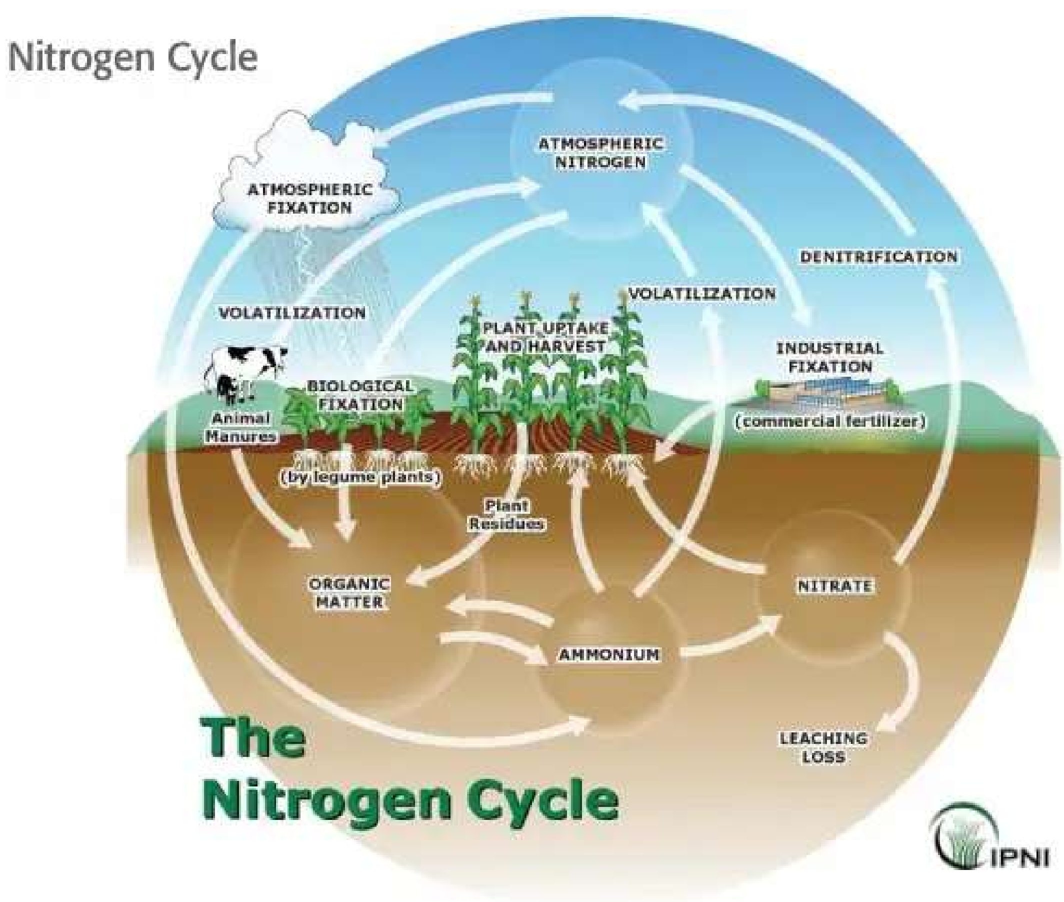
Efficacy of Cover Crops to Improve Nitrogen Use Efficiency and Reduce Leaching to Groundwater

Nitrogen Targeted Performance Standards: Technical Support Document (Rule No. WT-19-19)

August, 2021



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Executive Summary

In December 2019, the Wisconsin Natural Resources Board directed the Dept. of Natural Resources (DNR) to develop Nitrogen Targeted Performance Standards (N-TPS) in sensitive areas of the state where groundwater was being exposed to excessive nitrate contamination from agricultural practices. As part of this endeavor, a Technical Advisory Committee (TAC) of 25 members (in addition to numerous DNR staff) was formed in February/March of 2020. The TAC was comprised of a wide cross-section of stakeholders from environmental groups and non-governmental organizations (NGOs), UW, UW Extension & Discovery Farms, partner agencies, and several representatives from agriculture including farmers, agronomists, and agricultural industry representatives. The TAC had 10 formal working meetings from February 2020 – March 2021, and several smaller focus group meetings that concentrated on detailed nuances of hydrogeology, agriculture, water quality, and human health-related concerns. Following direction from DNR Secretary Cole, the TAC committed to "working together" to find solutions that would protect groundwater while also be "workable" for farmers (financially, logistically, etc.).

Numerous excellent questions and important discussions helped shape the direction of the TAC meetings and inform the rule making process. This document was prepared largely based on these. Examples of some the questions include:

- Why do different nations/regions have different nitrate standards?
- What are the different terms used to communicate nitrate related issues and standards?
- Is nitrate pollution of groundwater really an issue in Wisconsin?
- What are the human health risks of high nitrates in drinking water?
- Is nitrate contamination only relevant to human consumption?
- How do we know the sources of nitrate pollution?
- What are other states doing to address these questions?
- What is/can agriculture do to use nitrogen more effectively and reduce nitrate leaching losses to groundwater?
- Can cropping practices, such as cover crops, be used in a manner that helps protect groundwater quality while also benefitting the farmers?

While many of these questions are addressed in this document, the origin was based on one of the proposed solutions that received broad support from the TAC - the use of winter cover crops to sequester nitrogen during periods of peak leaching, in fall, following harvest, and over winter into spring, before the next crop is planted. The state of Minnesota has included these practices as exceptions in their groundwater protection rule, and the states of Iowa, Illinois, Indiana, Nebraska, Kansas, Ohio, and California (among others) include cover crops as one of the recommended practices to reduce nitrate losses to leaching and contamination of groundwater. Members of the TAC meeting heard from representatives from both MN and IA on their exceptions and the rationale behind inclusion of cover crops as an agricultural practice that can both mitigate nitrate leaching and be economically viable and desirable practice among farmers. Consequently, this practice has been included in the N-TPS rule as exceptions to prohibitions for commercial fertilizer and liquid manure applications.

> The major purpose of this document is to present the state of our knowledge on the ability of cover crops to minimize nitrogen leaching losses from agricultural systems.

While there is a long history of using cover crops to better manage and sequester nitrogen in agricultural systems (evidence going back over 2,000 years), this practice largely fell by the wayside with the advent of synthetic nitrogen fertilizer in the early 1900's. Recognition that excess agricultural nitrogen has contaminated groundwater with nitrates goes back well over 50 years. Coincident with this, growing demand for nitrogen fertilizer, especially over the most recent 30+ years, has produced widespread groundwater nitrate contamination concerns around the United States. As farmers, agronomists, drinking water and human health scientists, and agencies look for ways to help combat the growing trends of groundwater nitrate contamination, a renewed interest and resurgence of utilizing cover crops to better manage agricultural nitrogen has been occurring nationwide.

However, because of climatic, geologic, agricultural cropping systems, and other reasons, the use of cover crops for these purposes is relatively "young" in the colder climates of the Midwestern United States (e.g. MN, IA, WI, etc.). This literature review was conducted to consolidate and summarize relevant literature, research, agency publications, and other related sources of information in one location to present the status of science with regard to the efficacy of using cover crops to reduce nitrate leaching to groundwater by improving nitrogen use efficiency in agricultural systems.

This document specifically provides a review of literature relating to the efficacy of cover crops to improve nitrogen use efficiency, reduce nitrogen losses from agricultural systems, and minimize nitrate contamination of groundwater. This review presents a high-level overview of the body of published literature investigating:

1. the history of synthetic nitrogen fertilizer uses for augmenting agricultural productivity,
2. the mechanism and role of nitrogen pollution of groundwater,
3. human health threats of nitrate pollution in drinking water,
4. the general history of the use of cover crops,
5. and the body of research specifically investigating the use of cover crops to reduce the potential of nitrate-nitrogen losses from agricultural systems.

The growing body of research clearly indicates cover crops can be used to help optimize management of agricultural nitrogen in cropping systems and significantly reduce nitrate leaching losses, including those typical in Wisconsin such as dairy, cash grain, and vegetable production. Early research was instrumental in identifying challenges to using cover crops, finding best practices for using cover crops, and explaining how cover crops can be used to sequester, retain, and provide nitrogen for subsequent cash crops. More recently, advances in research methods, farming practices, cover crop species selection, and perhaps most importantly, the growth of farmer-led groups, on-farm demonstrations and field trials have greatly advanced the value, viability, and utility of cover crops as a sound and profitable agricultural best practice. Further, extensive, independent farm-based research initiatives on working farms not only in Wisconsin, but also Minnesota and throughout the corn-belt, have concluded conservation practices (including cover crops) being used by farmers can be highly profitable and provide the tools that allow farmers to meet important environmental performance metrics, including protecting drinking water. For this reason, much of this document is dedicated to sharing the numerous examples that capture and celebrate these advances as proactive solutions that work for farmers, are profitable, and reduce the potential for groundwater nitrate contamination.

Terminology

With regional differences in terminology, there can be confusion during discussions relating to agricultural nitrogen, nitrate, and related terms. The term "nitrate" is often used generically and may be used to reference one of two different forms (depending on field of research, country, etc.) being NO_3- and NO_3-N. Inherent in this is the manner in which NO_3- concentration is calculated with these two different terminologies. These are clarified, below:

- Nitrate-nitrogen (NO_3-N): This is the "nitrate" in U.S. drinking water standards, being 10 mg/l, and is calculated based on the molecular weight of Nitrogen (14g/mol), hence Nitrate-<u>Nitrogen</u>.
- Nitrate (NO_3^-): This is the true nitrate anion (molecular weight 62 g/mol). In Europe, many other nations, and other fields of science, "nitrate" concentrations are reported as the nitrate anion. For example, the World Health Organization (including all of Europe) drinking water standard is 50 ppm (or mg/l) of "nitrate".
  - 1 ppm NO_{3-} = 0.2266 mg/l NO_{3-}N
  - European standard of 50 mg/l NO_{3-} = 11.3 mg/l NO_{3-}N
    - 10 mg/l is U.S. drinking water standard and considered essentially equivalent with European standards (Ward, et. al., 2018)
  - Recommended drinking water standard for calves, young livestock, and breeding heifers = 44 mg/l NO_{3-}
    - 44mg/l NO_{3-} = 10 mg/l NO_{3-}N (the U.S. drinking water standard)
- Throughout this publication, we will use the term "nitrate", meaning Nitrate-Nitrogen (NO_{3-}N), as this is common use for human health and water quality standards.

"Cover crops", and related terms, are commonly interchanged and their definitions can vary across literature and geographic regions. In this document, we use the definition of Delgado, et. al. (2006):

> Cover Crops: *"Cover crops have been defined as crops grown to protect the soil from erosion losses and losses of nutrients via leaching and runoff (Reeves 1994). This definition was expanded in the <u>Encyclopedia of Soil Sciences</u> to those crops that are grown for improving soil, air, and water conservation and quality; nutrient scavenging, cycling and management; increasing populations of beneficial insects in integrated pest management; and/or for short-term (e.g., over-winter) animal-cropping grazing systems (Delgado et al. 2006)."*

Within the scope of the N-TPS, the inclusion of cover crops as an exception and as a nutrient management tool to minimize nitrogen leaching losses is a practice historically called "catch cropping". The agronomic benefit of cover crops to retain nitrogen, minimize leaching losses in spring, and slowly release nitrogen to a subsequent cash crop is known as "green manure" (adapted from Dabney, et. al., 2009):

> Catch Crop: "*A catch crop is a cover crop grown to take up available N in the soil and thereby reduce leaching losses of N already in a cropping system. To be most effective, cool season catch crops should be planted early in the fall to maximize root growth and N uptake before cold weather limits growth. Brassicas or oat (Avena sativa L.) catch crops may grow faster in the fall than more winter-hardy species like rye (Secale cereal L.) or wheat (Triticum aestivum L.). Catch crop effectiveness is highly correlated with rooting depth but not with root density (Delgado, 2001; Thorup-Kristensen, 2001). Where nitrate leaching is a serious problem, catch crops can beneficially fill any "fallow" periods in a rotation."*

> Green Manure: *"Green manure is a cover crop grown mainly to improve the nutrition of subsequent main crops; it often includes legumes that can add N to the cropping system. To be most effective, green manure crops should winter-kill, be grazed, or be killed early in the spring. Doing so prevents pre-emptive competition and allows green manure N to become available during the following crop's growing season. Incorporation of green manure crops with tillage usually speeds the mineralization of organic N."*

Abbreviations

Ac: acre

AM: Adaptive Management

ARS: Agricultural Research Service

BMP: Best Management Practice

DATCP: Wisconsin Department of Agriculture, Trade and Consumer Protection

DNR: Wisconsin Department of Natural Resources

In: Inch

Mg/l: milligrams per liter

N: Nitrogen

NMP: Nutrient Management Plan

NRCS: Natural Resources Conservation Service

N-TPS: Nitrogen Targeted Performance Standard

NUE: Nitrogen Use Efficiency

> Nitrogen use Efficiency (NUE) = Difference in Yield / Nrate
> Difference in Yield = difference in yield between fertilized and unfertilized plots
> Nrate = rate of Nitrogen fertilizer application

P: Phosphorus

PPM: Parts per Million (equivalent to Mg/l)

TSS: Total Suspended Solids

USDA: United States Department of Agriculture

UW: University of Wisconsin

WQT: Water Quality Trading

Forward

This document was prepared as supporting material for the Nitrogen Targeted Performance Standard rule package. A primary goal was to compile relevant information supporting the rule, and to facilitate adoption and implementation of the rule. The wealth of research and information available on nitrogen use in agriculture, groundwater quality, and related topics is vast and extends back well over 100 years. While the authors attempted to consolidate as much of the relevant information available by reaching out to numerous experts and professionals in these fields across the Midwest, invariably some may have been missed. More importantly, new information and lessons are being learned every day as innovative farmers, agronomists, researchers, and other professionals work together to proactively address our shared challenges of having profitable, efficient farms that work for our farm families, while also protecting our groundwater and drinking water for our citizens. We see these shared challenges and endeavors as opportunities to grow, learn, and improve our world for all our citizens. As such, we hope and anticipate this document will not be viewed as “set in stone”, rather it may serve as an initial comprehensive resource, catalyst, and steppingstone for continued improvement going forward.

Acknowledgements

We express the most sincere gratitude to the Technical Advisory Committee members (Appendix 1) who volunteered their time to share information, participated during the nine TAC meetings between 2020 and 2021, provided feedback on development of the methods for the Targeted Performance Area, Performance Standards, Prohibitions and Exceptions, and the overall rule language. There is always a delicate balancing act when trying to weigh the costs and benefits of developing regulatory protections to protect drinking water, that may also have the economic impacts on our farmers and agricultural community. The willingness, professionalism, and courtesy of the TAC members to work together and try to find a “Common Ground” approach to looking to positive agricultural solutions that will help protect our groundwater from nitrate pollution was fundamental to development of this rule.

Document Review

We thank the following individuals for their review of this document and their insightful comments and suggestions; Francisco Arriaga, Larry Gunderson, Kevin Masarik, Matt Ruark, and Ashley Waggoner.

Farmer-Led Watershed Groups

We are profoundly grateful to our farmers in Wisconsin, their innovative farmer-led watershed groups, and the county staff and agronomists who support them. Their openness, wiliness to share, provide helpful feedback and suggestions, and “can do” attitude embody “Wisconsin”. In particular, our experiences working with farmers and agronomists from the following groups, who generously shared their insights, trials, “failures”, and experiences, helped strengthen, shape and inform our efforts.

- Dodge County Farmers for Healthy Soil and Water
- Farmers for the Sugar River
- Farmers of the Upper Sugar River
- Farmers of Lake Country
- Lafayette Ag. Stewardship Alliance
- Milwaukee River Watershed Clean Farm Families
- Watershed Protection Committee of Racine County
- Yahara Pride Farms

Introduction

Background

In December 2019, the Wisconsin Natural Resources Board directed the Dept. of Natural Resources (DNR) to develop Nitrogen Targeted Performance Standards (N-TPS) in sensitive areas of the state where groundwater experienced excessive nitrate contamination from agricultural practices. As part of this endeavor, a Technical Advisory Committee (TAC) of 25 members (in addition to DNR staff) was formed in February/March of 2020. The TAC was comprised of a wide cross-section of stakeholders from environmental groups and non-governmental organizations (NGOs), UW, UW Extension & Discovery Farms, partner agencies, and several representatives from agriculture including farmers, agronomists, and agricultural industry representatives. The TAC had 10 formal working meetings from February 2020 – March 2021, and several smaller focus group meetings that concentrated on detailed nuances of hydrogeology, agriculture, water quality, and human health-related concerns. Following direction from DNR Secretary Cole, the TAC committed to “working together” to find proactive solutions that would protect groundwater that and are also “workable” for farmers (financially, logistically, etc.).

Subsequently, the TAC met with a number of farmers, agronomists, and groundwater experts from neighboring states (primarily IL, IA, & MN) to learn about farming solutions to optimize nitrogen utilization, increase farm profitability, reduce nitrate losses to leaching, and protect groundwater from excessive nitrate contamination. A common theme that has been evolving over the past 15+ years is the “rediscovery” of cover crops’ abilities to capture nitrogen and reduce nitrogen losses. Part of the “Soil Health Initiative”, originally led by the U.S. Dept. of Agriculture, Natural Resources Conservation Service, and Agricultural Research Service, this approach to protecting soil health and water quality has experienced explosive growth via the burgeoning “famer-led watershed group” movement (WDATCP, 2020; USDA, 2018a; USDA, 2018b; USDA, 2018c; USDA, 2016; USDA, 2014; USDA, 2012; USDA, 1998). The use of cover crops, especially cereal grains (e.g. cereal rye) to sequester nitrogen, build organic matter, reduce erosion, improve soil fertility, and protect groundwater is now becoming a common practice amongst farmers across the Midwest, is recognized as a best practice in neighboring states, and even included in Minnesota’s groundwater protection rule (MDoA, 2021; WDATCP, 2020; USDA, 2018c; USDA, 2016; USDA, 2012). Based on the input from agricultural experts and research shared by colleagues from neighboring states, the TAC supported the use of cover crops and perennial crops as exceptions in the Nitrogen-Targeted Performance Standards rule.

The purpose of this document is to provide a comprehensive review of literature and readily available sources relevant to the N-TPS, the prohibitions, and exceptions.

Overview

This document provides a review of literature relating to the efficacy of cover crops to improve nitrogen use efficiency, reduce nitrogen losses from agricultural systems, and minimize nitrate contamination of groundwater. The purpose is to present a high-level overview of the body of published literature investigating:

1. the history of synthetic nitrogen fertilizer uses for augmenting agricultural productivity,
2. the mechanism and role of nitrogen pollution of groundwater,
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4. the general history of the use of cover crops,
5. and the body of research specifically investigating the use of cover crops to reduce the potential of nitrogen-nitrate losses from agricultural systems.

Document Structure

- Executive Summary
- Introduction: this section
- Meeting the N-TPS Performance Standard: A summary of real-world farms, farming practices, and on-farm research across the Midwest that have demonstrated the management practices, technologies, and tools that are vital to making progress towards meeting the N-TPS. Agriculture is entirely dependent on the two main ecosystem driving variables of climate and geology and inherits all the complexities and uncertainties of both. Consequently, agricultural Best Management Practices (BMPs) are those practices which, on average, over time, provide the best protection of soil and water resources. BMPs may not perform well in some years, other years they will perform better than expected, as such, they are not a "silver bullet", or guarantee for resource protection. Rather, they fall under the "wise use" concept, which focuses on long-term sustainable management of resources that balances present-day delivery of goods and services with long-term viability of the resource to maintain such services for future generations (Gifford Pinchot, 1910).
- Literature Review: a summary of the reviewed literature focusing on history of nitrogen in agriculture, nitrate pollution of groundwater, and the use of cover crops as a means of optimizing nitrogen use and minimizing nitrate losses to leaching and groundwater.
- Annotated Bibliography – an alphabetical listing of citations for each source. Where applicable, hyperlinks are also provided to direct the reader to online, digital sources of the cited reference. Each citation includes a summary paragraph relevant to the task of developing N-TPS in Wisconsin to reduce agricultural losses of nitrogen to groundwater and protect/improve groundwater quality.

Sources of References

To the extent practicable, this review has attempted to rely on peer-reviewed publications that include journal articles, agency reports, conference proceedings, academic materials, and books. However, as the rediscovered use of cover crops and nitrogen research are young and actively evolving, some of the most recent sources include presentations, magazine articles, and other "layman" publications that may not meet the most rigorous standards in academia.

Meeting the N-TPS Targeted Performance Standard

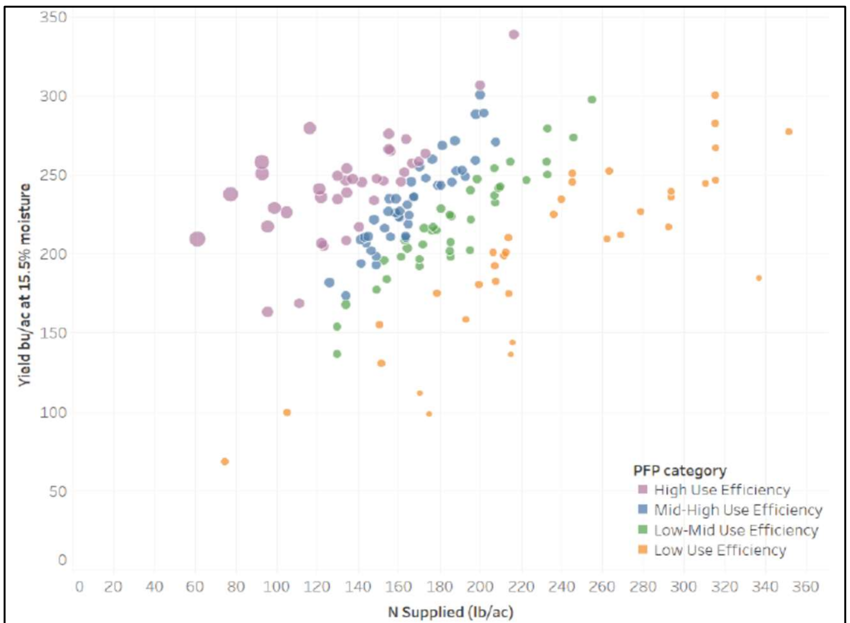
Many farmers throughout Wisconsin are working diligently to find solutions to protect water quality (both surface and groundwater) on their farms, whether working with farmer-led watershed groups, county ag. agents, the Corn Growers or Discovery Farms Nitrogen Use Efficiency Trials, or simply on their own with private agronomists. These innovative nitrogen management solutions benefit not only the farmer, but all of us (MDoA, 2021; Clary, et. al., 2020b; Mathewson, et. al., 2020; Myers, et. al., 2019; WGCC, 2020; WDATCP, 2020; Abdalla, et. al., 2018; WLWCA, 2017; Ward, et. al., 2018; Ribaudo, et. al., 2011; Robertson and Vitousek, 2009; Delgado, et. al., 2007). This is because we all have shared goals of keeping the nitrogen in the soil, so farmers can benefit, and groundwater can be protected.

An Important Point

The N-TPS is designed to minimize the amount of nitrate-nitrogen that is lost, or "leaks" past the root zone of crops and pollutes groundwater. Nitrogen that is not converted into plant tissue (e.g. crops) or soil organic matter is "lost nitrogen" and represents lost yield, lost investment, and lost revenue to farmers. Clearly, minimizing nitrogen leaching losses benefits both the farmer and groundwater quality.

> *The N-TPS does not establish or regulate the amount of nitrogen a farmer might apply to a field or crop. Maximizing crop uptake of available nitrogen (nitrogen use efficiency) by reducing losses will benefit groundwater quality. The N-TPS establishes an allowable pollutant load of leachable Nitrate-Nitrogen that is protective of the drinking water quality standard of 10 mg/l NO_3-N.*

Throughout the duration of TAC meetings and the draft rule-making process, TAC members engaged with farmers, agronomists, conservationists, and other agricultural professionals across the Midwest. These partners generously provided examples of farming operations that successfully utilize farming practices that optimize nitrogen utilization, contribute to high nitrogen use efficiency (figure at right), minimize nitrogen leaching losses to groundwater, and contribute to meeting the N-TPS performance standards. Results from these studies clearly show that more nitrogen does not directly mean more yield. In fact, some of the highest yielding fields had lower nitrogen application rates compared to lower efficiency fields (50% or less applied nitrogen). This section shares these examples and resources to help farmers, agronomists, and



Example of nitrogen use efficiency results from corn and dairy farmers in Minnesota and Wisconsin illustrating how improved nitrogen utilization (High and Mid-High Use Efficiency) can produce similar or better yields, often at half the rate of supplied N, compared to farms with poor nitrogen use efficiency (adapted from Augarten, et. al., 2019).

other agricultural professionals identify proactive and economical farming approaches that help to protect groundwater from nitrate leaching.

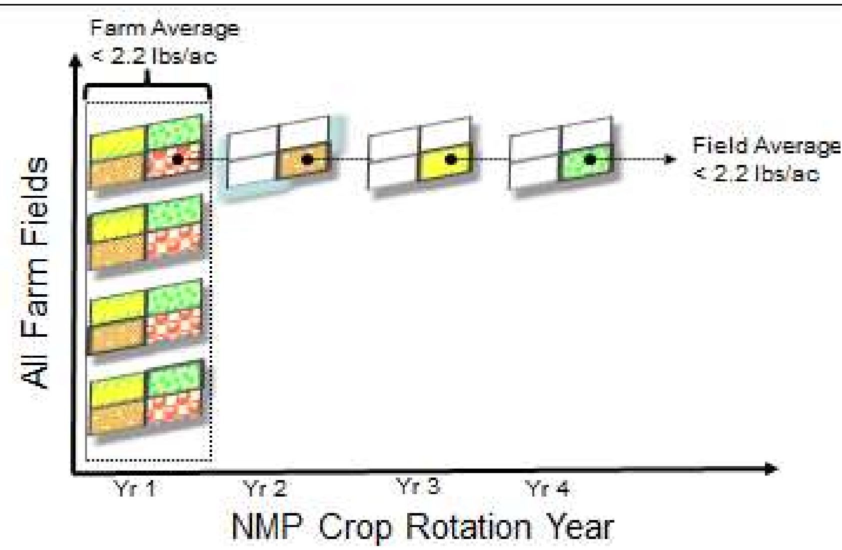
Understanding the Wisconsin Nitrogen Targeted Performance Standard

There are a couple of critical elements to meeting the requirements spelled out under the N-TPS for sensitive areas. These are:

1. Nutrient Management Planning (NMP)
2. Meeting the nitrate leaching target of <=2.2 lbs NO_3-N/inch of recharge below the root zone

To comply with the N-TPS performance standards, Nutrient Management Plans must be developed for all fields in a farming operation. Indeed, nutrient management plans have been required for all agricultural fields since 2002 (WDNR, 2013). Given the numerous inherent challenges and variability in farming from year-to-year and season-to-season, the performance standard target leaching amount is averaged across all fields in a given year (spatial averaging) and throughout the duration of a rotation for a given field (time averaging). This approach recognizes that not all fields will have the same nitrogen management or cropping systems in a given year, nor will a single field have the same nitrogen management or cropping system throughout the crop rotation for that individual field. As explained in the rule language below, and illustrated by the following figure:

- An average annual nitrogen leaching amount over all acreage that is less than 2.2 pounds per acre per inch of groundwater recharge provided that nutrient application rates on any field may not exceed application rates allowed under s. ATCP 50.04 (3).
- For each individual field, a nitrogen leaching amount that is less than 2.2 pounds per acre per inch of groundwater recharge averaged over the accounting period provided that in no year may nutrient application rates on any field exceed application rates allowed under s. ATCP 50.04 (3).

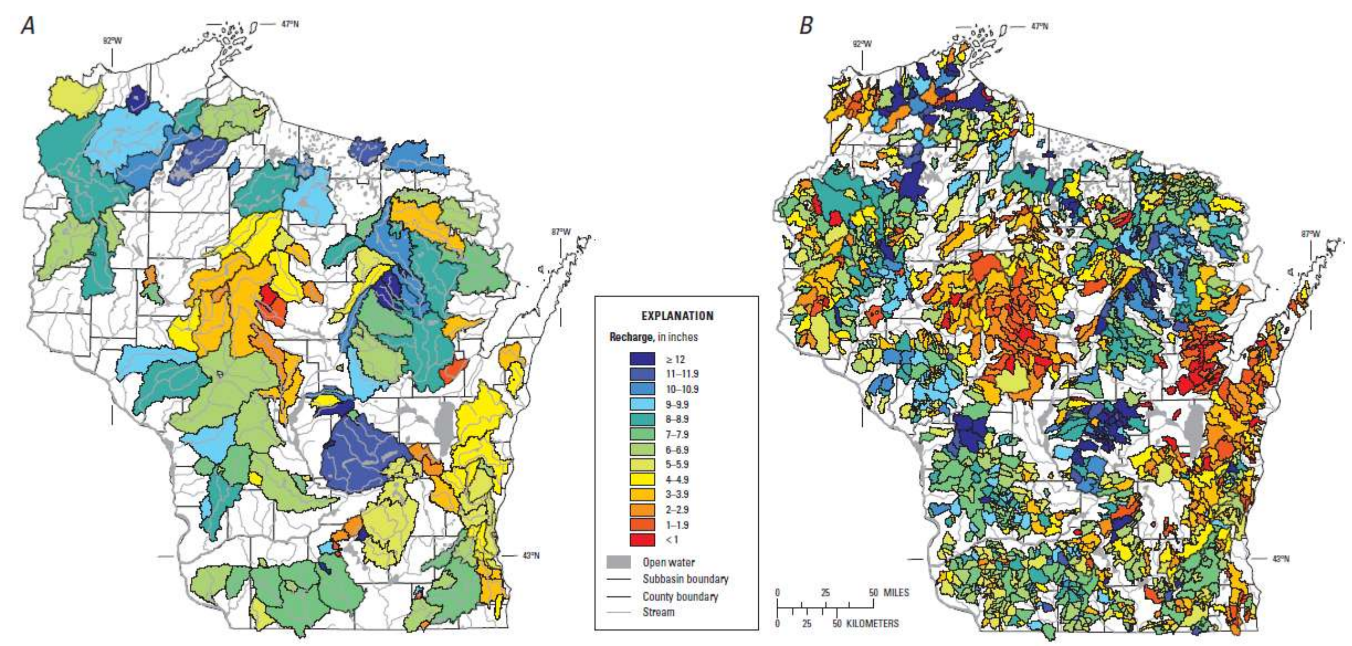


Example: A farm with 4 sets of fields, with each field having a 4-year crop rotation. To comply with the N-TPS, the Nutrient Management Plan documents that the average NO_3-N leaching is <2.2 lbs NO_3-N/ac/inch of recharge for each year across all fields AND on any given field for the duration of the rotation cycle. Thus, there can be fields that exceed the N-TPS, as long as the average across all acres and years meets the N-TPS.

The fundamental concept underlying the N-TPS is to limit nitrate leaching (from below the root zone) to the drinking water criteria of 10 mg/l (ppm). Converting this value to units consistent with agricultural practices, this is equivalent to an area weighted leaching rate of 2.2 lbs NO_3-N, per inch of recharge, per acre (value is rounded DOWN to 2.2lbs, rather than up to 2.3lbs, to provide a safety factor).

- 1 mg/l (or ppm) = 0.2266 lb/ac-inch

It can be difficult to determine groundwater recharge and the establishment, maintenance and operation of gaging stations and monitoring wells can be both cost and time prohibitive. Fortunately, the U.S. Geological Survey has developed methods for estimating groundwater recharge across much of Wisconsin. Gebert, et. al., (2011) developed and published a methodology using available data from gaging stations and produced maps of generalized groundwater recharge for Wisconsin (Figure below).



Spatial distribution of average annual groundwater recharge (1970-1999) as estimated from river gaging stations (A) and partial-record sites (b) (adapted from Gebert, et. al., 2011).

While the analyses and maps of Gebert, et. al., (2011) provide a good overview of recharge patterns across the state, more refined data and estimates for a particular area may be available from other sources. Examples of such sources include:

- Peer reviewed literature (e.g. Booth, et. al., 2016)
- Regional water supply planning documents (SEWRPC, 2008)
- Agency reports (e.g. Muldoon & Bradbury, 2019; Greve & Hart, 2018; McDonald, et. al., 2015)
- County Land and Water Conservation Plans
- Local groundwater studies (e.g. Haserodt & Fienen, 2020)

Using the range of recharge results provided by Gebert, et. al., (2011) and conversion factor from above, the following table presents the equivalent leachable amount of nitrate-nitrogen that would be consistent with meeting the N-TPS standard of 2.2 lbs N/inch of recharge for Wisconsin:

Groundwater Recharge (in/yr)	1	2	3	4	5	6	7	8	9	10	11	12
Equivalent Nitrogen Targeted Performance Standard (lbs N/acre)	2.2	4.5	6.7	9.0	11.3	13.5	15.8	18.1	20.3	22.6	24.9	27.1

The following examples illustrate how this table may be interpreted in various farm scenarios.

Examples

Example 1: A farmer, working with their agronomist, determines they are in the targeted area for the N-TPS. The farmer already has a nutrient management plan. Working with their agronomist, they evaluate their fields over a 4-year rotation. While each of the fields has an individual estimate of potentially leachable nitrogen, which may or may not be in excess of crop need and potentially leach, the farm-wide average across all acres is 10.5 lbs/acre of excess Nitrogen per year. Based on recharge estimates provided here and the farm location, the farmer determines their fields are in an area with an average of 5 inches of groundwater recharge per year. Given the farmer is below the equivalent 11.3 lbs N/ac/yr, the farm would be meeting the N-TPS.

Example 2: A farmer, working with their agronomist, determines they are NOT in the targeted area for the N-TPS and their fields are not subject to the N-TPS. However, evaluating their nutrient management plan (NMP) to determine potential leaching loss rates could be financially beneficial to the farmer and allow them to be more profitable. Further, it would help to protect groundwater quality by minimizing nitrate leaching losses.

Example 3: This is the same as Example 1, however under their current practices and prohibitions, the farmer determines they can't meet the 11.3 lbs N/acre/yr N-TPS for their farm. Working with their agronomist and a local farmer-led organization, the farmer adopts some of the available exceptions, including application of fertilizer on perennial pasture, and applying manure on living covers in the fall. With these modifications, the farmer is now able to meet the 11.3 lbs N/ac/yr N-TPS.

Example 4: A farmer, working with the county, determines they are in the targeted area for the N-TPS. While the farmer does not currently have a nutrient management plan, the farmer IS required to comply with the N-TPS. The farmer may choose to develop a NMP (perhaps with an agronomist or by themselves working with county land conservation staff). Alternatively, if cost-share is offered to the farmer, the farmer must develop a NMP and comply with the N-TPS.

Comparing Farming Practices to Minimize Nitrogen Leaching Losses and Protect Groundwater

What innovative practices are farmers using? What sorts of management measures and field operations are farmers employing to optimize their nitrogen use efficiency, improve profitability, and reduce nitrogen losses to groundwater leaching? Based on results of the literature review conducted, we have summarized the following common answers to these questions. Note, these are not "all inclusive", but represent the more commonly reported practices recommended to optimize nitrogen utilization and minimize leaching losses.

Practice	General Explanation
Nutrient Management Planning	A thorough nutrient management plan helps a farmer manage their fertilizer and manure resources for fields over crop rotations. This is an important first step in best accounting for nitrogen budgets and management measures to best optimize utilization of crop nutrients.
SNAP+	The SNAP+ Nutrient Management Planning software allows farmers to track nitrogen sources, including manure credits, per field and crop year. Target yields and actual data can be included. Using "book values" and tissue test results from harvest data can allow a farmer or agronomist to compare nitrogen supplied to nitrogen removed by harvest and estimate potential unused nitrogen that can be lost to leaching. Li and Ruark (2021) demonstrated this approach on a number of farms across Wisconsin and reported that potentially over 70%-75% of corn silage fields and approximately 24%-29% of corn grain fields may already be meeting, or doing better than the proposed N-TPS. Further, once these fields would be averaged across rotations and all fields in a farm, a larger percentage would be meeting the N-TPS.
Nitrogen Budget Calculator	A nitrogen budget calculator approach builds on the "partial budget" analysis approach to more carefully account for additional nitrogen processes. An example of this approach is provided by Kraft and Stites (2003), the large and small farms analyses conducted as part of the N-TPS rules packages (included as separate supporting documents in the rule package, and based on the Nitrogen Budget calculator of Kevin Masarik, UW Stevens Point (Masarik, personal communication, April 2021). This approach is similar to the Nitrogen Use Efficiency example provided, below. The reader is directed to UW Discovery Farms references and Li & Ruark (2021) for additional information.
Nitrogen Use Efficiency	UW Discovery Farms provides a simple step-by-step process for farmers and Agronomists to evaluate nitrogen use efficiency on farms (UW Discovery Farms, 2019; UW Extension, 2019).
Cover Crops	Most nitrogen loss occurs before planting and after harvest, because there is no crop with active roots to take up nitrogen and prevent losses to soil drainage during spring and fall rain. Late season, winter-hardy cover crops can use nitrogen in the fall to get established, then begin taking up nitrogen in late winter/early spring. This minimizes the amount of nitrogen that can be lost to leaching during these vulnerable periods (Brady, 1990b).
Manure, Cover Crops, and Forage Quality	Integrating cover covers into livestock operations can improve nitrogen use efficiency, significantly reduce potential for nitrogen leaching losses, boost yields, improve diversify and forage production, and contribute to improving forage quality (Ruark, et. al., 2019; Everett, et. al., 2018; Pellerin, et. al., 2016; Stute, et. al., 2007; Robertson and Vitousek, 2009). Improved forage quality and manure management have been found to be major contributing factors to overall dairy profitability, especially with smaller dairy farms (Bernhardt, 2021; Jette-Nantel, 2018; Pellerin, et. al., 2016).
Perennial Cover/Pasture	Managing agricultural fields for perennial pasture has been experiencing a resurgence across Wisconsin, with growing demand for beef and dairy sourced from sustainable farming practices. Perennial pasture provides for continuous living roots and plants during the fall and spring periods when nitrogen leaching losses are highest under conventional row crop systems. When nitrogen inputs are limited to manure from grazing on established pastures, nitrogen leaching losses were found to be significantly lower compared to row crop agriculture. However, additions of commercial nitrogen fertilizer, if not carefully managed, may increase in NO_3-N leaching loads beneath the pastures (Jackson, 2020).

Practice	General Explanation
No-till, Conservation Tillage	Tillage introduces oxygen into the soil and facilitates oxidation and breakdown of soil organic matter. This oxidizes organic nitrogen which is then lost and further reduces the ability of soil to "hold onto" nitrogen. Ideally, in fertile soils with good nutrient availability, the carbon-nitrogen ratio is typically in the 10:1 to 12:1 range (Brady, 1990a). This is because nitrogen is a major component of plants and plant tissues, including cells, amino acids, proteins, hormones, and virtually every component of plants (Brady, 1990a). Thus, building and preserving organic matter is one of the most robust means of building and stabilizing soil nitrogen reserves. Further, soil organic matter is the primary source of energy for all soil biota. Reductions in soil organic matter can cause a dramatic decline in soil biochemical reactions and effectively "starve-out" soil biota (Brady, 1990a). In fact, over 90% of soil functions are biologically driven and depend on soil organic matter (Stika, 2016).
Split Applications	Splitting applications of fertilizer and manure can "spoon feed" nutrients to the crops when they need it most, rather than overloading the nutrients at levels the crops cannot absorb.
Test Strips and Fields	Farmers who use "reduced rate" test strips in fields can identify the ability of their soils to deliver nitrogen (and other nutrients) and optimize application of fertilizer and manure by using reduced rates on more productive fields, more strategic use of fertilizer on other fields, and perhaps identify "losing fields" – fields that simply cannot produce enough crop to offset input costs.
Variable Rate	Variable rate technology allows farmers to adjust application rates according to field needs, as they drive through a field. If a field has highly variable natural fertility, variable rate allows a farmer to optimize their fertilizer investment and maximize profits by not wasting valuable fertilizer in areas that don't need it.
Fall Application	Fall application of nitrogen fertilizer or manure alone, can greatly increase the risk of nitrogen leaching losses (Brady, 1990b). The use of cover crops and perennial crops (e.g. pasture, alfalfa, etc.) are excellent tools to help "hold onto" nitrogen and reduce potential for leaching losses. Nitrogen inhibitors may also be used to reduce nitrate leaching losses, however the efficacy, cost, and availability of these varies greatly and there is not consensus in published literature of the effectiveness of inhibitors.
MRTN	A Maximum Return to Nitrogen (MRTN) approach to nutrient management places an emphasis on overall farm profitability, rather than maximum yields. This approach rewards farmers for being more diligent with their nitrogen utilization and helps identify ways to best manage field practices and nitrogen use such that excess nitrogen is not wasted, and consequently can help reduce nitrate leaching losses. The MRTN approach incorporates many of the following practices.

Resources for Farmers and Agronomists to Improve Profitability and Meet the N-TPS

There are several tools and resources already in use by farmers and agronomists that aim to improve nitrogen use efficiency and farm profitability, while also reducing leaching losses and nitrate contamination of groundwater (MDoA, 2021; Clary, et. al., 2020b; Myers, et. al., 2019; ISU, 2019; Christianson, et. al., 2017;USDA, 2015; EPA, 2013; ISU, 2013; Dzurella, et. al., 2012; Robertson & Vitousek, 2009). A common concept with these is the concept of prioritizing profitability, rather than maximum yields, and using a "whole farm" approach. While using only one of the following concepts or practices may not guarantee meeting the 2.2lbs nitrogen/acre/inch of recharge, the farm data we have of farms that are close to or meeting this performance standard are all taking advantage of some, or all, of these tools. Additionally, all of these approaches are currently being taken advantage of in WI, and many are being adopted, encouraged, and taught via the farmer-led groups.

- SNAP+ : By using NMP's, SNAP+ and A2809 recommendations, a farmer can generate an approximate nitrogen budget so they can understand where they are most likely to be losing nitrogen (e.g. Li and Ruark, 2021). Combined with the 4R program (see below), these are incredibly powerful tools

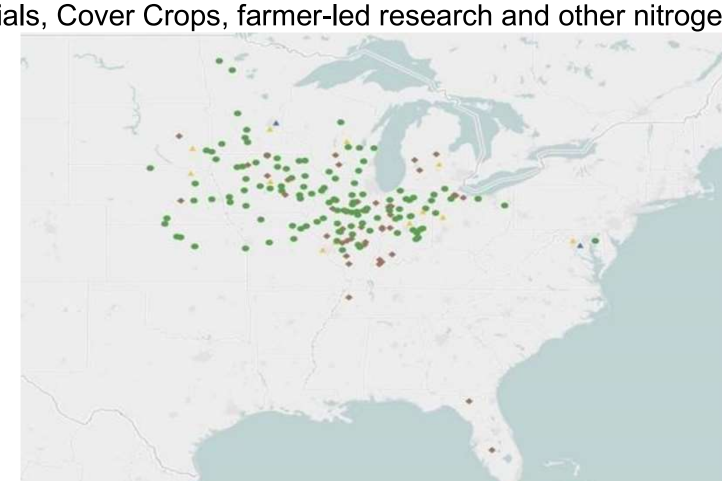
- Discovery Farms Nitrogen Use Efficiency Tools: Farms that are taking advantage of these tools clearly have higher nitrogen use efficiency
    - Nitrogen Use Efficiency Field Trials
    - Nitrogen Use Efficiency Self-Guided Tools for Farmers
    - Nitrogen Use Efficiency Recommendations for Corn Grain and Sileage
- Corn Growers Association Soil Health Partnership
    - Farming practices to optimize Nitrogen Use Efficiency
    - Field Trials and Example Farms
    - Certified Practices for Optimizing Nitrogen Utilization
- The '4 R's' of Nutrient Management: This is a nutrient management concept based on nutrient optimization and profitability. Many of our Certified Agronomists in WI have this extra certification and practice this approach with their farmers.
    - 4R Nutrient Management
- IA Field Practices to Optimize N Utilization and Reduce Leaching These farming and field practices were developed over a few decades to help farmers realize the Maximum Return to Nitrogen (MRTN). This is a profit-based model using practices from actual on-farm research and economics.
- Illinois MRTN Program and Tools
    - Similar to IA, this toolbox, developed and supported in concert with fertilizer industry, encourages farmers to shift focus to MRTN targets rather than yield totals.
- MN NITROGEN FERTILIZER BMPS FOR AGRICULTURAL LANDS
    - A series of tools, practices, and programs from MN ag research stations, field trials, and other on-farm research that help guide farmers to profitable operations using practices that will help them meet the new MN Groundwater Nitrate Law and fall fertilizer restrictions. These are broken down by climatic regions, and include special practices for the excessively drained central sands region of west-central MN.
- Partnership for Ag. Resource Management (PARM)
    - PARM originated in the Sandusky Basin to address HAB's in Lake Erie. This is a field research based approach (think UW Discovery Farms) partnered with the entire agricultural commodity chain to certify producers, agronomists, and fertilizer retailers using the 4R approach. PARM has been incredibly successful (enrolling literally millions of acres) and has expanded into WI. They are now based in Madison and beginning expansion of this model approach across the state. Originally focused on phosphorus, they have adapted the approach to nitrogen fertilizer and other soil nutrients using soil testing, variable rate technology, field mapping, and combine yield monitors.

Farm Profitability

During the TAC meetings, TAC members heard from farmers, agronomists, and other agriculture experts from various locations across the state about numerous examples of profitable farming practices that optimize nitrogen utilization and will contribute to meeting the N-TPS. The farm examples that were provided reflected various crop and farming systems on wide array of soils, across multiple years of being profitable. In many examples, these farms were more profitable than conventional farming systems, due to improved efficiency and lower equipment, labor, and input costs. Similar results have been reported at a broader geographic scale, examples of which include the following:

- The Minnesota Dept. of Agriculture recently published the results of their economic analyses of farm profitability from their database of 2,246 commercial farms across the state (MDoA, 2021), Farms using conservation farming principles (“environmental farming”) had net farm income of $212,892 in 2020, compared to $172,687 for the average farm (conventional farming). Similarly, in 2019, it was $92,821 compared to $73,643, a tougher year for all farmers to make any profit (MDoA, 2021).

- Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops: This comprehensive 5 year study evaluated the role of cover crops in whole farm profitability (from 2012-2017) across the north-central United States and identified seven areas where cover crops were found to significantly improve farm profitability. Depending on farm and crop type, typical “break-even” periods for investments in cover crops was 2-3 years, with net profits increasing significantly beyond the third year. Numerous other benefits associated with cover crops were also noted including being able to plant earlier, better retention and utilization of soil moisture, reduced weed pressure and improved crop health, and overall improvements in soil fertility (Myers, et. al., 2019).
- Corn and Soybean digest, October 2017, Iowa corn grain farmer saving $97/acre ($65 equip, $27 labor) using conservation farming practices, including cover crops, compared to conventional farming. These results are consistent with numbers reported for these practices across the state. His practices are helping keep nearby creek below 10 mg/l NO_3-N drinking water criteria. As of 2015, cover crops were being profitably used on over 600,000 acres in Iowa, with an ultimate target of 12M-15M acres. Conservation demonstration farms spread across Iowa, along with numerous partner farmers have demonstrated that Iowa’s water quality problems can be profitably solved if farmers adopt no-till, conservation tillage and cover crops across the state. Similar other examples from Corn & Soybean Digest include:
    - Rye cover crops in Minnesota were found to reduce leaching losses in sandy soils by up to 45% while preserving corn yields (Rye cover crop impact on nitrogen leaching and corn yield, 2018)
    - “Can cover crops, conservation tillage be profitable?”: farmers using conservation practices including reduced tillage and cover crops, “The analysis also found that farmers achieved profitable conservation systems by aiming to address specific management challenges with in-field conservation practices, such as improving soil structure as a way to improve water management and reduce erosion, and minimizing passes across the field to save time, machinery and overhead costs.”
- National Corn Growers’ Association, through their “Soil Health Partnership Initiative (SHP)”, encourages Nitrogen Use Efficiency trials, Cover Crops, farmer-led research and other nitrogen optimization strategies to optimize nitrogen utilization, protect groundwater from nitrate leaching, and improve farm profitability. The SHP focuses specifically on “Sustainable farming practices that build up soil health allow you to take more control of your farm by strengthening productivity and enabling profitability.” Cover Crops are one of the primary practices they endorse, for a multitude reasons, including profitability and reduction of nitrate leaching losses to groundwater.



Farm and Field Locations of the Corn Growers’ Association & Soil Health Partnership Nitrogen Use Efficiency Field Trials

- “The SHP research network spans over 16 states and more than 200 farmers and 7,000 research acres. With this vast network we are learning how changes in management are affecting numerous soil types, varying cash crop rotations, and many other variables that could benefit you at a local level.”
- Corn Growers Association, via their Soil Health Partnership initiative, strive to “Achieving Profitability with On-Farm Conservation”. From their annual 2020 annual report “Conservation’s Impact on the Farm Bottom Line”, their partner farmers using cover crops **were significantly more profitable than conventional farmers** (by decreasing overall input/operating costs). However, “Unlike the immediate cost savings of conservation tillage, cover crops have annual costs, and efficiencies and soil health benefits can take time to achieve”. Key factors include learning to be profitable with cover crops may take a few years of experience, learning from other farmers and initiatives such as SHP can reduce the “learning curve”, and ultimately farmers learn they can reduce input costs when using cover crops and that is critical to profitability. There are “up front” costs to using cover crops, which can vary widely depending on what a farmer chooses to do. However, these farmers more than recoup their costs, comparted to conventional farming, and ended up being more profitable (net income of $362.40/acre compared to $324.48/acre for conventional farming).
- The Soil Health Partnership is a network of these farmers with shared goals of building profitability by using sustainable soil health and farm conservation practices throughout the Midwest. These corn farmers collaborate on research, work with agronomists, do extensive soil sampling, and try numerous farming techniques that focus on building healthy, resilient, productive soils that improve farm profitability and optimize input costs and farm efficiency. Their efforts, through support of the national Corn Growers’ Association, are gaining national interest and attention for their dedication to stewardship and profitable farming. In 2015, a Soil Health Partnership Farmer Leader, Tim Smith, Earned a prestigious **White House Award** for his ongoing dedication and efforts to advance profitable and sustainable agriculture in Iowa through his outreach and education work with other farmers. While Mr. Smith uses numerous conservation farming practices that he has found to be profitable, he strongly advocates for growing cover crops,

> “..like cereal rye on 550 of his 800 acres. Cover crops help store excess nitrates that might otherwise leach into groundwater. They also help prevent erosion.”

Real Farm Examples of Using Cover Crops to Meet Exceptions

Throughout the TAC meeting process, we received extensive feedback and input from famers and the broader agricultural community to learn about practices that farmers are utilizing to conserve nitrogen and minimize nitrate losses to leaching. It is important that these practices are not merely concepts or rare examples that only work under extremely controlled conditions. For this reason, we have collected examples of commercial farming operations that have successfully and profitably developed farming strategies and field practices that are protective of groundwater quality. Many of these examples came directly from farmers, agronomists, and other agricultural professionals who work directly with farmers. To them, we are extremely grateful for their generosity in sharing and their “can-do” attitude to work together to find positive solutions that work for all of us to not only protect our groundwater quality, but also ensure our farmers can run profitable businesses and help guide us to find workable solutions to our shared challenges. These examples are shared for purposes of reference and information and do not constitute guarantees of meeting the N-TPS requirements:

Dairy and Cash Grain Farming Examples

- Wisconsin Land & Water Conservation Farm Awards: These awards recognize farmers who have gone above and beyond with their leadership and significant contributions to county land and water conservation.
  - T&R Dairy Farm
- Sand County Foundation Leopold Award
  - Gold Star Dairy
  - Brickstead Dairy
  - Koepke Farms
- UW Discovery Farms Nitrogen Use Efficiency Trial Farms
  - Koepke Farms
- WI NRCS Success Stories
- No-till Corn Silage and Cover Crops – Southeastern Minnesota (video)
- MN Nitrogen Fertilizer Best Management Practices
  - Best Management Practices for Nitrogen Use in Minnesota (PDF)
  - Best Management Practices for Nitrogen Use on Coarse Textured Soils (PDF)
  - Best Management Practices for Nitrogen Use in Southeastern Minnesota (PDF)
- Green County Corn Grain Yield Champion – Jake Kaderly
- Hammer and Kavazanjian Farm - Dodge County

Vegetable Farming and Sandy Soils Examples

- Rye Cover Crop Impact on Nitrogen Leaching and Corn Yield
- MN Best Practices for Nitrogen on Irrigated Potatoes
- MN Best Practices for Nitrogen on Sandy Soils

General Practice Recommendations

The following online resources provide guidance and examples of farming practices that optimize nitrogen use, have been demonstrated to be functional and profitable on working farms, and will help to reduce nitrate leaching losses to groundwater:

- USDA 2012
- Nitrogen Cycling and Cover Crops (Farm Progress article)
- Research tracks cover-crop effect on nitrogen fate (AgriView article)
- Discovery Farms Nitrogen Use Efficiency
- NRCS Cropland Practices to Protect Drinking Water (USDA 2016)
- Protecting Groundwater Sources of Drinking Water (USDA practices to reduce nitrate leaching)
- MN NRCS practices to protect groundwater
- MN Groundwater Protection Rule practices
- Leopold Award Recipients
- Wisconsin Land & Water Conservation Farmer Award
- Soil Health Partnership Farmers
- PARM Farms and 4Rs

Summary of Research Findings for Best Practices to Optimize Cover Crop Performance, Maximize Nitrogen Sequestration, and Minimize Nitrate Leaching Losses

The following summations represent general trends, results, and findings that wove a common thread through much of the reviewed literature. Farmers, agronomists, soil scientists, and other agricultural practitioners recognize the wide variability and challenges facing farmers from weather patterns, soils, pests, and other variables that may complicate the best made plans. As such, while there are no "rules" or guarantees (to coin the old adage, "your results may vary"), these generally reflect concepts that are commonly among "best practices" in the utilization of cover crops.

- To start, let's address what is perhaps the most fundamental question to ask; "Is the N-TPS achievable and profitable on working farms in Wisconsin?"
    - Li and Ruark (2021), reviewed five years (2015-2020) of nitrogen use, nutrient management, and yield data from 91 farms, including 197 corn-grain fields and 97 corn-silage fields, spread across the common agricultural lands of Wisconsin. Using a partial nitrogen budget analysis (which is conservative), they calculated 24%-29% of corn-grain and 70%-75% of corn-silage fields would be meeting or doing better than the proposed N-TPS of 2.2 lbs NO_{3-}N/acre-inch recharge/yr. While more research is needed in this field and these numbers could change with refinement, many farmers in Wisconsin are already being innovative and efficient with their nitrogen use. So much so, in fact, that they are likely already protecting our groundwater from excess nitrate contamination. While these farmers are all voluntary participants in the UW Discovery Farms research trials and their results may not reflect broader trends in current practices, these are all privately operated, successful, and efficient farms. Similar results from comprehensive farming databases have been reported in Minnesota (MDoA, 2021) and more broadly across the corn-belt region of the United States (NCGA, 2020; Myers, et. al., 2019).
- Species selection: the following notes only highlight some general themes that were found reported multiple times in published research. The reader is encouraged to review the literature review, references, and induvial sources cited in the document for more information.
    - Dabney, et. al. (p233, 2010): Grasses are typically the most cold-tolerant and produce residues most resistant to decomposition; legumes can contribute N through symbiotic dinitrogen (N_2) fixation; and brassicas can be the most rapid growing under warm conditions, have the ability to take up large quantities of N, and their residues mineralize N rapidly. Brassicas are not used as much as legumes and grass cover crops, but offer promise in a variety of management systems as catch crops and green manure crops and also may significantly impact soil porosity, disease control, and weed populations (Collins et al., 2007; Snapp et al., 2005; Williams and Wiel, 2004; Haramoto and Gallandt, 2004; Thorup- Kristensen, 2003; Isse et al., 1999; Francis et al., 1998; Smolinska et al. 1997; Mojtahedi et al., 1991).
    - Grasses: perennial (winter hardy) grass cover crops including cereal rye (considered optimal), triticale, winter wheat, etc. Overwintering crops were generally found to be most effective to reduce nitrogen leaching losses and provide multiple spring planting benefits.
        - In general, cereal rye, by far, is the most reported cover crop to specifically reduce nitrogen leaching losses, provides optimal sequestration, and the potential to provide slow-release nitrogen to subsequent cash crops. Literature

    - included in this study reported nitrogen leaching loss reductions consistently averaging in the 40% - 60% range.
    - Rye reduced nitrate leaching by 31%, on average, across a compendium of trials, studies, and reviewed literature cited in the Iowa Nutrient Reduction Strategy (ISU, 2019).
  - Brassicas: Brassicas (e.g. radish, mustard, turnips, etc.) can provide a number of benefits as cover crops including nutrient storage, breaking up compaction, providing forage, and building organic matter. These family of cover crops are usually included as part of a seed mix to help address specific needs of a given field. Brassicas are effective at sequestering and retaining nitrogen, though subsequent availability to crops is widely variable and not consistently reported results for improving yields (Christianson, et. al., 2017).
  - Legumes: While legumes provide little to no reduction in leaching losses, they can provide nitrogen for subsequent crops and reduce need for supplemental nitrogen fertilizer applications. If not managed appropriately, legumes have potential to increase leachable soil N in the spring.
- Fall planting date: as soon as possible following fall harvest, time for seed to sprout, and growth of shoots and roots to begin. Late planting date can still provide benefit, though it may be reduced.
- Winter hardiness: Northern climates (e.g. midwestern states including Wisconsin) have historically had lower cover crop utilization due to shorted growing seasons, soil temperatures, and related growing season variables (Dinnes, et. al., 2002). However, ongoing research and field trials in WI, MN, and IA have shown growing interest, utilization, and success with cover crops (Dougherty, et. al., 2020; Hivey, et. al., 2020; DATCP, 2019; ISU, 2019; Ruark, et. al., 2019; Ruffatti, et. al., 2019; Cates, et. al., 2018; Everett, et. al., 2018; Ruark, et. al., 2018; USDA, 2018c; Armstrong, et. al., 2017; Sawyer, et. al., 2017; Marcillo & Miguez, 2017; Martinez-Feria, et. al., 2016; USDA, 2015; Moore, et. al., 2013; USDA, 2012; Krueger, et. al., 2011; Ruark & Stute, 2009; Zhiming & Helmers, 2009; Stute, et. al., 2007).
  - Winter hardy cover crops should be planted in autumn with time to establish and germinate. Winter hardy cereals will actually continue to grow down to 34ºF and may grow roots deep into the soil profile through the entire winter.
  - Non-hardy cereal annuals (e.g. barley, oats, etc.) typically do not survive winter and provide reduced ability to limit nitrate losses to leaching.
- Spring harvest or termination date
  - Higher sequestration occurs as the cover crop is allowed to grow longer into spring,
  - Highest rates (measured from tissue sampling and soil sampling) when cover crop allowed to fully grow and harvested for forage,
    - followed by “planting green” into the living cover crop, or
    - followed by cover crop terminated immediately before planting
  - early spring termination followed by delay in harvesting provides slightly to greatly reduced rates of nitrogen scavenging,
- Crop yields
  - Cereal grasses (being related to corn) are very competitive for nitrogen,
  - Cereal rye has long been known as the most aggressive N-scavenging of the grain crops and is a preferred species for phytoremediation of contaminated groundwater and soils (Pandey & Maiti, 2020; EPA, 1999),

    - Cereal grasses are "thirsty" and should be managed appropriately. In wet springs, they can help dry the soil quickly and allow for earlier planting. In drought years, they may create water stress and delay seed germination for the subsequent crop.
    - Due to these factors – aggressive N-scavenging and being "thirsty", cereal rye, in particular, may have a negative drag on subsequent corn yield (sileage and grain) when the cover crop was not terminated properly, nitrogen demand was not accounted for at planting (e.g. N-starter required for corn), and insufficient moisture delayed germination.
- Nitrogen Leaching and No-Till Systems
    - In no-till fields, where soil macropores (e.g. old root channels, worm burrows, etc.) remain intact, nitrate leaching with drainage via the macropores has been identified as a potential mechanism that may partially offset the effectiveness of cover crops to reduce nitrate losses via leaching, compared to strip-till or conventionally tilled fields that disturb the macropores.

Literature Review

Introduction

The term “cover crops” has become far more commonplace and used with wide ranging definitions. For example, in some conservation programs, “cover crops” are a crop planted for the sole purpose of providing a conservation benefit (e.g. a cover crop planted to protect bare soil during the winter, that is then terminated in the spring, before planting the next cash crop). Conversely, in agronomic references, a cover crop may refer to an ADDITIONAL value-added crop (e.g. rye grown to protect bare soil during the winter, which then is allowed to grow and harvested as ryelage for forage). For the purposes of consistency, the term “cover crop” is used herein meaning:

> *“Cover Crops: Cover crops have been defined as crops grown to protect the soil from erosion losses and losses of nutrients via leaching and runoff (Reeves 1994). This definition was expanded in the <u>Encyclopedia of Soil Sciences</u> to those crops that are grown for improving soil, air, and water conservation and quality; nutrient scavenging, cycling and management; increasing populations of beneficial insects in integrated pest management; and/or for short-term (e.g., over-winter) animal-cropping grazing systems (Delgado et al. 2006).”*

Historically, the research and practice of using cover crops were most widespread in the more temperate-humid agricultural regions of the United States (Dabney, et. al., 2010; Dines, et. al., 2002). There was a widespread consensus (though, not necessarily accurate) that cover crops could not “fit” into the shorter growing seasons of more northern states like Wisconsin and Minnesota. This line of thinking stemmed from past efforts to translate southern cropping practices into northern climates, and largely failed to account for differences in climate, soil types, cropping practices, farm types, and related variables that made it difficult to directly adapt the research and practices from the more temperate climates to our region. Much of the early cover-crop research in the Midwest from the 1980’s and even into the 1990’s reported failed cover crops, dramatic yield reductions, and numerous financial and logistical hurdles that discouraged farmers from considering cover crops as a strategy for their farms (Cates, et. al., 2018; Masarik, et. al., 2014; Dabney, et. al., 2010; Dinnes, et. al., 2002). Dines, et. al. (2002) summarized one of the biggest challenges of the time;

> *“Presently, there are no cover crop species or geno-types that integrate well with corn and soybean production practices in the northern Corn and Soybean Belt. Cultural and plant-breeding research is needed to improve the compatibility of cover crops with current cropping systems. For example, rye cover crops grow well in the northern Corn and Soybean Belt, but rye geno-types that do not reduce corn yields need to be found or developed.”*

For these reasons, the effects of winter cover crops on soil quality and nitrogen sequestration in this region had not been investigated extensively and adoption in these colder climates has lagged compared to southern states (Roesch-McNally, et. al., 2017; Masarik, et. al., 2014; Krueger, et. al., 2014; Moore, et. al., 2013; Ruark and Stute, 2009). In their review of research, Moore, et. al. (2013) concluded;

> *“Few, if any, long-term studies have investigated whether a cereal rye cover crop can be used to enhance soil quality in the corn-soybean cropping systems of the upper Midwest. In this region, the period between harvest and planting of corn and soybean crops is short and unfavorable for plant growth, and it is not known whether cover crops could increase annual biomass inputs enough to improve soil quality.”*

However, over the past fifteen years, or so, corn and soybean farmers in the upper Midwest have been increasingly using winter cover crops. The use of cover crops to augment agricultural productivity, improve farm profitability, build soil health, and protect water quality has found resurgent interest in Wisconsin (Ruark and Stute, 2009). The reasons for this growth are multifaceted and represent an intersection of public and private interests to improve degraded water quality while building soil productivity and enhancing farm profitability. Over a decade ago, the Natural Resources Conservation Service (NRCS) began a concerted outreach, education, and incentive funding initiative to build "Soil Health" and protect water quality through direct county staffing cooperation with farmers and local conservation professionals. The "Soil Health" initiative focused on four key elements to build soil health and protect water quality: minimize soil disturbance, maximize soil cover, maximize biodiversity, and maximize continuous living roots (USDA 2018a; USDA, 2018b; USDA, 2014). Incorporating cover crops into agricultural systems is encouraged in all four of these concepts, with two of the major benefits being to improve fertility and minimize nitrate leaching losses (USDA 2018a; USDA 2014).

Meanwhile, the national Corn Growers Association developed their own "Soil Health Partnership" program to deliver on-farm research into nitrogen use efficiency (NUE) and farm profitability by partnering with corn farmers and conducting extensive on-farm research trials. Some of the earliest participants in this initiative were corn farmers in Rock County, south central Wisconsin. This initiative has continued in Wisconsin with farmers signing up for 3-year NUE trials in numerous counties throughout southern Wisconsin.

Similarly, the University of Wisconsin and UW Extension Discovery Farms began conducting field trials at research stations and private farms, respectively, to evaluate and refine field practices and specifically cover crops that would benefit farm profitability and water quality via protection of soil, building soil health, optimizing nutrient utilization, and reducing sediment and nutrient losses from farm fields (Augarten, 2019).

During this same time, the Dept. of Natural Resources drafted and began implementing watershed-based permit compliance for permitted point-source wastewater facilities. The two permit compliance options, known as Water Quality Trading (WQT) and Adaptive Management (AM), allow eligible point sources to partner with farmers, agronomists, counties, and other watershed stakeholders to reduce nonpoint source (NPS) phosphorus and TSS loading to receiving waters, in lieu of having to invest in much more expensive wastewater treatment plant facility upgrades. The first adaptive management project, Yahara WINs, was a partnership formed between numerous permitted facilities and communities, Dane County, and a fledgling farmer-led group, Yahara Pride Farms. While Yahara Pride Farms was not the first farmer-led group in the state, the injection of funds from facilities partnering with farmer-led groups increased funding and resources for some groups to grow and flourish. Just as important was a change in the discourse and a willingness of urban communities to shift away from finger-pointing and blaming farmers, to seeing farmers as fellow stakeholders and proactive problem-solvers. With the growth in WQT and AM, cover crops quickly became a "go-to" practice to generate NPS pollutant reductions. With this, technical standards for establishing and growing cover crops (along with other practices) have been developed and formally recognized in state statute for compliance with state (WPDES) and federal (NPDES) permit requirements. This formal acknowledgement of the benefits of cover crops for reducing NPS pollutant loading at both state and federal levels has greatly facilitated the spread of cover crop utilization across the state.

With the success of Yahara Pride Farms, not only did farmers in other parts of the state start to ask about forming farmer-led groups, but so did agency partners, representatives, and industry groups. This led to perhaps the most fundamental shift that has accelerated the adoption of cover crops and soil health farming principles in Wisconsin, the inception of the Producer-Led Watershed Grant Program (DATCP, 2019). The Producer-Led Watershed Grant Program provides direct financial, administrative and technical support to local farmers wishing to form their own farmer-led groups. These groups emphasize “hands on” peer-to-peer education with farmers developing their own education programs, field days, and conservation programs with financial, logistical, and administrative support from numerous partners. As part of the grants, these groups must commit to implementing conservation practices at the local level and cover crops are one of their most preferred options.

Literature Review Presentation

To present material in the most accessible format for all audiences, this review is written in a manner summarizing literature from general background information to increasingly specific topics like comprehensive trials, research experiments, and comprehensive peer-reviews exploring the nuances of how field practices, nitrogen management, and cover crops interrelate with climatic drivers and nitrate losses to leaching. This approach somewhat mimics how the research has progressed through time, from more general to increasingly focused. The review begins with background information for the general reader and graduates into more focused topics. These sections are:

1. History of Nitrogen Fertilizer Use to Augment Agricultural Productivity
2. Agriculture and Groundwater Nitrate Contamination
3. Human Health Risks from Nitrates
4. Cover Crops and Nitrogen Management
5. Cover Crops and Nitrogen Leaching
6. Rye and Cereal Grain Cover Crops to Optimize Nitrogen Sequestration

1. History of Nitrogen Fertilizer Use to Augment Agricultural Productivity

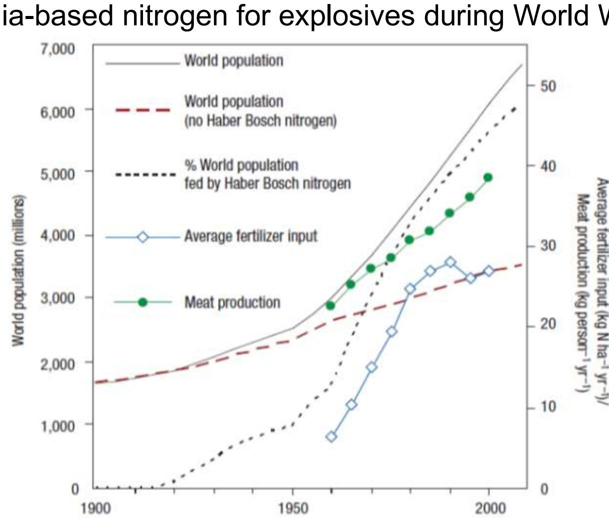
Before the discovery of the Haber-Bosch process for the synthesis of commercial nitrogen fertilizer nearly 100 years ago (1933), the use of cover crops was widespread and recognized as the primary means for "growing and supplying" nitrogen to other "cash crops" (Erisman, et. al., 2008; Meisinger, et. al., 1991; Pieters, 1927). In fact, this is where the term "green manure" originated, as farmers would plant cover crops that would sequester nitrogen, then till the cover crops into the soil before planting their main crops. The plant residue and nutrients from the cover crops were seen as being similar to the benefits provided by manure, hence "green manure". This practice was common among European farmers, with documented use going back over 2,000 years, and these farmers brought the practice to the "new world" as farming immigrants to the United States of America (Pieters, 1927).

Some of the earliest agronomic research in America was investigating means to optimize the "growth and generation" of soil nitrogen by using cover crops. Meisinger, et. al., (1990) noted, "The use of winter cover crops to conserve N and reduce leaching is an old practice which has not been exploited in modern agriculture systems". For example, published, peer reviewed trials looking at various plant species to identify which provided the most benefit to soil nitrogen, tilth, and other plant growth factors were reported in the early 1900's, with additional research to use cover crops to generate nitrogen for cotton in the late 1800's. Meisinger, et. al., (1991) reported farmers had already identified rye grass as one of the best grasses to sequester nitrogen, build organic matter, and reduce nitrogen losses:

> *"Winter cover crops of rye (Secale cereale L.), crimson clover (Trifolium incarnatum L.), and hairy vetch were systematically evaluated as N sources for cotton (Gossypium hirsuturn L.) in Alabama as early as 1898. A summary of the excellent work of agricultural scientists in the early 1900s is provided in Pieters' compilation of literature (38). This work emphasized the benefits of increasing N availability to the next crop. Later in this century (1930-1945), the role of cover crops in conserving N against leaching was studied. Reported lysimeter work (7, 22, 32) clearly shows that winter cover crops can significantly reduce nitrate (NO_3) losses in water percolating through soil."*

7 Chapman, H. D., G. F. Liebig, and D. S. Rayner. 1949. A lysimeter investigation of nitrogen gains and losses under various systems of covercropping and fertilization and a discussion of error sources. Hilgardia 19(3):57-95.
22 Jones, R. J. 1942. Nitrogen losses from Alabama soils in lysimeters as influenced by various systems of green manure crop management. J.Am. Soc. Agron. 34574-585
32 Morgan, M. F., H. G. M. Jacobson, and S. B. LeCompte Jr. 1942. Drainage water losses from a sandy soil as affected by cropping and cover crops. Bull. 466. COM. Agr. Exp. Sta., New Have
38 Pieters, A. J. 1927. Green manuring principles and practices. John Wiley & Sons, Inc., New York, N.Y. 356 pp.

With the Haber-Bosch process to synthesize ammonia-based nitrogen for explosives during World War II and America entering the "*Golden Age of Chemistry*", a fundamental shift began to occur in agriculture, as farmers began to depend on chemistry and engineering to provide plant nutrients, rather than working with those available from nature. Analyzing trends in global population growth, agricultural production, and commercial nitrogen fertilizer production, Erisman, et. al. (2008) estimated that nearly forty percent of the current global population, approximately 3 billion people, are dependent on food produced using synthetic nitrogen fertilizer (figure at right). While the widespread use of nitrogen has been



fundamental to the growth of agriculture and agricultural productivity in the United States, the impacts of excessive nitrogen on water quality pose serious challenges across the nation for drinking water and eutrophication of surface waters. Before the dependence on commercial nitrogen fertilizers began, typical nitrogen use efficiency was around 50% (Robertson and Vitousek, 2009). Nitrogen use studies in corn production dating back to the 1930's indicated less than 50% of nitrogen applied was utilized in the corn, and broadly there was little observed benefit in yield, per unit of added fertilizer (Robertson and Vitousek, 2009, Nafzier, 2008 - figure at right; Stevens, et. al., 2005). These results should not be misconstrued to indicate added nitrogen did not improve yield on a given field, rather, the addition of synthetic fertilizer has been so widespread and liberal that, in many cases synthetic fertilizer is being applied in manners where no crop-benefit is realized (e.g. wrong timing, wrong form, wrong amount, or wrong method of application).

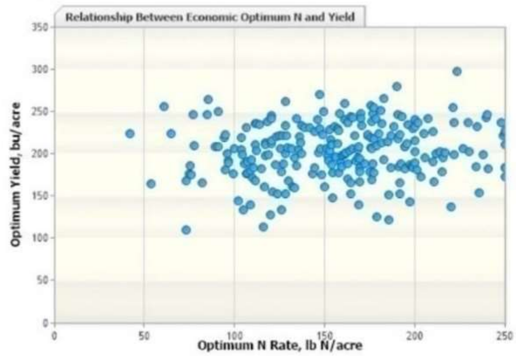


Figure 1. Economically optimum N rate and yield at that N rate for each of 245 N rate trials with corn following soybean in central Illinois. Each symbol represents one trial. This figure is from the N rate calculator website (address in text.)

While synthetic nitrogen fertilizer use has grown, with a more than 5-fold increase in Wisconsin since 1960 (WLWCA, 2017), most estimates of average crop nitrogen utilization still hover around 50% of nitrogen applied, with higher exceptions of up to +80% being reported in well managed cropping systems (Cates, et. al., 2018; Nafzipowerger, 2018; Stewart, et. al., 2018; USDA, 2018; Dabney, et. al., 2010; Erisman, et. al., 2008; Dinnes, et. al., 2002; Sainju and Singh, 1997; Meisinger, 1991, Brady, 1990c). The pattern of increasing nitrogen applications beyond crop need mirrors a concept of "cheap insurance", in which farmers apply more nitrogen to focus on maximizing yields, rather than an approach that optimizes the economic return (profitability) for the farmer and most efficient utilization of applied nitrogen fertilizer (Sawyer, 2006).

While there are a number of challenges to addressing the negative impacts of nitrogen loss from agricultural systems, the nitrogen cycle is fairly well understood, loss pathways have been established in science, and a couple of key loss mechanisms can be targeted to dramatically reduce agricultural losses of nitrogen to leaching (Malcom, et. al., 2018; Marcillo and Miguez, 2017; USDA, 2015; Meisinger and Delgado, 2002; Meisinger, et. al., 1991; Brady, 1990c). These losses are leaching during periods when no active crop is growing, typically in the spring before planting and in the fall after harvest (USDA, 2018; Dabney, et. al., 2010; Meisinger and Delgado, 2002; Muldoon, 1998; Brady, 1990b) and is illustrated by Dines, et. al. (2002) (Figure at right). These patterns of nitrate losses to leaching in the spring and fall, before and after active crops are growing, was similarly observed during 3 years of a groundwater monitoring study in sandy farmland near Arena, WI

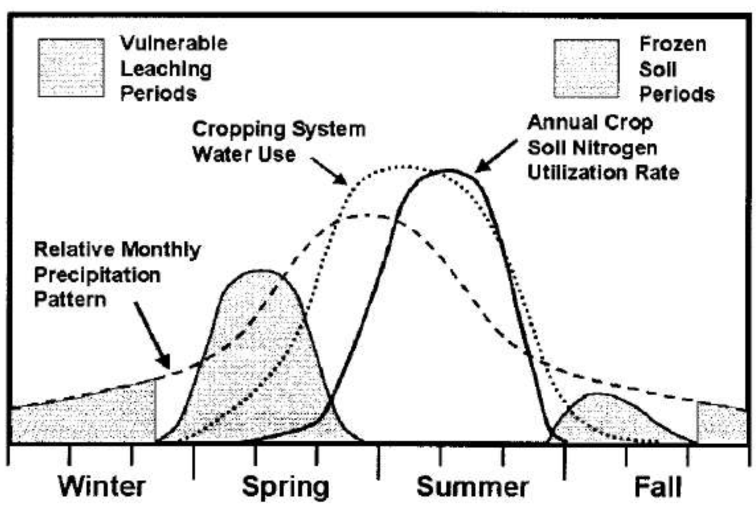


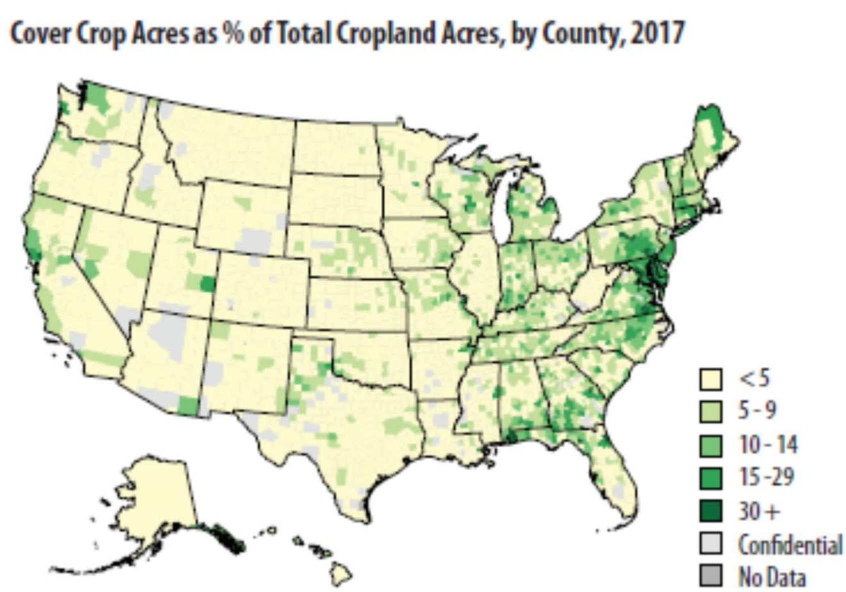
Fig. 3. General seasonal patterns for precipitation, N uptake rate by a corn crop, cropping system water use, and periods potentially favorable for NO_3 leaching from midwestern corn production (adapted from Fig. 4 of Power et al., 1998).

(Muldoon, et. al., 1998). Less nitrate was mobilized to groundwater and concentrations stabilized once crops were established. However, the vast majority of nitrogen applied in the fall, once crops are mature and harvested, leached to the water table (Powell, et. al., 1998).

The use of cover crops, especially cereal grains such as cereal rye and triticale, is one of the most effective cropping practices to reduce nitrate leaching in agricultural systems (NCGA, 2020; TNC, 2020; ISU, 2019; USDA, 2018; Martinez-Feria, et. al., 2016; USDA, 2015; ISU, 2013; Dabney, et. al., 2010; Meisinger, et. al., 1991). So much so, in fact, that grass cover crops have been widely used to reduce shallow groundwater contamination from excessive nitrates in many parts of the United States (Abdalla, et. al., 2019; Dabney, et. al., 2010; Meisinger and Delgado, 2002). However, if timing and use of cover crops is not done correctly, there may be no benefit, or with the case of legume cover crops, may even have the potential to contribute to a potential increase in nitrogen that might leach (Roesch-McNally, et. al., 2017; Meisinger, et. al., 1990).

With the growing reliance on synthetic nitrogen fertilizer sources, many of the cover-cropping, or “Green Manure” practices of past became lost memories (Meisinger, et. al., 1991). As cover crops began to be revisited with interest in reducing soil erosion rates, declining soil productivity, and losses in soil organic matter, early trials often had mixed results or even entirely negative results, with cover crops being blamed for reductions in corn yields due to competing demand for nitrogen (known as “yield drag”) (Koehler-Cole, 2020; Abdalla, et. al., 2018; Roesch-McNally, et. al., 2017; Dinnes, et. al., 2002; Sainju and Singh, 1997). Farmers who have been successful in adopting cover crops and incorporating them into cropping systems have often been described as utilizing a “whole-system”, or holistic, approach where cover crops are considered an integral part of their successful farming operation to bolster overall farm productivity and improve profit margins, rather than an “add-on” farming cost or environmental “band-aid”. In synthesis of literature and review of numerous cover crop trials from around the nation, the latter approach was often the underlying cause of why cover crops weren’t used, “failed to perform” or resulted in yield drag, in contrast to the former, “whole-systems” approach adopted by farmers who were successful in their adoption and utilization of cover crops (Cates, et. al, 2018; Roesch-McNally, et. al., 2017; Delgado and Gantzer, 2015; Dabney, et. al., 2010; Delgado, et. al., 2007; Dinnes, et. al., 2002).

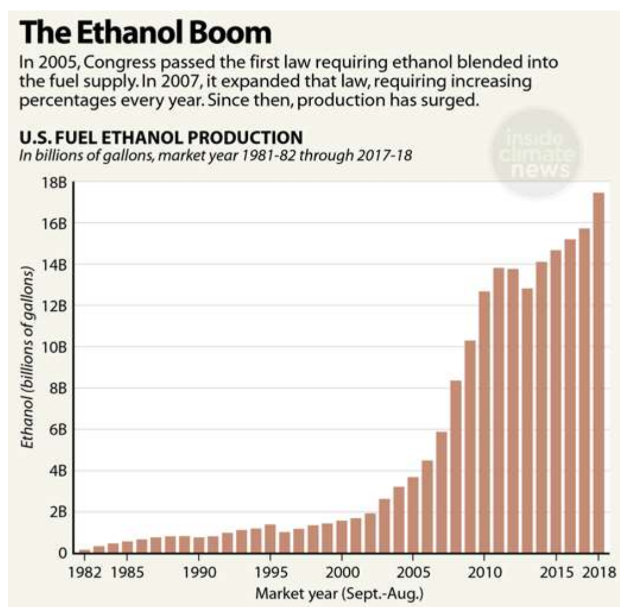
While still not considered a widespread agricultural practice, the use of cover crops (crops planted in addition to a primary grain or forage crop) has been growing steadily and significantly over recent years. In the most current “U.S. Census of Agriculture”, cover crop use grew by more than 50% nationwide, corresponding with the USDA’s nationwide “Soil Health” initiative (figure at right). Wisconsin is one of the top ten states for growth of cover crops acreage in the nation (USDA, 2017).



2. Agriculture and Groundwater Nitrate Contamination

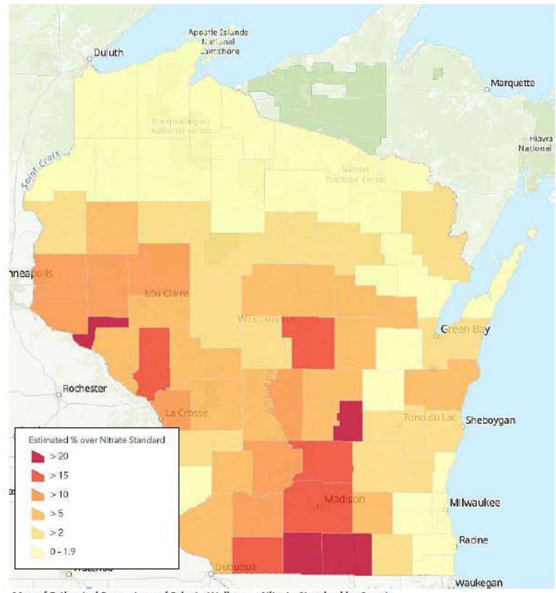
“Typical” background nitrate concentrations in groundwater from around the nation, as well as in Wisconsin, average < 1 mg/l (Mathewson, et. al., 2020; WDNR, 2020; Green, et. al., 2018; Muldoon, et. al., 1998; Puckett, 1994; Kraft, 1991). Nitrate concentrations above 2 mg/l are generally looked at as a potential indicator of nitrate contamination above background levels, and concentrations above 5 mg/l (the Preventative Action Limit (PAL) in WI that triggers additional drinking water requirements) are typical in areas dominated by agricultural land use. Concentrations above the “Enforcement Standard” (ES) of 10 mg/l are most commonly found in landscapes dominated by agricultural lands. In areas where nitrogen fertilizer use is high, for example, areas producing high nitrogen demanding crops and/or with highly permeable soils, it is not uncommon to have groundwater nitrate concentrations well above the E.S. (e.g. > 20 mg/l). Direct linkages between commercial agricultural land uses, increasing use of synthetic nitrogen, and resulting groundwater contamination by nitrates have been conclusively established in peer reviewed literature going back well over 30 years (Mathewson, et. al., 2020; WDNR, 2020; Green, et. al., 2018; Stewart, et. al., 2018; McDonald, et. al., 2015; Dzurella, et. al., 2012; Chern, et. al., 1999; Kraft, et. al., 1999; Muldoon, et. al., 1998; Puckett, 1994; Kraft, 1991; Brady, 1990b; WDNR,1989; Jackson, et. al., 1987).

Indeed, agricultural studies dating back nearly 100 years identified nitrogen losses to leaching as one of the main challenges for farmers to overcome (Meisinger, et. al., 1991; Pieters, 1927). The most current county and statewide fertilizer sales data across the contiguous United States clearly illustrates a consistent and long-term trend of increasing fertilizer sales tracking closely with local agricultural land use across river basins (Stewart, et. al., 2018). Specific sources of nitrogen pollution in rivers had previously been attributed to the full array of nitrogen sources such as fertilizer, manure, atmospheric deposition, sewage, and industrial sources. Fertilizer sources of nitrogen were proportionally greater in agricultural areas of the West and the Midwest than in other parts of the Nation. Throughout rural areas in the Midwest, elevated nitrogen pollution of surface waters was directly correlated with high amounts of agricultural land use. In areas of Wisconsin with excessive nitrates in groundwater, it is estimated that approximately 90% of these originate from agricultural sources including manure spreading and fertilizer applications (WDNR, 2020). The most recent trends driving increases in nitrogen fertilizer sales and application rates over the past two decades are attributed to the renewable fuels production laws of 2005 and 2007. This greatly increased demand for ethanol, and the corn used to produce it throughout the corn-belt states, with a more than 9-fold increase in ethanol production over the last 20 years (figure at right, USDA Economic Research Service, 2018).



Agriculture and Groundwater Nitrate Contamination in Wisconsin

Yearly, the Wisconsin Groundwater Coordinating Council is tasked with providing annual summaries of their operations and activities, the state of the groundwater resource and its management, and making recommendations to address groundwater related concerns to the legislature. The breadth of the report covers all topics relating to groundwater, including use, quality, allocation, availability, etc. Specifically relating to nitrogen and nitrate pollution, nitrate is Wisconsin's most widespread groundwater contaminant. Nitrate contamination of groundwater is increasing in extent and severity in the state. Most nitrate in groundwater (about 90%) is due to agricultural inputs, including manure spreading and fertilizer application The most current report summarizes the total number of wells within the state, by county, where drinking water nitrate standards are exceeded (figure at right; WGCC, 2020).



Map of Estimated Percentage of Private Wells over Nitrate Standard by County.

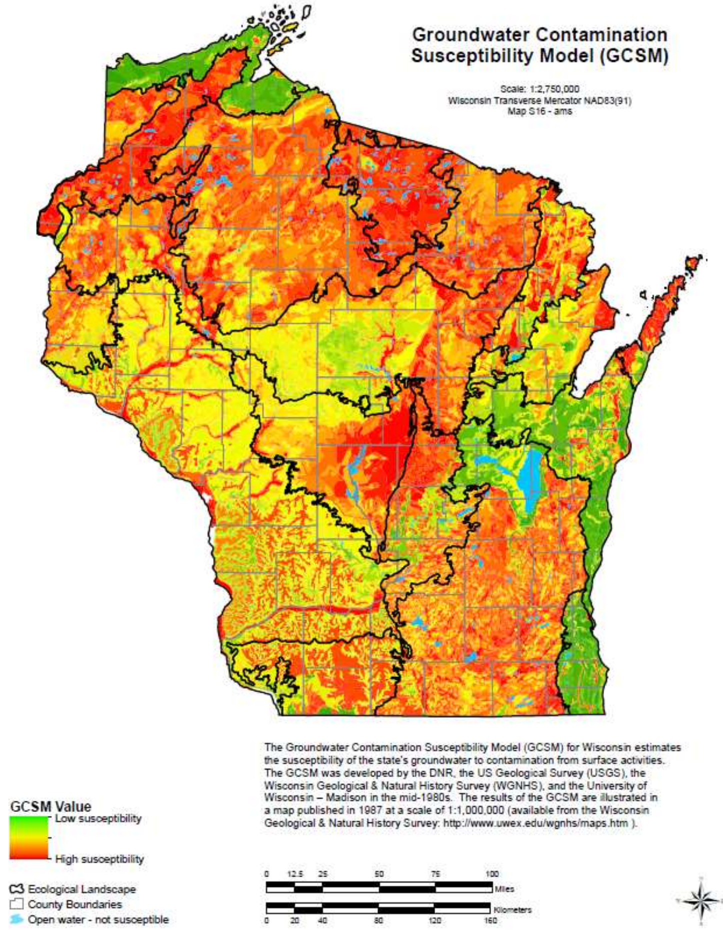
Warm fall conditions in Wisconsin promote both the mineralization of the organic N in manure and the nitrification of ammonium to nitrate. This results in NO_3-N losses in the winter and spring through seepage to groundwater. Residual fall soil moisture combined with spring rains readily mobilize nitrate in the soils before traditional crops can be planted, resulting in significant losses of nitrate to leaching. Extensive research field trials conducted by the University of Wisconsin have resulted in recommendations to use cover crops to provide ground cover and to trap excess N from leaching into groundwater or tile drains (Ruark, et. al., 2019).

Excessive nitrate loading to shallow groundwater in the Wisconsin central sand plains has limited the groundwater across this region to non-potable uses and required alternative water sources for those dependent upon residential wells for drinking water (Kraft and Stites, 2003). Groundwater NO_3^-N concentrations averaged 20 mg/l beneath a study field with sweet corn and potato rotation, with 77% of fertilizer N being lost to groundwater. As most orthodox nitrate control strategies (e.g., decreasing and splitting fertilizer, irrigation scheduling) had already been implemented in the region, better control will require new and unconventional approaches for controlling nitrate leaching from mineralized crop residue as well as additional curbing of direct fertilizer nitrogen leaching.

Nolan, et. al. (2018) paired comprehensive groundwater modeling and statistical analyses of groundwater quality data from 120 wells across the Fox, Wolf and Peshtigo River Basins. Looking at 58 predictor variables, results from the calibrated models were generally consistent with expectations, e.g. greater source concentrations and NO_3^-N at the groundwater table in areas of intensive crop use and well drained soils (Nolan, et. al., 2018).

Data from farm trials in Wisconsin have focused on improving farm profitability by maximizing nitrogen use efficiency and reducing nitrogen losses. Some of the earliest comprehensive research conducted by UW Discovery Farms found timing of nitrogen to ground water (via tile drains) was consistent with periods of leaching and the highest losses were typically in the month of April, with elevated losses from March through June (Drummy, et. al., 2011). The majority of nitrogen loss occurred during the non-frozen ground period for both surface and tile. In tile water, nitrate nitrogen was the dominant form of nitrogen loss.

Excessive nitrates in Wisconsin's groundwater have been an expanding problem, with the contamination of both private and public wells a concern recognized decades ago (Chern, et. al., 1999; Kraft, et. al., 1999; Bundy, et. al., 1994; WDNR, 1989). One of the earliest (and most reproduced) maps illustrating this challenge is the "Groundwater Contamination Susceptibility Map" (WDNR 1989). The map was developed based on physical resource characteristics identified as important in determining how easily a contaminant can be carried through overlying materials to the groundwater. These factors are type of bedrock, depth to bedrock, depth to water table, soil characteristics, and characteristics of surficial deposits. The map was used to help guide resource planning and decision making by the DNR in a manner that would be consistent with groundwater contamination susceptibility. This map was updated using refined data, modeling, and geospatial analytical techniques to produce the Wisconsin Groundwater Contamination Susceptibility Model (figure at right, WDNR, 2015).



3. Human Health Risks from Nitrates

A wealth of research has been conducted to investigate the potential impacts of excessive nitrate on human health (see Ward, et. al., 2018). A brief summary is provided here, and the reader is directed to cited references for greater detail. General sources of information on human health risks from nitrate contamination of drinking water may be found from the following publications:

- Year of Clean Drinking Water Governor's Report (2020)
- What is Nitrate? Groundwater Coordinating Council Annual Report (2020)
- Nitrate in Private Water Wells – WI Dept. of Health (2019)
- Nitrates and Methemoglobinemia – MN Dept. of Health (2018)
- Nitrate in Drinking Water - WDNR Pamphlet (2017)

Mathewson (et. al., 2020) evaluated exposure and the impacts of groundwater nitrate contamination on human health and societal costs in Wisconsin. They provided estimates of potential nitrate-related cancer cases for the 28% of the state's residents who use private wells. The direct medical cost estimates for all nitrate-attributable adverse health outcomes range between $23 and $80 million annually. Focusing on counties with highest nitrate concentrations in drinking water, reductions in adverse health outcomes resulted from simulated nitrate reductions of 20%. However, trend analyses indicated groundwater nitrate concentrations are overall increasing across Wisconsin. Thus, nitrate contamination of water supplies in Wisconsin is a public health problem that needs to be addressed.

Excessive nitrate consumption is harmful to infants, pregnant women, and those wishing to conceive (Mathewson, et. al, 2020; WDNR, 2020; WDoH, 2019; Ward, et. al., 2018; Christianson, et. al., 2017; Dzurella, et. al., 2012; Kraft, 1991). Although identification of standards to minimize occurrences of methemoglobinemia (Blue Baby Syndrome) in human infants were established in 1945 (MNDofH, 2018; Comly, 1945), most research through the 1980's was focused on acute occurrences. When rural wells averaged < 3 mg/l NO_3-N, there was no relationship to methemoglobin blood levels in pregnant women. Prior research into documented cases of methemoglobinemia found that positive occurrences had NO_3-N concentrations exceeding 20 mg/l. Consequently, half this value was selected to include a "safety factor" and the 10 mg/l limit was established. Scientific methods of the times did not allow for greater refinement of analyses required to identify chronic exposure health risks (Dzurella, et. al., 2012; Chern, et. al, 1999; Bundy, et. al., 1994; Kraft, 1991).

The early recognition of Blue Baby Syndrome is due to toxicity of nitrate to infants introduced via baby formula made with nitrate contaminated water. Once in the blood, the nitrate blocks oxygen receptor sites in the hemoglobin and reduces the ability of the lungs to effectively filter the blood, scrub it of waste carbon dioxide, and recharge the blood with fresh oxygen. When oxygenated, the iron molecules in the hemoglobin are bright red. Conversely, when the blood is starved of oxygen, the hemoglobin is blue or purple. Initially, this will cause infants to have blue-tinted lips, tongue, fingers and toes, a medical symptom known as "cyanosis". However, as hypoxia worsens, the bluish color will spread across the infant's body. Even at low levels of oxygen deprivation, infants may suffer brain damage and other physiological ailments (Mistovich and Karren, 2019).

Since the 1990's, there has been growing evidence that ingestion of lower levels of nitrate (below the E.S. of 10 mg/l) contributes significantly to a number of developmental (spina bifida, etc.), reproductive (inability to conceive, spontaneous abortions, etc.), and chronic exposure risks associated with increased rates of certain types of cancer (Mathewson, et. al., 2020; WDoH, 2019; MNDofH, 2018; Ward, et. al., 2018; WDNR, 2017). Ward, et. al. (2018), conducted a comprehensive literature review of epidemiologic studies before 2005 of nitrate intake from drinking water and cancer, adverse reproductive outcomes, and other health effects. Since that review, more than 30 epidemiologic studies have evaluated drinking water nitrate and these outcomes. The most common endpoints studied were colorectal cancer, bladder, and breast cancer (three studies each), and thyroid disease (four studies). Considering all studies, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects.

Research on the impacts of nitrates on human health evolved from historic research addressing nitrate toxicity in livestock from forage and drinking water. During the early and mid-1900's, farmers in the Midwest were identifying issues of calf fatalities, still births, poor milk production, and poor reproduction of livestock (Prewitt and Merilan, 1957). This research was supported by the livestock industry and continues to be the basis for veterinary research and safe drinking water recommendations for livestock, including UW Large Animal Veterinary guidelines (Undersander, et. al., 2016; Adams, et. al., 2016; Oetzel, 2008). The mechanism of nitrate toxicity is similar across all mammals (Thompson, 2019; Adams, et. al., 2016; Undersander, et. al., 2016), because nitrate from drinking water is the precursor to toxic N-nitroso compounds (NOC's), known carcinogens and teratogens (agents that cause brain damage, conception and pregnancy issues, and developmental issues in fetuses, children and livestock) (e.g. Ozman, 2004). Numerous states publish recommended forage, housing, and drinking water guidelines for optimal livestock health (including Wisconsin, Nebraska, Michigan, Minnesota, among others). Recommendations specific to the dairy industry (especially for calves, pregnant livestock, and during reproduction) are consistent with standards for drinking water intended for human consumption (Thompson, 2019; Kononoff & Clark, 2017; Oetzel, 2008). Safe nitrate levels in drinking water for vulnerable livestock populations (calves, pregnant heifers, breeding heifers, etc.) are similar to those recommended for humans (44 mg/l NO_3 is equivalent to 10 mg/l NO_3-N (nitrate-nitrogen)). Full grown livestock and those not intended for breeding are able to process higher nitrate concentrations, though these animals' life expectancy is very short-lived compared to human beings, so chronic effects may not materialize.

4. Cover Crops and Nitrogen Management

Overview

Nitrogen in agricultural systems can be managed at three specific life-cycle phases using a combination of prevention and treatment approaches (USDA, 2015). As the adage goes, "An ounce of prevention is worth a pound of cure", so it is with nitrogen. It is far more cost effective and relatively easier to manage inputs and stores, preventing nitrate pollution of groundwater, than it is to treat contaminated groundwater (Dines, et. al., 2002; Meisinger and Delgado, 2002). These life-cycle phases are:

1. Source (Prevention - e.g. prevent over-application using nutrient management planning)
2. Field Practices (Prevention – e.g. use cover crops to minimize leachable soil nitrates)
3. Runoff/Export (Treatment – e.g. build bioreactors to absorb nitrate in groundwater, denitrification systems for drinking water, etc.)

The use of cover crops to help improve soil fertility, protect soil from erosion, reduce weed pressure, and improve crop yields has a long history in American agriculture, literally going back to the founding fathers, and more broadly, in agriculture in general, over at least a couple thousand years (Meisinger, et. al., 1991; Pieters, 1927). Albeit, adopting and using cover crops as a new practice can present challenges to farmers, with some of the most commonly cited being increased costs, yield losses (often called "yield drag"), and management constraints (Koehler-Cole, 2020; Abdalla, et. al., 2019; Ruark, et. al., 2019; Sawyer, et. al., 2017; Krueger, et. al., 2011; Robertson and Vitousek, 2009; Ruark and Stute, 2009). The struggle between these positive benefits and management challenges is often cited as one of the leading impediments to farmers adopting and utilizing cover crops. Dabney, et. al. (2001) conducted a seminal research review of cover crop trials and experiments from around the world during the 1980's and 1990's and identified common threads across most of the published studies. Their findings, summarized below, have been verified by nearly 20 years of subsequent research (Abdalla, et. al., 2019; Thapa, et. al., 2018; Marcillo & Miguez, 2017):

- *"While actively growing, cover crops increase solar energy harvest and carbon flux into the soil, providing food for soil macro and microorganisms, while simultaneously increasing evapotranspiration from the soil.*
- *Cover crops reduce sediment production from cropland by intercepting the kinetic energy of rainfall and by reducing the amount and velocity of runoff.*
- *Cover crops increase soil quality by improving biological, chemical and physical properties including: organic carbon content, cation exchange capacity, aggregate stability, and water infiltrability.*
- *Legume cover crops contribute nitrogen (N) to subsequent crops. Other cover crops, especially grasses and brassicas, are better at scavenging residual nitrogen before it can leach. Because growth of these scavenging cover crops is usually N limited, growing grass/legume mixtures often increases total carbon inputs without sacrificing N scavenging efficiency."*

Marcillo and Miguez (2017) conducted a "meta-analysis" on the effects of cover crops on corn and soybean yields. Their summary of peer-reviewed research from the United States and Canada spanning 1965 through 2004 comprises 268 observations. While results varied across cropping practices and regions, they found no significant yield penalties and up to 30+% yield improvement on fields using winter cover crops in general. The history of research reviewed showed an improving trend in cover crop utilization and management, with more recent studies showing more favorable results and better yields compared to earlier research.

Midwest Examples

Cover crops provide multiple ecosystem benefits when used in agricultural fields through the reduction of erosion and compaction, general improvement of the soil physical condition and microbial community, and building of soil organic carbon. Within the Midwest, while fewer in total numbers, there are numerous examples of cover crops being successfully used to not only protect soil from erosion and runoff, but to also improve overall nitrogen management through a combination of nitrogen generation (e.g. legumes such a clover, peas, soybeans, etc.), sequestration (primarily brassicas (radish, turnip, etc.) and grasses (cereal rye, winter wheat, triticale, oats, etc.)), and retention until nitrogen can be used by actively growing crops (Waggoner and Arriaga, 2021).

Comprising the most comprehensive review of on-farm based field trials, Li and Ruark (2021) analyzed results of the university of Wisconsin Discovery Farms field trials and research looking at nitrogen use efficiency across 91 farms and 291 fields across WI and MN. These farm data include nutrient management plans with fertilizer and manure applications, along with yield and harvest data. Using a "partial budget" approach comparing yields and harvests to nitrogen added, Li and Ruark estimated corn sileage rotations for dairy were net -22 lbs NO_3-N, whereas corn for grain was, on average, +40lb NO_3-N. Comparing these numbers with groundwater recharge rates and the proposed N-TPS standard, the results indicated approximately 70%-75% of corn silage fields and 24%-29% of corn grain fields may already be close to, or meeting the proposed N-TPS. Li and Ruark noted limitations to the partial budget approach and that more comprehensive monitoring and ongoing research would provide more details and beneficial results.

Ruark, et. al., (2018) evaluated nine site-years in northeastern and southern Wisconsin, with radish planted mid-August following winter wheat (*Triticum aestivum L.*) harvest. Results were mostly neutral on corn yield, some fields exhibited yield bumps, while others had declines. This research supports the use of radish as a trap crop for fall N, as environmentally meaningful yields of N were contained in plant biomass, but also demonstrates that radish provided no N fertilizer replacement value to the subsequent crop.

Extensive research and field trials in Illinois have shown winter hardy cover crops established in the year preceding soybeans can sequester and retain significant nitrogen during the late fall, through spring planting. This significantly enhances organic nitrogen pools, reduces needs for nitrogen fertilizer, and builds organic matter in soybean fields (Armstrong, et. al., 2017).

Jake Kaderly, a grain farmer and agronomist in south-central Wisconsin, has relied on a combination of extensive soil testing and detailed nutrient management, combined with no-till and cover crops to build high levels of organic matter, soil nitrogen pools, and produce record yields of corn over a number of years. Using strip and field trials, Kaderly attributes a 20 bushel bump in corn yield to his fall cover crop program and this has allowed him to completely eliminate fall fertilizer applications (Betts, 2018).

In northern Illinois, the 2,600 acre soybean/corn Thorndyke grain farm shifted management practices to protect soil and optimize nitrogen management. Conventional tillage ground was converted to strip till with cereal rye as a fall cover crop. These practices allowed the farmer to completely eliminate fall nitrogen application. Through improved efficiency in nutrient management, reduced field work, and lower fertilizer costs, Thorndyke farms saved an average of $36/acre. (American Farmland Trust & U.S.D.A., 2019a).

Eric Niemeyer's 1,250 cash grain (soybean/corn) farming operation is saving $38/acre, following his shift from a conventional farming operation to one based on farming using "soil health" principles. Eric has converted his operation to no-till, reducing nitrogen and organic matter losses to volatilization. Combined with switching his planting and fertilizer regiment to variable rate and utilizing fall cover crops to “grow” and sequester nitrogen, Eric has significantly reduced his fertilizer costs and reduced field work expenses. (American Farmland Trust & U.S.D.A., 2019b).

Discovery Farms, an applied, “working farm” research initiative through University of Wisconsin and Extension, conducts research on private working farms throughout Wisconsin. Augarten (2019) reported on a synthesis of their results looking at nitrogen use efficiency (NUE) across 157 corn grain fields and 101 corn silage fields in nine regions of Wisconsin to create benchmarks specific to WI cropping systems and soils. NUE “is a field level assessment tool that can be used to evaluate efficiency relative to other monitored fields and determine if a farm can make improvements to its nitrogen management”, and is computed as the yield divided by lbs of nitrogen applied. Research results found “fields in the low use efficiency category had either very low yields or high N rates, which could be responsible for lower efficiencies.” The lowest use efficiency was found in corn-grain fields with over 250 lb N/ac applied. In contrast, fields with NUE in mid-high use or high use efficiency had N rates applied at less than 170 lb N/ac (the average N rate). On average, many of the high use efficiency fields were producing the same yield, with half the applied nitrogen, as compared with low use efficiency fields. While inclusion of manure, as well as alfalfa in rotations, tended to result in lower N-use efficiencies, the results were not conclusive because of challenges in quantifying and accounting for these nitrogen sources.

5. Cover Crops and Nitrogen Leaching

Directly quantifying leaching losses in agricultural systems is especially difficult due to a number of challenges. First and foremost, when looking at nitrogen leaching as a dependent variable, an almost incomprehensible amount of variability in driving variables exists across agricultural systems, making it a monumental challenge to detect a statistically significant signal response in leaching rates at a broad scale. These driving variables include (but are not limited to) climatic regime, weather patterns, soil types, soil physical, chemical, and biologic properties, hydrogeology, cropping systems, field scales, field practices, and cover crop species. Further, even when driving variables are accounted for, methods for measuring leaching losses can be extremely time consuming, expensive, difficult to implement, and produce results that may be challenging to interpret. Consequently, while the practice of using cover crops to manage nitrogen in agricultural systems has a very long history, more exhaustive scientific investigation to quantify the benefits is far younger, going back only a few decades (Thapa, et. al., 2018; Dabney, et. el., 2001).

Meta-Analyses

Due to the numerous challenges of measuring a singular response at a point in time, researchers have turned to the power of computers to conduct "meta-analysis". This "weight of evidence" approach relies on numerical analyses of large independent datasets of field trials, research plots, and other sources of cover crops research data to analyze results across the driving variables and identify potential signal response in nitrogen leaching data. Results from the most current large-scale meta-analyses are summarized here. Combined, these studies include thousands of independent field data years and, while there can be significant variability in results across such a broad sample population, results indicate cover crop utilization consistently reduced nitrogen leaching losses across the agricultural systems in their databases. In cases where there was no treatment-effect of the cover crops, common variables and experimental methods were found to explain these results. First, we present common findings across all of the meta-analyses, followed by a figure illustrating reported reductions in nitrogen leaching losses, and finally summary of each of the meta-analyses.

General take-aways and findings:

- In experiments specifically conducted to evaluate the treatment effects of cover crops on nitrogen sequestration and leaching (e.g. in contrast to experiments looking at yield benefits), the average result across all studies was a significant reduction in nitrogen leaching losses.
- The effectiveness of cover crops to sequester and retain and reduce nitrogen leaching losses was dependent on numerous variables.
- Cover crops that were planted and managed in a manner specifically intended to optimize nitrogen use were most effective at minimizing nitrogen loss to leaching.
- Cover crop species selection, planting, weather, crop rotations, harvest/planting dates, and overall goals for use of cover crops were important in influencing successful attainment of cover crop goals.
- Cover crops were effective for sequestering nitrogen and reducing leaching losses for crop rotations common across Wisconsin including corn for grain, silage, and potato/vegetable rotations.
- Cereal grains, especially cereal rye, were the most aggressive species for sequestering and retaining nitrogen and reducing nitrogen leaching losses.
- Cover crop blends that included cereal grains and brassicas were most effective at minimizing leaching losses.

- Leguminous cover crops were typically used to produce nitrogen for subsequent crops, whereas grains and brassicas, while they may produce some of their own nitrogen, were used to sequester and retain nitrogen. Multi-species mixes that included legumes also reduced nitrogen leaching losses.
- Release of nitrogen from cover crops was dependent upon weather, timing, methods of termination, soil conditions, and subsequent crops.
- The ability of subsequent cash crops to utilize residual nitrogen from cover crops was dependent upon weather, timing, methods of termination, soil conditions, and other factors.
- Weather related conditions often contributed to poor performance of cover crops (e.g. late planting, wet spring, late spring, etc.).

Impacts of Cover Crops on Nitrogen Leaching

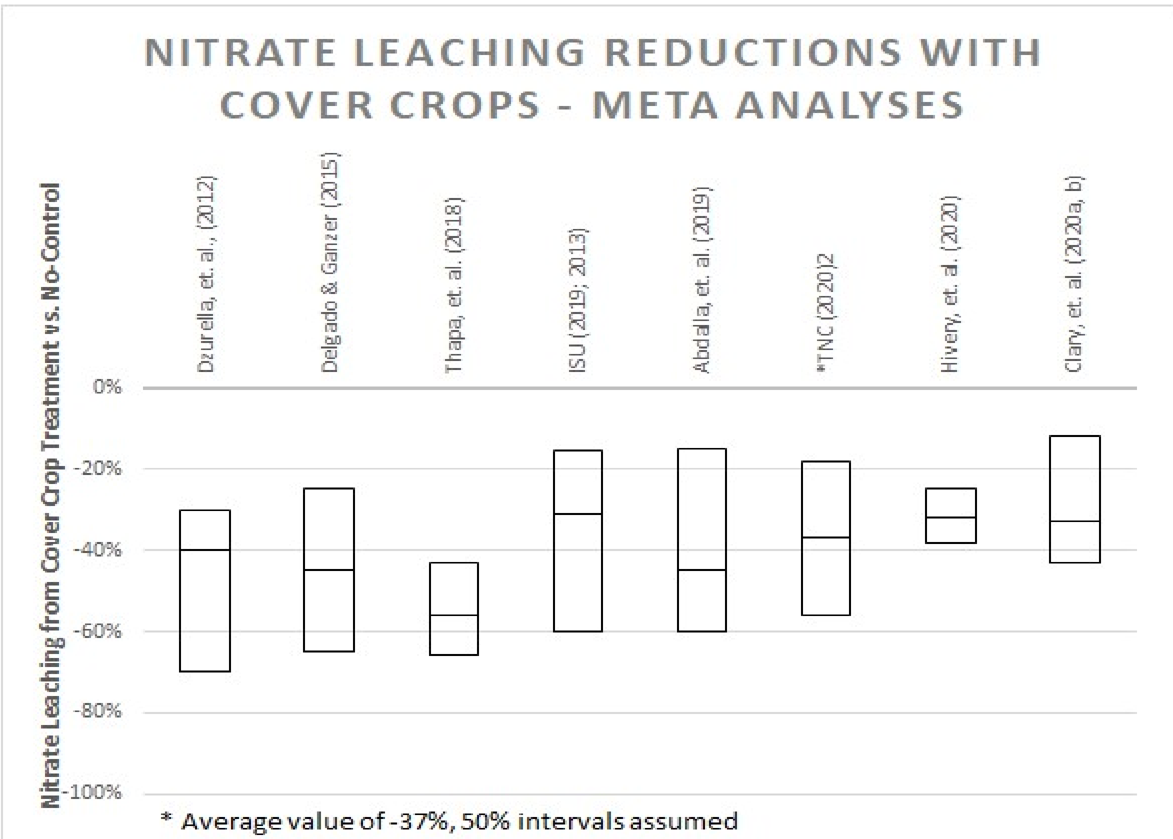


Chart 1: Reductions in Nitrate Leaching Losses under Cover Crops vs. No Cover Crops

Summary of Cover Crops Meta-Analyses Studies:

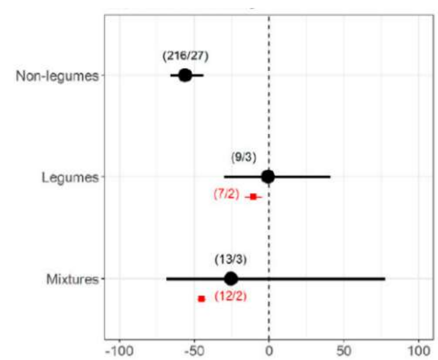
Clary, et. al., (2020a) queried the comprehensive Agricultural Best Practices database, which reports results from participating research organizations, National Corn Growers Association Nitrogen Use Efficiency trials, and other sources to mine results of cover crop studies across the Midwest. Results of published studies showed "…clear evidence of the benefits of cover crops in reducing subsurface nitrate concentrations". While reported overall load reductions were more variable, those studies reporting reductions in concentration were more consistent and less variable. Across 37 reported cover crop fields in the database, all fields showed reduced nitrate concentrations with cover crops with a range of 12% - 43%, and an average of 33% reduction (Clary, et. al., 2020b).

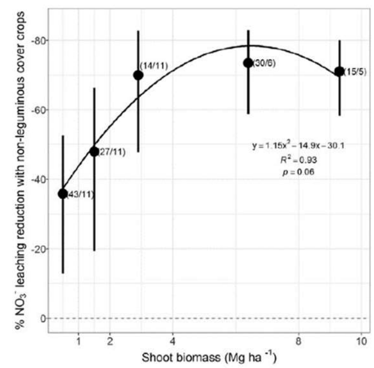
As part of the national Conservation Effects Assessment Project (CEAP) initiative to evaluate effectiveness of federal conservation programs from the U.S. Dept. of Agriculture, Hivey, et. al. (2020) conducted a 10-year numerical modeling and statistical analysis of cover crop, water quality, and conservation enrollment data in an agricultural tributary to Chesapeake Bay. Their research found a more than 3-fold increase in the use of cover crops (from <27% to nearly 90%) in corn rotations and 5-fold increase with soybean rotations (<9% to > 46%). While climate variability strongly influenced the performance of cover crops and observed results, they found a 25% overall 10-year reduction in nitrate (NO_3-N) leaching from cropland attributable to cover crop adoption, rising to an estimated 38% load reduction in 2016 when 64% of fields were planted to cover crops.

The Nature Conservancy (TNC, 2020) funded the development of the interactive online database AgEvidence, to provide a user-friendly searchable database to present and summarize results of agricultural conservation research across the Midwest. While the database includes a vast array of conservation practices, results focusing exclusively on cover crops found their use as highly effective at reducing both nitrogen and phosphorus runoff (at least 30% overall), as well as reducing nitrate losses via leaching by 34%.

Abdalla, et. al., (2019) conducted a comprehensive analytical review of independent cover crop research from peer reviewed literature spanning 106 studies and 372 sites representing numerous different countries, climatic zones and management practices from around the world. They found cover crops significantly ($p < 0.001$) decreased N leaching and significantly ($p < 0.001$) increased carbon sequestration without having significant ($p > 0.05$) effects on direct denitrification (as N_2O emission). They did report that a potential disadvantage of cover crops was reduction in grain yield of the primary crop among some of the studies. However, proper selection of mixed cover crops (with legumes) increased yield by ≈13%. Based upon the survey of results, they concluded the advantages of cover crops justify their widespread adoption.

Iowa has been aggressively implementing their Statewide Nutrient Reduction Strategy to combat widespread pollution of surface and groundwaters by nitrogen, phosphorus, sediment, and other agricultural NPS pollutants (ISU, 2019; ISU, 2013). This strategy has focused on working closely with the agricultural industry and farmers to find best practices to minimize NPS pollution and optimize use of agricultural nutrients. Recommendations focus on scientifically based practices that have been proven to work to reduce nutrient loss, to be functional practices that can be implemented on working farms, and economically viable for farmers to adopt and utilize the practices. Key practices to optimize uptake of nitrogen and reduce leaching from nitrogen fertilizer sources include shifting from fall to spring applications, employing fall cover crops to sequester nitrogen (this shows the largest overall reductions in nitrogen loss), the use of variable rate technology, and shifting from broadcast to side-dress applications.





Thapa, et. al. (2018) conducted a comprehensive meta-analysis across 238 observations from 28 studies to review the effectiveness of winter cover crops to reduce nitrate leaching, potential effects on subsequent crop yields, and potential influences of soil, cash and cover crop management, and climate drivers. Results indicated clear and significant treatment effect of non-leguminous cover crops to substantially reduce nitrate leaching (on average by 56%, figure at right). Nonlegume–legume cover crop mixtures were also effective, with pure legumes being the least effective. Treatment effects of non-legumes on crop yields were minimal, while leguminous cover crops significantly enhanced yields. Interactions between cover crops and the types of tillage, soils, and organic matter were somewhat influential on leaching and yields, though the results were highly variable and cover crop selection/type and planting date were far more influential. Soils with the lowest organic matter and coarsest texture showed the strongest reductions in nitrate leaching from cover crop treatments, indicating that cover crops can be very important in highly permeable soils which are the most prone to groundwater nitrate contamination. Nitrate leaching losses under cover crops also tended to be lower under reduced/no-till systems, as compared to conventional tillage. The largest reductions in nitrate leaching losses occurred under non-leguminous cover crops that were allowed to have the most growth. These broad results, across a wide variety of field, cropping, climatic, and management conditions indicated that non-leguminous cover crops can clearly be an effective way to significantly reduce nitrate leaching losses in agriculture.

Cates, et. al. (2018) conducted a “meta-analysis” of published literature to report on the performance of cover crops in the north-central United States. Across the reviewed literature, while acknowledging costs, management, and yield challenges, cover crops improved nitrogen retention, provided weed suppression benefits, improved carbon-nitrogen ratios, increased storage of organic nitrogen in soil, and reduced nitrate in tile-drainage and leaching to groundwater.

Delgado & Gantzer (2015), building on previously reported cover crops research (Delgado, et. al., 2007) summarized numerous newer studies and more recent research that was encouraged by the increased adoption of cover crops. Cover cropping results “show enormous potential to improve the sustainability of corn and soybean cropping systems, add soil organic matter and reduce its loss, reduce soil erosion, improve soil health, fix N, and reduce loss of nutrients”. They also acknowledge the challenges of using cover crops, with some studies reporting improved yields with cover crops, while others showed a yield penalty.

In their comprehensive report to the California Legislature as part of a statewide initiative to combat groundwater nitrate contamination, Dzurella, et. al. (2012), summarized a wealth of experimental data, reports, and technical papers evaluating agronomic practices that can reduce nitrogen losses to leaching, and subsequent groundwater nitrate contamination. While results varied across such a large dataset, the authors concluded the inclusion of cover crops and nutrient management can be very effective tools to reduce nitrogen losses and leaching to ground water. Reduction of nitrate leaching from cropland and livestock operations can be achieved through changes in farm management that result in improvements in crop nitrogen use efficiency (NUE) and by proper storage and handling of manures and fertilizers. In particular, the synchronizing of fertilizer and manure applications with cropping practices that sequester nitrogen need to be included in strategies moving forward to reduce agricultural nitrogen losses to groundwater.

Delgado, et. al. (2007) reported the results of a multi-disciplinary, inter-agency research team investigating studies on cover crop utilization in the United States. They reported cover crops not only scavenge the residual soil nitrate-nitrogen (NO_3-N) that was leached from the previous crop, but can also reduce the nitrate-nitrogen leaching of the following crop. Additionally, they found with the use of new research tools that cover crops can potentially vertically mine nitrate-nitrogen from irrigated water. Hence, cover crops may be used to lower the amount of NO_3-N than that added to the system with irrigation water.

Winter cover crop trials incorporated into vegetable production systems (e.g. potato, sweet corn, green beans, etc.) have also been shown to improve nitrogen availability for vegetable crops, while mitigating nitrogen leaching losses (Ruark, et. al., 2019; Thapa, et. al., 2018; Ruark & Stute, 2009; Weinert, et. al., 2002). In Wisconsin, Colquhoun (2020) reported, "…it's the norm in Wisconsin potato rotations to plant winter cereal cover crops post-harvest…". The ability of rye to reduce nitrate leaching is reported as well established in peer review literature and is a common practice.

Cover Crops and Manure Management

While there are significantly fewer published studies specifically looking at nitrate leaching losses when using cover crops with manure, Everett, et. al. (2018), Malcom, et. al (2018), Stute, et. al. (2007), Dinnes, et. al. (2002), and Sainju and Singh (1997) all reported improved nitrogen management, and/or reductions in nitrate leaching losses when rye cover crops were incorporated into crop rotations that included manure applications. Ruark, et. al., (2019) has developed specific recommendations for using cover crops to optimize nitrogen management in agricultural systems that include manure in their crop rotations. Reviews of nutrient, forage, and herd management practices typical of midwestern dairy operations (and commonly recommended practices) indicate many dairy farms have the opportunity to significantly improve net farm profitability by altering their manure, forage and crop rotations to include cover crops for improved nitrogen utilization, forage quality, and milk production (Spratt, et. al., 2021; Pellerin, et. al., 2016; Delgado and Ganzer, 2015). Similarly, in grazed pasture settings, winter and spring nitrate leaching losses were significantly reduced/lower when cereal rye and other cover crops were incorporated into pasture mixes for grazing (Spratt, et. al., 2021; Jackson, et. al., 2020; Fraser, et. al., 2012; Robertson and Vitousek, 2009).

Everett, et. al. (2018) conducted 19 field trials across central and southern Minnesota to determine how crop yields and soil nitrogen varied with manure applied to fall seeded winter rye cover-crops. Manure was applied through knife injection under a variety of tillage and soil conditions. Subsequent growth of the rye was dependent on the degree of disturbance caused by manure injection. In all cases, spring soil nitrate (NO_3-N) was significantly reduced in fields with the established rye cover crops (35% to > 50% reduction). There was no reduction in yields on fields where recommended nitrogen rates (combined manure and fertilizer) were followed, compared to test strips.

Dairy farming and milk production have been a vital part of the agricultural farm economy in New Zealand since the mid 1800's. Nitrate contamination of groundwater from agricultural practices has long been one of the main concerns in New Zealand, much of the research has focused on field practices to reduce contamination by fertilizer and manure sources. Focusing on grazing impacts of field operations and waste products from dairy herds, Malcolm, et. al., (2018) summarized extensive research across New Zealand and reported establishment of winter cover crops reduced leaching by up to 49%, reductions in leaching were directly associated with N-uptake by the cover crops, and the cereal grains used as covers showed no significant reductions on subsequent forage biomass production.

Replicate field trails (2005 – 2006) from 3 experimental farms in Lancaster, Arlington, and Janesville Wisconsin documented rye's ability to reduce the amount of soil nitrate. Despite frozen soil preventing leaching for much of the winter, rye can significantly reduce soil nitrate following fall manure application (nearly 50% reduction). This benefit occurs even if rye is not harvested and will help protect groundwater quality where heavy manure applications have been made. Manure applications following rye planting and emergence expanded manure application window and prevented planting delays. Liquid manure with excessive solids or heavy application rates slightly stunted rye growth and development (Stute, et. al., 2007).

Sainju and Singh (1997) conducted one of the earliest comprehensive literature review summarizing research into the effects of cover crops on soil properties, water quality and crop yields. Emphasis is on field trials and experiments reported in peer-reviewed literature. Tables summarizing the results of numerous studies include soil carbon, nitrogen and leaching losses under a wide variety of cover crops. Nitrate leaching reductions with cereal rye ranged from 29% - 94%, with highest rates in more humid climates.

6. Rye/Cereal Grain Cover Crops

Cereal rye has previously been identified as one of the preferred cover crop grasses for sequestering nitrogen and minimizing nitrogen leaching losses to groundwater. Documented research studies extolling the benefits of cereal rye as a cover crop date back to the late 1800's in the United States (Meisinger, et. al., 1991; Pieters, 1927). These benefits include winter hardiness, ability to actively grow to temperatures as low as 34ºF, extensive root networks, ability to flourish under poor soil conditions, aggressive growth and nutrient sequestration, disease resistance, rapid regrowth in spring, and production of relatively large amount of organic matter (Doughtery, et. al., 2020; Pandey & Maiti, 2020; Christianson, et. al., 2017; Martinez-Feria, et. al., 2016; Stute, et. al., 2007; Meisinger, et. al., 1991; Meisinger, et. al., 1990). For these same reasons, cereal rye has long been recommended as one of the preferred species for phytoremediation of contaminated soils and polluted groundwater (Pandey & Maiti, 2020; EPA, 1999). Conversely, these same properties may present challenges to manage in an agricultural setting. Cereal rye that has over-wintered can outcompete other crops (especially for nitrogen and water) if not carefully managed/terminated, potentially contributing to yield reductions of subsequent crops, especially corn (Doughtery, et. al., 2020; Christianson, et. al., 2017; Sainju and Singh, 1997; Meisinger, et. al., 1990). Given the long history of using cereal rye as a cover crop and recognition of its ability to aggressively sequester nitrogen, there is relatively more research specifically looking at rye as a cover crop.

Analyses

Due to the very specific nature of looking at a single cover crop species, cereal rye, there is not as much of a wealth of multiple, replicate cover crop treatment experiments to conduct a "Meta-Analysis"-based approach. Literature specifically investigating the potential treatment effect of cereal rye on soil nitrogen, while growing in frequency over the past decade, is still somewhat limited. Conversely, compared with many of the other cover crop studies that looked at a wide array of treatment effects, most of the cereal rye studies were designed specifically looking at the role of cereal rye to sequester soil nitrogen, reduce leaching losses, effects on yield, and how to best manage cereal rye to optimize nitrogen management.

General take-aways and findings:

- Cereal rye was from 50% to over 100% more effective at reducing nitrate leaching losses, compared to results for other cover crops and cover crop blends (from fall harvest through spring planting of primary cash crops).
- While highly variable, average reductions in nitrogen leaching were approximately double that reported for other cover crops.
- Reductions in nitrate leaching losses were comparatively more consistent when cereal rye was used as a cover crop (or included in blends).
- Cereal rye, if terminated too late, could have a negative effect on nitrogen available to subsequent cash crops (usually corn) and cause yield reductions.
- Cereal rye was also beneficial in protecting soils from compaction, facilitated earlier planting, and reported positive benefit for weed suppression
- As with other cover crops, the planting window for cereal rye in autumn, following crop harvest, was sometimes a limitation and could result in poorer stands of the cover crop.
- Cereal rye is winter hardy and generally showed much later growth into late fall/winter, and earlier growth in late winter/spring of the following year.

Impacts of Cereal Rye Cover Crops on Nitrogen Leaching

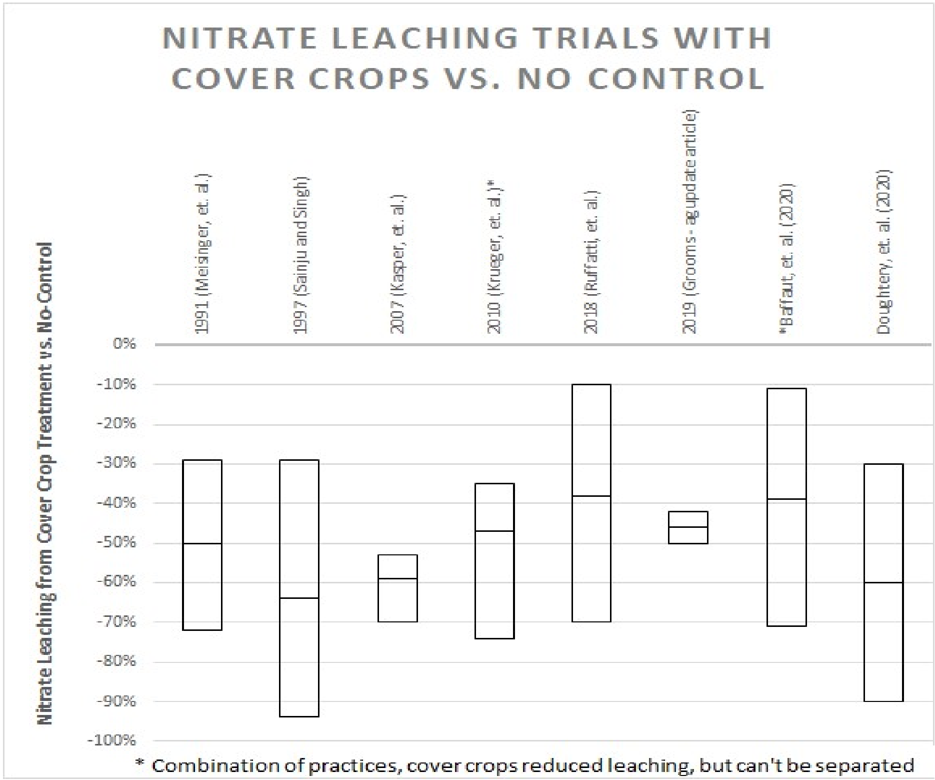


Chart 2: Comparison of Nitrate Losses to Groundwater from Cereal Rye Cover Crop Trials (Treatment) vs. No-Control.

Summary of Cover Crop Studies Investigating Cereal Rye for Nitrogen Sequestration:

Given natural variability in climate, soils, geology, and farming practices, the ability of agricultural conservation practices to perform specific beneficial functions can vary year to year. In some years, BMPs may not function well, conversely in other years, their performance may exceed expectations. Consequently, a “long-term” average and “weight of evidence” approach is typically employed to convey the performance expectations of a practice. For example, Ritter, et. al. (1998) investigated the use of cereal rye as a winter cover crop to reduce nitrate leaching over a three-year period on a loamy sand soil. Soil and shallow groundwater seepage were monitored during the duration of the experiment and showed mixed results, with nitrate leaching lower under the rye cover crop one year, and no difference the subsequent year. Ritter, et. al., (1998) suggested the rye may have been planted too late or harvested too early to provide sufficient uptake of nitrate from the soil profile. They also noted rainfall may have limited nitrogen uptake in the fall.

Noting the challenges in this one small study and highly variable results, it wouldn’t be prudent to make sweeping extrapolations and generalizations about the study results. However, if we include the results of dozens of studies, representing a wide array of conditions and hundreds of crop years, we might observe common results reported in the literature. So it is, with the studies specifically looking at using cereal rye (and other cereal grains, to a lesser extent) to sequester soil nitrogen for crop use and minimize nitrogen leaching losses. Multi-year studies across the midwestern corn-belt of the United States have consistently reported significant reductions in nitrogen leaching losses when winter cereal rye (and other winter hardy cereal grains) were employed as cover crops (Baffaut, et. al., 2020; Ruffati, et. al., 2018; Snapp and Surapur, 2018; Christianson, et. al., 2017; Sawyer, et. al., 2017; Martinez – Feria, et. al., 2016; Zhiming & Helmers, 2009; Kaspar, et. al., 2007; Shipley, et. al., 1992; Meisinger, et.

al., 1990; & Staver, et. al., 1990). Results of these studies are illustrated in Chart 2 and briefly summarized below.

A seven-year evaluation, across 36 field trials of tillage, crop rotations, crop residue, manure applications, and cereal rye (*Secale cereale L.*) in Iowa, Illinois, Indiana, Ohio, and Minnesota found a rye cover crop significantly reduced NO_3-N loss, whereas tillage and residue management had little impact on NO_3-N loss (Doughtery, et. al., 2020). Results showed that cropping management affected N leaching but impacts on P leaching were minimal. Corn yield was negatively affected by both no-till management and cereal rye cover crops. Similarly, a longer 10-year study conducted as part of the Conservation Easement Assessment Program (CEAP) reported significant reductions in intrate leaching when cereal rye was included as a cover crop. Nitrate-N (NO3-N) losses were lower (212lbs/yr to 129 lbs/yr) than conventionally farmed fields (Baffaut, et. al., 2020).

Ruffatti et. al. (2018) evaluated the impacts of N application timing and cover crop inclusion on NO_3-N loss (leaching) from agricultural sub-surface drainage across five nitrogen management scenarios: a zero control, applying the dominant portion of the N rate in the spring, applying the dominant portion of the N rate in the fall, augmenting the spring and fall N application systems with cover crops. Cereal rye cover crops, when used in a nitrogen management fertilizer regime, reduced the flow-weighted NO_3-N concentrations by 39% and 38% and the N load by 40% and 47%.

An 8-year field experiment comparing a traditional intensive nitrogen (N) fertilization cropping regime with one relying on cover crops to generate and retain nitrogen in SW Michigan found no significant differences in yield between the regimes. Soil C, water retention, pH and nutrient status were negatively affected by high N fertilizer. Rye cover had almost no detectable soil amelioration, but did maintain mid-season N availability relative to fallow plots, as indicated by soil inorganic N. Soil C pools had resulted in significantly more large particulate organic matter C under the rye cover crop treatment. Over 8 years corn yields were not reduced in plots with a winter rye cover, under widely variable weather conditions. Overall, a rye cover crop had minimal impact on soil C but was an effective N management tool with no corn yield penalty (Snapp and Surapur, 2018).

A comprehensive review of cover crop literature and research focusing on water quality in the Upper Mississippi River Basin and reducing gulf hypoxia, with an emphasis on nitrogen losses from agricultural lands reported widespread findings of improvements in overall crop, yield, and soil benefits (Christianson, et. al., 2017). While numerous results, challenges, and benefits were reported for a wide array of trials, one consistent conclusion was “there is evidence to suggest that planting grass-based cover crops markedly improves water quality relative (*sic: reduced nitrate leaching)* to fallow land.

Sawyer, et.al. (2017) summarized four years of cover crop research across multiple research fields in Iowa specifically investigating the influences of winter cereal rye on nitrogen dynamics under various corn and soybean rotations. Research in Iowa shows cereal rye has an average nitrate leaching reduction of 31% across trials. Due to competition for nitrogen, rye was found to hurt corn yields in areas where the rye was not terminated early enough.

A large-scale analysis of experimental field trial data from multiple sources across Iowa and evaluated the use of rye cover crops with corn to determine the effects on yield and nitrogen fluxes, and support nutrient management decision making. The dataset included measurements (2009–2014) of soil water and temperature, drainage water and NO_3-N losses, soil NO_3-N, rye shoot and root biomass and C:N, and maize yields under control and treatment fields. Experimentally, rye cover crop reduced NO_3-N losses by 20% (or 31% per unit of N applied) (Martinez – Feria, et. al., 2016).

Zhiming & Helmers (2009) evaluated the ability of cereal rye as a winter cover crop to sequester nitrate by planting into lysimeters and measuring drainage over 3 years. The rye was planted in October and terminated in June. Nitrate leaching was reduced by 21% in May and June and was overall significantly lower compared to drainage nitrate from bare soil “control” plots over all 3 years. During height of growth in late spring, the rye consumed an average of 64% more soil water than the bare control plots.

Kaspar, et. al. (2007) investigated two cropping system modifications in the Midwest Corn Two cropping system modifications were compared for NO_3-N concentration and load in subsurface drainage water for a no-till corn management system. In one treatment, eastern gamagrass was grown in permanent 3.05-m-wide strips above the tiles. For the second treatment, a cereal rye winter cover crop was seeded over the entire plot area each year near harvest and chemically killed before planting the following spring. Averaged over 4 yr, the rye cover crop reduced flow-weighted NO_3-N concentrations by 59% and loads by 61%. The gamagrass strips did not significantly reduce cumulative drainage, the average annual flow-weighted NO_3-N concentrations, or cumulative NO_3-N loads averaged over the 4 yr. Rye winter cover crops grown after corn and soybean have the potential to reduce the NO_3-N concentrations and loads delivered to surface waters by subsurface drainage systems.

Shipley, et. al. (1992) evaluated winter cover crops were evaluated to determine their ability to sequester residual fertilizer nitrogen using isotopic nitrogen (^{15}N depleted) over two years. Cover crop treatments following corn included hairy vetch, crimson clover, cereal rye, or annual ryegrass. These results show that grass cover crops conserved the most free nitrogen. Cereal rye recovered more free nitrogen (45%) through mid-April because of its growth in cool weather, although annual ryegrass was equally effective if grown to mid-May.

Fall cover crops trap and retain nitrogen through the subsequent winter and spring, scavenging nitrogen and significantly reducing leaching losses and protecting groundwater from nitrate pollution. Grass cover crops are superior to legumes in recovering previously applied nitrogen. Grass covers have the potential to markedly increase N retention within the soil-crop system and thereby reduce N leaching into ground water. However, grass cover crops can also have negative effects on the next crop by requiring extra fertilizer N (usually about 10-20 lbs N/acre) and by using water in the late spring which could reduce germination (Meisinger, et. al., 1990)

Staver, et. al. (1990) conducted 5-year study investigating nutrient transport from corn production systems in the mid-Atlantic Coastal Plain. Its primary objective is to evaluate the potential of cereal grain winter cover crops for reducing NO_3-N leaching to groundwater. Growth of the rye cover crop during the fall and winter following the 1988 corn harvest removed more than 134 pounds N/acre from the soil profile, substantially reducing the soil NO_3-N pool. Lysimeter samples collected at a 24-inch depth below the soil surface showed reduced NO_3-N levels in the soil profile.

Annotated Bibliography

* References preceded by an asterisk are literature reviews.

*Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M., & Smith, P. (2019). A Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity. *Global Change Biology* 25, 2530–2543. https://doi.org/10.1111/gcb.14644.

> Abdalla, et. al., (2019) conducted a comprehensive analytical review of independent cover crop research from peer reviewed literature spanning 106 studies and 372 sites representing numerous different countries, climatic zones and management practices from around the world. They found cover crops significantly ($p < 0.001$) decreased N leaching and significantly ($p < 0.001$) increased carbon sequestration without having significant ($p > 0.05$) effects on direct denitrification (as N2O emission). They did report that a potential disadvantages of cover crops was reduction in grain yield of the primary crop among some of the studies. However, proper selection of mixed cover crops (with legumes) increased yield by ≈13%. Based upon the survey of results, they concluded the advantages of cover crops justify their widespread adoption.

Adams, R. McCarty, T., & Hutchinson, L. (2016). Prevention and Control of Nitrate Toxicity in Cattle. Penn State Extension. https://extension.psu.edu/prevention-and-control-of-nitrate-toxicity-in-cattle

> Examines the complex factors that contribute to nitrate toxicity and provides recommendations for testing and feeding forages with high nitrate content.

American Farmland Trust & U.S.D.A. (2019a). Soil Health Case Study: Larry, Adam, and Beth Thorndyke, Thorndyke Farms, IL. *Soil Health Case Studies – July, 2pp.;* https://s30428.pcdn.co/wp-content/uploads/sites/2/2020/02/IL_ThorndykeFarms_Soil_Health_Case_Study_AFT_NRCS.pdf

> Farmer from N. Illinois switches to strip till, begins using cereal rye as a fall cover crop on his 2,600 acre soybean/corn grain farm and is able to completely eliminate fall Nitrogen application. Through improved efficiency in nutrient management, reduced field work, and lower fertilizer costs, Thorndyke farms saved an average of $36/acre. (American Farmland Trust, U.S.D.A., 2019a)

American Farmland Trust & U.S.D.A. (2019b). Soil Health Case Study: Eric Niemeyer, MadMax Farms, OH. *Soil Health Case Studies – July, 2pp.;* https://s30428.pcdn.co/wp-content/uploads/sites/2/2020/02/OH_MadMaxFarms_Soil_Health_Case_Study_AFT_NRCS.pdf

> Eric Niemeyer's 1,250 cash grain (soybean/corn) farming operation is saving $38/acre, following his shift from a conventional farming operation to one based on farming using "soil health" principles. Eric has converted his operation to no-till, reducing Nitrogen and organic matter losses to volatilization. Combined with switching his planting and fertilizer regiment to variable rate and utilizing fall cover crops to "grow" and sequester Nitrogen, Eric has significantly reduced his fertilizer costs and reduced field work expenses. (American Farmland Trust, U.S.D.A., 2019b)

Armstrong, S., Gentry, L., Schaefer, D., Miller, E., & Pike, J. (2017). Considerations for First Time Cover Crop Adopters. Illinois Nutrient Research & Education Council, 8 Pp., https://illinoisnrec.org/wp-content/uploads/2017/09/Cover-Crop-Guide-2017.digital.pdf

> Extensive research and field trials in Illinois have shown winter hardy cover crops establish in year preceding Soybeans can sequester and retain significant Nitrogen during the late fall, through spring planting. This significantly enhances organic Nitrogen pools, reduces needs for Nitrogen fertilizer and build organic matter in soybean fields.

Augarten, A. (2019). Nitrogen Use Efficiency Results. Discovery Farms, April.

> Discovery Farms, an applied, "working farm" research initiative through University of Wisconsin and Extension, conducts research on private working farms throughout Wisconsin. Augarten (2019) reported

on a synthesis of their results looking at Nitrogen Use Efficiency (NUE) across 157 corn grain fields and 101 corn silage fields in nine regions of Wisconsin to create benchmarks specific to WI cropping systems and soils. NUE "is a field level assessment tool that can be used to evaluate efficiency relative to other monitored fields and determine if a farm can make improvements to its nitrogen management", and is computed as the yield divided by lbs of Nitrogen applied. Research results found "fields in the low use efficiency category had either very low yields or high N rates, which could be responsible for lower efficiencies." The lowest use efficiency corn-grain fields applied over 250 lb N/ac. In contrast, fields with NUE in mid-high use or high use efficiency had N rates less than 170 lb N/ac (the average N rate). While inclusion of manure, as well as alfalfa in rotations, tended to result in lower N-use efficiencies, the results were not conclusive because of challenges in quantifying and accounting for these Nitrogen sources.

Baffaut, C., Ghidey,F., Lerch, R., Veum, K., Sadler, E., Sudduth, K., & Kitchen, N. (2020). Effects of Combined Conservation Practices on Soil and Water Quality in the Central Mississippi River Basin, J. Soil & Water Conservation. May/June 75(3):340-351.

Results from a 10-year study conducted by USDA as part of the Conservation Easement Assessment Program (CEAP) to document the effectiveness of widespread application of conservation practices across targeted watersheds located throughout the United States. This study focuses on results from a long-term agricultural research watershed in Missouri. A number of practices were used in various combinations throughout fields on the watershed to determine the most effective practices to reduce soil erosion, runoff, and nutrient losses, including nitrate leaching to groundwater. Nitrate-N (NO_3-N) losses decreased dramatically (212lbs/yr to 129 lbs/yr), when compared to the conventionally farmed fields, and cover crops were found to be a critical element in contributing to this reduction in losses. Explanations included a greater soil water content, a different timing of N applications, and N uptake by cover crops.

Bernhardt, K. (2021). What Distinction do Profitable Dairies Hold? Hoard's Dairyman. June 14. 2 pp.

A comprehensive review of Minnesota dairy farm profitability segregated farms by herd size, and subsequently compared the top 40% of most profitable farms to the lowest 40%. When simply looking at herd size, larger farms tended to have higher revenues, but that was simply attributed to greater production capacity. Looking at profitability, herd size makes some difference, especially for the low net revenue farms, negligible for high net revenue farms. Production costs and efficiency proved to be important factors determining overall profitability, with the smaller farms having significantly greater potential and profits from each additional cow ($1,190) compared to larger farms (> 500 cows, $970).

Betts, L. (2018). Soils Soil Sampling Foundation Helps No-Tiller Hit Higher Yields. *No-Till Farmer*, P 3., January.

Jake Kaderly, a grain farmer and Agronomist in south-central Wisconsin, has relied on a combination of extensive soil testing and detailed nutrient management, combined with no-till and cover crops to build high levels of organic matter, soil nitrogen pools, and produce record yields of corn over a number of years. Using strip and field trials, Kaderly attributes a 20 bushel bump in corn yield to his fall cover crop program and this has allowed him to completely eliminate fall fertilizer applications.

Booth, E. Zipper, S., Loheide, S. & Kucharik, C. (2016) Is Groundwater Recharge Always Serving Us Well? Water Supply Provisioning, Crop Production, and Flood Attenuation in Conflict in Wisconsin, USA. *Ecosystem Services 21(Oct):* 153-165.

Ecosystem services mapping is explored in a case study of groundwater recharge, water supply, flooding, and agricultural production in an urbanizing agricultural watershed in southern Wisconsin, USA. While groundwater recharge may be considered beneficial, it may contribute to to flooding and crop damage. The authors suggest moving beyond groundwater recharge as a stand-alone ecosystem service, and instead propose that observations and biophysical models should be used to quantify the final service humans receive from groundwater (e.g. reliability of water supply from a municipal well). Integration of such derived, point-based metrics with other ecosystem services that are more easily represented at the landscape scale remains a challenge for regional ecosystem service inventories and analyses.

Brady, N.C. (1990a). Soil Organic Matter and Organic Soil. Chpt 10 in *The Nature and Properties of Soils.* MacMillan Publishing Co. NY, NY, pp279-314.

This chapter is part of one of the most published undergraduate/graduate college level soils textbooks. The chapter explains full physical, biological and chemical nature, roles, forms, and processes of organic matter, and carbon, in soils. An emphasis is placed on the disproportionate role (by mass) and influences of soil organic matter on soil processes and aspects such as soil tilth, fertility, nutrient retention and availability, moisture holding capacity, infiltration capacity, nutrient cycling, temperature buffering, and pH buffering, among others.

Brady, N.C. (1990b). Losses of Soil Mositure and Their Regulation. Chpt 14 in *The Nature and Properties of Soils.* MacMillan Publishing Co. NY, NY, pp279-314.

This chapter is part of one of the most published undergraduate/graduate college level soils textbooks. The chapter explains full physical, biological and chemical nature, roles, forms, and processes of soil moisture in soils. Water fluxes, along with dissolved nutrients and pollutants are explained.

Brady, N.C. (1990c). Nitrogen and Sulfur Economy of Soils. Chpt 11 in *The Nature and Properties of Soils.* MacMillan Publishing Co. NY, NY, pp279-314.

This chapter is part of one of the most published undergraduate/graduate college level soils textbooks. The chapter explains full physical, biological and chemical nature, roles, forms, and processes of nitrogen in soils. The complexities, stores, pathways, and transformation processes of nitrogen are explained, including the complete nitrogen cycle. Nitrogen availability to crops, as well as losses to leaching and volatilization are explained.

Bundy, L., Knobeloch, L., Webendorfer, B., Jackson, G., & Shaw, B. (1994). Nitrate in Wisconsin Groundwater: Sources and Concerns, UW-Extension publication number G3054, 8 pp.

Although nitrogen can cause environmental and health problems, it is an essential element in living matter. Nitrogen is a major component of proteins and DNA, and is indispensable in the production of food and fiber. This publication explains how this complex and dynamic element works in the environment, its role in agriculture, the numerous nitrate sources that can contaminate groundwater, its impact on human and animal health, and what can be done to keep nitrate from building up to potentially harmful levels in groundwater.

*Cates, A.M., Sanford, G.R., Good, L.W., & Jackson, R.D., (2018). What Do We Know About Cover Crop Efficacy in the North Central United States? *J. Soil and Water Conservation*, Nov, 73(6) 153A-157.

Cates, et. al. (2018) conducted a review of published literature to report on the benefits and performance of cover crops in north-central United States. Across the reviewed literature, while acknowledging costs, management and yield challenges, cover crops improved Nitrogen retention, provided weed suppression benefits, improved carbon-nitrogen ratios, storage of organic Nitrogen in soil, and reduced Nitrate in tile-drainage and leaching

Chern, L., Kraft, G., & Postle, J. (1999). Nitrate in Groundwater - A Continuing Issue for Wisconsin Citizens. *The Nutrient Management Subcommittee of the Nonpoint Source Pollution Abatement Program Redesign, DNR, DATCP, 15pp.*

This paper summarizes the information available concerning nitrate in Wisconsin's groundwater. Previous papers have summarized the sources and concerns related to nitrate in groundwater (Bundy et al, 1994); the occurrence of nitrogen in groundwater and best management practices to reduce nitrate pollution (DATCP, 1989); and nitrogen application rates (Bundy et al, 1994). This paper provides additional information on the extent of nitrate pollution, the costs resulting from nitrate pollution and nitrate pollution sources and trends.

*Christianson R., Fox, J., Wong, C., Caraco, D., Daniels, A., Law, N., & Stack, B. (2017). Literature Review and Synthesis of the Effectiveness of Cover Crops for Water Quality Management in the Upper Mississippi River Basin. Center for Watershed Protection, Inc., Ellicott City, Maryland.

Christianson, et. al. (2017) conducted a review of cover crop literature and research focusing on water quality in the Upper Mississippi River Basin and reducing gulf hypoxia, with an emphasis on nitrogen losses from agricultural lands. They reported numerous variables across the research (e.g. types of cover crops, species mixes, climate, field management, etc.) that made it difficult to generalize about the overall benefits of cover crops. While in some cases, cover crops were found to curtail yields, it was reported this was due to management challenges such as late termination, improper species selection, and other manageable variables. Conversely, there was widespread overall crop, yield, and soil benefits reported from many of the studies, including sequestration of nitrogen, reduced leaching losses, and improved soil tilth and organic matter content. One clear result they reported was "there is evidence to suggest that planting grass-based cover crops markedly improves water quality relative (*sic: reduced nitrate leaching)* to fallow land.

*Clary, J., Flynn, N., Wardle, E., and Bauder, T., Leisenring, M., & Zhang, H. (2020a). Growing the Agricultural Best Management Practices Database. Advances in Water Resources Research, July-Sept (30)3. (*see below for summary*)

*Clary, J., Flynn, N., Leisenring, M., Harmel, D., & Zhang, H. (2020b). Update: Agricultural Best Management Practices Database. The Water Research Foundation and The National Corn Growers Association, Project Report #SIWM18R16/4847, 10 Pp.

Clary, et. al., (2020a) queried the comprehensive Agricultural Best Practices database, which reports results from participating research organizations, National Corn Growers Association Nitrogen Use Efficiency trials, and other sources to mine results of cover crop studies across the Midwest. Results of published studies showed "…clear evidence of the benefits of cover crops in reducing subsurface nitrate concentrations". While reported overall load reductions were more variable, those studies reporting reductions in concentration were more consistent and less variable. Across 37 reported cover crop fields in the database, all fields showed reduced nitrate concentrations with cover crops with a range of 12% - 43%, and an average of 33% reduction (Clary, et. al., 2020b).

Colquhoun, J. (2020). Reducing Groundwater Contamination at the Field Level. Badger Comon'tater. December. 72:12(58-61).

A summary of nitrogen and groundwater concerns is presented relevant to potato production in the central Wisconsin Sand Plains. Numerous nitrogen use and optimization examples are provided, with specific examples currently in use for commercial scale potato production. The importance of using a "holistic" approach, looking at the entire farm and crop year, to optimize nitrogen use, yield quality and profitability is suggested. Cover crops are noted as already being a widespread and common practice among potato growers in the region, with data to their ability to sequester nitrogen and reduce leaching losses to groundwater.

Comly, H.H., (1945). Cyanosis in Infants Caused by Nitrates in Well Water. JAMA 129: 112-116.

Two examples of a previously unrecognized condition which may be confused with congenital heart disease are cited in this report. The condition may occur anywhere in rural areas where well water is used in infant feeding. The health conditions and circumstances of infant exposure are described, including use of well water in infant formula.

DATCP. (2019). Producer-Led Watershed Protection Grants Impact Report FY18-19. Wisconsin Dept. of Agriculture, Trade and Consumer Protection. 37pp.

This annual program report presents results of a grant program in Wisconsin specifically designed to empower local farmers in development and implementation of practices that work for farmers. The program has five main goals: improve water quality and soil health; Foster locally-led decision making by producers; Increase farmer awareness and use of soil and water conservation practices via farmer-led initiatives and peer-to-peer communication; and Encourage and test innovative ideas for conservation.

*Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J., & Reeves, W. (2010). Using Cover Crops and Cropping Systems for Nitrogen Management. in *Advances in Nitrogen Management*, Soil and Water Conservation Society, Delgado, J.A, and Follett, R.F., eds., pp 230-281.

The authors provide a comprehensive literature review documenting published agronomic research on nitrogen management. An overview of cropping systems and practices are provided, including definitions for cover crops and catch crops. Results are reported by agronomic and climatic regions to identify trends, patterns, and practices that are applicable to each area. Across the published research, numerous practices are identified that promote more efficient nitrogen utilization and management, minimize nitrogen leaching losses, and were found to be “workable” on commercial farming operations. The use of cover crops and catch crops is found to be one of the most promising tools for farmers to minimize nitrogen losses.

*Dabney, S.M., Delgado, J.A., & Reeves, D.W. (2001). Using Winter Cover Crops to Improve Soil and Water Quality. *Communications in Soil Science and Plant Analytics*, 32(7&8),1221–1250.

This is a seminal research review of cover crop trials and experiments from around the world during the 1980’s and 1990’s. Their findings, summarized here, have been reinforced by additional research since then: *“While actively growing, cover crops increase solar energy harvest and carbon flux into the soil, providing food for soil macro and microrganisms, while simultaneously increasing evapotranspiration from the soil; Cover crops reduce sediment production from cropland by intercepting the kinetic energy of rainfall and by reducing the amount and velocity of runoff; Cover crops increase soil quality by improving biological, chemical and physical properties including: organic carbon content, cation exchange capacity, aggregate stability, and water infiltrability; Legume cover crops contribute nitrogen(N) to subsequent crops. Other cover crops, especially grasses and brassicas, are better at scavenging residual nitrogen before it can leach. Because growth of these scavenging cover crops is usually N limited, growing grass/legume mixtures often increases total carbon inputs without sacrificing N scavenging efficiency.”*

*Delgado, J. & Gantzer, C. (2015). The 4Rs for Cover Crops and Other Advances in Cover Crop Management for Environmental Quality. *J. Soil and Water Conservation* 70(6):142A-145A.

Delgado and Gantzer (2015), building on previously reported cover crops research (Delgado, et. al., 2007) summarized numerous newer studies and more recent research that was encouraged by the growth in adoption of cover crops. Cover crops results “show enormous potential to improve the sustainability of corn and soybean cropping systems, add soil organic matter and reduce its loss, reduce soil erosion, improve soil health, fix N, and reduce loss of nutrients”. They also acknowledge the challenges of using cover crops, with some studies reporting improved yields with cover crops, while others showed a yield penalty.

Delgado, J., Dillon, M., Sparks, R., & Essah, S. (2007). A Decade of Advances in Cover Crops. *J. Soil and Water Conservation.* 62(5):110A-117A.

Delgado, et. al. (2007) reported the results of a multi-disciplinary, inter-agency research team investigating studies on cover crop utilization in the United States. They reported cover crops not only scavenge the residual soil nitrate-nitrogen (NO3-N) that was leached from the previous crop, they can also reduce the nitrate-nitrogen leaching of the following crop. Additionally, they reported with new research tools, they’ve found cover crops can potentially vertically mine nitrate-nitrogen from irrigated water. Hence, cover crops may be used to lower the amount of NO3-N than that added to the system with irrigation water.

Delgado, J.A., Reeves, W., & Follett, R. (2006). Winter Cover Crops. In Encyclopedia of Soil Science, ed. R. Lal, 1915-1917. New York, NY: Markel and Decker.

Winter cover crops (WCC) are important universal tools that can be used to conserve environmental sustainability. In general, the term 'winter cover crop' is used to describe a cover crop grown to protect the soil during the winter fallow period. A cover crop can be used even during summer, especially in the tropics. A cover crop can also be used on a more permanent basis during the entire year. Winter cover crops serve as a soil conservation tool by sheltering the soil against wind and water erosion and reduce the off-site transport of soil particles, nutrients and soil organic matter by erosive processes. Winter cover crops improve air quality by reducing the aerial transport of light soil particles and chemicals associated with them due to wind erosion. Winter cover crops improve water quality and conservation by increasing N use efficiency by serving as 'catch crops' to scavenge NO_3-N. Leguminous winter cover crops can fix atmospheric N_2 and serve as green manures. Among other benefits of growing cover crops are weed suppression, carbon sequestration, and integrated pest management. WCC are a viable tool for soil and water conservation.

*Dinnes, D., Douglas, K., Jaynes, D.B., Tom, K., Hatfield, J., Colvin, T., & Cambardella, C. (2002). Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile Drained Midwestern Soils. *Agronomy Journal*. 94(10)21-34.

This is a comprehensive literature review specifically looking at agronomic practices that can reduce nitrogen losses to leaching in tile-drained fields. The objectives were to examine how changes in agricultural management practices have affected Nitrogen in midwestern soils and to identify the types of practices to reduce the NO3 leakage. Improved N management strategies to best match N application with crop needs was identified as a crucial underpinning of minimizing nitrate leaching. Cover crops were specifically called out as a field practice that was reported in numerous studies to significantly reduce nitrate losses.

Dougherty, B.W., Pederson, C., Mallarino, A.P., Andersen, D.S., Soupir, M.L., Kanwar, R.S., & Helmers, M.J. (2020). Midwestern Cropping System Effects on Drainage Water Quality and Crop Yields. *J. Environmental Quality* 49(3)1-12.

Doughtery, et. al. (2020) coordinated a seven-year evaluation of tillage, crop rotations, crop residue, manure applications, and cereal rye (Secalecereale L.) cover crops on nitrate-N (NO3-N) and total reactive phosphorus (TRP)loss via subsurface drainage. Thirty-six field trials were conducted in Iowa, Illinois, Indiana, Ohio, and Minnesota. They reported the lowest NO3-N loss was under no-till corn–soybean rotations with rye cover crops. Overall, a rye cover crop reduced NO3-N loss, whereas tillage and residue management had little impact on NO3-N loss. Results showed that cropping management affected N leaching but impacts on P leaching were minimal. Corn yield was negatively affected by both no-till management and cereal rye cover crops. Precipitation was the strongest driver of nitrate leaching, with little dependence observed during the growing season and active plant growth.

Drummy, N., Cooley, E., Wunderlin, A., Radatz, A., Frame, D., & Klingberg, K. (2011). Understanding Nutrient & Sediment Loss at Koepke Farms, Inc. U.W. Discovery Farms, Fall, 16 Pp.

Drummy, et. al. (2011) conducted extensive monitoring of working farm fields on the Koepke Farm, a family operated dairy farm in central Wisconsin, as one of the first Discovery Farms monitoring field trials. Nitrogen loss in surface water was 5 pounds/acre/year and connected to surface runoff. The timing of tile nitrogen loss was very consistent for all years and for both basins. The highest losses were typically in the month of April, with elevated losses from March through June. The majority of nitrogen loss occurred during the non-frozen ground period for both surface and tile. In tile water, nitrate nitrogen was the dominant form of nitrogen loss. The losses of ammonium nitrogen and organic nitrogen dominantly occurred during frozen ground conditions in tile. Surface runoff from a single storm can contribute nearly 90% of the sediment loss, over 80% of total phosphorus loss, and over 70% of total nitrogen loss for the entire field year. Tile fl ow from a single event basis delivered over 30% of the sediment loss, up to 27% of total phosphorus loss, and 18% of total nitrogen loss for the entire field year.

*Dzurella, K., Medellín-Azuara, J., Jensen,V., King, A., De La Mora, N., Fryjoff-Hung, A., Rosenstock, T., Harter, T., Howitt, R., Hollander, A., Darby, J., Jessoe, K., Lund, J., & Pettygrove, G.S. (2012) Technical Report 3: Nitrogen Source Reduction to Protect Groundwater Quality. Report for the State Water Resources Control Board Report to the Legislature, July, 186 Pp. http://groundwaternitrate.ucdavis.edu

In their comprehensive report to the California Legislature as part of a statewide initiative to combat groundwater nitrate contamination, Dzurella, et. al. (2012), summarized a wealth of experimental data, reports, and technical papers evaluating agronomic practices that can reduce nitrogen losses to leaching, and subsequent groundwater nitrate contamination. While results clearly varied across such a large dataset, the authors concluded the inclusion of cover crops and nutrient management can be very effective tools to reduce nitrogen losses and leaching to ground water. Reduction of nitrate leaching from cropland and livestock and operations can be achieved through changes in farm management that result in improvements in crop nitrogen use efficiency (NUE), and by proper storage and handling of manures and fertilizers. In particular, the synchronizing of fertilizer and manure applications with cropping practices that sequester Nitrogen need to be included in strategies moving forward to reduce agricultural nitrogen losses to groundwater.

EPA. (2013). Agricultural Nitrogen Management for Water Quality Protection in the Midwest. Report RP189, May. 32 p.

A multi-partner initiative summarizing the issues of nitrogen pollution of surface and groundwater from agricultural sources, including contributions from federal, state, and university researchers from Missouri, Nebraska, Kansas, and Iowa. Numerous strategies are presented to reduce nitrogen losses to groundwater, including an overview of agricultural field practices and cover crops. Presents general “high-level” summary of findings and concludes cover crops are an important tool and part of a multi-faceted strategy to reduce overall nitrogen utilization and losses.

EPA. (1999). Phytoremediation Resource Guide. United States Environmental Protection Agency Solid Waste and Emergency Response Report EPA 542-B-99-003. June. 56 pp.

Identifying and accessing pertinent information resources that will help site cleanup managers evaluate innovative technologies is key to the broader use of these technologies. This Guide is intended to increase awareness about technical information and specialized resources related to phytoremediation technologies. Specifically, this document identifies a cross section of information intended to aid users in remedial decision-making, including abstracts of field demonstrations, research documents, and information to assist in the ordering of publications. In addition, the look-up format of this document allows the user to quickly scan available resources and access more detailed abstracts.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a Century of Ammonia Synthesis Changed the World. *Nature Geoscience* (1), 636–639. https://doi.org/10.1038/ngeo325

A high-level review and summary of the history of nitrogen fertilizer synthesis in the United States, how it has affected agriculture, society’s dependence on nitrogen fertilizer for food production, and related environmental challenges from excessive nitrate pollution. Population growth, ethanol fuel production, and agricultural productivity are reviewed in conjunction with the Haber-Bosch process for synthetic fertilizer production.

Everett, L., Pepin, R., Coulter, J., & Wilson, M. (2018). Managing Nitrogen from Manure with a Winter Rye Cover Crop: Results of On-Farm Trials in Minnesota. U. of Minnesota – Extension, 13 Pp.

Everett, et. al. (2018) conducted 19 field trials across central and southern Minnesota to determine how crop yields and soil Nitrogen varied with manure applied to fall seeded winter Rye cover-crops. Manure

was applied through knife injection under a variety of tillage and soil conditions. Subsequent growth of the Rye was dependent on the degree of disturbance caused by manure injection. In all cases, spring soil nitrate (NO3) was significantly reduced in fields with the established Rye cover crops (35% to > 50% reduction). There was no reduction in yields on fields where recommended nitrogen rates (combined manure and fertilizer) were followed, compared to test strips.

Fraser, P., Curtin, D. Harrison-Kirk, T., Meenken, E., Beare, M., Tabley, F., & Gillespie, R., (2012). Winter Nitrate Leaching under Different Tillage and Winter Cover Crop Management Practices. Soil Science Society of America Journal. July-August. 77(4)1391-1401.

The authors examined the impacts of tillage intensity and winter cover crops on NO3– leaching following cultivation of permanent pasture to grow arable crops. Permanent pasture and permanent fallow treatments were included as controls. Losses of NO3—N were calculated from soil solution NO3—N concentrations (measured in ceramic suction cups installed at 600 mm) and drainage volumes. Cumulative NO3—N leached over 7 yr ranged from 20 to 428 kg N ha– 1, with least N lost under pasture. Nitrate leaching under arable crops generally increased rapidly as winter rainfall increased. Winter cover crops were effective in reducing NO3—N leaching losses, particularly in drier winters when about 50% less N leached where cover crops were grown. On average, annual leaching was only 10 to 18 kg N ha– 1 in the presence of cover crops. Largest leaching losses were recorded in the unfertilized, permanent fallow where there was no plant sink for NO3–N derived from SOM mineralization. Growing a crop during the winter period, combined with good N management practices to minimize pre-winter soil mineral N, provides the best option to keep NO3– leaching within the acceptable range for arable cropping in New Zealand.

Gebert, W.A., Walker, J.F., and Hunt, R.J., 2011, Groundwater Recharge in Wisconsin—Annual Estimates for 1970–99 Using Streamflow Data: U.S. Geological Survey Fact Sheet 2009–3092. 4 p.

Estimates of groundwater recharge are important for understanding the flows within a groundwater system, as well as baseflow in surface water systems and potential transport of contaminates. The groundwater component of streamflow is important because it is indicative of the sustained flow of a stream during dry periods, is often of better quality, and has a smaller range of temperatures, than surface contributions to streamflow. All three of these characteristics are important to the health of aquatic life in a stream. Further, groundwater recharge is fundamental to understanding the quantity and quality of groundwater that might be available for human consumption as well-water, along with other beneficial uses. This study presents two methods of estimating groundwater recharge in Wisconsin, a baseflow separation method using continuous streamflow gaging data, and a low-flow partial-record approach to estimate recharge when fewer data are available. Estimates of groundwater recharge via both methods are provided across Wisconsin.

Green, C., Liao, L., Nolan, B., Juckem, P., Shope, C., Tesoriero, A., & Jurgens, B. (2018). Regional Variability of Nitrate Fluxes in the Unsaturated Zone and Groundwater, Wisconsin, USA. Water Resources Research 54, 301–322.

Process-based modeling of regional NO–3 fluxes to groundwater is critical for understanding and managing water quality, but the complexity of NO– 3 reactive transport processes makes implementation a challenge. This study introduces a regional vertical flux method (VFM) for efficient estimation of reactive transport of NO– 3 in the vadose zone and groundwater. The regional VFM was applied to 443 well samples in central-eastern Wisconsin. Chemical measurements included O2, NO– 3, N2 from denitrification, and atmospheric tracers of groundwater age including carbon-14, chlorofluorocarbons, tritium, and tritiogenic helium. VFM results were consistent with observed chemistry, and calibrated parameters were in-line with estimates from previous studies. Results indicated that (1) unsaturated zone travel times were a substantial portion of the transit time to wells and streams, (2) since 1945 fractions of applied N leached to groundwater have increased for manure-N, possibly due to increased injection of liquid manure, and decreased for fertilizer-N, and (3) under current practices and conditions, approximately 60% of the shallow aquifer will eventually be affected by downward migration of NO– 3, with denitrification protecting the remaining 40%. Recharge variability strongly affected the unsaturated zone lag times and the eventual depth of the NO_3^- front. Principal components regression demonstrated that VFM parameters and predictions were significantly correlated with hydrogeochemical landscape features. The diverse and sometimes conflicting aspects of N management (e.g., limiting N volatilization versus limiting N losses to groundwater) warrant continued development of large-scale holistic strategies to manage water quality and quantity

Greve, R. & Hart, D. (2018). Central Sands Lakes Study: Annotated Bibliography. Wisconsin Geological and Natural history Survey Open-File 2018-04. 46pp.

A comprehensive literature review compiled as part of a 4-year study to investigate water use and lake levels on four lakes in the Central Sands region of Wisconsin. As one of the first steps in this effort, the WDNR and WGNHS compiled this annotated bibliography so that the knowledge and results from previous studies in the Central Sands could be incorporated into this study and to prevent duplication of existing work. In addition to studies specific to the Central Sands, this bibliography also includes studies and references to provide background. These references include discussion of the geology of tunnel channel and valley formation and methodologies for determining recharge and lake water budgets. This bibliography provides an overview of available research related to the hydrogeologic setting and water budget components of the Central Sands Lakes Study.

Haserodt, M.J., and Fienen, M.N. (2020). Assessment of groundwater trends near Crex Meadows, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2020–5149, 32 p.

Crex Meadows Wildlife Area (Crex) is a 30,000-acre property in Burnett County, Wisconsin. Crex is managed by the Wisconsin Department of Natural Resources (WDNR) with the goal of providing public recreation opportunities while also protecting the quality of native ecological communities and species on the property. The WDNR's management strategy includes controlling water levels at flowages in Crex using a system of dikes, water control structures, ditches, and a diversion pump. For the study, a network of 12 monitoring wells was installed in and to the west of Crex. This study successfully collected groundwater elevations in 11 study wells during a 3-month period in 2019 when water elevations in the Dike 6 flowage and Erickson flowage were lowered and then raised. The groundwater elevation trends were compared with groundwater elevation trends at a regional U.S. Geological Survey well. This analysis was done by (1) evaluating study well groundwater elevation trends compared to the regional well, (2) using a scatter plot of study well and regional well data during raising and lowering periods, (3) assessing horizontal hydraulic gradient data during the study period, and (4) assessing the cumulative departure from the mean groundwater elevation for each well.

Hively, W., Lee, S., Sadeghi, A., McCarty, G., Lamb, B., Soroka, A., Keppler, J., Yeo, I., & Moglen, G. (2020). Estimating the Effect of Winter Cover Crops on Nitrogen Leaching Using Cost-Share Enrollment Data, Satellite Remote Sensing, and Soil and Water Assessment Tool (SWAT) modeling, *J. Soil and Water Conservation*, May, 75 (3) 362-37, DOI: https://doi.org/10.2489/jswc.75.3.362

As part of the national Conservation Effects Assessment Project (CEAP) initiative to evaluate effectiveness of federal conservation programs from the U.S. Dept. of Agriculture, Hivey, et. al. (2020) conducted a 10-year numerical modeling and statistical analysis of cover crop, water quality, and conservation enrollment data in an agricultural tributary to Chesapeake Bay. Their research found a more than 3-fold increase in the use of cover crops (from <27% to nearly 90%) in corn rotations and 5-fold increase with soybean rotations (<9% to > 46%). While climate variability strongly influenced the performance of cover crops and observed results, they found a 25% overall 10-year reduction in nitrate (NO_3^-) leaching from cropland attributable to cover crop adoption, rising to an estimated 38% load reduction in 2016 when 64% of fields were planted to cover crops.

**ISU (2019). Reducing Nutrient Loss: Science Shows What Works. Iowa State University, Extension and Outreach, SP 435 A, October 2019, 4p.

The State of Iowa has been aggressively implementing their Statewide Nutrient Reduction Strategy to combat widespread pollution of surface and groundwaters by Nitrogen, Phosphorus, sediment, and other agricultural NPS pollutants. This strategy has focused on working closely with the agricultural industry and farmers to find best practices to minimize NPS pollution and optimize use of agricultural nutrients. Recommendations focus on scientifically based practices that have been proven to work to reduce nutrient loss, to be functional practices that can be implemented on working farms, and economically viable for farmers to adopt and utilize the practices. Key practices to optimize uptake of Nitrogen and reduce leaching from Nitrogen fertilizer sources include shifting from fall to spring applications, employing fall covers crops to sequester Nitrogen (this show the largest overall reductions in Nitrogen loss), the use of variable rate technology, and shifting from broadcast to side-dress applications.

**ISU (2013). Iowa Nutrient Reduction Strategy: Section 2.1 - Iowa Science Assessment of Nonpoint Source Practices to Reduce Nitrogen and Phosphorus Transport in the Mississippi River Basin. Iowa State Univ. Nutrient Reduction Team, 163 pp.

A comprehensive review of published literature and research to support the Iowa nutrient reduction strategy. This strategy aims to significantly reign in agricultural phosphorus and nitrogen losses from crop lands. Numerous strategies are presenting for optimizing nitrogen use and minimizing nitrogen losses from agriculture, primarily through leaching. A comprehensive review of cover crop trials and research, along with trials specifically in Iowa and conducted to support these efforts is presented.

Jackson, G., Keeney, D., Curwen, D., & Webendorfer, B. (1987). Agricultural Management Practices to Minimize Groundwater Contamination. Univ. of WI Extension. 115p.

Jackson, R. (2020). Soil Nitrate Leaching Under Grazed Cool-season Grass Pastures of the North Central U.S. J. Science, Food, and Ag. June. Pp1-6.

A review of nitrate leaching studies and data from the north-central U.S. was conducted to determine how nitrogen leaching losses from perennial pastures compared to traditional row-crop agriculture in the region, predominantly corn/soybean rotations. Overall nitrogen loading was generally higher under conventional row crop agriculture due to exogenous nitrogen (N) amendments. Conversely, nitrogen inputs of pastures come from wet and dry deposition, livestock manure from imported feed, biological fixation and inorganic N fertilizer. Nitrate loads were highest beneath corn and lowest beneath restored prairie and switchgrass managed for bioenergy. Cool-season grass pastures had relatively low levels of nitrate leaching loads where little or no N was applied. However, where grazed perennial grasslands had inorganic N applied, nitrate leaching loads rivaled those of corn in some cases. When producing milk and meat from livestock, grazed perennial cool-season grass pastures should reduce nitrate leaching loads compared to growing corn that is used to feed livestock in confinement. However, cool-season grass pastures can lose significant nitrate to leaching with moderate- to high-levels of exogenous N inputs.

Jette-Nantel, S. (2018). Getting Better, or Getting Larger? Hoard's Dairyman. Sept. 24. 2pp.

A review of what makes dairy farms profitable in Wisconsin during the dairy bankruptcy crisis of 2016-2019, included factors such as economies of scale, forage production, and efficiencies and management approach. Simply looking at herd size, larger dairies appeared to be more profitable, compared to smaller farms. However, when farm data were controlled for herd size, there were plenty of small dairies (<100 cows) that were just as profitable as large dairies (>1,000 cows). The chief differences in costs (per hundred weight of milk production) attributed better quality forage/forge production numbers of small farms balancing with better economies of scale with larger farms (who spent more on feed purchases, comparatively). The author concluded that it is not dairy size, per se, that improves farm profitability, but the overall quality of the management, with larger dairies having to invest in professionally trained managers. Conversely, many smaller farmers don't have this luxury, and looking for opportunities to improve overall dairy management (economics, forage production, agronomics, etc.) can be successful ways for them to be just as profitable as larger dairies.

Kaspar, T., Jaynes, D., Parkin, T., & Moorman, T. (2007). Rye Cover Crop and Gamagrass Strip Effects on NO3 Concentration and Load in Tile Drainage. *J. Environmental Quality* 36, 1503–1511.

A significant portion of the NO_3-N from agricultural fields that contaminates surface waters in the Midwest Corn Belt is transported to streams or rivers by subsurface drainage systems or "tiles." Previous research has shown that N fertilizer management alone is not sufficient for reducing NO_3-N concentrations in subsurface drainage to acceptable levels; therefore, additional approaches need to be devised. We compared two cropping system modifications for NO_3-N concentration and load in subsurface drainage water for a no-till corn management system. In one treatment, eastern gamagrass was grown in permanent 3.05-m-wide strips above the tiles. For the second treatment, a cereal rye winter cover crop was seeded over the entire plot area each year near harvest and chemically killed before planting the following spring. Averaged over 4 yr, the rye cover crop reduced flow-weighted NO_3-N concentrations by 59% and loads by 61%. The gamagrass strips did not significantly reduce cumulative drainage, the average annual fl ow-weighted NO_3-N concentrations, or cumulative NO_3-N loads averaged over the 4 yr. Rye winter cover crops grown after corn and soybean have the potential to reduce the NO_3-N concentrations and loads delivered to surface waters by subsurface drainage systems.

Koehler-Cole, K., Everhart, S., Gu, Y., Proctor, C., Marroquin-Guzman, M., Redfearn, D. & Elmore, R. (2020). Is allelopathy from winter cover crops affecting row crops? Agricultural & Environmental Letters. 2020;5:e20015.

The authors reviewed studies that document allelopathic effects of cover crops on subsequent row crops in field and laboratory settings. The influence of management, including biomass production, planting and termination timing on allelochemical quantity were noted. Few studies conclusively documenting allelopathic effects of cover crops on row crops (corn, soybeans, etc.) in field settings existed and the authors were unable to determine a negative allelopathic effect of cover crops on cash crops.

Kononoff, P. & Clark, K. (2017). Water for Dairy Production: Where Does it Go and Why Does Quality Matter? *In: Proc. Wisconsin Agribusiness Classic*. pp46-52.

Drinking water is vital to both the vitality and production of the lactating dairy cow. Although much remains to be learned about water quality and concentration, it is important to test water. By obtaining estimates for water intake, these data may help nutritionists further understand the mineral consumption and DCAD levels of the herd. Furthermore, water testing may indicate problematic constituents of water. Recommendations for dairy livestock drinking water standards are provided to optimize herd health, longevity, and milk production.

Kraft, G. & Stites, W. (2003). Nitrate Impacts on Groundwater from Irrigated Vegetable Systems in a Humid North-central US Sand Plain. *Agriculture, Ecosystems, and Environment* 100:63-74.

The authors investigated groundwater nitrate loading in the Wisconsin central sand plains over four years under a typical sweet corn (3yrs) and potato rotation (1 yr). Groundwater nitrate-N concentrations averaged 20 mg/l beneath the study field. Nitrate-N loading from the sweet corn ranged from 126 to 169 kg/ha/a; loading from potato was 228 kg/ha/a. Groundwater loading amounted to 61% of total available N and 77% of fertilizer N. Measured loadings compared well with those calculated using a budget approach, supporting the validity of both methods. Budget-derived loadings imply that limiting the basin-averaged nitrate-N concentration in groundwater to 10 mg/l would require each irrigated-vegetable hectare to be offset by 4.5–6.5 ha of land supplying nitrate-free groundwater recharge. As most orthodox nitrate control strategies (e.g., decreasing and splitting fertilizer, irrigation scheduling) had already been implemented in the region, better control will require new and unconventional approaches for controlling nitrate leaching from mineralized crop residue as well as additional curbing of direct fertilizer nitrogen leaching.

Kraft, G., Stites, W., & Mechenic, D. (1999). Impacts of Irrigated Vegetable Agriculture on a Humid North-central U.S. Sand Plain Aquifer. *Ground Water J*. 37:572-580

The authors evaluated the effects of irrigated vegetable agriculture on groundwater quality (nutrients, cations/anions, agricultural chemicals) in the Wisconsin central sand plains, where vegetable fields (potatoes, snap beans, sweet corn, peas, field corn, soybeans). Nitrate (among other pollutants) contamination plumes were found under 54% of the fields and extended to full depth of the shallow aquifers (>16m). Residual agricultural chemicals were widespread, but normally at very low concentrations outside of the fields (< 1um). Agricultural water quality impacts limited groundwater utilization as a potable source of drinking water in the region.

Kraft, G. (1991). Nitrate in Groundwater: Is It a Problem and Should We Care? *In Nitrate in Wisconsin's Groundwater: Strategies and Challenges. University of Wisconsin – Steven's Point. Pp1-6.*

An overview of the historical and current conditions of groundwater nitrate contamination is provided for the United States. Data specific to Wisconsin, from sampling, community wells, and other sources are provided. Groundwater nitrate contamination is not spread uniformly, rather it occurs in clusters. Therefore, looking at averages across a large geographic area can be very misleading. While contaminated wells (those about EPA std. 10 mg/l) might be low for a very large areas, the contaminated wells tend to be clustered in "hot spots", where all of the available groundwater may be contaminated for a local population. One such area in Wisconsin includes the central sands region. Groundwater contamination is clearly tied to agricultural land use in the "hot spot" areas, whereas areas with relatively less agricultural land tend to have significantly lower groundwater nitrate concentrations with few to none of the wells exceeding drinking water standards.

Krueger, E., Ochsner, T., Porter, P., & Baker, J. (2011). Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. *Agronomy Journal* 103(2):316-323.

A 2-year field study in Morris, MN was conducted to determine the impact of killed vs. harvested rye cover crops on soil moisture and NO3–N, and to monitor the impact of the rye on subsequent corn yield. Soil moisture after killed rye was similar to the control, but after harvested rye was 16% lower. Available soil NO3–N was decreased after both killed rye (35%) and harvested rye (59%) compared to the control. Corn biomass yield after killed rye was similar to the control, but yield following harvested rye was reduced by 4.5 Mg/ha. The environmental benefits of a winter rye cover crop can be achieved without impacting corn yield.

*Malcolm, B., Carey, P., Teixeira, E., Johnstone, P., Maley, S. & De Ruiter, J. (2018). Potential of Catch Crops to Reduce Nitrogen Leaching in New Zealand Winter Grazing Systems. *J. New Zealand Grasslands* (80):207-214.

Dairy farming and milk production have been a vital part of the agricultural farm economy in New Zealand since the mid 1800's. Extensive research has supported advances in the industry to improve both productivity and address environmental challenges, many of which are very similar to what is faced by the dairy industry in the midwestern United States. As Nitrate contamination of groundwater from agricultural practices has long been one of the main concerns in New Zealand, much of the research has focused on field practices to reduce contamination by fertilizer and manure sources. Focusing on grazing impacts of field operations and waste products from dairy herds, Malcolm, et. al., (2018) summarized extensive research across New Zealand and reported establishment of winter cover crops reduced leaching by up to 49%, reductions in leaching were directly associated with N-uptake by the cover crops, and the cereal grains used as covers showed no significant reductions on subsequent forage biomass production.

*Marcillo, G. & Miguez, F. (2017). Corn Yield Response to Winter Cover Crops: An updated meta-analysis. *J. Soil and Water Conservation*, 72(3):226-239.

Marcillo and Miguez (2017) conducted a "meta-analysis" of agronomic investigating the effects of cover crops on corn and soybean yields. Their summary of peer-reviewed research from the United States and Canada spanning 1965 through 2004 and comprises 268 observations. While results varied across cropping practices and regions, in general, they found no significant yield penalties and up to 30+% yield improvement on fields using winter cover crops. The history of research reviewed showed an improving trend in cover crop utilization and management, with more recent studies showing more favorable results and better yields, compared to earlier research.

Martinez-Feria, R., Dietzel, R., Liebeman, M., Helmers, M., & Archontoulis, S. (2016). Rye Cover Crop Effects on Maize: A System-Level Analysis. *Field Crops Research* (196): September Pp 145-159. https://www.sciencedirect.com/science/article/abs/pii/S0378429016302027

Martinez- Feria, et. al., conducted a large-scale analysis of experimental field trial data from multiple sources across Iowa and evaluated the use of Rye cover crops with corn to determine the effects on yield and nitrogen fluxes, and support nutrient management decision making. The dataset included measurements (2009–2014) of soil water and temperature, drainage water and NO3-N losses, soil NO3, rye shoot and root biomass and C:N, and maize yields under control and treatment fields. Experimentally, rye cover crop reduced NO3-N losses by 20% (or 31% per unit of N applied). These results are valuable for decision-making and add new fundamental knowledge on rye water and nitrogen use. (Martinez – Feria, et. al., 2016).

Masarik, K., Norman, J., & Brye, K. (2014). Long-Term Drainage and Nitrate Leaching below Well-Drained Continuous Corn Agroecosystems and a Prairie. *J. Environmental Protection* (5)240–254. https://doi.org/10.4236/jep.2014.54028

Nitrate-N leaching from tile-drained agricultural soils was investigated at Arlington Research Station, Wisconsin. Leaching below chisel-plow and no-tillage continuous-corn was monitored to evaluate the potential effects of common agricultural practices on subsurface water quality. Drainage, nitrate-N leaching loss, and flow-weighted mean nitrate-N concentrations for 8 years of data (1996-2003) 18%, 19%, 0.5% of the total N input was leached as nitrate-N in the CP, NT, and PR, respectively. Nearly three-quarters of the total nitrate-N was leached in spring (April-June). Annual drainage volumes and nitrate-N leaching losses were highly variable.

Mathewson, P., Evans, S., Byrnes, T., Joos, A., & Naidenko, O. (2020). Health and Economic Impact of Nitrate pollution in Drinking Water: A Wisconsin Case Study. *Environ. Monitoring and Assessment* (2020)192:724, 1-18.

Mathewson (et. al., 2020) evaluated exposure and the impacts of groundwater nitrate contamination on human health and societal costs in Wisconsin. They provided estimates of potential nitrate-related cancer cases for the 28% of state's residents who use private wells. The direct medical cost estimates for all nitrate attributable adverse health outcomes range between $23 and $80 million annually. Focusing on counties with highest nitrate concentrations in drinking water, reductions in adverse health outcomes resulted from simulated nitrate reductions of 20%. However, trend analyses indicated groundwater nitrate concentrations are overall increasing across Wisconsin. Thus, nitrate contamination of water supplies in Wisconsin is a public health problem that needs to be addressed.

McDonald, C., Parsen, M., Lathrop, R., Sorsa, K., Bradbury, K. & Kakuska, M. (2015). Characterizing the Sources of Elevated Groundwater Nitrate in Dane County, Wisconsin. *Final Report to WDNR for Wisconsin Groundwater Joint Solicitation Program, Project #218.* R. Lathrop, ed. 43pp.

Private domestic wells are the source of drinking water for about one-quarter of Wisconsin residents. These wells are frequently shallow and thus vulnerable to nitrate (and other chemical) contamination from current and past land use practices. In Wisconsin, 90% of the groundwater nitrate contamination is estimated to have originated from agriculture, 9% from septic systems, and 1% from other sources. This study evaluated over 61,000 nitrate records dating back to the 1970s in Dane County, WI. Spatial distribution of wells and landuse were analyzed using groundwater modeling techniques. Strong spatial patterns in shallow well nitrate concentrations throughout Dane County were found. The patterns are tied to combination of agricultural land use and hydrologic setting (highest concentrations of nitrates in youngest water near groundwater divides). Historical nitrogen loading corresponded well with historical nitrogen fertilizer use, suggesting leaching of agricultural nitrogen sources is primarily responsible for nitrate contamination at the county-wide scale.

MDoA (2021). Influence of Intensified Environmental Practices on Farm Profitability. Minnesota Dept. of Agriculture Centers for Agriculture Excellence. April - 4pp

The "Influence of Intensified Environmental Practices on Farm Profitability" study examined financial and crop production information from farmers enrolled in the Minnesota State Farm Business Management education program. The 64 MAWQCP farms in the study saw 2020 profits that were an average of $40,000 or 18% higher (median of $11,000) than non-certified farms. The 2019 data showed an average of $19,000 or 20% in higher profits (median of $7,000) for certified producers. Other key financial metrics are also better for those enrolled in the MAWQCP, such as debt-to-asset ratios and operating expense ratios.

Meisinger, J.J. & Delgado, J., (2002). Principles for Managing Nitrogen Leaching. *J. Soil and Water Conservation* (57). pp485-498.

Agricultural Nitrogen-leaching losses can range from 10% to over 3o% of the total N input. Leaching is a hydrologic process and most prevalent when water moving through the soil exports excessive soil nitrates. The universal tools for managing N leaching include understanding the soil-crop hydrologic cycle, avoiding excess N applications, and applying N in phase with crop demand. Specific cropping system tools for managing leaching include use of grass cover crops, adding a legume to a rotation, and adding crops that more fully utilize the soil-water resources. The primary water-management tool to reduce N leaching is irrigation scheduling. The application of the above N management tools to fields, or to specific management areas within fields, will improve crop N recoveries with subsequent reductions in N leaching.

Meisinger J., Hargrove W., & Mikkelsen R. (1991). Effects of Cover Crops on Groundwater Quality. In: *Cover Crops for Clean Water*, Hargrove, W. (ed.) 77–78. Ankeny, IA: SWCS.

Fall cover crops trap and retain Nitrogen through the subsequent winter and spring, scavenge Nitrogen, significantly reducing leaching losses and protecting groundwater from Nitrate pollution. Grass cover crops are superior to legumes in recovering previously applied nitrogen. Grass covers have the potential to markedly increase N retention within the soil-crop system and thereby reduce N leaching into ground water.

*Meisinger, J., Shipley, P., & Decker, A. (1990). Using Winter Cover Crops to Recycle Nitrogen and Reduce Leaching. In *Conservation tillage for agriculture in the 1990's.* J.P. Mueller and M.G. Wagger (eds.) North Carolina State univ. Spec. Bulletin 90-1. p 3-6.

There are multiple tools to balance the competing goals of "maintaining farm profitability, by ensuring an adequate supply of N to the crop, yet avoiding excessive N rates that could degrade groundwater quality". These include adjusting N rates based on expectations for productivity, adjusting timing of N applications, adjusting fertilizer placement, and modifying cropping systems to take advantage of N conserving crops (cover crops). Summarizing a series of cropping studies that included extensive monitoring, use of N-isotopes as traces, and monitoring leaching water, Meisinger, et. al. (1990) concluded grass cover crops are superior to legumes in recovering previously applied nitrogen. Grass covers have the potential to markedly increase N retention within the soil-crop system and thereby reduce N leaching into ground water. However, grass cover crops can also have negative effects on the next crop by requiring extra fertilizer N (usually about 10-20 Ibs N/acre) and by using water in the late spring which could reduce germination.

Mistovich, J. & Karren, K. (2019). Airway Management, Artificial Ventilation, and Oxygenation. Chpt 10 *in: Prehospital Emergency Care.* Werman, H. M.D., eds. Pearson Publishing, NY, NY.

MNDofH (2018). Nitrate and Methemoglobinemia. MN Dept. of Health Pamphlet. 4p.

An educational pamphlet for the general public. This pamphlet presents the risks of nitrate contamination of drinking water, specifically Methemoglobinemia, risk factors, drinking water standards, mitigation measures, and emerging health threats.

Moore, E., Wiedenhoeft, M., Kaspar, T., & Cambardella, C. (2013). Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage-Soybean Cropping Systems. *Soil Science Society of America Journal* (78), 968–976. https://doi.org/10.2136/sssaj2013.09.0401

Corn and soybean farmers in the upper Midwest are increasingly using winter cover crops. The effects of winter cover crops on soil quality in this region, however, have not been investigated extensively. The authors investigated the effects of a cereal rye winter cover crop on a corn silage–soybean rotation. Four cereal rye winter cover crop treatments were established in 2001: no cover crop, rye after soybean, rye after silage, and rye after both. In general, the rye cover crop plots 15% greater soluble organic matter, 44% greater particulate organic matter, and 38% greater potentially mineralizable Nitrogen than the treatment with no cover crops. In general, the treatments that had a rye cover crop after both crops or after corn silage had a positive effect on the soil quality indicators relative to treatments without a cover crop or a cover crop only after soybean. Rye after soybean did not add enough residues to the soil to cause measurable changes in SOM, POM, or PMN.

Muldoon, M. & Bradbury, K. (2019). Assessing Seasonal Variations in Recharge and Water Quality in the Silurian Aquifer in Areas with Thicker Soil Cover. Wisconsin Geological and natural history Survey, Open-File Report 2019-04. 45pp.

The fractured Silurian dolomite aquifer is an important, but vulnerable, source of drinking water in northeast Wisconsin. Well contamination events in the Town of Morrison in Brown County and Cooperstown in Manitowoc County refocused public attention on the aquifer's susceptibility to contamination. Previous work in Door County, where soils are typically less than five feet thick, has demonstrated that recharge to the dolomite aquifer can be exceedingly rapid. Additional research was needed to determine vulnerability of these resources to contamination. This study collected an analyzed additional groundwater data to charatierize groundwater recharge and potential vulnerability to contamination.

Muldoon, M, Madison, F., & Lowery, B. (1998). Variability of Nitrate Loading and Determination of Monitoring Frequency for a Shallow Sandy Aquifer, Arena, *Wisconsin. Wisconsin Geological and Natural History Survey Open File Report WOFR1998-09*. 26p.

The authors conducted a 3 year groundwater monitoring study in sandy agricultural soils in SW WI to determine the pattern and timing of nitrate movement in soil and leaching to groundwater under a corn, potato, soybean rotation. Spatial and temporal variability of fluxes were analyzed to develop recommendations for future groundwater nitrate monitoring studies. Results of nitrate movement indicted primary losses of nitrate to leaching occurred before spring crop growth and following autumn harvest, when there was no plant-water demand. During growing season, crop demand largely controlled nitrate fluxes to crops, with the exception of during large rain events.

Myers, R., Weber, A., & Tellatin, S. (2019). Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops. Sustainable Agriculture Research and Education Tech. Bulletin. June. 24pp.

Farmers around the country are planting cover crops on millions of acres to protect and improve the soil, and the more that farmers use cover crops, the more they value this conservation practice. Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops looks at the economics of cover crops in corn and soybean rotations to help farmers answer that big question, when do cover crops pay? Based primarily on yield and economic data gathered through five years of national cover crop surveys, the study addresses the kinds of economic returns that can be expected from cover crops, both under various management scenarios and as cover crops improve soil health over time. Because there is no one-size-fits-all answer to when cover crops start paying for themselves, this study takes a holistic approach, exploring seven common management situations for commodity farmers that can affect how quickly they receive a positive net return from cover crops, including savings from herbicide-resistant weeds, improved profits when cover crops are used for grazing, improved yields from reduced soil compaction, improved profitability by using cover crops to facilitate reducing tillage, improved soil moisture conditions, nutrient savings from reduced fertilizer use, and the potential to take advantage of incentive payments.

Nafziger, E. (2018). Comparing Actual N Rate Responses to the N Rate Calculator (MRTN) Approach to Setting N Rates (2014-2017). Department of Crop Sciences, University of Illinois at Urbana-Champaign, April 11., 5 pp.

Agronomic experts working on nitrogen fertilizer optimization in Illinois worked to develop an alternative to the yield-goal-based N recommendation system that had been in widespread use for some three decades. Practitioners noted nitrogen application rates were not consistently resulting in improved yields, and results varied significantly with soil texture. The main concern with the yield goal-based system was that, as corn yields increased over time, N rate trials were showing that the amount of fertilizer N needed to maximize yields was not going up as fast as yields. On the other hand, the amount of fertilizer N needed on lighter soils, including those in southern Illinois, was consistently higher than the amount suggested using the yield goal. An alternative approach was used to take advantage of recent N rate trial data and develop improved N rate guidelines. Results from several hundred field trials in Illinois were employed to calculate the "(net) return to N" (RTN) – yield produced by N x corn price minus N rate x N price – for each N rate over a range of rates from low to high. For each region – Northern, Central, and Southern Illinois – and for corn following corn and corn following soybean, average RTN curves were developed from all the trials. The N rate that produced the high point of that average curve was dubbed the "maximum return to N" (MRTN) rate. This approach is now employed Seven states – Minnesota, Iowa, Wisconsin, Illinois, Indiana, Michigan, and Ohio.

NCGA. (2020). Cover Crops. National Corn Growers Association Soil Health Partnership Brochure. 2pp.

A two-page brochure targeting farmers and agronomists summarizing the benefits of using cover crops and considerations encouraging incorporation of cover crops into farming systems. Numerous benefits are presented including: improving organic matter, fertility, water holding capacity, weed resistance, and reducing nutrient leaching losses. Cover crops are broken into four categories and presented in a manner encouraging farmers/members to include cover crops in their farming operations.

Nolan, B., Green, C., Juckem, P., Liao, L., & Reddy, J. (2018). Metamodeling and Mapping of Nitrate Flux in the Unsaturated Zone and Groundwater, Wisconsin, USA. *J. Hydrology* (559): Pp 428-441.

Comprehensive groundwater modeling and statistical analyses of groundwater quality data from 120 wells across the Fox, Wolf and Peshtigo River Basins, Wisconsin were analyzed using machine learning and compared across 58 predictor variables. Results from the calibrated models were generally consistent with expectations, e.g. with greater source concentrations and NO3 at the groundwater table in areas of intensive crop use and well drained soils (Nolan, et. al., 2018).

Oetzel, G. (2008). Water Quality Standards for Livestock Water. UW School of Veterinary Medicine. 3p.

A published table of drinking water quality standard recommendations for common livestock produced by UW School of Veterinary Medicine - Large Animals.

Ozmen, O., Mor, F., Sahinduran, S. & Unsal, A. (2004). Pathological and Toxicological Investigations of Chronic Nitrate Poisoning in Cattle. *Toxicological and Environmental Chemistry* 87(1):99-106

Clinical evaluations and autopsies were performed on stillborn and sick calves. Complete necropsy was performed on all the eight affected calves. Calves exhibited numerous external an internal medical issues including hydroperitoneum and ascites, pulmonary edema and hemorrhage, and hemorrhages in the digestive systems. Levels of nitrates and nitrites in blood samples from cows and calves were found to be high. While hemoglobin values were found to be low, methemoglobin values were very high. No differences were observed between liver enzyme levels of the affected and control cattle. There were no bacteria or virus isolated from these animals, and histopathological examination revealed no indication of any other diseases.

Pandey, V. & Maiti, D. (2020). Perennial Grasses in Phytoremediation - Challenges and Opportunities. *Chpt 1 in Phytoremediation Potential of Perennial Grasses.* Elsevier, Amsterdam, Netherlands. pp1-29.

Polluted sites, coal mine spoil, fly ash deposits, red mud dumpsites, and other dumpsites are a worldwide problem, contaminating nearby communities. These disposal sites are major source of environmental pollution. Phytoremediation has been popularized to remediate heavy metal-contaminated sites in the past few decades due to its cost-effectiveness and environmental sustainability. In this regard, the use of grasses is of utmost importance due to their rapid growth, large biomass, resistance to phytotoxicity, and genotoxicity by heavy metals as compared to herbs, shrubs, and trees. Phytostabilization by the compact root system of grasses retards the formation, mobility, and bioavailability of hazardous leachates by high uptake and accumulation of the complex mixtures of heavy metals within them. Such grasses prevent natural succession by weeds and other plants leading to safe grazing by animals. Among the members of Poaceae, aromatic grasses are economically important plants due to their essential oil production. They rank higher than edible grasses, which are susceptible to heavy metal contamination in their edible parts. This chapter describes the role of grasses in ecological and socio-economic sustainability of phytoremediation of polluted sites.

Pellerin, D., Charbonneau, E., Fadul-Pacheco, L., Soucy, O., & Wattiau, M.A. (2017). Economic Effect of Reducing Nitrogen and Phosphorus Mass Balance on Wisconsin and Québec Dairy Farms. J. Dairy Science. October. 100:8614-8629.

The authors conducted a farm profitability, economic, and environmental analyses of dairy farms to evaluate trade-offs between economic performance and environmental outcomes. Nutrient management and fertility programs balanced nutrient inputs (fertilizer and manure), with various forages blends (including feed purchase, cover crops, etc.) and crop rotations with yields, forage production, and expected milk yields. Simulations were conducted on a typical WI farm of 107 cows and 151 ha of cropland and, a Southern QC farm of 87 cows and 142 ha of cropland and all results were expressed per kg of fat- and protein-corrected milk (FPCM). Optimizations to maximize Farm Net Income determined it was possible to reduce P balance, N balance, and both together by up to 33% without a substantial effect on FNI. This study demonstrated that even when recommended guidelines are followed for herd nutrition and crop fertilization, the optimization of herd feeding, cropping, and manure spreading as a single unit of management may help identify management options that preserve FNI, while substantially reducing whole-farm nutrient balance.

Pieters, A. (1927). Organic Principles and Practices – Green Manuring. PhD Dissertation. Reprinted by Soil and Health Library, Braunworth and Co. Inc. Publishers, Brooklyn, NY. 259pp.

This comprehensive PhD dissertation from 1927 provides an exhaustive review of the practice of "Green Manuring", using cover crops and catch crops to sequester nitrogen, build organic soil nitrogen sources, improve overall soil fertility, and boost crop yields. The dissertation explores the long history of green manuring, an agricultural practice among European farmers for more than two thousand years. Entire sections are dedicated to the following topics: History of Green Manuring; Soil Organic Matter; The Nitrogen Problem; Nitrogen Fixation; Chemical Composition of Green Manure Plants; Decomposition of Green Manure Plants; Benefits Other Than Increases in Nitrogen; Various Practical Considerations; Yields After Green Manuring; Crops Used for Green Manuring; Green Manuring in the United States; Green Manuring in Other Countries; and, Economics of Green Manuring. At the time of publication, the practice of green manuring was widespread in the United States. Farmers already recognized the benefits of various cover crop species for weed control, legumes for sequestering nitrogen, building organic matter, boosting yields, and improved profits, among a multitude of other reasons.

Power, J.F., Wiese, R. & Flowerday, D. (2001). Managing Farming Systems for Nitrate Control: A Research Review. From: Management Systems Evaluation Areas. *Journal of Environmental Quality.* 30 (November-December):1866-1880.

The U.S. Department of Agriculture funded the Management Systems Evaluation Area (MSEA) research project in 1990 to evaluate effectiveness of present farming systems in controlling nitrate N in water resources and to develop improved technologies for farming systems. This paper summarizes published research results of a five-year effort. Most research is focused on evaluating the effectiveness of farming system components (fertilizer, tillage, water control, cropping systems, and soil and weather variability). The research results show that current soil nitrate tests reliably predict fertilizer N needed to control environmental and economic risks for crop production. A corn (Zea mays L.)–soybean [Glycine max (L.) Merr.] rotation usually controls risk better than continuous corn, but both may result in unacceptable nitrate leaching. Reduced tillage, especially ridge-till, is better than clean tillage in reducing risk. Tile drainage controls nitrate in ground water, but discharge may increase nitrate in surface waters. Sprinkler irrigation systems provide better water control than furrow irrigation because quantity and spatial variability of applied water is reduced. Present farming systems have two major deficiencies: (i) entire fields are managed uniformly, ignoring inherent soil variability within a field; and (ii) N fertilizer rates and many field practices are selected assuming normal weather for the coming season. Both deficiencies can contribute to nitrate leaching in parts of most fields.

Prewitt, R. & Merilan, C. (1957). Effects of Potassium Nitrate Intake on Dairy Calves. Missouri Agricultural Experiment Station, Journal Series No. 1787. Pp807-810.

This study provides infornmtion on the effects of level, frequency, and duration of nitrate intake on the nitrate tolerance of young dairy animals. Administration of KNO~to bull calves indicated that the minimum lethal dose for initial intake was in excess of 30 g. per 100 lb. body weight. Toxic response to the compound was found to varybetween animals, but was not materially affected by experimental method of intake (by capsule or dissolved in milk). The level of KNO~ ingestion exerted little, if any, influence on the time required for the in vivo formation of maximal levels of methemoglobin (determined spectrophotometrically). Up to 1.3 g. % nitrate, but no nitrite, was detected by microbiological assay of the urine from two calves receiving 25 g. KNQ per 100 lb. body weight and showing low levels of methemoglobin

Puckett, L. (1994). Nonpoint and Point Sources of Nitrogen in Major Watersheds of the United States. U.S. Geological Survey *Water-Resources Investigations Report 94–4001*, 12Pp.

Puckett (1994) conducted and reported a seminal review and analysis of Nitrogen pollution from 107 watersheds located throughout the conterminous United States. The proportions of nitrogen originating from fertilizer, manure, atmospheric deposition, sewage, and industrial sources were found to vary with climate, hydrologic conditions, land use, population, and physiography. Fertilizer sources of nitrogen are proportionally greater in agricultural areas of the West and the Midwest than in other parts of the Nation. Throughout rural areas in the Midwest, elevated nitrogen pollution of surface waters was directly correlated with high amounts of agricultural land use.

Qiang, L. & Ruark, M. (2021). Partial Nitrogen Budges and Nitrogen Use Efficiency Measurements as a Tool to Reduce Nitrate Leaching to Groundwater. DRAFT DNR Project Report. P.O.# 37000-0000017234. 8pp.

This is a DRAFT project report from UW-Madison, Dept. of Soil Science to conduct an independent research project summarizing results of nitrogen use efficiency research with UW Discovery Farms, to develop nitrogen budgets, and assess the results to determine what types of farming operations and practices are used that may help limit nitrate leaching losses to groundwater. Results of the analyzed farm data indicated corn sileage production fields had a net negative partial nitrogen budget of -22 lbs. N/ac/yr, while corn for grain had a net surplus of 40 lbs. N/ac/yr. Interpreting these values relative to the proposed N-TPS rule of limiting leaching to 2.2 Lbs N.ac.yr and estimated groundwater recharge, approximately 70%-75% of corn sileage fields and 24%-29% of corn grain fields were anticipated to meet the N-TPS.

Ribaudo, M., Delgado, J., Hansen, L., Livingston, M., Mosheim, R., & Williamson, J. (2011). Nitrogen in Agricultural Systems: Implications for Conservation Policy. USDA Economic Research Service, Economic Research Report No. 127. Sept. 89 p.

Nitrogen is an important agricultural input that is critical for crop production. However, the introduction of large amounts of nitrogen into the environment has a number of undesirable impacts on water, terrestrial, and atmospheric resources. This report explores the use of nitrogen in U.S. agriculture and assesses changes in nutrient management by farmers that may improve nitrogen use efficiency. It also reviews a number of policy approaches for improving nitrogen management and identifies issues affecting their potential performance. Findings reveal that about two-thirds of U.S. cropland is not meeting three criteria for good nitrogen management. Several policy approaches, including financial incentives, nitrogen management as a condition of farm program eligibility, and regulation, could induce farmers to improve their nitrogen management and reduce nitrogen losses to the environment.

Ricks, N. & *Fernández, F. (2018).* Rye Cover Crop Impact on Nitrogen Leaching and Corn Yield. Corn & Soybean Digest.

University of Minnesota study shows reduction of nitrogen leaching when using the cover crop in a corn, soybean rotation on sandy soils of up to 45%. This is likely because rye residue is tying up residual nitrate early in the spring when there is high precipitation and little crop uptake. As the season continues, the rye decomposes and nitrogen is released into the system when the plants are consuming nutrients. This allows the plants to utilize the nutrients, rather than losing them through leaching. The preliminary data show promising results with rye decreasing nitrate leaching without negatively impacting yield or EONR. We found that rye had no effect on corn yield in either rotation. The presence of rye had an inconsistent effect on the EONR. In 2016, the EONR for rye plots in corn-soybean rotation was 50 lbs nitrogen/acre less than the conventional (no rye) treatments. In 2017, the EONR for rye plots in the rotation was 17 lbs N/acre greater than for no rye treatments.

Ritter, W., Scarborough, R., & Chirnside, A. (1998). Winter Cover Crops as a Best Management Practice for Reducing Nitrogen Leaching. *J. Contaminant Hydrology*, 34(1–2), October, 1-15.

Ritter, et. al. (1998) investigated the use of cereal rye as a winter cover crop to reduce nitrate leaching over a three-year period on a loamy sand soil. Replicate block trials, under no-till and conventional tillage systems were used to test the effect of rye on leaching. Corn yields were not affected by the rye cover crop. Soil and shallow groundwater seepage were monitored during the duration of the experiment and showed mixed results, with nitrate leaching lower under the rye cover crop one year, and no difference the subsequent year. Ritter, et. al., suggested the rye may have been planted too late or harvested too early to provide sufficient uptake of nitrate from the soil profile. They also noted rainfall may have limited nitrogen uptake in the fall

Robertson, G.P. & Vitousek, P.M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Ann. Review Env. Resources* 34:97-125.

A review of the benefits of commercial nitrogen (N) fertilizer in agriculture, offset by environmental costs, including coastal hypoxia, nitrate leaching losses, atmospheric nitrous oxide (N2O), reactive N gases in the troposphere, among others. A summary of how fertilizer N escapes cropped ecosystems and the complex N cycle is presented. Several technologies and management measures to improve nitrogen utilization, reduce loses, and improve overall efficiency are presented. These include adding rotational complexity to cropping systems to improve N capture by crops (specifically using cover crops to sequester and retain nitrogen to mitigate nitrate leaching), providing farmers with decision support tools for better predicting crop fertilizer N requirements, improving methods for optimizing fertilizer timing and placement, and developing watershed-level strategies to recapture N lost from fields. Solutions to the problem of agricultural N loss will require a portfolio approach in which different technologies are used in different combinations to address site-specific challenges. The authors noted incentives may likely be required to promote adoption of some of these solutions

Roesch-McNally, D., Basche, A., Arbuckle,J., Tyndall,J., Miguez,F., Bowman, T.,& Clay, R. (2017). The Trouble with Cover Crops: Farmers' Experiences with Overcoming Barriers to Adoption. In *Natural Resource Ecology and Management Publications - Renewable Agriculture and Food Systems*: 206:1-12.

While cover crops have been proven to promote many aspects of soil and water quality and many farmers have been exposed to them, in 2012 only 2.3% of the total agricultural lands in the Midwestern USA were using cover crops. Focus groups were conducted across Iowa to better understand how farmers confront barriers to cover crop adoption in highly intensive agricultural production systems. Farmers input indicate a complex relationship between management decisions and the broader agricultural context in the region that constrains their decisions. Farmers shared that generally homogenized agricultural and economic landscape makes cover crop integration challenging. Many who joined the focus groups have found ways to overcome barriers and successfully integrate cover crops into their cropping systems. This is illustrated through farmers' descriptions of their 'whole system' approach to cover crops management. These producers also engage with farmer networks to gain strategies for overcoming management challenges associated with cover crops. They tended to believe that greater economic incentives and/or more diverse crop and livestock markets would encourage adoption of the practice. Structural and field-level barriers constrain individual actions, as it is not simply the basic agronomic considerations (such as seeding and terminating cover crops) that pose a challenge to their use, but also the broader economic and market drivers that exist in agriculturally intensive systems. Reducing structural barriers may be necessary to increase the use of cover crops and recognize their benefits in intensive agricultural regions.

Ruark, M., West, J. & Siemering, G. (2019). Cover Crops, Manure, and Nitrogen Management. University of Wisconsin-Madison, Extension, A4178; https://learningstore.extension.wisc.edu/products/cover-crops-manure-and-nitrogen-management

In Wisconsin, warm fall conditions promote both the mineralization of the organic N in manure and the nitrification of ammonium to nitrate. This results in N-NO3- losses in the winter and spring through seepage to groundwater. Residual fall soil moisture, combined with spring rains readily mobilize nitrate in the soils before traditional crops can be planted, resulting in significant losses of nitrate to leaching. Extensive research and field trials Cover crops are a recommended management practice in this cropping system to provide ground cover and to trap excess N from leaching into groundwater or tile drains

Ruark, M., Chawner, M., Ballweg, M., Proost, R., Arriaga, F., & Stute, J. (2018). Does Cover Crop Radish Supply Nitrogen to Corn? *Agronomy Journal*, 110(4): 1513-1522.

Recognizing multiple benefits of cover crops through the reduction of erosion and compaction, general improvement of the soil physical condition and microbial community, and building of soil organic carbon, the value of Radish to provide nitrogen to subsequent corn crops was investigated across nine site-years in northeastern and southern Wisconsin. Results indicated mostly neutral effects of radish on corn yield, although corn yield increases and decreases following radish occurred. This research supports the use of radish as a trap crop for fall N, as environmentally meaningful yields of N were contained in plant biomass, but also demonstrates that radish has no N fertilizer replacement value to the subsequent crop

Ruark, M. & Stute, J. (2009). Cover Crops and Nitrogen Credits. In *Proc. 2009 Wisconsin Crop Management Conference* (48), 167-170.

Use of cover crops provides many agronomic and environmental benefits to agricultural systems in Wisconsin. Field research conducted over the past decades confirms the economic benefit of using cover crops in both the Central Sands and the Driftless regions of the state. Additionally, this research has discovered that berseem clover, crimson clover, and medic are equally effective of reducing EONR as more established green manures such as alfalfa, red clover, and hairy vetch.

Ruffatti, M.D., Roth, R.T., Lacey, C.G., Armstrong, S.D., 2019. Impacts of Nitrogen Application Timing and Cover Crop Inclusion on Subsurface Drainage Water Quality. *Agricultural Water Management* 211, 81–88.

The impacts of N application timing and cover crop inclusion on NO_3-N loss (leaching) from agricultural sub-surface drainage was determined across five nitrogen management scenarios: a zero control, applying the dominant portion of the N rate in the spring, applying the dominant portion of the N rate in the fall, augmenting the a spring and Fall N application system with cover crop. Each of the five nitrogen management scenarios was replicated three times on individually monitored sub-surface drainage plots established in Lexington, IL. During the experiment, a cereal rye and radish blend was interseeded within both corn and soybean. Fertilizer did not affect cover crop growth or N uptake. Cover crops resulted in more consistent and greater NO_3-N loss reductions relative to adjusting fertilizer N application timing from fall to spring. Cover crop reduced the flow-weighted NO_3-N concentrations by 39% and 38% and the N load by 40% and 47% when added to spring and fall fertilizer N management systems, respectively. Cover crop proved to be effective in reducing NO_3-N loss through sub-surface drainage across the spectrum of N fertilizer management systems common to the Upper Mississippi River Basin.

*Sainju, U. & Singh, B. (1997). Winter Cover Crops for Sustainable Agricultural Systems: Influence on Soil Properties, Water Quality, and Crop Yields. *Hort Science* 32(1):21-28.

This is a comprehensive literature review summarizing research into the effects of cover crops on soil properties, water quality and crop yields. Emphasis is on field trials and experiments reported in peer-reviewed literature. Tables summarizing the results of numerous studies include soil carbon, nitrogen and leaching losses under a wide variety of cover crops. Nitrate leaching reductions with cereal Rye ranged from 29% - 94%, with highest rates in more humid climates.

Sawyer, J., Patel, S., Pantoja, J., Barker, D., & Lundvall, J. (2017). Nitrogen Dynamics with a Rye Cover Crop. In *Proc. 29th Annual Integrated Crop Management Conference*, Nov. 29 – 30, Iowa State University, AEP 0302 – 2017, pp 161-168.

Sawyer, et.al. (2017) summarized four years of cover crop research across multiple research fields in Iowa specifically investigating the influences of Winter Cereal Rye on Nitrogen dynamics under various corn and soybean rotations. Research in Iowa shows cereal Rye has an average nitrate leaching reduction of 31% across trials. Rye was found to hurt corn yields in areas where Rye wasn't terminated early enough due to competition for Nitrogen. The average Nitrogen uptake of cereal Rye during the trials was 16 – 28 lbs N/acre and limited by relatively low biomass production due to weather conditions, and reduced soil profile N by an average of 14 lbs N/acre. Degradation of the terminated Rye biomass occurred through the growing season, with 60% of the Nitrogen from Rye residue after corn was decomposed within 105 days.

Sawyer, J. (2006) Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn. *Iowa State University Extension Report PM 2015.* April. 27 pp.

This publication focuses on rates of nitrogen application in rain-fed conditions, and corn-soybean and corn-corn rotations. The information is designed primarily for agronomists and crop consultants, and includes specific scientific rationale for corn nitrogen use and a regional approach to nitrogen rate guidelines.

SEWRPC (2008). Groundwater Recharge in Southeastern Wisconsin Estimated by a GID-Based Water Balance Model. Southeastern Wisconsin Regional Planning Commission Tech. Report 47. 23pp.

In 2005, the Regional Planning Commission undertook the preparation of a regional water supply plan. The planning effort included the preparation of five supporting technical reports that provide an important foundation for the system planning that is to result in completion of a recommended regional water supply plan. The technical reports were to address water law, the state-of-the-art of water supply practices, groundwater recharge, groundwater sustainability under varying land use scenarios, and groundwater budget indicators for use in assessing alternative water supply plans. This report, the third such report to be completed, provides technical information on groundwater recharge within the Southeastern Wisconsin Region.

Shipley, R., Meisinger, J., & Decker, A. (1992). Conserving Residual Corn Fertilizer Nitrogen with Winter Cover Crops. *Agronomy J.* 84(Sep-Oct): 869-876.

Excess fall fertilizer readily leaches into groundwater in humid climates. Winter cover crops were evaluated to determine their ability to sequester residual fertilizer Nitrogen using isotopic Nitrogen (15N depleted) over two years. Cover crop treatments following corn included hairy vetch, crimson clover, cereal rye, or annual ryegrass. These results show that grass cover crops conserved the most FN. Cereal rye recovered more FN (45%) through mid-April because of its growth in cool weather, although annual ryegrass was equally effective if grown to mid-May.

Snapp, S., & Surapur, S. (2018). Rye cover crop retains nitrogen and doesn't reduce corn yields. *Soil and Tillage Research*, Volume 180, August, Pp 107-115.

An 8 year field experiment comparing a traditional intensive nitrogen (N) fertilization cropping regime with one relying on cover crops to generate and retain Nitrogen in SW Michigan found no significant differences in yield between the regimes. Soil C, water retention, pH and nutrient status were negatively affected by high N fertilizer. Rye cover had almost no detectable soil amelioration, but did maintain mid-season N availability relative to fallow plots, as indicated by soil inorganic N. Soil C pools had resulted in significantly more large particulate organic matter C under the Rye cover crop treatment. Over 8 years corn yields were not reduced in plots with a winter rye cover, under widely variable weather conditions. Overall, a rye cover crop had minimal impact on soil C but was an effective N management tool with no corn yield penalty.

Spratt, E., Jordan, J., Winsten, J., Huff, P., van Schaik, C., Jewett, J., Filbert, M., Luhman, J., Meier, E., & Paine, L. (2021). Accelerating Regenerative Grazing to Tackle Farm, Environmental, and Societal Challenges in the Upper Midwest. J Soil & Water Conservation. 76(1)15A-23A.

The authors present a review of research comparing and contrasting the environmental, societal, and economic effects of farming systems that incorporate animal grazing/pasure to more conventional farming row-crop agricultural systems that rely on animal confinement. Regenerative grazing is an agricultural practice that uses soil health and adaptive livestock management principles to improve farm profitability, human and ecosystem health, and food system resiliency. Regenerative grazing is a component of regenerative agriculture, which emphasizes reduction or elimination of synthetic inputs and tillage; increased diversity of plant, animal, and microbial life.

Stannard, M., Pan, W., Brunty, J. & Gillespie, R. (1998). Management of Residual Nitrogen with Cover Crops. USDA NRCS Technical Note No. 38. August. 5pp.

This is an agronomic best practices technical note addressing winter nitrogen leaching losses under a variety of crops. Number of cover crop recommendations are suggested, with specific species recommended to minimize leaching losses for sweet corn and potato rotations.

Staver, K., Brinsfield, R. , & Magette, W. (1990). Relating nitrogen uptake by cereal grainwinter cover crops to changes in groundwater nitrate concentration. In: Cover Crops for Clean Water Edited by: Hargrove, W. L. 77–78. Ankeny, IA: SWCS.

5-year study investigating nutrient transport from corn production systems in the mid- Atlantic Coastal Plain. Its primary objective is to evaluate the potential of cereal grain winter cover crops for reducing NO, leaching to groundwater. Following the 1988 corn harvest, we planted a rye (Secale cereale L.)Growth of the rye cover crop during the fall and winter following the 1988 corn harvest removed more than 134 pounds N/acre from the soil profile, substantially reducing the soil NO_3-N pool. Lysimeter samples collected at a 24-inch depth below the soil surface showed reduced NO_3-N levels in the soil profile.

Stevens, W., Hoeft, R., & Mulvaney, R. (2005). Fate of Nitrogen-15 in a Long-Term Nitrogen Rate Study: II. Nitrogen Uptake Efficiency. Agronomy J. 97(4):1046-1053

Recognizing from extensive past research that excessive N application reduces nitrogen use efficiency, the authors employed isotopic tracing to determine the fate of commercial nitrogen fertilizer in commercial corn-grain agricultural systems. Estimates of plant overall NUE (including all N sources) ranged from 31% - 69%, depending on the method of calculation and application rates. Fertilizer N accounted for an increasing proportion of crop N uptake as the N rate was increased, but soil N uptake was always more extensive, accounting for 54 to 83% of total plant N.

Stewart, J., Schwarz, G., Brakebill, J., & Preston, S. (2018). Catchment-level Estimates of Nitrogen and Phosphorus Agricultural Use from Commercial Fertilizer Sales. Scientific Investigations Report 2018–5145, U.S. Geological Survey, Reston, VA., 66Pp.

Stewart, et. al. (2018) used county and state fertilizer sales data from 2012 across the continental United States to evaluate patterns of Nitrogen and Phosphorus fertilizer sales, relative to metrics of agricultural land use and production. Geographic information systems (GIS) and geospatial modeling were used to generate maps of sales and use patterns at the county level, for every county in the nation, aggregated by river basins. Model predictions of fertilizer sales and mass used were tightly correlated with agricultural land use practices. Predictor variables for manure use showed importance of manure application as a substitute for commercial fertilizer.

Stika, J. (2010). A Soil Owner's Manual: How to Restore and Maintain Soil Health. Las Vegas, NV. 88 pp.

Essentially written as an "Owner's Manual" for soil, this book presents a concise explanation of soil science and the concept of soil health. Akin to the tasks and functions a healthy human being can perform, soil health encompasses all of the "goods and services" we ask of soils. The basic concepts of soil health are explained, along with examples, tools, and practices that an be employed to help rebuild healthy soils.

Stites, W. & Kraft, G. (2001). Nitrate and Chloride Loading to Groundwater from an Irrigated North-central U.S. Sand-plain Vegetable Field. *J. of Environmental Quality*. 30:1176-1184.

Authors monitored nitrate and chloride loading in a central sand irrigated vegetable field to potential for nitrate and chloride loading to shallow aquifer. A mass-balance budget method agreed well with the monitoring data. Nitrate-N loading exceeded 50% of plant available nitrogen, approximately 70% of the applied nitrogen fertilizer for sweet corn and potato crops. Additional fertilizer applications due to heavy rains contributed to higher losses. Significant nitrate loading to groundwater would continue, even with adherence to published recommended agronomic rates for these crops in this region. To meet the drinkingwater criteria of 10 mg/l, results indicate these loadings would need to be offset by 5-8 times as much land area with zero nitrate-nitrogen loading.

Stites, W.& Kraft, G. (2000). Groundwater Quality Beneath Irrigated Vegetable Fields in a North Central U.S. Sand Plain. *J. of Environmental Quality*. 29:1509-1518

The authors review expansion of irrigated agriculture for vegetable production in the central sands of Wisconsin. Authors monitored water chemistry up and down gradient from numerous vegetable fields over a 2-year period. Groundwater from fields had significantly greater concentrations of solutes, especially Ca, Cl, K, Mg, and NO3 differences, with concentrations 5 to 26 times greater than non-ag sites. Nitrate averaged 21 mg/l under fields, compared to 1 mg/l from non-field sites. The authors noted, that even fields with recommended best management practices in place, nitrate concentrations were nearly double the 10 mg/l drinking water criteria.

Stute,J., Shelley, K., Mueller, D., & Wood, T. (2007). Planting Winter Rye after Corn Silage: Managing for Forage. U.W. Extension Integrated Pest Management, NPM I-0907-5C, 4p. https://fyi.extension.wisc.edu/forage/planting-winter-rye-after-corn-silage-managing-for-forage/

Replicate field trails (2005 – 2006) from 3 experimental farms in Lancaster, Arlington, and Janesville Wisconsin documented Rye's ability to reduce the amount of soil nitrate. Despite frozen soil preventing leaching for much of the winter, rye can significantly reduce soil nitrate following fall manure application (nearly 50% reduction). This benefit occurs even if rye is not harvested and will help protect groundwater quality where heavy manure applications have been made. Manure applications following rye planting and emergence expanded manure application window and prevented planting delays. Liquid manure with excessive solids or heavy application rates slightly stunted Rye growth and development (Stute, et. al., 2007).

*TNC (2020). AgEvidence - the Impact of Agricultural Practices on Crops and the Environment, The Nature Conservancy, https://www.agevidence.org/

The Nature Conservancy (2020) funded the development of the interactive online database AgEvidence, to provide a user-friendly searchable database to present and summarize results of agricultural conservation research across the Midwest. While the database includes a vast array of conservation practices, results focusing exclusively on cover crops found their use as highly effective at reducing both nitrogen and phosphorus runoff (at least 30% overall), as well as reducing nitrate losses via leaching by 34%.

*Thapa, R., Mirsky, S., & Tully, K. (2018). Cover Crops Reduce Nitrate Leaching in Agroecosystems: A Global Meta-Analysis. *J. Environmental Quality*. November.

Cover crops are well recognized as a tool to reduce NO_3^- leaching from agroecosystems. However, their effectiveness varies from site to site and year to year depending on soil, cash and cover crop management, and climate. We conducted a meta-analysis using 238 observations from 28 studies (i) to assess the overall effect of cover crops on NO_3^- leaching and subsequent crop yields, and (ii) to examine how soil, cash and cover crop management, and climate impact the effect of non-leguminous cover crops on NO_3^- leaching. There is a clear indication that nonleguminous cover crops can substantially reduce NO_3^- leaching into freshwater systems, on average by 56%. Nonlegume–legume cover crop mixtures reduced NO_3^- leaching as effectively as nonlegumes, but significantly more than legumes. The lack of variance information in most published literature prevents greater insight into the degree to which cover crops can improve water quality. Among the factors investigated, we identified cover crop planting dates, shoot biomass, and precipitation relative to long-term mean precipitation as potential drivers for the observed variability in nonleguminous cover crop effectiveness in reducing NO_3^- leaching. We found evidence indicating greater reduction in NO_3^- leaching with nonleguminous cover crops on coarse-textured soils and during years of low precipitation (<90% of the long-term normal). Earlier fall planting and greater nonleguminous shoot biomass further reduced NO_3^- leaching. Overall, this meta-analysis confirms many prior studies showing that nonleguminous cover crops are an effective way to reduce NO_3^- leaching and should be integrated into cropping systems to improve water quality.

Thompson, L. (2019). Overview of Nitrate and Nitrate Poisoning. In: *Merck Veterinary Manual. 3p.*

An overview of veterinary diagnosis and care for livestock exposed to or suffering from nitrate poisoning. The etiology, clinical findings, diagnosis, treatment and control/remediation of nitrate exposure are covered. Many species are susceptible to nitrate and nitrite poisoning, but cattle are affected most frequently. Ruminants are especially vulnerable because the ruminal flora reduces nitrate to ammonia, with nitrite (~10 times more toxic than nitrate) as an intermediate product. Acute intoxication is manifested primarily by methemoglobin formation (nitrite ion in contact with RBCs oxidizes ferrous iron in Hgb to the ferric state, forming stable methemoglobin incapable of oxygen transport) and resultant anoxia. Secondary effects due to vasodilatory action of the nitrite ion on vascular smooth muscle may occur. The nitrite ion may also alter metabolic protein enzymes. Ingested nitrates may directly irritate the GI mucosa and produce abdominal pain and diarrhea. Although usually acute, the effects of nitrite or nitrate toxicity may be subacute or chronic and are reported to include retarded growth, lowered milk production, vitamin A deficiency, minor transitory goitrogenic effects, abortions and fetotoxicity, and increased susceptibility to infection. Chronic nitrate toxicosis remains a controversial issue and is not as yet well characterized, but most current evidence does not support assertions of lowered milk production in dairy cows due to excessive dietary nitrate exposure alone.

Undersander, D., Combs, D., Shaver, R., Schaefer, D. & Thomas, D. (2016). Nitrate Poisoning in Cattle Sheep and Goats. U of WI Extension. 7p.

Educational pamphlet for livestock owners describing the nature of excessive nitrate toxicity on common livestock in Wisconsin. Nitrate poisoning is a condition which may affect ruminants consuming certain forages or water that contain an excessive amount of nitrate. Horses are much less sensitive to nitrate toxicity since they are hindgut ferments and do not have a rumen. The mechanism of nitrate toxicity from drinking water is the same as for humans. Drinking water nitrate concentrations are most important for calves, heifers, and pregnant livestock. Excessive nitrates in forages is more problematic for juvenile and adult animals.

USDA. (2018a). Effects on Soil Water Holding Capacity and Soil Water Retention Resulting from Soil Health Management Practices Implementation. March. 30pp.

An agency literature review providing a broad summary on available water holding capacity and water retention as affected by soil health conservation practice implementation. Available Water Holding Capacity (AWC) relates to the total crop available water holding potential between wilting point and field capacity. Water retention (WR) relates to the actual amount of water retained in the soil for crop use. The concept of soil health practices is presented, along with examples of how these practices may influence the ability of soils to infiltrate, absorb, and retain water and nutrients. Cover crops, along with numerous other practices, are presented as an important tool to build soil health, improve aggregate stability and organic matter, improve infiltration, and optimize nutrient retention.

USDA. (2018b). Principles for High Functioning Soils. Natural Resources Conservation Service. February. 2p.

A two-page summary of the four principles of "soil health" intended for farmers and agronomists. An overview of the importance of; 1. minimizing soil disturbance, 2. Maximizing soil cover, 3. Maximizing biodiversity, and 4. Maximizing the presence of living roots year-round is presented. Cover crops are highlighted as a practice that contributes to all four of these principles and one of the most effective tools to protect soils, build soil health, and minimize nutrient losses to erosion and leaching.

USDA. (2018c). Iowa Agronomy Technical Note 38 (Cover Crop Management). USDA NRCS Iowa Technical Note 38. 6p.

A fact-sheet that describes the applications, benefits, methods, and challenges to using cover crops in midwestern agriculture. Example planting rates, seed mixtures, and method are presented to meet specific goals of producers including alleviating compaction, nitrogen fixation, grazing/fodder production, nitrogen sequestration, soil organic matter, and erosion control.

USDA. (2017). 2017 Census of Agriculture. National agricultural Statistics Service, https://www.nass.usda.gov/Publications/AgCensus/2017/index.php

USDA. (2016). Cropland Conservation Practices for Protecting Groundwater. Brochure. 4p.

A USDA brochure for farmers, agronomists, and local conservation staff specifically addressing agricultural practices that are protective of groundwater. Emphasis is on economical practices that have been found to be profitable, retain and enhance soil productivity and yields, and are specifically applicable to agricultural settings in the Minnesota region where groundwater quality and contamination are a known concern. Cover crops, and the NRCS 340 technical standard for cover crops are presented.

USDA. (2015). Cropland Conservation Practices to Protect Groundwater Sources of Drinking Water. Natural Resources Conservation Service, Des Moines, Iowa, 4p.

Ninety-two percent of Iowa's public water systems use groundwater as their source. Rainwater is the source of much of this water, which infiltrates and leaches nitrogen through Iowa's farmland. Landowner and farm operator decisions influence water quality, safety, treatment costs, and even drive the need to find alternative water sources to replace contaminated public and private water supplies. A three-prong approach is required to address groundwater nitrate pollution from agriculture: first, use nutrient management to avoid excessive use of nitrogen; second, trap nitrogen using cover crops; and third, build a resilient N management system using multiple conservation strategies and improve your soil's health.

USDA. (2014). Cover Crops Fact Sheet. Natural Resources Conservation Service, Wisconsin. 1p. May.

A cover crops factsheet intended for farmers and agronomists. Includes information specifically relevant to Wisconsin and describes many of the benefits and strategies for using cover crops. Specifically includes recommendations of using cover crops to protect soil from erosion, build organic matter, improve infiltration, minimize nitrogen losses to leaching and retain nitrogen for subsequent agricultural crops.

USDA. (2012). Cover and Green Manure Crop Benefits to Soil Quality. Natural Resources Conservation Service Wisconsin Agronomy Tech. Note 7.10p.

A federal technical note on using cover crops and green manure in Wisconsin. The note summarizes practices, standards, benefits, and methods of incorporating cover crops to protect soil from erosion, build organic matter, improve infiltration, minimize nitrogen losses to leaching and retain nitrogen for subsequent agricultural crops. Species recommendations, planting rates, benefits, soil characteristics, ability to build and store nitrogen, and other specifications are included.

USDA. (1998). Agronomy Technical Note No. 38: Management of Residual Nitrogen with Cover Crops. Natural Resources Conservation Service, Portland, OR. 5p. August.

Agronomy technical standard summarizing groundwater contamination data and a number of field trials to illustrate how fall-seeded cover crops can be an effective tool to minimize nitrate leaching losses and groundwater contamination. Performance of cover crops is described, along with challenges that led to reduced efficacy of cover crops to sequester nitrogen.

UW Discovery Farms (2019). Nitrogen Use Efficiency: A Guide to Conducting Your Own Assessment. UW Discovery Farms. 11 pp.

This document provides a step-by-step guide for farmers and Agronomists to assess nitrogen use efficiency on farm fields. The purpose if to help farmers maximize nitrogen use by crops, reduce the chances of wasting unnecessary nitrogen fertilizer,improve farm profitability and protect water quality. Efficient use of nitrogen is essential for crop production, whether the nitrogen source is commercial fertilizer, manure, legumes or some combination. Assessing the efficiency of N application on a per field basis is a valuable first step in evaluating your N fertilizer management plan. Calculating nitrogen use efficiency (NUE) can be relatively simple and offers insight into how N management can be altered in order to achieve economically optimum yields while reducing nutrient losses to the environment

UW Extension (2019). Nitrogen Use Efficiency: Statewide NUE benchmarking for Corn Grain and Silage. UW Extension Publication A4167. 12pp.

Efficient use of nitrogen (N) is essential for crop production, whether the N source is commercial fertilizer, manure, legumes or some combination. Assessing the efficiency of N application on a per field basis is a valuable first step in evaluating your N fertilizer management plan. Nitrogen use efficiency (NUE) calculations can be relatively simple and offer insight into how N management can be altered to achieve economically optimum yields while reducing nutrient losses to the environment. However, measuring your NUE is only useful if there are appropriate benchmarks for comparison. Wisconsin's unique management practices and soil types create a need for Wisconsin-specific benchmarks

Waggoner, A. & Arriaga, F. (2021). A Review of Published Research on Nitrate Leaching to Groundwater from Wisconsin Agroecosystems. DRAFT DNR Project Report, P.O. #37000-0000017232. 36 pp.

This is a DRAFT project report for WI Dept. of Natural Resources to UW-Madison, Dept. of Soil Science to conduct an independent review summarizing agronomic research in Wisconsin investigating nitrate leaching losses to groundwater and best farming practices that minimize nitrate leaching losses and improve nitrogen use efficiency. An initial search found only 14 studies in Wisconsin specifically reporting nitrogen losses under agricultural systems. The authors extended the study areas to include similar agronomic and physiographic regions in MI and MN, bringing the total number of studies up to 33, representing six different types of field/cropping operations, five soil textural classes, and fields that included a variety of irrigation practices. The reviewed research occurred over nearly five decades and included a broad array of experimental methods, measurements, climatic conditions, and trial methods. Most of the studies were of relatively short duration (e.g. a few growing seasons). Results from the studies were highly variable. One clear conclusion from the review was "Annual cropping systems, such as continuous corn or corn-soybean rotations, which generally have increased fertilizer inputs and fallow periods, have been consistently found to have increased NO3-N leaching compared to perennial systems. Within these annual systems, it has also been found that the corn phases of rotations tend to have higher proportional losses of NO3-N than other phases of the crop rotations."

Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking Water Nitrate and Human Health: An Updated Review. *International J. Environmental Research and Public Health*, *15*(7),1557. https://doi.org/10.3390/ijerph15071557

Historic research on Nitrate pollution of drinking water was done based on acute health effects and focused on a regulatory limit to protect against infant methemoglobinemia. Other health effects were not considered. With longer exposures to chronic levels of nitrates and improved research tools, we have learned risk of specific cancers and birth defects may be increased. This occurs through formation of *N*-nitroso compounds. Building on epidemiologic studies before 2005 and more than 30 new epidemiologic studies we evaluated outcomes from drinking water nitrate exposure including colorectal cancer, bladder, and breast cancer (three studies each), and thyroid disease (four studies). Considering all studies, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Many studies observed increased risk with ingestion of water nitrate levels that were below regulatory limits.

WDATCP (2020). Producer- Led Watershed Protection Grants Program Conservation Outcomes. Wisconsin Dept. of Agriculture, Trade and Consumer Protection. Program Fact-Sheet, 1p.

A one-page fact-sheet summarizing results of the Producer-Led Watershed Grant program, including farmers adopting conservation practices, such as cover crops, no-till, and nutrient management planning, to protect water quality and build soil health.

WDNR (2020). Year of Clean Drinking Water – 2019. WI Dept. of Natural Resources Report. 16pp.

A report by the WI Dept. of Natural Resources focusing on drinking water concerns as part of a Governor's initiative to improve drinking water quality across the state. The initiative focuses on a wide range of topics, however nitrate contamination of drinking water is one of the primary topics. A result of this initiative was initiating numerous investigations to document the nature and extent of groundwater nitrate contamination across the state, and a directive from the Natural Resources Board to the DNR to develop the Nitrogen Targeted Performance Standards rule.

WDNR (2017). Nitrate In Drinking Water. *WI Dept. of Natural Resources PUB-DG-001 2017. 2p.*

A 2-page pamphlet of information, compiled with the Groundwater Coordinating Council, written for the general public that explains nitrate contamination of drinking water This publication explains what nitrate is, how groundwater is contaminated by nitrate, risks to well contamination, the health risks of consuming nitrate contaminated drinking water, and resources for homeowners and the general public to asses and remediate private wells for nitrate contamination.

WDNR (2015). Groundwater Contamination Susceptibility Model (GCSM) for Wisconsin. *The ecological landscapes of Wisconsin: An assessment of ecological resources and a guide to planning sustainable management.* Wisconsin Department of Natural Resources, PUB-SS-1131-2015, Madison

The Groundwater Contamination Susceptibility Model (GCSM) for Wisconsin estimates the susceptibility of the state's groundwater to contamination from surface activities. The GCSM was developed by the DNR, the US Geological Survey (USGS), the Wisconsin Geological & Natural History Survey (WGNHS), and the University of Wisconsin – Madison in the mid-1980s. The results of the GCSM are illustrated in a map published in 1987 at a scale of 1:1,000,000

WDNR (2013). Wisconsin's Runoff Rules: What Farmers Need to Know. DNR Pub. No. WT 756 Rev 1/13. January. 2pp.

This "plain language" 2-page factsheet was written for farmers and agronomist and explains the NR151 agricultural runoff rules. The fact sheet summarizes agricultural standards and prohibitions, additional standards for unique circumstances, the Farmland Preservation Tax Credit program, implementation and financial assistance programs, and related permits and licensing requirements.

WDNR (1989). Groundwater Contamination Susceptibility in Wisconsin,1:1,000,000 map produced by WI Dept. of Natural Resources, UW Extension Geologic and Natural History Survey. 1p.

The map of groundwater contamination susceptibility in Wisconsin was developed based on physical resource characteristics identified as important in determining how easily a contaminant can be carried through overlying materials to the groundwater. These factors are type of bedrock, depth to bedrock, depth to water table, soil characteristics, and characteristics of surficial deposits. Whether an area will have groundwater contamination depends on the likelihood of contaminant release, type of contaminants released, and the sensitivity of the area to contamination. In turn, the likelihood of contaminant release depends on the type and intensity of land use and contaminant sources in an area. This map highlights areas sensitive to contamination and shows them in a generalized way. Some groundwater contamination in Wisconsin has occurred in Door County and in the central part of the state known as the Central Sands. Both areas are very sensitive to contamination because of the materials that overlie the groundwater. In many parts of Door County, there is thin soil on top of the bedrock that has large fractures leading directly to the groundwater. In the Central Sands, sandy soil on top of sandy glacial deposits allows water and accompanying contaminants to infiltrate quickly to the groundwater.

WDoH (2019). High levels of nitrate in drinking water can affect everyone. WI Dept. of Health Services Pamphlet P-02559 (12/2019). 2p.

Two-page infographic/digital pamphlet describing the health risks and effects of excessive nitrates in drinking water. These include blue babby syndrome, developmental disorders in-utero, neural and spinal birth defects, thyroid disease, and numerous cancers.

Weinert, T., Pan, W., Moneymaker, M., Santo, G., & Stevens, R. (2002). Nitrogen Recycling by Nonleguminous Winter Cover Crops to Reduce Leaching in Potato Rotations. Agronomy J. March. 94:2 365-372.

The authors conducted a 2-year study to evaluate the ability of winter cover crops to sequester nitrogen over winter and into spring, and provide subsequent nitrogen for potato crops. Cover crops were seeded following sweet corn. Cover crops sequestered nitrogen, but uptake rates were lower for delayed cover crop planting. Soil mineral N was reduced over-winter. Winter cover crops improved N cycling and reduced the amount of N below the root zone in potato-based rotations.

WGCC (2020). Wisconsin Groundwater Coordinating Council Report to the Legislature Fiscal Year 2020. Wisconsin Groundwater Coordinating Council, 183pp.

The report summarizes the annual operations and activities of the WGCC, describes the state of the groundwater resource and its management and makes recommendations. This is the most current report and covers fiscal year 2020 (July 1, 2019 – June 30, 2020). The breadth of the report covers all topics relating to groundwater, including use, quality, allocation, availability, etc. Specifically relating to Nitrogen and Nitrate pollution, Nitrate is Wisconsin's most widespread groundwater contaminant. Nitrate contamination of groundwater is increasing in extent and severity in the state. Most nitrate in groundwater (about 90%) is due to agricultural inputs, including manure spreading and fertilizer application.

WLWCA (2017) Food, Land and Water: Moving Forward. *Wisconsin Land and Water Conservation Association Workgroup Report*. Jim VandenBrook (eds.). 71pp.

The Wisconsin Food, Land and Water Project brought Wisconsin civic leaders together for a serious, in-depth discussion about the future of Wisconsin's food, land, and water. This was a chance for stakeholders of all kinds to come together, look beyond the present moment, see the big picture, and think about our shared resources in a more systematic and collaborative way. Conservation challenges and possible solutions were developed by workgroups on four critical topics: Surface Water Quality, Groundwater Quality, Groundwater Quantity (Central Sands), and The Future of Wisconsin's Working Lands. The workgroups involved a wide range of stakeholders, including representatives from agriculture, business, local communities, civic and environmental groups, government, and academia. Federal and state government representatives participated as advisors. Each workgroup met four times. The workgroup recommendations represent the general consensus of each workgroup. This report summarizes workgroup recommendations and workgroup reports, including key issues, goals and strategies.

Zhiming,Q. & Helmers,M.J. (2009) Soil Water Dynamics under Winter Rye Cover Crop in Central Iowa. *Vadose Zone Journal*, Feb (1):53-60.

Zhiming and Helmers (2009) evaluated the ability of cereal rye as a winter cover crop to sequester nitrate by planting into lysimeters and measuring drainage over 3 years. The Rye was planted in October and terminated in June. Nitrate leaching was reduced by 21% in May and June, and overall significantly lower compared to drainage nitrate from bare soil "control" plots over all 3 years. During height of growth in late spring, the rye consumed an average of 64% more soil water than the bare control plots.

Appendix 1: Technical Advisory Committee Members

Participant	Occupation	Representing	Area
Rick Adamski	Dairy Farmer	Wisconsin Farmers Union	Seymour, WI
Larry Alsum	Vegetable Farmer	Wisconsin Potato & Vegetable Growers Association	Friesland, WI
Donald Maum	Vegetable Farmer	Wisconsin Potato & Vegetable Growers Association	Friesland, WI
Andrew Aslesen	Source Water Specialist	Wisconsin Rural Water Association	Plover , WI
Eric Birschbach	Agronomist	Wisconsin Association of Professional Agricultural Consultants	Verona, WI
Ken Bradbury	Geologist	Wisconsin Geological and Natural History Survey	Madison, WI
Jed Colquhoun	Horticulture Professor	UW-Madison Department of Horticulture	Madison, WI
Eric Cooley	Co-director	Discovery Farms Wisconsin	Green Bay
Chase Cummings	County Conservationist	Wisconsin Land + Water	Menomonie, WI
Sarah Yang	Groundwater Toxicologist	Wisconsin Department of Health Services	Madison, WI
Scott Firlus	Agronomist	Wisconsin Agribusiness Association	Mauston, WI
~~Shannon Haydin~~	~~County Conservationist~~	~~Walworth Co.~~	~~Elkhorn, WI~~
Steve Hoffman	Agronomist	Wisconsin Association of Professional Agricultural Consultants	Manitowoc, WI
Eric Hurley	State Resource Conservationist	Natural Resources Conservation Service	Madison, WI
Kevin Krentz	Dairy Farmer	Wisconsin Farm Bureau Federation	Berlin, WI
Carrie Laboski	Soil Fertility Professor	UW-Madison Department of Soil Science	Madison, WI
Scott Laeser	Water Program Director	Clean Wisconsin	Madison, WI
Kevin Masarik	Groundwater Education Specialist	UW-Stevens Point	Stevens Point, WI
Maureen Muldoon	Hydrogeology Professor	UW-Oshkosh	Oshkosh, WI
Mark Witecha	Section Manager	Department of Agriculture, Trade and Consumer Protection	Madison, WI
Amber Radatz	Co-director	Discovery Farms Wisconsin	Pigeon Falls, WI
David Rebout	Corn and Soybean Farmer	Wisconsin Corn Growers Association	Janesville, WI
Katy Schultz	Dairy Farmer	Tri-Fecta Farms	Fox Lake, WI
Mike Stanek	State Agronomist	Natural Resources Conservation Service	Madison, WI
David Styer	Dairy Farmer	Alfalawn Farm	Menomonie, WI
Chris Newberry	Conservation Specialist	Rock County Land Conservation Department	Janesville, WI
Michael Tiboris	Clear Water Farms Director	River Alliance of Wisconsin	Madison, WI