Upper Mississippi River Basin Association

Water Quality Task Force
Virtual Meeting

September 28-29, 2021

Agenda

with

Background

and

Supporting Materials

Upper Mississippi River Basin Association
Water Quality Task Force Virtual Meeting

September 28-29, 2021

Agenda

Connection Information

- Web, video conferencing, click on the following link:
  - September 28: https://umrba.my.webex.com/umrba.my/j.php?MTID=m291b4655af8df3bd57b5a4afd7447ae6
  - September 29: https://umrba.my.webex.com/umrba.my/j.php?MTID=m332d2cd7e876422b2632b72f1e084b5f
- Dial-in number: (312) 535-8110
  - September 28 access code: 182 771 1053
  - September 29 access code: 182 652 7413
  - Passcode: 1234

September 28, 2021

Time (CDT)	Attachment	Topic	Presenter
1:00 p.m.		**Welcome and Introductions**	***John Hoke,*** *MODNR*
1:05	**A1-14**	**Approval of the June 8-9, 2021 WQ Executive Committee and WQ Task Force Meeting Summary**	***All***
1:10		**UMRBA WQ Task Force Updates**	
	B	• How Clean is the River? Report	***Erin Petty,*** *MODNR*
		• Reaches 8-9 Pilot	***Dan Kendall****, IADNR*
1:25		**Harmful Algal Blooms**	
		• State and Federal Updates	***All***
		• Cyanotoxin Mixture Models	***Dr. Vicki Christensen,*** *USGS*
2:40		**Break**	
3:00		**Harmful Algal Blooms (Continued)**	
	C1-14	• Environmental Factors Controlling Phytoplankton Dynamics	***Shawn Giblin,*** *WIDNR*
3:30	**D**	**Water Quality Monitoring Plans**	
		• Missouri	***John Hoke,*** *MODNR*
		• Iowa	***Dan Kendall,*** *IADNR*
		• USEPA Region 7	***Steve Schaff****, USEPA R7*
		• Discussion	***All***

(Continued)

September 28, 2021 (Continued)

Time (CDT)	Attachment	Topic	Presenter
4:20		**CWA Program Updates** • 305(b) and 303(d) Consultation • TMDL Updates	***All***
5:00 p.m.		**Adjourn for the Day**	

September 29, 2021

Time (CDT)	Attachment	Topic	Presenter
8:00 a.m.		**Reflection**	***All***
8:05	**E1-13**	**The Best Places to Tackle U.S. Farm Nitrogen Pollution**	***Dr. Eric Roy,*** *University of Vermont*
8:35	**F1-8**	**Constructed Wetlands are Best Protection for Agricultural Runoff into Waterways**	***Dr. Amy Hansen,*** *University of Kansas*
9:10		**Nutrients** • State and Federal Updates	***All***
9:45		**Chloride Technical Workgroup**	***Sydney Weiss,*** *USEPA*
10:20		**[Break]**	
10:35		**Hazardous Spills Strategic Planning**	***Mark Ellis,*** *UMRBA*
10:50		**HAB Notification at Recreational Sites**	***Gregg Good,*** *Illinois EPA* ***Mark Ellis,*** *UMRBA*
11:45		**Administrative Items** • Future Meeting Schedule	***All***
12:00 noon		**Adjourn**	

ATTACHMENT A

Draft Summary of the June 8-9, 2021 WQEC-WQTF Joint Virtual Meeting

(A-1 to A-14)

Upper Mississippi River Basin Association Water Quality Executive Committee and Water Quality Task Force Virtual Meeting

June 8-9, 2021

Draft Highlights and Action Items Summary

Tuesday, June 8

Approval of the January 27, 2021 WQTF Draft Meeting Summary

The UMRBA Water Quality Task Force (WQTF) approved the January 27, 2021 draft highlights and action items summary pending an edit to Illinois EPA's Clean Water Act (CWA) update on page A-8.

UMRBA Meeting Review

January 26, 2021 WQTF Technical Session and May 6, 2021 Technical Session Follow-up

Before diving into the meeting review, Lauren Salvato announced that UMRBA has a new and updated website. She encouraged participants to explore the new features, and to be aware that UMRBA staff are still adding pages, resources, and content.

Salvato reflected that the goals of the January 26, 2021 WQTF Technical Session were to 1) consider the benefits and drawbacks of using Environmental Monitoring and Assessment Program Great Rivers Ecosystem initiative (EMAP-GRE) vs. Long Term Resource Monitoring (LTRM) methods for the Interstate Water Quality (WQ) Monitoring Plan, and 2) discuss the applicability of the total suspended solids (TSS) supplementary indicator for the Reaches 8-9 pilot. As a reminder, the EMAP-GRE method was selected for the UMR Interstate WQ Monitoring Plan for its focus on CWA-type assessments. The Reaches 0-3 pilot (northern pilot) utilized the EMAP-GRE method, while the Reaches 8-9 pilot (southern pilot) is also utilizing the EMAP-GRE method but has opted to use the LTRM approach for fish assemblage monitoring. Part of the reason for making the switch was that the transects in the EMAP-GRE method consist of 1-1,000 meter stretch. The Reaches 0-3 pilot field staff had to break halfway through the transect to keep fish healthy and for the crews to take a break if needed. Andy Bartels from Wisconsin DNR found that breaking up the transects into 4-250 meter transects did not greatly affect the index of biotic integrity (IBI) scores. The other aspect is that the LTRM method is widely adopted across other parts of the UMRB (see table below). Unless otherwise stated, the number of samples and agency represents annual sampling.

Reach	Number of Samples, Agency	Reach	Number of Samples, Agency
2		15	
3		16	15, Illinois NHS, 12, Iowa DNR
4	24, LTRM	17	12, Illinois NHS
5		18	15, Illinois NHS, 13, Iowa DNR
5A		19	27, Illinois NHS
6		20	12, Illinois NHS
7		21	12, Illinois NHS
8	12, LTRM	22	
9	6, Iowa DNR (alternate years)	24	
10	12, Iowa DNR	25	18, Illinois NHS
11	4, Iowa DNR (alternate years)	26	24, LTRM
12	4, LTRM	Chain of Rocks	21, Illinois NHS
13	12, LTRM	Kaskaskia Confl.	30 Illinois NHS
14		Cape G.	24, Missouri DOC

For total suspended solids (TSS), Salvato reminded participants that the analysis is supplementary to the dual assemblage fish and macroinvertebrate analysis associated with the aquatic life use assessment. TSS median values equate to a good, fair, or poor condition and serve as a tie breaker if the dual assemblage disagrees. The question that the Reaches 8-9 pilot considered was given the higher TSS values in Reaches 8-9, is the river automatically in "poor" condition, or do another set of thresholds make sense for the lower impounded UMR?

Following the meeting an initial set of research questions and needs were compiled:

EMAP GRE vs. LTRM

1) Can the LTRM design meet CWA needs?

2) Can we validate the use of the Great Rivers Fish Index (GRFIn) IBI for both EMAP-GRE and LTRM methods? Is the tool sensitive enough to respond to changes in condition?

3) What investigations can be made on the IBI rating categories?

4) Aggregate Illinois Natural History Survey data to compare the GRFIn scores with those produced with Reaches 8-9 pilot data.

TSS

1) Explore the needs for TSS thresholds in different areas of the UMR (e.g., lower impounded, Open River).

The goal of the follow-up WQTF call on May 6, 2021 was to 1) refine the research questions, and 2) discuss logistics e.g., timeline, availability of datasets, sources of funding. The WQTF agreed to a few next steps. For EMAP-GRE vs. LTRM to 1) seek outside input on research questions, and 2) recruit university interest in graduate students working on the research questions. For TSS, to determine if there is surplus in the Reaches 8-9 pilot budget, and if so, investigate the potential for TSS thresholds in the lower impounded and open river reaches.

Jim Fischer said that from a purely pragmatic standpoint, LTRM methods cover a wide range of the river. If there is a way to utilize the method, it makes sense. Karen Hagerty supports the use of the LTRM methods. For TSS, she asked whether the Missouri River confluence reduction in sediment is being considered. Salvato replied that the analysis is not that far along, but they will keep that in mind.

Nutrient Reduction Strategy (NRS) Progress Tracking Workshops April 9 and 13, 2021

Salvato reviewed that the objectives of the workshop were to 1) strengthen regional collaboration among individuals and organizations involved in nutrient reduction strategy development, 2) exchange information regarding how the UMR states track nutrient reduction progress and associated challenges, and 3) identify priorities and actionable items for UMRBA and the states to pursue collaboratively. To enable detailed discussion, four topics were selected over two three-hour workshop sessions:

1) Measuring Nutrient Reduction from nonpoint source (NPS) BMP Implementation

2) Capturing Private Investment in BMPs

3) Monitoring Water Quality to Detect Changes in Nutrient Reduction

4) Incorporating New Datasets

The workshop itself was by invitation only. In addition to state agencies working on the NRS, other participants included university and extension staff, county conservationists, and federal partners from USEPA and NRCS. The next steps are to put a survey together for feedback from workshop participants, determine topics for future in-person meetings, and distribute a summary of the workshops.

Adam Schnieders thanked UMRBA staff for putting the meeting together. There was a good exchange of information and ideas. Since the workshops occurred, Iowa has had a spin off meeting with Minnesota. It was nice to relate to the other states on similar challenges faced with regard to nutrient reduction progress tracking. And the virtual meeting format was set up well to facilitate discussion. Chris Wieberg agreed and said that Missouri benefited from the workshop.

<u>TSS in the Upper Mississippi River</u>

Pam Anderson provided a high-level overview of the TSS impairments in the Upper Mississippi River (UMR). The UMR in Minnesota refers to the reaches near the headwaters of the Mississippi River, near Itasca State Park. Approximately 140 miles of river are exceeding the 15 mg/L TSS standard. The standard is for April to September and is a 10% exceedance.

When looking at the biological communities across the state, fish communities are in good shape even if they are located in the most impacted river systems. The macroinvertebrate tool is still in development for larger rivers. It will include criteria for use of Hester Dendys, and is based on Wisconsin's tool. Anderson said that PCA is finding that across in the state, in sediment laden rivers, increases in tolerant or very tolerant taxa are observed. However, it does not appear to be bringing the IBI score to an impairment threshold. While there is a TSS threshold, there is not necessarily a corresponding response in biological community. It may be that the impacts are not yet being observed. Anderson noted that PCA does not have a tool for mussels or plants. The TSS value is okay if it does not have a 1:1 relationship with the two biological assemblages that are collected.

In terms of sources of TSS, the permitted sources are not huge contributors. On the non-permitted side, sources include glacial lake deposits, which are highly erodible fine sediments. This is a major driver in this part of the state. Ditching is another source, in which instream erosion occurs and the stream channel moves. This area of the state does not have a lot of elevation gradient. And there is plenty of near stream disturbance from pastured animals. These areas of the state were historically pine forest. In order to make meaningful reductions, the TMDL report identified priority areas both on the non-regulatory and regulatory side.

In response to a question from Shawn Giblin, Anderson replied that the lead for the report is either biologist Ben Lundeen or project manager Bonnie Finnerty. Giblin said that Wisconsin DNR is forming a group to look at TSS criteria in Wisconsin. In response to a question from Salvato, Giblin replied that this is a state-wide effort and the group will first look at large rivers.

<u>Nutrients</u>

<u>State Updates</u>

Minnesota – Anderson reviewed that Dave Wall is lead on NRS work for PCA. The agency is working on compiling guidance to integrate NRS into PCA's watershed work. Anderson said the goal is to be able to ensure that nutrient reduction at a national level is tied to local watershed plans and implementation. Minnesota PCA has partnered with the University of Minnesota to develop WQ trading documents specific to permitted facilities. The research involves modeling on how to optimize nitrogen and phosphorus reduction.

Another NRS related item is figuring out how to take counts of BMPs and average load reductions to track progress looking back in time as well as forecasting. The Agriculture BMP certification program is gaining a lot of interest. The story map highlights the work producers are doing: https://mnag.maps.arcgis.com/apps/Shortlist/index.html?appid=f5f1c86e75cd48bf9a79b5eccb51d36e. Schnieders read an article about Minnesota achieving record high acres enrolled for the Ag BMP certification program. What is the target and how many acres are enrolled? Kessler responded that she believes Minnesota has more than 750,000 acres and 1,050 producers. Governor Walz has set a goal of a million acres by the end of his term. Kessler added that Minnesota is working on pilot projects to catalyze WQ markets. One is in central Minnesota to develop carbon and nutrient credit markets. The state wants to capitalize on Ag BMP certification success and grow urban/farmer partnership opportunities. There is good momentum so far. Schnieders asked if as more producers participate in the certification program, are they sharing it with their neighboring farmers? Is there an opportunity for cities as well? In response, Kessler said that Minnesota worked with farm business management program data, and they independently found that an Ag BMP certified farms averaged significantly greater net profit then non certified farms for two consecutive years. That type of success and actual money that comes with these practices are going to accelerate the program even more. She believes that the two pilots will help get cities involved. If Minnesota had a credit bank, all of these practices could be ready for people who needed them. They don't always line up geographically and value on the credit, but we see that this presents a big opportunity going forward as well.

Illinois– Good announced that the at the June 10, 2021 Nutrient Monitoring Council meeting, participants will discuss alternative options for the continuation of the USGS super gages. He reminded the WQTF that Illinois EPA has eight super gages, one funded by the Metropolitan Water Reclamation District of Greater Chicago near Joliet. The network was started in support of the NLRS to calculate loads leaving the state. The funding will run out at the end of November 2021, and Good believes a feasible option is to keep a few of the gages going. Chris Wieberg asked whether the Illinois River Basin (ILRB) NGWOS could pay for the super gages. Jim Duncker confirmed that two of the sites are within the Illinois River Basin. He could talk to USGS HQ about directing the funding towards the gages but is aware of potential funding constraints. Salvato asked whether the super gage and loading calculations are comparable. Good responded that the methods are within 7-8% of one another and Duncker confirmed that Dr. Tim Hodson from the Urbana USGS was the lead researcher. Robert Voss asked if Illinois collects phosphorus grab samples. Good said the super gages provide phosphate results, every 2-4 hours. He added there were considerable issues with the phosphate analyte during the first couple years. USGS has played around with the method, and will be looking at new phosphorus analyzers with the ILRB NGWOS. The Illinois EPA ambient WQ sites do include total and dissolved phosphorus collection. Super gages are no doubt expensive but a hybridization may be the best option. Voss contributed that it would be beneficial to see flux and flow at high loading events, especially looking back 10 years and trending high flow events to watershed efforts.

Iowa – Schnieders said it is an exciting time for water. Cities, counties and states are trying to figure out what to do with American Rescue plan dollars. Some cities applied dollars to WWTP upgrades in a few instances, and some are including nutrient reduction technology. The Iowa legislative session recently concluded, and one thing of note was an increase in nutrient reduction strategy funding. The funding would be extended for 10 years and target roughly $20 million towards conservation practices across the state. Schnieders said he hopes that RCPPs will continue to evolve in the state. He would like to better leverage resources and work with watershed coordinators on the source water protection funding from the Farm Bill.

The University of Iowa received funding from the Iowa Finance Authority to test out new technologies at smaller WWTPs, and take existing treatment plants and optimize nutrient reduction. This project is a USEPA priority. Schnieders reminded participants that Iowa is doing a lot of work with nutrient reduction and agriculture-urban partnerships. Four cities in Iowa have MOUs to make investments in the watershed.

Finally, Schnieders thanked the UMRB states for the letters of support provided in the USEPA farmer to farmer grant. Iowa received a grant for cover crop seed production in partnership with the Practical Farmers of Iowa. Schnieders hopes that seed production will double in fall 2021.

Wisconsin – Greg Searle said the next NRS implementation progress report will be complete in spring 2022. Wisconsin does not have plans to update the strategy itself at this time, but will instead focus on the improvement of tracking agriculture NPS. Wisconsin DNR established a watershed restoration team to implement TMDLs. DNR wants to standardize the tracking of implementation and is having conversations with organizations in the state to compare reduction in agriculture BMPs. Two nitrogen workgroups have been formed within DNR with the intent of examining DNR authorities to reduce nitrogen contamination and explore new legislation or initiatives to address nitrogen pollution.

The State's nutrient trends website has updated information on trends and loading for L&D 9. The gage was previously discontinued but is up and running again. The update can be found linked here: https://wisconsindnr.shinyapps.io/riverwq/

Shawn Giblin added that the one of the workgroups will talk about criteria and standards for nitrogen and the other will discuss nitrogen goals for the state. Giblin is developing a manuscript to look at UMR backwaters and potential endpoints for algal toxins. The research will hopefully wrap up in the fall, concluding a second year of data collection on backwater residence time. Another study is being conducted in Trempealeau County, linking to nitrate loading. In response to a question from Salvato, Giblin replied he is interested in presenting the work and will follow up on the progress.

Missouri – Wieberg said Missouri's nutrient lake criteria was developed in 2018. Litigation followed and Wieberg announced that the criteria were upheld and will continue to be implemented.

Missouri DNR is working on rule making and putting a total phosphorus (TP) reduction requirement on point sources (PS) within the state and applying effluent regulations. Wieberg is in the process of setting up stakeholder meetings and going through the rule making process. The domestic wastewater side will not be as much of a challenge. Technology has proven itself to make the reductions feasible for point source phosphorus. The industrial side with meat and food processing, chemical manufacturing, etc. is going to be more challenging. Wieberg and staff are in the process of learning more about the feasibility of reductions. There are opportunities to trade within the watersheds of those facilities. The same facilities are subject to carbon emission credits under the Clean Air Act. Stakeholder engagement will be ongoing through the rest of the calendar year.

The HTF grant used to set up a WQ trading clearing house is coming to an end. The grant money was used to look at the soil and water conservation program and capture the average reduction of conservation practices across a few pilot HUC-8 watersheds. The technical papers are being wrapped up now. The next step would be to do the same work across all 64-HUC 8 watersheds in the state to have a total bank of credits to implement the lake nutrient criteria and facilitate new conservation practices on the ground.

Missouri is working on a revision of its NLRS, and talking to stakeholders during summer 2021 about the NPS side of the nutrient reduction strategy and setting a baseline to establish conservation goals and tracking mechanisms for aspects such as fertilizer that is bought, sold and applied in the state.

Wieberg described that the nutrient criteria rule includes screening thresholds for phosphorus (P), nitrogen (N), and chlorophyll-a (chl-a) and eutrophication factors. Coupled together, the water body qualifies for impairment. Recently, Missouri has been challenged by the amount of data available about eutrophication and its many forms e.g., state agency generated data and citizen complaints. USEPA Region 7 started mining those databases and believes that certain lakes should be impaired. USEPA Region 7 and Missouri DNR are currently deliberating on this matter. Wieberg said that if the agency wants to list the water bodies as impaired it will upset some of their stakeholder groups.

Good asked if Missouri has minimum data requirements on lake impairment for 303(d) listing. Voss replied that at least four samples must be collected of N, P and chl-a in between May and September. Some of the eutrophication factors pull in suspended sediment, a ratio of chl-a to TP, and Secchi depth to determine if lakes are light limited. And there is consideration of allowable exceedance frequencies in the last three years. In response to a question from Good, Voss said regarding data quantity, it is a mixed bag whether there is or is not enough data. Some of the data are fish kill information. Wieberg added that most of the controversy is on Lake of the Ozarks, a popular recreation site in the state. The fish kill recorded that was utilized by USEPA Region 7 encompassed 100 fish, and it was a citizen report that was not verified by any scientists. The actual number of fish killed is unknown, nor is the cause of death. In response to a question from Good, Wieberg clarified this is related to aquatic life use assessments. Voss added that another unusual aspect of Missouri's nutrient lake criteria is that with the eutrophication standards, if one is exceeded in one year, the water is listed as impaired. It is fairly strict when eutrophication factors happen. Any of the five eutrophication factors can be exceeded i.e., pH, fish kills, algal toxin or algal cell counts, limit limitations and fish community data.

Federal Updates

USEPA Region 5 – Micah Bennett reported that the national lake nutrient criteria recommendations will be finalized in summer 2021. There are a lot of priorities for the Biden-Harris Administration that are still being discussed and prioritized. USEPA recently finalized its cyanotoxin preparedness and response tool kit that includes resources for responding to cyanobacterial blooms. The tool kit can be accessed here:
https://www.epa.gov/sites/production/files/2021-05/documents/cyanotoxins-preparedeness-response-toolkit-2021.pdf

Presentations

Soil Loss in the Corn Belt Region

Evan Thaler introduced his work with advisor Dr. Isaac Larsen to quantify rates and magnitude of historical soil loss in the Midwestern U.S. Soil erosion is an undervalued issue, effecting both the human side of food production, and impacts to waterways e.g., nitrogen in the Gulf Hypoxic Zone and excessive sediment delivery. Qualitatively, it is known that soil erosion is a big issue and widespread, but the magnitude of erosion is heavily debated.

The USDA puts out a National Resources Inventory (NRI) every five years. While it is a useful tool for conservation planning it does not provide insights on soil lost since cultivation began. The calculations in the NRI do not include tillage and gully erosion.

There are visible signs of erosion in light color pattern on hilltops and hillslopes, which are indicative of decreasing organic carbon. Thaler and Larsen developed a soil organic carbon index to map out A-horizon soil loss. Once the carbon indices are calculated, the imagery can be classified into different soil horizons. Thresholds are applied to high resolution satellite imagery and then final calculations are made for fields with no-A-horizon. This method was repeated across 28 sites in the Corn Belt region, but a method was needed to scale up estimates to the entire region. Thaler developed a relationship between B-horizon soil exposure and landscape curvature. The data were used because found that A-horizon loss disproportionately occurs on convex hillslopes.

The results were that 35% of the Corn Belt no longer has any A-horizon soil, an estimate far greater than USDA's estimate. The most A- horizon soil losses occur at Iowa/Missouri border and driftless areas of WI. A-horizon losses translate to decreases in crop yields. Estimates include 6% decrease annually, amounting to about $2.8 billion in annual losses. The areas identified A-horizon loss, and does not capture where A-horizon has thinned. This also impacts crop yield.

Thaler believes the erosion driven on convex hilltops is from tillage. A way to estimate the erosion rate can be done using the thickness of soil in a prairie compared to an agricultural field. Using the land transfer records to determine the cultivation timeline, Thaler used the following equation: erosion rate = thickness loss divided by the cultivation time. Scaling this equation up to twenty plus sites, Thaler estimated a median erosion rate of 1.9 mm/year. If you compare historical erosion rates (Thaler and Larsen) with current erosion rates (USDA NRI), the modern erosion rates exceed the historical rate in 68% of the counties.

On a global scale, the Corn Belt erosion rate is in the 99th percentile and comparable to the steepest mountain ranges like the Himalayas. Thaler believes the eroded soil may be accumulated in local depressions, but may be exported to water bodies during larger storm events.

Good asked Thaler to explain his comment on the USDA not including tillage in national erosion estimates. Good knows that USDA will do field inspections and assign categories based on whether a field has crop residue. How is tillage not being considered? Thaler replied that USDA applies a coefficient and looks at tillage in the way that it effects water erosion. It does not consider the mechanical removal of soil. On hilltops, the USDA is saying the drainage is essentially zero and not active on those parts of the landscape. Good commented that another interesting point Thaler put forth was that 35% of the A-horizon has been lost but the NRI says 0% has been lost. Thaler added that the NRI classifies erosion in four phases and phrase four is the complete loss of the A-horizon. Jim Fischer asked whether the hilltops are experiencing more erosion due to wind than water. Thaler replied that the soil is being moved by the plow and soil progressively moves down the slope.

Schnieders said that Iowa actively tracks conservation practices such as cover crops and no-till that change the landscape. Is there evidence that shows erosion rates may be slowing in the last 20 years? Between the Dust Bowl and present day? Thaler is not sure what soil erosion rates look like in the last 40 years. Conservation practices started in the later 1960s and 70s. One way to measure that is taking cesium cores in the soil, which reached peak deposition in the mid 1960s in prairie landscapes and conducting a mass balance equation with the farm field across the road.

Salvato asked the WQ committees if they are aware of RCPPs or other programmatic decisions made in the areas experiencing great soil loss. Schnieders said that Iowa has utilized LiDAR to map practices. In the southern hills of Iowa, a lot of practices such as terraces and no till have been implemented. From the management standpoint, Iowa has been able to use tools like the Agricultural Conservation Planning Framework from USDA ARS to locate where practices can go relative to what has already been implemented. The tool has been able to save time in figuring out what is possible. The information provided in Thaler and Larsen's research is definitely useful and adds to the weight of evidence to continue with landscape changes. Wieberg said over the last five fiscal years, Missouri has cost shared $8-10 million annually on conservation practices in the northern part of the state where there are a lot of agronomic crops. There is a lot of money put into conservation practices annually and there are still challenges associated with losing productive land to erosion. More resources are necessary and research like this helps to bring that to light.

Hydraulic Connectivity for Sediment and Nutrient Sequestration in UMR Floodplains

Chuck Theiling reflected on the study question of what it would take to create 500-year flood protection for the UMRS. He was asked to take a watershed approach to think about protecting communities from flooding impacts.

The health and function of the floodplain has been compromised by development. There is opportunity is to restore floodplain connection using existing infrastructure and nature-based technology to sequester nutrients from the surface water, ultimately reducing runoff to the Gulf of Mexico.

The tools Theiling conceptually modeled for nutrient reduction were floating treatment wetlands and algal turf scrubbers (ATF). Floating treatment wetlands, as the name implies, include a cluster of plants that float on the water's surface. The plants have a concentrated wetland effect that grow a biofilm and support processes like nitrogen uptake and denitrification. They can also provide habitat and operate in areas that natural wetlands do not, e.g., they are less sensitive to TSS and discharge. ATF are mats of native algae that reduce pollutants in waterbodies. Biomass can then be utilized as a fertilizer or turned into a biofuel. The cost of biofuel, however, has not been made cheap enough to compete with oil. Land availability is another constraint.

Theiling's conceptual model for hydroponic nutrient abatement included individually understanding nutrient reduction from wetlands, open ditches, floating islands, ATF raceways, and a combination of the options for two sites Fabius River and Marion County. He modeled the existing conditions, pre-settlement and "pump-off" scenario, in which drainage operations are stopped or reduced and groundwater seeps into wetlands. The main take away is that hydroponic enhancements are effective at nutrient reduction.

Theiling concluded that nutrient trading has a lot of potential to simultaneously improve economic and environmental outcomes. The levee districts in the lower impounded areas of the UMRS are in the best location to generate credits from nutrient reduction.

Bennett asked Theiling to discuss the denitrification rates used for the models. Do you expect the outcomes to be affected by their high variability? Theiling replied the rates are simplistic. He hoped to integrate the values into a habitat evaluation procedures model.

CWA Program Updates

State Updates

Missouri – Wieberg said Missouri is working on the 2022 impaired waters list, but is currently resolving aspects of the 2020 list with USEPA Region 7.

For TMDLs, DNR has been working on revisions over the last few years to ensure that the TMDLs are implementable based on new data and information. Some TMDLs have been approved while others have hit road blocks on the modeling. USEPA Region 7 has had some challenges in the way they run Missouri DNR models.

Minnesota – Kessler said the 2020 impaired waters list was approved by USEPA Region 5 in April 2021. An ongoing point of contention is that tribes in Minnesota have asked that water bodies be listed as impaired for wild rice be included, however, PCA is prohibited by the state legislature to list wild rice impairments, which is in direct conflict with the CWA. USEPA is taking action on its own and has put out upwards of 30 waters in amendment to PCA's impaired waters list on public notice. These waters would include portions of the UMR impaired based on the sulfate standard for wild rice. These areas of the UMR are directly below the drainage area of WWTPs in the Twin Cities Metro Area, which means the ramifications could be more restrictive sulfate permit limits for upwards of 800 WWTPs. Kessler is unsure when the process will end. PCA will need new permit limits for a lot of stakeholders. While that is in progress, PCA has begun working on the 2022 list. In response to a question from Salvato, Kessler said the current sulfate standard was adopted in the late 1970s. She believes the 10 mg/L standard is right for a large majority of the state, but other parts of the state need site specific standards.

Watershed restoration and protection strategies (WRAPs) consider impaired waters and waters that are trending towards impairment. WRAPs are required for 80 major watersheds, and 66 are completed. Each WRAP includes TMDLs, and close to 1,700 TMDLs have been approved in the last 17 years.

Kessler shared a recently approved TMDL on the Shell Rock River, located 12 miles upstream of the Iowa border. The river is a drainage point for city of Albert Lea, the third largest discharger in the state. PCA has been fighting with the city for a decade about eutrophication standards and whether the city needs a limit. The center of the dispute was around data quantity and modeling calibration. PCA argued that the modeling and data collection supported their perspective, and eventually everyone agreed on a technically sound process. Anderson added when the WQ Task Force last met, PCA was submitting Lake Pepin TMDL and it has since been approved by USEPA Region 5.

Wisconsin – Shupryt said Wisconsin's 2020 integrated report was approved and the proposed 2022 list is going out for public comment in July 2021. New components of the report include reporting the number of impaired waters covered by a TMDL and breaking those impaired waters up that are in sub restoration plans.

Some of the listings removed were for mercury fish consumption advisories. That was related to changes in methodology and available data. For TMDLs in the UMRB, DNR is in its second year of monitoring the Fox River and Des Plaines flows into Rock River and eventually the UMR. The TMDL is related to TP and TSS. There may be plans to add monitoring, as some spring runoff monitoring was missed in 2020 due to COVID-19.

Wisconsin DNR is in the early stages of implementation of the Wisconsin River TMDL for TP and TSS. The TMDL covers 20% of the state by land area. The endpoints are to protect downstream reservoirs, and hopefully benefits will be seen by all downstream, including the UMR. Searle added that DNR wants to have a higher success of implementing TMDLs. The agency is using a prioritization framework and the NRS and looking at different parts of the state. The Sugar River TMDL in SW Wisconsin is an example. Prior to development of the TMDL, DNR wants to work with local stakeholders to determine what are the best chances of implementation and success. Searle added he hopes this leads to more success in restoration.

Illinois – Good said Illinois submitted its 2018 report in ATTAINs and it is fully approved. In past discussions, Illinois has had partial approval dating back to 2008, and 10 years later it has been resolved. Illinois will start the 2020/2022 combined report next, with the hope of meeting the April 1, 2022 deadline.

Iowa – Kendall said Iowa received approval for its 2020 list in May 2021. DNR is getting ready to start the 2022 list, and is hoping to meet the submission date. DNR is also working on a fish kill methodology update, and is looking to how neighboring states define the magnitude of a fish kill(s). Iowa has a long history of impairment based on a single fish kill.

Kendall said Iowa submits its data to ATTAINS and Region 7 states are leading the nation in submittals.

Tuesday, June 9

<u>Illinois River Basin NGWOS Science Plan</u>

Duncker described the Next Generation Water Observing System (NGWOS) as part of the USGS Integrated Water Science. The Illinois River Basin is the third basin selected by USGS. Resources are being brought to the Basin to address science questions and observe water quantity and quality issues in a high-density fashion, with a focus on HABs and nutrients. The data garnered from the NGWOS can be transferred to other areas of the Midwest.

Efforts are in year one of a 10-year commitment. During the first year, the major effort is to engage with stakeholders, identify basin priorities, and start purchasing equipment. Stakeholder engagement is valuable during this time.

Duncker review questions provided by UMRBA based on previous stakeholder meetings:

Upgrading three locations for continuous monitoring, where specifically those locations are on the Fox, Calumet and Illinois Rivers.

The three locations are 1) the Fox River at New Munster, WI, 2) the Grand Calumet River at Hammond, IN, and 3) the Illinois River at Starved Rock L&D, IL. The interest in adding continuous monitoring to these stations is to understand the nutrient loads coming into the State of Illinois. It is an easier lift for USGS to utilize existing gage stations where infrastructure and permitting are already in place. The Grand Calumet River is a tributary to the Chicago Waterway. The river is highly industrialized and borders underserved communities. USEPA has also been in the area for the last decade trying to restore portions of the river. The Illinois River at Starved Rock is a dividing point between the Upper and Lower Illinois River. There is a sharp change in slope below Starved Rock, and there have been existing water quality issues including HAB events at the location. Duncker said that the Illinois River is a wastewater dominated system, especially in times of low flow, which can lead to HAB events. There are many unknowns associated with HAB research including what turns a nuisance bloom to a harmful bloom. In response to a question from Kessler, Duncker said the USGS NGWOS program is paying for the installation and maintenance of continuous monitoring.

Whether USGS is utilizing new technology components e.g., next generation fluorometers

Examples of new technology being deployed are multispectral cameras, continuous monitoring, and next generation fluorometers. Duncker hopes that USGS can contribute to a better understanding of HABs. This is partially supported by the proxies group within USGS. The group is interested in measuring fluorescence and correlations with parameters of interest. In response to a question from Salvato, Duncker replied that both grab samples and fluorometer will be utilized to measure the correlation with wastewater compounds.

For HABs, you mentioned plans to add 1) instrumentation at multiple fixed locations, 2) mobile rapid response instrumentation, and 3) intensive sampling. What will you do if you encounter a HAB?

USGS will have fixed and mobile sets of equipment for HAB events. While the fixed and super gages are upgraded for continuous monitoring, USGS can respond to HAB events in inland reservoirs or lakes with the mobile equipment. The cameras can see wavelengths beyond the human eye. Their use can potentially improve early detection of HAB events with better identification of algal communities, and the cameras can be linked to remote sensing data.

USGS hopes to encounter a HAB from the research standpoint. Duncker said that USGS has protocols in place to notify Illinois EPA and the Department of Health. Otherwise, response to HAB events is reactionary once the public records the bloom. The HABs work crew is set to monitor and sample HAB outbreaks intensively. The crew will be led by Dr. Tim Straub from Urbana-Champaign USGS office during summer 2021.

Water chemistry sampling, how much data do you need to establish a baseline? Where are the three strategic locations in FY 21?

The baseline data depends on the research questions. Asian carp migration and water quality was studied in 2015. USGS researchers found that the carp have not advanced past Joliet, or the Dresden Island pool. One theory is that the carp are not moving past the pool because of the water quality coming out of Chicago. Several sites were studied on the Des Plaines, Kankakee, and Illinois Rivers and over 639 constituents were sampled. Of the 639, 280 were detected at least once, and many were emerging contaminants. No one compound was deemed responsible for the stalling of carp migration. The effects of the constituents on biota are still being understood. The constituents could be part of HAB formation, and to begin answering that question, baseline data is needed.

Nicole Manasco said that Corps staff are in the field this morning at Starved Rock and they noticed blue green algae bloom at the marina. Manasco said staff grabbed a bottle to send in for analysis, and are currently filling out an Illinois EPA bloom report. If USGS are ready, there is an opportunity to study a bloom. Duncker thanked Manasco and will pass the message along to the USGS HABs team.

Giblin understands there is a growing body of literature linking emerging contaminants and HAB events. Are there specific compounds that have that linkage? Duncker said specific compounds have not yet been identified. Fischer said there is a lot of interest in macroinvertebrate abundance and emerging contaminants. Is macroinvertebrate sampling occurring with the NGWOS? Dunker replied USGS is collaborating with external research groups, and is interested in timing sampling with WQ monitoring. There is also an interest in fish communities. Duncker reiterated that NGWOS is truly about leveraging federal dollars and aligning external research efforts where possible. In response to a question from

Salvato, Duncker said the professors are Cory Suski at the University of Illinois and Reuben Keller at Loyola University Chicago. Duncker said the NGWOS is also working with colleagues at UMESC on the HABs work to look at historic LTRM data. It is nice to be able to pull in different expertise in USGS offices.

Fiscal Year (FY) 2022 (22) will be a big roll out of field deployment. Duncker will be speaking with the Illinois Nutrient Monitoring Council on June 10, 2021. The NGWOS wants to build upon the work that has been done in the Illinois River Basin for the last five years and the NGWOS study plan will be built upon partners' feedback.

Kessler said states are interested in ways to leverage existing monitoring networks. Minnesota PCA has asked the state legislature for bonding dollars to add continuous monitoring sites with mixed success. Kessler asked Duncker to elaborate on what makes the right combination of USGS partners, LGUs, states and funding for monitoring efforts. In areas where there are not relationships for continuous monitoring, what is missing? Duncker reiterated the value of personal relationships between scientists and managers. Agencies can go off on their own but continuous monitoring is expensive. The investment was made back in 2015 with Illinois EPA, USGS, and other entities to stand up gages.

NGWOS can come into the basin and work at the basin level, but there are real constraints at the national level. Duncker wants to bring USGS federal resources to the local issues and address priorities. USGS has to do it equitably and in a manner that answers Congressional mandates. Wallace asked how UMRBA can build relationships with the Water Mission area and strengthen them. She added that the President's Budget includes a big increase in the Water Mission area, and there may be an opportunity to discuss the support of mutual goals with FY 22 spending. Duncker encouraged UMRBA to communicate with the USGS Water Mission area. He added that when a basin was being selected in the Midcontinent region, letters of support from partners to select the Illinois River Basin went a long way. Wallace suggested two approaches to the WQEC: 1) have a call with USGS leadership and talk about priorities and questions, and 2) write a letter of support related to the FY 22 budget cycle. The letter can describe excitement of being engaged with the Illinois River Basin NGWOS and lay out some priorities in a higher-level way. Is the WQEC interested in the follow-up? Good, Kessler, and Wieberg agreed. Kessler emphasized that the needs of the ILRB NGWOS go beyond the basin. Kelly Warner said if UMRBA writes a letter to the Water Mission area, it would be informative for them to hear which aspects UMRBA is already supporting e.g., the Reaches 8-9 pilot and how new technology can be integrated or extrapolated.

The Impact of Drought on Arsenic Exposure in Private Wells

Melissa Lombard said the arsenic exposure study was conducted in partnership with the US Center for Disease Control and builds off previous work of Dr. Joe Ayotte and collaborators. The study's focus was on natural sources of arsenic in groundwater, not anthropogenic sources.

Arsenic has numerous impacts to human health. The USEPA has a public drinking water standard of 10 µg/L. Private wells are not regulated, and water quality testing falls on the responsibility of the homeowner.

The original model put forth by Dr. Ayotte and collaborators was based off 20,000 domestic well samples. The modeling aspect was brought in to be able to predict the entire country, especially areas that are not well sampled. The most significant model variables included geologic binary indicators, geochemical data, and hydrologic/meteorologic variables (e.g., precipitation and groundwater recharge).

In the new study, Lombard et al., 2021, Lombard took the original model and tweaked it to see how drought would affect the outputs from the model. Drought simulations reduce precipitation and groundwater recharge values. However, if just precipitation decreases, arsenic increases, and if groundwater recharge decreases, arsenic decrease. Lombard and collaborators had to figure out based on different simulations what the ultimate result was for arsenic concentrations. Drought simulation #7 in Table 1 of Lombard et al., 2021 simulated a decrease in precipitation by 25% and decrease in recharge by 50%. This scenario was the most similar to the 2012 drought in the Midwest. Under average arsenic and climate conditions, 2.6 million people are potentially exposed to high arsenic. Using drought simulation #7, the number increases to 4.1 million people. For the UMRB states, the biggest increases in high arsenic in areas with domestic well use include south central Minnesota, north central and central Iowa, and roughly one third of the state of Illinois.

Lombard concluded that the model results suggest that the probability of exceeding 10 g/L in domestic wells increases during drought. During longer durations of drought, the probability of high arsenic tends to increase. She added that a limitation of the study is that this is a national study and local results may vary. Lombard hopes to ground truth the model predictions to verify or dispute the results, and work towards future scenario prediction.

Lombard mentioned other studies of interest to the WQ committees. She is involved in a USGS hydrologic drought prediction project FY 20-24 to predict hydrologic drought e.g., impacts to streamflow, groundwater, and reservoir. Right now, the group is focusing in on metrics to determine when hydrologic drought occurs. They are also interested in conditions leading up to a drought and what occurs when drought is lifted as well as impacts to society and wildlife. The project manager is currently in the process of reaching out to stakeholders, and UMRBA certainly seems like the right audience. USGS wants to know what resources and outputs to provide that are useful to stakeholders. Wallace said she will follow up on the drought prediction study. UMRBA and the states put together a report on the most impactful things to do related to resilience plan and there are a few key things related to drought identified in the report that were also identified in the drought prediction study. UMRBA would appreciate being a key stakeholder.

Salvato asked Iowa, Illinois, and Minnesota what their agency's role is in arsenic exceedances, understanding the Departments of Health likely have the main authority. Anderson said arsenic is naturally occurring in the Red River Basin and impaired waters are identified in the basin. Minnesota PCA does have some arsenic data across the state, but the Minnesota Department of Health has the authority on the drinking water component. Kendall replied that Iowa DNR does not have many impairments for arsenic, but the standard is for arsenic (III). The naturally occurring arsenic is concentrated in the northern region of the state. Kendall asked Lombard if the study looked at various species of arsenic. Lombard said the focus was on total arsenic. She is aware that arsenic (III) on the human health side usually includes collecting blood samples.

Administrative Items

Election of Officers

Salvato thanked Chris Wieberg, WQEC chair and Dan Kendall, WQTF chair for their leadership over the past two years. The next chairs are Katrina Kessler (WQEC) and John Hoke (WQTF).

Future Meetings

- The next WQTF meeting will be convened in person September 28-29, 2021 in Dubuque, Iowa.

Attendance

Gregg Good	Illinois Environmental Protection Agency
Daniel Kendall	Iowa Department of Natural Resources
Adam Schnieders	Iowa Department of Natural Resources
Pam Anderson	Minnesota Pollution Control Agency
Katrina Kessler	Minnesota Pollution Control Agency
Molly Sobotka	Missouri Department of Conservation
Robert Voss	Missouri Department of Natural Resources
Chris Wieberg	Missouri Department of Natural Resources
Jim Fischer	Wisconsin Department of Natural Resources
Shawn Giblin	Wisconsin Department of Natural Resources
Greg Searle	Wisconsin Department of Natural Resources
Mike Shupryt	Wisconsin Department of Natural Resources
Karen Hagerty	U.S. Army Corps of Engineers, Rock Island District
Leo Keller	U.S. Army Corps of Engineers, Rock Island District
Nicole Manasco	U.S. Army Corps of Engineers, Rock Island District
Chuck Theiling	U.S. Army Corps of Engineers, Mississippi Valley Division, Engineer Research and Development Center
Catherine Thomas	U.S. Army Corps of Engineers, Mississippi Valley Division, Engineer Research and Development Center
Eric Summa	U.S. Army Corps of Engineers, Jacksonville District
Micah Bennett	U.S. Environmental Protection Agency, Region 5
Tim Elkins	U.S. Environmental Protection Agency, Region 5
Kim Harris	U.S. Environmental Protection Agency, Region 5
Jason Daniels	U.S. Environmental Protection Agency, Region 7
Amy Shields	U.S. Environmental Protection Agency, Region 7
Aleshia Kenney	U.S. Fish and Wildlife Service, Iowa-Illinois Field Office
Jim Duncker	U.S. Geological Survey, Central Midwest Water Science Center
Kelly Warner	U.S. Geological Survey, Central Midwest Water Science Center
KathiJo Jankowski	U.S. Geological Survey, Upper Midwest Environmental Science Center
Melissa Lombard	U.S. Geological Survey, New England Water Science Center
Ingrid Gronstal	Iowa Environmental Council
Isaac Larsen	University of Massachusetts Amherst
Evan Thaler	University of Massachusetts Amherst
Lauren Salvato	Upper Mississippi River Basin Association
Kirsten Wallace	Upper Mississippi River Basin Association

ATTACHMENT B

How Clean is the River? (6/1989)

[Link to the report https://umrba.org/document/umrba-how-clean-river-report.]

ATTACHMENT C

Harmful Algal Blooms

- **Environmental Factors Controlling Phytoplankton Dynamics in a Large Floodplain River with Emphasis on Cyanobacteria (5/25/2020)** *(C-1 to C-14)*

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RESEARCH ARTICLE

WILEY

Environmental factors controlling phytoplankton dynamics in a large floodplain river with emphasis on cyanobacteria

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Abstract

Harmful algal blooms are occurring in large river ecosystems and at the mouth of large rivers with increasing frequency. In lentic systems, the chemical and physical conditions that promote harmful algal blooms are somewhat predictable but tracking prevalence and conditions that promote harmful algal blooms in lotic systems is much more difficult. We captured two of the most extreme discharge years within the last 20 years occurring in the Upper Mississippi River, allowing a natural experiment that evaluated how major shifts in discharge drive environmental variation and associated shifts in phytoplankton. Statistical models describing significant environmental covariates for phytoplankton assemblages and specific taxa were developed and used to identify management-relevant numeric breakpoints at which environmental variables may promote the growth of specific phytoplankton and/or cyanobacteria. Our analyses supported that potentially toxin-producing cyanobacteria dominate under high phosphorus concentration, low nitrogen concentration, low nitrogen-to-phosphorus ratio, low turbulence, low flushing, adequate light and warm temperatures. Cyanobacteria dominated in 2009 when low discharge and low flushing likely led to optimal growth environments for *Dolichospermum*, *Aphanizomenon* and *Microcystis*. Rarely will a single factor lead to the dominance, but multiple positive factors working in concert can lead to cyanobacteria proliferation in large rivers. Certain isolated backwaters with high phosphorus, low nitrogen, warm water temperatures and low potential for flushing could benefit from increased connection to channel inputs to reduce cyanobacterial dominance. Numerous examples of this type of habitat currently exist in the Upper Mississippi River and could benefit from reconnection to channel habitats.

KEYWORDS
algal blooms, connectivity, cyanobacteria, eutrophication, phosphorus, phytoplankton, Upper Mississippi River

1 | INTRODUCTION

Toxic cyanobacteria blooms are on the rise globally and are occurring in large river ecosystems and at the mouth of large rivers with increasing frequency (Huisman et al., 2018; O'Neil, Davis, Burford, & Gobler, 2012; Paerl & Otten, 2013). Algal blooms cause decreased clarity, reduced macrophytes, oxygen depletion, fish kills and the production of cyanotoxins (Paerl & Otten, 2013). The production of cyanotoxins can result in illness and/or death of exposed pets and occasionally humans. Cyanotoxins are especially concerning when blooms occur in drinking water supply locations (Cheung, Liang, & Lee, 2013). High phosphorous concentration, low nitrogen concentration, low nitrogen-to-phosphorous (N:P) ratio, low turbulence, low flushing, adequate light and warm water temperature conditions are all known to promote cyanobacterial blooms (Baker & Baker, 1979; Dodds & Smith, 2016; Elliot, 2012; Schindler, Carpenter, Chapra, Hecky, & Orihel, 2016; Wehr & Descy, 1998). In lentic systems, the chemical and physical conditions that promote harmful algal blooms are somewhat predictable but tracking prevalence and conditions that promote harmful algal blooms in lotic systems is much more difficult.

The heterogeneity of habitats and continuous movement of water in large river ecosystems make understanding ecological dynamics especially challenging. Expansive lateral connectivity between high-velocity main channel waters and lower-velocity off-channel areas requires application of lentic and lotic models that must then be integrated based on levels of connectivity and water exchange. Annual variation in discharge and water level further complicates understanding in large river ecosystems. Shifting water levels, seasonally and annually, change residence times, connectivity, and riparian/littoral interactions (K. K. Baker & Baker, 1981; Remmal, Hudon, Hamilton, Rondeau, & Gagnon, 2017). Light and temperature also change seasonally, and timing of water level shifts is highly correlated with seasonal changes in discharge relating to thaw and overland runoff. Discharge is directly related to water residence time, water depth and dilution rates (Wehr & Descy, 1998). The multidimensional and ever-changing physical environment in large rivers makes predicting biological dynamics difficult.

Phytoplankton dynamics are tightly tied to variable physical conditions in both lentic and lotic systems. Early work in lotic systems focused heavily on light and residence time as factors driving phytoplankton dynamics (Baker & Baker, 1981). High water velocity washes out phytoplankton, especially cyanobacteria (Baker & Baker, 1979, 1981; Huisman et al., 2004). Differential sinking rates of taxa depend on buoyancy (Baker & Baker, 1981) and the shape of cells (Reynolds & Irish, 1997). Different sinking rates interact with water velocity and turbulence (Bouma-Gregson, Power, & Bormans, 2017; Reynolds, 1994) to drive highly variable taxa-specific light environments for species living in riverine environments (Remmal et al., 2017; Reynolds & Descy, 1996). Seasonal shifts in overland run-off change sediment load and directly impact light availability for benthic and water column primary producers. Overland run-off, suspended solids, discharge, water-velocity, residence times and dilution are all directly linked for many river systems, and each physical factor impacts the types and volume of primary producers present in river habitats.

More recent work acknowledges the role of nutrients in driving lotic phytoplankton dynamics (Bussi et al., 2016; O'Neil et al., 2012). The relationship between nutrients and phytoplankton in lentic environments is well established (Carpenter, Booth, Kucharik, & Lathrop, 2015; Smith, 1986). The heavy application of nitrogen-rich fertilizers to agricultural fields, increasing human waste and increasing atmospheric deposition have resulted in rapid increases in nitrogen (N) concentrations in North America (Galloway & Cowling, 2002; Smith & Schindler, 2009). In some systems, where N-fixation fails to meet phytoplankton requirements, reductions in N loading can bring about a reversal in eutrophication. However, in most cases, phosphorus (P) loading is generally viewed as the predominant driver of increased phytoplankton production, especially for cyanobacteria (O'Neil et al., 2012; Schindler, 1978; Schindler et al., 2016). High nutrient waters are often associated with elevated biovolume of potentially toxin-producing cyanobacteria (Paerl & Otten, 2013).

The ratio of N–P (N:P) plays a role in driving phytoplankton dynamics if either nutrient becomes limiting (Dodds & Smith, 2016; Dolman, Mischke, & Wiedner, 2016; Dolman & Wiedner, 2015). Heavy P loading relative to N loading results in low N:P, which can favour cyanobacteria dominance, especially for N_2-fixing genera (Downing, Watson, & McCauley, 2001; Smith, 1983). Profound seasonal shifts in N and P are frequently observed in the Upper Mississippi River (UMR) and have been related to shifts in biological productivity, ranging from chlorophyll a shifts to transitions in free-floating plant dominance (Giblin et al., 2014; Houser, Bierman, Burdis, & Soeken-Gittinger, 2010).

Prior studies of phytoplankton on the UMR have demonstrated a 40-fold increase in phytoplankton biomass following impoundment in the 1930s (Baker & Baker, 1981). The large increase in phytoplankton biomass post-impoundment is concerning in the UMR since a substantial proportion of UMR phytoplankton is comprised of potentially toxin-producing cyanobacteria (Decker, Wehr, Houser, & Richardson, 2015; Paerl & Otten, 2013). Our data include the growing season of phytoplankton and environmental monitoring data collected in 2009 and 2011 across replicated backwater and main channel sites in Pool 8 of the UMR. We captured two of the most extreme flow years within the last 20 years, allowing a natural experiment that evaluates how major shifts in discharge drive environmental variation and shifts in phytoplankton between extreme hydrologic conditions in the UMR. Analyses include the quantification of potentially toxin-producing cyanobacteria genera to test how these taxa are impacted by environmental variation.

2 | MATERIALS AND METHODS

2.1 | Study site

The UMR consists of a series of navigation pools extending from Minneapolis, MN to the confluence of the Ohio River at Cairo, IL, USA. The 27 navigation dams within this area are low-head dams built to maintain sufficient depth in the river for navigation during the low flow season and were designed to have little impact on discharge or water level during high flow and flood conditions (Anfinson, 2003; Sparks, 1995). Navigation pools are unlike reservoirs, in that, they remain mostly riverine in nature. More detailed descriptions of these contrasting aquatic areas can be found in Strauss et al. (2004).

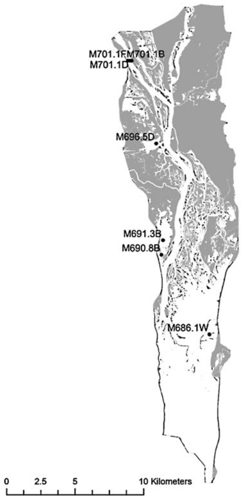

FIGURE 1 Location of study sites within Navigation Pool 8 of the Upper Mississippi River

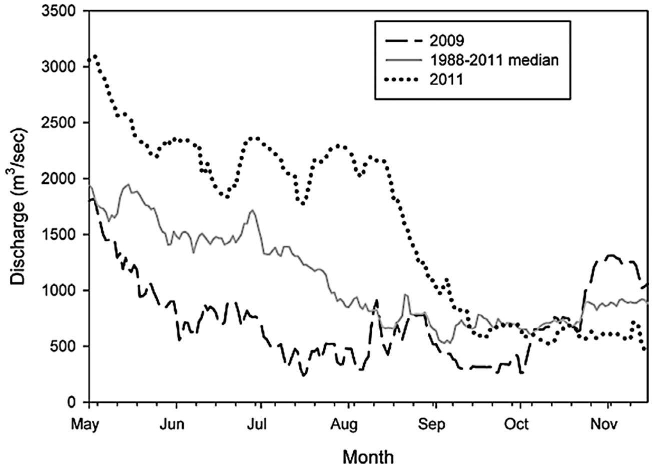

FIGURE 2 Discharge ($m^3\ s^{-1}$) at Lock and Dam 8 during 2009 and 2011 by Julian date. The long-term median (1988–2011) is denoted with a solid line

Collections took place in Navigation Pool 8 of the UMR (Figure 1), a 39 km long, ~90 km^2 stretch of river located between Lock and Dam 7 (Dresbach, MN, USA) and Lock and Dam 8 (Genoa, WI, USA). Pool 8 is a highly heterogeneous stretch of large river habitat where the area of water in backwaters is 19.4 km^2 compared with 12.6 km^2 flowing through the main channel. Pool 8 also includes 36.9 km^2 of open-water, impounded the area upstream of the downstream dam and 13.2 km^2 of the side channel habitat (Strauss et al., 2004; Wilcox, 1993). The main channel is >3 m deep and is characterized by water velocities of 0.20–1 m s^{-1}. Side channels are lotic but exhibit depth and water velocity that are generally less than the main channel. Backwaters typically exhibit very low water velocity (often below detection) and are connected to main or side channel habitats at mean river stage. The average water residence time in Pool 8 is 1.7 days (Wasley, 2000), but this number is influenced by the changing volume of water moving through the main channel—water residence time in backwaters may range from days to months.

2.2 | Sampling and data collection

Our data were collected as part of the Long-Term Resource Monitoring (LTRM) program on the UMR, which has been observing water quality, aquatic plant and fish communities since 1993. Part of the federally mandated Upper Mississippi River Restoration (UMRR) program, LTRM conducts annual assessments using both fixed and spatially stratified randomized sampling designs (Soballe & Fischer, 2004). This study utilized fixed-site sampling data from seven sites within Navigational Pool 8 of the UMR. Three sites (M701.1B, M701.1D, M701.1F) were main channel sites sampled as a lateral transect near Dresbach, MN (Figure 1). There is a lateral gradient among these three sites based on differences in water moving in and out of backwater complexes upstream. Site M701.1B is the most different among the three sites as it is ~2 km downstream of the outlet of a large backwater complex (Lake Onalaska). The four remaining sites sampled (M686.1W, M690.8B, M691.3B and M696.5D) were backwater sites representing a wide range of connection to channel inputs (Figure 1). The composite of these seven sites represents a substantial range of the limnological variability within the UMR and collectively represent a realistic view of water quality condition and, therefore, phytoplankton assemblage, in Pool 8 of the UMR. Analysing all seven sites together was an a priori decision designed to represent a realistic range of limnological conditions across varied levels of connectivity to the main channel in Pool 8. Discharge in 2009 was consistently less than the long-term median, whereas 2011 discharge was consistently greater than the long-term median (Figure 2). The combination of high discharge and low discharge years resulted in a dataset representative of a robust range of environmental conditions.

2.3 | Water quality and discharge

Water samples were collected by inverting a 2-L amber bottle at a depth of 0.20 m at each site to assess water column total suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) concentrations. SS was determined gravimetrically following standard methods (Greenberg, Clesceri, & Eaton, 1992). TN and TP samples were preserved in the field with concentrated H_2SO_4, transported on ice, and refrigerated until analysis. TN and TP were determined colorimetrically using standard methods (Greenberg et al., 1992). Measurements of water depth (m) and water velocity (m sec^{-1}; Marsh-McBirney, model 2000, Flo-Mate, Frederick, MD, USA) were collected at each site. Water temperature measurements were taken at 0.20 m using a multiparameter sonde (Minisonde MS5, Hach Company, Loveland, CO, USA). Further details regarding LTRM field methods can be found in Soballe and Fischer (2004). Discharge data were collected by the U.S. Corps of Engineers at Lock and Dam 8 (LD8) at Genoa, WI and measured in $m^3\ s^{-1}$.

TABLE 1 Wilcoxon signed-rank sum test results indicating the *Z-statistic and p value* for environmental covariates between paired dates in late 2009 and late 2011 in Pool 8 of the Upper Mississippi River

Variable	Late 2009			Early 2011			Late 2011			Late 2009 vs. Late 2011	
	25th	Median	75th	25th	Median	75th	25th	Median	75th	Z	p
Water temperature (°C)	18.4	22	23.8	11.5	16.7	21	20	24	26	−3.86	<.001
TP: Total phosphorus (mg L^{-1})	0.073	0.162	0.186	0.064	0.08	0.092	0.086	0.131	0.158	2	.046
TN: Total nitrogen (mg L^{-1})	0.73	0.96	1.34	2.27	2.62	3.07	0.98	1.49	2.91	−4.65	<.001
N:P: Nitrogen to phosphorus by mass	5.6	7.5	13.3	29.8	35.9	39.9	9.2	12.4	33.9	−3.1	.002
SS: Total suspended solids (mg L^{-1})	1.5	3.1	6.2	9.3	11.2	15.2	1.9	7.1	11.7	−4.05	<.001
Water depth (m)	0.87	1.59	5.20	1.62	2.36	6.55	1.59	2.04	5.60	−4.55	<.001
Water velocity (m s^{-1})	0.000	0.020	0.140	0	0.03	0.86	0.000	0.000	0.460	−2.1	.036
Discharge at lock and dam 8 (m^3 s^{-1})	360	651	706	2,141	2,456	2,908	821	2033	2,186	−4.72	<.001

Note: The early 2011 data, from May 4 to June 13, are presented for demonstrative purposes. The 25th percentile, median and 75th percentile are also presented for each timeframe.

2.4 | Phytoplankton

Phytoplankton samples were collected in conjunction with water chemistry samples, preserved with Lugol's solution and stored in amber bottles at room temperature until enumeration was performed. Samples were collected during 2009 (n = 30; from 1 July to 7 October) and 2011 (n = 84; from 4 May to 7 November). Phytoplankton enumeration was performed during August of 2014. Phytoplankton enumeration was performed by BSA Environmental Services (Beachwood, OH, USA). Phytoplankton slides were prepared using a standard membrane filtration technique (McNabb, 1960). This technique preserved the cell structure and provided good resolution for both the 2009 and 2011 samples, allowing them to be examined at high magnifications. Samples were thoroughly mixed as a part of the filtering process to ensure that the organisms were evenly distributed. A Leica DMLB compound microscope (100×, 200×, 400×, 630×, 1000×) was used for enumerating filtered phytoplankton samples. The magnification used depended upon the size of dominant taxa and presence of particulates. The goal was to count at multiple magnifications such that enumeration and identification of taxa, which vary over several orders of magnitude in size, was achieved. If a sample was dominated by cells or natural units below 10–20 μm, or when cells were fragile and difficult to identify, most of the counting was completed at 630×. The abundance of common taxa was estimated by random field counts. At least 400 units (colonies, filaments, unicells) were enumerated and identified to the lowest possible taxonomic level for each sample. In accordance with Lund, Kipling, and LeCren (1958), counting 400 natural units provided accuracy within 90% confidence limits. In addition, an entire strip of the filter was counted at high magnification (usually 630×) along with half of the filter at a lower magnification (usually 400×) to further ensure complete species reporting. Cyanobacteria were assigned to trait-separated functional groups as defined by Reynolds, Huszar, Kruk, Naselli-Flores, and Melo (2002).

Cell biovolumes of all identified phytoplankton taxa were quantified on a per liter basis. Biovolumes (in μm^3 L^{-1}) were estimated using formulae for solid geometric shapes that most closely match the cell shape (Hillebrand, Dürselen, Kirschtel, Pollingher, & Zohary, 1999). Biovolume calculations were based on measurements of 10 organisms per taxon for each sample where possible.

For taxa with substantial size variation (such as diatoms), size classes were designated arbitrarily to determine average cell size (biovolume). For each taxon, 25 cells were measured from each size class, assuming that sufficient numbers were available. Mean biovolumes within each size class were used to calculate the total biovolume contributed by the taxon to its representative sample (Burkholder & Wetzel, 1989).

2.5 | Statistical analyses

Differences among water chemistry, discharge and site physical characteristics between the two sampling years were analysed using a

Wilcoxon signed-rank test using the coin package in R (Hothorn, Hornik, Van De Wiel, & Zeileis, 2008). Samples were paired from June 29 to October 7 for both years utilizing samples that occurred within 5 days of each other during the different sampling years.

Phytoplankton biovolumes were converted to relative volume based on sampling date and collection location. Canonical correspondence analysis (CCA) was conducted using the matrix of phytoplankton taxa relative volume tested against a suite of environmental variables (water depth, water temperature, water velocity, total suspended solids [SS], total phosphorous [TP], total nitrogen [TN] and nitrogen-to-phosphorous ratio by mass [N:P]). The output of CCA provides quantification of the variability within the plankton community and breaks out how much of that variation can be explained by the specified environmental factors. Rather than present CCA ordinations for each date, we used the breakdown of variation from the CCA analyses to represent how environmental factors impact phytoplankton community assemblage throughout the 2009 and 2011 sampling periods.

Critical environmental thresholds predictive of phytoplankton biovolume were modelled using a regression tree analysis (rpart, R Core Development Team, 2011). The tree was built by selecting the single variable that best split the data into two groups. This

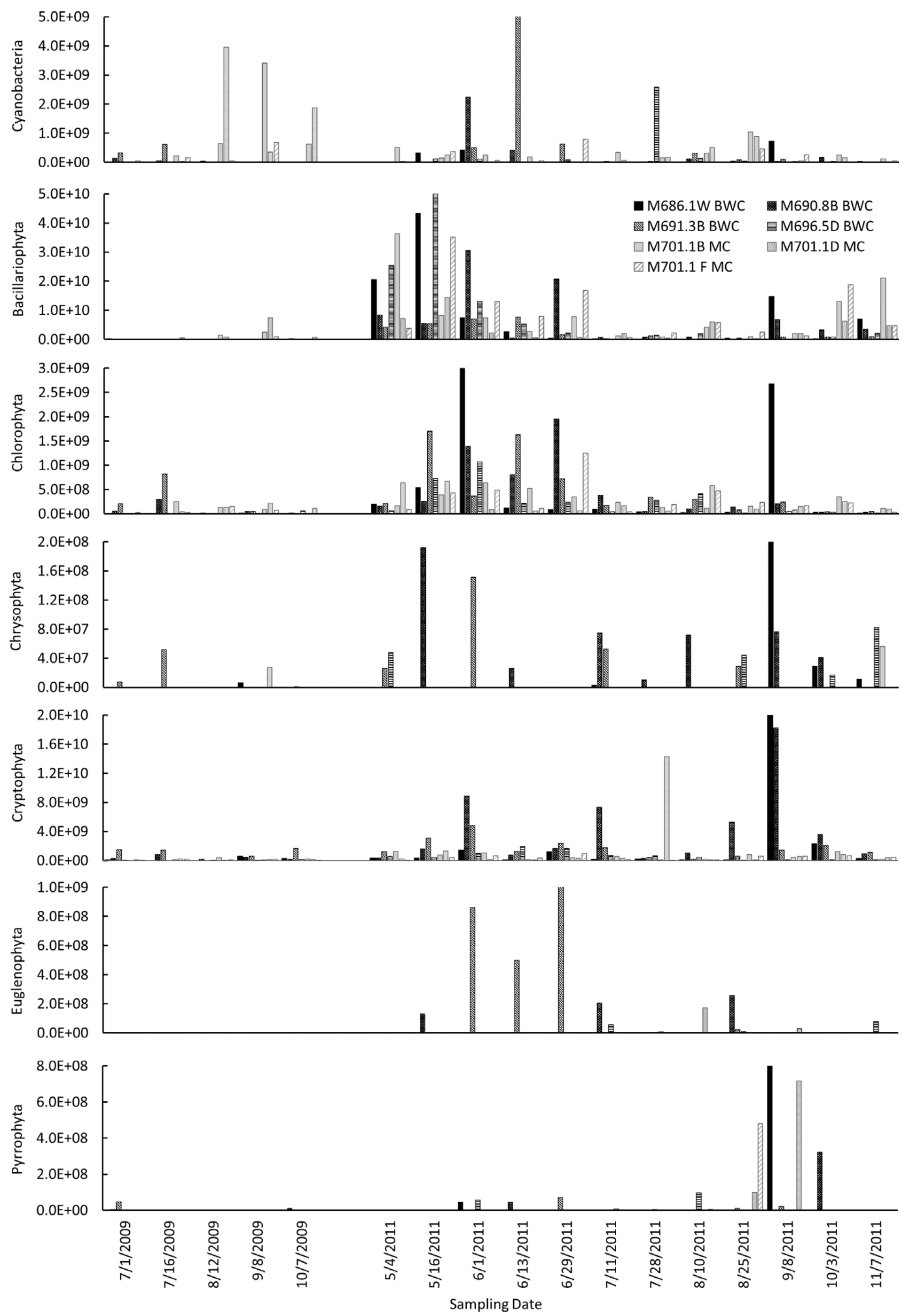

FIGURE 3 Phytoplankton biovolume (in $\mu m^3 L^{-1}$) for "phyla" across dates in 2009 and 2011 from backwater and main channel habitats of the Upper Mississippi River. Backwater (BWC) sites are outlined in black colour and main channel (MC) sites are shaded in grey colour

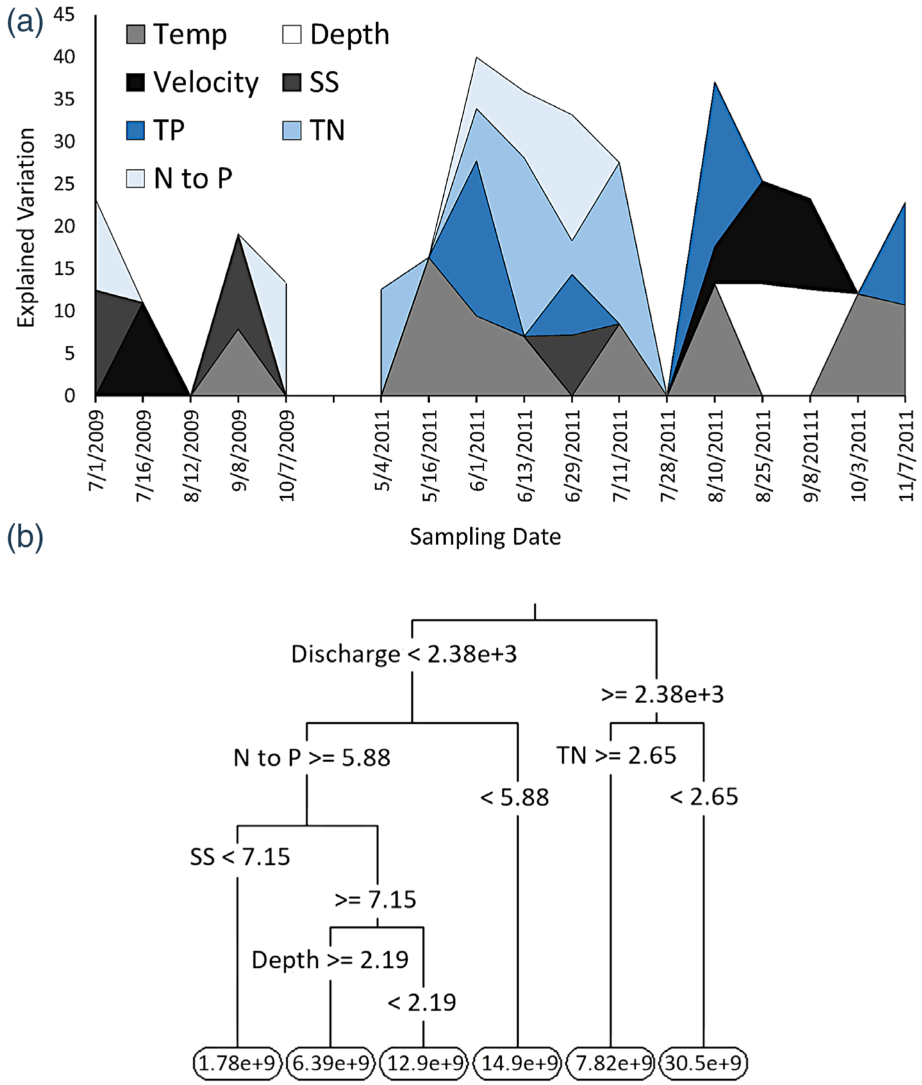

FIGURE 4 Environmental predictors of phytoplankton taxa abundances in 2009 and 2011. (a) Values represent the amount of variation in phytoplankton assemblage explained by each environmental factor as determined using PCA variance partitioning. (b) Regression tree model of predictors across all dates and all habitats. Predicted total phytoplankton biovolume for each branch of the tree is in the lower ovals. The numeric breakpoint for each parameter defining a branch is presented on each split

process was then performed on each sub-group until no further improvement can be made (Therneau, Atkinson, Ripley, & Ripley, 2018). For each model, phytoplankton, toxin-producing cyanobacteria or a specific taxa biovolume served as the response variable tested using uniform environmental covariates (discharge, water depth, water temperature, water velocity, SS, TP, TN and N:P). TP was significantly correlated with soluble reactive phosphorus (SRP; r^2 = .866, p < .05), and TN was significantly correlated with dissolved inorganic nitrogen (DIN; r^2 = .948, p < .05). TP and TN were used for analysis due to being highly correlated with dissolved nutrients and commonly used among the river management community relative to dissolved nutrients. The regression models provide relevant numeric breakpoints for each explanatory environmental covariate.

3 | RESULTS

River discharge differed significantly between 2009 and 2011 (Table 1, Figure 2). With these extreme differences in discharge, physical and chemical environmental parameters also differed significantly between 2009 and 2011. Values for SS, TN, N:P, water temperature, water velocity and water depth were significantly higher in 2011 than in 2009, while TP was significantly lower in 2011 than in 2009 (Table 1). Growth limiting dissolved nutrient concentrations were observed during both years using thresholds suggested by Maberly et al. (2002; <100 μg L^{-1} for DIN and <10 μg L^{-1} for SRP). In 2009 and 2011, respectively, 33 and 18% of samples were below the DIN threshold, while 7 and 32% of samples were below the threshold for SRP.

Biovolume of primary producers differed between 2009 and 2011 (Figure 3). In 2009, volume and taxa richness (# of phyla at each site) were lower, and the river was dominated by cyanobacteria, which reached highest biovolumes in the main channel sites (Figure 3). Overall phytoplankton biovolume and taxonomic richness were much higher in 2011, especially in backwater habitats. Community composition shifts occurred throughout the summer months of 2011. Diatoms (Bacillariophyta) and green algae (Chlorophyta) dominated the early and mid-summer water column while Cryptophyta and Pyrrophyta were more abundant in late summer (Figure 3). It is possible that these

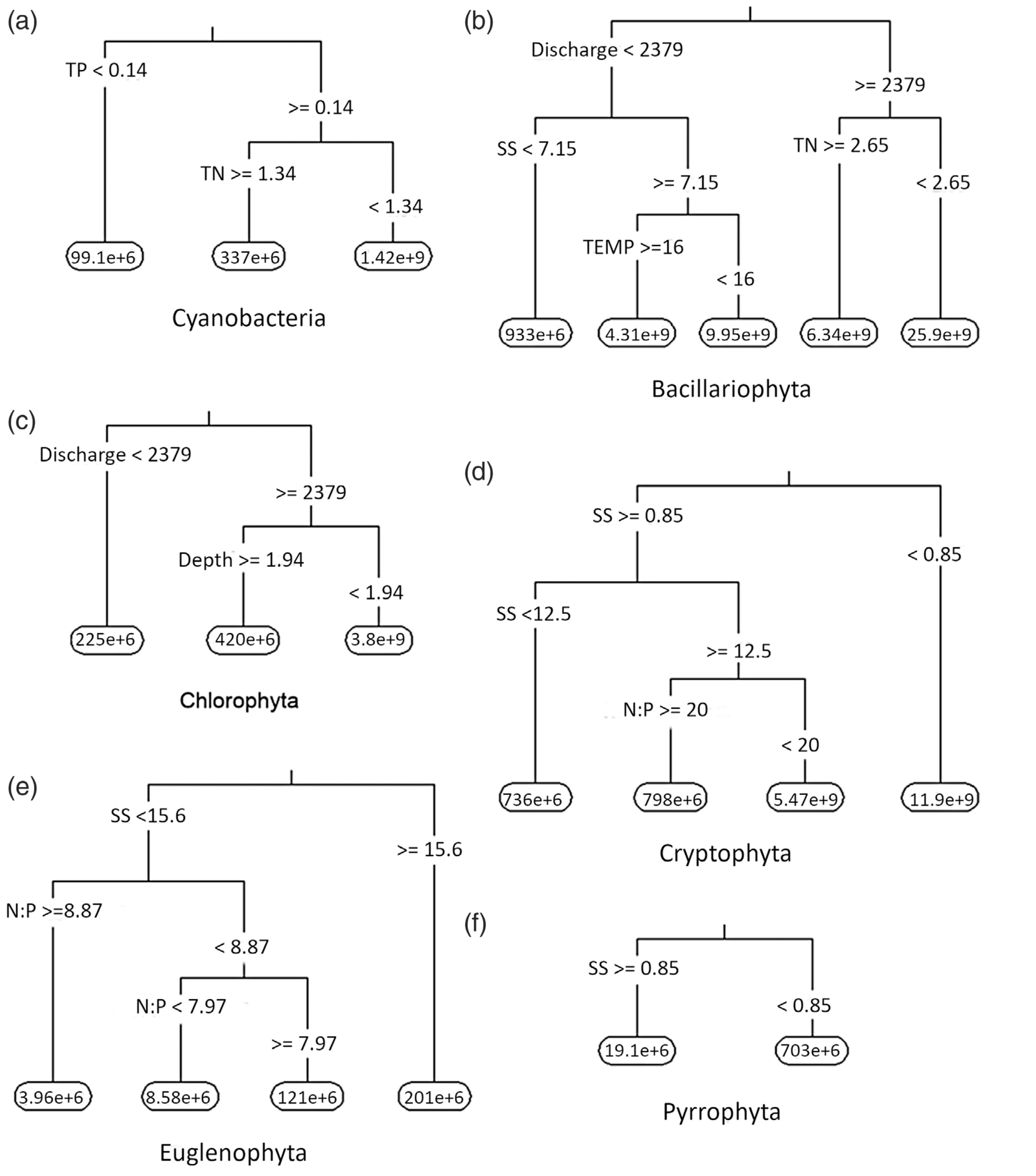

FIGURE 5 Regression tree models predicting specific phytoplankton "phyla" biovolume (in $\mu m^3 L^{-1}$) using uniform environmental covariates: (a) Cyanobacteria, (b) Bacillariophyta, (c) Chlorophyta, (d) Cryptophyta, (e) Euglenophyta, (f) Pyrrophyta. Predicted biovolume for each branch of the tree is in the lower ovals. The numeric breakpoint for each parameter defining a branch is presented on each split

early season taxa were not captured in 2009 since sampling in 2009 did not begin until early July.

Low numbers of phytoplankton and limited taxa representation resulted in low overall variation of primary producers in 2009 (Figure 3). Variation in the 2009 phytoplankton assemblage was mostly explained by differences in physical traits like SS and water velocity (Figure 4a). Higher variation in phytoplankton assemblage was observed in 2011. During the high-water period in early summer 2011 (5/4–7/11), nutrients (TP, TN and N:P) explained the majority of variation in phytoplankton assemblage. In late summer 2011

TABLE 2 Phytoplankton taxa related to explanatory environmental covariates based on general regression tree models

	Higher discharge	Warmer water temperature	Higher TP	Higher TN
General	Higher total biovolume	Lower Bacillariophyta biovolume	Higher cyanobacteria biovolume	Lower total biovolume
Regression	Higher Bacillariophyta biovolume	Higher *Microcystis* biovolume	Higher potentially toxic cyanobacteria biovolume	Lower Bacillariophyta biovolume
Tree	Higher Chlorophyta biovolume		Higher *Dolichospermum* biovolume	Lower cyanobacteria biovolume
Trends	Lower *Aphanizomenon* biovolume		Higher *Aphanizomenon* biovolume	Lower potentially toxic cyanobacteria biovolume
			Higher *Microcystis* biovolume	

	Higher N:P ratio	Higher SS*	Greater water depth	Higher water velocity
General	Lower total biovolume	Higher total biovolume	Lower total biovolume	Lower potentially toxic cyanobacteria biovolume
Regression	Lower Cryptophyta biovolume	Higher Bacillariophyta biovolume	Lower Chlorophyta biovolume	
Tree	Higher Euglenophyta biovolume	Higher *Dolichospermum* biovolume	Lower *Dolichospermum* biovolume	
Trends		Higher *Pseudanabaena* biovolume	Lower *Pseudanabaena* biovolume	
		Higher *Planktothrix* biovolume		

*Higher within study sites; maximum SS = 21.9 mg L^{-1}.

(8/10–11/7), as high waters receded, physical parameters (temperature, water depth and water velocity) explained more variation in phytoplankton assemblage (Figure 4a).

Regression tree models of environmental covariates support that discharge explains phytoplankton differences between 2009 and 2011 and between early and late 2011 (Figure 4b). TN and N:P ratio were also drivers of total phytoplankton biovolume. Low levels of nitrogen (<2.65 mg L^{-1}) and low N:P ratio (<5.88) in 2009 allowed for nitrogen-fixing cyanobacteria to outcompete eukaryotic algae. It follows that TP and TN are the only significant environmental factors explaining the variation in cyanobacteria volume (Figure 5a). High discharge (>2,379 m^3 s^{-1}), low TN (<2.65 mg L^{-1}), high SS (>7.15 mg L^{-1}) and cooler water temperature (<16°C) tended to result in higher Bacillariophyta biovolume (Table 2, Figure 5b). Chlorophyta biovolume was highest at high discharge and reduced water depth (Table 2, Figure 5c). Cryptophyta, Euglenophyta and Pyrrophyta volumes were explained by the variation in SS and N:P ratio (Table 2, Figure 5d–f).

Cyanobacteria biovolume was further analysed to evaluate environmental drivers of potentially toxin-producing genera. Differences among the five potentially toxin-producing cyanobacteria genera (*Dolichospermum*-previously *Anabaena*, *Aphanizomenon*, *Microcystis*, *Pseudanabaena* and *Planktothrix*) were observed between the 2 years (Table S1). *Microcystis*, *Aphanizomenon* and *Dolichospermum* were dominant during the low discharge conditions of 2009 (Figure 6). *Pseudanabaena* and *Planktothrix* were more dominant during higher discharge periods of 2011 (Figure 6). Variation in cyanobacteria volume was best explained by suspended solids and nutrient ratios in 2009, while more variation in genera was explained by physical factors (temperature, water depth, SS and water velocity) throughout 2011 (Figure 7a).

The regression tree for the five potentially toxin-producing cyanobacteria genera supported that TP and TN concentrations were the major explanatory factors (Figure 7b, Table 2). The highest predicted biovolume for potentially toxin-producing cyanobacteria was under high TP conditions (≥0.14 mg L^{-1}), in conjunction with low TN (<1.34 mg L^{-1}). High *Dolichospermum* biovolume occurred with higher SS, shallow water depth (<0.815 m) and high TP (>0.185 mg L^{-1}; Table 2, Figure 8a). *Aphanizomenon* was the highest at high TP (≥0.186 mg L^{-1}) and lowest with lower TP and higher discharge conditions (>467 m^3 s^{-1} Table 2, Figure 8b). The highest *Microcystis* biovolume was predicted under high TP conditions, while the lowest predicted biovolume was with low TP (<0.14 mg L^{-1}; Table 2, Figure 8c). Water temperature also played a role, with sites greater than 24.3°C showing high *Microcystis* biovolume. *Pseudanabaena* and *Planktothrix* exhibited similar patterns in relation to environmental factors. *Pseudanabaena* biovolume was highest under shallow conditions (<1.19 m) with higher SS (≥2.2 mg L^{-1}; Table 2, Figure 8d). *Planktothrix* biovolume was highest at elevated SS (≥15.8 mg L^{-1}) and lowest at reduced SS (<8.45 mg L^{-1}; Table 2, Figure 8e).

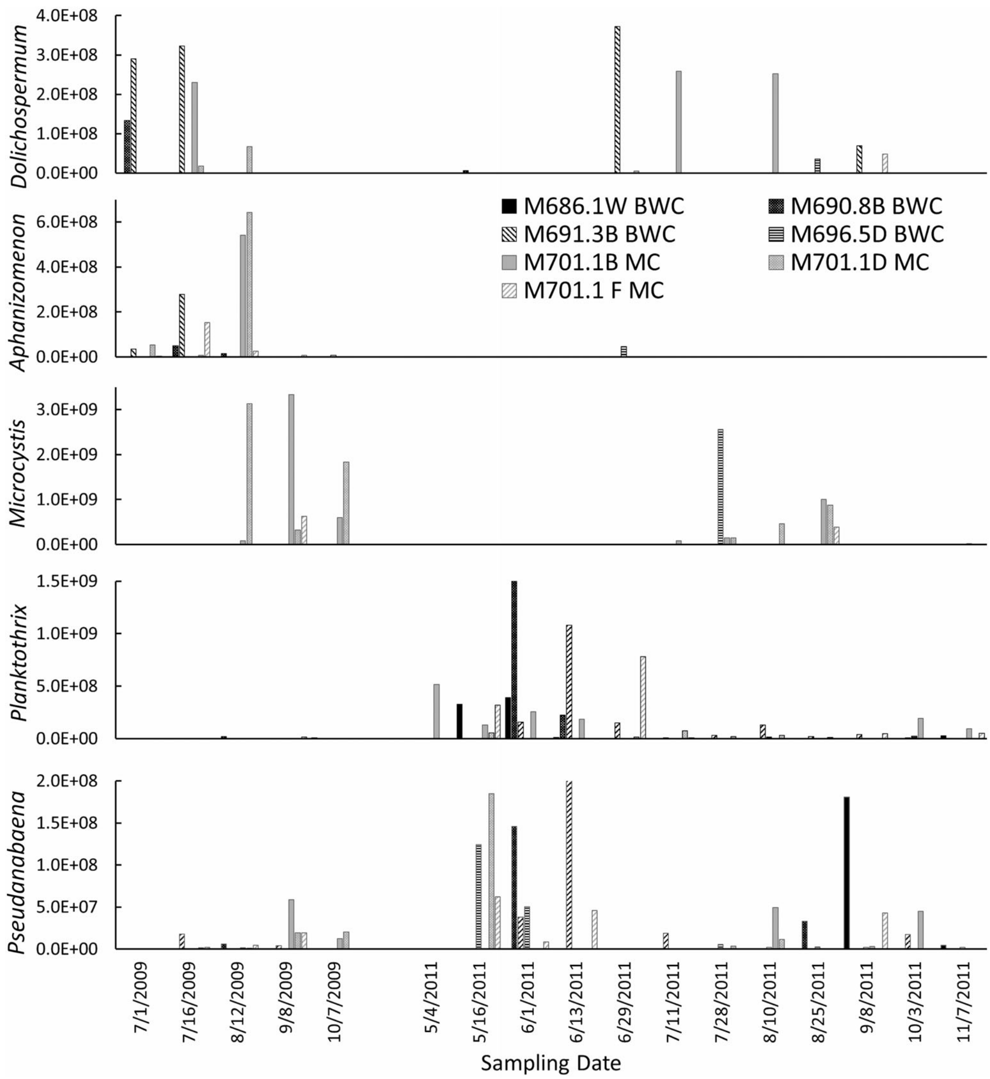

FIGURE 6 Cyanobacteria biovolume (in $\mu m^3 L^{-1}$) for genera across dates in 2009 and 2011 from backwater and main channel habitats of the Upper Mississippi River. Backwater (BWC) sites are outlined in black colour and main channel (MC) sites are shaded in grey colour

Large differences in the physical and chemical environments between 2009 and 2011 resulted in profound differences in the phytoplankton community assemblage. Trait-separated functional groups, S1 and R (as described by Reynolds et al., 2002), which are tolerant of low light, were dominant during high discharge in 2011 (Table 3). Conversely, functional groups, SN, H1, LM and M, which are tolerant of high light, low TN, and sensitive to flushing, poor light and low TP, were dominant during low discharge in 2009 (Table 3).

4 | DISCUSSION

Cyanobacteria dominated in 2009 when water level and discharge were much lower. This finding supports the previous work that low discharge, low water velocity and reduced water depth correspond to increased water clarity and higher water temperature to promote harmful algal blooms (Descy, 1993). Both the variance partitioning and regression show that physical characteristics are prominent drivers of the cyanobacteria community composition in both 2009 and 2011. Nutrient ratios explain less variation, overall, but help explain the 2009 succession of cyanobacterial species. In 2009, the increase in *Dolichospermum* and *Aphanizomenon* during early summer low discharge, low nitrogen and high phosphorus conditions is partially attributable to their sensitivity to flushing and tolerance of low dissolved inorganic nitrogen (Paerl & Otten, 2013; Reynolds et al., 2002). *Dolichospermum* achieved its greatest dominance at site M691.3B, the most isolated backwater site, as dissolved inorganic nitrogen was below 100 $\mu g L^{-1}$ in July of 2009. *Aphanizomenon* production was also stimulated in the backwaters during July of 2009 and may have seeded the main channel blooms that were observed in August of 2009.

Our results closely follow detailed evaluations of optimal cyanobacteria temperatures, with *Dolichospermum* and *Aphanizomenon* dominance at intermediate water temperature and *Microcystis* dominance at higher temperatures (Dokulil & Teubner, 2000; Paerl & Otten, 2016; Robarts & Zohary, 1987). The late summer 2009 dominance of *Microcystis* (a non-N fixer) under low discharge is likely explained by its tolerance of high light, affinity for elevated TP, and its

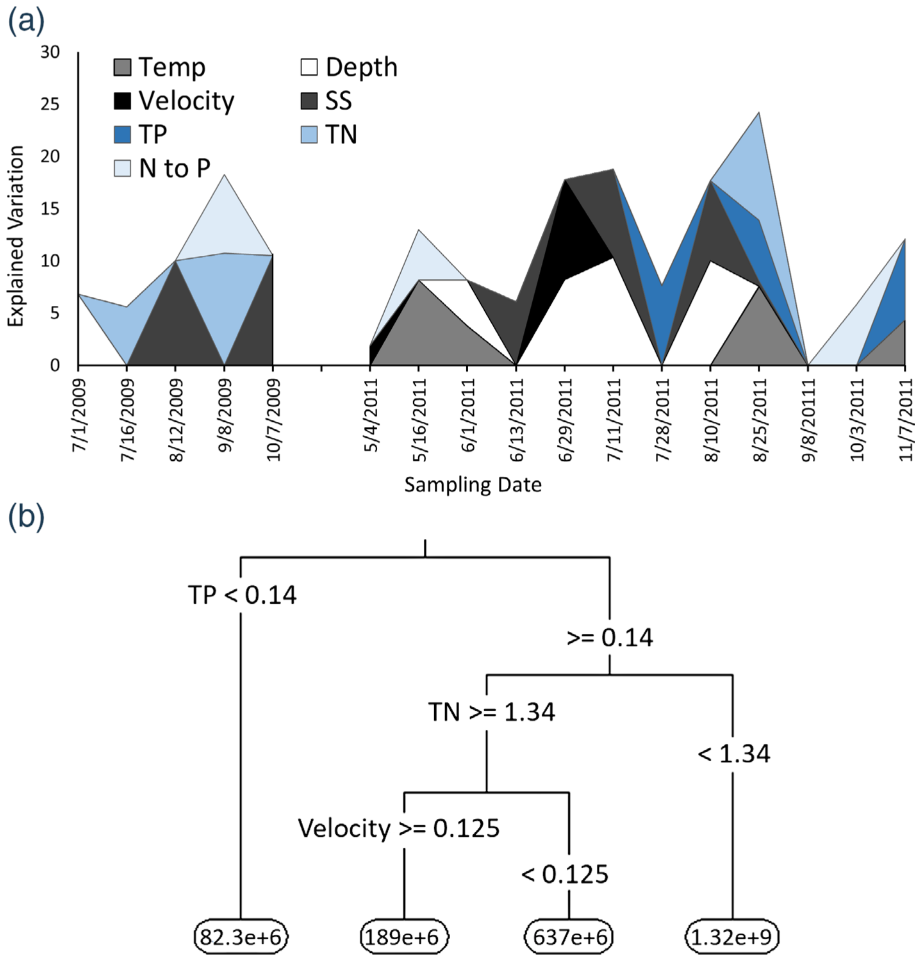

FIGURE 7 Environmental predictors of cyanobacteria genera abundances across 2009 and 2011. (a) Values represent the amount of variation in cyanobacteria assemblage explained by each environmental factor as determined using PCA variance partitioning. (b) Regression tree model. Predicted total toxin-producing cyanobacteria genera biovolume for each branch of the tree is in the lower ovals

ability to optimize position in the water column under conditions of minimal turbulence (Ha, Cho, Kim, & Joo, 1999; Ibelings, Mur, & Walsby, 1991). *Microcystis* also achieves dominance at elevated water temperatures (Dziallas & Grossart, 2011).

In the main channel, a late summer transition to *Microcystis* was observed in 2009. This trend of main channel dominance of *Microcystis* was not observed in the high discharge conditions of 2011. The difference was likely related to low growth rates typical of *Microcystis*, making it intolerant of short residence time (Lehman et al., 2017; Mitrovic, Hardwick, & Dorani, 2011). *Aphanizomenon* is also susceptible to shorter residence and was less abundant in 2011 (Paerl et al., 2016). Differing levels of turbulent flow have also been reported to determine the presence of cyanobacteria in river systems (Williamson, Kobayashi, Outhet, & Bowling, 2018). Elevated *Aphanizomenon* and *Microcystis* biovolume have previously been reported under low discharge conditions worldwide, including the UMR (De Leon & Yunes, 2001; Descy, 1993; Ha et al., 1999; Mitrovic et al., 2011; Williamson et al., 2018). During the low discharge of 2009, it is likely that backwater areas, upstream of the main channel transect, served as a seed source to the main channel (Sommer, Harrell, & Swift, 2008). *Aphanizomenon* is large and buoyant, resulting in competitive advantage under low discharge conditions (Köhler, 1994). *Microcystis* can optimize position in the water column under lower turbulence conditions to harvest light (Huisman et al., 2004; Ibelings et al., 1991). *Microcystis* and *Aphanizomenon*, which are known to be intolerant of low light, were also dominant under low SS conditions (De Leon & Yunes, 2001; Ha et al., 1999; Reynolds et al., 2002). Conversely, the dominance of *Planktothrix* and *Pseudanabaena* during low light is likely linked to their ability to tolerate the higher turbidity (Reynolds et al., 2002).

The general paradigm of increasing cyanobacterial dominance, especially potentially toxin-producing genera, under high phosphorus concentration, low nitrogen concentration, low N:P ratio, low turbulence, low flushing, adequate light and warm temperatures, was supported in our analysis of the UMR (Paerl & Otten, 2013). Rarely will a single factor lead to the dominance, but multiple positive factors working in concert can lead to cyanobacteria proliferation. The principal action to reduce cyanobacteria biovolume is the reduction of nutrients, with phosphorus reductions being of foremost importance. Certain isolated backwaters, with high phosphorus, low nitrogen, warm water temperatures and low potential for flushing, could benefit from increased connection to channel inputs to reduce cyanobacterial dominance (Paerl, Hall, & Calandrino, 2011). Numerous examples of

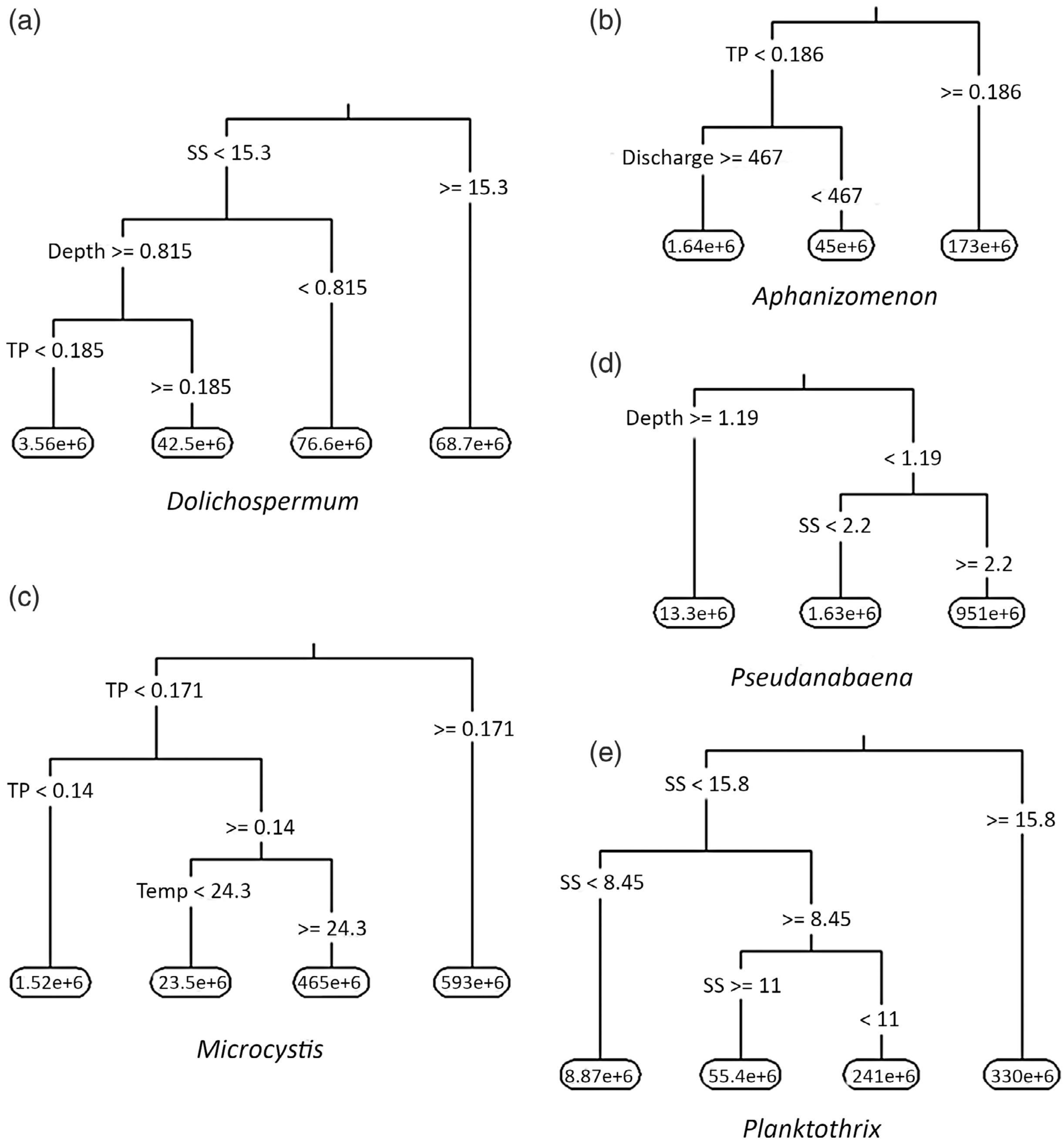

FIGURE 8 Regression tree models predicting specific cyanobacteria genera biovolume (in $\mu m^3 L^{-1}$) using uniform environmental covariates: (a) *Dolichospermum*, (b) *Aphanizomenon*, (c) *Microcystis*, (d) *Pseudanabaena*, (e) *Planktothrix*. Predicted biovolume for each branch of the tree is in the lower ovals. The numeric breakpoint for each parameter defining a branch is presented on each split

this type of habitat currently exist in the UMR and could benefit from reconnection to channel habitats.

Climate change scenarios and the increased dominance of cyanobacteria at water temperatures >25°C would predict increased dominance of cyanobacteria into the future (Paerl & Huisman, 2008; Wells et al., 2020). Extreme precipitation events are likely to increase in the future, resulting in increased nutrient loading (Carpenter et al., 2015). What is currently unclear is how the interplay between increased flushing and increased nutrient loading due to increased precipitation will play out (Kreiling & Houser, 2016). Additional future predictions involve increased hypoxia and increased internal loading of phosphorus related to backwater hypoxia at the sediment interface (Paerl et al., 2011). While reducing external nutrient input is the most direct method to reduce cyanobacterial dominance, mitigation measures to alter connectivity to the main channel will improve conditions if backwater residence time is decreased sufficiently (Paerl et al., 2016). Backwater sediment removal to reduce internal nutrient loading within the UMR will also have high potential to lessen cyanobacterial dominance related to expected climate change.

TABLE 3 Trait-separated functional groups of cyanobacteria described by Reynolds et al. (2002)

Codon	Habitat	Tolerances	Sensitivities	Year dominant
S1	Turbid mixed layers	Highly light-deficient conditions	Flushing	2011
SN	Warm mixed layers, P rich, low N	Light, nitrogen-deficient conditions	Flushing	2009
H1	Eutrophic, but with low N (N-fixers)	Low nitrogen, low carbon	Mixing, poor light, low phosphorus	2009
LM	Summer epilimnia in eutrophic lakes	Very low C	Mixing, poor stratification, light	2009
M	Mixed layers of small eutrophic, low latitude lakes	High insolation (light)	Flushing, low total light	2009
R	Metalimnia of stratified lakes	Low light, strong segregation	Instability	2011

Note: Preferred habitat type, tolerances, sensitivities and year dominant for each functional group are presented.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, SMG, upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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ATTACHMENT D

Water Quality Monitoring Plans

- **Missouri DNR: A Proposal for a Water Quality Monitoring Strategy for Missouri FFY 2015-2020**

  [Link to full report is available here: https://dnr.mo.gov/document-search/proposal-water-quality-monitoring-strategy-missouri-ffy-2015-2020]

- **Iowa DNR: Ambient Water Monitoring Strategy for Iowa 2016-2021**

  [Link to full report is available here: http://publications.iowa.gov/23682/1/2016%20Ambient%20Water%20Monitoring%20Strategy%20%28Final%29.pdf]

ATTACHMENT E

<u>U.S. Farm Nitrogen Pollution</u>

- **Hot Spots of Opportunity for Improved Cropland Nitrogen Management Across the United States (2/16/2021)** *(E-1 to E-13)*

ENVIRONMENTAL RESEARCH
LETTERS

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Hot spots of opportunity for improved cropland nitrogen management across the United States

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LETTER

Hot spots of opportunity for improved cropland nitrogen management across the United States

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Abstract

Nitrogen (N) is a vital input to crop production, but its excess use is a cause of environmental and human health problems in many parts of the world. In the United States (US), as in other nations, reducing N pollution remains challenging. Developing effective N policies and programs requires understanding links between cropland N balances (i.e. N inputs minus N harvested in crops) and potential contributing factors. We present novel insights into these links using a national county-level assessment and propose a criteria-scoring method to inform US N policy and programs. First, we characterize cropland N balances across the US in 2011–2013 and identify counties (∼25%) where N input reductions are less likely to result in crop yield declines. Second, we identify agronomic, environmental, social, demographic, and economic factors correlated with N balance, as well as counties that are underperforming based on these characteristics. Finally, we employ criteria scoring and hot spot analysis to identify 20 spatial clusters of opportunity for improved cropland nitrogen management. These hot spots collectively account for ∼63% of total surplus N balance for croplands but only ∼24% of cropland area in the US. N flows for these hot spots indicate variable opportunities across the US landscape to improve cropland N balances by reducing N fertilizer use, better managing manure N, and/or increasing N use efficiency. These findings can guide future efforts to integrate N balance into regulatory and voluntary frameworks in US policy and programs.

1. Introduction

Nitrogen (N) is an essential nutrient for life and its bioavailability in croplands is critically important for crop yields and maintaining food security [1, 2]. Human alterations of the N cycle—through industrial N fixation via the Haber-Bosch process and the resulting widespread use of synthetic N fertilizers—has led to important increases in the productivity of agriculture [3]. However, it has also resulted in accumulation of reactive N at multiple scales and a host of associated costs for the environment and human health [4, 5]. These costs include air pollution linked to human illness and disease, biodiversity loss, freshwater pollution, coastal "dead zones", and N_2O emissions that contribute to climate change and stratospheric ozone depletion [6].

As a result, N pollution has been a critical focus of environmental policy across the globe. Many regions have shifted towards limiting N inputs to agriculture, especially in high-income countries where N fertilizer use has been high for decades [2, 7]. This includes policies ranging from the EU Nitrates Directive and National Emission Ceilings [8] to the world's first N cap and trade policy in Lake Taupo of New Zealand [9]. In the United States (US), regional strategies such as the Gulf Hypoxia Action Plan [10] exist, and efforts derived from the Clean Water Act have aimed to meet total maximum daily loads (TMDLs) for N in impaired waters. This includes the Chesapeake Bay

TMDL [11]. However, meeting N management goals remains challenging [8], and the impacts of excess reactive N on ecosystems are likely to be exacerbated by climate change [12]. To be effective, N policies need to account for, and link, the environmental losses of N in cropland systems and the social, demographic, and economic factors that are associated with N use. However, this comprehensive assessment across US agriculture nationally does not yet exist, limiting intervention-targeting efforts.

Accounting for environmental losses of N in cropland systems is difficult due to the multiple pathways that exist [1]. However, there is compelling evidence that N balance—the difference between human-mediated N inputs and N outputs in an agricultural production system—is a robust yet straightforward proxy for N losses to the environment [13]. For example, McLellan *et al* [13] found that N balance calculated as fertilizer N minus N removed in grain for corn cropping systems in North America was a strong predictor of yield-scaled total N losses, nitrous oxide (N_2O) emissions, and nitrate (NO_3^-) leaching. Other studies similarly support strong correlations between the efficiency of N use on croplands and N losses to the environment [14–16], even though the N surplus in a given year does not necessarily account for all N losses that year. N balance has been used in environmental monitoring of agriculture and in policy in Europe [17–19], but limited policy application of N balance has occurred in the US. While previous research has focused on calculating N balances at different scales in the US [20–23] and investigating how changing magnitudes of fertilizer and manure N use drive N imbalance on croplands [22, 23], knowledge of how underlying factors contribute to surplus N use across the US is lacking. Policy design and targeting requires both an inventory of N balances and understanding of the factors that influence those N balances.

N balance is likely a function of various agronomic, environmental, social, demographic, and economic factors that influence reactive N inputs to croplands and the subsequent crop yields. A robust body of social science and economics literature has studied how various factors drive conservation practice adoption, including practices related to N use [24]. While few variables consistently predict the adoption of conservation practices in US agriculture, there are both individual and institutional factors that matter, including environmental attitudes, previous adoption of conservation practices, awareness of conservation programs or practices, farm size, education, and income. Nevertheless, the literature specifically focused on farmer adoption of N management practices is much more limited [25]. Currently, existing research in this area predominantly examines only the socio-economic factors driving N use or adoption of N-efficient technologies [26, 27] without assessing the relationship of social, economic, and demographic factors to actual N balance outcomes. The current landscape of understanding N balance and its use in the US is mostly divided by discipline with biophysical research assessing N balance and flows while social science research assesses potential adoption of N management practices, without a strong link between the two.

Here we fill the existing gap in this understanding through a comprehensive US assessment that links N balances with agronomic, environmental, social, demographic, and economic factors. We focus on county-level N balances across the US during 2011–2013. These years correspond with the most recent comprehensive N balance 3 yr dataset centered on a Census of Agriculture year (2012) available in the International Plant Nutrition Institute's Nutrient Use Information System (NuGIS) [20]. We use a 3 yr average over this period because 2012 was an exceptional drought year [28]. Our analysis draws upon a new, 10-group cropland typology [29] to provide new insights into how N balance varies with dominant crop mix. Finally, to inform the design and assessment of regulatory or voluntary N policies or programs, we combine criteria scoring and hot spot analysis to identify primary target areas that would be especially relevant due to a combination of excessive N use and characteristics that suggest potential to better balance N input and output.

2. Materials and methods

2.1. N balance

We obtained county-level N flows for the contiguous US in 2011, 2012, and 2013, including farm fertilizer N, recoverable manure N, N fixation by legumes, and N in crop harvests, from the NuGIS database [20]. Cropland N balance is calculated in NuGIS as:

$$N_{balance} = (N_{farm\_fertilizer} + N_{recoverable\_manure} + N_{fixation}) - N_{crop\_harvest}$$

This is a partial N mass balance because it does not account for a number of additional N flows including atmospheric deposition, nutrients in irrigation water, land application of biosolids, or several pathways of N loss to the environment, such as eroded soil, gaseous N emissions, and leaching [20]. Previous studies have used this calculation for partial cropland N balance as well [21, 30]. 'Recoverable' manure N represents the amount of N in excreted manure that would be available to apply to cropland and does not include N lost during manure storage and handling [20]. The areal version of the mass balance is calculated by dividing $N_{balance}$ by the total cropland area for each county. County-level N use efficiency (NUE, %) is calculated as:

$$\mathrm{NUE} = \left(\mathrm{N}_{\mathrm{crop\_harvest}} / \left(\mathrm{N}_{\mathrm{farm\_fertilizer}} + \mathrm{N}_{\mathrm{recoverable\_manure}} + \mathrm{N}_{\mathrm{fixation}}\right)\right) \times 100$$

We provide more discussion on the N balance methodology, including its limitations, in the supplementary materials.

2.2. Additional data

We collected county-level data spanning government program participation, farm economics, population demographics, climate change belief and policy support, biophysical characteristics, and crop type as potential predictors of areal cropland N balance (table S1 (available online at stacks.iop.org/ERL/16/035004/mmedia)). All data were for the year 2012 or the 2011–2013 annual average, with the exception of population density (2010) and climate change belief and policy support (2016). In some cases, data filling and manipulation were required as described in the supplementary materials. We also created a cropland typology for 2012 based on county-level crop land areas and consisting of ten categorical variables (i.e. typology groups), which we described in detail in a previously published data note [29] and summarize here in table 1 and figure 1.

2.3. Breakpoints in the relationship between N input and N harvest

We used the 'segmented' package in R [31, 32] to determine breakpoints in segmented linear regression for county-level N harvested in crops versus county-level total N inputs, using 2011–2013 means [20]. We identified one breakpoint for all counties included in the study, as well as for individual cropland typology groups as a whole (i.e. not based on individual crops) and determined multiple related statistics, including the standard error and P-value for the breakpoint, as well as slopes, r^2, and P-values for the linear correlations below and above the breakpoints. 'Total N input' here includes N fixation by legumes ($\mathrm{N}_{\mathrm{input}} = \mathrm{N}_{\mathrm{farm\_fertilizer}} + \mathrm{N}_{\mathrm{recoverable\_manure}} + \mathrm{N}_{\mathrm{fixation}}$), which is important when considering N balances. Note that the results of this analysis do not represent any single crop type, but rather the groups of counties having similar crop mixes according to the typology ([29]; table 1).

2.4. Hierarchical random effects model

To analyze factors correlated with mean N balance (kg N ha^{-1} yr^{-1}) in 2011–2013, we ran a series of stepwise hierarchical random effects models. We used stepwise models because of the large number of potential independent variables. First, we ran five separate models to predict county-level areal N balance, including models using the following variable types (a) government program participation; (b) farm economics; (c) population demographics; (d) biophysical attributes; and (e) cropland typology groups. Stepwise models included a random effect at the state level, to account for factors that may influence N balance within a given state (e.g. state policies) that are not captured in the model. Statistically significant variables from the stepwise models ($P < 0.05$), as well as the aggregated climate scale variable, were included in a final hierarchical random effects model, also with a random effect at the state level.

2.5. Spatial analysis

Our spatial analysis included a combination of criteria scoring and hot spot analysis, as described in figure 2 and the supplementary materials. We qualified 20 hot spots of mostly contiguous counties based on the sum of three criteria scores (Total N Surplus, Excessive N Input, Potential for Improvement; figure 2), including the majority of high scoring counties. Finally, we aggregated data for these hot spots, including total cropland and different N flows in metric tons, and calculated the areal N balance and the ratio of $\mathrm{N}_{\mathrm{farm\_fertilizer}}$ to $\mathrm{N}_{\mathrm{recoverable\_manure}}$ for each hot spot.

3. Results

3.1. Cropland N balances during study period

During 2011–2013, the 2887 US counties included in our study were characterized by a mean overall N balance of +4.0 million metric tons N per year (MMT N yr^{-1}) across all croplands, or +25 kg N ha^{-1} yr^{-1}, and an overall N recovery in crops of 79%. Cumulative mean annual cropland N flows for that period included 11.6 MMT N yr^{-1} in farm fertilizer, 1.05 MMT N yr^{-1} in recoverable animal manure, 6.0 MMT N yr^{-1} via N fixation by legumes, and 14.7 MMT N yr^{-1} harvested in crops for 157.3 million ha of total cropland. County-level N balances per hectare of cropland (i.e. areal N balance) during 2011–2013 varied greatly across the US, as did the total N balance per county (figures 3(a) and (b)) and NUE (figure S1) [20].

Considering all counties, the input and output components of the N balance were strongly correlated up to a breakpoint in N input (mean ± std. error = 175 ± 3 kg N ha^{-1} yr^{-1}, $P < 0.001$) with peak crop N yield response, after which increased total N input was negatively correlated with N output in crop yields (figure 4(a), table S2). Therefore, we assume that additional N input beyond the breakpoint is more likely to be lost to the environment. We further identify breakpoints in N input for counties within different cropland typology groups (figure 1). We find significant breakpoints in total N input for eight out of the ten cropland typology groups ranging from 83 ± 11 to 230 ± 5 kg N ha^{-1} yr^{-1} ($P < 0.02$ in all cases; figure 4(b), table S2). For approximately 25% of counties in our analysis, total N inputs exceeded the most appropriate breakpoint value (see section 2), which indicates excessive N use beyond the levels associated with peak yield response (figure S2).

Table 1. Cropland typology for 2012 originally presented in Hammond Wagner *et al* [29] and used in this study. (Adapted from [29]. Copyright © 2019, The Author(s). CC BY 4.0.)

Group	# of counties	Crop(s) driving group membership in cluster analysis	Top 3 crops in group (in order of total land area across all counties in cluster)
1	308	Corn silage, other crops	Other crops, hay, corn grain
2	53	Tobacco	Soybeans, hay, wheat
3	840	Hay	Hay, corn grain, soybeans
4	44	Barley, beans, sugarbeets	Wheat, soybeans, corn grain
5	202	Alfalfa, barley	Alfalfa, wheat, hay
6	277	Sorghum, sunflower, wheat	Wheat, corn grain, hay
7	21	Oranges, sugarcane	Sugarcane, oranges, other crops
8	31	Rice	Rice, soybeans, corn grain
9	993	Corn grain, soybeans	Corn grain, soybeans, wheat
10	153	Cotton, peanuts	Cotton, peanuts, hay

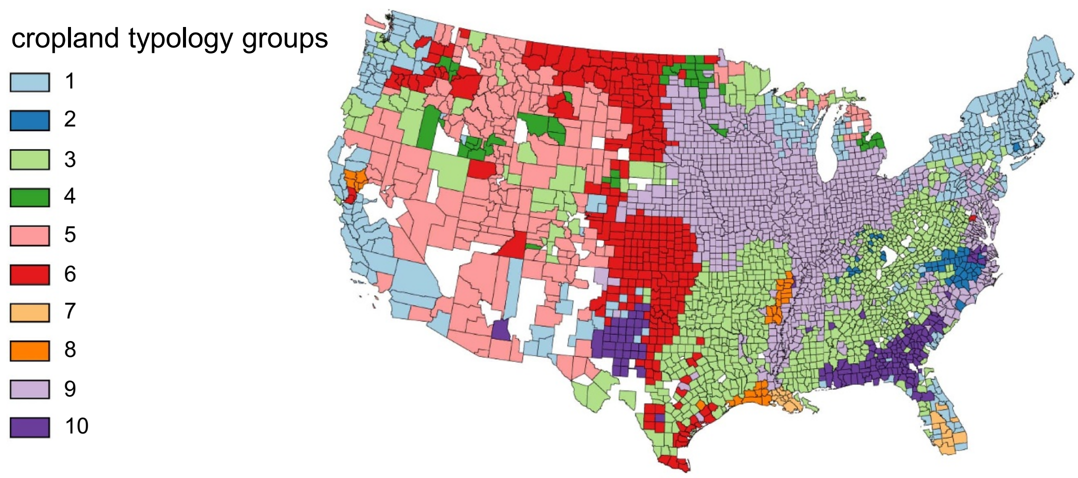

Figure 1. Cropland typology groups for 2012. See table 1 for more details. Adapted from [29]. Copyright © 2019, The Author(s). CC BY 4.0.

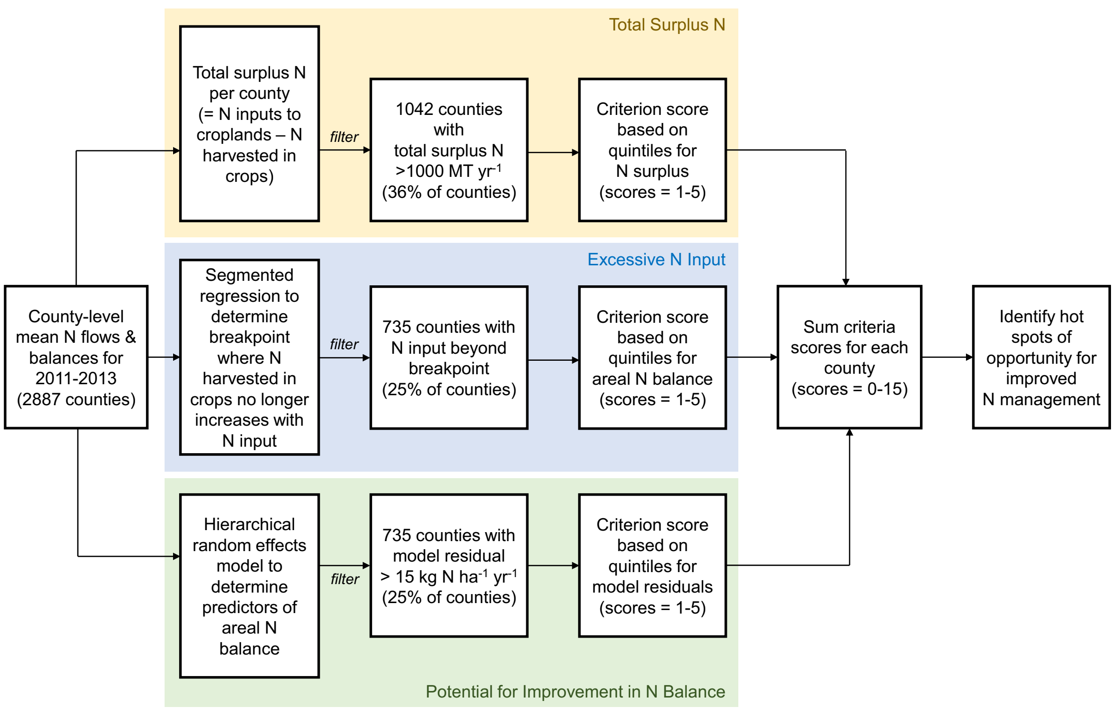

Figure 2. Methodology used in spatial analysis.

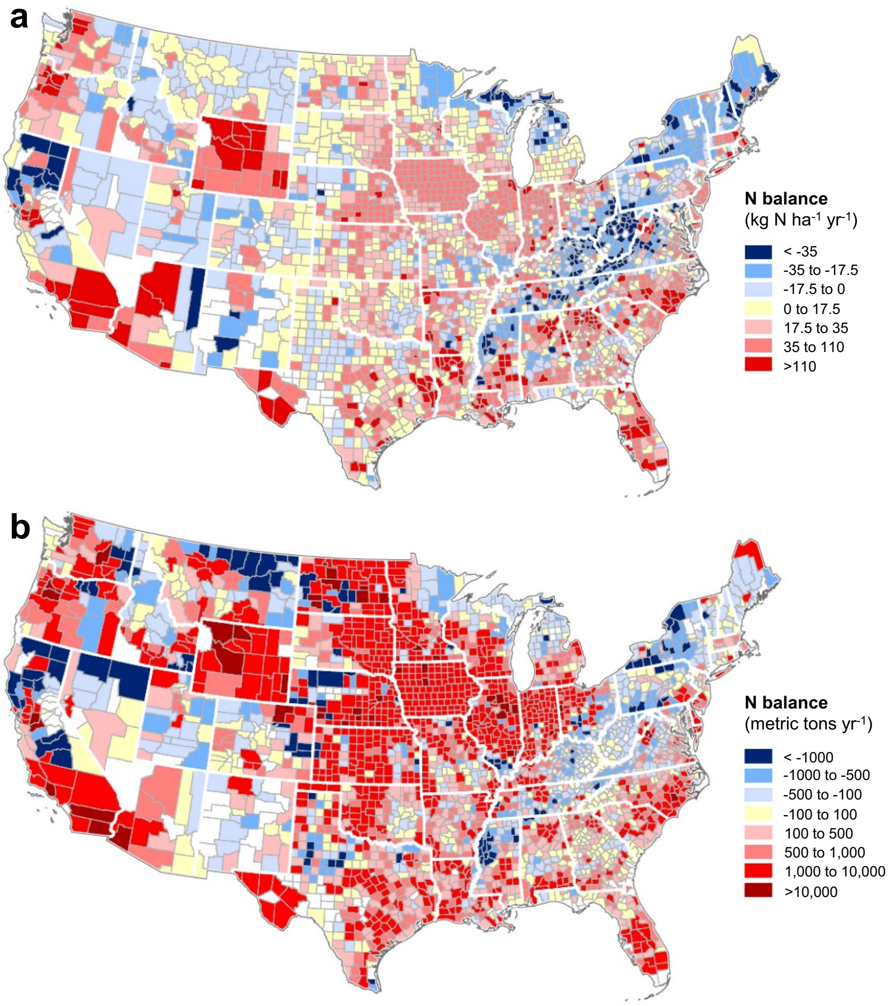

Figure 3. Mean annual cropland partial nitrogen (N) balance on (a) cropland areal basis (kg N ha^{-1} yr^{-1}) and (b) overall county basis (metric tons N yr^{-1}) during 2011–2013 for the 2887 U.S. counties included in this study, based on total N input (fertilizer, recoverable manure, and N fixation by legumes) and N output in the form of harvested crops [20].

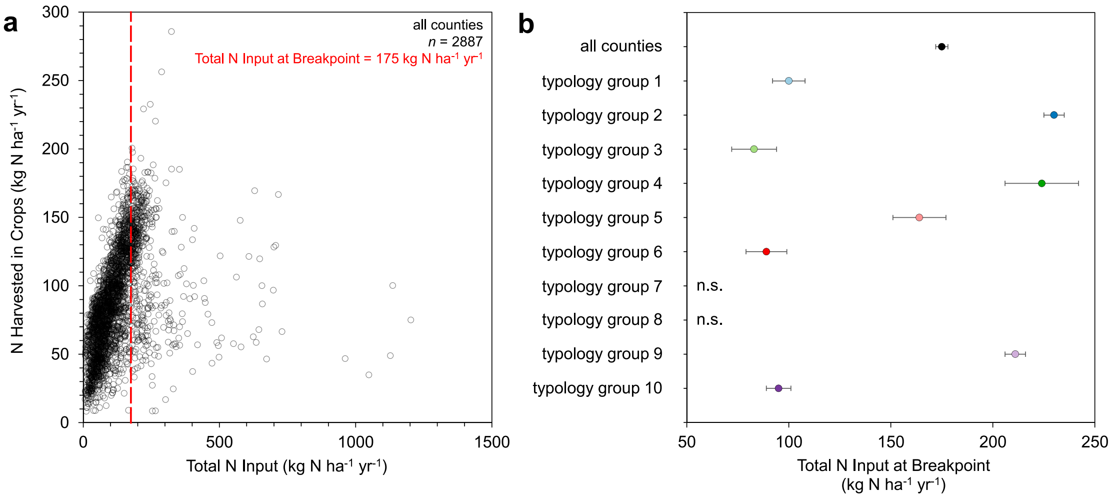

Figure 4. Breakpoints in segmented linear regression for county-level N harvested in crops vs. county-level total reactive N input (fertilizer + recoverable manure + N fixation by legumes) for (a) all counties in our analysis ($n = 2887$) and (b) ten cropland typology groups defined in table 1 and [29]. Based on mean values for 2011–2013. n.s. = breakpoint not significant.

Table 2. Results for full hierarchical random effects model predicting average areal nitrogen balance in US counties in 2011–2013.

Variable	Coefficient	Std. error	Z	$P =$	95% Confidence interval	
Total operating expenses	0.004	0.000	9.220	0.000	0.003	0.004
Other federal program participation	−0.006	0.004	−1.780	0.075	−0.014	0.001
Farm size	−0.006	0.006	−0.920	0.355	−0.017	0.006
Population density	0.055	0.005	11.290	0.000	0.045	0.064
Climate-scale	−0.975	0.424	−2.300	0.022	−1.806	−0.144
Soil productivity	−1.732	0.673	−2.570	0.010	−3.051	−0.412
Precipitation	0.016	0.008	1.920	0.055	0.000	0.031
Typology group 1	39.337	15.372	2.560	0.010	9.208	69.467
Typology group 2	8.055	18.367	0.440	0.661	−27.943	44.054
Typology group 3	30.945	14.548	2.130	0.033	2.431	59.458
Typology group 4	63.648	18.895	3.370	0.001	26.615	100.680
Typology group 5	29.342	16.423	1.790	0.074	−2.847	61.531
Typology group 6	21.933	15.583	1.410	0.159	−8.610	52.475
Typology group 7	−20.857	22.518	−0.930	0.354	−64.991	23.277
Typology group 9	31.947	14.667	2.180	0.029	3.199	60.694
Intercept	−16.552	16.121	−1.030	0.305	−48.149	15.044
State constant	1369.205	335.986			846.436	2214.843
State random effect	5271.114	140.058			5003.632	5552.896

3.2. Factors contributing to cropland N imbalance

We find multiple factors across a number of different categories predict N balance (table 2). Greater N balance was associated with counties having farms with greater total operating expenses ($P < 0.001$), greater population density ($P < 0.001$), lesser climate change belief and policy support ('climate-scale') ($P = 0.022$), and lesser soil productivity ($P = 0.010$), as well as, to a weaker extent, greater precipitation ($P = 0.055$) and lesser participation in other federal USDA programs (i.e. federal programs excluding the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), and Conservation Reserve Enhancement Program (CREP)) ($P = 0.075$). We also find that a number of cropland typology groups (table 1) correlate with greater N balance, including groups 1 ($P = 0.010$), 3 ($P = 0.033$), 4 ($P = 0.001$), and 9 ($P = 0.029$).

3.3. Guidance for spatial targeting of N policy

Twenty hot spots emerged in our analysis, including 759 counties across the West, Midwest, and South (figure 5). These hot spots hosted ∼24% of the cropland area included in our study, but accounted for ∼63% of the total N surplus (table 3). The overall areal N mass balance rate for hot spot counties (+68 kg N ha^{-1} yr^{-1}) was 2.7 times greater than the overall rate for all counties. Overall NUE (% of N inputs recovered in harvested crops) in hot spots ranged from 17% to 75% (table 3), indicating that while some hot spots are characterized by markedly inefficient use of N per hectare of cropland, others hosted substantial tonnage of surplus N use despite more efficient N use per hectare due to their large total cropland area. N input metrics for each hot spot, including fertilizer, recoverable manure, and N fixation by legumes, indicate that the importance of different inputs in N balances varies greatly across hot spots (table 3). For example, fertilizer to manure input ratios on an N basis ranged from 1 to >100. Additionally, N fixation by legumes was a sizeable reactive N input, accounting for 26% of N inputs for all hot spots combined, but was of differing importance in N balances across hot spots (table 3). Hot spots accounted for 38% and 49% of overall fertilizer and manure inputs to US croplands, respectively.

Table 3. Characterization of hot spots of opportunity for improved cropland nitrogen management (annual averages for 2011–2013). Hot spot numbers correspond to those in figure 5(e).

				N input				N output		Croplands N balance	
		Cropland typology groups[b]	Total cropland area	Fertilizer	Manure	Legume N fixation	Fertilizer to manure ratio	Harvested crops	N use efficiency	Total surplus	Areal surplus
Hot spot[a]	# of counties		ha	Metric tons N			Ratio on N basis	Metric tons N	%	mt N yr^{-1}	kg N ha^{-1} yr^{-1}
1 (IL,IN,MO,WI)	61	9	5 930 866	765 822	15 338	395 042	50	802 111	68	374 092	63
2 (KS,NE)	55	9,6,3	5 989 517	691 787	27 012	224 309	26	580 614	62	362 494	61
3 (IA,MN,SD)	38	9	4 736 338	590 598	29 630	310 296	20	651 235	70	279 290	59
4 (AR,KY,IL,IN,MO,TN)	64	9,3,2,10	3 070 461	400 926	16 519	178 024	24	375 933	63	219 535	71
5 (ID,MT,UT,WY)	32	5,3,4,6	1 559 401	225 548	5150	63 224	44	136 091	46	157 831	101
6 (CA)	21	1,6,3,8	2 624 327	376 530	65 196	97 914	6	397 259	74	142 381	54
7 (OR,WA)	33	1,3,6,5	1 760 516	228 400	14 108	41 032	16	160 978	57	122 562	70
8 (ND)	11	6,9	2 370 800	218 484	475	53 097	460	156 429	57	115 627	49
9 (TX)	32	3,6,10,8	1 007 780	117 448	10 580	1702	11	36 739	28	92 990	92
10 (IN,MI,OH)	29	9,1	1 986 030	190 537	18 624	166 818	10	283 775	75	92 204	46
11 (AZ, CA)	14	5,1	690 944	131 410	20 308	49 026	6	118 554	59	82 190	119
12 (NC,SC)	38	3,9,2,10,1	788 791	72 328	52 913	25 349	1	70 443	47	80 147	102
13 (AL,LA,MS)	66	3,10,7	828 351	80 225	33 696	20 356	2	62 370	46	71 907	87
14 (AL,GA,NC,SC,TN)	80	3,10,1	573 124	37 355	67 368	8342	1	43 575	39	69 489	121
15 (AR,LA,OK,TX)	50	3,8,9	642 469	64 634	33 713	4286	2	34 650	34	67 983	106
16 (AR,KS,MO,OK)	36	3,9,8	1 040 153	69 823	47 705	18 120	1	68 813	51	66 835	64
17 (DE,MD,VA)	44	9,3,10,1,2,6	795 662	65 602	44 351	39 846	1	93 003	62	56 796	71
18 (FL)	37	1,3,10,7	453 842	68 118	8586	5272	8	40 009	49	41 967	92
19 (TX)	7	3,5,1	165 067	21 888	667	251	33	3951	17	18 855	114
20 (CT,MA,NY,RI)	11	1	77 854	10 434	1463	645	7	5788	46	6753	87
Grand total	759	3,9,1,6,10,5,2,7,8,4	37 092 293	4427 897	513 402	1702 951	9	4122 320	62	2521 928	68

[a] Ranked by total N surplus, greatest to smallest. Numbers correspond to those shown in figure 5(e).
[b] In order of most common to least common by county. See table 1.

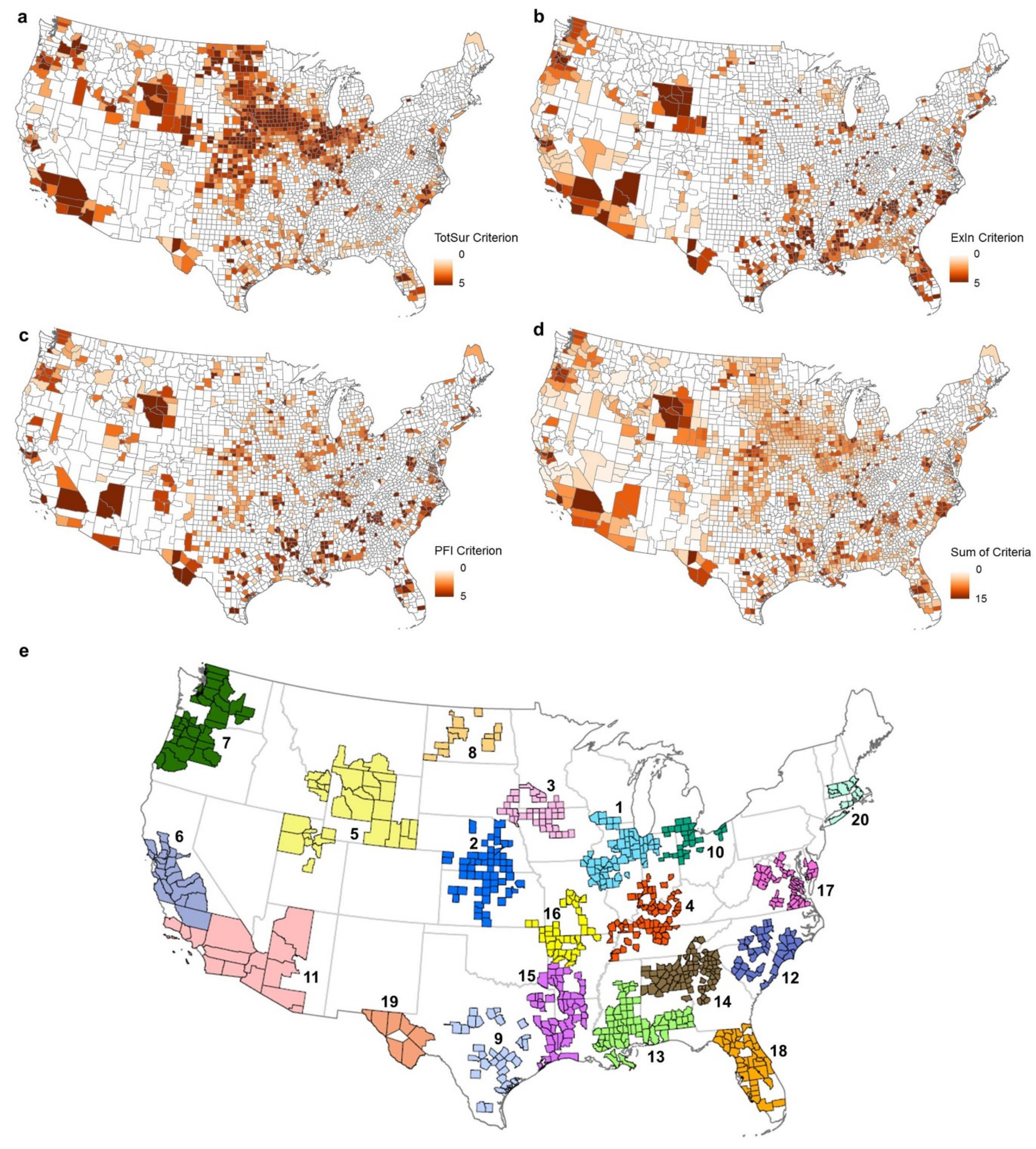

Figure 5. Scores for (a) the Total Surplus N (TotSur) Criterion (0–5), (b) the Excessive N Input (ExIn) Criterion (0–5), (c) the Potential for Improvement (PFI) Criterion (0–5), and (d) the sum of the three criteria (0–15) (see figure 2 for criteria methods). (e) Hot spots of opportunity for improved cropland nitrogen management—numbers correspond to rankings by total N surplus (metric tons N yr^{-1}), greatest to smallest (see table 3).

4. Discussion

4.1. Novel insights

Our findings contribute several important advancements in the context of current literature. First, we provide new insights into the relationship between cropland N inputs and outputs in the US using county-level data, including breakpoint values that can identify excessive N use (figure 4). Data aggregated by state in 2011–2013 (figure S3) or at the national level over time [7] do not to reveal breakpoints in the relationship between N inputs and outputs for US croplands. Furthermore, our use of a new cropland typology [29] (figure 1, table 1) allows us to better associate county-level N balances, as well as breakpoints in the relationship between cropland N input and output, with specific dominant crop mixes across the US for our study period (figure 4(b)). Previous investigators have been unable to assess N balance in this way, instead focusing on USDA ERS Farm Resource Regions based on farming characteristics in the 1990s [22]. Crop-specific analysis for the US has identified N fertilizer input above which corn yields plateau (150 kg N ha^{-1} yr^{-1}) and at which peak yield occurs for winter wheat (50 kg N ha^{-1} yr^{-1}), but spatial resolution is limited to the state scale [33]. Our analysis of county-level data in figure 4 is analogous to the economically optimal N rate (EONR) approach commonly used at the farm- or field-scale [34]. Like EONR analyses, we observe diminishing returns beyond the breakpoint associated with peak crop N yield response in the model including all counties, as well as in the model for cropland typology group 9 (dominated by corn grain and soybeans) (table S2).

Second, our results highlight diverse factors that are significantly correlated with areal N balance for US croplands, including total farm operating expenses, population density, climate change belief and policy support, inherent soil productivity, and crop typology groups (table 2). Our analysis is unique in its integration of disciplinary perspectives and can inform future N modeling and policy efforts, including guidance for considering specific populations. Additionally, we highlight counties with greater N balance than predicted based on the factors in our model, which could potentially be areas of focus more capable of shifting N practices (figure 5(c)). Previous efforts to model N flows, budgets, and mitigation in the US have generally not included social, demographic, and economic factors that can influence N management [8, 35, 36]. Simultaneously, analyses to understand the social and economic factors that predict N management generally have not been linked to biophysical data assessing whether such behaviors influence environmental outcomes [26].

Third, our use of spatial clustering methods to assess nutrient flows and balances across large spatial scales has few precedents in the literature [37, 38]. Spatial targeting is expected to improve the cost-effectiveness of agri-environmental policy because applying conservation measures in the most suitable regions can provide environmental benefits at lower costs [39, 40]. Additionally, spatial targeting of N policy and programs can likely help alleviate some of the major challenges faced by producers transitioning to new N management practices, if it involves the creation of new networks of farm advisors along with new infrastructure and technologies needed to overcome path dependency associated with habituated models of N management [41]. Finally, there is some evidence that spatial targeting of agri-environmental policy provides neighborhood effects such as higher levels of social acceptability [42].

4.2. Implications for N management in the United States

Our results have several implications for future N management, policy, and programs. First, our analysis can inform efforts to increase uptake of existing, and currently underutilized, voluntary carbon offset programs for N management, specifically incentive programs including efforts to pay producers to reduce their N fertilizer use [43–45]. The adoption of these programs is very low, in part because of concerns over negative yield impacts from N input reductions. Evidence suggests that producers are much more likely to support adoption of N use efficiency practices, rather than N input reduction practices, likely because of the potential yield implications of N input reduction [46]. The discrepancy for the Midwest between figures 5(a) and (b) lends some support to this concern. While numerous Midwest counties score high for the Total Surplus N criterion (due to large cropping areas), most do not score high for the Excessive N Input criterion. This is because their county-level N inputs per hectare, while relatively high, are still below the N input breakpoint beyond which N in crop harvests plateaus or declines (figure S2). Our analysis also suggests that, for other counties and regions (largely in the South and West), N use efficiency and N input reduction strategies are likely one in the same, providing environmental gains without necessarily risking losses in terms of crop yield, farm profits, and food security (figures 5(b), S1 and S2). This finding may be critical for producer acceptance because it could suggest minimal economic losses or even increased profitability [34]. While continued focus on the Mississippi River watershed is necessary due to the scale of agriculture, associated N flows (figure 3(b)), and environmental impact [10, 47], improvements in cropland N cycling on a per hectare basis may be more easily achieved elsewhere in the US. However, uptake of protocols in these regions may require additional field data to parameterize models of given crop types by region for location-specific understanding of the impact of N input reductions on yields, profitability, and environmental outcomes [45].

Our analysis also highlights important crop types to consider in N policy efforts, and illuminates the relative importance of fertilizer N versus manure N by location. The three most common cropland typology groups for hot spot counties (in descending order) were groups 3, 9, and 1, which include substantial areas of hay, corn grain, soybeans, wheat, and other crops (tables 1 and 3). Thus, many of the hot spots in figure 5(e) are dominated by animal feed crops, highlighting the link between food system trends toward meat consumption and N dynamics [48]. In hot spots where the fertilizer:manure N input ratio is high (e.g. >10), many counties are producing animal feed destined for animals located outside the county or state, and local manure availability is limited [49]. Conversely, in regions where the fertilizer:manure N input ratio is relatively low (e.g. <10), manure management should be an especially critical focus, including ways to optimize its use as an N source to croplands on its own and in combination with fertilizer and/or biological N fixation [49, 50]. From a policy standpoint, this is a critical distinction, because relevant government programs to improve N fertilizer and manure management vary in their focus; for example, the Environmental Quality Incentives

Program (EQIP) mandates 60% of funding be utilized for livestock projects, especially relevant where animal agriculture is prevalent and characterized by excess manure N. Conversely, other programs may be most relevant in regions where synthetic fertilizer N is more dominant. Appropriate scaling of co-located cropping and livestock systems, whether neighboring or fully integrated, is one approach that has potential to reduce the need for imported N-containing feed and fertilizer while facilitating more effective manure N use on croplands [48]. However, a number of policy barriers exist in the US, as compared to other countries, to integrated crop and livestock systems [51].

There are other important N management practices that focus on the efficient use of N fertilizer. These include soil testing, chemical plant tissue analysis, use of adaptive in-season N recommendation tools to optimize split N fertilizer applications, predictive N management approaches, and sensor-based N management [34]. These strategies are all being developed and tested at land-grant universities in the US, including within the hotspots identified here in table 3.

Finally, in some hot spots intensive production of fruits and/or vegetables (many of which fall under 'other crops' in our cropland typology) is prominent and likely plays an important role in N dynamics (e.g. Washington, Oregon, California, and Florida) (table 3). N fertilization rates for crops such as oranges, lettuce, tomatoes, and potatoes are typically high, with averages ranging from 165 to 241 kg N ha^{-1} yr^{-1} based on USDA NASS data collected during 2002–2016 [52]. For comparison, mean N fertilization rates for corn grain, wheat, and other small grains using the same data source were 151, 74, and 53 kg N ha^{-1} yr^{-1}, respectively.

5. Conclusions

This study, building on existing literature, illustrates several ways in which N balance can serve as a useful tool to help guide N management policy and programs. Potential applications include:

(a) Use of N balance as a performance metric at county, state, watershed, and regional levels, in addition to the farm-scale;
(b) Analysis of N balance components, particularly the relationship between N inputs and outputs, to identify policy-relevant thresholds and opportunities for improvement that carry less risk of yield loss; and
(c) Consideration of factors correlated with N balance during N policy or program design and outreach, including farm economics and federal program participation, attitudes towards environmental issues such as climate change, soils, and crop type.

More research, including pilot programs in hot spot regions identified in figure 5(e), is needed to increase knowledge on the factors that influence producer participation and increased N use efficiency on the ground. Additionally, more field trials are needed to clarify how the relationships between the components of the partial N balance (N inputs and N in harvested crops) and N losses of concern (e.g. N_2O emissions, NO_3^- leaching) vary with cropping system, soil characteristics, and management. These additional data can provide a pathway for appropriately scaled and relevant policies for a given region, which can contribute environmental benefits while minimizing negative impacts to yields and farm profits, goals that are shared by diverse stakeholder groups.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.4302031.

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Author contributions

E D R and M T N designed research; E D R, M T N, and C R H W performed research; E D R and M T N analyzed data; E D R, M T N, and C R H W wrote the paper.

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ATTACHMENT F

<u>Constructed Wetlands</u>

- **Integrated Assessment Modeling Reveals Near-Channel Management as Cost-Effective to Improve Water Quality in Agricultural Watersheds (5/28/2021)** *(F-1 to F-8)*

Integrated assessment modeling reveals near-channel management as cost-effective to improve water quality in agricultural watersheds

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Despite decades of policy that strives to reduce nutrient and sediment export from agricultural fields, surface water quality in intensively managed agricultural landscapes remains highly degraded. Recent analyses show that current conservation efforts are not sufficient to reverse widespread water degradation in Midwestern agricultural systems. Intensifying row crop agriculture and increasing climate pressure require a more integrated approach to water quality management that addresses diverse sources of nutrients and sediment and off-field mitigation actions. We used multiobjective optimization analysis and integrated three biophysical models to evaluate the cost-effectiveness of alternative portfolios of watershed management practices at achieving nitrate and suspended sediment reduction goals in an agricultural basin of the Upper Midwestern United States. Integrating watershed-scale models enabled the inclusion of near-channel management alongside more typical field management and thus directly the comparison of cost-effectiveness across portfolios. The optimization analysis revealed that fluvial wetlands (i.e., wide, slow-flowing, vegetated water bodies within the riverine corridor) are the single-most cost-effective management action to reduce both nitrate and sediment loads and will be essential for meeting moderate to aggressive water quality targets. Although highly cost-effective, wetland construction was costly compared to other practices, and it was not selected in portfolios at low investment levels. Wetland performance was sensitive to placement, emphasizing the importance of watershed scale planning to realize potential benefits of wetland restorations. We conclude that extensive interagency cooperation and coordination at a watershed scale is required to achieve substantial, economically viable improvements in water quality under intensive row crop agricultural production.

water quality | agriculture | wetlands | integrated assessment modeling

Intensive agricultural production, as practiced in the Midwestern United States, is now recognized as the primary cause of impaired surface water quality (1–3). Dominated by corn and soybean row crops, land management in this agricultural system has negative impacts on water quality via both direct losses of nutrients and sediment from fields and indirect effects through modifications of runoff, streamflow, and channel networks (4, 5). Extensive networks of artificial agricultural drainage, such as straightened streams and subsurface tile drainage, have amplified storm runoff intensity, reduced water residence time, and increased sediment erosion from near-channel sources downstream (4, 6, 7). The effects of degraded water quality extend throughout the Mississippi River network and into the northern Gulf of Mexico (5, 8). This degradation of surface water compromises its safety for drinking (9), the suitability of lakes and rivers for recreation (10), and the ability of both inland and coastal waters to support aquatic life (5, 11).

Despite consensus on the overall cause of water quality degradation and financial investment toward more sustainable management of agricultural fields, water quality has not significantly improved in the Midwestern United States (1, 12). Although several assessments show reductions in direct nutrient and sediment losses from agricultural fields and some improvement in river water quality (13, 14), these localized improvements have not translated into meeting water quality targets within the receiving rivers, nor a reduction in the size of the northern Gulf of Mexico hypoxic zone (1, 3, 12). Lack of improvement in river water quality, despite ongoing conservation efforts, is linked to five factors. First,

Significance

Water quality is severely degraded in landscapes cultivated for intensive corn and soybean production. Current water quality policy focuses on reducing nutrient and sediment losses from agricultural fields, yet recent studies have highlighted important roles of near-channel areas as sources of sediment and sinks for nitrogen. We developed an integrated modeling approach to assess water quality cost-effectiveness tradeoffs for watershed management scenarios that include a wide range of both field and near-channel management actions, yielding estimates of reductions in sediment and nitrate loads and associated costs for alternative management actions. Our results indicate that near-channel management, most notably fluvial wetland restoration, was most effective for achieving longstanding policy goals for sediment and nitrate reduction.

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SUSTAINABILITY SCIENCE

intensively managed agricultural landscapes in the Midwestern United States still receive annual or biannual applications of fertilizer and manure, despite large legacy stores of nutrients (2, 15), leading to increasing nutrient saturation of landscapes. Second, key pollutants (nitrogen, phosphorus, and sediment) have spatially distinct sources from one another and are mobilized by different mechanisms. Conservation strategies that target single contaminants may not be effective for or may even augment delivery of other contaminants (16, 17). Third, the extent of artificial drainage has continued to increase, leading to more rapid movement of water into and through drainage networks, increasing field nutrient losses and riverbank erosion (4, 7, 18). Fourth, climate change has increased rainfall and runoff in the Upper Midwestern United States, increasing nutrient (19, 20) and sediment (18) losses. Finally, agriculture-related water quality programs do not sufficiently account for heterogeneity in water quality benefits nor in costs of the management practices they incentivize, and thus, both the level and allocation may be mismatched with the magnitude of the issue (21–23). In essence, sustainable solutions to management of Midwestern US agricultural watersheds must address the spatial complexity of sediment and nutrient sources in the context of increasing water yield from greater rainfall and rapid drainage.

Recent studies suggest that near-channel processes significantly alter water quality in intensively managed agricultural regions. Wetlands, including fluvial wetlands (e.g., flow-through wetlands, shallow lakes, floodplains, and backwaters) have been shown to reduce river nitrate concentration in intensively managed agricultural watersheds (24–26). Similarly, near-channel sources of sediment (e.g., river bluffs, streambanks, and ravines) often dominate sediment loading (18, 27). However, despite evidence of the potential importance of near-channel processes, current water quality policy heavily promotes field management (e.g., tillage management, precision fertilizer applications) (28, 29). This is partly due to the limited ability of planning tools such as watershed models to predict improvements from near-channel management (30). The lack of a comprehensive, watershed-scale analysis tool that incorporates both near-channel and in-channel processes likely has resulted in misdirected conservation funding to management actions with limited cost-effectiveness for water quality. Given that water quality impairment in intensively managed agricultural watersheds poses a complex and spatially distributed problem, effective management solutions must address near-channel as well as agricultural field contributions to both the problem and the solution.

In this study, we evaluated the capabilities of watershed-scale management plans—consisting of diverse portfolios of field and near-channel management (*SI Appendix,* Table S1)—to cost-effectively restore water quality. In this approach, we approximate trade-offs in cost-effectiveness across multiple monetized and nonmonetized objectives for an intensively managed landscape, similar to refs. 31–38. To date, such analyses have not been possible due to the limited ability of watershed models to capture near-channel processes (30). We overcame this barrier by integrating three biophysical models into one agricultural field-to-river integrated model, hereafter referred to as the AgRiver model. The framework integrates two models of near-channel processes: the Nitrate Network Model (NNM) (39) and the Management Option Simulation Model (MOSM) (40), with the Soil and Water Assessment Tool (SWAT), a watershed model that is widely used to assess field management effectiveness (41). Using the AgRiver model and an evolutionary optimization approach, we compared performance of watershed management portfolios based on their ability to simultaneously reduce nitrate loads (N), sediment loads (S), and cost across a broad range in reduction targets. Field-derived phosphorus (P) was tracked, but P was not an optimization target in this study due to significant gaps in scientific understanding of near-channel P contributions and management action effectiveness for riverine water quality (16, 20). The AgRiver model and an optimization approach allowed us to address the pressing challenge of water quality impairment in intensively managed landscapes through advances in watershed modeling that enabled analyses of the role of near-channel actions and spatial arrangement of management actions on overall conservation cost-effectiveness.

We applied the integrated watershed modeling framework to the Le Sueur River Basin (LSRB), a subwatershed of the Minnesota River basin. At the time of this study, water quality goals for the LSRB were a 45% reduction in total nitrogen and a 65% reduction in total suspended solids over 10 y (42). Average annual spending to improve water quality in the LSRB was \$4.3M USD over 2,900 km^2 or \$14.7 USD/ha/yr during 2004 to 2018 (43). The LSRB contributes S, N, and P to the Minnesota River basin far in excess of its proportion of the drainage area and has been the subject of detailed field studies quantifying the spatially explicit origins of S and N (6, 25, 44). While many watersheds in the Mississippi River Basin share similar water quality problems, the LSRB was chosen due to the availability of extensive observational datasets used to construct, constrain, and calibrate the AgRiver model (45), the degraded quality of water within and exported from the basin (46), and the extent of intensively managed agriculture (47). Near-channel S loading is higher in the LSRB than most in the region due to its historic connectivity to the drainage pathway for glacial Lake Agassiz (6). Land use and nutrient yields from the LSRB are similar to other intensively managed agricultural basins in the region (26, 48), and thus, insight gained from the LSRB can inform management effectiveness throughout the region.

Results and Discussion

Recent analyses show that current conservation efforts are not sufficient to reverse widespread water degradation in Midwestern agricultural systems (48). In contrast, our analyses show that comprehensive water quality improvements for N and S could be achieved at economically viable investment levels, provided that they target the most cost-effective methods for addressing the problem. In particular, we found that the most cost-effective conservation programs must 1) prioritize construction of fluvial wetlands at optimal locations on the river network. Due to wetland construction costs and performance sensitivity to location, this further requires programs to 2) develop one integrated watershed management plan that allows for federal, state, and private entities and 3) pool resources. This broad conclusion is supported by analyses that identified near-channel management, specifically fluvial wetlands, as the most cost-effective watershed management action for all portfolios with budgets large enough to support them (i.e., >\$300K/yr). Fluvial wetland performance was highly dependent on spatial location, however, underscoring the need for coordination across a watershed. While other management actions were also effective for reducing N and S, none were as cost-effective.

Synergies and Trade-offs for Cost-Effective Watershed Management Scenarios. Watershed management portfolios that best met the combined targets for N, S, and cost, (i.e., cost-effective portfolios) were identified by a multiobjective optimization algorithm. The collection of cost-effective management portfolios for all combined targets forms a frontier of optimality in N-S-cost space that consists of the lowest achievable simultaneous N and S reduction and cost targets and provides insight into trade-offs and synergies between targets (49). Cost-effective management portfolios synergistically reduced N and S loads with larger reductions in both N and S loads as spending increased (Fig. 1 and full frontier at *SI Appendix,* Fig. S2). This observation broadly held true regardless of how S versus N were prioritized (S heavily prioritized shown with red outline, and N heavily prioritized shown with black outline; Fig. 1). Scatter between N and S in Fig. 1 is due to trade-offs between the two objectives and increased as cost targets decreased (Fig. 1*B*). The high degree of scatter for low-cost targets indicates that the need to clearly define water quality management objectives is greatest at low investment rates. Although not an optimization target, the reduction in field-derived P load was also synergistic with N and S (*SI Appendix*, Fig. S3). Relatively small increases in investment resulted in large gains in water quality when management actions were optimized. For $2M/yr ($6.90/ha/yr), N loads could be reduced by 32 to 86%, S loads could be reduced by 23 to 50%, and field-derived P could be reduced by 6.5 to 21%, with the range for each depending on prioritization of N versus S targets (Fig. 1 and *SI Appendix*, Fig. S3). At a cost of $12M/yr (~3% of commodity sales in 2017), essentially all achievable reductions in S (77% reduction) and N (~100% reduction) were met, and field-derived P was reduced by 46 to 65% (*SI Appendix*, Fig. S3). Due in part to the inclusion of a broad range in field and near-channel management actions compared to previous models, our analysis predicted sizeable reductions in sediment load for much lower costs than previously reported (40, 50). In comparison to studies investigating nutrient reduction via wetland placement, our results are similar: a 20 to 40% N reduction was achieved via wetland optimization in (51) for $3.30/ha/yr and 25% reduction in N for $4.50/ha/yr (52) compared to ~$2.00/ha/yr in our results.

Cost-Effective Budget Allocation. Overall, near-channel management emerged as more cost-effective than field management with the exception of scenarios with budgets below $300K/yr, which were incapable of supporting fluvial wetland construction (Fig. 2). For investments at $500K/yr or more above current spending, the budget was primarily allocated for implementing near-channel management actions (Fig. 2 *A* and *B*). For new investments between $300K/yr and $500K/yr, loads were reduced by ~30% (N) and 13 to 17% (S), and spending was more evenly distributed between near-channel and field actions regardless of how N and S were prioritized relative to one another (Fig. 2 *C* and *D*). For new investments less than $300K/yr ($1.03/ha/yr), minimal reductions in N (4%) or S (3%) were achieved, field management was preferentially funded for portfolios prioritizing N reductions, and a balance of field and near-channel management was selected for portfolios prioritizing S reductions (Fig. 2 *C* and *D*).

Individual management actions may reduce both N and S (e.g., cover crops and wetlands) or primarily a single water quality target (e.g., bank stabilization for S or fertilizer management for N). For watershed management portfolios in which N reductions were prioritized, N decreased linearly with the number of wetlands and showed no trend with the extent of field management (Fig. 3*A*). Near complete removal of N was achieved with ~20 fluvial wetlands (out of 103 potential wetland restorations). When S reductions were prioritized, reductions in S were influenced by the extent of fluvial wetlands, ravine stabilization, and field management (Fig. 3*B*). The asymptotic shape of the relationship between S and these three management actions demonstrates a diminishing return on investment in efforts to control S.

For budgets sufficiently large enough to construct at least one wetland, near-channel management in the form of fluvial wetland construction was found to be highly cost effective. This is evident in both the relative allocation of funds to each management action (Fig. 2) and in the extent to which each action was selected relative to its maximum potential extent with increasing costs (Fig. 3*C*). Fluvial wetlands reduce peak streamflow and thus reduce near-channel S loading and at the same time promote internal N removal processes. Interestingly, the number of fluvial wetlands and not the size of selected wetlands increased linearly with increased spending (*SI Appendix*, Fig. S4). Within wetland options, small, shallow fluvial wetlands (individual wetland area = 2.02 ha, average depth <1.1 m) were preferentially selected over larger or deeper wetlands (*SI Appendix*, Fig. S4). The selection preference for numerous small, shallow fluvial wetlands instead of

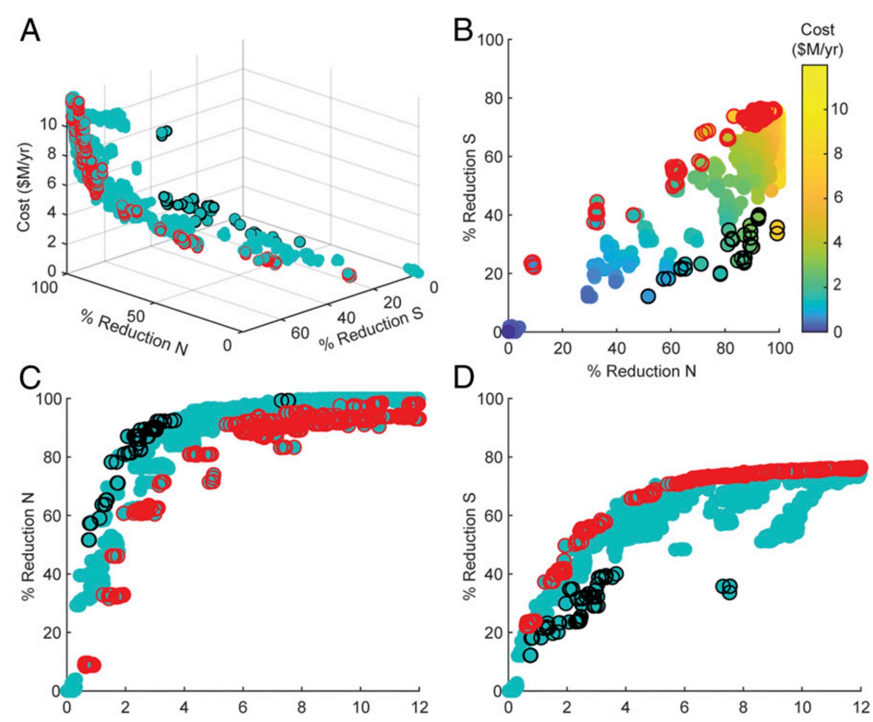

Fig. 1. Cost-effective watershed (Pareto) frontier. (*A*) Three-dimensional frontier of cost-effective watershed management portfolios (individual points) that meet simultaneous targets to reduce S, N, and cost. All cost-effective watersheds meeting cost targets under $12 million/y are shown as solid circles. Outlined circles show water quality target prioritization—watersheds where S was prioritized over N (red outlines) and watersheds where N was prioritized over S (black outlines). (*B*) Two-dimensional plot shows synergy and scatter between N and S objectives with cost shown using color. (*C* and *D*) Two-dimensional plot of N load reductions versus cost and S load reductions versus cost.

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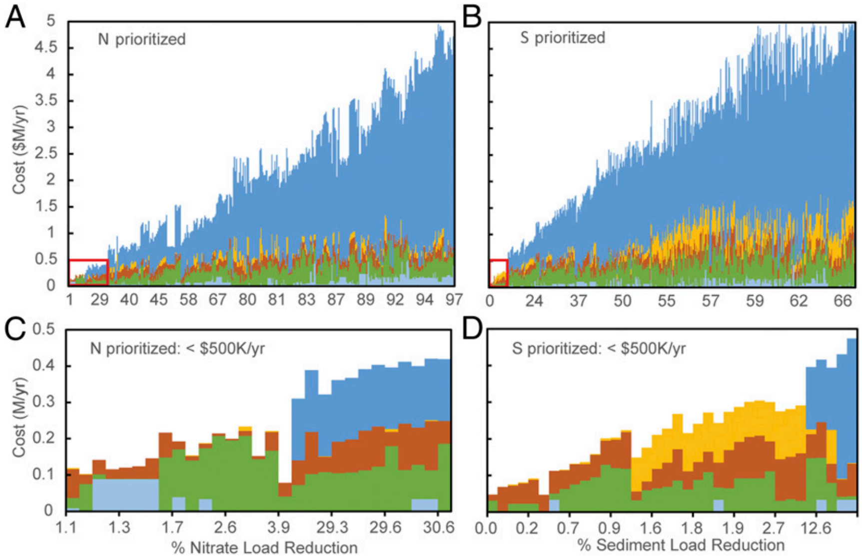

Fig. 2. Cost allocation by management action. Stacked bar charts showing how spending is allocated across management actions within cost-effective watershed portfolios that prioritize N reduction (*A* and *C*) or S reduction (*B* and *D*) in which the bottom panels are enlargements of red boxes region in the upper panels. Candidate management actions include the following: isolated wetlands (light blue), all field management actions (green), bank/bluff stabilization (red), ravine stabilization (yellow), and fluvial wetlands (blue). On average, fluvial wetlands account for a linearly increasing proportion of spending for cost targets above $500,000/y for both N and S prioritization (*A* and *B*). In contrast, at cost targets <$500,000/y, field management and other near-channel management actions are selected (*C* and *D*). Note that *x*-axes are categorical, thus not linear, and sorted by increasing load reduction.

fewer, larger, or deeper wetlands may be due to their preferable ecological function and lower construction costs. Rates of denitrification, a primary N removal mechanism, depend on both N and organic carbon supply so small, shallow wetlands with high rates of internal dissolved organic carbon production from emergent vegetation likely have higher N removal rates compared to deeper or larger wetlands. Economics likely also plays a role in the selection preference for small, shallow fluvial wetlands since dredging is one of the highest costs of wetland construction (53).

When S reduction was prioritized, near-channel management in the form of ravine stabilization was preferentially selected (Figs. 2 *B* and *D* and 3*B*). Ravines form through focused erosion in ephemeral channels linking uplands with deeply incised mainstem channels and are found throughout the lower watershed. Ravine erosion leads to high sediment concentrations, but they are limited in area. Although highly cost-effective, the potential of ravine stabilization to improve water quality was restricted by the limited contribution of ravines to total S loading in the LSRB (14% of total S loading under baseline conditions).

Field management was found to be a persistent component of cost-effective watershed management portfolios regardless of the rate of new investment or N versus S prioritization at cost targets under approximately $20M/yr. Because there were only minor increases in investment in field management, as total investment increased (Fig. 2 *A* and *B*), the relative allocation of funds to field management decreased. Although relatively less cost-effective than near-channel management, there are reasons to continue to promote field management that are not addressed within this study. First, field management is a preventative solution and may be more effective at reducing byproducts of excess fertilizer application that were not included in this study including greenhouse gas emissions (nitrous oxide) and contributions to legacy stores of N

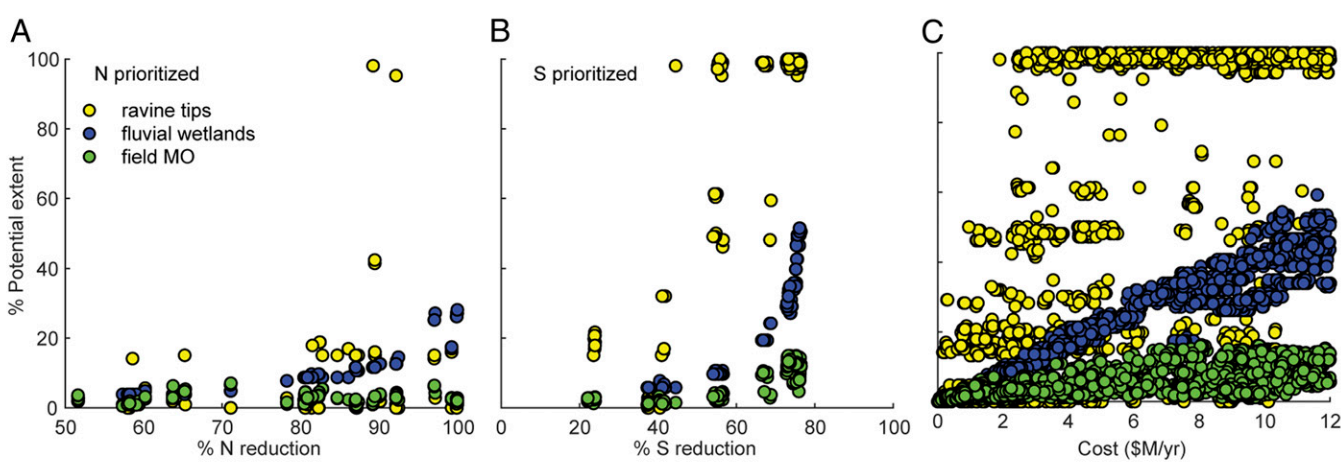

Fig. 3. Utilization of potential management action extent. Percent of potential locations for each management action that were selected for N reduction when N was prioritized (*A*), S reduction when S was prioritized (*B*), and extent of each management action versus cost for all cost-effective solutions (*C*). A 100% potential extent means all possible locations for a management action within the watershed were selected.

and P. Second, off-site management actions are removed from the input location and "out of sight" of upstream farmers, which may reduce the sense of personal responsibility of landowners which could, in turn, lead them to disregard the externalized, downstream costs of excess fertilizer and increase application rates (54).

Dependency on Location. To understand the flexibility with which managers can accommodate political or private preferences yet still achieve their water quality goals, we evaluated the extent of preferential spatial placement of individual management actions within clusters of cost-effective watershed management portfolios (Fig. 4). The first cluster consisted of 30 cost-effective watershed management portfolios that met the current policy target to reduce N by 45% at minimal cost (42). The second cluster consisted of 31 cost-effective watershed management portfolios which met the current policy targets for both N and S (reduce S by 65%) at minimal cost (42). Within these two clusters, near-channel management actions were consistently positioned in the same locations in the watershed (Fig. 4 *B* and *D*). In cost-effective watershed management portfolios that met the N target only, wetlands were positioned near the outlet (Fig. 4*B*). Portfolios that satisfied both N and S targets contained more wetlands, and these were positioned further upstream, typically along the three major tributaries (Fig. 4*D*). The preferential placement of wetlands along major tributaries may be due to a trade-off between high N interception rates and sufficient wetland volume to reduce peak streamflows and thus downstream near-channel S generation. In contrast to wetland placement, no strong location preference was observed for field management actions (Fig. 4 *A* and *C*).

Need for Collaboration. Our results provide much needed guidance toward cost-effectively achieving water quality goals. Nonetheless, the costs are substantial in comparison to a single agency's annual budget, and the performance for the most effective management actions (i.e., fluvial wetlands) is spatially dependent, suggesting that strong coordination across agencies in spending and planning is needed. During the study period, an average of $4.3 M/yr was spent on water quality measures in the LSRB by federal, state, and local agencies with an average budget per agency of $610K/yr (43). However, budgets must be above $500K/yr for fluvial wetlands, the most cost-effective management action, to be feasible. For example, based on the results in Fig. 2, four agencies working independently with annual budgets of $250K/yr would reduce S and N by ∼10% of current loads. However, if they were to coordinate their spending the $1M/yr total investment would collectively achieve a 30% reduction in S and ∼50% reduction in N. By collaboratively developing a whole-watershed plan as well as combining financial resources, S load reductions would be three times greater, and N load reductions would be five times greater than if agencies worked separately, due to their ability to pool resources and thus construct more wetlands as well as choose more optimal locations for wetland construction. An ongoing policy challenge is creation of a system of incentives to implement an (approximately) cost-effective allocation in the context of system-wide interdependencies of the effectiveness of management actions and informational asymmetries with respect to costs of private management efforts (55). While theoretical and empirically grounded advances have been made (56, 57), practical implementation will require substantive agency and stakeholder collaboration. Furthermore, although it is likely that our results are fairly robust to the estimates of the water quality effectiveness and cost (*SI Appendix*), investments in long-lived wetlands would need to be evaluated for their performance in light of ongoing climate change and under deep uncertainty (58).

Future Directions. This analysis concludes that near-channel management, primarily in the form of fluvial wetlands, was most cost effective toward reducing both N and S loads. Because of this, we expect the results of this study to be transferable, in concept, to agricultural basins throughout the Midwestern United States where near channel sources are known to be an important yet poorly constrained source of S (59). Additional research is to constrain the proportion of sediment derived from near-channel sources in other watersheds and better represent near-channel sediment sources in watershed models. Similarly, field and modeling studies that constrain near-channel P sources and transport are needed in order to include P as an optimization target and better align model output with the full suite of typical goals for water quality programs. Finally, management action effectiveness was modeled as a static function, but many actions have a limited life-expectancy that should be considered for full cost-benefit analysis.

Our focus with this research was to consider an expanded suite of management actions that included near-channel in order to identify more cost-effective watershed management portfolios for improved water quality. To facilitate this, we use a simplified economic component in the form of estimates of exogenously determined annualized costs of management actions. Future research could expand on these results by 1) considering the structure of economic incentives for cost-effective outcomes under the challenges presented by nonpoint source pollution problems (55, 56, 60) in the context of integrated assessment models (61, 62), 2) incorporating the broad set of factors known to influence private conservation and program participation (63), and 3) considering collaborative management of complex systems under changing external regimes and uncertainty (58).

SUSTAINABILITY SCIENCE

Conclusion

Our analyses show that achieving cost-effective management of riverine water quality in intensively managed agricultural systems requires a watershed perspective and collaborative cross-agency decision making. Near-channel management actions, specifically small, shallow fluvial wetlands and ravine stabilization, were clearly more cost effective than field management. However, wetland performance was highly dependent on optimal positioning, and wetlands can be prohibitively expensive for individual farms or agencies. Thus, a comprehensive watershed planning strategy that considers the watershed as a system, combines fiscal resources, and carefully selects fluvial wetland location will yield the most efficient reductions in N and S loads. Our results are supported by decades of scientific investment in understanding watershed scale processes in an intensively managed watershed and will enable better use of limited conservation investments to achieve water quality goals.

Materials and Methods

Biophysical Modeling Framework. Three biophysical models of the LSRB were linked to fully capture both terrestrial and near-channel processes (*SI Appendix*, Fig. S5). Terrestrial inputs, transformations, and transport of water, N, S, and P were modeled using the SWAT (41). The base unit in SWAT is the hydrologic response unit (HRU) in which each HRU represents a distinct combination of land use, land cover, soil type, and slope within a subbasin. The computational unit in SWAT is the subbasin, which accounts for the spatial distribution of basin characteristics and land management. The LSRB SWAT model consisted of 103 subbasins (average area 15 km^2) and 934 HRUs. Output from SWAT was routed to two river network models to model near-channel processes. Near-channel N removal was modeled using the NNM (39). Upland S delivery and near-channel S loading were modeled with the MOSM (40). NNM, MOSM, and SWAT are all publicly available (39–41). Weather was modeled at a daily time step and as spatially uniform in order to separate the effect of watershed spatial context from localized variability in weather patterns. Persistent or future spatial patterns in weather may also contribute to decisions about appropriate conservation actions and location and are the subject of future study. Further model details, including model calibration and validation, are provided in *SI Appendix*.

Management Actions. This analysis considered a broad suite of candidate management actions that have previously been shown to reduce N or S loads (*SI Appendix*, Table S1). Management actions were classified as either field management (i.e., actions on current agricultural land) or as near-channel management (i.e., actions within the riverine network). Field management actions

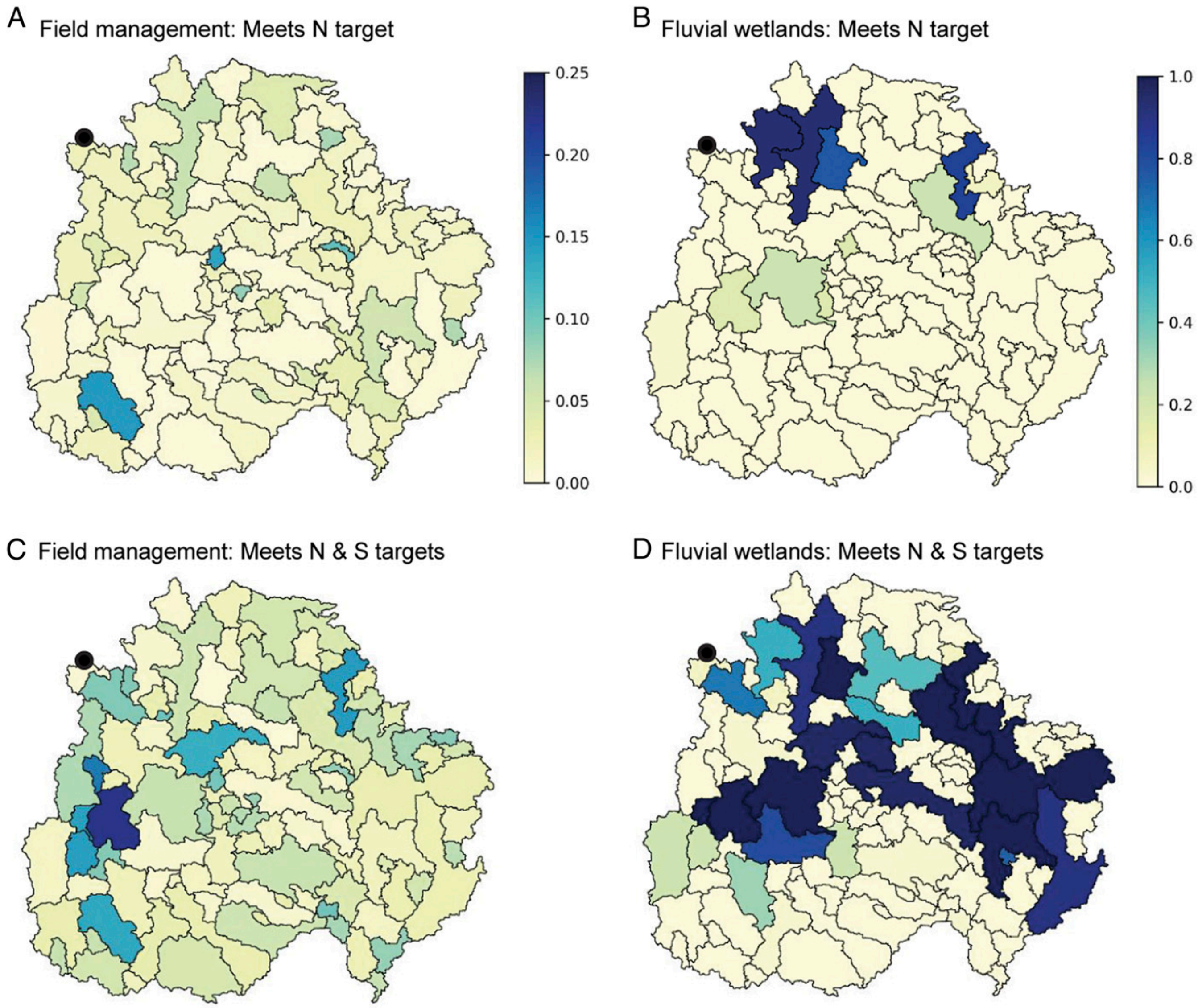

Fig. 4. Spatial dependency of management actions. Watershed subbasins colored by the fraction of watershed portfolios in which they were selected for either field management or wetland placement within clusters of portfolios meeting the N target reduction (*A* and *B*; 30 portfolios) or both N and S policy target (*C* and *D*; 31 watersheds). Note that the color bar scales are different for field management (*A* and *C*) and fluvial wetlands (*B* and *D*). The subbasins selected for wetland remediation (*B* and *D*) are more spatially persistent than those selected for field management actions (*A* and *C*). The watershed outlet is shown with a solid black circle located in the top left corner.

included cover crops, grassed waterways, isolated wetlands or ponds, which all retain N and S on agricultural fields, and fertilizer management to reduce the quantity of N applied. SWAT architecture restricts isolated wetlands to one per subbasin; in the model, isolated wetlands were sized to reflect aggregated relative area for individual wetlands (1, 3, or 5% of the subbasin area) and shape (i.e., shallow marsh versus deep pond). Near-channel management actions included fluvial wetlands, ravine stabilization, and toe protection for banks and bluffs. Ravine stabilization and toe protection for banks or bluffs both reduce the magnitude of near-channel contributions to S (40). Previous research has identified 106 ravines and 480 mapped bluff or exposed banks within the LSRB (64). Fluvial wetlands reduce N by increasing removal rates and reduce S by reducing the magnitude of peak streamflow. Similar to isolated wetlands, the number of modeled fluvial wetlands was constrained by SWAT to one per subbasin. Fluvial wetlands were further specified by aggregated size (70, 450, or 1,700 ha and shape [marsh versus pond]). Spatially explicit costs were assigned to each management action within the candidate watershed. These costs included land opportunity costs modeled using a real options analysis (finding a critical payment sufficient for private landowners to devote their land to wetlands), construction, engineering and maintenance costs, and losses due to yield reduction. Further details describing the representation and costs of management actions are provided in *SI Appendix*.

Optimization Framework. A multiobjective evolutionary optimization algorithm (MOEA) was used to identify watershed portfolios that most cost-effectively satisfied simultaneous targets for cost, N load reduction, and S load reduction. We used an elitist modification of a strength Pareto evolutionary algorithm 2 (SPEA2) algorithm, in which nondominated solutions are maintained in the archive (65–67), to solve the multiobjective optimization problem. We followed the recent work of Lang et al. to overcome the "curse of dimensionality" in large-scale MOEAs (68). Evolutionary algorithm iterations were stopped upon reaching the consolidation ratio of 0.9 (68). P load was not included as an optimization target due to insufficient understanding of near-channel P dynamics and legacy storage (16, 20, 69). Optimizing field-derived P only without an adequate representation of near-channel storage and generation processes would not reflect true P load reductions.

Data Availability. Optimization genome and output file data have been deposited in Open Science Framework (DOI 10.17605/OSF.IO/JEMKN) (67).

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