Literature Review on the Impact of Small Grains on Water Quality

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Nutrient loading from agricultural sources is one of the greatest barriers to water quality in the Upper Midwest. The potential for integration of small grains—cereal crops including barley, oats, rye, and wheat—into existing dominant corn and soy rotations may provide an opportunity to reduce nutrients leaving fields. Despite the acknowledgement of diversification and extension of cropping systems (including with small grains) as a conservation practice, the ability for these crops to manage nutrients is not well understood, specifically when planted as a cash crop rather than a cover crop. Nutrient reductions from agricultural land as a whole would contribute significantly to nutrient reduction goals throughout the region, thus supporting beneficial and designated uses of water bodies including the Great Lakes. Lowering nutrient and sediment loading will lead to greater water clarity, improve oxygen levels, and reduce toxicity related to algal blooms.

Research supports the addition of small grains to rotations to promote organic matter, increase microbial biomass, and enhance water and nutrient retention, all resulting in improved soil health. Increased diversity in above- and below-ground biomass supports soil life, leading to improved soil structure, reduced soil erosion, improved water infiltration, and bolstered system resilience. Other documented small grains benefits include reductions in pesticide and synthetic fertilizer use by smothering weeds, breaking pest/disease cycles, and opening windows to plant nitrogen-fixing legumes and spread manure.

This review of literature seeks to better understand the nutrient reduction qualities and potential of small grain crops in the Upper Midwest.

The following 5 papers address data collected from the same study at the Iowa State University Marsden Farms in Boone County, Iowa. Although each paper reviews different aspects of the trial, all treatments (including crop rotations, fertilizer, and herbicide management) are the same.

Key takeaways for this section:

- Nitrate concentrations in surface runoff are related to crop rotation, but leaching losses are not.
- Nutrient benefits from crop diversification are most visible in a system with both a small grain and a leguminous perennial crop.
- The usual mechanisms through which small grains could limit nutrient and water losses are affected by the previous and following crop year, signaling the importance of understanding system management as a whole.
- Small grain crops influence other management decisions that reap water quality benefits, such as a reduction in herbicide use and the use of green manure as a nitrogen input.

- The most prominent benefits of small grains in respect to nutrient losses have been seen when viewed as one aspect of an integrated strategy that impacts the relationships between other components of nutrient management.

Nutrients in soil water under three rotational cropping systems, Iowa, USA

Tomer, M. D., & Liebman, M. (2014). Nutrients in soil water under three rotational cropping systems Iowa, USA. *Agriculture, Ecosystems & Environment*, *186*, 105–114. https://www.sciencedirect.com/science/article/abs/pii/S0167880914000474?via%3Dihub

Overview: This paper explores how cropping rotation systems can impact N and P nutrient losses in central Iowa. **It measures nitrate-N and P concentrations in soil water under three different cropping systems,** including corn-soybean (2YS), corn-soybean-small grain/red clover (3YS) and corn-soybean-small grain/alfalfa-alfalfa (4YS) for eight years. **The paper finds a strong influence between the cropping system, as well as crop year, on nitrate-N concentrations in soil water at a 1.2 m depth.** The totality of data over the study period finds that NO3-N and frequency of detectable P concentrations are significantly less under the 4YS system, with the 3YS system resulting in the highest average N concentrations at 14.3 mg NO3-N. Results for individual cropping years differ between cropping systems.

Key Takeaways:

- **Nutrient balances:** Differences in soil water nutrient concentrations can be understood by comparing nutrient balances between specific crops, which is defined by nutrient additions minus removal by crop harvest. Within the study, a significant amount of N was provided by legume (soybean or alfalfa) fixation during those respective years in each cropping system.
- **Nitrate concentrations:** The paper explains that study **data represents "temporal patterns of nitrate losses better than nitrate loads" which are influenced by many factors** including mineralization rates, seasonal patterns and crop uptake.
- **Cropping years/crop residues:** Average differences in **nutrient concentrations over the study period are mostly driven by specific cropping years, which are largely influenced by the previous crops' residue**. In the 2YS system, N concentrations are reduced in the soybean year by immobilization from corn residue, along with the absence of fertilizer application. **The small grain/clover year found smaller N concentrations in the 3YS system, which the paper hypothesized is due to greater water use that limited movement of N within the soil** as well as the greatest amount of mineralized N. Finally, the alfalfa year in the 4YS system results in the lowest soil water N concentrations, which is attributed to its perennial nature.
- **Conclusion:** Dynamics between cropping years, which are influenced by previous crop rescue and mineralization rates, drive average difference between cropping systems. In the data presented by the paper, **the 4YS system has the lowest measured average N concentrations in the soil water, followed by the 2YS system, then the 3YS system**. However, individual cropping years also follow predictable patterns: **within the 3YS system, the small grain/clover year has the lowest measured N concentrations**, and

alfalfa in the 4YS system is presumably the largest influence on the 4YS system's total data results.

Cropping System Diversity Effects on Nutrient Discharge, Soil Erosion, and Agronomic Performance

Hunt, N. D., Hill, J. D., & M. Liebman. (2019). Cropping System Diversity Effects on Nutrient Discharge, Soil Erosion, and Agronomic Performance. *Environmental Science & Technology*, *53*(3), 1344–1352. https://pubs.acs.org/doi/10.1021/acs.est.8b02193

Overview: Using the same study system as the previous paper in Boone, Iowa, this paper uses modeling analyses to connect previous empirical data to estimate nutrient losses through runoff and leaching. Essentially, this study's purpose is to **explore the relationship between cropping systems of differing amounts of diversity and water quality by measuring nutrient loads. It uses an ArcSWAT model, calibrated to a similar watershed and ran for 25 years,** to estimate N and P runoff, nitrate-N leaching, and sediment erosion. According to the model analyses, **runoff losses are curbed up to 30% in the diversified systems**, while no correlation between nitrate-N losses and cropping systems is demonstrated in the data. Erosion losses are reduced up to 60%.

Key Takeaways:

- **Soil Sediment:** The data show a significant relationship between additional diversification and soil sediment yields and total N runoff. Estimates of soil sediment yields decrease with each crop addition, with the highest level at 2.6 Mg/ha under the 2YS system, and the lowest at 1.0 Mg/ha under the 4YS system. This is a resulting **reduction of erosion losses of more than 60% when the cropping system was diversified**.
- **Nutrient Losses: Rotations significantly reduce N and P runoff, with an additional crop year reducing runoff estimates by 30-39%**. Both nutrients follow similar reduction patterns with each diversified system in order; while the 2YS system has the highest estimates of N and P runoff, the 3YS and then the 4YS system sequentially reduce runoff rates. **However, analyses do not find a significant relationship between cropping system and nitrate-N leaching**; the 3YS system having the highest concentration of N, and the 4YS system having the smallest. These results are in line with Tomer and Liebman (2014) measurements of N concentrations in soil water below the root zone (see above paper).
- **Mechanisms: The paper attributes their results to crop properties, such as robust root systems in oat-legume mixtures and alfalfa, which can reduce soil water and sediment loss and improve soil structure. The study also credits crop residue**, such as from oats, red clover, or alfalfa as a mechanism to enhance soil structure and reduce erosion.
- **Conclusion:** According to hydrological modeling, cropping system and diversity is the strongest influence out of several management strategies present on the study site in reducing runoff and sediment losses, while maintaining consistent results with other data on leaching. The paper also discusses **the potential for crop diversification to**

provide additional benefits, such as nitrogen fixation and nutrient storage and enhanced physical and biological characteristics of the soil. This paper does not address specific mechanisms between crop years to explain resulting nutrient loss reductions, but does **provide hydrological evidence that including small grains and other crops in a crop rotation will have inferred benefits to water quality.**

Agronomic and Economic Performance Characteristics of Conventional and Low-External-Input Cropping Systems in the Central Corn Belt

Liebman, M. et al. (2008). Agronomic and Economic Performance Characteristics of Conventional and Low-External-Input Cropping Systems in the Central Corn Belt. *Agronomy Journal*, *100*(3), 600–610. https://access.onlinelibrary.wiley.com/doi/full/10.2134/agronj2007.0222

Overview: Using the same study system as Tomer and Liebman (2014), this paper analyzes the yields and economic performance characteristics of three different crop rotations. **The purpose of the study is to compare conventional agricultural systems, including crop, herbicide and fertilizer use, to an alternative system designated an LEI, or "low-external-input."** An LEI system includes a comprehensive crop management strategy that in part emphasizes crop diversification to reduce herbicide and fertilizer use. This experiment tests the yield and economic potential of LEI and conventional systems over the course of five years. **Synthetic N fertilizer application is 59% and 74% lower in the 3YS and 4YS systems, respectively, compared to the 2YS system.** The main finding of the study from the data provided is that the LEI systems produce higher average yields of corn and soybean for a given year, while gross revenues are highest in the conventional system. However, the 4YS system results in the lowest production costs, as well as higher returns to land.

Key Takeaways:

- **Fertilizer inputs: Fertilizer inputs in the LEI system are reduced through the use of legumes**, red clover and alfalfa in this study, due to their biological fixation abilities. Other management strategies attributed to an LEI system can also reduce fertilizer use such as crop residue and manure application.
- **Water quality:** According to the study data, water quality can be potentially positively impacted by synthetic fertilizer input reductions by preventing nitrogen contamination. A second benefit explored by this paper is a reduction of herbicide use. Within the scope of this study, **oat and triticale crops are effective at acting as nurse crops for alfalfa while simultaneously suppressing weed cover. A reduction in reliance on herbicide products could reduce the concentration of such chemicals in hydrological systems.**
- **Conclusion:** Although this study does not address nutrient loading and water quality as a direct outcome of small grains, it does offer a comprehensive perspective on alternative crop management as a whole. This experiment presents the idea of small grain and perennial crop rotations as intrinsically part of a multi-faceted management strategy that harnesses the benefits of alternative cropping systems by understanding the agro-ecological relationships of farming.

Reducing Freshwater Toxicity While Maintaining Weed Control, Profits, And Productivity: Effects of Increased Crop Rotation Diversity and Reduced Herbicide Usage

Hunt, N.D., Hill, J.D. & M. Liebman. (2017). Reducing Freshwater Toxicity While Maintaining Weed Control, Profits, And Productivity: Effects of Increased Crop Rotation Diversity and Reduced Herbicide Usage. *Environmental Science and Technology,* 51(3), 1707-1717. https://pubs.acs.org/doi/abs/10.1021/acs.est.6b04086

Overview: Utilizing the same study systems as Tomer & Liebman 2014, this paper evaluates alternative weed management within the context of crop rotation diversification. Following the guiding principle that reducing chemical herbicide use can have positive agronomic and water quality effects, the **study seeks to understand how crop rotations could be integrated as a weed management strategy using a USEtox model to measure freshwater toxicity loads from herbicides and pesticides**. Weed management regimes are assigned to the same rotations explained previously: corn and soybean years of all systems receive a conventional and a low herbicide treatment, while all years of oat, clover and alfalfa receive no herbicides; instead, "weeds were suppressed by mowing stubble and removing hay." Analyses are performed on freshwater toxicity loads, as well as the agronomic effects of alternative strategies.

Key Takeaways:

- **Freshwater Toxicity:** Herbicides differ in their toxicity in corn and soybean depending on the application method. Overall, herbicides from soybean are more toxic than corn; but within the low treatment, soybean herbicides are more toxic compared to the conventional treatment, and 85 times more toxic than corn herbicides. This is largely due to the selection of herbicides. Toxicity of the conventional treatments drop significantly, resulting in rates sometimes comparable with low treatments, when certain chemicals are discontinued in their use (specifically, S-metolachlor was retired in 2012). However, the low treatment still emerges overall as 89% less toxic. **Freshwater toxicity is also influenced by rotation and its coinciding weed management, with a 50% decrease in toxicity from adding two additional non-treated crop phases.**
- **Weed Suppression:** Although reducing herbicide application will clearly reduce herbicide toxicity in water, effectiveness of alternative weed management remains a key question. Within the data of this study, the conventional and low treatments result in no significant difference in weed biomass produced within the 2YS and 4YS system. However, in the 3YS system, the low treatment is less effective. This could result in the interpretation that **an addition of oat and alfalfa to a cropping system (the 4YS rotation) could result in equal weed suppression compared to a conventional system**.
- **Conclusion:** The alternative weed management strategies used in this study have no significant impacts on crop yields or net returns, suggesting that they are feasible solutions to chemical herbicide use. **Although not directly related to nutrient losses and water quality, this study still places crop rotation diversification, including the use of oats, into a framework of integrated sustainable management.** Along with other papers looking at losses of nitrogen, t**his study provides the perspective that oats within crop rotations can fit into and benefit management that aims to improve water**

quality. Although oats and alfalfa themselves are not directly found to reduce herbicide toxicity in water, **their presence in a rotation results in a low input herbicide treatment becoming feasible** while still maintaining adequate levels of weed suppression and crop yields.

Fossil Energy Use, Climate Change Impacts, and Air Quality-Related Human Health Damages of Conventional and Diversified Cropping Systems in Iowa, USA

Hunt et al. (2020). Fossil Energy Use, Climate Change Impacts, and Air Quality-Related Human Health Damages of Conventional and Diversified Cropping Systems in Iowa, USA. *Environmental Science & Technology,* 54, 11002–11014. https://pubs.acs.org/doi/10.1021/acs.est.9b06929.

Overview: This study integrates study systems from Tomer & Liebman, 2014, including the rotations, fertilizer and herbicide treatments into an analysis of other environmental quality impacts. The implications of these results are important to the formation of integrated management systems that take into account multiple environmental impacts at once. Fossil fuel consumption is mostly driven by fertilizer production and is reduced significantly with each additional crop rotation. **Greenhouse gas emissions are also reduced 54% when a third crop is added, and 64% with a fourth. Reduced herbicide use results in lower mean annual emissions of $PM_{2.5}$ particles, and NO_x emissions are reduced by 33% when an oat/clover year is added to the cropping system**.

Conclusion: Many of the impacts of integrated alternative management strategies that involve small grains also often result in additional environmental benefits, a common phenomenon in environmental systems. Although not crucial to aspects of research studying water quality benefits, understanding the full impact of management decisions can be beneficial and provide further guidance in decision making.

Marsden Long-Term Rotation Study at Iowa State University - Ames, Iowa
Learn more at: https://www.cals.iastate.edu/inrc/marsden-long-term-rotation-study

The remaining papers look at a variety of different aspects of crop diversification systems and small grains as cover crops.

Key takeaways from this section:

- Green manure from small grain residue could result in greater nitrogen immobilization rates compared to synthetic fertilizer and reduce leaching, **signaling the potential for small grains to impact a crop system beyond a single year of growth.**
- Nitrate loss through drainage water is both a function of water loss and nutrient loss, which can be affected by precipitation and crop water uptake; **likewise, nitrate concentrations can be curbed by both manipulations of soil water and soil nitrogen through crop rotations.**
- Because a crop year is impacted by the properties of the previous crop, planning crop rotations to match water uptake to available water could minimize tile drainage losses.
- Rye has a higher biomass and is a more winter hardy species compared to other small grains, making it more favorable as a cover crop, and it could be especially helpful as an early planted cover crop in corn-soybean rotations.
- Soil erosion loss is more a function of tillage than crop type, but the effects of perennial or small grain crops on how tillage is implemented could impact phosphorus losses.

Legume-based cropping systems have reduced carbon and nitrogen losses

Drinkwater, L. E., Wagoner, P., & M. Sarrantonio. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature*, *396*(6708), 262–265. https://www.nature.com/articles/24376

Overview: This paper compares diversified cropping systems that included legumes, small grains, corn and soybean to a conventional two-year rotation. The alternative rotations are designed as an organic system with dependence on nitrogen fixation from legumes, while the conventional system receives synthetic fertilizer inputs. Carbon and nitrogen retention in the soil is compared between systems as a function of crop, residue and fertilizer management. While **the study reports reduced nitrogen leaching in the diversified systems, this is mainly attributed to greater immobilization of nitrogen into microbial biomass from green manure compared to synthetic fertilizer.** It is also hypothesized that alternative crops to corn and soybean that can forage for nitrogen could also reduce leaching, but this is not explored in depth from the data.

Conclusion: Although the specifics of the role of small grains is missing from this paper, the study offers further evidence of the benefits of diversified crop rotations for reducing nitrogen loss. In contrast with Tomer and Liebman (2014) and Hunt et al., 2019, leaching is reduced in rotations that include small grains and legumes, but this is difficult to interpret and compare precisely, given the lack of detail on the specific crop rotations used in the study. One interesting perspective offered by this paper is that of green manure- **although it places a heavy emphasis on legumes, there is opportunity to understand how the benefits of alternative crops continue beyond their time growing in the field**.

Subsurface Drain Losses of Water and Nitrate following Conversion of Perennials to Row Crops

Huggins, D. R., Randall, G. W., & M. P. Russelle. (2001). Subsurface Drain Losses of Water and Nitrate following Conversion of Perennials to Row Crops. *Agronomy Journal*, *93*(3), 477–486. https://acsess.onlinelibrary.wiley.com/doi/10.2134/agronj2001.933477x

Overview: Although the benefits of sequential years of perennial and alfalfa crops on reducing nitrate losses are well supported, **less is known about the effects of conversion to a row crop system after a period of conservation cropping.** This study's main purpose is to evaluate how drastically nitrate losses change after conversion to corn, compared to a conventionally managed row crop system that had not had any perennial cropping. In southwest Minnesota, **an alfalfa system and a perennial grass system designed to mimic Conservation Reserve Program (CRP) land are maintained for six years before being converted to a corn-corn-soybean system for two years.** This shift is compared to continuous corn and and corn-soybean sequences that were maintained throughout the entire study period. The main avenue of nitrate loss this paper followed is through artificial drainage. Nitrate concentrations and flow rates are measured from subsurface drainage water below each plot.

Key Takeaways:

- **Soil Water:** Subsurface drainage is directly related to precipitation. Soil water levels are nearly equal in all treatments during high precipitation years, almost overriding the characteristics of high water uptake crops like alfalfa and grass. However, over the entire study period, **perennial systems see a reduction in annual drainage, with treatments that were previously alfalfa averaging a 20% decrease from continuous row crop treatments. Because different crop years can result in varying amounts of soil water, tile flows could potentially be reduced by using a crop rotation where crop water demand is appropriate for the available water.** The study also hypothesizes that drivers besides enhanced water uptake in alfalfa/grass crops may drive reductions in drainage, but specific mechanisms are not discussed.
- **Soil N**: Upon conversion from a perennial to a row crop system, residual soil nitrate begins to accumulate; this is particularly evident in the CRP to C-C-S treatment. This accumulation of nitrate occurs more quickly in the upper portion of the soil and slower below the root zone (an indicator of leaching). **This suggests that there could be residual benefits of CRP and alfalfa that persist for a few years after conversion to row crops. However, these benefits seem to quickly diminish after three years.** Treatments that were previously perennial have increased nitrogen uptake efficiency in the first corn year, also suggesting benefits from a perennial rotation.
- **Conclusions:** Although not directly related to small grains, this study evaluates the mechanisms that contribute to rotation-effect benefits, including an analysis of whether benefits are perennial or leguminous in nature. **Both alfalfa and CRP treatments reduce nitrate-N losses through drainage during the following corn year, and increase nitrogen uptake efficiency.** However, these benefits are depleted after multiple years of row crops. This study provides strong data that **well-planned and consistent rotations can have direct and residual benefits on nitrogen loss through**

water. The mechanisms for these are similar to characteristics of small grains, including increased water uptake, but this study presents evidence that leguminous crops can also play a large role in rotation effects.

Corn-Soybean and Alternative Cropping Systems Effects on NO_3-N Leaching Losses in Subsurface Drainage Water

Kanwar, R. S. et al. (2005). Corn-Soybean and Alternative Cropping Systems Effects on NO_3-N Leaching Losses in Subsurface Drainage Water. *Applied Engineering in Agriculture,* 21(2), 181-188. https://elibrary.asabe.org/abstract.asp??JID=3&AID=18151&CID=aeaj2005&v=21&i=2&T=1

Overview: This study focuses on non-traditional cropping systems incorporating small grains, specifically, strip intercropping with oats and alfalfa rotation. In a 6-year study in northeast Iowa, two alternative rotations which included an **intercrop system of corn, soybean and alternating years of oat and berseem clover, and three years of alfalfa followed by corn and soybean,** are compared to a traditional soy-corn system, and nitrate-N in subsurface drainage flows are measured. **Interestingly, non-traditional systems result in greater total drainage flow (46% more than traditional) over the entire study period**, which the paper hypothesizes is due to deeper roots and larger macropores accelerating percolation. Results for nitrate losses are in line with other studies, with **non-traditional systems decreasing subdrainage losses, while leaching losses remain statistically insignificant** compared to traditional systems.

Key Takeaways:

- **Intercropping: Strip intercropping is used to support *interactions* between crops.** Research suggests that including a small grain, such as oat or wheat, as a strip crop can improve corn and soybean yields by adding spatial and temporal diversity and reducing border effects. The study's data suggests that nitrate concentrations in drainage can be reduced through strip intercropping by increasing nutrient use efficiency and crop yields.
- **N Leaching:** Leaching losses of N vary widely, but in general are proportional to the relative amount of subsurface drainage that year. In wet years when drainage increases due to precipitation, the alfalfa rotation sees the largest amount of nitrate leaching losses, a result the study explains could be due to decomposition of the alfalfa roots. In drier years, results vary, with **non-traditional systems resulting in less leaching losses for only two out of the six years.** However, when assessing the entire study period, non-traditional systems result in 6% less leaching losses overall compared to the traditional systems. This is not statistically significant, and provides further reason for understanding drainage losses in more depth. The paper emphasizes that **drainage losses will have more of an impact on surface water quality.**
- **Drainage:** Although rainfall variation influences drainage flow amounts, **non-traditional systems consistently have lower nitrate-N concentrations in subsurface drainage water** across all years. The average across the entire study period is **42% lower than traditional systems.** Within the study data, strip intercropping generates nitrate concentrations lower than the drinking water standard of 10 mg/L.

- **Conclusion:** This paper provides a unique perspective on small grains and focuses on their role as a growing season crop. It provides evidence that **small grains can influence nitrate concentrations in water in a single year.** The paper also analyzes **the impact that spatial and temporal diversity, and interactions between crops, can have on soil water dynamics**.

Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water

Kasper, T. C. et al. (2012). Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. *Agricultural Water Management,* 110, 25-33. https://www.sciencedirect.com/science/article/abs/pii/S0378377412000960

Overview: The purpose of this study is to evaluate the effects of two cover crops on nitrate leaching losses, as well as study post-cover crop effects on soil nitrogen in central Iowa. It is also designed to test the effectiveness of cover crops for a longer term than generally studied, with the paper noting that most studies have not evaluated cover crop performance for more than five years. **A rye and an oat cover crop are applied to a standard corn-soybean rotation** and compared to a control. **On average, both cover crop treatments reduce nitrate-N *flow-weighted average concentrations* in drainage water, although year-to-year comparisons fluctuate**. Annual differences are significantly correlated with cover crop growth in the short-term, with larger shoot biomass corresponding to lower drainage concentrations. **The rye cover crop on average has higher biomass and N concentrations, and is more effective at reducing flow-weighted drainage concentrations than the oat cover crop.** However, **nitrate *loads* are not significantly reduced**. This result is in contrast to a paper by the same authors that find a 61% load reduction under a rye cover crop (Kaspar et al., 2007). The study has difficulty measuring the long-term effectiveness of the rye cover crop due to several interfering factors and suggests that the cover crops remain effective at reducing nitrate concentrations in drainage water throughout the study period.

This paper breaks down the differences between nitrate measurements in water and looks at how concentrations and loads will differ. Different crops will impact nitrogen in water by affecting drainage flows and soil nitrogen dynamics. Amongst other papers in this review including this one, **total drainage compared between years is largely a function of annual precipitation, but on average could be affected by the intensity of water use in crops.**

Paper cited in overview (same authors, similar study system and results):
Kaspar, T.C. et al. (2007). Rye Cover Crop and Gamagrass Strip Effects on NO_3 Concentration and Load in Tile Drainage. *Journal of Environmental Quality,* 36, 1503-1511.

Benefits of Diversifying the Corn-Soybean Rotation: Data from WICST 1995-2003

Hedtcke, J., Posner, J. & J. Baldock. (2003). BENEFITS OF DIVERSIFYING THE CORN-SOYBEAN ROTATION: Data from WICST 1995-2003. WICST 10th Technical Report, 27-20. https://wicst.webhosting.cals.wisc.edu/wp-content/uploads/sites/107/2018/04/WICST__10th__report__complete.pdf

Overview: In this technical report, continuous corn and corn-soybean systems are compared to a corn-soybean-winter wheat / red clover rotation. The diversified system receives half the amount of both N fertilizer and pesticide applications. The data from this report finds higher nitrate concentrations in the soil in all continuous corn systems. Soil erosion in the traditional system is above tolerable levels on slopes above 300 ft. **Erosion losses in the diversified system consistently stay below a tolerable loss of 5 ton/acre/year due to additional soil coverage throughout the year and modified tillage**. Minimizing soil erosion can reduce phosphorus losses.

Increasing Crop Rotation Diversity: A comparison of conventional grain systems on WICST (1998-2006)

Hedtcke, J. L. & J. L. Posner. 2006. INCREASING CROP ROTATION DIVERSITY: A COMPARISON OF CONVENTIONAL GRAIN SYSTEMS ON WICST (1998-2006). WICST 11th Technical Report, 41-50. https://wicst.webhosting.cals.wisc.edu/wp-content/uploads/sites/107/2017/07/WICST_11th_report.pdf#page=49

Overview: In a technical report similar to the one prior, this study compares years in a corn-soybean-winter wheat/ red clover rotation to continuous corn and corn-soybean systems. **The diversified system sees soil nitrate levels significantly lower compared to continuous corn but not corn-soybean.** This is due to lowered fertilizer inputs as a result of green manure and the extended winter phase of the wheat crop. **All conventionally managed systems see soil erosion below the tolerable level of 5 tons/acre.** These numbers are compared to an organic system that receives frequent tillage and sees an excessive level of soil loss of 10 tons/acre/year. **In general, soil loss is less impacted by crop rotation than other management strategies,** but soil nitrate is influenced by management decisions that are directly related to crop diversification.

Nutrient losses through tile drains under three cropping systems and two fertility levels on a Brookston clay soil

Bolton, E. F., Aylesworth, J. W. & F. R. Hore. (1970). Nutrient losses through tile drains under three cropping systems and two fertility levels on a Brookston clay soil. *Canadian Journal of Soil Science*, 50: 275-279. https://cdnsciencepub.com/doi/pdf/10.4141/cjss70-038

Overview: This short paper evaluates nutrient losses under three cropping systems that include continuous corn, a corn-oats-alfalfa-alfa rotation, and continuous bluegrass. The study is conducted in Ontario and specifically compares data to estimates of nutrient inputs into Lake Eerie. Water samples are taken from drainage tiles during peak flow. **Fertilizer application has a large effect on nutrient losses, with fertilized continuous corn producing the largest nutrient losses of N, P and K. Cropping system significantly affect nitrate losses, but P losses are relatively similar across treatments**. Nitrogen concentrations in the soil are attributed to both N produced by alfalfa and fertilizer input; clear reductions in N losses are seen in the shift from continuous corn to oats + alfalfa, especially under a fertilized system. **Nitrogen losses drop from 15.1 kg/ha/year in the corn rotation to 5.7 kg/ha/year in the oats + alfalfa rotation.** The table on p. 276 breaks down nutrient losses by year for each rotation.

Impacts of Watershed Characteristics and Crop Rotations on Winter Cover Crop Nitrate-Nitrogen Uptake Capacity within Agricultural Watersheds in the Chesapeake Bay Region

Lee, S. et al. (2016). Impacts of Watershed Characteristics and Crop Rotations on Winter Cover Crop Nitrate-Nitrogen Uptake Capacity within Agricultural Watersheds in the Chesapeake Bay Region *PLoS ONE,* 11(6), 1-22. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0157637

Overview: This paper uses a similar SWAT hydrological model to the one deployed by Hunt et al. 2019. Its main objective is to measure watershed-scale impacts on nitrogen loads of winter cover crops, including rye, winter wheat and winter barley, in the Chesapeake Bay Region when added to traditional corn-soybean systems. The model is used to calculate eight years of measurements in two watersheds. Within the model parameters, the rye cover crop has a slightly larger effect on total water flow in both watersheds due to a greater biomass and water uptake, but total flows are not significantly impacted. **Total nitrate loads are reduced by cover crops, especially by early planted crops**, due to their ability to remove nitrogen during the growing season and accumulate biomass; **early-planted cover crops reduce NO_3-N loads on average by .5 kg/ha compared to late-planted cover crops**. Nitrate loads are also impacted by the drainage capacity of site soils, and **cover crop effectiveness is correlated with factors such as crop rotation and amount of residual soil nitrate**. The paper suggests that **early-planted rye cover crops could be especially useful in areas that are well-drained and cultivated for soybeans, which see larger nitrate loads with no cover crop practice**. In less at-risk sites, such as those more poorly drained and with lower residual nitrate, winter wheat or barley could be adequately effective.

Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin

Kladivko, E.J. et al. (2014). Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. *Journal of Soil and Water Conservation,* 69(4), 279-291. https://www.jswconline.org/content/jswc/69/4/279.full.pdf

Overview: This paper is model-based and attempts to estimate environmental impacts of cover crop adoption across five states in the Upper Midwest. It focuses only on winter rye, given that it is the most popular choice of cover crops currently and is the most winter hardy species. The objective of this paper is to understand how much nitrate benefits can be increased by an appropriate estimate of cover crop use across a regional scale, a different approach than other papers cited in this document. The paper determines that a **rye cover crop will provide significant benefits when used in corn and corn-soybean systems that are artificially drained**, which are the most widely used rotations in the region studied and result in the largest nitrate loads. Model simulations suggest that **nitrate loads to the Mississippi River could be reduced by 20% when cover crops are adopted into conventional systems.**

Interviews were conducted with key experts throughout the region to better understand some of the above referenced work, and to gain insight on ongoing or future research. In most conversations, the deficiencies in research addressing small grains impact to water quality - especially as a cash crop - were discussed. The knowledge gained from these interviews brought clarity to the additional research needed to strengthen the connection between use of small grains and enhanced water quality.

Constance Carlson-University of Minnesota, Forever Green Initiative

Interview Date: 11/24/20

In an interview with Ms. Carlson, we discussed current research surrounding the use of Kernza®, a perennial wheatgrass growing in popularity for its potential ecological benefits in agriculture and culinary uses. Ms. Carlson mentioned several colleagues working on Kernza research with a focus on water and nutrients: Evelyn Reilly (nitrate reduction), Dr. Jacob Jungers (wellhead research), and Dr. David Mulla (nutrient movement). Other names mentioned included Erin Meier from Green Lands Blue Waters and Josh Gamble and Dr. Jessica Gutknecht (carbon sequestration).

Potential benefits of Kernza discussed included reduced nitrogen input requirements, use as a forage crop to cut feed costs, and enhanced soil benefits from a no-till system. Kernza is known for its lengthy root structure, which could provide many soil health benefits in a perennial system. Because Kernza is so new, all current production is organic since there are no approved herbicides or pesticides. Current research around Kernza is asking questions such as: Where does Kernza fit into a crop rotation, such as being planted after a small grain? Can small grains be used to break up weed cycles? How can we successfully manage Kernza without traditional tools like pesticides? How can Kernza enhance soil structure, retain nutrients and improve water quality and carbon sequestration? How can Kernza improve cropping systems and provide security in the future? How can we build a market for Kernza?

- Kernza is a perennial wheatgrass that has recently gained popularity in research for its potential plethora of benefits in agriculture.
- Kernza is currently managed as a perennial, no-till and organic crop.
- Benefits could include less nitrogen fertilizer requirements, and enhanced soil structure and stability.
- Current research questions are uncovering Kernza's suite of environmental benefits and how other small grains could be grown with Kernza.

Dr. Jochum Wiersma-University of Minnesota, Extension Small Grain Team

Interview Date: 12/3/2020

Dr. Wiersma is a Minnesota state extension specialist for small grains. He also has a background in plant pathology and plant genetics. Our conversation mostly centered around a discussion of the adoption and feasibility of small grains. Dr. Wiersma pointed out recent trends in small grain agriculture, which included the observation that attitudes towards rotation diversification were positive while adoption was low. He attributed this to concerns about profitability and affordability, as well as a lack of markets, accentuating risk. He suggested that an increase in small grain adoption would occur alongside an already existing and viable market, such as hogs; this is because hog manure could be useful for small grain management.

Dr. Wiersma also provided some insight into research around the benefits of small grains. He brought up a point that research may seem unavailable due to new and fashionable keywords, and that older research may have desirable results hidden in other terminology. He suggested using proxies during literature searches, and looking at past research that analyzes small grains or rotations and organic matter stability (especially as it relates to phosphorus losses) or water holding capacity.

Some colleagues working on related research include Drs. Jeff Strock (rye and nutrient runoff in the upper midwest), Don Flaten (spring cereals, conservation tillage and phosphorus runoff), and Lindsey Pease (subsurface drainage in cropping systems at the watershed scale).

- Attitudes towards crop diversification are positive, while adoption rates are low.
- Small grain adoption seems likely to develop alongside an existing market such as hogs.
- Using proxies during literature search could be helpful in uncovering 'hidden' information, such as how small grains impact organic matter stability or water holding capacity.

Dr. Natalie Hunt-University of Minnesota, Department of Bioproducts and Biosystems Engineering

Interview Date: 11/12/20

Dr. Hunt is an assistant professor whose research focuses on modeling the impacts of alternative and diversified cropping systems on air, water and soil quality, as well as climate change. Our interview focused on current research in this area, as well as an introduction to new cropping concepts that are currently being explored. We first went over the main mechanisms that drive benefits of small grains, including fertilizer reduction, longer growing seasons, and covering bare ground. Dr. Hunt also mentioned the rise of relay cropping vegetable crops research currently being explored in winter oilseeds.

Because her work focuses on creating sustainable systems that are resilient for the future, we discussed whether creation of markets and reduction of risk would support adoption of more diverse practices. She specifically mentioned oat milk as a rising market that involves small grains. We also discussed that small grains go hand-in-hand with other management, including conservation tillage, precision agriculture, organic fertilizers and cover cropping. She emphasized that the way that these management strategies influence soil structure and stability will influence leaching and nutrient losses. Some names she provided included Drs.

Lucia (Lucy) Levers (modeling water quality impacts) and Brent Dalzell, a biogeochemist with the USDA.

- Relay cropping is currently applied to vegetable crops but has potential for adoption into small grain systems.
- Rising markets for small grains include oat milk and cereals, which could reduce risk and increase adoption.
- Small grains often provide benefits from their role in integrated management systems, which includes other factors such as conservation tillage, precision agriculture, manure use and cover cropping.

Dr. Laura Good-University of Wisconsin-Madison, Department of Soil Science
Interview Date: 11/5/20

Dr. Good is an associate scientist at UW-Madison whose research focuses on phosphorus modeling within agricultural systems, especially to measure risk of phosphorus loss to surface waters. Our discussion mostly centered around key concerns in current research around crop rotations and nutrient movement. Laura stressed the importance of viewing a system in all of its parts throughout time, emphasizing the fact that modeling only one year of nutrient loss under a certain crop is not going to capture the whole picture. She mentioned that the effectiveness of cover crops and small grains are dependent on factors such as reaching a biomass threshold, and the crop years that come before and after. Small grains could have an impact on a following corn year, but this would be impacted by other management strategies at work, including residue and the use of an overwintering forage crop. She suggested looking through Wisconsin Extension nutrient guidelines and the UMN Kernza® CAP project for new research and recommendations.

- Small grain benefits depend on previous and following crop years, as well as other management strategies, so picking out a single small grain year will not provide the whole story.
- It's important to view a system in all of its parts rather through time.
- The benefits of small grains could be impacted by management such as crop residue and use of overwintering forage crops.

Sarah Carlson and Rebecca Clay- Practical Farmers of Iowa
Interview Date: 11/30/20

Sarah Carlson is the Strategic Initiatives Director for PFI, and focuses on small grain programming, as well as communication with farmers and supply chain partners, including Cargill, McDonalds and Land O Lakes. Rebecca Clay's work centers around soil health and water quality in small grains, and measuring the impact of cover crops. Both Sarah and Rebecca agreed that data for a single small grain year is lacking. They mentioned a project that monitored tile lines from a small grain rotation that was to be harvested. This project was completed with the intention of collecting data to make edits to the Iowa nutrient reduction plan. Rebecca explained that this project measured nitrate levels in tile drainage in six different sites. However, because there was no landform average to compare sites, phosphate levels were not able to be measured. Preliminary data showed a 40% reduction in nitrate over the six sites during the small grain year.

We also discussed the limitations of phosphorous modeling and models that exclude subsurface water in their nitrate measurements. The general consensus was that PFI is not particularly interested in producing numerous studies of large data to support small grains; because they are production-, rather than academically-focused, they principally aim to gather enough evidence to meet their objectives and take action within the market.

- Preliminary data from a small study saw a 40% reduction in nitrate over six sites during a small grain year.
- Models used in this study have limitations; there was no landform average to compare sites, and phosphorus levels were not able to be measured.
- Hydrologic modeling often excludes subsurface water in their nitrate measurements, also a key limitation.
- PFI feels that they have enough evidence to reintroduce small grains as an option to the Iowa Nutrient Reduction Strategy for practice approval, a petition that previously failed due to insufficient data.

Conclusion

Our survey of literature and interviews with experts in the field demonstrated to us that we were not alone in assuming that small grains have beneficial impacts on water quality, yet also not alone in discovering that the literature is not conclusive on small grains' potential as a nutrient reduction strategy. This is not because of data suggesting that small grains do not or could not play an important role in reducing nutrients in the region, but more that their role has not received focused research and thus is not sufficiently understood or documented. While the many research studies cited and summarized above demonstrate the role of diversification in reducing runoff and sediment losses, and more specifically how small grains can reduce nitrate concentrations in water in a single year, more research is needed to focus on the complex roles that small grains play in the hydrologic and agronomic interactions regarding nutrient losses. Given the other known and documented benefits of small grains, either through crop rotation diversification or deployed as a cover crop, investment into the investigation of the nutrient reduction potential is warranted.

This survey and series of interviews highlights the need for replicated, long-term/multi-year trials to assess the potential role that small grains should play, and the need to calibrate existing models to more precisely determine the impact of small grains in crop rotations, particularly when grown as cash crops. While models that can provide meaningful information do not currently exist, they are under development and should be available within two to three years. As researchers continue to report relevant data, these models should become increasingly useful.

Opportunities for developing more research in this area may present themselves in the context of current and upcoming federal legislation calling for increased research and outreach to build agricultural systems that build soil health. Small grains, with their extensive root systems, their placement in the seasonal agricultural production calendar, and their facilitative role in crop rotations, are prime candidates as strategies in those cropping systems.