Science Assessments Quantifying the Contribution of Interannual Weather Variability and Nutrient Processes to Nonpoint Source Nutrient Losses from Croplands in Iowa

Abstract:

A primary difference between nutrients transported to streams from cropland “nonpoint sources” and nutrient discharge to streams from city/industrial wastewater “point sources” is that interannual weather patterns create large interannual variability in the amount of nonpoint losses. Nonpoint sources are largely the result of excess precipitation water movement to streams carrying cropland nutrients with it, while point source discharges are largely under human control of the wastewater treatment facilities. Nonpoint sources from corn and soybean croplands are also driven by long periods outside of the growing season when land is fallow with no nutrient demand. Nonpoint source nutrient loads from these croplands can be partially mitigated through use of various conservation and nutrient management practices identified in the Iowa Nutrient Reduction Strategy (INRS), but weather dynamics create large year-to-year variability in the amount of nonpoint nutrient source loads. In some years weather can overwhelm the capacity for INRS practices to mitigate nutrient loads. The primary purpose of this assessment is to review the state of the science on the contribution of interannual weather variability to the magnitude of nonpoint sources of nutrient loss.

Approach:

The study consists of assessments by various science experts on the contribution of interannual weather variability to interannual variability in N and P nutrient loading. Review of existing science literature and past empirical and modeling studies were the primary approach.

Primary Questions:

Nitrogen

1. How much of the load is from applied nutrients and how much is from soil organic matter?
2. How has nitrogen use efficiency changed over time?
3. How can nitrogen mass balance be re-confirmed, re-characterized?

Phosphorus

1. How much of stream phosphorus load is from in-stream bed and bank sources?
2. What flow conditions are the most critical for local water quality concerns?

Climatology

1. How much of the nutrient load to water resources is due to weather?
2. What weather frequency is most important to the policy options of the Iowa Nutrient Reduction Strategy?

Work Product:

Assessments were completed separately for nitrogen, phosphorus, and climatology by each of the PIs. The goal is to create an overall summary report which integrates the findings of each individual assessment. Following are the key summary points from the individual assessments.

Key Summary Points:

Nitrogen

- Long periods of zero or low plant nitrate demand (outside of growing season and before vigorous growth) are the primary cause of high nitrate loss to water resources, but the amount and timing of precipitation cause variability in the year-to-year amount of loss.
- Year-to-year variability in the amount of nitrate losses is high (40-78% of the interannual mean) due to variability in weather.
- On average, 2/3 of nitrogen fertilizer is recovered in plants and soils and 1/3 is unrecovered (i.e., lost to air or water resources).
- There is no difference in nitrate loss from fertilized corn and unfertilized soybean phases of the 2-year corn-soybean rotation.
- The optimum nitrogen fertilizer input to corn can vary by more than 100% across fields and years (e.g., 150 to 300 pounds of nitrogen per acre per year).
- Optimum nitrogen fertilizer input is required to maintain soil health. Insufficient nitrogen fertilizer input results in a loss of soil organic matter because plant residue input at insufficient nitrogen fertilizer input is too low to maintain soil organic matter levels.
- A variety of people (including scientists) have mistakenly attributed or are at risk of mistakenly attributing increases or decreases in nitrate load and flow-weighted nitrate concentration to changes in land use and cropping systems management when the real cause of the increases or decreases is interannual weather patterns. As a result, progress towards water quality goals could be over- or under-estimated.

Phosphorus

- Streambank erosion represents a significant, albeit highly variable, source of both suspended sediment and phosphorus to stream loads in Iowa.
- The product of water discharge and stream slope is commonly referred to as "stream power", which is the sediment transport capacity of a stream. Rivers and streams maintain a dynamic equilibrium between stream power and sediment transport.
- Historic landscape/land use and climate changes in Iowa and the Midwest have altered stream power.
- Sediment and phosphorus flux from a watershed are episodic and closely related to peak event discharge rates.
- Streambank erosion has been found to be a major contributor to total watershed suspended sediment and phosphorus export in several watersheds in Iowa.
- Over a long-term annual basis, streambank erosion contributes approximately one-third of riverine phosphorus export from Iowa.
- A greater understanding of the erosion and transport of sediment and phosphorus from both upland and channel sources will help natural resource managers make improved recommendations for implementing effective soil and water conservation practices at the appropriate location and scale to achieve cost-effective nutrient reduction.

Climatology

- Over the last few decades, rainfall events have become more frequent and more intense across portions of the state, leading to increased run-off and flooding events. Iowa's average annual precipitation has increased by 0.43 inches per decade.
- What we have seen across Iowa is a seasonal shift in precipitation; we are experiencing a shift of more precipitation in the spring and fall. In between, we are seeing a decrease in rainfall in the summer months, particularly in early July through August.
- High intensity rainfall events and droughts are often coupled together. Dry soil profiles can release stored nutrients after heavy rainfall events. Abnormally dry and drought condition can have an impact in nutrient runoff if there is a transition into wetter conditions after application, especially at 30-45 days.

Sources of Non-Point Nitrate Transport to Iowa's Water Resources

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Executive Summary

- Nitrate losses from corn and soybean croplands to Iowa waterways are high because corn and soybean croplands – as currently managed – have zero or low plant nitrate demand for long periods of the year.

- Year-to-year variability in the amount of nitrate losses is high (40-78% of the interannual mean) due to year-to-year variability in weather.

- Nitrate losses from conventional well-managed corn and soybean croplands to Iowa waterways are generally 20-40 lbs of nitrogen per acre per year.

    - Approximately half of this nitrate loss can be attributed to inefficient use of nitrogen inputs.

    - Approximately half of this nitrate loss can be attributed to a lack of synchrony between soil nitrate availability and plant nitrate demand.

- The asynchrony between soil nitrate availability and plant nitrate demand is a major factor controlling nitrate losses from corn and soybean croplands and is evidenced by the following results that are consistent across research studies from different universities and teams of scientists:

    - There is no difference in nitrate loss from fertilized corn and unfertilized soybean phases of the 2-year corn-soybean rotation.

    - Perennial crops such as alfalfa and native perennial vegetation lose negligible amounts of nitrate to water resources (generally much less than 5 lbs per acre per year). Moreover, nitrogen fertilizer inputs to perennial crops and vegetation generate little-to-no increase these very low nitrate losses.

  - Drainage water quality monitoring research demonstrates that nitrate losses from unfertilized corn fields is substantial.

  - Cover crops create plant nitrate demand at times when there is a lack of plant nitrate demand. As a result, cover crops are generally more effective at reducing nitrate losses than state-of-the-art technologies to best manage nitrogen fertilizer inputs.

- There is critical lack of data that describe nitrate losses with direct reference to nitrogen fertilizer inputs that are empirically determined to be agronomically (and economically) insufficient, optimum, and excessive. The economic optimum nitrogen fertilizer input is 95-99% of the agronomic optimum nitrogen fertilizer input (i.e., the input at which grain production is not limited by nitrogen). This lack of data severely limits our ability to estimate the potential contribution of optimum nitrogen fertilizer management to nitrate loss reduction.

- Research that measures nitrate losses with direct reference to nitrogen fertilizer inputs is critically important for the following reasons:

  - The optimum nitrogen fertilizer input to corn can vary by more than 100% across fields and years (e.g., 150 to 300 pounds of nitrogen per acre per year). At present, there is no way to forecast this variability.

  - Optimum nitrogen fertilizer input is required to maintain soil health. Insufficient nitrogen fertilizer input results in a loss of soil organic matter because plant residue input at insufficient nitrogen fertilizer input is too low to maintain soil organic matter levels.

  - Research suggests that yield-scaled nitrogen losses (i.e., lbs of nitrogen loss per pound of grain production) are minimized at the agronomic optimum nitrogen fertilizer input.

Why do Iowa croplands lose nitrate to water resources?

Nitrate loads and concentrations are elevated in Iowa and other Corn Belt states because corn and soybean croplands – as currently managed – dominate land use and lack plant nitrate demand for a large portion of the year. During this portion of the year when plant nitrate demand in conventionally managed corn and soybean croplands is zero or low (i.e., the time outside the corn V7 to maturity and soybean R1 to R5 growth stages) most nitrogen fertilizer applications occur, and soil microbes produce nitrate from soil organic matter. This nitrate is easily transported to water resources by precipitation. Hence, long periods of zero or low plant nitrate demand cause high nitrate loss to water resources but the amount and timing of precipitation cause variability in the year-to-year amount of loss.

The total amount of nitrate loss

In cropping systems with artificial subsurface drainage, nitrate losses from corn and soybean croplands can be measured in research plots that are instrumented to measure the amount and nitrate concentration of drainage water from a specific area. A database of more than 300 unique nitrate loss measurements from drainage monitoring research plots in Iowa, Illinois, Indiana and Minnesota that received 0-448 pounds of nitrogen per acre per year reports annual nitrate losses ranging from 0.40 to 138 pounds of nitrate-nitrogen per acre per year (Zhao et al. 2016).

The range in these losses is consistent with the quotient of the total annual Iowa nitrate load to the Gulf of Mexico and the acres of corn and soybeans in Iowa. From 1999-2016 state-wide nitrate loads ranged from approximately 150,000,000 to 1,300,000,000 pounds of nitrogen (Jones et al. 2018). There are approximately 23,000,000 acres of corn and soybeans. This results in annual per acre nitrate losses of 6 to 54 pounds of nitrogen. Although Jones et al. (2018) report that the total state-wide load was increasing during this monitoring period, it is difficult to determine if this putative increase was due to weather patterns (i.e., wetter years later in the record) or changes in land use and management (Danalatos et al. 2021). Monitoring of flow-weighted nitrate concentration can help to control for the effects of weather. All reports of nitrate losses should include load and FWNC.

The role of fertilizer

The contribution of inefficient nitrogen fertilizer management towards total nitrate losses can be estimated with three methods: i) isotopically 'labeled' nitrogen fertilizer can be purchased, applied to the field, and tracked using isotope ratio mass spectrometry; ii) comparisons of nitrate loss from side-by-side drainage monitoring plots that receive and do not receive nitrogen fertilizer inputs; iii) cropping systems process models, which are mathematical representations of the biology, chemistry and physics of the complete cropping system (plants, soils, and management) and are similar to weather forecast models, can reveal information about the amount, source, and timing of nitrate loss.

Isotopically labeled nitrogen fertilizer: Nitrogen consists of two stable isotopes that are functionally identical but differ in mass by 1 gram per mole. A nitrogen fertilizer that is enriched in the heavy stable isotope of nitrogen can tracked with high accuracy through plants, soils, air and water because the heavy stable isotope of nitrogen makes of only 0.4% of nitrogen in the environment. However, high costs generally prohibit tracking of the fertilizer to water and air resources. Instead, the fertilizer is generally tracked to three fates: i) crop uptake; ii) soil nitrogen including residual nitrate and nitrate that was transformed to soil organic matter; and iii) loss to air or water resources.

I know of only one Iowa-based study in the last 25 years that traced nitrogen fertilizer through corn and soil using this method (several studies exist from the 1980s and early 1990s and are listed in an appendix below). The lack of recent studies is likely due to consistent results in older studies, which were reviewed by Gardner and Drinkwater (2009). These authors found that, on average, 2/3 of nitrogen fertilizer is recovered in plants and soils and 1/3 is unrecovered (i.e., lost to air or water resources).

The one recent study was conducted by my research group and includes two site-years of research in Ames, IA and Chariton, IA (Poffenbarger et al. 2018). Both site-years were managed in continuous corn with conventional management (fall tillage, spring cultivation, spring pre-plant urea ammonium nitrate fertilization, and no cover crop). Very importantly, the study applied nitrogen fertilizer at the rate that was empirically determined to be optimum for specific field at each site using thirteen years of prior nitrogen fertilizer response data. The optimum rates were 180 pounds per acre in Ames and 240 pounds per acre in Chariton. In Ames, a highly productive site, 44% of the nitrogen was recovered in the crop, 22% in the soil from 0-4 feet, and 34% was lost to air or water resources or perhaps could be stored in soil below the sampling depth of 4'. In Chariton, a poorly productive site, 14% was recovered in the crop, 18% was recovered in the soil and 69% was lost to the air and water resources or perhaps stored in the soil below the sampling depth of 4'.

Drainage monitoring plots: Using data from drainage monitoring plots, nitrate losses from corn without fertilizer can be compared to nitrate losses from corn with fertilizer to allow estimation of the amount of nitrate loss that is derived from mineralization of soil organic matter vs. nitrogen fertilizer use inefficiencies. However, it is important to caution that these studies are rarely conducted at the agronomic optimum nitrogen rate. Comparison of a nitrate leaching from a plot receiving zero N and a plot receiving insufficient N would underestimate N losses due fertilizer use inefficiency where comparison of nitrate leaching from a plot receiving zero N and plot receiving excessive N would overestimate N losses due to fertilizer use inefficiency (fertilizer use efficiency always declines as N fertilizer inputs increase; deWit 1992). Hence, a properly designed study would measure grain yield and nitrate leaching across a range of nitrogen fertilizer rates and use statistical models to estimate the exact optimum nitrogen fertilizer rate and nitrate loss at that rate. The database of nitrate loss measurements from drainage monitoring studies (Zhao et al. 2016) indicates that research plots receiving zero nitrogen fertilizer lost approximately 33% less nitrate than fertilized plots. In the authors analysis of the database, they provide an equation across all studies (including some beyond the Corn Belt) relating nitrogen fertilizer rate to nitrate load: nitrate load = $21.10+1.738^{(0.008*\text{fertilizer input})}$ where 21.10 is the nitrate loss in kg per ha at zero nitrogen fertilizer input (18.8 pounds nitrate per acre). This equation suggests that at 150 pounds of nitrogen fertilizer per acre, 24% of nitrate loss can be attributed to inefficient fertilizer use and at 200 pounds of nitrogen fertilizer per acre, 33% of nitrate loss can be attributed to inefficient fertilizer use. Lawlor et al. (2008) provide a similar equation for flow-weighted nitrate concentration. At zero nitrogen fertilizer, the FWNC is 5.72 mg nitrate-nitrogen per liter. This equation suggests that at 150 pounds of nitrogen fertilizer per acre, 57% of nitrate loss can be attributed to inefficient fertilizer use and at 200 pounds of nitrogen fertilizer per acre, 70% of nitrate loss can be attributed to inefficient fertilizer use. The FWNC is likely a more reliable indicator of the role of nitrogen fertilizer because it helps to control for the effect of weather. However, the Lawlor et al. (2008) equation is limited to one research site whereas the Zhao et al. (2016) equation is derived from a database that includes hundreds of observations and more than 90% of the observations are from Iowa, Illinois, Indiana and Minnesota.

Process modeling: The one process modeling study available that explored the contribution of nitrogen fertilizer to nitrate loss (Martinez-Feria et al. 2018) attributed 45% of nitrate losses in well managed corn-soybean cropping systems to inefficient nitrogen fertilizer use. The authors including Drs. Archontoulis, Castellano and Helmers from ISU reported *"Modeling of maize-soybean rotations indicated that despite their high crop NUE, only 45% of N losses could be attributed to the inefficient use of N inputs, whereas the rest originated from the release of native soil N into the environment, due to the asynchrony between soil mineralization and crop uptake."*. Although there is only one modeling analysis that addresses this question, it is clear that modeling is powerful tool to improve nitrogen fertilizer use efficiency and understand the contribution of nitrogen fertilizer to environmental losses and crop production. The model simulations are carefully calibrated and validated with the best available data. Personnel (expert computer scientists and agronomists) with modeling skills are in short supply but critical the future of Iowa agriculture.

The role of weather

In a recent report to the Iowa Department of Natural Resources (not yet public), ISU Agronomy graduate student Gerasimos Danalatos (co-advised by Castellano and Archontoulis), analyzed year-to-year variability in annual nitrate loads and mean annual flow-weighted nitrate concentration (FWNC) in 38 Iowa watersheds where these variables were stable during the period of 2001 to 2018 (i.e., no statistically significant linear change over time).

Because we analyzed only watersheds without increases or decreases in load and FWNC from 2001 to 2018, we attributed the year-to-year variability in these variables to year-to-year variation in weather. Across the watersheds weather-related variability in FWNC ranged from 12-39% and the weather-related variability in nitrate load ranged from 40-78%. Hence, in the absence of any change in land use or management, a mean annual FWNC of 10 mg nitrate-N per liter would be expected to fluctuate by 12-39% due to weather only. For example, if the mean FWNC was 10 mg nitrate-nitrogen per liter in the least variable watershed (12%), the FWNC would be expected to fluctuate from 8.80 to 12.2 mg nitrate-N per liter due to weather variability alone. In contrast, if the mean FWNC was 10 mg nitrate-nitrogen per liter in the most variable watershed (39%), the FWNC would be expected to fluctuate from 6.1 to 13.9 mg nitrate-N per liter due to weather variability alone. The same exercise could be conducted with loads.

As a result of this variability, it is possible to observe an increase or decrease in nitrate loads and concentrations due to weather patterns alone rather than changes in cropping systems management.

For example, several dry years following a period of wet years would result in lower stream nitrate loads and FWNC whereas several wet years following a period of dry years would result in higher stream nitrate loads and FWNC. A variety of people including scientists have or are at risk of mistakenly attributing increases or decreases in nitrate load and FWNC to changes in land use and cropping systems management when the real cause of the increases or decreases is interannual weather patterns (or vice versa). This is why measuring the implementation and efficacy of conservation practices at field and watershed scales is very important.

Note, it is possible that nitrate load and FWNC were changing due to management in some of the watersheds we analyzed but we could not detect the change due to the variability introduced by weather. Also, we assumed that the effect of weather on interannual variation in nitrate load is proportional to the mean FWNC and load.

Regional studies of isotopically labeled fertilizer:

Blackmer, A. M., and C. A. Sanchez. 1988. Response of corn to nitrogen-15-labeled anhydrous ammonia with and without nitrapyrin in Iowa USA. Agronomy Journal 80:95–102.

Cerrato, M. E., and A. M. Blackmer. 1990. Effects of nitrapyrin on corn yields and recovery of ammonium nitrogen at 18 site-years in Iowa USA. Journal of Production Agriculture 3:513–521.

Jokela, W. E., and G. W. Randall. 1997. Fate of fertilizer nitrogen as affected by time and rate of application on corn. Soil Science Society of America Journal 61:1695–1703.

Poffenbarger, H. J., Sawyer, J. E., Barker, D. W., Olk, D. C., Six, J., & Castellano, M. J. (2018). Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize. *Agriculture, ecosystems & environment*, *265*, 544-555.

Sanchez, C. A., and A. M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa, USA. Agronomy Journal 80:102–108.

Stevens, W. B., R. G. Hoeft, and R. L. Mulvaney. 2005. Fate of nitirogen-15 in a long-term nitrogen rate study: II. Nitrogen uptake efficiency. Agronomy Journal 97:1046–1053.

Timmons, D. R., and J. L. Baker. 1992. Fertilizer management effect on recovery of labeled nitrogen by continuous no-till corn. Agronomy Journal 84:490–496.

Timmons, D. R., and R. M. Cruse. 1991. Residual nitrogen-15 recovery by corn as influenced by tillage and fertilization method. Agronomy Journal 83:357–363.

Timmons, D. R., and R. M. Cruse. 1990. Effect of fertilization method and tillage on nitrogen-15 recovery by corn. Agronomy Journal 82:777–784.

Contribution of Streambank Erosion to Stream Phosphorus Load in Iowa

A summary prepared for Iowa Nutrient Research & Education Council
Iowa State University
February 2021
Not for Citation without Author Permission

Core Ideas:

- Rivers and streams maintain a dynamic equilibrium between stream power and sediment transport.
- Historic landscape/land use and climate changes in Iowa and the Midwest have altered stream power.
- Unstable streams proceeding through a channel evolution sequence can exacerbate downstream water quality and sedimentation issues.
- Annual variations in streambank recession rates have been attributed to riparian land cover, cattle grazing, variations in precipitation and discharge, and alluvial stratigraphy.
- Sediment and phosphorus flux from a watershed are episodic and closely related to peak event discharge rates.
- Streambank erosion has been found to be a major contributor to total watershed suspended sediment and phosphorus export in several watersheds in Iowa.
- Resuspension of temporary storage within the channel-floodplain complex that accumulated from bank erosion between large discharge events is a potential large source of transported sediment.
- Over a long-term annual basis, streambank erosion contributes approximately one-third of riverine phosphorus export from Iowa.

Stream Equilibrium and Channel Evolution

Fluvial systems (rivers and streams) maintain a dynamic equilibrium between discharge, slope, sediment load, and sediment size. Over time, the shape of rivers and streams changes via erosion, deposition, and sediment transport to maintain this equilibrium. This relationship is described by Lane's principle of fluvial hydraulics (Lane, 1955):

$$Q_s d \propto Q_w S$$

in which Q_s = sediment discharge, d = particle diameter [sediment size], Q_w = water discharge, and S = slope of the stream [gradient]. The product of $Q_w S$ is typically referred to as “stream power”. Although qualitative, this relation is useful in assessing how changes in any variable impacts either stream power or sediment discharge. According to Lane, an increase/decrease in any of these variables will trigger a corresponding change [increase or decrease] in one [or more] of the others, until a new equilibrium is established. For example, if stream slope (S) increases due to removal of meander bends and straightening of the channel, then stream bed degradation will likely occur, increasing sediment load to the degree that the balance will reestablish. A limitation of this conceptual model is that it does not indicate which variable will adjust, the magnitude of the adjustment, or the timeframe involved (USDA-NRCS, 2007). While the principle may be used to identify possible stability problems, analytical methods would be required to predict their magnitude.

Channel evolution models are idealized depictions of the morphologic stages through which a river or stream channel progresses in response to disturbance (Simon and Rinaldi, 2006). The purpose of a channel evolution model is to simplify stream adjustment processes into a relatively small number of observed states with predicable sequences. Models that describe the response of incising channels are common (Schumn, Harvey and Watson, 1984; Simon and Hupp, 1986) and share the same fundamental sequence: 1) An initial disturbance, causing an imbalance between sediment-transport capacity (stream power) and sediment supply; 2) Incision of the channel bed; 3) Channel bank collapse and subsequent channel widening as streambanks adjust to new equilibrium conditions; and, 4) The reestablishment of a lower floodplain/channel system, regarded as the new stable system. The range of evolutionary trajectories included in any channel evolution model reflects a context determined by local conditions.

Assessment of the factors contributing to a shift in stream equilibrium and resulting sediment dynamics in streams and rivers of the Midwest and elsewhere has been the focus of a number of studies. General conclusions of these studies include:

- Land use/land cover change and increasing precipitation have contributed to increased base flow and streamflow in many Midwestern rivers and streams, but the relative importance of causal factors is open to debate (Ayers et al., 2019: Gupta et al., 2015; Foufoula-Georgiou et al. 2015; Kelly et al., 2017; Schilling et al. 2008, 2010; Slater and Villarini, 2017; Tomer and Schilling, 2009; Zhang and Schilling 2006 a,b).
- Artificial subsurface (tile) drainage contributes to changes in baseflow and streamflow in Midwestern rivers and streams (Schilling et al., 2019; Schilling and Helmers, 2008; Schottler et al., 2014; Sloan et al., 2017; Skaggs et al. 1994).
- Stream channelization increases reach-scale stream gradient (James, 2018; Simon and Rinaldi, 2006), altering stream power and sediment dynamics.
- Anthropogenic sediment stored in the riparian zone can be source of stream sediment load (Stout et al., 2014), but its relative importance is context dependent (Downs and Piegay, 2019; Gran et al., 2013). A critical gap in understanding the sediment routing system lies in the prediction of temporary storage and resuspension within the channel-floodplain complex (Beck, 2018; Belmont et al. 2014).
- Channel incision resulting from stream disequilibrium can reduce floodplain storage of sediment and phosphorus (Beck et al., 2019; Hamlett et al., 1983).

Streambank Erosion Contribution to Sediment and Phosphorus Transport in Iowa

The Iowa Nutrient Reduction Strategy stated that "Streambanks are known to be a potentially large source of stream sediment…. However, accurately accounting for streambank sources of P is extremely difficult and methods have not been developed to quantify streambank sediment contributions beyond a local scale. Therefore, evaluating strategies to reduce P losses from point sources and eroding streambanks (i.e., runoff volume reduction or bank stabilization) are beyond the scope of this effort". However, for nearly two decades researchers at Iowa State University, Iowa Geological Survey, University of Iowa, U.S. Department of Agriculture, and the Iowa Department of Natural Resources have been conducting research intended to address this issue. The objectives of this research have been to evaluate: 1) streambank recession rates within different landform regions of Iowa; 2) temporal variability of watershed sediment and phosphorus flux; 3) total watershed suspended sediment export in several watersheds; and, 4) total phosphorus concentrations and bulk density of streambank soils; 5) statewide streambank erosion; and, 6) contribution of streambank sources to sediment and phosphorus export from the state.

While the work is ongoing and addresses an inherently complex issue, the growing body of research suggests that streambank erosion often represents a significant, albeit highly variable, source of both suspended sediment and phosphorus to stream loads in Iowa. Results to date are generalized below.

Additional details can be found in the cited peer-reviewed literature. Results related to the overall contribution of eroding streambanks to phosphorus export from Iowa are reported in a manuscript that is under review (Schilling et al. *In Review*) and should not be cited without author permission.

1) Streambank Recession Rates within Different Landform Regions of Iowa

A variety of methods have been used to evaluate rates of streambank recession in Iowa watersheds, including cross-section surveys, bank erosion pins and photogrammetric methods that including the use of Light Detection and Ranging (LiDAR) systems and sequential aerial photographs. In low order (smaller) Iowa streams, erosion pins have been widely used to measure bank recession at targeted eroding bank segments (e.g., Beck et al., 2018; Palmer et al., 2014; Tufekcioglu et al., 2012; Zaimes et al., 2008; 2019).

Since the early 2000's, researchers at Iowa State University have used erosion pins at several hundred streambanks across Iowa to measure bank recession in wadable 3rd to 4th order channels. Annual streambank erosion estimates for 385 streambank-years from five different long-term monitoring sites in the state are reported in Schilling et al. (*In Review*). In a separate study, Zaimes et al. (2019) compiled recession rates from nine different Iowa studies that included sites sorted by riparian land cover.

Published results from the pin studies show wide variability in annual streambank recession rates, ranging from -1.2 (deposition) in central Iowa to 34.2 cm yr^{-1} of bank erosion in a southern Iowa watershed. Among all sites, an average streambank recession rate for 385 bank years was approximately 12.4 ± 10.3 cm yr^{-1}, with a median value slightly less (11.0 cm yr^{-1}). Since many of the streambank sites were the same, compilation of annual streambank recession rates reported in Zaimes et al. (2019) produced similar results, averaging approximately 12.9 cm yr^{-1}. It is important to note that erosion pins were typically installed in banks identified as severely eroding according to USDA-NRCS criteria so the recession rates reflect variations measured in exposed banks and not all channels.

Variations in annual recession rates are attributed to many factors, including riparian land cover (Zaimes et al., 2004; 2006; 2008), cattle grazing (Tufekcioglu et al., 2012), variations in precipitation and discharge (Palmer et al., 2014) and alluvial stratigraphy (Beck et al., 2018). Such factors are site dependent and are consistent with mechanistic processes controlling bank erosion at individual sites in other watersheds (e.g., Simon and Collison, 2002; Pollen et al., 2004; Fox et al., 2016). Some variation in erosion pin data are also due to measurement limitations associated with erosion pins (Palmer et al., 2014).

2) Temporal Variability of Watershed Sediment and Phosphorus Flux

Studies in Iowa and surrounding states have illustrated that sediment flux from a watershed is episodic. In one study over a four-year period in central Iowa, streambank recession rates and sediment export were both closely related to peak event discharge rates (Noonan, 2016). Over the study period, 79% of the cumulative bank recession and 49% of the sediment export occurred in about 12 days during three major storm flow events.

3) Total Watershed Suspended Sediment Export in Several Watersheds

Streambank erosion was been found to be a major contributor to total watershed suspended sediment export in several watersheds in Iowa, with streambank contributions to annual sediment load ranging from <10 to 80% (Beck et al., 2018; Gellis et al., 2019; Palmer, 2014; Wilson et al. 2008). In one four-year study in central Iowa, sediment loss from streambanks exceeded export from the watershed by 29%, indicating significant storage within or adjacent to the stream channel (Noonan, 2016). However, one of the few studies that addressed the issue identified that a potential source of the transported sediment was resuspension of temporary storage within the channel-floodplain complex that accumulated from bank erosion between large discharge events (Beck et al. 2018).

4) Total Phosphorus Concentrations and Bulk Density of Streambank soils

Results of a statewide evaluation of streambank soil total phosphorus concentrations and bulk density are reported in Schilling et al. (*In Review*). Among riparian soils, total phosphorus concentrations were observed to range from 109 to 1569 mg kg^{-1} and average 470 ± 192 mg kg^{-1}. Although minor differences were observed among various USDA Major Land Resource Areas or stream order classifications, the variability was mainly associated with an occasional low or high value not representative of the entire sample population of samples. Bulk density of exposed streambank soils averaged 1.17 ± 0.14 g cm^{-3}.

5) Statewide Streambank Erosion

A geographic information system (GIS) routine was developed to estimate severe streambank erosion using a 1-m digital elevation model (DEM) developed from a statewide Light Detection and Ranging (LiDAR) coverage (Wolter et al., *In Press*). Field reconnaissance data from intensive streambank mapping campaigns in selected Iowa watersheds was used to develop, calibrate and validate the DEM-based method to estimate eroding streambank extent.

Using model criteria, it is estimated that 35,200 km of streambanks along 3rd through 6th-order rivers are severely eroding in Iowa. Total stream length evaluated in this study was 42,985 km, and doubling this length to account for streambanks on both sides (85,970 km of streambanks), suggests that approximately 41% of the streambanks in Iowa are severely eroding. More streambank erosion was identified in southwest and southern Iowa than other portions of the state, with approximately 35-84% of all streambanks in these regions estimated to be severely eroding. Across northern Iowa, the topography is flatter, soils are coarser-textured, and bank heights are lower. The fraction of stream kilometers with severe bank erosion increased with bank height. In southern and southwest Iowa, bank heights exceed 5 m in larger order streams, but across the state of Iowa, the mean streambank height in 3rd through 6th-order streams in Iowa was 3.2 m.

6) Contribution of Streambank Sources to Phosphorus Export from the State

Based on quantification of individual terms derived in the multiple studies, the mass of streambank phosphorus lost from eroding streambanks was estimated (Schilling et al., *In Review*). Assuming that 35,200 m of 3.2 m high streambanks are actively eroding in Iowa rivers at an annual rate of 12.4 cm yr^{-1}, and a streambank soil total phosphorus concentration of 470 mg kg^{-1} and bulk density 1.17 gcm^{-3}, it was estimated that approximately 7,681 Mg of total phosphorus is eroded from streambanks and annually delivered to Iowa streams. To estimate the contribution of streambank sources to total phosphorus export from Iowa, this estimate was compared with total annual phosphorus export from Iowa rivers (Schilling et al., 2020). Based on area weighting watershed-scale total phosphorus yields, it was estimated that total phosphorus export ranged from 5,377 to 72,182 Mg and averaged 24,842 Mg (Schilling et al., 2020). Comparing these values, it is estimated that on a long-term annual basis, streambanks contribute approximately one-third of the riverine total phosphorus export from Iowa (7,681 Mg of streambank TP / 24,842 Mg of TP export).

It is important to note that this estimated fraction represents a long-term average because annual riverine total phosphorus export from Iowa varies considerably. While this estimate is consistent with the range of annual values reported in the literature for individual watersheds, it is only appropriate at the regional scale of Iowa and should not be used for site-specific classification. In addition, due to procedural limitations, the estimate does not include eroding lengths in 1st and 2nd order (smaller) channels. Hence, the one-third value is, in all likelihood, a conservative estimate of the contribution from Iowa streambanks.

Management Implications

Research over the last two decades in Iowa and surrounding states point out the critical need to develop and implement conservation practices that address both upland erosion and in-stream sources to help mitigate sediment and phosphorus impacts on downstream water quality. Sediment and phosphorus delivery from streambanks are controlled by both natural and anthropogenic factors such as geology, historical and contemporary land use, climate, and other management actions (Noe et al. 2020). Improved understanding of the location and timing of streambank erosion within a watershed context is needed and it will be important to evaluate the interactions of mitigation actions (e.g. increased water storage, streambank stabilization) on hydrologic and erosion processes at both the reach and watershed scale (Fox et al., 2016; Mitchell et al. 2018; Palmer et al., 2014). Best management practices for streambank protection tend to be constructed to protect individual banks and there is a need to clarify the benefits of these small-scale restorations or stabilizations on total watershed sediment and phosphorus load (Enlow et al., 2018; Lenhart et al. 2018). A greater understanding of the erosion and transport of sediment and phosphorus from both upland and channel sources will help natural resource managers make improved recommendations for implementing effective soil and water conservation practices at the appropriate location and scale to achieve cost-effective nutrient reduction.

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Science Assessments Quantifying Natural and Uncontrollable Sources of Cropland Nutrient Transport to Water Resources – Weather and Climate Impacts

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Key Questions:

- How much of the nutrient load to water resources is due to weather?

Over the last few decades, rainfall events have become more frequent and more intense across portions of the state, leading to increased run-off and flooding events. As weather patterns become more variable, more in-depth research needs to be completed regarding how run-off events on varying timescales impact nutrient transport in Iowa's river and stream system.

- What weather frequency is most important to the policy options of the Iowa Nutrient Reduction Strategy?

When discussing the frequency of weather events, which is "climatology", two event types stand out in terms of run-off, namely higher intensity rainfall events and droughts. What is notable about these two events is that they are often coupled together; specifically, growing season high intensity rainfall events during or after a longer-term drought (i.e., a drought having a temporal scale that is greater than six months). Dry soil profiles can release stored nutrients after heavy rainfall events as rain rates fall outside of the normal frequency versus intensity distribution. Defining appropriate time scales and modeling scenarios will help create better, more robust tools for forecasting anomalous transport events, for example.

- Are there scenarios in which run-off events can become more extreme?

With an eye towards the scenario question, longer-term drought conditions followed by several weeks of above normal precipitation may produce spikes in run-off events. However, this scenario is contingent on the time of year and sub-soil conditions, for example. Specifically, late-spring drought conditions coupled with precipitation deficits through summer into early fall. The second component of this scenario involves anomalously wet conditions developing in the fall and early winter. With total uptake of applied substances hindered by dry conditions, above-average wetness could be a catalyst for rapid run-off events.

From 2011 through 2013, a long-lived and pervasive drought was present across much of the central United States. Southeastern Iowa experienced a particular dry period from early summer through early fall followed by several weeks of wet conditions into late fall. Scenario one will concentrate on Iowa's Climate Division 9 (Figure 1) and analyze the impacts of a transition from persistent dryness to wet conditions within the growing season.

Assessments:

- Analyses of short-term climate and weather variability compared to long-term weather trends

Typical atmospheric climatologies consist of an averaging period covering the last full three decades. As such, the current climatology for temperature and precipitation is computed using the 1991 – 2010 climate decade. For the INREC study and in terms of nitrate analyses, two unique and separate climatologies will be computed for Iowa's nine climate divisions the first of which is the pre-baseline period of 1980-1996; a post baseline climatological span will be used for 1996 onward. The next step will be to compare the most recent five years to historical pre and post baseline periods, which will give a better understanding on how recent changes in the applicable variables has impacted nutrient load during run-off events.

- Climatological Forecasts – Explore near term (next 5-10 year) climatological forecasts to inform issue

Global climate change projections: Global Climate Model (GCM) projections are also discussed in concert with observational trend and statistical analysis. Issues that are touched upon in-depth include projected changes in the frequency and intensity of rainfall events and the impacts on soil run-off and large-scale flooding. Climatological trends since 1895 show a 0.1°F increase in atmospheric temperature per decade across Iowa. With an increased atmospheric temperature, the physical relationship known as the Clausius-Clapeyron equation demonstrates that the water vapor holding capacity of the atmosphere must also increase. Thus, Iowa's average annual precipitation has also increased by 0.43 inches per decade, given an increasing amount of atmospheric water vapor availability (typically 4% increase per degree °F of warming).

Decoupling annual behavior into seasonality, trends and projections show an increase in precipitation across Iowa in all seasons except meteorological summer (June-July-August). What we have seen across Iowa is a seasonal shift in precipitation; we are experiencing precipitation events earlier in spring and also in fall. In between, we are seeing a decrease in rainfall in the summer months, particularly in early July through August. These conditions can exacerbate abnormally dry conditions, especially during the hottest time of the year when crops are maturing and using sub-soil moisture. Moisture stress in corn and soybeans is one indicator of evolving drought conditions. Abnormally dry and drought condition can have an impact in nutrient runoff if there is a transition into wetter conditions after application, especially at 30-45 days.

In terms of the frequency and intensity of rainfall events, Iowa has experienced an increase in both the amount of rainfall over a 24-hour period and how often these events occur. With such behavior, run-off events have become more numerous and broader in scope. Shorter-term trends over the last 30 years show that weather patterns are becoming more variable and somewhat more extreme – warmer warms and colder colds. We should expect to see both, though the frequency of hotter and longer duration heat waves has been increasing and, as mentioned above, is projected to continue on this trend into the near future.

- Explore defining recurrence interval climatological analysis approach similar to that for engineering design storm criteria, example 25-year, 24-hour precipitation event, etc. Example once in 5 years, once in 10 years, once in 25 years, etc. precipitation.

Recurrence intervals, or the timeframe in which a specific magnitude event can occur, can be calculated for pointwise locations. For example, Table 1 shows that a 24-hour precipitation total of 5.81 inches has the probability of occurring once in 25 years at a 90% confidence interval. Probabilistic precipitation intensity can also be produced for point locations for specific time intervals. Specifically, the 30- and 45-day estimates (Figure 2) within 90% confidence intervals can also be plotted to show how extremes in the intensity of rainfall events may impact run-off.