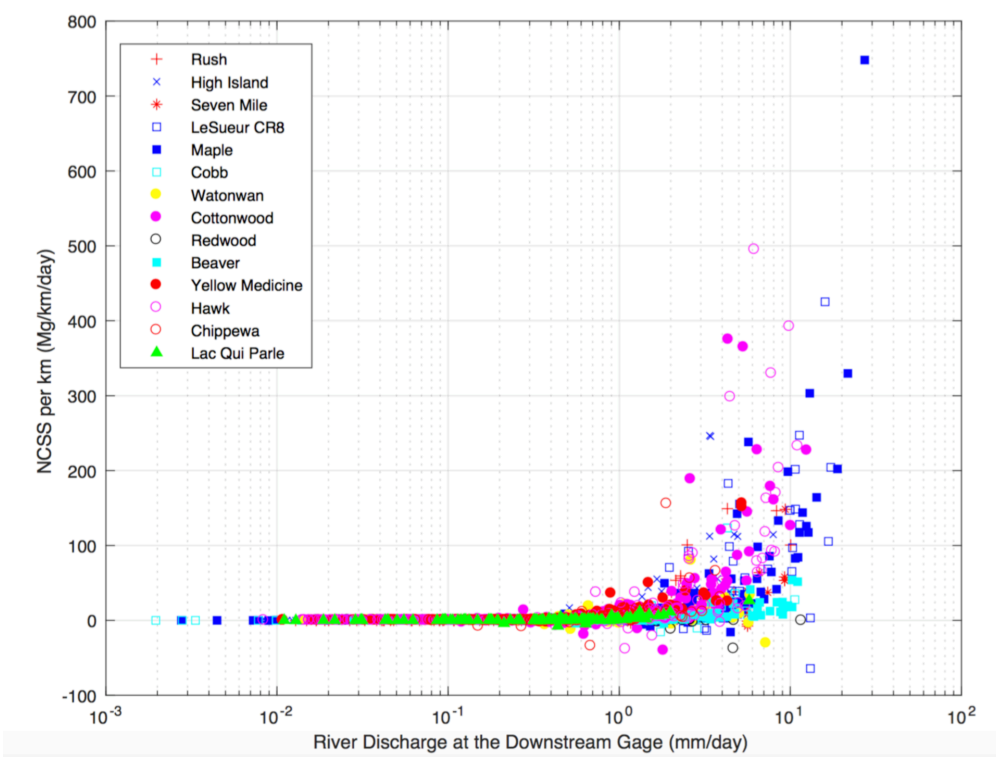


Figure 2: Sediment loading from near-channel sources in the incised zone of the watersheds across the Minnesota River Basin

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

2.1. The influence of fertilizer, erosional hotspots and runoff on the form and transport of phosphorus in U.S. Midwestern rivers

J. Finlay, E. Boardman, M. Danesh and E. Foufoula-Geourgiou

While inputs of phosphorus from human activities are very often the main source of P affecting freshwaters, non-point source P transport is controlled by complex processes that govern movement of P across the land water interface. We sought to determine how land cover, phosphorus inputs, and climate interact to influence P losses in watersheds across Minnesota. The study watersheds spanned gradients of agricultural and urban land cover, anthropogenic inputs from fertilizer, food, and feed imports, annual runoff, and wetland presence. We examined climate and landscape conditions to explain variation in annual total, dissolved, and particulate P export and retention. We hypothesized land cover and phosphorus inputs would be related to P losses, but expected that landscape features such as lake cover and climate would modify these relationships. We integrated datasets representing P inputs and outputs to examine how watershed scale P balances and environmental factors influenced rates of river exports and watershed retention across 62 watersheds distributed across Minnesota.

We used the Net Anthropogenic Phosphorus Input (NAPI) toolbox (Version 3.0.1β, available from Cornell University http://www.eeb.cornell.edu/biogeo/nanc/nani/nani.htm) to estimate net P inputs for study sites completely within the boundaries of the United States. The balance of direct human inputs and outputs of P from watersheds determines NAPI. We calculated the proportion of P retained by the watersheds as follows, in units of kg/km^2:

$$\frac{NAPI - Hydrologic\ P\ Export}{NAPI}$$

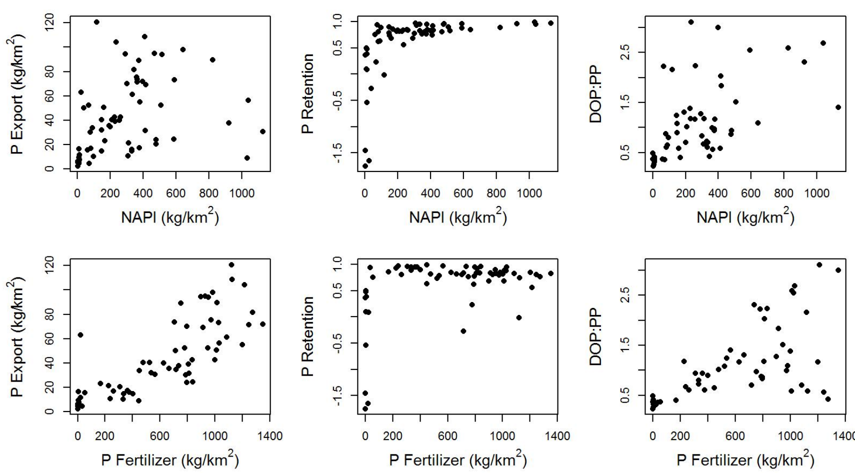


Figure 3: Bivariate plots of P export, P retention, and DOP:PP vs. NAPI (top row) and P export, P retention, and DOP:PP vs P fertilizer inputs (bottom row). Units of P retention and DOP:PP are proportions (e.g. 1 indicates 100%).

Fertilizer inputs from row crop cultivation were the dominant source of P to agricultural watersheds (Figure 3). A large majority of P inputs to watersheds were retained in soils or removed in agricultural products. However, fertilizer inputs were the most important factor associated with increased river transport of total, dissolved, and particulate P (PP). Annual runoff increased total and dissolved P losses and decreased P retention (Figure 4). Dissolved P made up a significant portion of annual loads at sites that had highest rates of P inputs and river TP export, with the ratio of dissolved to particulate P export increasing with crop cover, and fertilizer inputs. PP export increased by sediment inputs from steep bluffs near channels, where erosion has increased due to human and climate driven changes to river hydrology. Together, our results suggest rising discharge and flow variability due to climate change and agricultural intensification coupled with high rates of P inputs will maintain elevated fluvial P export into the future without appropriate management efforts aimed at reducing both soluble P losses and stream bank erosion.

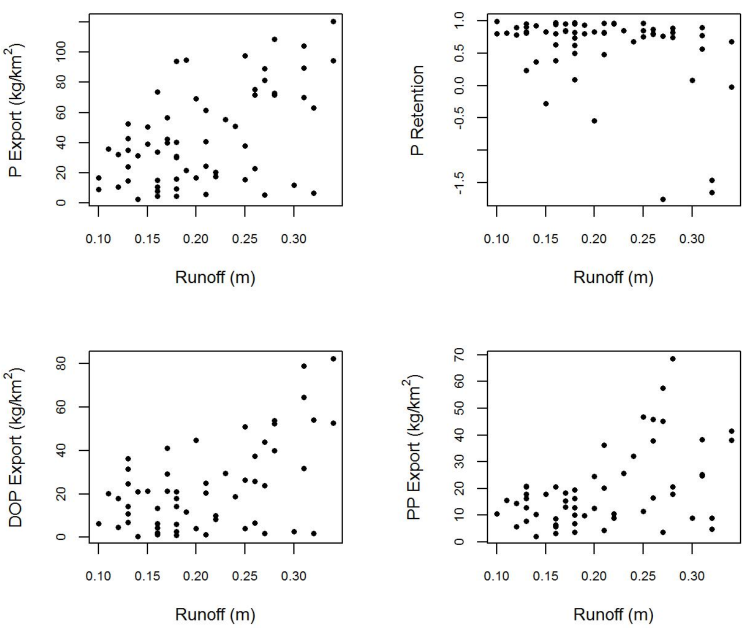


Figure 4. Relationship between (top left) TP, (bottom left) DOP, (top right) P retention and PP export (bottom right) with watershed runoff.

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

A. Hansen

Fluvial wetlands are one of the most promising available conservation interventions to reduce nitrate export from agricultural river networks. However, reported wetland nitrate removal on an event time scale is highly variable, limiting the confidence needed for widespread implementation. Because fluvial wetlands are also one of the most costly management options for water quality and require permanent conversion of land use, it is imperative to accurately predict wetland performance so that the investments represent an efficient use of limited conservation funds. Unlike treatment wetlands for waste water, which can be designed for a constant and known input of water and nitrate, agricultural wetlands are subject to a wide range of hydraulic and nitrate loading conditions. In this study we examine the spatial variability in nitrate removal processes (denitrification and assimilation) and determining characteristics of the efficiency of these processes. A better understanding of first order controls on nitrate removal processes and how they vary under different loading conditions will allow us to better predict wetland performance as a function of load and thus design treatment wetlands to target loading conditions most relevant to the water quality impairment they are meant to prevent.

Using repeated field observations in two constructed treatment wetlands and denitrification incubations from substrates collected at these wetlands, we assessed how nitrate removal via denitrification and assimilation vary with location and substrate throughout a constructed wetland located in an intensively managed row-crop agricultural landscape.

We found that denitrification rates ranged over two orders of magnitude within the wetland and that the highest rate occurred when the nitrate and dissolved organic carbon concentrations in overlaying water were high and approximately balanced (Figure 5).

Our results also indicated that as long as low oxygen conditions were present, denitrification occurred at equivalent rates on detritus and sediment but at lower rates on live plant tissue (Figure 6). Dissolved oxygen measurements in mats of submerged aquatic vegetation showed that anoxic conditions, which favor denitrification, extended over half the water column depth for over 12 hours every day implying that substrates other than sediment may meaningfully contribute towards the microbial assemblage and overall denitrification potential of the wetland. Anoxic conditions extended throughout the entire water column in stands of emergent vegetation when measured at mid-day, perhaps due to the abundance of floating vegetation.

We used these results to calculated whole wetland nitrate removal via denitrification and compared that to calculated total nitrate removal from a mass balance between the inlet and outlet. The results of this study elucidate the relative contribution of denitrification to nitrate removal in a treatment wetland, the spatial variation in rate, and the key variables regulating its efficiency. Together, this information can be used to improve treatment wetland design by identifying and promoting conditions most favorable to denitrification.

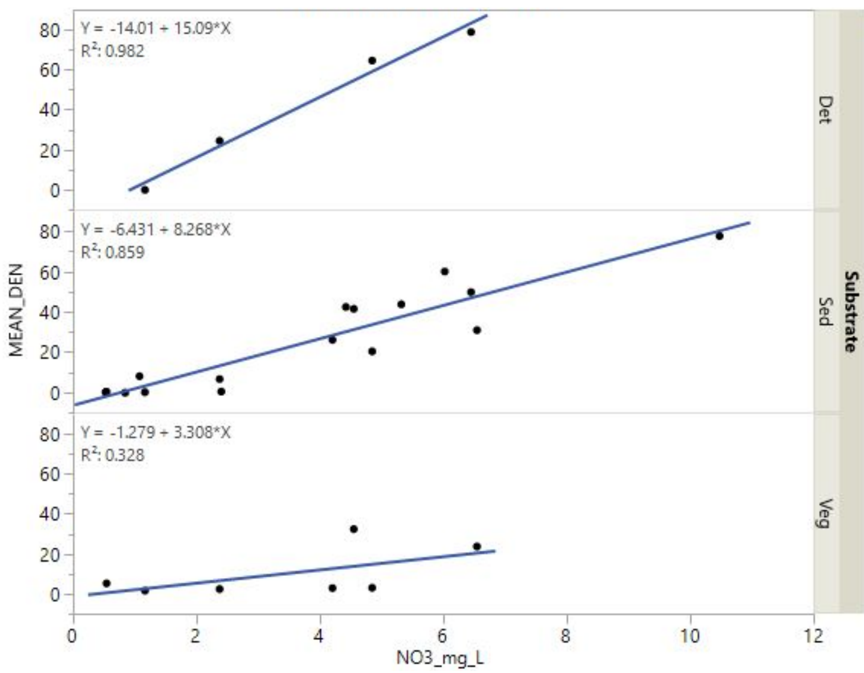


Figure 5. Top panel: Locations of denitrification and water chemistry measurements in a constructed treatment wetland. Bottom panel: mean denitrification rate (across replicate samples) collected from each sampling location, in relation to nitrate concentration in water at the sampling location. Samples were collected from benthic substrates dominated by detritus (Det), sediment (Sed), and vegetation (Veg).

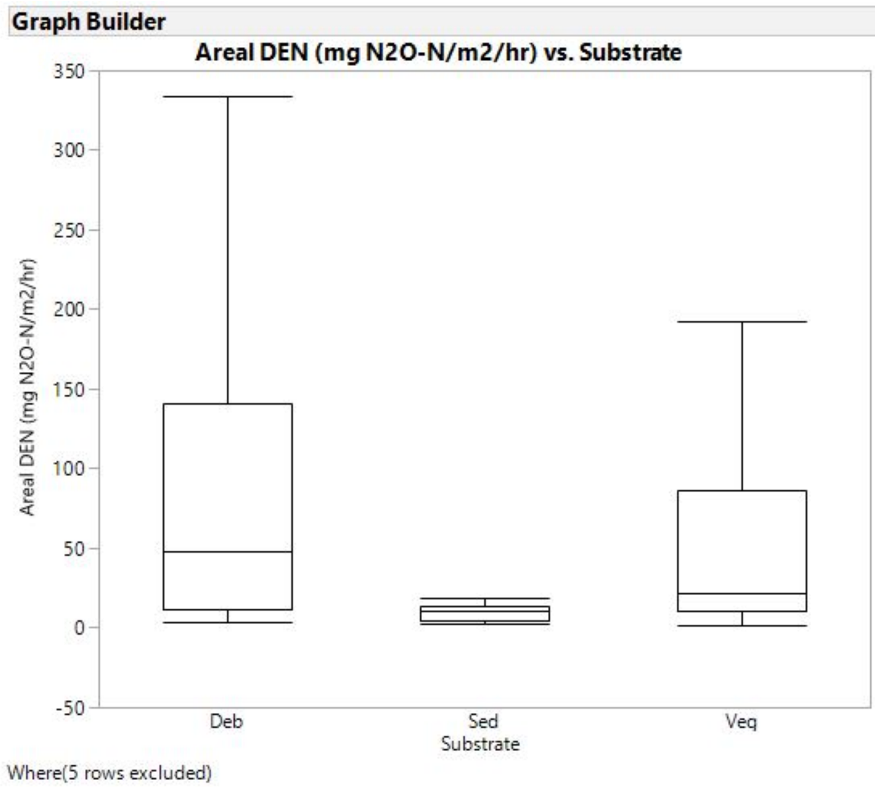


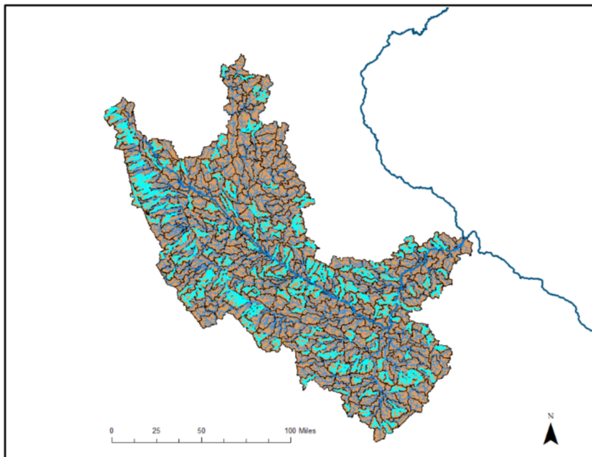
Figure 6. Aerial denitrification rates calculated from different benthic substrates (Organic debris (Deb), Sedment (Substrate), and Vegatation (Veg)

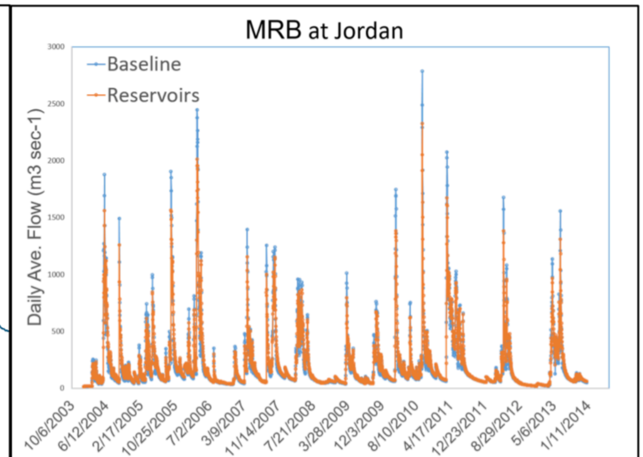
2.3. Incorporating new science into existing biophysical models

B. Dalzell, A. Hansen, P. Hawthorne, S. Cho, C. Braudrick, and C. Dolph

The Soil Water Assessment Tool (SWAT) is a widely used, well established watershed model that has been applied extensively to assess conservation planning in agricultural landscapes, especially in the midwestern U.S.A. (Arnold et al. 2012). Briefly, SWAT models spatially explicit inputs, transformations and transport of water, nutrients and sediment including surface sources of water, N, P and S, terrestrial nutrient transformation processes, evapotranspiration, soil moisture and groundwater contributions. As described above, the integrated modelling effort at the Minnesota River Basin scale relies on SWAT. However, SWAT has not historically accounted for 1) the importance of hydrology-driven inputs of near channel sediment sources to suspended sediment loads, and 2) the importance of denitrification in modifying nitrate loads. Both of these processes have been identified by REACH as key modulators of the linkages between land use, hydrology, and downstream pollutant loads, and have been overlooked in previous modelling efforts.

For example, aquatic nitrate removal processes available in SWAT to date have been limited to algal assimilation and settling. Previous work has shown that aquatic nitrate removal via denitrification can be a significant source of reduction in nitrate exports at a watershed scale (e.g., Hansen et al., 2018). Further, one of the management options that we evaluate with this model is constructed treatment wetlands which, individually, have been shown to significantly reduce nitrate concentrations and loads. We therefore included aquatic denitrification in the landscape model by altering the SWAT source code. Denitrification rate is defined as a power law function of nitrate concentration based on previous observational studies from a wide range of landscapes (Böhlke et al. 2009, Mulholland et al 2008, Hansen et al. 2016b). This change was included in the code for wetlands, reservoirs and channels. A preliminary example for the Minnesota River Basin, shown in Figure 7, demonstrates the effect of these changes in the source code to SWAT outputs. In this example, we compared SWAT outputs generated for a baseline scenario (i.e., given current land use conditions) with those generated from a modelled scenario in which wetlands were added uniformly throughout basin (Figure 7; top left). Both flow and nitrate export were substantially reduced under the wetland addition scenario compared to baseline.





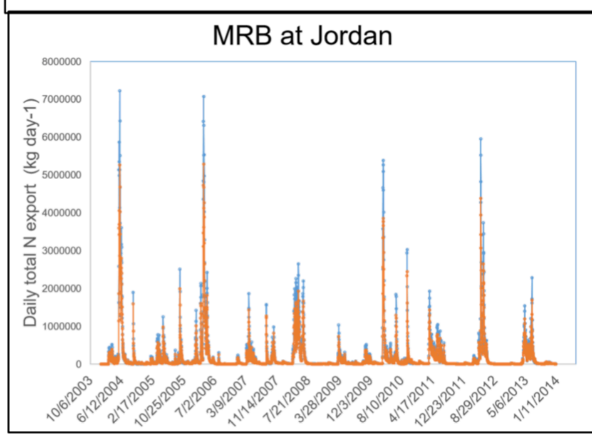


Figure 7. Top left: highlighted areas show locations of simulated wetland additions across the MRB landscape. Top right: SWAT output comparing average daily flows under the baseline scenario (i.e., MRB landscape under current land use conditions; blue) and under the simulated wetland addition scenario (orange). Bottom left: SWAT output comparing total daily nitrogen export under the baseline scenario (blue) and the wetland addition scenario (orange). The SWAT model included modifications to the source code to account for nitrate removal by wetlands).

Additional modifications to SWAT capture inputs of near-channel sediment from major watersheds across the Minnesota River Basin; these inputs have been estimated in a collaborative effort by Se Jong Cho (UMN), Christian Brauderick (Utah State), Peter Wilcock (Utah State), Christine Dolph (UMN), Patrick Belmont (Utah State), Karen Gran (University of Minnesota-Duluth). Near channel sediment supply is generated as a function of discharge according to parameters identified by Cho et al., (in prep), and have been added to the SWAT model as point source files.

Lastly, recently published tile drainage routines in SWAT have been implemented and tested for impacts to modelled flows. Subsurface tile drainage is common across the corn and soybean growing region of the upper Midwest including the Minnesota River Basin. Systematic and widespread surveys of the extent of tile drainage do not exist, but smaller local surveys have shown that up to 96% of cultivated land have been modified with drainage systems (Kuehner, 2004). In our SWAT model of the Minnesota River Basin, we assume that cultivated lands with slopes of less than 3% have subsurface tile drainage systems present. This amounts to roughly 84% of the cultivated land in the watershed (and 69% of the total watershed area). In order to determine whether or not simulated tile drainage volumes are reasonable, we compare simulated drainage efficiency against observed data from field-scale studies. Drainage efficiency is the volume of drainage water divided by total precipitation (expressed annually, as a percent). Observed data from field-scale plots show that typical drainage efficiency values range from roughly 5 to 20%, depending on total annual precipitation, with some values up to 34% (Dalzell et al., 2011; Figure 8). Additional ongoing work has shown that drainage efficiency can be up to 40-45% (Strock and Zhang, unpublished data). SWAT-simulated values for drainage efficiency generally agree with the range of values measured from sites in the Minnesota River Basin (Figure 8). This is important because it shows that subsurface tile drainage can comprise a major component of the annual water budget in watersheds where subsurface tile drainage is common.

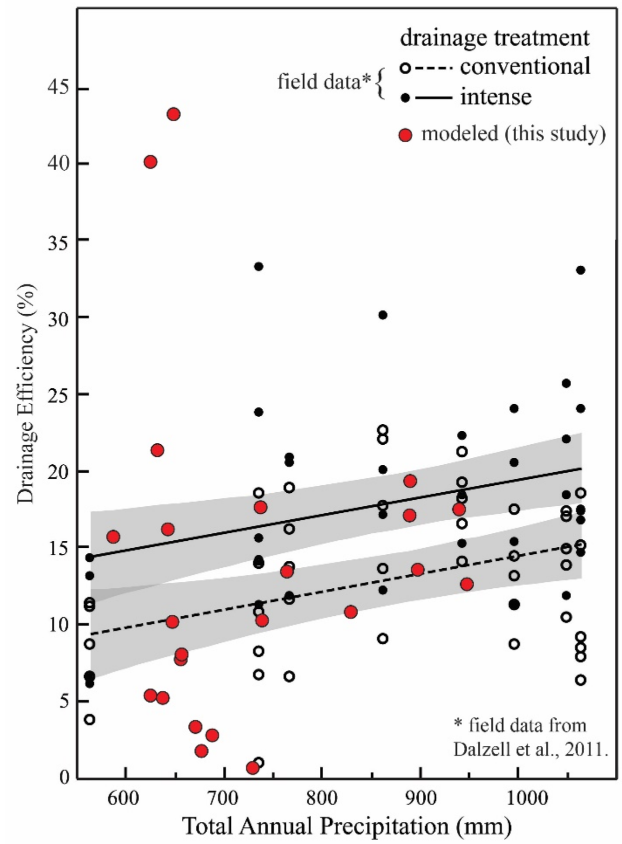


Figure 8. Observed and modelled drainage efficiency from tile-drained watersheds in relation to total annual precipitation.

3. Biogeochemical interactions and near channel sources modify nutrient and phosphorus cycling in agricultural river networks

3.1. Characterizing phosphorus export across agricultural watersheds: biogeochemical processes and near channel sources modify hydrology driven export behavior

C. Dolph, E. Boardman, M. Danesh & J. Finlay

Phosphorus (P) transport through river networks is complex because of rapid transformations between dominant forms (i.e., dissolved vs particulate), facilitated by multiple biogeochemical and hydrological processes. We used concentration-discharge (c-Q) relationships, daily load estimates and a number of export metrics to characterize total, dissolved and particulate P export at daily to annual scales for 105 gaged river sites with agriculturally-dominated watersheds in Minnesota, USA. We supplemented our analysis with water chemistry data collected from an additional 176 stream and river sites over a range of flow conditions.

For gaged sites with significant and reasonably strong power law relationships between c and Q ($p<0.05$ & $R2>0.2$), we used the slope b of the log-log c-Q power law together with the coefficient of variation of concentration relative to the coefficient of variation of discharge (*CV_C/CV_Q*), to summarize key elements of transport on event-based (i.e., daily) time scales. This approach, demonstrated by Musolff et al. (2015), provides useful information about multiple possible transport behavior mechanisms. A *CV_C/CV_Q* <<1 suggests that concentrations are relatively constant compared to variability in flow, indicating chemostatic behavior; by contrast, a larger *CV_C/CV_Q* indicates chemodynamic behavior (i.e., comparatively large variations in concentration relative to variation in flow). Thompson et al. (2011) suggested that *CV_C/CV_Q* values ≈ 0.3 or less were indicative of chemostatic behavior. Plotting *CV_C/CV_Q* in relation to the slope *b* of the power law yields information about whether chemodynamic behavior follows a diluting, mobilizing, or reactive (i.e., *b* ~=0) pattern.

On event time scales, we found that the large majority of gaged watersheds exhibited mobilizing behavior for both dissolved and particulate phosphorus , when using the *CV_C/CV_Q* vs b approach (Figure 9). However, power law relationships, though significant, were weak in many cases. The power law relationship was a reasonably strong fit (R2>0.2) to the PP-Q and OP-Q data for less than half of all gage sites included in this study, and just over half (61%) of sites for TP. Moreover, while many sites exhibited considerable variation in P concentration relative to variation in flow (i.e., high *CV_C/CV_Q*) and had b values >0, they also exhibited b values considerably less than 1, indicating that mobilizing behavior was weak. These findings suggest that flow can be an important driver of phosphorus concentrations in river networks, but not universally so. On an interannual basis, most watersheds appeared chemostatic or chemodynamic for P, although approximately 30% of sites showed mobilizing behavior for dissolved P. Regardless of relationships between concentration and flow, the majority of P export in terms of load occurred under high flow conditions (flow exceedance probability <10%) at nearly all sites.

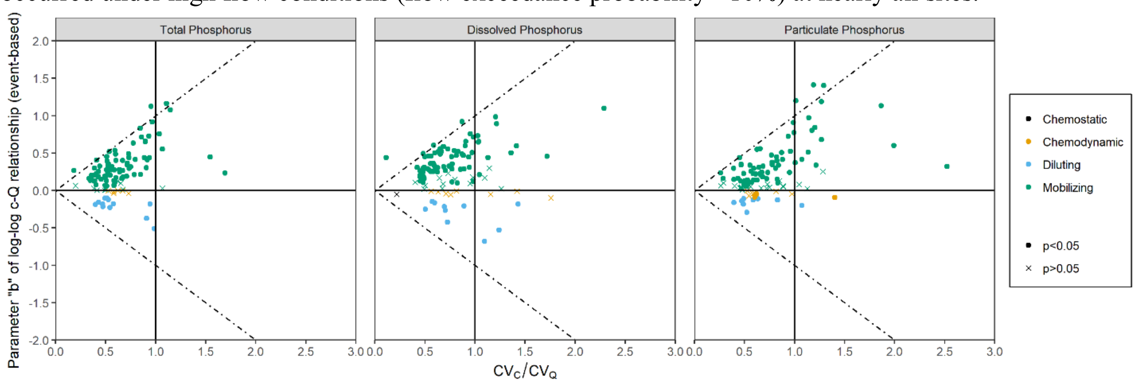


Figure 9. Parameter "b" (slope) of the log-log c-Q relationship for total phosphorus (left), dissolved phosphorus (middle) and particulate phosphorus (right), in relation to *CV_C/CV_Q* for 105 agriculturally dominated (agricultural land cover > 50%) gaged watersheds. Symbols indicate whether the power law relationship for c-Q was significant (p< 0.05, solid circles) or not (p> 0.05, cross hatches) for each P constituent. Color indicates export behavior based on criteria defined for b and *CV_C/CV_Q*. Chemostatic: -0.1<*b*<0 and *CV_C/CV_Q* <0.3 (sensu Thompson et al., 2011); chemodynamic: -0.1<*b*<0 and *CV_C/CV_Q* >0.3; diluting: *b*<-0.1; mobilizing: b>0.

Mobilization of total and particulate P was positively related to the extent of river bluffs across watersheds, indicating that presence of large near-channel sediment sources increases sensitivity of river P export to increasing flow (Figure 10). Evaluating the relationship between *b* and bluff extent separately by major river basin revealed distinct sub-regional trends that reflected threshold vs linear nature of c-Q relationships for PP in the MRB vs the Red and Upper Mississippi Black Root Basins, respectively. These differences are likely explained by the unique geologic history of these different basins, as well as the varying importance of biogeochemical processes in modifying c-Q export across different basins.

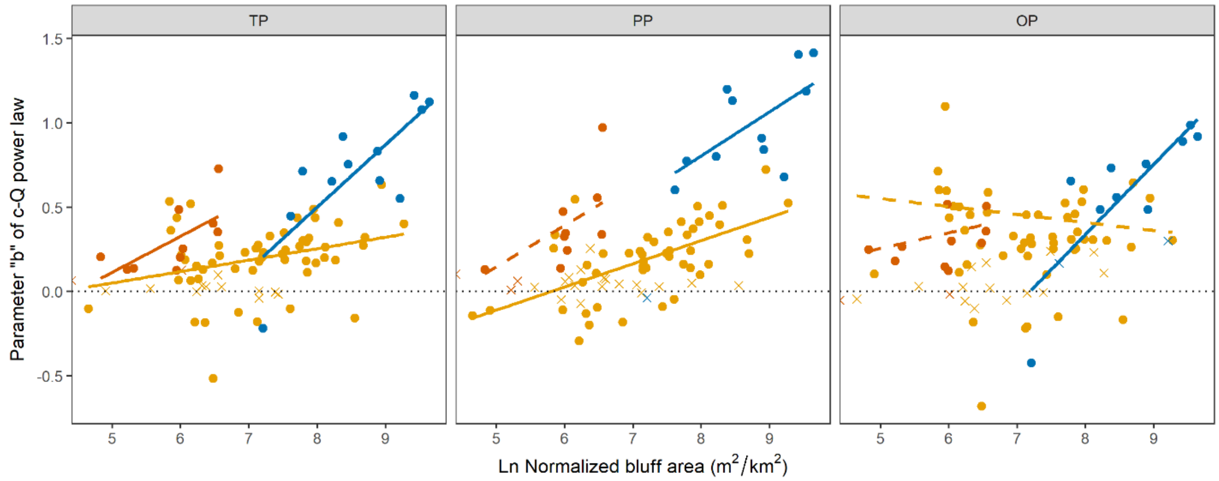


Figure 10. Parameter "*b*" of the c-Q power law relationship for TP, PP and OP, in relation to normalized bluff area (log transformed), across sites in the Red River (dark orange; n=12), Minnesota River (light orange; n=64) and Upper Mississippi-Black Root River (blue; n=12) basins. Symbols indicate whether the power law relationship for c-Q was significant ($p < 0.05$, solid circles) or not ($p > 0.05$, cross hatches) for each P constituent. Solid lines show significant statistical relationships between b and bluff extent for each P constituent (across sites with statistically significant power law relationships); Dashed lines indicate non-significant statistical relationships between b and bluff extent.

We also observed that c-Q relationships can be modified by trends in P concentrations that occur predominantly in certain seasons. For example, at many sites, elevated concentrations of dissolved phosphorus at low flow conditions in late summer obscured and/or weakened c-Q relationships that otherwise would have conformed more strongly to the power law (Figure 11). High concentrations of dissolved phosphorus at this time of year are consistent with anoxic conditions that can result in phosphorus release from both lakes and river bottom sediments (Correll, 1998). Anoxic conditions are likely associated with high primary productivity. Indeed, many of the river systems studied here are known to exhibit high concentrations of chlorophyll and associated biological oxygen

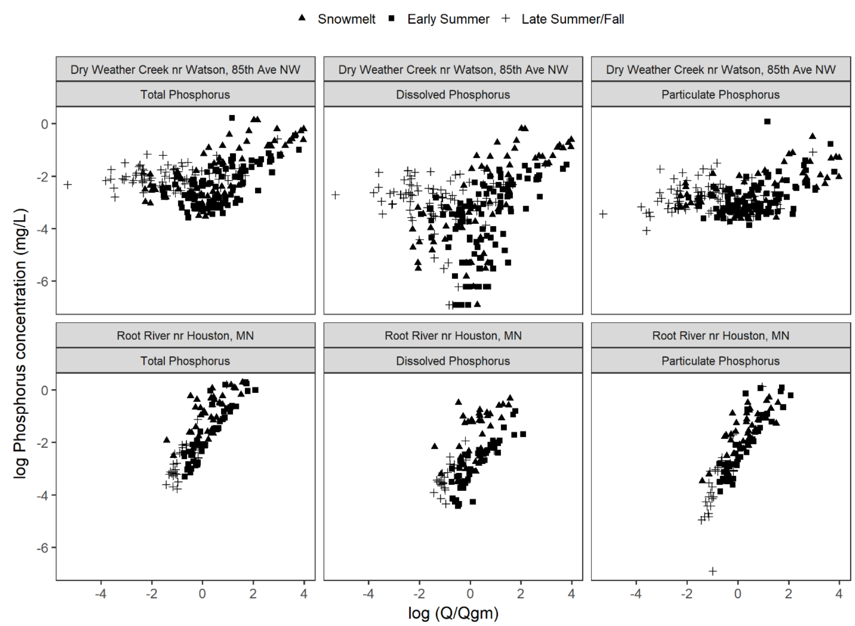


Figure 11. Concentration-discharge relationships for total, dissolved and particulate phosphorus from two representative sites characterized by high bluff extent in the Minnesota River Basin (top) and the Upper Mississippi Black Root River Basin (bottom). Symbols indicate the season in which phosphorus samples were collected.

demand in summer, resulting in low oxygen conditions (MPCA, 2014) Thus, it appears that biogeochemical processes can conditionally modify and obscure flow-driven changes in phosphorus concentrations.

Likewise, analysis of our field dataset indicated that particulate and dissolved P concentrations were often influenced by water column chlorophyll *a* concentrations (Figure 12). These findings suggest that high rates of assimilation and algal production in some agricultural river networks may be associated with draw down of dissolved phosphorus and conversion to particulate phosphorus in the water column, and thus modifying c-Q relationships towards chemodynamic behavior. Our findings also indicate that role of algal biomass in modifying phosphorus concentrations is much stronger at moderate to low flow conditions; at high flows dilution of algal biomass and mobilization of sediment sources likely renders the contribution of algal P relatively small compared to inorganic PP sources, especially for sites with considerable extent of near channel sediment sources.

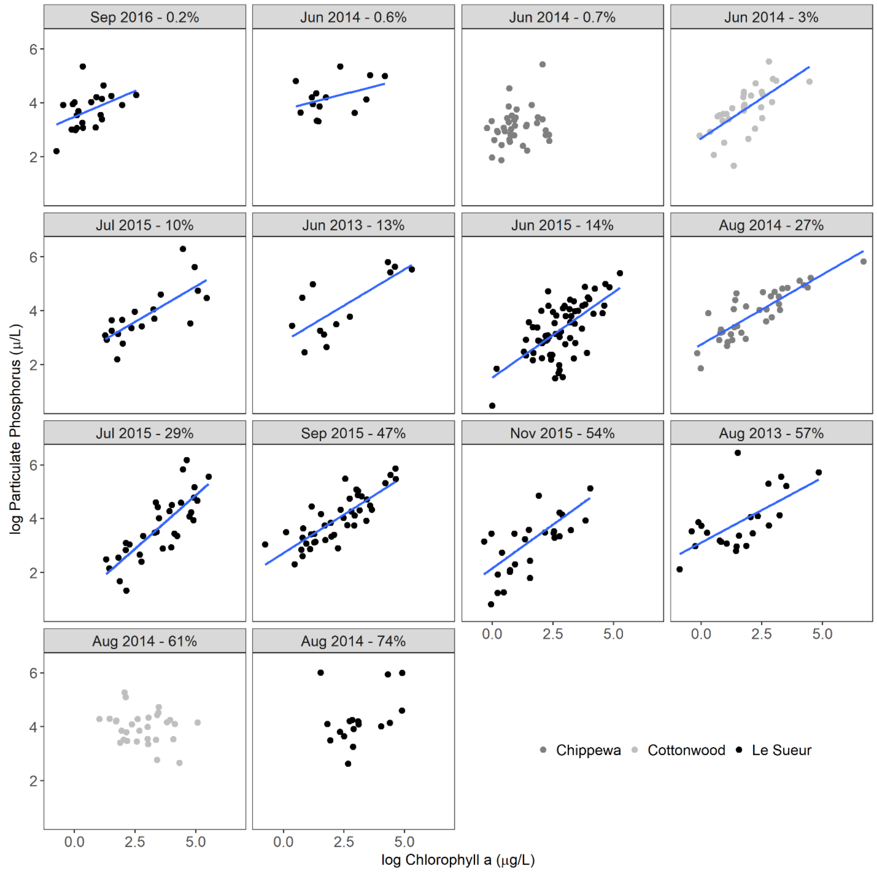


Figure 12. Particulate phosphorus concentrations in relation to chlorophyll a concentrations measured at a total of 176 ditch, stream and river sites sampled over 12 different sampling events and three major (HUC8 scale) watersheds. Point color indicates major watershed where sites were located. Lines indicate statistically significant linear regression relationships. The % values in the facet titles indicate the exceedance probability of flow at the outlet of each major watershed during sampling.

Our findings indicate that phosphorus transport, even among watersheds that are similarly dominated by extensive agricultural land use, can exhibit diverse patterns across watersheds, seasons and flow conditions. Moreover, hydrology-driven export behavior for phosphorus can be modified by both extent of near channel sources, and biogeochemical processes.

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

A. Baker, K. Gran, J. Finlay, D. Karwan,, D. Engstrom, W. Atkins, M. Muramoto-Mathieu, T. Belo

Interactions between sediment and phosphorus are known to be important in governing phosphorus bioavailability. We examined the role of interactions between phosphorus and sediment in driving watershed-scale phosphorus dynamics in the Le Sueur River Basin via the development of a mass balance for sediment-derived phosphorus. This budget built upon a sediment budget previously developed by project PIs (Gran et al., 2011), and incorporated newly collected sediment geochemical data including total and water-extractable dissolved phosphorus and sorptive capacity for sediments from the primary sources in the basin. Sediment sources included bluffs, stream banks, ravines, and agricultural topsoil and ditch sediment. Estimates of sediment-derived phosphorus from these distinct sources were then compared to measured loads of total and dissolved phosphorus at a network of gages maintained by the Minnesota Pollution Control Agency.

This budget showed that, while some source sediment has high background phosphorus concentrations, only 24% of total phosphorus exiting the basin is derived from erosional sediment inputs on an average annual basis, with 23% of this in particulate form and 1% in dissolved form (Figure 13). Dissolved orthophosphate comprises 37% of the measured average annual total phosphorus load at the Le Sueur watershed outlet. Incorporation of data describing the sorptive properties of sediment into this budget suggests that the true dissolved phosphorus load is masked by sorption of dissolved phosphorus to sediment, potentially reducing the fraction of total phosphorus that we observe as dissolved load by as much as 39%.

Results of sorption tests conducted to mimic natural stream conditions were also incorporated into this budget. These sorption tests were carried out using natural stream water from the Le Sueur River, a range of dissolved phosphorus concentrations that mimics observed concentrations from the monitoring network on the Le Sueur, and a ratio of sediment to solution that is representative of high TSS in the basin. Results of these tests showed that, under average stream conditions during storm events which export high sediment loads, agricultural top soil and ditch sediment desorb phosphorus while glacial till bluff sediment and alluvial streambank sediment serve to bind phosphorus from the water column (Figure 14).

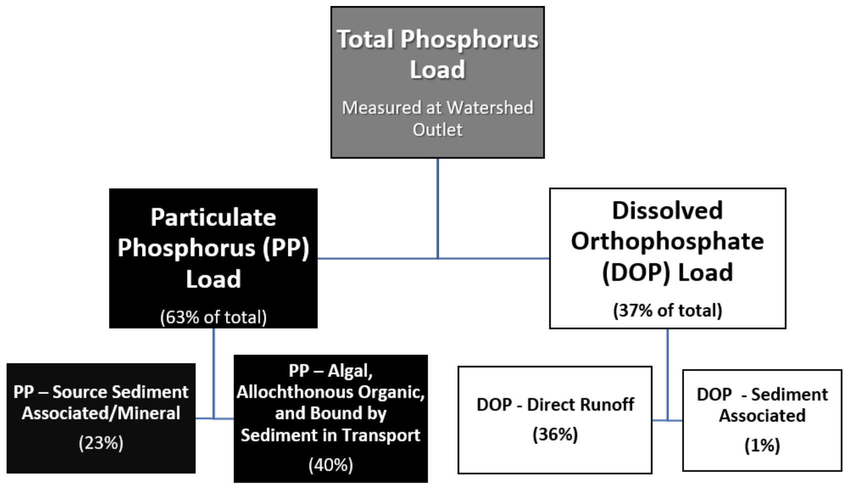


Figure 13. Flow chart showing apportionment of total phosphorus load into distinct pools, approximated using load monitoring data from the network of gages on the Le Sueur and its tributaries and results of mass balance for sediment associated phosphorus. This mass balance reveals that only 24% of total phosphorus measured at the watershed outlet can be attributed directly to source-sediment.

These findings have important implications for management. These results suggest that despite high sediment loading rates, even if we were able to address 100% of erosion, this would only reduce total phosphorus loads by at most 24%. Furthermore, if the signal of dissolved phosphorus loss is in fact muted by sorption to sediment, then reducing erosion may only serve to alter the form of phosphorus in transport, resulting in higher dissolved, bioavailable phosphorus loads. Therefore, management strategies which reduce dissolved phosphorus source will be equally important as those that reduce erosion if phosphorus reductions are to be achieved.

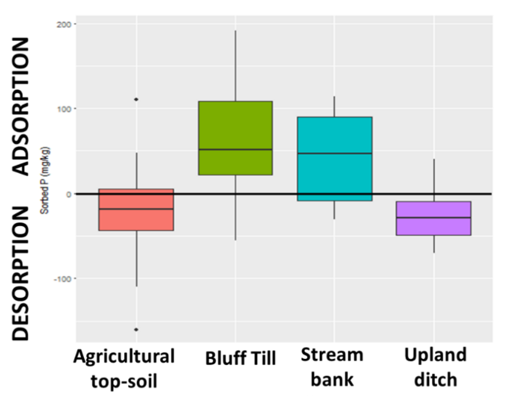


Figure 14. Boxplots showing distribution of sorbed phosphorus corresponding to stream orthophosphate conditions that occur when a majority of sediment export occurs.

4. Optimizing conservation landscapes for multiple ecosystem services

4.1. Development of benefits transfer functions for additional services: wildlife and pollinator conservation

S. Rabotyagov, Z. Lang, and T. Campbell

Improvements in water quality (i.e., reductions in pollutant loads of nitrogen, phosphorus and sediment) are often the explicit goal of state, regional and federal policy, and thus are important targets around which we have organized our modelling efforts in the Le Sueur and Minnesota River Basins. However, the full range of water quality-related ecosystem services are not adequately represented by improvements in water quality alone. Achieving a full estimate of the costs and benefits of conservation action for water quality improvement requires a valuation approach that can link specific actions on the landscape to the full complex suite of resulting changes in ecosystem services (Keeler et al., 2012). We have sought to develop objective functions that link conservation actions designed to address water quality with a broader array of services, which will be included in landscape optimization for a fuller suite of ecosystem benefits. For example, restored wetlands are one conservation option that we have shown can reduce nitrate and sediment loads to downstream river networks (Hansen et al., 2018; Mitchell et al., in review). However, wetlands of course are linked to numerous other benefits that have been valued at trillions of dollars a year globally (Millennium Ecosystem Assessment, 2005). We have developed benefits transfer functions that additional quantify the impact of wetland restoration on duck production, an endpoint which is valued by hunters, bird watchers, and conservationists.

Following USDA (2015) and Hansen et al., (2015), we estimated the spatially-explicit expected number of new duck hatchlings produced by a new wetland for 5 main duck species as

$$H = Nesting\ Pairs \cdot Nest\ Success \cdot Renesting\ Propensity \cdot Clutch\ Size$$

We estimated H for 5 species of duck and 3 types of wetlands (temporary, seasonal, and semipermanent), and assumed that ½ H survive to adulthood. As an example of how duck production functions can be integrated with other biophysical models developed under REACH, we performed landscape optimization across a suite of conservation management options (including wetlands) for the Le Sueur River Basin, using the Management Option Simulation Model (MOSM) to simulate sediment transport (Cho et al., in prep) and our duck production functions to quantify benefits associated with additional waterfowl habitat.

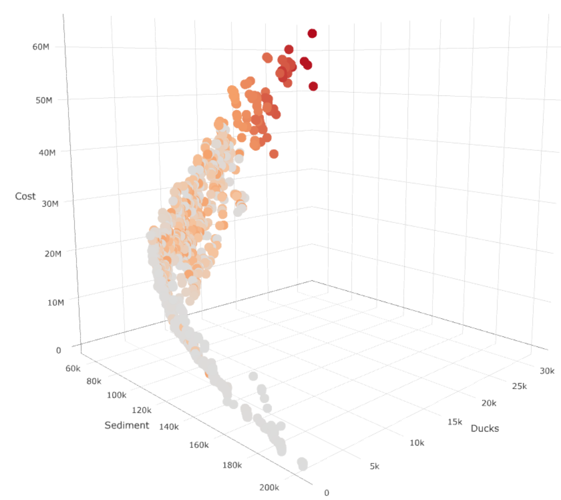


Figure 15. Multi-objective tradeoffs between cost, sediment reduction and duck production for simulated conservation landscapes modelled for the Le Sueur River Basin.

Using this approach, we observed mostly synergistic relationships between duck production and sediment reductions, as a function of conservation options on the landscape. However, we did observe some tradeoffs; mainly, considerable support for duck habitat only occurs at higher sediment reductions, as wetland restorations become increasingly incorporated into the model (Figure 15).

We are also working to account for changes in ecosystem services that could arise from management decisions related to nutrient and sediment reduction agricultural landscapes by quantifying the impact of conservation options on pollinator habitat (Table 2). Benefits to pollinators can subsequently be included as criteria when optimizing modelled conservation landscapes. Commodity crops such as corn and soybean are considered to be poor habitat for pollinators (Lonsdorf et al. 2009; Kennedy et al. 2013; Koh et al. 2016), although some management practices could provide some resources. When commodity crops are intensively managed, they provide almost no forage resources because other plants, such as weeds, are not present. If some cover crops are planted or less intense management allows some flowering weeds to grow, the crop field could provide some floral resources. Tilling the soil is particularly detrimental to ground nesting bees (Winfree et al. 2009; Williams et al. 2010), so a switch to no-till practices could amend that. Most other practices in commodity crops, such as fertilizer management and grass waterways are unlikely to provide any additional pollinator habitat. Buffer strips could provide some habitat if they consisted of prairie plants which would provide pollinator forage resources. Typically these changes in management would not have much impact if only done in one field because pollinator abundance is driven by landscape level (multiple field) processes. The biggest improvement would occur if the land were retired to prairie.

Table 2. Impact of conservation management options for nutrients and sediment on pollinator habitat.

Management Options	**Hydrologic Functions**			
Tillage Mgt Options	**Pollination**	**Primary**	**Secondary**	**Tertiary**
Reduced Tillage	Improves ground nesting slightly	↓ Erosion	Trap sediment	↓ Nutrients
No Till	Improves ground nesting			
Ag Field Mgt Options				
Fertilizer management	No impact	↓ Nutrients		
Grass waterways	No impact	Trap sediment	↓ Flow	Habitat creation
Cover Crops	Slightly better – 2%	↓ Nutrients	↓ Flow	Habitat?
Near Channel Mgt Options				
Buffer strips	No real impact unless they are prairie	Trap sediment	↓ Nutrients	Habitat creation
Water Cons. Mgt Options (upland & in channel)				
Water control basins	No impact	↓ Flow	Trap sediment	↓ Nutrients, Habitat creation?
Shallow marshes	No impact	↓ Nutrients	↓ Flow	Habitat creation
Land retirement Options				
Land retirement	If prairie, creates pollinator habitat; general reduced intensity is helpful	↓ Nutrients	Habitat creation	

4.2. Improving multi-objective spatial optimization results under epistasis with benefit to cost ratios

Use of coupled simulation-optimization approaches using optimization heuristics (e.g., evolutionary algorithms) is fairly well established and is likely to continue in the future both as a research methodology approach and a source of decision support for landscape management. The adoption of these methods involves non-trivial costs in terms of custom programming and model/data management but these may be decreasing in the future as more researchers invest in the development of relevant skills and as better computational tools become available (Maier et al., 2014). The broader evolutionary algorithm (EA) and engineering literature has discussed some ways of improving EA performance by different seeding methods (e.g., Bai et al., 2015).

In addition to the computational challenges of EA approaches, many biophysical models exhibit epistasis, where a conservation action impacts the effectiveness of a conservation action elsewhere. The ability of EAs to handle epistasis was discussed by Reed et al. (2013) and Maier et al (2014), with a recent direct application for BMP optimization by (Wu et al., 2018).

Realistic landscape management optimization problems, once appropriate decision-making units and conservation actions are outlined, are characterized by a very large search space. Under simplifying assumptions on the nature of biophysical process models, exact optimization can address large decision and search spaces. Thus, modellers often face a tradeoff - Heuristic approaches represent the consequences of landscape actions in a manner exactly consistent with process model assumptions, but we cannot be assured of the optimality of solutions obtained. Meanwhile, exact approaches assure us of optimality of the solutions obtained yet introduce error which is due to the simplification of the underlying process (model); there is always error associated with representing reality in an incomplete way.

Some exact optimization methods have a close connection to the intuitive (and still fairly often used, especially in applied conservation contexts), benefit-to-cost ratio ranking rule. Specifically, under certain conditions, solutions obtained by ranking decisions in descending order by their (weighted, in case of multiple objectives) benefit-to-cost ratio, are members of the efficient Pareto-frontier.

In our application, we employ a hybrid method where solutions obtained via benefit-to-cost rankings serve as starting points for an evolutionary algorithm employing a novel epistatic biophysical model. While ranking-based solutions do not survive in the final Pareto-front, their inclusion improves both the performance of the evolutionary algorithm and the interpretability of results for the environmental economics and conservation community. Our application utilizes a variety of landscape conservation actions, including wetland restoration, cover crops, and fertilizer management and a suite of biophysical models assessing the effects of those actions on nutrient and sediment reductions in the study watershed (LeSueur River Basin, Minnesota, USA).

4.3. Tradeoffs in conservation modelling for diverse endpoints

P. Hawthorne, E. Lonsdorf, and B. Dalzell

Through the supplemental funding provided by NSF, we have connected the work in Minnesota with a similar project in Iowa to build connections with NGOs. This project, a partnership between the University of Minnesota, The Nature Conservancy and World Wildlife Fund, focuses on the Wolf Creek watershed in Iowa, and provides a springboard for the broader application of the biophysical and policy lessons learned in Iowa to the larger scale efforts underway for the Minnesota River Basin.

We applied ecosystem services valuation functions for air quality, water quality, and climate to estimate the social benefits of adopting best management practices (BMPs) in the Wolf Creek Watershed, along with economic costs to farmers. We compared the spatial allocation of BMPs and resulting social values when optimizing BMP choice for different sets of objectives. We found a strong trade-off between nitrate loading reduction and total social value (Table 3; Figure 16). The practices selected and spatial patterns were quite different depending on the objectives. For example, a landscape optimized to provide the highest total public value for water quality only resulted in a 4% reduction in nitrate.

Table 3. Reduction in nitrate (N) and value of ecosystem services derived from modelled landscapes optimized for each objective.

	20% N reduction budget equivalent: $1.63 million		41% N reduction budget equivalent: $4.52 million	
Objective	**N reduction (percent)**	**Total public value (million $USD/yr)**	**N reduction (percent)**	**Total public value (million $USD/yr)**
N reduction	**20%**	**2.10**	**41%**	**6.41**
Water quality ($)	**4%**	**4.04**	**13%**	**7.67**
Air quality + GHGs ($)	**4%**	**4.38**	**15%**	**7.96**
Total social value ($)	**4%**	**4.97**	**14%**	**9.87**

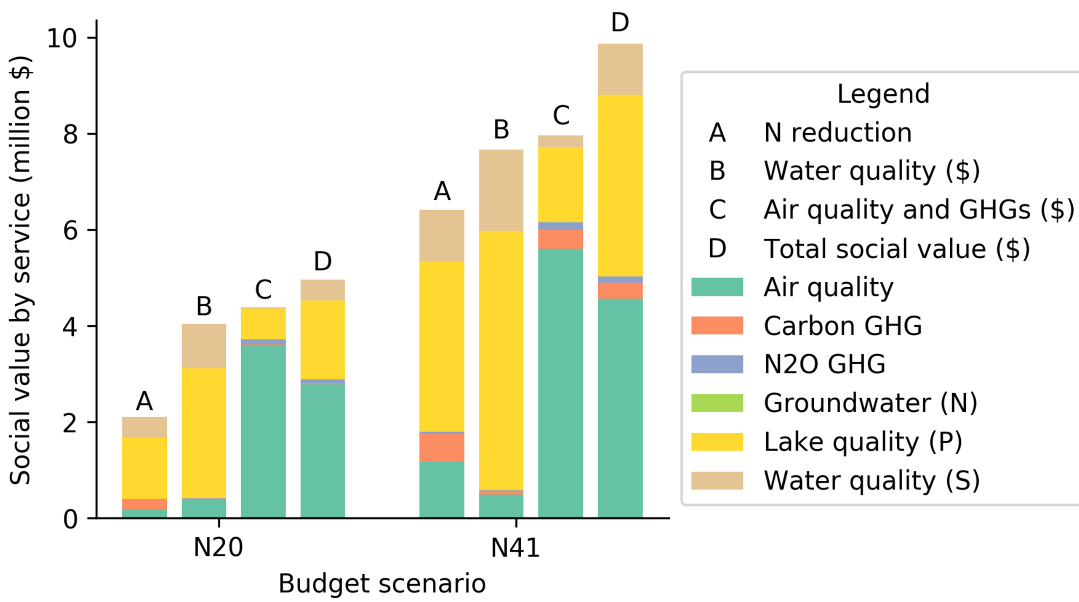


Figure 16. Total social value by individual service, under two different budget scenarios (i.e., budget required to reduce N by 20% and by 40%), under four different scenarios (A-D). Each scenario represents a landscape configured to optimize the value of an individual ecosystem service: A – N reduction; B – Water quality; C – Air quality; D – Total social value. All ecosystem services have been translated into dollar terms.

4.4. Evaluating multiple policy mechanisms for cost effective agri-environment management schemes

P. Hawthorne, E. Lonsdorf, and B. Dalzell

We have connected ecosystem services modeling described in section 4.3 with an agent-based policy analysis framework to assess cost-efficiency of different policy approaches for approaching the first-best “frontier” landscapes. We evaluated changes to current agri-environment schemes (AES) that could improve their cost-effectiveness. Three key elements were spatial targeting, coordination between programs, and a new approach that uses simple machine-learning based classifications to refine policy instruments. We evaluated increased costs relative to the first-best policy from policies with uncoordinated activities (100%) and with flat-rate payment models (36-133%), both characteristics of current Farm Bill programs. We demonstrate a simple spatially-targeted per-acre payment policy that increases costs only ~30% relative to the best-case alternative (Table 4).

Table 4. Cost of potential policy approaches to achieve nitrate reduction targets.

	Reduction target: 20%		**Reduction target: 40%**	
Policy	**Cost (million $/yr)**	**Cost increase over ECT**	**Cost (million $/yr)**	**Cost increase over ECT**
Exact cost targeting	1.63	0%	4.27	0%
Exact cost targeting multi-program	3.25	100%	8.54	100%
Uniform payment	3.79	133%	8.63	102%
Uniform payment by HRU class	2.24	37%	5.32	**25%**
Pay for performance	2.21	36%	8.11	90%
Pay for performance by HRU class	2.13	**31%**	6.87	61%

We are additionally working to determine how patterns of land ownership might interact with policy analysis outcomes to affect interpretation of the results. We've gathered publicly- available land ownership records for Wolf Creek and are exploring how nitrogen, phosphorous and sediment contributions vary among ownership, what proportion of each owner's land would be enrolled as a function of AES program budget and the characteristics of their land (Figure 17).

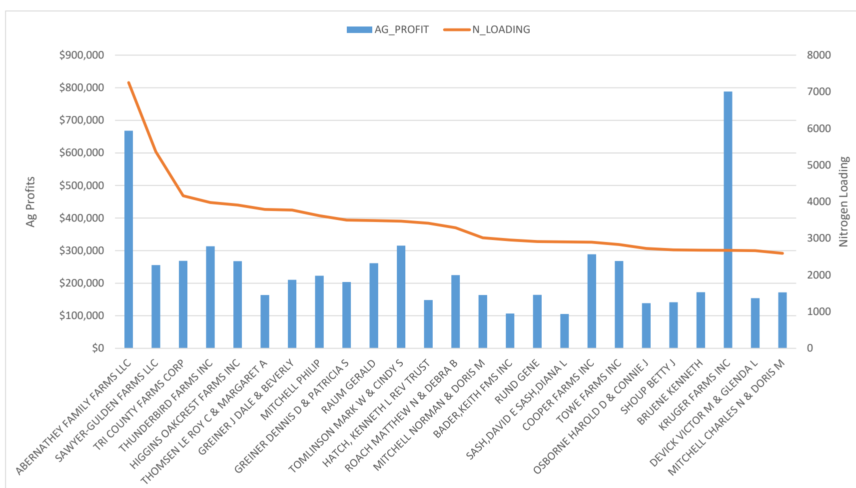


Figure 17. We aggregated the total nitrogen loading in Wolf Creek by land ownership and are plotting the loading (orange line) and expected agriculture profits (blue bars) for conventional farming. Note the one farm with the highest profits (Kruger Farms Inc) does not have the largest N loading value and the ratio of profits to N-loading is one measure of initial efficiency of farming and targeting for the AES programs. Ideally, targeting would first be to farms with inefficient practices (low profit to N-loading ratios).

5. Engaging and educating the public

5.1. Coherent systems learning using nitrogen and carbon cycling as subject matter

N. Ghalichi and G. Roehrig

One of the central questions in ecology is how the sum of local ecological processes gives rise to ecological patterns at a larger spatial scale. Systems thinking is important because it allows the consideration of how objects interact within a system. It was theorized that one way of advancing students' system thinking is to incorporate learning about the biological and chemical processes that connect objects within the system. A curriculum was developed that asked students to investigate the mechanisms behind molecular transformations within the nitrogen cycle. This curricular unit focused on the impact of agricultural practices on ecosystems. It was implemented during a one-semester long elective course on wild-life ecology available to high school seniors. This presentation intended to investigate how the ways in which students connect objects reflect their systems thinking. In order to evaluate the effect of instruction in this unit on systems thinking, students were provided pre- and post-concept maps that included molecular and macro level objects from nitrogen and carbon cycles within the context of agroecosystem. Forty-two concept maps (21 pre- and 21 post-) were coded for accuracy of connections, and assessed for the patterns of connections. Based on patterns, a theoretical framework was developed to show how students connect objects within and across nitrogen and carbon cycles.

Development of this framework addressed multiple goals. First, it provided a clear definition for broad categories of links that connect objects within the nitrogen and carbon cycles (intra-subsystem) and across the two cycles (inter-subsystem). Second, it identified whether students are linking objects at the macro and molecular levels or only on one level, reflecting students' ability to move across these two levels. This framework served as a basis to explore patterns in the ways in which students connect matter objects within and across subsystems. Few concept maps demonstrated nitrogen intra-subsystem category in the pre-assessment (9 out of 21), while most students connected objects within the carbon cycle (20 out of 21). This difference probably reflects a relative lack of familiarity with the nitrogen cycle as opposed to the carbon cycle. On the post-assessment, more concept maps (20 out of 21) demonstrated nitrogen intra-subsystem category. The number of concept maps that showed connections within the carbon cycle remained about the same pre- to post-assessment (21 out of 21). The shift to more nitrogen cycle connections in post-assessment concept maps was accompanied by a shift in the number of concept maps making inter-subsystem links across nitrogen and carbon cycles (from 3 pre-instruction to 17 post-instruction). Moreover, there is a pattern between the level of complexity in intra-subsystem links within the nitrogen cycle and ability to link nitrogen and carbon cycles. Sixteen out of seventeen post-instruction concept maps that show links connecting macro and molecular scales within nitrogen cycles also create inter-subsystem links connecting nitrogen and carbon cycles. The research suggests that instruction in a unit that focuses on developing understanding of the mechanism connecting objects in one cycle (the nitrogen cycle) can improve students' understanding of how objects are connected within that cycle. Concomitantly, students show improved understanding of how two cycles are connected within an ecosystem. Thus, pedagogically, developing mechanistic understanding within a subsystem has the potential to increase systems understanding at a larger scale, an educational principle that is potentially broadly applicable to the undergraduate biology curriculum. Moreover, the theoretical framework on object connections within and across systems is an instrument that could be used by instructors and researchers to evaluate students' systems thinking at both the high school and college level.

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