Christianson, L.E., 2020. Scaling a mountain: An opportunity for denitrifying bioreactors. In: *Nutrient Management in Farmed Landscapes*. (Eds. C.L. Christensen, D.J. Horne and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

SCALING A MOUNTAIN:

AN OPPORTUNITY FOR DENITRIFYING BIOREACTORS

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Abstract

Agricultural productivity in the US Midwest is underpinned by more than 19 million ha of subsurface drainage networks which are also a key source of nitrogen (N) transport from fields. A large-scale database of subsurface drainage nutrient loss was used to provide context for nitrate-N loss and establish rationale for the necessity of edge-of-field practices like denitrifying bioreactors. Growers across the region often ask what a "baseline" level of nitrate loss would have been prior to modern agriculture. The database showed nitrate loss from today's corn-soybean (*Zea mays-Glycine max*) rotation was significantly greater than losses from grass or prairie land uses (i.e., more native land uses) with medians of 22, 19, and 1.6 kg N/ha for corn, soybean, and grass site-years, respectively. Along those lines, there is a misconception that N fertilizer, which is essential for profitable corn production, is the sole culprit for this nitrate loss. However, N losses were not significantly different between corn site-years that did and that did not receive N fertilizer (22 and 21 kg N/ha, respectively) when grouped across the database, possibly due to trade-off effects between drainage nitrate concentration and discharge. The likelihood of meeting water quality goals with in-field practices alone is small given the necessity of artificially improved drainage on soils that are inherently N-rich. Edge-of-field practices like denitrifying woodchip bioreactors provide targeted and cost-effective N treatment while allowing growers to maintain in-field production in the face of highly variable cropping markets. Denitrifying bioreactors are a proven N-mitigation technique, but there are also design barriers to their performance. Examples include a limited ability to treat a significant proportion of highly variable drainage flow and nitrate loadings as well as cool water temperatures in the early spring. Several bioreactor design solutions that have been constructed in Illinois to address these challenges will be presented. Tweaking N fertilizer use will not solve N loss challenges in the US Midwest but advances to edge-of-field practices like denitrifying bioreactors can help fill a significant gap in scaling this water quality mountain.

Introduction

Agricultural non-point source nitrogen (N) pollution generated in the US Midwest is a key contributor to harmful algal blooms, one of the most notable of which is the Gulf of Mexico hypoxic zone. Much of the N causing the Gulf of Mexico hypoxic zone was originally transported from cropped fields in the Midwest via subsurface "tile" drainage systems (David et al., 2010). Agricultural productivity in this region is underpinned by the more than 19 million ha of subsurface drainage networks which account for nearly 90% of the total tile-drained lands in the US (USDA NASS, 2019). Subsurface drainage systems are necessary infrastructure supporting the economy of the Corn Belt region. After more than 150 years of improving land drainage in this way, this practice is truly integrated into the culture of agriculture in this region.

Midwestern states' nutrient reduction strategies, developed to accelerate progress toward Mississippi River/Gulf of Mexico Watershed Nutrient Task Force goals, provide information on best management practices especially in tile-drained landscapes (IDALS, 2014; IDOA, 2015; MN PCA, 2014). The likelihood of meeting Task Force goals is small with in-field practices alone (e.g., changing N fertilizer management) considering inherent landscape vulnerability to nutrient loss given the necessity of tile drainage on soils that are inherently N-rich. Edge-of-field practices like denitrifying woodchip bioreactors provide targeted and cost-effective N removal but face limitations of both the physical scaling of the technology and the scaling of their adoption.

A denitrifying bioreactor is a trench full of woodchips through which nitrate-laden tile drainage water is routed. Woodchips serve as a carbon source for the denitrifying bacteria which naturally colonize woodchip surfaces and convert the nitrate-N in the water to dinitrogen gas. Technically, the woodchips provide organic carbon to serve as the terminal electron acceptor in the dissimilatory reduction of nitrate-N to dinitrogen performed by chemo-heterotrophic denitrifiers under anaerobic water chemistries. Thus, woodchip bioreactors enhance the natural process of denitrification in a practical way to clean nitrate-N from tile drainage at the edge-of-field (Christianson et al., 2012; Schipper et al., 2010). Wood-based denitrifying bioreactors have never required denitrifier inoculation; nitrate removal is nearly always observed immediately. Moreover, bioreactors do not "pollution swap" nitrate for nitrous oxide as less than 6% (often less than 1%) of the influent nitrate-N is converted to nitrous oxide (Davis et al., 2019).

Despite the "mountain" of a challenge to meet established water quality goals, some across the Midwest maintain these goals can be met with in-field practices alone. Tweaking N fertilizer management, in particular, is a recommended practice that receives much attention. While appropriate N fertilizer management certainly an important controllable factor impacting N in subsurface drainage, it will be insufficient on its own to achieve upper Mississippi River basin water quality goals. This proceedings paper sets the context for edge-of-field practices by exploring what might have been a baseline N loss prior to today's most common Midwestern cropping systems and then assessing what those N losses are when N fertilizer is removed from the equation. The second part of this work explores ways to improve performance of edge-of-field bioreactors by presenting several case studies to overcome current design challenges.

Methods and materials

Establishing context for edge-of-field practices

Annual subsurface drainage nitrate-N concentrations, N losses, and drainage discharge for corn (*Zea mays*), soybean (*Glycine max*) and "grass" were sourced from the Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database. The MANAGE database is a publicly available database of annual agricultural nutrient and sediment loss compiled from peer-reviewed studies performed in North America (DOI: 10.15482/USDA.ADC/1372907) (Christianson and Harmel, 2015; Harmel et al., 2006; Hertzberger et al., 2019).

The grass land use was chosen to represent N loss from pre-modern Midwestern cropping systems similar to prairie. This included: "grass", bluegrass (*Poa pratensis* L.), orchard grass (*Dactylis glomerata* L.), switchgrass (*Panicum virgatum*), miscanthus (e.g., *Miscanthus* × *giganteus*), and "prairie" site-years across the database. Note, the grass land use was not intended to represent drained pastures, but rather to be a proxy for a historic Midwestern land use. The second part of the analyses included looking more specifically at the corn and soybean site-years and their associated N application rates. The non-normally distributed data were compared using a Kruskal-Wallis One Way Analysis of Variance on Ranks (Sigma Plot 14.0).

Results and discussion

What would a baseline N loss have been prior to modern Midwestern cropping systems?

Annual drainage discharge, nitrate-N concentrations, and nitrate-N losses from a grass land use were significantly lower than from corn or soybean land uses (Figure 1). For example, corn, soybean, and grass site-years had median drainage nitrate-N concentrations of 12.3, 11.3, and 1.2 mg NO_3-N/L, respectively (Figure 1a). The three land uses had annual subsurface drainage N losses through of 21.6, 19.0, and 1.6 kg N/ha, respectively (median values; Figure 1c). The two annual crops did not differ in annual discharge or N loss.

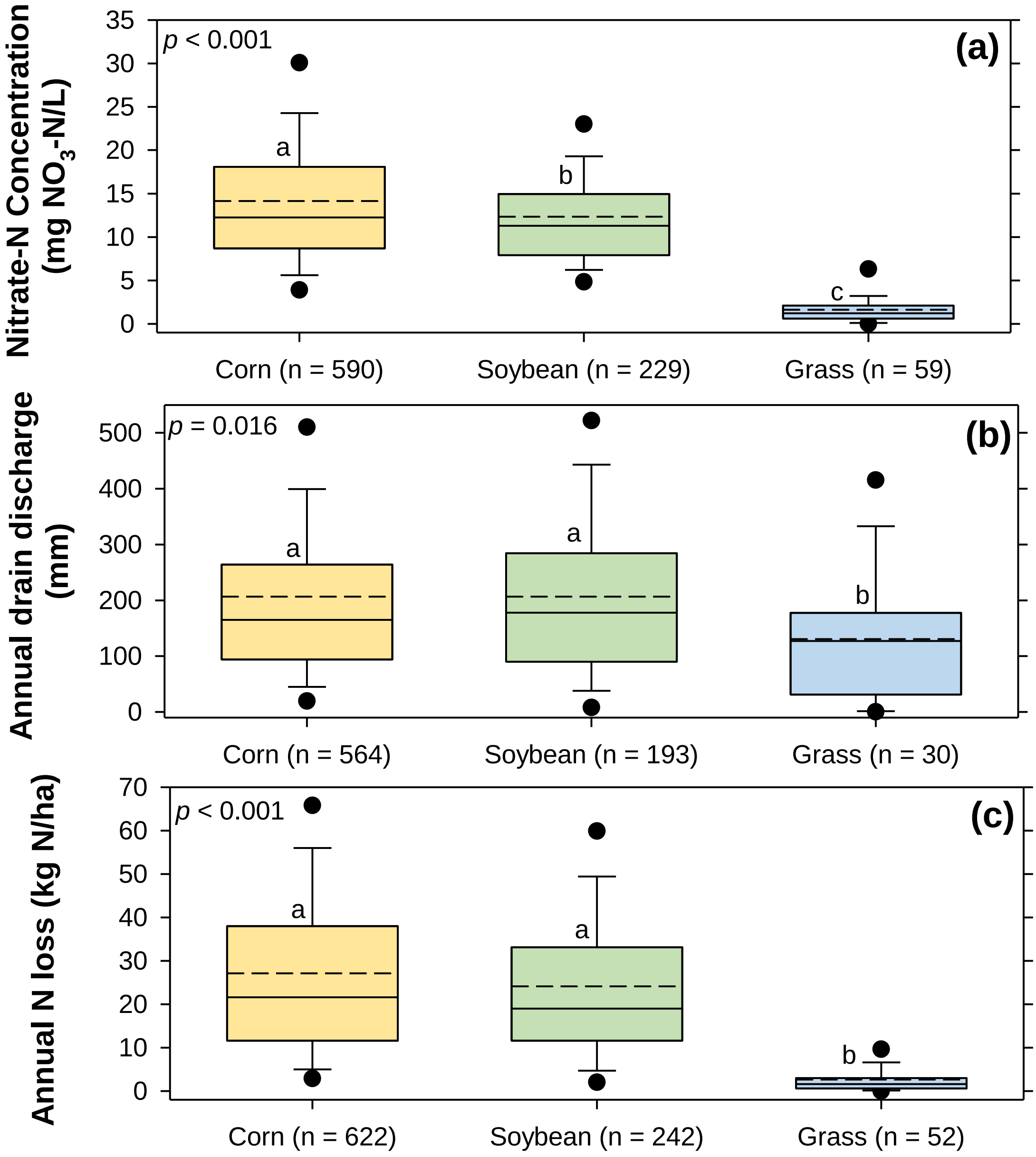

Figure 1. Annual nitrate-N concentrations (a), drainage discharge (b), and nitrate-N losses (c) from three land uses as sourced from the Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database. The "grass" land use was intended to serve as a proxy for a historic prairie land use in the Midwest (i.e., not a drained dairy

pasture). "n = " represents the number of site-years for each grouping. Bars followed by the same lowercase letters are not significantly different in each panel. The box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dashed line represents the mean, and the whiskers show the 10th and 90th percentiles.

Annual site-year precipitation did not differ between the three land uses (Figure 2a) which provided evidence toward the comparison of the three. However, the percent of precipitation that left the field as drainage was significantly lower for the grass land use than corn or soybean land uses (medians of 15, 20, and 22%, respectively; Figure 2b). This corroborated the drainage discharge between the three land uses (Figure 1b) which indicated a more perennial cropping system (e.g., grass or prairie) resulted in a different water balance compared to annual crops.

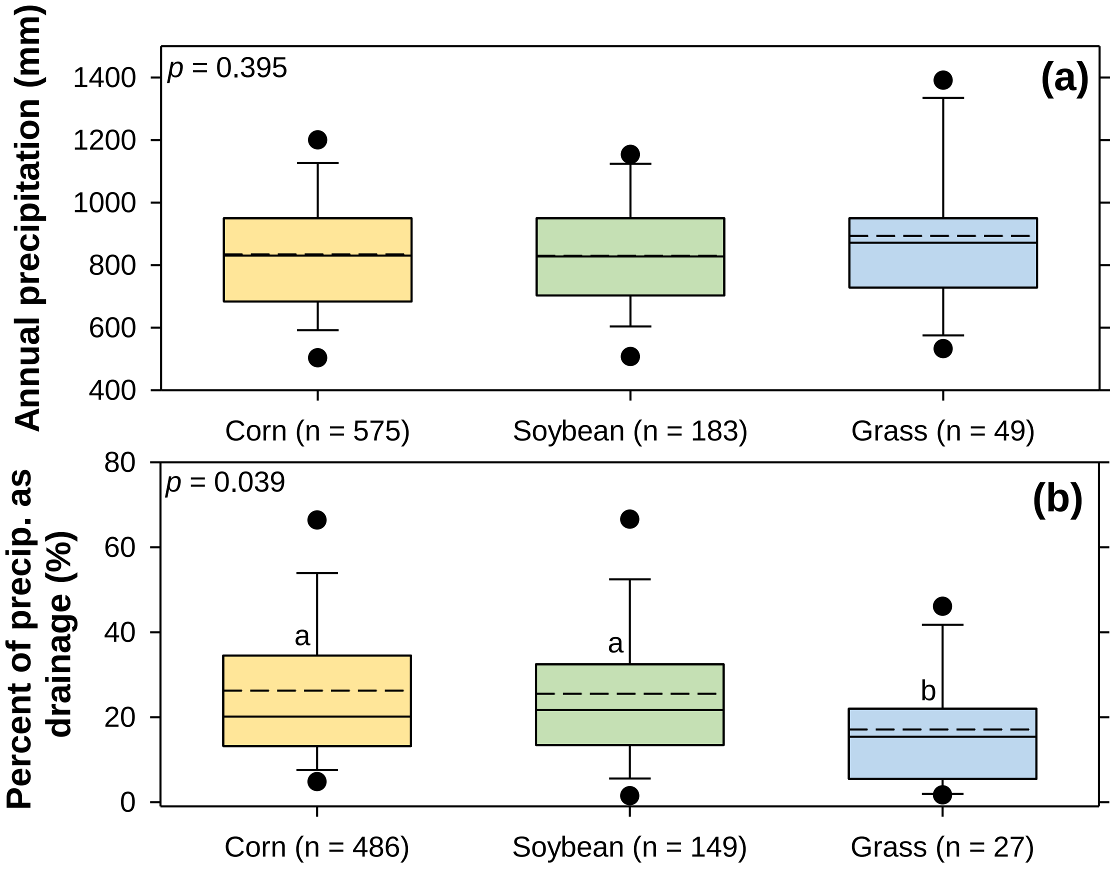

Figure 2. Annual precipitation (a) and percentage of annual precipitation leaving the field as subsurface drainage (b) across three land uses as sourced from the MANAGE database. The "grass" land use was intended to serve as a proxy for a historic prairie land use in the Midwest (i.e., not a drained dairy pasture). "n = " represents the number of site-years for each grouping. Whisker legend as defined for Figure 1.

Admittedly, this analysis oversimplifies "pre-modern" Midwestern cropping systems and ignores the fact that artificial drainage wasn't initiated until approximately the mid-1800s across much of the US Midwest. Thus, representation of pre-modern agriculture with an artificially drained grass or prairie land use is somewhat out of context. This analysis also ignores the well-established fact that artificial subsurface drainage can reduce surface runoff and reduce peak watershed outflow rates (Skaggs and van Schilfgaarde, 1999). Nevertheless, while it is impossible to know exactly what the N loss would have been prior to modern agriculture and modern drainage systems, it was extremely likely less than it is today.

Can't US Midwest water quality challenges be solved with N fertilizer management?

Annual nitrate-N losses were not significantly different between corn site-years that did and that did not receive N fertilizer when grouped across the database (median: 22 and 21 kg N/ha, respectively; Figure 3c). This may have been due to a possible trade-off effect between drainage nitrate-N concentration and discharge (Figures 3a and b), although the very different population sizes across this analysis should be noted (e.g., corn with N > 390 site-years; corn without N ≈ 10 site-years). Lawlor et al. (2008) clearly showed N fertilizer application rate had a strong influence on subsurface drainage N concentrations. However, applying this essential nutrient at rates lower than required for plant growth (or not applying N at all, here) had a negative yield impact (Figure 3d) which may be reflected by the relatively increased drainage discharge (Figure 3b). Conceptually, if the plants don't grow as well due to nutrient limitation, they won't uptake as much water, and the water balance may be relatively shifted towards drainage which can correspondingly impact nutrient losses.

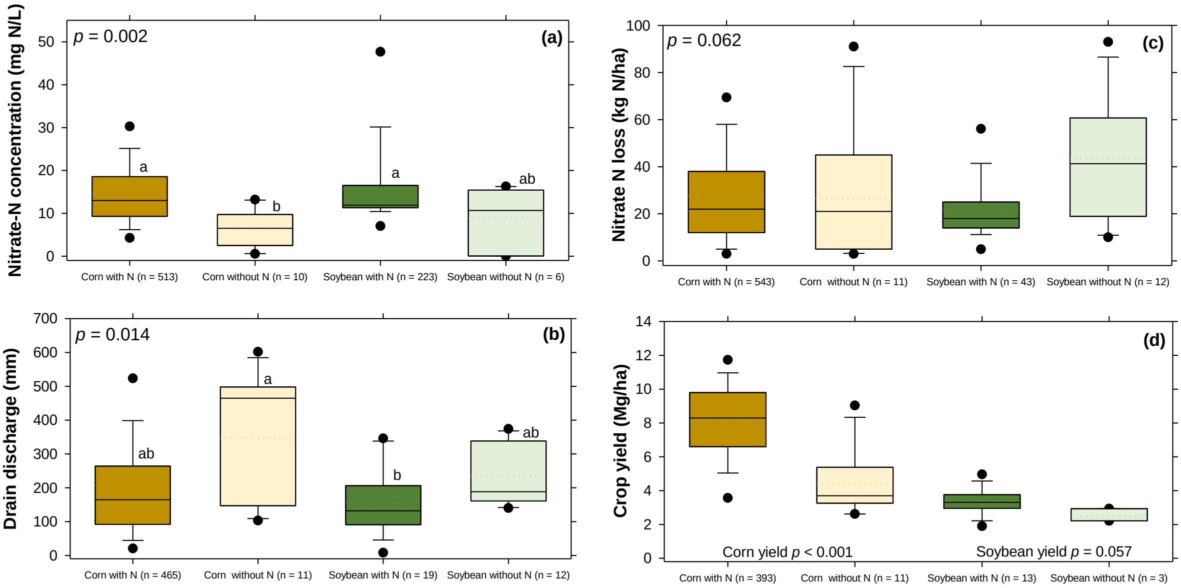

Figure 3. Annual nitrate-N concentrations (a), drainage discharge (b), nitrate-N losses (c), and crop yield (d) from corn and soybean site-years with and without nitrogen fertilizer as sourced from the MANAGE database. "n = " represents the number of site-years for each grouping. Bars followed by the same lowercase letters are not significantly different in each panel. Whisker legend as defined for Figure 1.

Another notable point is that the corn site-years where no fertilizer was applied did not result in annual nitrate-N concentrations of zero or even approximately the concentrations observed from the grass land use described above. The corn and soybean median concentrations when no N fertilizer was applied were 6.5 and 10.7 mg NO_3-N/L, respectively (Figure 3a), compared to the median from the grass land use of 1.2 mg NO_3-N/L (Figure 1a).

In summary, there is a misconception that N fertilizer, which is essential for profitable corn production, is the sole culprit for Midwestern subsurface drainage nitrate-N loss. The likelihood of meeting water quality goals with in-field practices like N fertilizer management alone is small given the necessity of artificially improved drainage on soils that are inherently

N-rich. Moreover, these data illustrated that eliminating N fertilizer for corn significantly reduced yield which is an important metric of sustainability in any cropping system.

Novel opportunities to improve denitrifying bioreactor performance

The design and construction of denitrifying woodchip bioreactors for the treatment of nitrate in subsurface drainage water in the US are generally guided by the United States Department of Agriculture Natural Resources Conservation Service federal design standard (Conservation Practice Standard 605: Denitrifying bioreactor; USDA NRCS, 2015). The NRCS design standard recommends a design hydraulic retention time of 3 h at a given design flow rate. An important current design challenge is the significantly variable flow rates that are inherent to gravity-fed subsurface drainage systems (Figure 4). The design flow rate used to size a denitrifying bioreactor is most often calculated from an estimation of the peak flow from the given drainage system. This static value is sized down by 15% (Figure 4, blue dashed versus red dotted horizontal lines) to create a bioreactor able to effectively treat the majority of annual flow volume, yet minimize cropland removed from production. A bioreactor's by-pass flow pipe is an essential design component to maintain in-field drainage capacity during higher flow events, although this means a portion of the annual flow volume goes untreated. Most drainage systems would require an impractically large bioreactor to treat the full annual water volume, with such a bioreactor overdesigned for the low flow rates occurring much of the year.

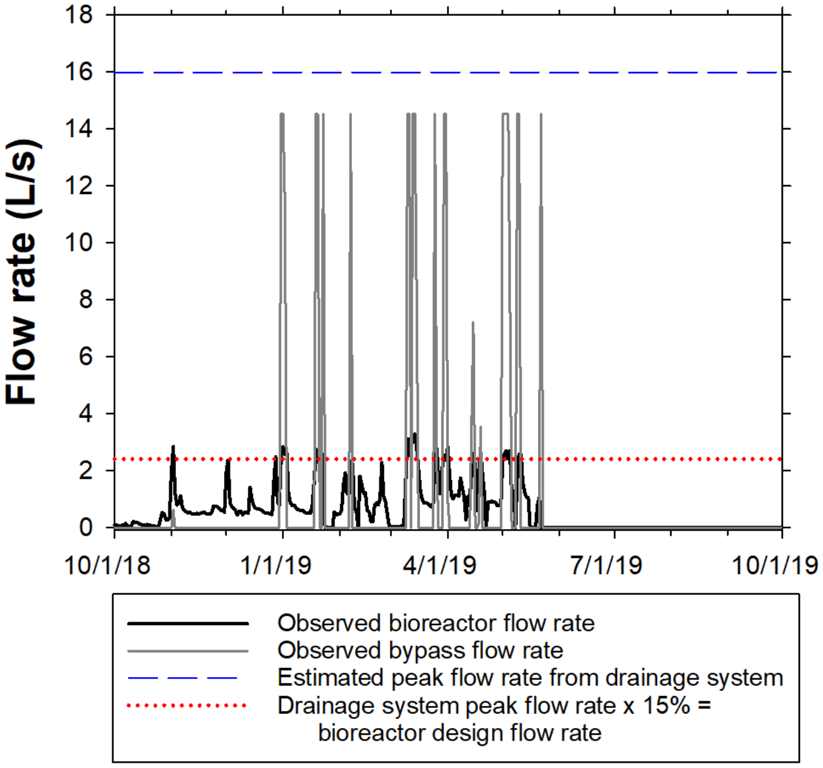

Figure 4. Example bioreactor and bioreactor-bypass flow rates for a bioreactor in Illinois shown with the estimated peak drainage system flow rate and the corresponding bioreactor design flow rate based on 15% of that estimate (data: L. Christianson). Note the subsurface drainage system was not flowing from June 2019 onward.

Denitrifying bioreactors are a proven N-mitigation technique, but sometimes have a limited ability to treat a significant proportion of highly variable drainage flow and nitrate loading. One design solution is to pair multiple bioreactors in parallel, with each coming on- or off-line depending upon flow. This was trialed at a 29-ha field in western Illinois at the

Department of Crop Sciences Research and Demonstration Center at Monmouth, Illinois (Table 1; Figure 5). This paired bioreactor was designed to treat at least at least 25% of the peak drainage system flow rate at a short design retention time of 1 h. The intent was to treat as much flow as possible, even at the sacrifice of hydraulic retention time, to better estimate trade-offs between the volume of annual flow treated versus effective treatment of that water.

Table 1. Denitrifying woodchip bioreactors being trialed in Illinois, USA to improve bioreactor N-removal performance.

Name	**Location**	**Installation date**	**Drainage area ha**	**L x W x D m**	**Chamber volume m^3**	**L:W**	**Notes**
Monmouth - Large	Northwest Research and Education Center, Monmouth, IL	01-Aug-17	29	6.0 x 18 x 1.8	197	0.33	Treats "base" flow
Monmouth - Small		05-Aug-17	Same as above	6.0 x 12 x 1.8	132	0.49	"high-flow booster"
Livingston Co. - In ditch	Private farm in Livingston County, IL	29-Oct-18	Surface drainage area TBD	18 x 2.1 x 0.1	3.8	8.6	"woodchip mattress"
Livingston Co. - Ditch diversion		30-Oct-18	A portion of the above	4.5 x 9.1 x 0.9	37	0.5	Ditch drainage routed to the side
Ag Eng Farm 1 - Insulated and Heated	UIUC Ag. Engineering Farm, Champaign County, IL	12-Jul-18	3.0	6.0 x 1.2 x 0.9	6.6	5.0	Incl. 30 solar-powered heat pads and tourmaline
Ag Eng Farm 2 - Insulated		12-Jul-18	3.0	6.0 x 1.2 x 0.9	6.6	5.0	Insulation boards but no enhanced heating

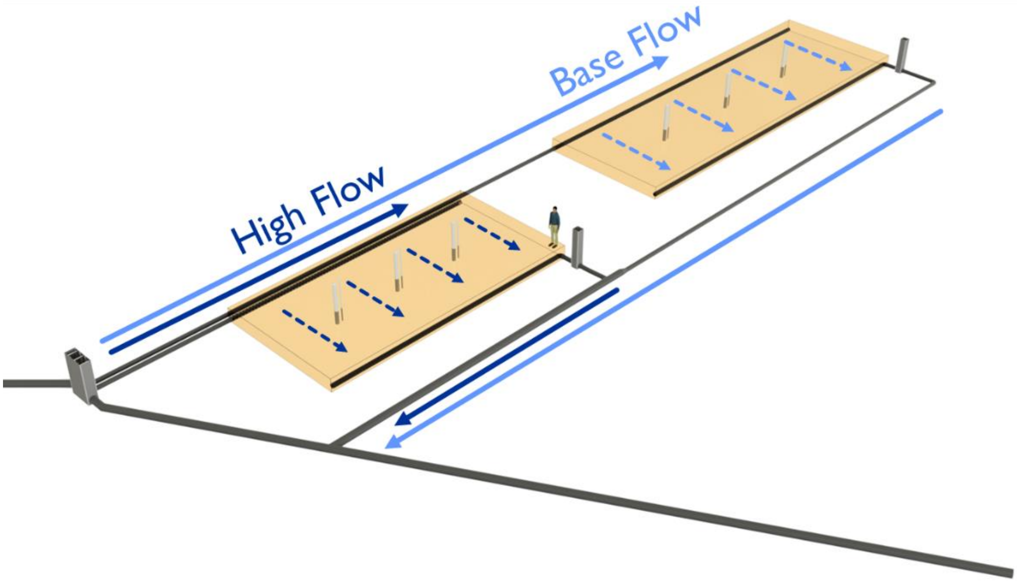

Figure 5. Illustration of the University of Illinois Department of Crop Sciences Monmouth Research and Education Center paired bioreactor constructed in 2017 with base-flow and high-flow bioreactor sections.

A variation on the bioreactors in parallel design concept is to pair in-ditch and ditch-diversion bioreactors. Some producers have shown interest in placing bioreactors in drainage ditches because this area is already not being cropped. However, ditch flow conveyance capacity must be maintained. Thus, it may be challenging to develop the sufficiently high retention times in in-ditch bioreactors that facilitate anaerobic conditions required for denitrification, especially during high flows that contribute significantly to annual N loadings. Integrating the desire to place bioreactors in ditches with the idea of paired bioreactors resulted in the Livingston County paired ditch bioreactor system (Table 1; Figure 6).

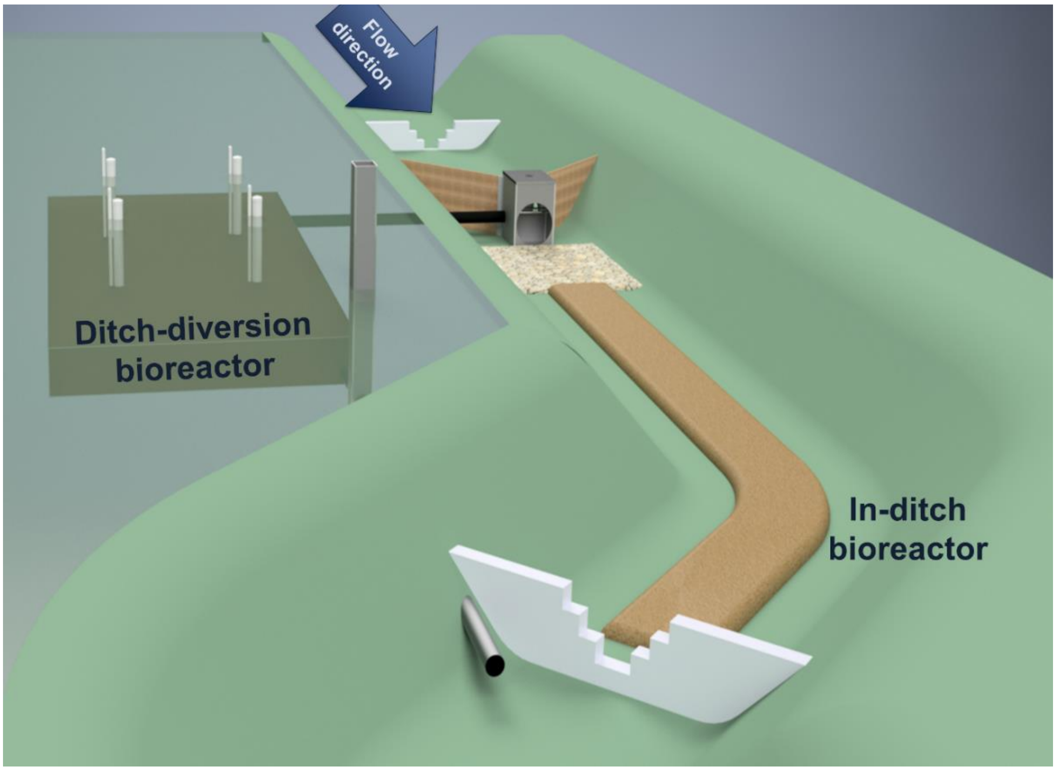

Figure 6. Illustration of the in-ditch and ditch-diversion bioreactors installed at a private farm in Livingston County, Illinois in fall 2018.

The Livingston County in-ditch bioreactor consisted of woodchips enclosed in a hand-made plastic mesh bag. A stone bed was installed directly upstream of this “woodchip mattress” to decrease the water velocity and provide some sedimentation. The ditch-diversion bioreactor was designed to treat nearly 50% of the estimated site flowrate at a very low design retention time (< 1.0 h) to maximize hydraulic loading under storm flow conditions.

Another significant design and operational barrier involves the widely documented importance of temperature on the denitrification process. Early season drainage not only occurs at higher flow rates than later in the season, but is typically much cooler (e.g., 5-10°C vs. >15°C for April versus July drainage water). For every 10°C decrease in water temperature, N removal rates within a bioreactor generally slow by a factor of approximately two ($Q_{10} \approx 2.0$; Addy et al., 2016), making temperature nearly as important as flow rate and retention time for bioreactor N removal. Heating a bioreactor has been attempted at least twice with mixed results (Cameron and Schipper, 2011; Rendall, 2015). Modifying bioreactor media to incorporate fill material conducive to solar-powered heating could provide an additional temperature boost to help overcome cool early-season water temperatures.

Four large pilot-scale bioreactors (Table 1, two of four described) were constructed on the University of Illinois Agricultural Engineering Farm (Urbana, Illinois) to revisit a ‘proof of concept’ experiment to assess if the quickly flowing water could be heated sufficiently to affect an increase in N-removal. Their design flows and retention times were less important than their replicated nature for this heating trial. The “treatment” bioreactor was insulated and contained thirty solar-powered heating pads under a layer of industrial-grade tourmaline, which has a favorable ability to hold heat (Figure 7). The first “control” bioreactor was insulated but did not have tourmaline or heating pads. The two other controls were neither insulated nor heated.

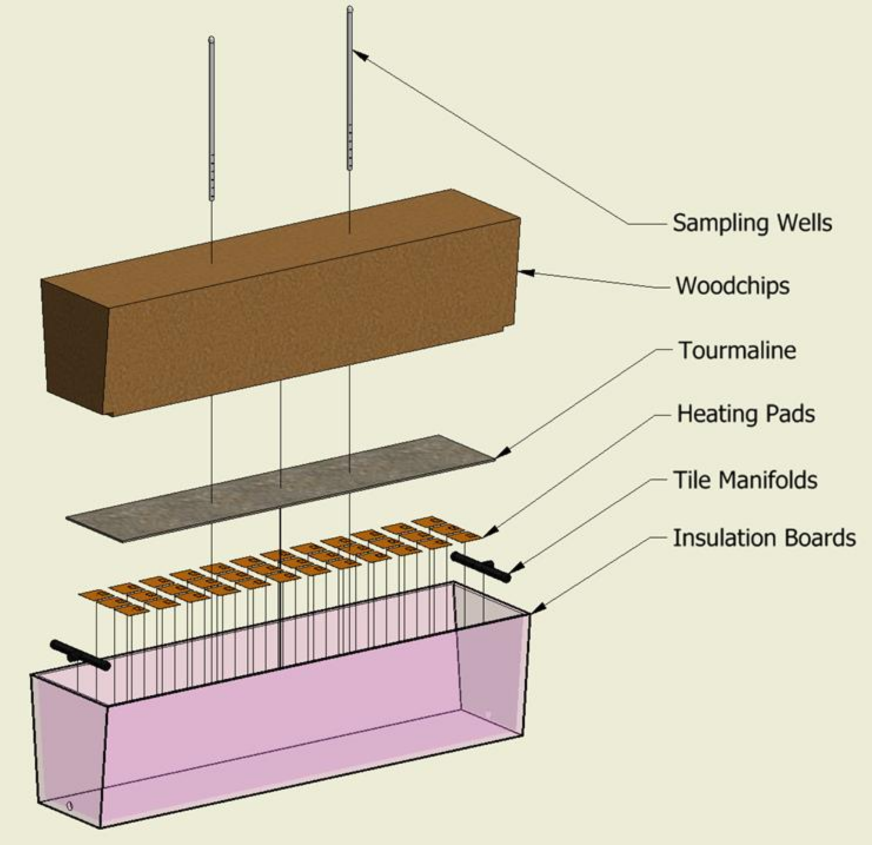

Figure 7. Illustration of heat-enhanced pilot-scale bioreactor constructed on the University of Illinois Agricultural Engineering Farm (Urbana, Illinois) in fall 2018 showing the 15 cm x 15 cm heating pads within the woodchip bioreactor. Solar panels and connections not shown.

Conclusions

This proceedings paper sets the context for edge-of-field practices by exploring what might have been a baseline N loss prior to today’s most common Midwestern cropping systems and then assessing what those N losses might be when N fertilizer is removed from the equation. Annual drainage discharge, nitrate-N concentrations, and nitrate-N losses from a grass land use (i.e., a proxy for a historic drained prairie land use) were significantly lower than from corn or soybean land uses. While it is impossible to know exactly what the N loss would have been prior to modern agriculture and modern drainage systems, it was extremely likely less than it is today.

Focusing on modern Midwestern cropping systems showed subsurface drainage N losses were not significantly different between corn site-years that did and that did not receive N fertilizer (22 and 21 kg N/ha, respectively), possibly due to trade-off effects between drainage nitrate-N concentration and discharge. There is a misconception that N fertilizer, which is essential for profitable corn production, is the sole culprit for this nitrate-N loss, but completely removing N fertilizer from the equation in this database assessment illustrated the complexity of the situation. The likelihood of meeting water quality goals with in-field practices alone is small given the necessity of artificially improved drainage on soils that are inherently N-rich.

This means that edge of field practices like denitrifying bioreactors have a role to play in achieving nutrient loss reduction goals for the US Midwest. However, these practices themselves are not without challenges. The designs of two paired bioreactor systems where bioreactors operate in parallel during high flow events were described to illustrate an idea being trialed to possibly maximize treatment of N loading. A pilot-scale bioreactor heat-enhancement study was also described. Continued and increased investment in (1) field-scale research of edge-of-field practices and (2) accelerating adoption of such practices are recommended.

Acknowledgements

The author would like to thank (1) Dr. Daren Harmel (USDA ARS) for leading and collaborating on the MANAGE database and (2) former graduate student, Mr. Allan Hertzberger, for leading development of the Drain Concentration component of the database. The drainage portions of the database were originally funded by the 4Rs Research Fund and later by the Illinois Nutrient Research and Education Council (IL NREC). Great acknowledgement is due to Dr. Richard Cooke (UIUC) for design collaboration on the bioreactors discussed here, and field work credit goes to Ms. Ana Paula Sanchez Bustamante Bailon, Mr. Ronnie Chacon, and the IDROP research team. These bioreactors would not have been possible without funding from the Illinois Nutrient Research and Education Council (IL NREC). We also acknowledge field partners for these bioreactor sites (Mr. Martin Johnson and Mr. Greg Steckel at the Monmouth Center; Mr. Tim Lecher at the UIUC Ag Engineering Farm; private landowners in Livingston County)

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