Ten Ways

to Reduce Nitrogen Loads from Drained Cropland in the Midwest

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Introduction

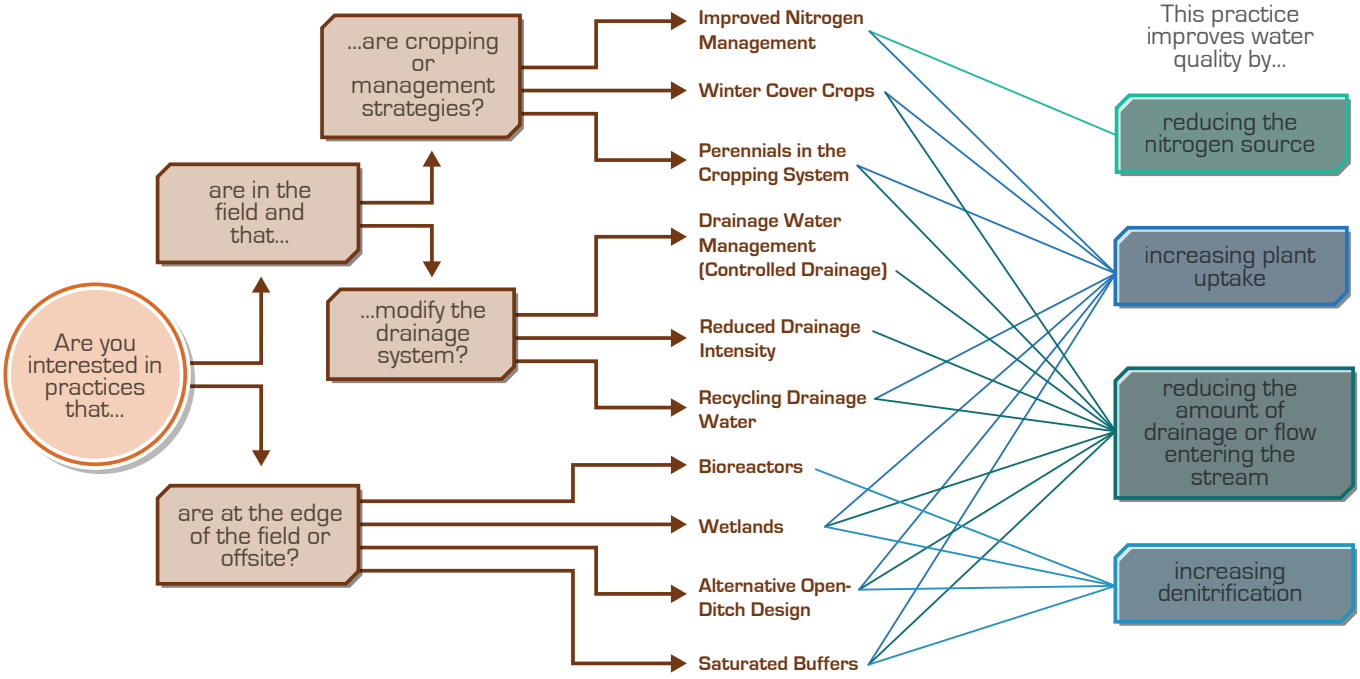
Agricultural drainage is an important contributing factor to high crop productivity in much of the Midwest. Modern crop production would not be possible in many parts of this region without artificial subsurface drainage. However, drainage is associated with an increase in nitrate loads to streams, rivers, and the Gulf of Mexico, where it contributes to the low oxygen or hypoxic zone (see Glossary). While the economic and environmental impacts of this "dead" zone make it one of the United States' largest national water quality concerns (USEPA, 2007), there is also reason to be concerned with nitrate in waters closer to home. For example, the city of Des Moines, Iowa operates one of the world's most expensive nitrate-removal facilities to treat local drinking water. Because of these water quality concerns at multiple scales, there is great interest in reducing nitrate loads from drained land.

Nitrate loads from agricultural lands drained with subsurface drainage occur for a number of reasons. Corn production is inevitably "leaky," since the precise amount of fertilizer needed by the crop cannot be known in advance. During the seven months (October through April) when no crop is growing in conventional corn-based rotations, nitrate in the soil is not taken up, and this nitrate can leach into drainage water. One way to reduce nitrate loads would be to reduce the amount of drained land, but this is unlikely due to the important role of drainage in midwestern agriculture.

Recent research is instead focusing on ways that cropping systems and drainage systems can be managed to reduce nitrate loads, while maintaining high agricultural productivity. This practice manual focuses on ten strategies for subsurface-drained corn-soybean systems that agricultural scientists and engineers have identified as being the most promising for reducing nitrate loads.

The nitrate load (also called nitrate loss) in drainage is the total amount of nitrate lost through a drain and is the product of the drainage water volume and the concentration of nitrate in that water (flow volume × concentration). The alternative practices described here reduce nitrate loads through two primary means: (1) reducing the nitrate concentration in the drain flow, or (2) reducing the amount of drain flow.

This publication first describes the complex processes that affect nitrate loads, and therefore need to be managed to decrease these loads and improve water quality. The ten promising practices are then described. The description for each practice includes an overview of the practice; how it reduces nitrate load; its effectiveness at doing so; where the practice is appropriate; the level of acceptance; and remaining questions and opportunities to make the practice more economical, more effective, or more likely to be adopted by agricultural producers.



Agricultural Drainage

Excess water is common in agricultural landscapes in the Midwest due to a greater amount of precipitation than is required by the crop during parts of the growing season, combined with soils that are slow to drain naturally. Agricultural drainage removes this excess water from the soil, which helps create a well-aerated root environment that enhances the availability and uptake of crop nutrients. Drainage of wet agricultural soils allows timely field operations and helps plant growth to begin early and continue vigorously, resulting in improved productivity.

Golden Rule of Drainage:

Drain only what is necessary for good trafficability and crop growth – and not a drop more.

Agricultural drainage can be implemented on the soil surface, in the subsurface, or as a combination of both. ***Surface drainage*** (see Glossary) is designed to remove standing water from the soil surface by means such as land leveling or the construction of shallow ditches and waterways. ***Subsurface drainage*** (see Glossary) is designed to remove excess water from the soil profile through a series of drainage pipes or tubing (often called "tile" due to its historic manufacture from clay tile) that are installed below the soil surface. Subsurface drainage pipes are typically installed just below the root zone, at a depth of 30 to 48 inches. Drain pipes may be regularly spaced (patterned tiled, at typical spacings of 30 to 100 feet) or only target particular areas of the field. The subsurface drainage network generally outlets to an open ditch or stream. This practice manual focuses on subsurface drainage.

Figure 1: *Drainage is implemented to allow crop growth on wet soils.*

Amount of drained agricultural land

The amount of cropland that has been drained is not precisely known, although various estimates have been developed through the years (Table 1). Regardless of the estimation method, four states (Iowa, Illinois, Ohio, and Indiana) each have more than 5 million acres with subsurface drains.

The percentage of drained land has not increased substantially in these states in recent years, since many of the current drainage installations intensify drainage on land that was already drained, rather than draining previously undrained land. However, new subsurface drainage systems are increasingly being installed in states and regions where subsurface drainage was historically less common, including North and South Dakota, northwestern Minnesota, and Missouri.

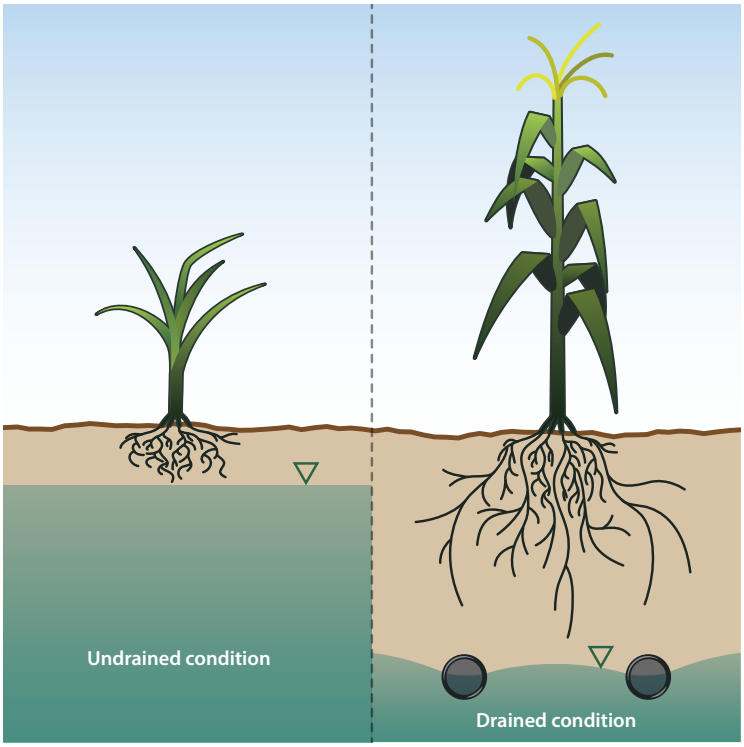


Figure 2: *Drainage helps roots grow deeper, enabling them to withstand dry conditions later in the season. Drainage tile spacing not drawn to scale.*

Nitrate loads from subsurface drained land

Subsurface drainage causes both positive and adverse water quality impacts. It reduces surface runoff, peak outflow rates, and soil erosion on cropland, compared to similar cropland that is not drained (Zucker and Brown, 1998; Robinson and Rycroft, 1999). Drainage, therefore, has the beneficial effect of reducing contaminant losses that are associated with surface runoff and erosion such as sediment, phosphorus, and pesticides. However, subsurface drainage exacerbates the transport of nitrate from the soil to surface waters. Because nitrate is a very soluble ion, it does not readily bind to soil particles and easily moves with water.

Numerous studies throughout the midwestern and southeastern U.S. and Canada document that the presence of a subsurface drainage system increases the movement of nitrate from fields to surface waters (see reviews by Skaggs et al., 1994, Fausey et al., 1995, Gilliam et al., 1999, and Blann et al., 2009). Annual average drainage water nitrate concentrations vary greatly from year to year due to precipitation and management differences, but values often exceed 10 mg nitrate-nitrogen per liter, which is the U.S. Environmental Protection Agency's standard maximum limit for drinking water. Sometimes drainage water nitrate concentrations exceed 20 or 30 mg NO_3^-N/L (Jaynes et al., 1999; Kaspar et al., 2007).

Table 1: *Estimates of subsurface-drained land based on three methods (from Sugg, 2007).*

	Pavelis, 1987[1] Total subsurface drainage		NRI, 1992[2] Total subsurface drainage		Sugg (2007) estimate[3] Total subsurface drainage	
State	million acres	% of all cropland	million acres	% of all cropland	million acres	% of all cropland
Iowa	8.9	33	6.0	22	8.8	32
Illinois	7.9	33	5.0	21	11.6	48
Ohio	5.8	49	6.7	56	5.7	48
Indiana	5.5	41	6.5	49	5.6	42
Minnesota	2.5	11	3.4	14	3.4	14
Michigan	2.1	26	2.3	29	2.3	29
Wisconsin	0.7	7	0.7	6	0.7	6
Missouri	0.7	4	0.1	1	0.6	3

[1] 1987 USDA report *Farm Drainage in the United States: History, Status, and Prospects.*
[2] National Resources Inventory (NRI), based on remotely sensed data at statistically sampled points. Newer versions available at www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/nra/nri/?cid=nrcs143_014196.
[3] Best estimate from a combination of soil drainage class with judgment of drainage experts and NRI information.

Figure 3: *A drain plow installing corrugated plastic tubing known as tile drainage. Vertical placement in the soil is guided by a laser system or GPS to ensure consistent grade.*

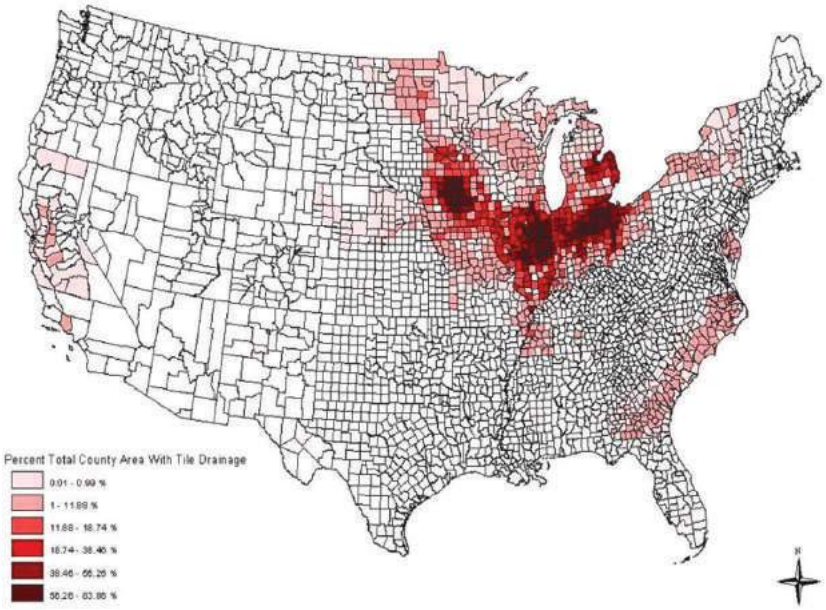


Figure 4: *Estimated subsurface drainage percentage, by county (from Sugg, 2007); darker colors represent greater percentages of a given county that is tile drained.*

Introduction

Factors Affecting Nitrate Loads from Drained Cropland

The nitrogen cycle is complex because nitrogen exists in many forms and can easily change from one form to another. A complete discussion of the nitrogen cycle is beyond the scope of this section, which focuses only on processes that affect nitrate loads in subsurface drains, as illustrated in Figure 5. Following this discussion, factors impacting the volume of drainage flow are explored, and then this Introduction closes with the basic principles underlying the ten strategies covered in this publication.

Nitrogen processes that affect the concentration of nitrate in drainage water

PROCESSES THAT INCREASE NITRATE IN THE SOIL

1. Nitrogen fixation (see Glossary)**:** The most abundant form of nitrogen in the world is gaseous nitrogen (N_2), because the atmosphere is composed of about 78% of nitrogen in this form. However, this form is not directly useable by plants. Nitrogen fixation is the process by which this atmospheric nitrogen can be converted to forms that plants can use. This process can be done biologically by microorganisms (such as by soil bacteria in symbiotic relationships with legumes) or it can result from lightning strikes.

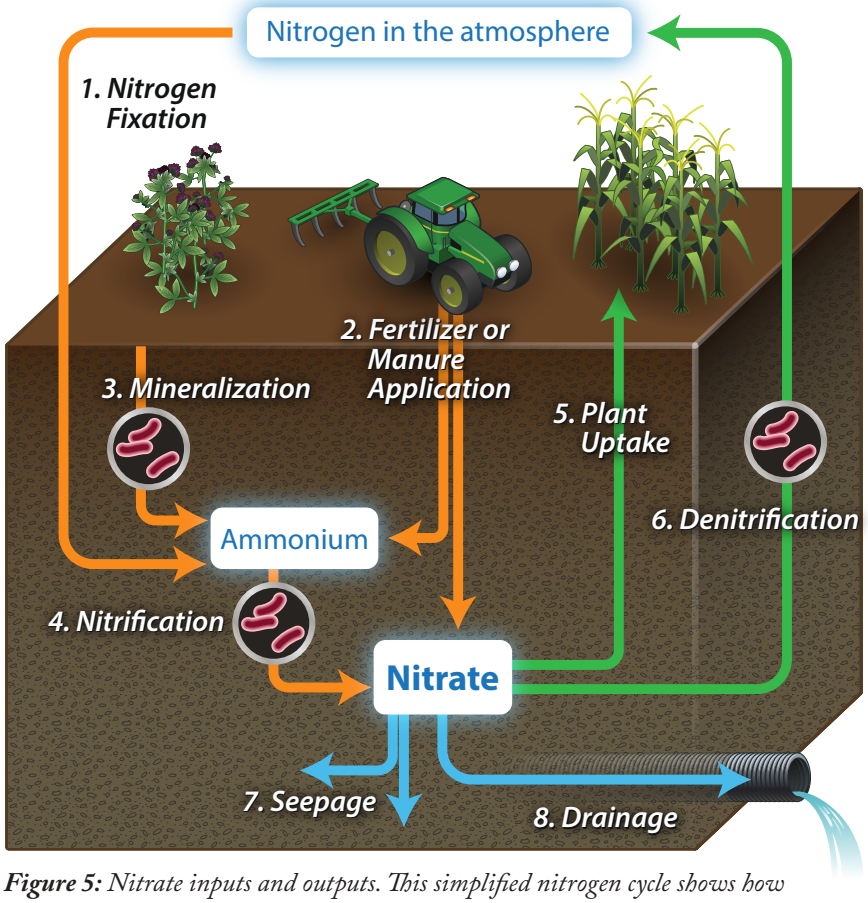


Figure 5: *Nitrate inputs and outputs. This simplified nitrogen cycle shows how nitrate becomes available to be lost in subsurface drainage. Inputs (orange arrows), outputs to plants and the air (green arrows) and outputs to water (blue arrows) are described below.*

2. Fertilizer application: Many forms of nitrogen are available for application, including inorganic commercial fertilizers (such as ammonium nitrate, urea, anhydrous ammonia, or UAN) and animal manure. Any of these will eventually be converted into nitrate for plant uptake, although the rate of conversion will vary by fertilizer type, soil, and climate conditions.

3. Mineralization (see Glossary)**:** Organic matter can be transformed into ammonium (NH_4^+) through the process of mineralization, or the conversion of an organic form of nitrogen to plant-available inorganic forms (both ammonium and nitrate). Mineralization of organic matter in many midwestern soils is moisture and temperature dependent, and contributes to N loads. Soil microbes mineralize organic nitrogen as they decompose organic matter.

4. Nitrification (see Glossary)**:** Ammonium (NH_4^+) in the soil can be transformed into nitrate by soil microbes, through the process of nitrification.

OUTPUTS TO PLANTS AND AIR

5. Plant Uptake: Nitrogen is the soil nutrient taken up in greatest quantity by plants and can only be taken up in the form of ammonium (NH_4^+) or nitrate (NO_3^-). Plants need nitrogen to grow and produce grain, and the amount of nitrate taken up by a crop is generally proportional to the yield. During times when no plants are growing, there is no nitrogen uptake which allows more nitrate to be available for leaching to drains during those periods.

6. Denitrification (see Glossary)**:** Under certain conditions, nitrate can be converted, or denitrified, into atmospheric nitrogen. Given anaerobic (low oxygen) conditions in either saturated soil or between soil particles in moist soil, certain soil microbes can use nitrate in place of oxygen for respiration. This results in denitrification of the nitrate to nitrogen gas (N_2 or N_2O, nitrous oxide). Because denitrification is a biological process, it is controlled by soil temperature, soil water content, and the availability of a food/energy source, that is, a carbon source.

OUTPUTS TO WATER

7. Seepage: When the soil is saturated, water can seep either laterally to neighboring fields or to a ditch, or vertically through the bottom of the soil profile into groundwater. Because nitrate is highly soluble, it is transported easily with seepage water. In well-drained soils, seepage occurs at rates that are high enough to remove excess water and keep the soil at sufficient moisture content for crop growth. In poorly drained soils, a restricting layer of soil, such as a fragipan or "hardpan," may prevent seepage, resulting in soil that is excessively wet for crop growth.

8. Drainage through subsurface drains allows excess soil water to leave the field. This process has been made very efficient in the last five decades, enabling farm fields to quickly export excess water. Highly soluble nitrate is transported with the drained water into ditches, streams, and rivers. Some of the alternative practices described in this practice manual work by reducing the amount of drain flow. The processes involved are detailed below.

Hydrologic processes that affect the amount of drain flow

Neglecting the complex impact of soil type (for this publication), the amount of drain flow depends on the amount and interaction of other components of the water cycle or water balance. Precipitation (and irrigation in some areas) is the source of all water in this balance and, as such, it usually has the greatest influence on drain flow. Incoming

precipitation water has five different potential fates, as shown in the water balance equation:

Precipitation = Surface Runoff + Evapotranspiration + Seepage + Storage in the Soil + Drainage

Drainage flow can be decreased through an increase in any of the other four flow paths. Surface runoff is determined by the soil, slope, and land cover, while ***evapotranspiration*** (see Glossary) is influenced by weather, the plants that are growing, and management factors (for example, tillage). For more information, see the publication *Soil Water Concepts* (Sands, 2001).

Figure 6 depicts some of the interrelationships between hydrologic (or water) processes and agricultural production practices that help explain the occurrence of periods that are vulnerable for nitrate leaching. The installation of subsurface drains shortens the flow path for infiltrating water (and nitrate) to reach a stream or lake and reduces the potential for denitrification in the soil. These management and production factors cumulatively increase the potential for nitrate to be in abundant supply and to be moved offsite with drainage water.

Characteristics of the drainage system also affect drain flow. The depth and spacing of subsurface drains determines the system's ***drainage intensity*** (see Glossary). This term refers to the rate at which excess soil water can be removed by the drainage system. Higher drainage intensity leads to increased drain flow and nitrate loads.

Some factors influencing nitrate loads cannot be controlled by producers. Key examples are the amount and timing of precipitation as well as ***mineralization*** (see Glossary) of nitrogen in the soil. These uncontrollable factors can strongly influence the magnitude of nitrate loads on artificially drained soils.

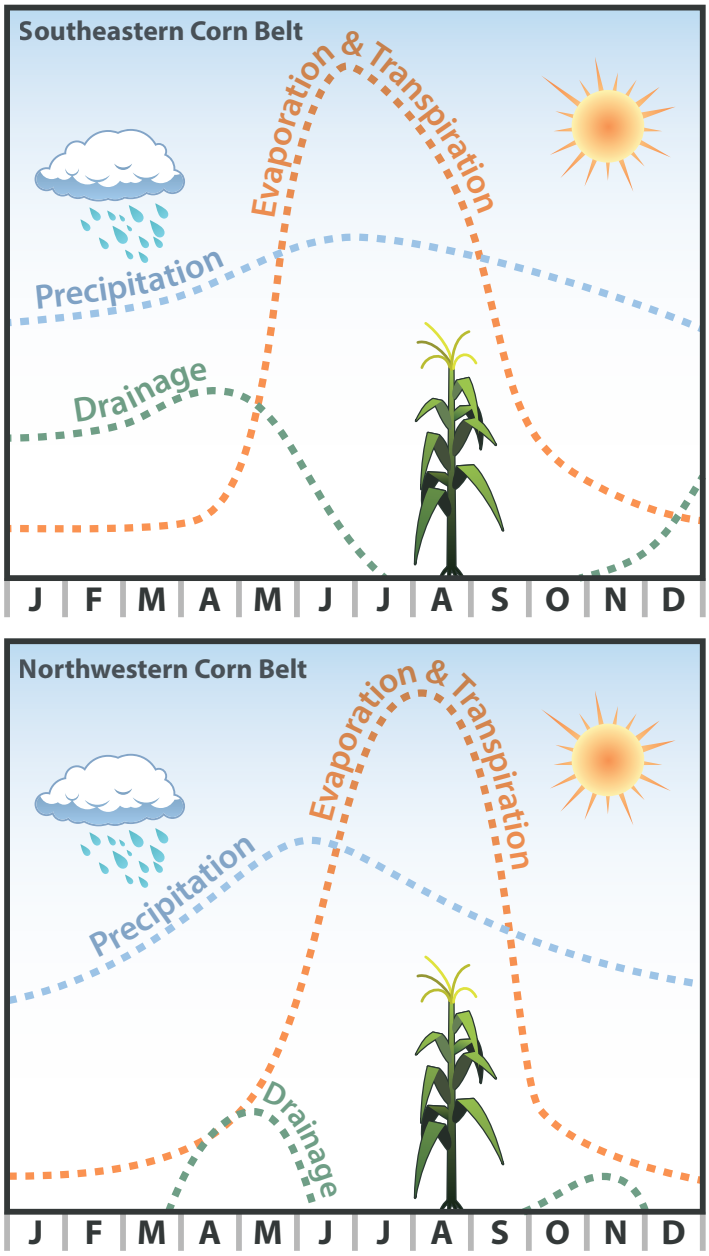


Figure 6: *Generic components of the annual water balance for midwestern conditions. Evapotranspiration (orange line) exceeds precipitation (blue line) during the height of the growing season, but at other times, precipitation exceeds evapotranspiration, leading to excess soil water and drain flow (green line). Southeastern examples include Indiana and Ohio, and northwestern examples include North and South Dakota.*

How the alternative practices reduce nitrate loads

All the strategies discussed in this practice manual rely on two basic methods for reducing nitrate in drainage outflow. Nitrate loads can be reduced by (1) reducing the concentration of nitrate in the drainage water and/or (2) reducing the amount of drain flow that arrives at the outlet. These two aims can be achieved through various biological, chemical, or physical processes, including the following:

1. Reduce nitrogen sources

The rationale here is simple: if less nitrogen is available in the soil, less will be lost. The practice described here as Improved Nitrogen Management has this goal. This practice is difficult to fine-tune, however, due to crop nutrient needs that change throughout the season and year to year.

2. Increase nitrogen uptake by plants

The fact that there is little or no living vegetation on the soil for seven or more months of the year in conventional midwestern cropping systems is a significant alteration from pre-agricultural conditions. Increasing nitrogen uptake by plants in the non-growing season through use of winter cover crops or ***perennials*** (see Glossary) or through edge-of-field and off-site vegetation in saturated buffers, open ditches, and wetlands helps decrease the nitrate concentration in drainage bound for streams and rivers.

Figure 7: *From the air, it is apparent that small wet depressions called "prairie potholes" are widespread over much of the northern and western Midwest.*

3. Reduce drain flow

Because nitrate loss depends on both nitrate concentration and flow, reducing the total amount of drainage flow is a very important strategy. Many of the practices discussed here use this method to improve water quality. Drainage water management (***controlled drainage***—see Glossary), wider drain spacing, shallow drains, recycling drainage water, and practices that allow plants to uptake increased amounts of soil water decrease the amount of drain flow, thereby decreasing nitrate load.

Figure 8: *Subsurface drains eventually connect to outlets and ditches that transport cumulative drainage flows to streams and rivers.*

4. Increase denitrification

Drainage nitrate concentrations can be reduced by taking advantage of the natural process of denitrification. Practices like bioreactors, wetlands, saturated buffers, and improved open ditch design can provide good environments for denitrifying microbes to live in. These environments allow nitrate in drainage water to be converted to nitrogen gas when there is a sufficient carbon source for the microbes and when low oxygen conditions are maintained.

Practices that Reduce Nitrate in the Plant Root Zone

1. Improved Nitrogen Management

Figure 9: *Fertilizer application rate, timing, form, and other factors can affect drainage nitrate loads.*

What is improved nitrogen management?

The four most widely known improved nitrogen (N) management practices are termed the "4R" practices, and aim to identify if the Right nitrogen source was applied at the Right rate, at the Right time, and in the Right place. These and other N management factors have complex agronomic and environmental impacts, thus only rate of N applied, time of N application, and use of a nitrification inhibitor are covered here. These improved N management strategies work together in different ways to reduce loss of nitrate in drainage water.

Rate of N application: Applying the proper rate of N has a greater influence on drainage water nitrate losses than any other N management factor including application timing, placement, source, or nitrification inhibitors. Many studies show drainage nitrate concentration and loading decrease as N fertilization rate decreases. When choosing an N rate, producers often consider factors such as soil characteristics (texture and organic matter content), previous crop, and tillage system, along with the potential for achieving optimal agronomic yield and profit and environmental stewardship. Determination of the proper rate may be enhanced by new methods of monitoring to determine crop nitrogen status. Site-specific technologies may be useful in assessing spatial variability and matching nitrogen rate to site-specific crop needs.

Time of application: Water quality studies often show application of N in spring is better than in fall because the time between application and plant uptake is decreased. Although this practice can affect drainage nitrate losses, the magnitude of loss is highly dependent on the amount of precipitation and resulting drainage in the spring; in other words, spring timing of N

Improved nitrogen management reduces nitrate loads by:

Reducing nitrogen source (rate)

or

Increasing plant uptake (timing, inhibitor).

application will provide relatively greater benefit in years with wetter winter/pre-planting conditions. The water quality impact of fall vs. spring N application can also be influenced by latitude. For example, this practice may be relatively more beneficial in southern locations that experience more winter drainage nitrate losses.

Nitrification inhibitors: Nitrification inhibitors, such as nitrapyrin (N-Serve®), are sometimes added to ammonium fertilizers to retard or slow the conversion of ammonium to nitrate (that is, ***nitrification***—see Glossary) after application (see Figure 5). Because ammonium is more tightly held by the soil, it is less susceptible to loss in drainage than nitrate. This ability to hold nitrogen in the soil until the plants are ready to use it can potentally both increase yield and reduce nitrate losses to drainage water. However, such agronomic and environmental benefits of nitrification inhibitors have been mixed, largely because their effectiveness is closely tied to N loss conditions, including soil type and weather. These benefits will be greatest in situations where there is potential for large drainage nitrate losses to occur before the inhibitor becomes inactive through degradation by soil microbes.

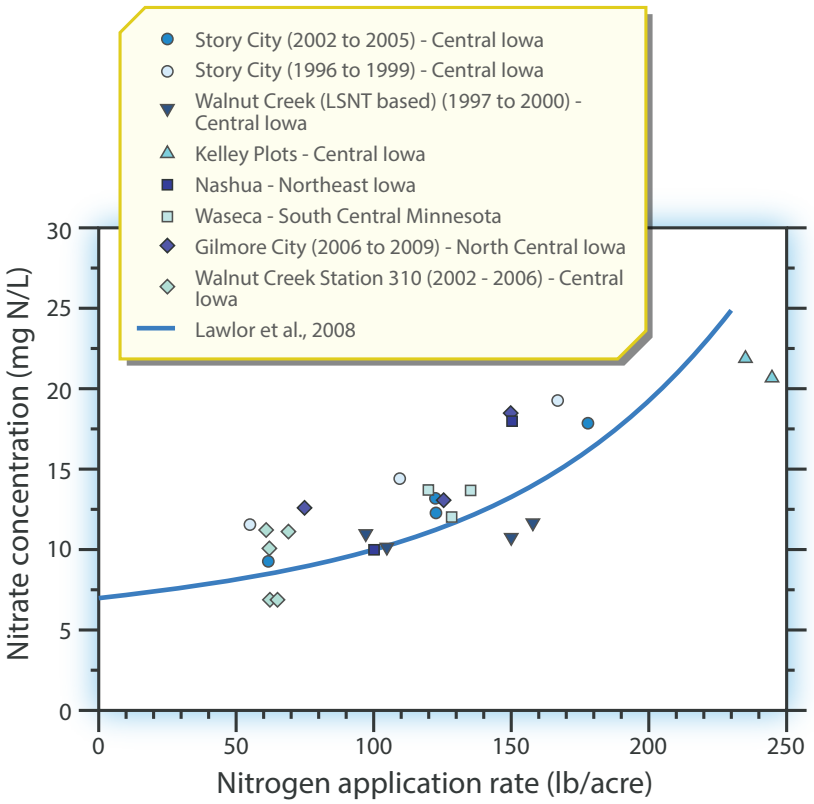


Figure 10: *Relationship between corn fertilizer application rate and concentration of nitrate in drainage water from various corn-soybean rotation studies in Iowa compared to the drainage-flow response curve developed by Lawlor et al. (2008)(from Iowa State University Science Team, 2012).*

How effective is improved N management?

The effectiveness of the practice of reduced application rate will be a function of the initial rate and revised rate (see Figure 10). For the practice of spring N application timing, Randall and Vetsch (2005) found that nitrate losses in subsurface drains could be reduced by more than 30% with spring application compared to fall, but a recent review showed a much more moderate average reduction of 6% (Iowa State University Science Team, 2012; primarily based upon studies from Iowa and Minnesota).

Where does improved N management work?

In general, at least one improved N management practice is appropriate everywhere. Improved N management is often considered the "lowest hanging fruit" for water quality improvement, though implementation of these practices alone will likely not be sufficient to meet all water quality goals.

Level of acceptance

These N management practices have been the focus of agricultural extension and outreach work for decades. However, current research suggests that although work in this area should continue, there are limits to the water quality benefits better N management alone can provide.

Questions and opportunities

Other improved N management practices include crediting nitrogen mineralization through post-planting soil sampling, reducing variability of fertilizer application equipment, application based on precision agriculture management prescriptions, and chlorophyll monitoring (Dinnes et al., 2002). While each of these is gaining recognition, research continues to refine this suite of improved N management practices to maximize agronomic and environmental benefits.

Specifically regarding the practice of improved N application rates, studies conducted over a wide range of climates, soil types, crops, and year-to-year precipitation variability are needed to confirm the relationship between N rate applied and resulting drainage nitrate concentration. In terms of policy development, this is likely to be highly sought-after information.

Additionally, there is a need for and an opportunity to conduct N management research in concert with the study of various drainage design systems (see, for example, the Reduced Drainage Intensity and Drainage Water Management sections) and different cropping systems (see the Cover Crops and Perennials sections). Drainage water quantity (and thus nitrate loads) can be greatly affected by drainage system design and cropping system; thus, research should consider this "entire system" approach.

Useful N Management Links

4R Nutrient Stewardship Information
http://www.nutrientstewardship.com/

Corn Nitrogen Rate Calculator (Iowa State University Extension)
http://extension.agron.iastate.edu/soilfertility/nrate.aspx

2. Winter Cover Crops

Figure 11: *Cover crops take up nitrate during the season when no annual crop is in the field (photo: Dan Jaynes).*

What are cover crops in the Midwest?

Cover crops, sometimes called "catch crops," are crops that cover the soil during the winter. They are planted in the fall and grow until the soil freezes. Some cover crops can overwinter and need to be killed using herbicides or tillage prior to planting the main crop in the spring. Others do not survive the winter, and therefore have the advantage of not needing to be killed in the spring; however, these types of cover crops often do not produce as much growth, resulting in less overall water quality benefit. Possible cover crops in the Midwest include small grains (oat, winter wheat, barley, triticale, and winter rye), legumes (alfalfa, hairy vetch, and clover), grasses (annual ryegrass), and brassicas (oilseed radish, oriental mustard, and winter canola).

How do cover crops improve water quality?

Cover crops can significantly reduce nitrate losses by taking up water and nitrate from the soil after the main crop is harvested in the fall, and before the main crop starts to use significant amounts of water and nitrogen in the spring. As these are times when nitrate losses in subsurface drains can be very high, the reduction in nitrate loss can be considerable. By extending the season of active water and nutrient uptake beyond that of annual grain crops, nitrate losses to drains can be reduced.

How effective are cover crops?

Research shows the reduction in nitrate load due to a cover crop has ranged from 13% in Minnesota to 94% in Kentucky (Table 2). While the effect of site-specific conditions has not yet been well tested, reductions in nitrate losses due to cover crops are likely greater for high organic matter, poorly drained soils. In general, cover crop improvement of water quality depends on growth and establishment. Cover crop establishment and growth can be limited by lack of rainfall, poor soil conditions at planting, or late planting of the cover due to delays in harvesting the grain crop.

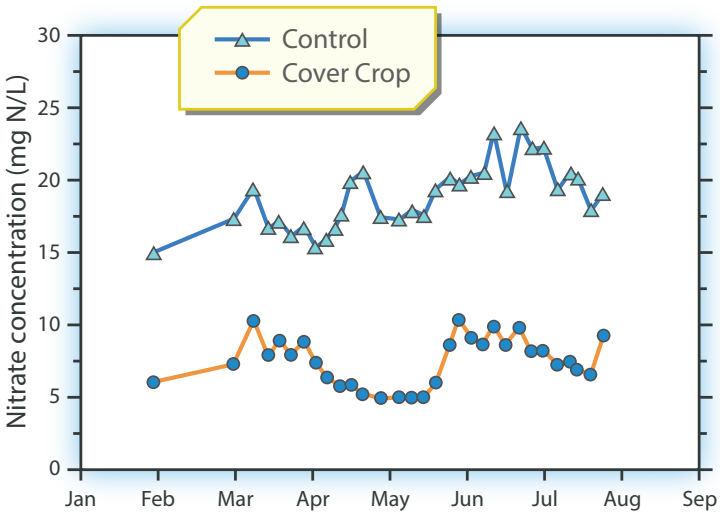


Figure 12: *Cover crops can significantly reduce nitrate concentrations in drainage (from Kaspar et al., 2007).*

Table 2: *Reductions in nitrate-N leaching due to rye or ryegrass winter cover crops (from Kaspar et al., 2008).*

Reference	Location	Cover crop	Reduction in N leaching
Morgan et al., 1942	Connecticut	Rye	66%
Karraker et al., 1950	Kentucky	Rye	74%
Nielsen & Jensen, 1985	Denmark	Ryegrass	62%
Martinez & Guirard, 1990	France	Ryegrass	63%
Staver & Brinsfield, 1990	Maryland	Rye	77%
McCracken et al., 1994	Kentucky	Rye	94%
Wyland et al., 1996	California	Rye	65-70%
Brandi-Dohrn et al., 1997	Oregon	Rye	32-42%
Ritter et al., 1998	Delaware	Rye	30%
Kaspar et al., 2007	Iowa	Rye	61%
Strock et al., 2004	Minnesota	Rye	13%
Kladivko et al., 2004	Indiana	Winter wheat + less fertilizer	61%

Where do cover crops work?

The reduction in nitrate loss depends on the amount of growth of the cover crop, so areas with a longer potential growing season after harvest are likely to benefit more from cover crops. Research generally indicates that the greatest reduction of nitrate load occurs when the cover crop has good fall establishment and growth in an area where drainage is greatest from January through March (for example, in Indiana). In areas where drainage flow initiates later in the spring (March to April), as in the more northern midwestern climates (for example, Minnesota), cover crop reductions in nitrate loss can occur if good growth of an overwintering cover crop occurs over both fall and early spring.

As with any crop in the Midwest, there can be considerable year-to-year variation in cover crop establishment and growth depending on weather in a given year. In northwestern portions of the region, fall establishment and growth are often problematic due to cool temperatures and dry soils in the narrow window between harvest and when the soil freezes. Even in these areas, however, cover crops can still be very effective when used with a short-season vegetable crop, corn silage, seed corn, or small grain. Additionally, although not as effective as planting directly into the soil, aerial seeding or overseeding of cover crop into standing crops before harvest can be successful with experience and timely rainfall.

Cover crops reduce nitrate loads by:

Increasing nitrogen and water uptake outside the annual crop growing season.

Additional benefits

Cover crops have many additional benefits beyond reducing nitrate in drainage waters. Often times, drainage water quality has not been the main driver for cover crop establishment. Many farmers use cover crops to improve soil physical properties and reduce compaction, increase soil organic carbon, recycle nutrients, and improve weed control. Cover crops are also very effective at reducing soil erosion caused by both wind and water. Legumes used as cover crops fix nitrogen as an added benefit. Brassica covers appear to suppress nematodes, some diseases, and winter annual weeds.

Level of acceptance

Due to these numerous benefits, cover crops are a popular conservation topic across the Midwest. However, implementation has been limited, with only 11% to 12% of farmers having grown a cover crop between 2000 and 2010 (Singer, 2008; ISU Extension, 2012). The recently formed

Cover crops can also reduce erosion and improve soil quality.

Midwest Cover Crops Council aims to increase adoption of this practice through efforts such as development of cover crop support tools to help producers make decisions suitable for their locations.

Questions and opportunities

Some key cover crop research needs include the following:

- Development of better adapted cover crop cultivars or species, especially in more northern (colder) and western (drier) climates
- Management strategies for more rapid fall establishment
- Information on long-term nutrient cycling and whether fertilizer rates can be reduced due to improvements in soil organic matter and nutrient cycling
- Proper accounting of the multiple environmental benefits of cover crops and modification of models and outreach information to include these benefits.

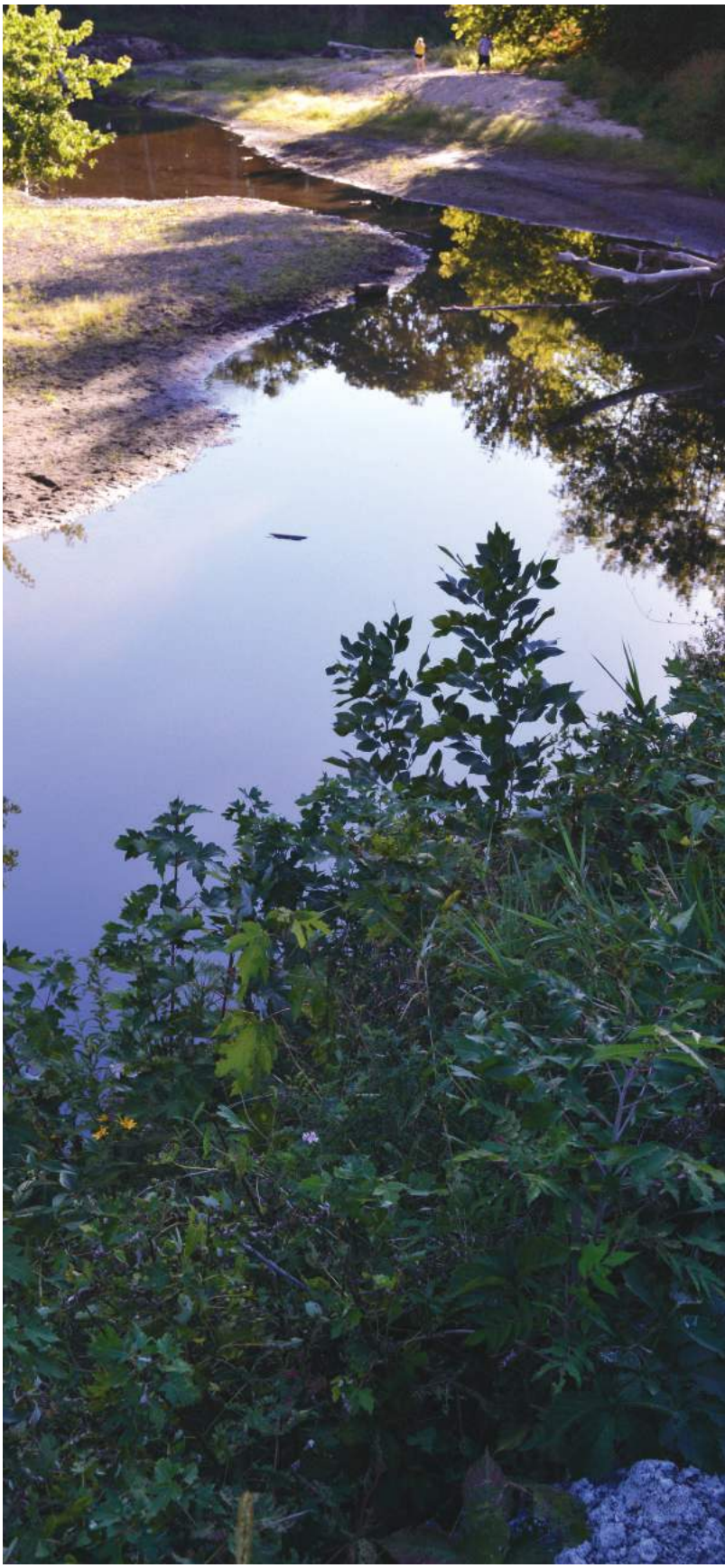
More Information on Cover Crops

"Innovator Profiles"—Experiences of 40 different farmers using cover crops:
http://www.mccc.msu.edu/innovators.html

Midwest Cover Crops Council (MCCC):
http://www.mccc.msu.edu/

USDA Plants Database Cover Crops information
http://plants.usda.gov/about_cover_crops.html

Are you covered? Minnesota Department of Agriculture
http://www.mda.state.mn.us/news/publications/protecting/conservation/coverforerosion.pdf



Practices that Reduce Nitrate in the Plant Root Zone

3. Increasing Perennials in the Cropping System

Figure 13: *Alfalfa is a perennial crop that was historically grown in much of the Midwest, but has largely been replaced by annuals (photo: Alfalfa – NREL 04084).*

What are perennials in midwestern cropping systems?

Reducing fertilizer rate is sometimes assumed to be the surest way to reduce nitrate loads, but the crops grown also exert great impact on nitrate losses. Perennials are plants that can grow for two or more years without re-planting. Midwestern agricultural landscapes before the 1960s typically included perennial crops like alfalfa that were used for livestock feed in mixed crop and animal agricultural systems. However, most farms today are highly specialized, resulting in the majority of the midwestern landscape providing only annual crops (usually corn and soybeans).

Annual row crops generally have much higher nitrate losses than perennial crops, and nitrate concentrations and losses are generally greatest for continuous corn and lowest for multiple years of alfalfa or grass sod crops. Perennial grass crops are the least "leaky" cropping system because they absorb N whenever soil mineralization is occurring. An example of these differences is shown in Table 3.

The major challenge for increasing the use of perennials in cropping systems is to identify crops that can be grown economically and are marketable. The most common or promising perennial crops include the following (Kaspar et al., 2008):

- forages (grasses and legumes) planted for hay, grazing, or pasture
- trees and woody species grown for nut, fruit, or wood production (apples, grapes, hazelnuts, poplars, and walnuts)
- perennial biomass crops (trees, shrubs, and grasses including poplar, willow shrubs, and switchgrass)
- perennial grains and oil seed crops (Illinois bundle-flower, wheat, sunflower, and flax)

Perennial grass crops are the least "leaky" cropping system.

Table 3: *Nitrate concentration and load from several different cropping systems.*

	Flow-weighted nitrate-N concentration (mg/L)		Nitrate-N load (lb/ac)	
Cropping System	Iowa[1]	Minnesota[2]	Iowa[1]	Minnesota[2]
Continuous corn	28	32	49	49
Corn-soybean	18	23	23	45
Soybean-corn	15	26	25	45
Alfalfa		2.3		1.6
CRP[3]		1.4		1.0

[1] Concentration means from a three-year study averaged across four tillage systems; adapted from Weed and Kanwar, 1996.
[2] Four-year study; adapted from Randall et al., 1997.
[3] Conservation Reserve Program grass (bromegrass, orchardgrass, and timothy): alfalfa mix.

Cellulosic or second-generation ethanol production has the potential to greatly increase perennial biomass crops as an economic strategy for midwestern agriculture.

How do perennials improve water quality?

In typical corn and soybean fields, water and nutrients are generally used by growing plants only between May and September. The long non-growing season during the other seven months of the year results in higher stream flow and nitrate loss than when perennial forage crops were historically more common. Adding perennial crops that can be economically grown in midwestern agriculture could reverse this trend through greater annual uptake of nitrogen and water.

Figure 14: *Cellulosic biofuels may provide an opportunity to grow perennials, such as the switchgrass shown here (photo: NREL 00204).*

Perennials reduce both drainage flow and nitrate loads by extending the season during which water and nitrate are removed from the soil. Compared to annual crops, perennials are able to continue using water and nitrogen much later into the fall/winter (until the soil freezes), and begin their uptake processes very early in the spring.

It also bears noting that less frequent tillage of perennials relative to annual crops reduces mineralization of soil organic matter, thus additionally reducing nutrient loss as the nitrogen is held longer in the organic form. The more established and extensive root systems of perennials are able to scavenge nutrients from a larger soil volume.

How effective are perennials?

Research in many states has shown that perennial crops result in reduced nitrate losses in drainage water. In Minnesota, unfertilized alfalfa lost 96% less nitrate over a year than continuous corn (Table 3: Randall et al., 1997).

However, management of forage or pasture using high rates of fertilizer or manure or intensive grazing may result in substantial nutrient losses. Killing, plowing down, or stresses such as drought can cause nitrogen losses from legume perennial forages or pastures, unless another crop or cover crop is present for nitrogen uptake.

Where do perennials work?

Most perennial crops are capable of being grown almost anywhere in the Midwestern region, but realistically their adoption is limited by availability of on-farm utilization, markets, processing facilities, and infrastructure. Although forage crops can be widely marketed, there may be limited local markets and high transportation costs in areas where row crops dominate and livestock production is small. Moreover, a rapid and widespread conversion of land currently cropped with annuals to these forage crops could cause forage price declines due to market saturation and the law of supply and demand. Increased demand for bioenergy or niche goods like grass-fed meat and dairy products may help open new markets for perennials.

Additional benefits

In addition to reducing nitrate loads in drainage waters, increasing perennials in the landscape can also benefit water quality by reducing surface runoff. Perennial vegetation provides other environmental benefits, such as reducing soil erosion and enhancing the soil through additional organic matter and improved infiltration. Increased biological diversity in perennial systems can help provide some weed and pest protection.

Level of acceptance

Confidence is very high that perennial crops would significantly reduce nitrate losses compared with annual grain crops. Even if a perennial crop receives N fertilizer or manures at the same rates as an annual grain crop, the annual losses would still be expected to be less than that from the annual grain crop system because the perennial crop would take up water and nutrients over a larger portion of the year. However, as noted, the adoption of this practice is currently limited by market and infrastructure factors.

Questions and opportunities

Kaspar et al. (2008) provided a list of research needed to more fully integrate perennials into the landscape:

- Selection and breeding programs for new cultivars and species for use as perennials
- Discovery and development of products derived from perennial plants such as oils and starches
- New production, harvesting, transporting, and processing technologies
- Development of markets for perennial crop products
- Guidelines for site- and soil-specific application of these practices to target sensitive areas within fields or ***watersheds*** (see Glossary) susceptible to nutrient and sediment loss in order to provide the maximum environmental benefit
- New strategies for dissemination of information concerning these systems to overcome cultural and societal implementation reluctance
- Quantification of the direct and indirect ecological benefits of these systems in diverse locations over a number of years
- Watershed-scale implementation projects to assess overall potential for water quality improvement

Perennials reduce nitrate loads by:

Increasing nitrogen uptake by plants and reducing drain flow

by increasing nitrogen and water uptake outside the annual crop growing season

Special applications of perennials

Perennials in specific areas of the landscape can provide functionality and diversity in addition to many other benefits. Examples include the following:

Perennial strips: the practice of planting narrow strips of deeply rooted perennial forages (grass or alfalfa) directly over drainage lines or in strategic places within the field. A study by Russelle et al. (2006) showed well-established perennial strips grown over a drainage pipe lowered the nitrate concentrations in the drainage. Other work has shown that targeted placement of perennial prairie filter strips within row-cropped watersheds provided significant water quality improvement, removing greater than 90% of the surface runoff sediment load (Helmers et al., 2012).

Prairies as part of multifunctional landscapes: Prairies composed of warm-season grasses and forbs (or wildflowers) formerly covered the majority of the central U.S. Today, implementation of prairie perennials can be used to reduce erosion and nutrient pollution, enhance habitat for wildlife and beneficial insects, and store carbon in the soil, among other benefits (Jarchow and Liebman, 2010).

Riparian buffer (see Glossary)**:** a zone of perennial vegetation including trees, shrubs, and grasses or native vegetation located along a stream bank. These buffers can help restore stream functions and prevent stream bank erosion. See the section on "Saturated Buffers" for more detail on how riparian buffers can be used for drainage water quality improvement.

Windbreak: a row or rows of trees planted perpendicular to the prevailing wind. The trees provide a microclimate within the sheltered zone and can help reduce wind erosion.

Agroforestry timberbelt: a specific application of windbreaks where multiple-row field windbreaks are planted with commercially valuable, fast-growing trees to provide conservation benefits while also producing economically beneficial wood products. Strategic harvesting of half of the rows (for example, after 7 to 12 years) allows income while the other rows are left to provide continued wind protection.

Alley cropping: the practice of growing an annual crop and a more long-term tree crop simultaneously by placing the annuals in "alleyways" between widely spaced tree rows. This allows short-term income from the annual agricultural or horticultural crop as the tree crop (for example: walnut, oak, pecan) matures.

Living mulch: a groundcover crop or plant that is grown underneath the main crop to provide benefits normally provided by mulch such as weed suppression and erosion protection.

For more information on perennials in agricultural landscapes, see:

National Agroforestry Center:
http://nac.unl.edu/Working_Trees/infosheets.htm
http://nac.unl.edu/Working_Trees/index.htm

Perennial Strips at the Neal Smith National Wildlife Refuge: www.prairiestrips.org

Incorporating Prairies into Multifunctional Landscapes Extension Publication: https://store.extension.iastate.edu/ItemDetail.aspx?ProductID=13357

Practices that Reduce Delivery of Nitrate to the Field's Edge

4. Drainage Water Management (Controlled Drainage)

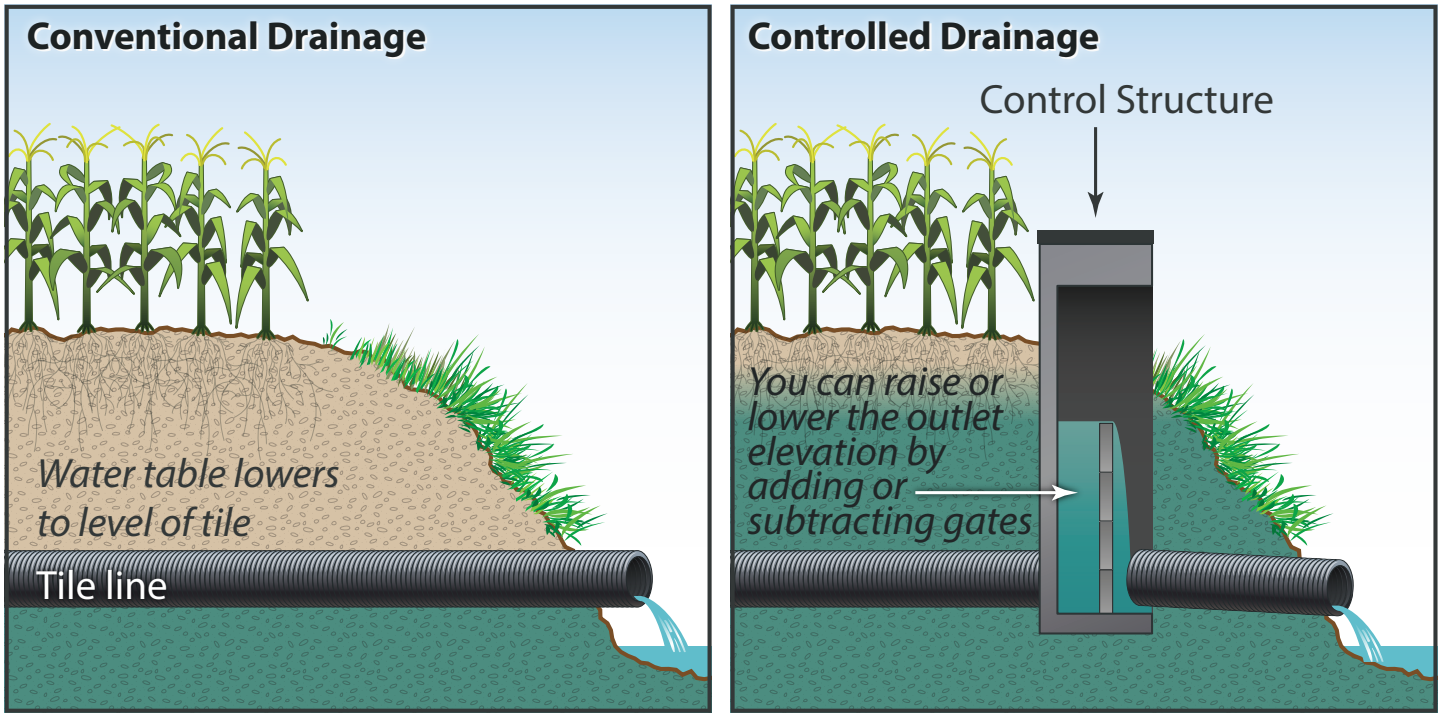


Figure 15: *Drainage water management, also known as controlled drainage, uses control structures to retain drainage water in the soil during periods of the year when drainage is less critical.*

What is drainage water management?

Drainage water management (or controlled drainage, terms which are used interchangeably here) consists of the use of adjustable, flow-retarding structures placed in the drainage system that allow the outlet level (or water depth) to be adjusted (see ***"control structure"*** in Glossary). Because the water table must rise above the outlet level before drainage will occur, shallower water table depths occur, holding more drainable water in the soil profile. Raising the outlet level during portions of the year when drainage is less critical reduces the overall amount of drainage (Figure 15).

A typical management scenario to reduce nitrate losses and improve crop production would involve these steps:

- Raise the outlet level after harvest to reduce drainage and nitrate loss during the non-growing season

- Lower the outlet prior to spring (and, if necessary, fall) to improve trafficability and to allow field operations
- Raise the outlet (within an acceptable limit) following spring field operations to potentially store water from early season rains for use later in the growing season.

How does drainage water management improve water quality?

Subsurface drainage systems are typically designed to remove up to 1/4 to 1/2 inch of "excess" soil water per day (that is, the ***drainage coefficient***—see Glossary). Subsurface drainage systems typically have free flowing outlets, so drainage occurs as long as the water table is above the elevation of the pipes. Since the optimum water table depth for most crops is in the range of 18 to 36 inches (Evans and Fausey, 1999), drainage may continue long after the water table has been lowered sufficiently to satisfy crop requirements. Thus, the intensive drainage system that is necessary to remove excess water during the wettest periods may remove more water than is necessary at other times. This "overdrainage" results in more outflow and transport of nitrate to surface waters than is necessary to achieve optimum drainage requirements for crops.

The dominant mechanism for reduction of nitrate loss from controlled drainage is the reduction in drainage volume (see reviews by Skaggs et al., 1994; Evans et al., 1995; Gilliam et al., 1999). Simply conserving drainage water in the field also retains nitrate in the field. Additionally, it was thought that by retaining water in the soil, controlled drainage may increase anaerobic conditions and thus increase denitrification of nitrate. However, the contribution of denitrification to the total reduction in nitrate loads with controlled drainage is small compared to the contribution of flow reduction.

How effective is drainage water management?

Drainage water management provides an average net decrease in nitrate loads of approximately 30% in the Midwest, though this can range from generally 15% to 75%.

Where does drainage water management work?

Controlled drainage is most practical on relatively flat fields with average slopes of less than 0.5%, although there is no absolute limit on slope. Because one structure is typically recommended for every 1 to 2 foot change in field elevation, flatter slopes require fewer control structures. As the slope increases, the number of control structures necessary to maintain a uniform water level increases and usually becomes economically prohibitive when the land slope exceeds 0.5% to 1%. New drainage systems can be designed specifically to optimize drainage pipe layout and control structure placement; however, existing drainage systems can also be retrofitted with controlled drainage structures.

Drainage water management reduces nitrate loads by:

Reducing drain flow.

The successful use of controlled drainage rests on satisfying two important objectives: (1) achieving optimum production efficiency and maximum nutrient utilization by the crop and (2) attaining maximum water quality benefits.

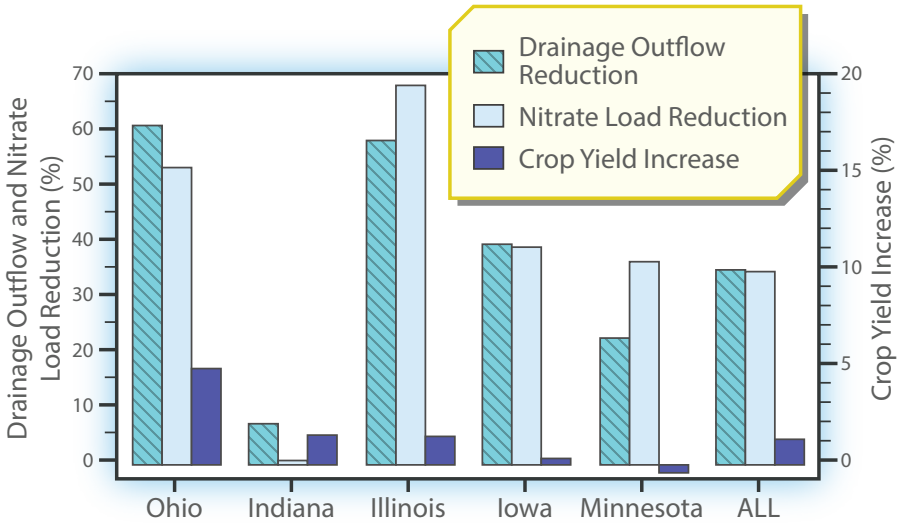


Figure 16: *Average drainage flow and nitrate load reduction (left axis) and crop yield impact (right axis) due to controlled drainage (ADMC and NRCS, 2013).*

Under some conditions, productivity, water quality, or both goals may need to be mutually compromised for the benefit of the other. The target water table level should be selected depending on the crop and its stage of development, the need to access fields with equipment, and prevailing weather conditions. By maintaining the water table behind the control structure risers (or stop logs), during non-cropping periods, efforts can be made towards nitrogen reduction goals with no adverse production impacts.

Additional benefits

One potential additional benefit of drainage water management is crop yield enhancement. However, research on this is limited and has been inconclusive to date. Computer modeling has shown a long-term yield benefit of up to 5% is possible in the Midwest, but not in every year. The benefit of the water saved depends on the rainfall amount and distribution during the growing season coupled with the water requirements of the crop. Controlled drainage has the greatest production benefit where drought conditions are intermittent and of short duration. Actual water storage provided by a controlled drainage system depends on the drainage intensity, drainage system layout, and soil drainable porosity.

Level of acceptance

While the technical feasibility of controlled drainage is well documented, it has not been widely adopted in the Midwest. The impact of slope upon cost effectiveness has partially limited controlled drainage's overall adoption, although Jaynes et al. (2010) estimated 24 million acres of cropland in the Midwest, or 12.5% of cropland in this area, may be suitable for this practice.

Questions and opportunities

Controlled drainage has been shown to reduce nitrate loss primarily through reduction in drainage volume. However, there are still several current and future research questions remaining:

- Where do the nitrate and water that are not lost through the drainage system go? Most likely the water ends up in deep or lateral seepage and the nitrate may be denitrified, but the extent of these processes is not known.
- To what extent does this practice increase surface runoff?
- To what extent are emissions of nitrous oxide, a greenhouse gas, increased due to potentially increased denitrification caused by controlled drainage?
- What are crop responses to controlled drainage for conditions across the midwestern U.S.?
- Can we develop accurate and reliable evaluation tools to extend results from isolated controlled drainage field studies to the watershed scale?
- How can we improve design and management strategies to optimize the water quality benefits of controlled drainage at the field, farm, and watershed scales?

More Information on Controlled Drainage

Questions and Answers about Drainage Water Management for the Midwest:

http://www.extension.purdue.edu/extmedia/WQ/WQ-44.pdf

5. Reduced Drainage Intensity

Advancements in technology, particularly over the past 35 years, have changed the economics of farm drainage and contributed to an intensification of drainage on agricultural lands. The advent of laser and ***GPS*** (see Glossary) guidance technologies, computer-aided design tools, corrugated polyethylene drainage pipe, and the drainage plow has revolutionized the installation of drainage systems. Due in part to these advances, farmers have found it economical to drain intensively, decreasing drainage spacing and increasing water removal rates, to minimize the production risks associated with excess water.

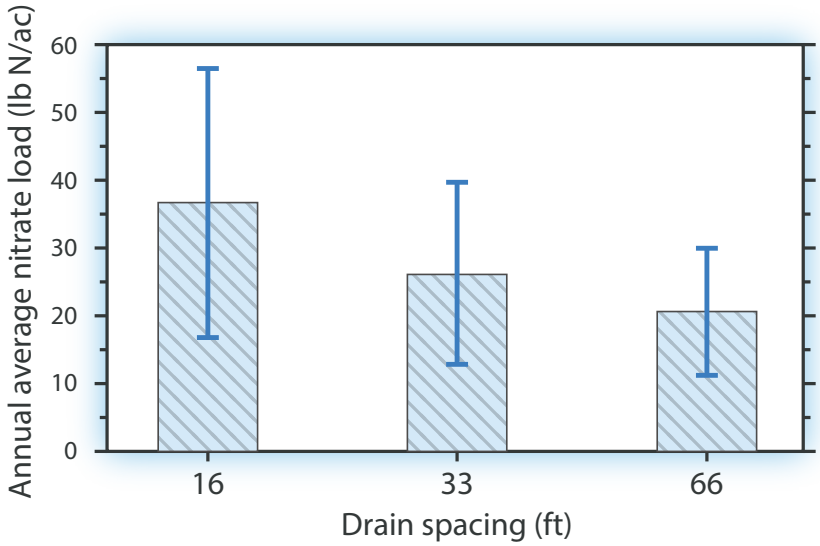


Figure 17: *Increasing the spacing between drainage pipes can help reduce drainage nitrate loss (from Kladivko et al., 2004).*

The practice of reduced drainage intensity can be achieved through installation of subsurface drains either with wider spacing or closer to the surface than conventionally done.

What is wider drain spacing?

Drainage design often starts with the selection of a desired water removal rate or drainage coefficient. A combination of drain spacing and depth is then selected to achieve this desired rate, based on soil physical properties. Research has shown that nitrate loss increases with higher drainage intensities, so decreasing the spacing between drains typically results in higher nitrate loss. Although the increased nitrate loss is a concern, the practice of drainage has nevertheless increased in recent years due to the desire to decrease the risks associated with excess soil water. Decreasing drainage to the minimum needed for economical crop production through the use of wider drain spacing has the potential to reduce nitrate loads from drained land.

What is shallow drainage?

Shallow drainage simply means using an average drainage depth shallower (for example, 30 to 42 inches) than the traditional 36- to 60-inch installation depth. Essentially the practice of shallow drainage maintains a "wetter" soil profile while still providing for crop needs. Drain spacing must be reduced for

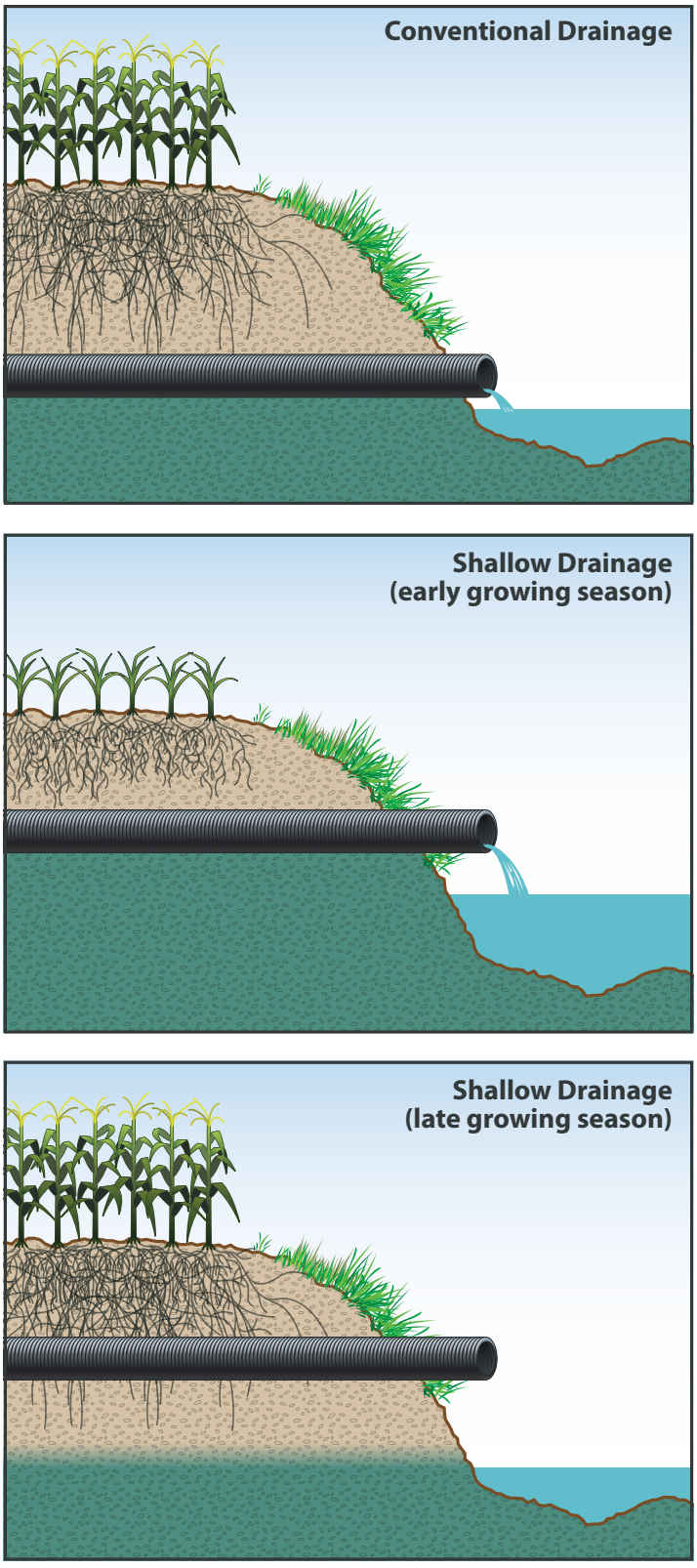


Figure 18: *Shallow drain placement removes less excess water than conventional drainage, but still meets crop growth needs.*

shallow systems, however, to achieve water removal rates equivalent to deeper systems. In addition, a minimum drain installation depth (about 24 inches) must be maintained for adequate cover to prevent drainage pipes from being crushed by equipment, and sufficient depth must be used to promote adequate crop root development.

How does reduced drainage intensity improve water quality?

These two drainage design strategies result in less total water drained, meaning less nitrate is transported from the field. Sometimes, reducing the volume of subsurface drainage, as these practices are intended to do, can result in increases in surface runoff; if these surface runoff increases are proportionate to the lower drainage volume, there will likely still be an overall reduction in nitrate loads. However, if drainage volume reductions result in significantly increased deep seepage below the drains, nitrate loads may not be reduced, just delayed in timing. Changes in annual drainage volumes due to these design modifications will depend on site-specific factors such as soil type, soil structure, and rainfall characteristics.

Another potential mechanism for reducing nitrate loads from shallow drainage systems is increased denitrification. Shallow drainage may increase the depth of saturated soil in the root zone, creating anaerobic conditions more favorable for denitrifying bacteria. Research to date, however, has not demonstrated significant denitrification benefits from shallow drainage systems.

Wider drain spacing and shallower drain placement reduce nitrate loads by:

Reducing drain flow.

How effective are these practices?

Research shows annual nitrate loads can be reduced with shallow drainage and wider drain spacing (Figure 19). Research from both Minnesota and Illinois shows an approximately 20% load reduction for drains placed at depths of 3 feet rather than 4 feet (Sands et al., 2008, Cooke et al., 2002). Computer modeling has shown that nitrate was reduced by roughly 15% when the drain depth was changed

from 4 feet to 3.5 feet, and was reduced an additional 20% by changing the drain depth from 3.5 feet to 3 feet (at 40 feet spacing; Yuan et al., 2011). Modeling has also shown increasing the drainage spacing from 40 feet to 50 feet reduces nitrate loads by approximately one third (Yuan et al., 2011), though field results have been more modest with research from Indiana, showing a 22% decrease in nitrate loads with 66 feet rather than 33 feet spacing (Kladivko et al., 1999).

Where does reduced drainage intensity work?

The primary advantage of these practices is that, in contrast to drainage water management, they can be practiced wherever drainage systems are installed. In other words, no minimum/maximum slopes, soil types, or specific climates are required. As old drainage systems are routinely replaced throughout the Midwest, shallow drainage or wider drainage spacing can potentially be put into practice.

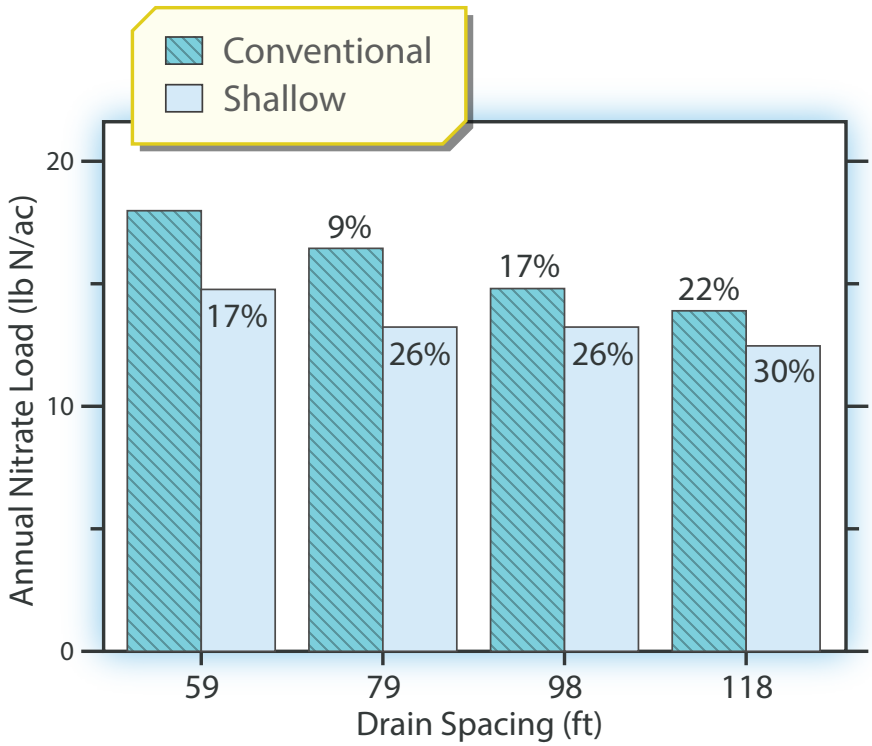


Figure 19: *Modeled nitrate losses for reduced intensity drainage systems. The percentages refer to the difference in nitrate loss compared to the conventional depth at the 59 ft spacing (the far left bar). "Conventional" and "Shallow" refer to 4 ft and 3 ft drainage depths, respectively (from Luo et al., 2010).*

Level of acceptance

The potential benefits and costs of shallow drainage, while based on sound theory, must be proven in the field before widespread application can be recommended. The practice is still in the research phase, and thus, has not experienced significant adoption levels. Additional capital costs are required with shallow drainage because of narrower drain spacing. These costs must either be offset by crop benefits of the system (for example, yield increases in dry years) or subsidized by society as a cost associated with improved water quality. However, an advantage of reduced drainage intensity practices over some other nitrate-reduction practices is that once installed, no additional maintenance or actions are needed to obtain the environmental benefits.

Questions and opportunities

Although these are new practices and research continues to fully quantify the benefits of wider drain spacing and shallow drainage, tools are in development to help drainage designers make the selection of drainage intensity more precise. The following questions are being addressed in current research programs in Illinois, Indiana, Minnesota, and Ohio through both field studies and computer modeling:

- What are the long-term, annual drainage flow impacts associated with these practices?
- How do these practices affect crop yields in wet, dry, and average climatic years?
- How much denitrification occurs with shallow drainage? And if significant denitrification occurs, is nitrate converted to benign nitrogen gas (N_2) or nitrous oxide (N_2O), a greenhouse gas?
- As with controlled drainage, what is the fate of the water and nitrogen not removed with drainage?

Practices that Reduce Delivery of Nitrate to the Field's Edge

6. Recycling Drainage Water

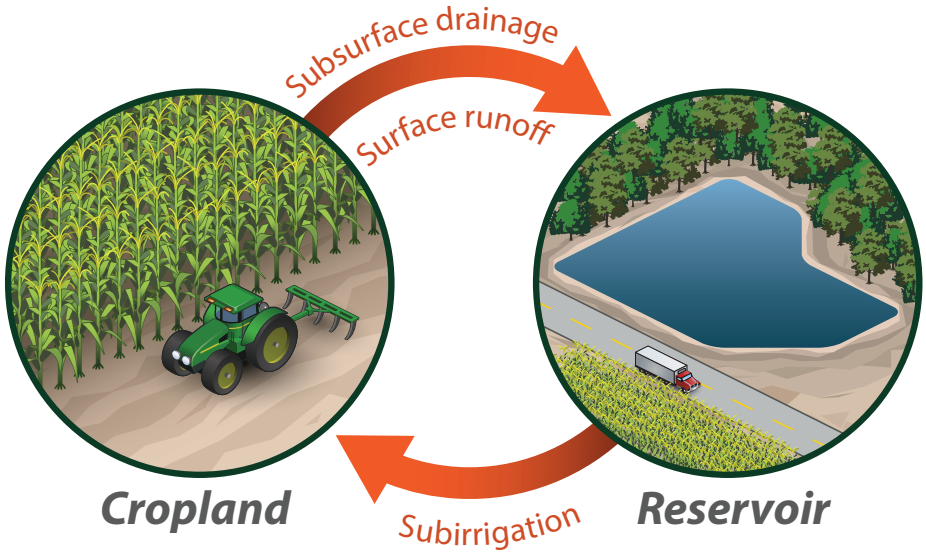


Figure 20: *Schematic of a drainage recycling system.*

What is drainage water recycling?

Drainage water recycling is the practice of storing drainage water in a pond or reservoir, and then returning it to the soil through irrigation during dry periods. In conventional drainage situations (when drainage water is not recycled) drainage water is routed to a channel to move it off site as quickly as possible, which means the water is no longer available to meet future crop needs. Although excess soil water is prevalent during the late winter and spring period in midwestern agriculture, soil water deficits during the late summer often limit grain production. During these times, having access to the drainage water that was routed away earlier in the season would be advantageous.

Drainage water recycling requires an initial construction and infrastructure investment. On-site storage of drainage water requires construction of a pond or reservoir, which takes some land out of production, and may require pumping facilities to move the drainage water to the reservoir and/or back to the soil. Pumping needs depend mainly on the type of irrigation practice chosen for applying the water to the soil and the location of the storage reservoir within the landscape (see, for example, "***subirrigation***" in Glossary). Site selection, sizing, and design are important considerations that require technical assistance.

How does drainage water recycling improve water quality?

Recycling the drainage water can reduce or even potentially eliminate nitrate loss, by reducing or eliminating the water that leaves the site. Even if some water does leave, there are several additional opportunities for nitrate loads to be reduced within this system. Because sufficient water is available to meet crop needs, nitrate in the soil will be more completely used in the production of increased biomass and grain. There should be minimal nitrate remaining in the soil profile at the end of the growing season, thus less leaching of nitrate during the non-growing season. Additionally, if a reservoir-wetland system is implemented (see the case study on p. 28), a portion of any nitrate reaching the wetland will be used by the vegetation present in the constructed wetland and may be removed by the process of denitrification, thus further reducing nitrate losses.

How effective is drainage water recycling?

Drainage water recycling has the potential to completely reduce drainage flow to surface waters and thus also to completely reduce nitrate loads. However, although research results have been promising, this is a new practice for which greater understanding of design, management, and overall benefits is required before it will progress beyond the demonstration phase.

Drainage water recycling reduces nitrate loads by:

Reducing drain flow.

Where does drainage water recycling work?

Drainage water recycling can be used in many midwestern crop production systems. The size of the water storage reservoir will be the limiting factor in most situations, meaning this practice will be most practical for relatively small scale agricultural systems. For example, storing 4 inches of runoff and drainage water from 100 acres requires a storage capacity of 33 acre-feet. This volume equates to construction of a 3 acre pond with an average depth of 11 feet. Therefore, to significantly reduce the off-site delivery of water and nitrate from a water-quality perspective, a large number of water storage reservoirs will be needed across the landscape.

Using the recycled water for irrigation of high value crops such as fresh market vegetables and fruits, rather than agronomic crops, makes the system more practical and cost effective. Even so, it is likely that the entire drainage contributing area would not receive recycled water through irrigation. This is because, in years when irrigation is required, the irrigation needs of the crop typically exceed the amount of drainage water available on a per acre basis.

Additional benefits

Drainage water recycling in Ohio has enhanced crop productivity especially during drier growing seasons (Figure 21).

Level of acceptance

Because this concept is relatively new, it is still largely in the farmer-managed field-scale demonstration phase, and has not been marketed widely to growers. The requirement of infrastructure capital expenditure for drainage water recycling may impede this practice's acceptance except perhaps for high value crop applications.

Questions and opportunities

There is great potential for improving water quality with drainage water recycling, but much more research is needed before this practice can move beyond the demonstration phase. It is thought yield enhancement benefits may help increase interest in this practice as work in this field moves forward.

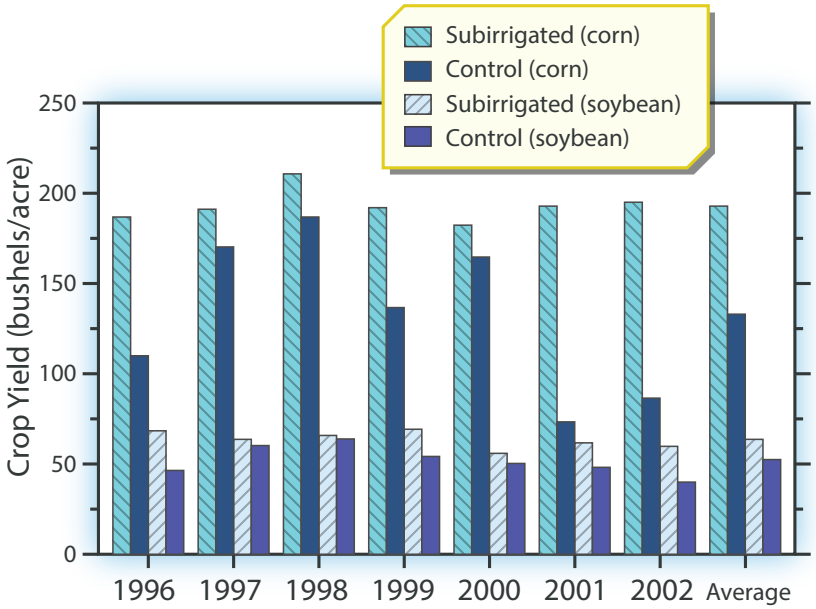


Figure 21: *Crop yield for corn and soybeans, with and without subirrigation using a drainage recycling system.*

Case Study: Recycling Drainage Water Combined with a Wetland

Researchers in Ohio have developed a drainage water recycling approach that is called Wetland, Reservoir, SubIrrigation System, or WRSIS. This system directs surface runoff and subsurface drainage water to a constructed wetland where there is opportunity for some sediment and nutrient removal from the water. As the water leaves the wetland, it is moved to a storage reservoir, where it remains until it is needed to meet crop water needs. In this system, the water is distributed back to the field using the subsurface drainage pipes in what is called subirrigation. This WRSIS is in use on two private farming enterprises, and the farmers are pleased with both the economic aspects of the system and the associated wildlife habitat that the wetland provides. For more information, see:

http://www.ars.usda.gov/sp2UserFiles/Place/36040000/WRSISfactsheet.pdf

http://hostedweb.cfaes.ohio-state.edu/usdasdru/WRSIS/wrsishome.htm

Practices that Remove Nitrate at the Edge of the Field or Downstream

7. Bioreactors

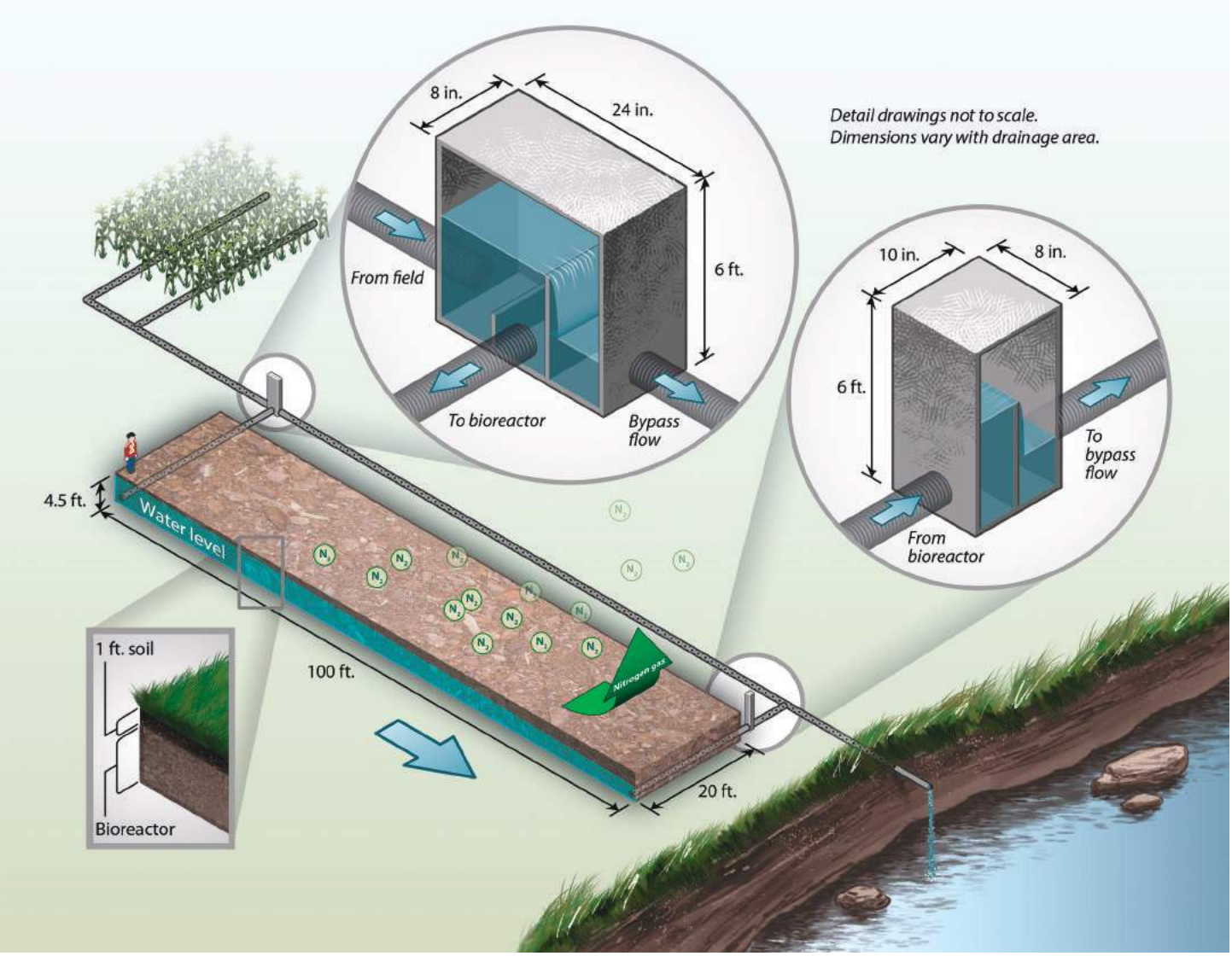


Figure 22: *Denitrification bioreactors are an edge-of-field water quality improvement option that enhances the natural process of denitrification (from Christianson and Helmers, 2011). This illustration shows only one orientation of a bioreactor by a field; a bioreactor could easily alternatively be aligned parallel to the stream and would likely be placed to best match a given site and drainage system.*

What are bioreactors?

Bioreactors are trenches filled with a carbon source, usually wood chips, through which drainage water is routed. Sometimes called a "woodchip bioreactor," this practice treats the water by enhancing the natural, biological process of denitrification. Most bioreactors use control structures to manage how the drainage water moves within the trench (Figure 22). The inlet structure allows water to be diverted into the bioreactor and also some water to bypass the bioreactor during periods of high drain flow. Incorporation of a bypass line means normal drainage will not be impeded. The outlet control structure allows the outlet level to be raised or lowered to maintain deeper or shallower depths of water in the bioreactor.

How do bioreactors improve water quality?

Denitrification bioreactors reduce nitrate in drainage water by significantly enhancing the process of denitrification as the water passes through the carbon source. By providing native denitrifying bacteria additional carbon (that is, food), these bacteria can be encouraged to denitrify at greater rates than in the surrounding soil. An anaerobic environment (with low levels of dissolved oxygen in the water) must also be provided for the denitrifying bacteria; hence an outlet control structure is needed to retain water for sufficient periods in the trench (see ***"retention time"*** in Glossary).

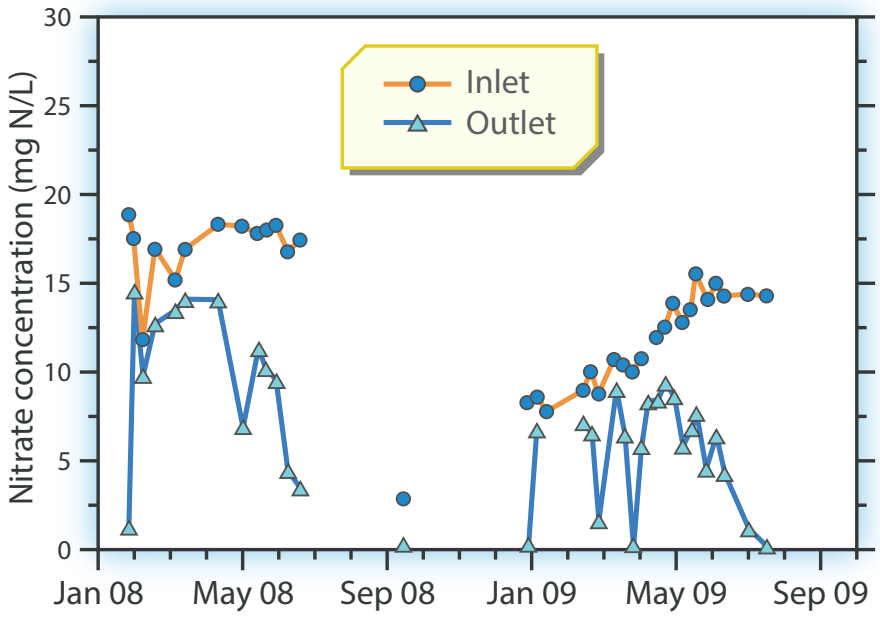


Figure 23: *Nitrate-N concentrations before and after passing through a bioreactor (from Woli et al., 2010).*

Because this is a biological process, nitrate removal can be negatively impacted by cooler water temperatures or flow rates that are too high. However, high flow rates, and the corresponding low retention times the water experiences within the bioreactor, can be managed to some extent by managing the control structures.

Bioreactors reduce nitrate loads by:

Increasing denitrification.

How effective are bioreactors?

Denitrification bioreactors in the field have been reported to remove from 12% to 98% of annual nitrate loads, with an approximate average of 30% to 40%. Figure 23 shows the relationship between inlet and outlet nitrate concentration for a bioreactor in Illinois. In this case, substantial reductions in nitrate concentrations occurred, especially in late spring and summer. It's important to note the water that passes through the bypass line receives no treatment in the bioreactor. Research is being undertaken to increase the percentage of annual drainage volume that can be treated in a bioreactor, thereby increasing the overall water quality impact of these systems. The design life of these systems is currently estimated at 10 to 15 years.

Where do bioreactors work?

One of the largest benefits of bioreactors is that they typically require no land be removed from agricultural production. They fit well in edge-of-field grassed buffer areas. However, consideration needs to be given to issues including space availability, soil type, and trafficability. It's also preferable to have a good understanding of the drainage system (drain size, slope, location), so the bioreactor can be designed more accurately.

Figure 24: *Bioreactor during construction (courtesy of the Iowa Soybean Association Environmental Programs and Services; from Christianson and Helmers, 2011).*

Level of acceptance

Over the past five years, a number of bioreactors have been installed throughout the Midwest, but it is critical to have a good research-based understanding of how well bioreactors work before they can be considered beyond the demonstration phase. Although bioreactors typically require no modification of current in-field practices and little annual maintenance, the cost of the wood chips and excavation may be an impediment to more widespread use.

Questions and opportunities

Research suggests denitrification bioreactors can significantly reduce the nitrate concentrations in drainage waters. However, like several other practices discussed here, because this practice is relatively new, there are opportunities to improve bioreactor nitrate-removal performance by better understanding these factors:

- Field-scale bioreactor performance at multiple sites throughout the Midwest, which will help refine design and management procedures for maximized nitrate removal.
- How to increase the percentage of flow that passes through the bioreactor while maintaining sufficient treatment.
- End of life issues such as fill media replenishment and spent media disposal.
- How to minimize potential for negative by-products such as nitrous oxide (greenhouse gas), sulfate reduction (and mercury methylation) at lower flow rates, and start-up flushing of organics.

For More Information on Bioreactors

Iowa State Extension Factsheet: Woodchip Bioreactors for Nitrate in Agricultural Drainage

https://store.extension.iastate.edu/ItemDetail.aspx?ProductID=13691

Designing and Constructing Bioreactors to Reduce Nitrate Loss from Subsurface Drains (University of Illinois)

http://www.wq.illinois.edu/DG/Equations/trifold_Bioreactor.pdf

Schipper et al. (2010): Denitrifying bioreactors—An approach for reducing nitrate loads to receiving waters

8. Wetlands

What is wetland treatment of drainage water?

Wetlands are dynamic ecosystems containing plants, soil, bacteria, and water. Constructed or reconstructed wetlands can benefit water quality by removal of nitrate through denitrification and other processes. When placed within the landscape to intercept subsurface drainage water from agricultural fields, they have high potential to reduce nitrate concentrations and loads. These nitrate-removal wetlands can be highly effective, but widespread implementation remains limited due, in part, to concerns about the high cost of taking land out of agricultural production.

Figure 25: *A constructed wetland in Iowa (Iowa CREP Program).*

How do wetlands improve water quality?

The primary process for removing nitrate in wetlands is denitrification, with plant uptake and reduction in flow (due to seepage) providing additional benefits. Bacteria naturally present in the wetland use dissolved oxygen in the water as they decompose dead aquatic plants, thus creating anaerobic conditions (no oxygen). Once these anaerobic zones are present, denitrification occurs. During this process, nitrate in the water is transformed to gaseous nitrogen (N_2) which is released back to the atmosphere. Wetland plants also contribute to water quality because they use nitrate in the water for plant growth. Lastly, wetlands can reduce the total volume of drainage water by allowing seepage into groundwater, through water transpired by plants, and by evaporation from the water surface.

Wetlands reduce nitrate loads by:

Increasing denitrification,
increasing plant uptake,
and
reducing downstream flow.

How effective are wetlands?

Wetland denitrification-based nitrate removal is significantly affected by temperature, the amount of nitrate available to the wetland, and the retention time of the water in the wetland. Generally, wetlands are more efficient at removing nitrate during warm months, from inflows containing high amounts of nitrate, and under lower flow conditions which allow the water to have a higher retention time in the wetland (that is, more time for the denitrification

process to occur). The biological and plant processes that help wetlands improve water quality work best during warmer temperatures, but a large part of midwestern drainage nitrate loads occurs during spring, when temperatures are cooler. An approximate average for wetland annual nitrate removal is 20 to 50% (Table 4).

Mitsch and Day (2006) noted a 40% decrease in nitrogen loads in the Mississippi River could be attained by creation of 2.2 million hectares of wetlands, which is less than 1% of the area of the Mississippi River Basin.

Where do nitrate-reduction wetlands work?

Siting and sizing wetlands appropriately are important. To maximize nitrate removal, a wetland must receive drainage waters from large areas to treat as much nitrate as possible and be sized correctly to allow sufficient time for denitrification to take place (that is, designed for adequate retention time).

In terms of siting a wetland, the ratio of drained land area to wetland size is critical. Crumpton (2001) showed that wetlands can be much more efficiently placed when considering the size of their contributing areas. The Iowa Conservation Reserve Enhancement Program (Iowa CREP) is based upon this "watershed" approach to wetland placement and design which recommends the following:

1. Locating wetlands on cropland and intercepting a small stream or drainage system from at least 500 acres of subsurface-drained cropland.

2. Wetland size should be 0.5% to 2% of its drainage area.

3. No more than 25% of the wetland should be greater than 1 meter deep.

4. A wetland buffer must surround the wetland stretching from the wetland surface to 1.5 meters in elevation above it, and the size of this buffer should not exceed twice the wetland area.

The soil of the site can also be important; low permeability soils capable of maintaining flooded conditions that allow wetland plants to grow are best. Targeting the most effective sites for wetlands can balance the need for maximized nitrate removal with reduced costs in agriculturally productive landscapes.

Wetlands can also provide flood regulation and wildlife habitat.

Additional benefits

In addition to reducing the amount of nitrate in drainage waters, wetlands provide other important water quality and quantity benefits. For example, wetlands allow time for sediment-bound phosphorus to settle out of water and for plant uptake of phosphorus; however, this phosphorus may eventually be washed out of the wetland once the wetland plants die. Wetlands can also help reduce flooding by allowing water time to infiltrate, evaporate, and be used by plants. As diverse transition zones between terrestrialt and aquatic ecosystems, wetlands play an important role in sustaining biodiversity and can provide wildlife habitat.

Level of acceptance

Nitrate-removal wetlands have been shown to reduce the export of nitrate from subsurface drained landscapes while also providing other valuable environmental benefits. Although this is well established, there has not been

Table 4: *Wetlands throughout the Midwest show annual nitrate removal of 16% to above 70%.*

Reference	Location	Wetland size as a percent of the watershed	Percent nitrate load removal
Kovacic et al., 2000	Illinois	1.6-3%	33-55%
Kovacic et al., 2006	Illinois	3-4%	16-43%
Crumpton et al., 2006	Iowa	0.57%	25-40%
Crumpton et al., 2006	Iowa	2.2%	78%
Crumpton et al., 2006	Iowa	2.3%	68%

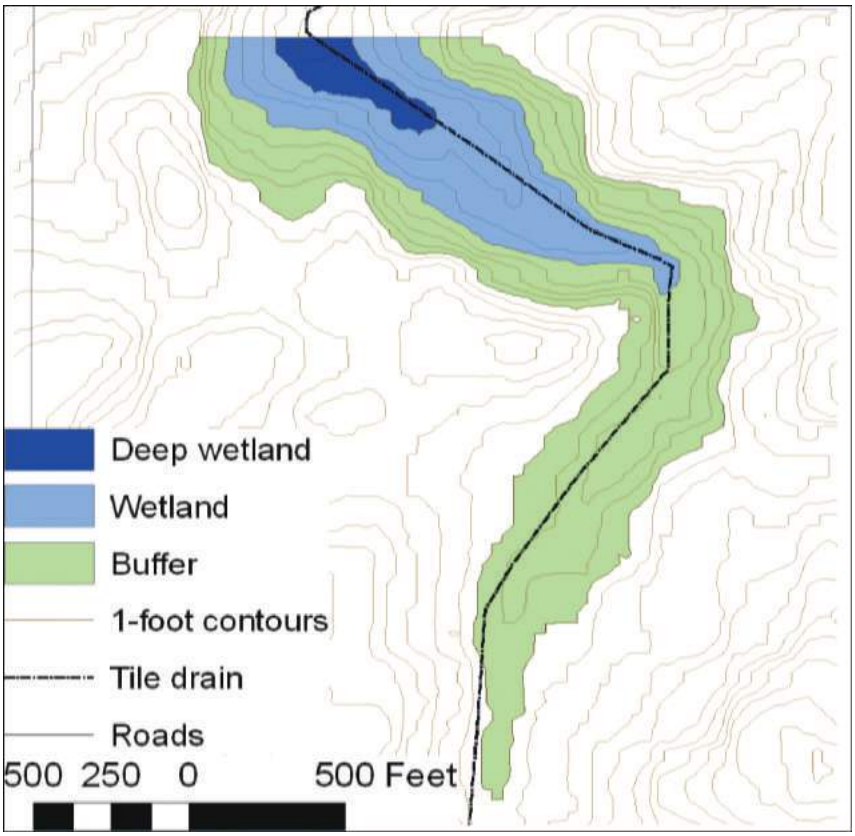


Figure 26: *Constructed wetlands for water quality include deep and shallow pools and a buffer.*

widespread implementation of this practice across the midwestern landscape. Economics is a major reason for this; a sizeable up-front capital investment is required for construction in addition to more long-term "opportunity costs" due to land removed from agricultural production. However, there are several governmental programs that assist with these costs to make wetlands a more amenable practice.

Questions and opportunities

Current research programs aim to better identify the long-term performance of nitrate-removal wetlands under varying climatic conditions and to optimize siting and design criteria for use in maximizing the performance of these wetlands.

For More Information on Wetlands

Iowa Conservation Reserve Enhancement Program:
http://www.iowaagriculture.gov/waterResources/pdf/LandownerGuide.pdf
http://iowacrep.org/

Practices that Remove Nitrate at the Edge of the Field or Downstream

9. Alternative Open-Ditch Design

Figure 27: *An open drainage ditch in Minnesota (from Needelman et al., 2007).*

What is open-ditch design?

Open-ditch systems are links between in-field drainage systems and downstream lakes and rivers. These open ditches are typically natural streams that have been artificially deepened and straightened or new channels constructed to serve as an outlet for field drainage systems. Alternative open-ditch systems have the following potential benefits compared to traditional drainage ditches: (1) improved and more efficient nitrogen retention within the open-ditch plants and soil, (2) reduced flood peaks and increased flow during low-flow periods, (3) improved biological diversity and integrity of open-ditch ecosystems, and (4) decreased maintenance cost associated with reduced frequency of open-ditch maintenance.

Alternative open-ditch systems, in combination with in-field and edge-of-field practices (such as those discussed in this practice manual), are strategic options for improving water quality. Alternative open-ditch design and management, ditch channel shape, ditch vegetation, and in-stream features have the potential to reduce nutrient loading from drainage waters.

How does open-ditch design improve water quality?

Natural ecosystems, such as streams and wetlands, are able to retain a portion of nitrate loads through natural processes such as uptake by microbes and plants. Open-ditch design combines these benefits of natural ecosystems with the ability to convey drainage waters from fields. The microbial process of denitrification is a good example of a natural process that can reduce nitrate loads in open ditches depending on interactions between water and underlying sediments, channel bottom features (pool and riffle sequences), sediment characteristics, and temperature.

Researchers think that a two-stage open-ditch channel design, in particular, may create zones within the channel for potential denitrification. A ***two-stage or compound ditch*** (see Glossary) consists of a small main channel and a second low, grassed floodplain within the open ditch (Figure 28). The main channel accommodates baseflow and low flow conditions, while the second stage accommodates higher flows. A two-stage open-ditch channel creates a zone of plants and soil within the ditch that has the capacity to absorb part of the nitrate load through both uptake and denitrification. The relatively narrower low-flow

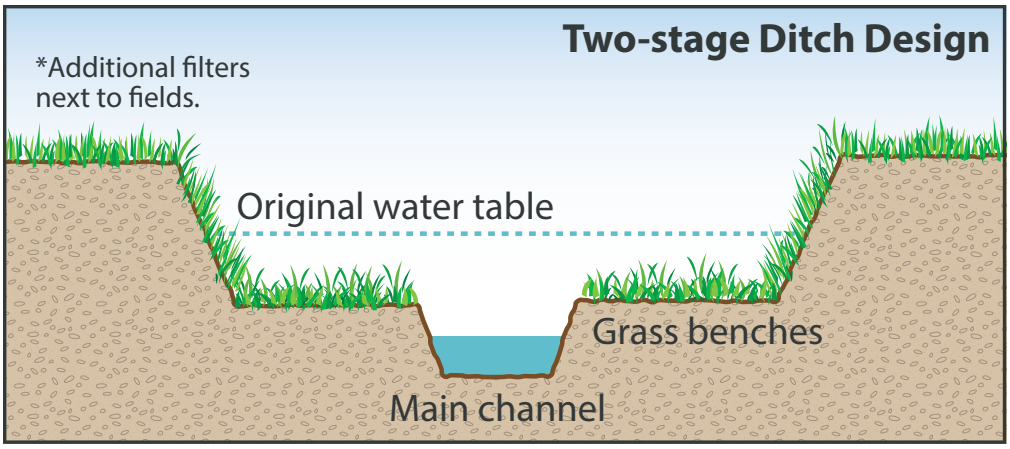


Figure 28: *Typical two-stage ditch design, a specific type of alternative open ditch.*

channel also may allow the water velocity to remain high enough to reduce sediment deposition in the channel. Flow is shallower and slower on the grassed benches, encouraging denitrification and biofiltration.

Biofiltration (see Glossary) is the process of removing dissolved and suspended pollutants from water by filtering the water through biological material such as plants, which allows microbes to interact with any pollutants in the water. Conceptually, in an open ditch, water would filter into the bed material of the ditch, where it would come in contact with microbes that either denitrify or biologically filter pollutants in the water.

Figure 29: *A paired open ditch research facility in Minnesota.*

How effective are alternative open ditches?

Because this is still a new practice, widespread nitrate-removal information is still forthcoming. However, this practice has shown potential to reduce both nitrate and sediment loads at several research sites in the Midwest (for example, see Tank et al., 2009, and Strock et al., 2007)

Where do alternative open ditches work?

Alternative open-ditch designs are being investigated in locations where drainage ditches already exist. Nevertheless, such practices may help decrease periodic costs associated with ditch maintenance, especially for ditches that require frequent cleanout (Kramer et al., 2011). Conditions such as soil type, slope, and biology (plants, microbes) will affect nitrogen removal within the ditch. Perhaps the most important, albeit uncontrollable, factor in reducing nitrogen loading from open-ditch channels is climate, including both seasonal temperature ranges and the balance between when precipitation occurs and when plants transpire (as in Figure 6). For example, plant growth and microbial activity (like denitrification) are reduced during cool periods. In warm, more humid midwestern areas the majority of nitrogen loss from subsurface drains occurs during winter, when there is no active vegetation growth and denitrification is limited. In colder midwestern locales where soil freezes during winter, the majority of nitrogen loss occurs during the spring.

Level of acceptance

The study of open-ditch systems is relatively new in the U.S. Research conducted on open ditches comes from Arkansas, Ohio, Maryland, Minnesota,

Mississippi, and the Netherlands. These research efforts encompass a wide range of approaches, including compound open-ditch channel design, biofiltration for nutrient removal, and other open-ditch management strategies that may lead to reduced nitrogen loading in surface waters.

Despite the newness of this research, this practice has gained support from agricultural producers, and from those responsible for drainage network evaluation, management, and maintenance, including county drainage managers and engineers, and soil and water conservation district and natural resources drainage technical staff.

Questions and opportunities

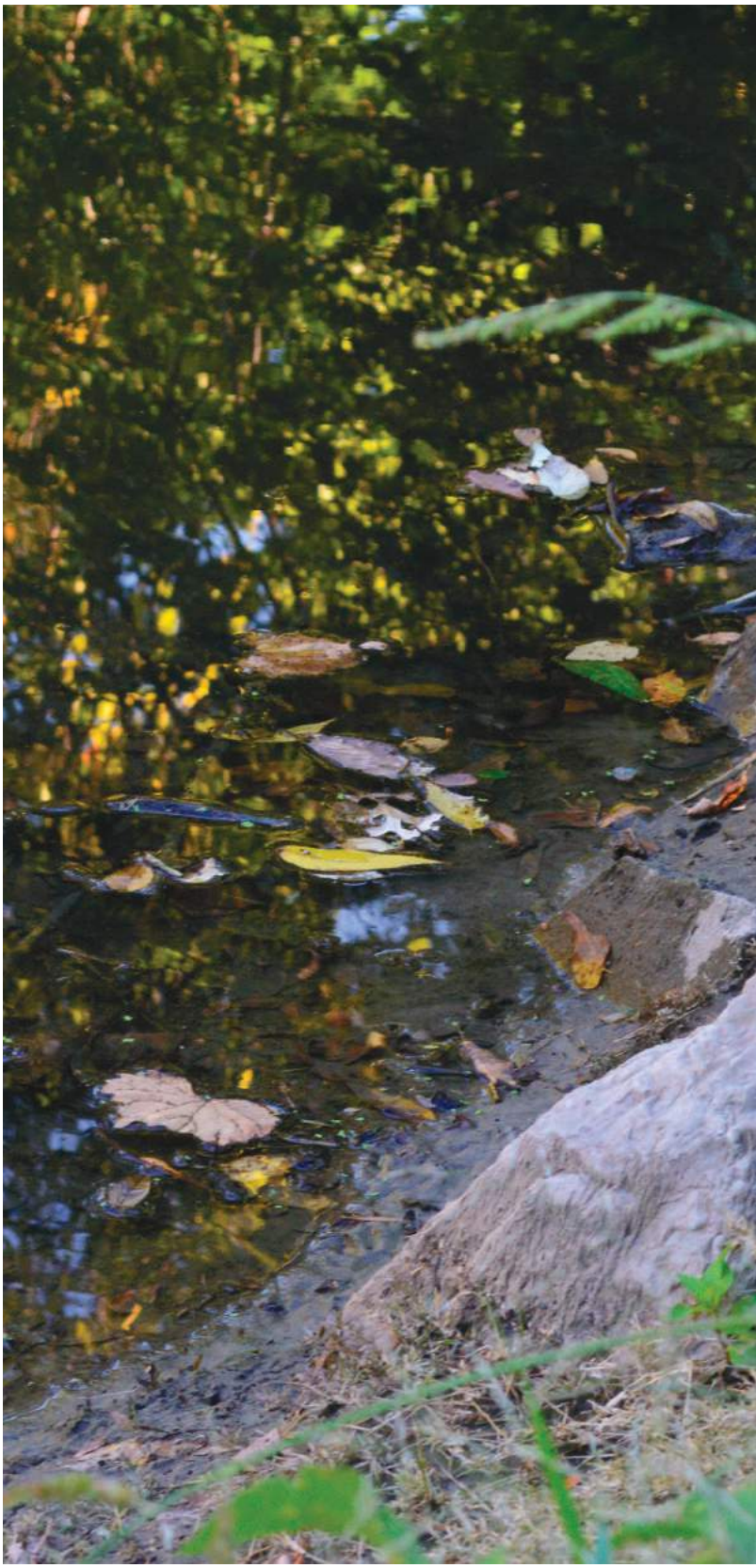
Current and future research is aimed at these objectives:

- Evaluating the overall ability of open ditches to reduce nitrate and other pollutants in drainage waters
- Identifying new open-ditch design and management strategies (such as modified channel design or vegetation) that may lead to reduced nitrate loads
- Determining the potential for flood reduction and stormwater storage
- Evaluating the construction and maintenance costs for open-ditch systems, and estimating the economic efficiency of open-ditch systems compared to other practices.

It is hoped these efforts provide lower cost, lower maintenance, and more attractive ditch practices producers will be willing to adapt to their farms to mitigate nutrient loading.

Alternative ditch design reduces nitrate loads by:

Increasing denitrification,
increasing plant uptake,
and
reducing flow to the stream.



10. Saturated Buffers

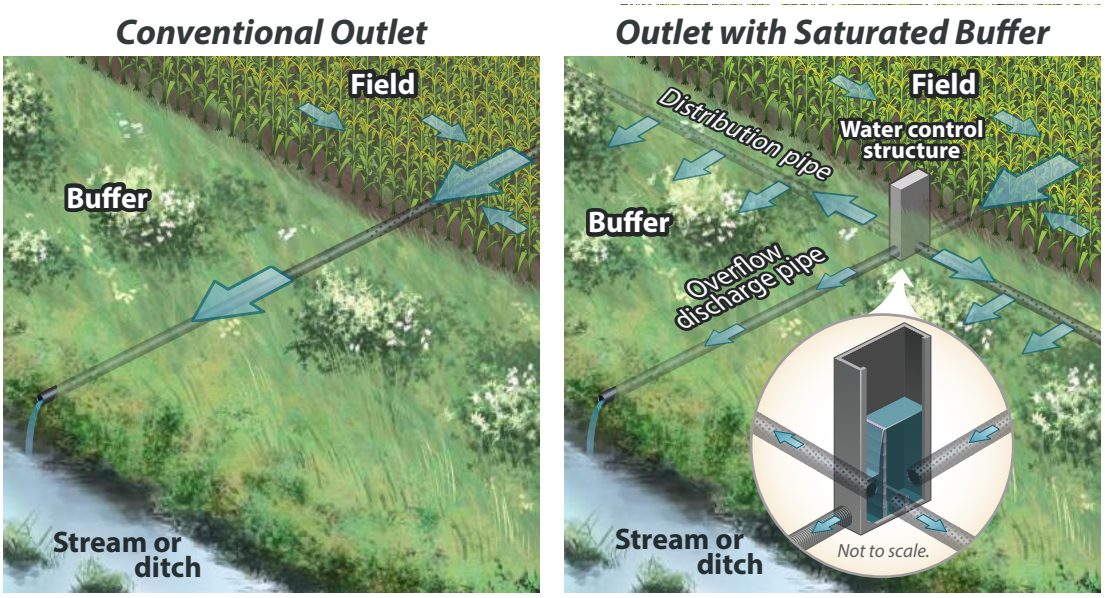


Figure 30: *The left figure shows subsurface drainage leaving the field and bypassing the existing vegetated riparian buffer, while the right picture shows a saturated buffer system where the drainage water is diverted through a perforated drain pipe to flow through the buffer's soil.*

What is a saturated buffer?

Riparian buffers, or zones of vegetation along stream banks or ditches, improve water quality by slowing surface runoff from cropped fields, allowing it to infiltrate, which both helps filter sediment in the runoff and traps nutrients in the buffer for later uptake by buffer plants. However, subsurface drainage short-circuits these benefits of riparian buffers, because drain pipes are routed through riparian vegetation zones, preventing any drainage water or nitrogen uptake by the buffer plants' roots.

The new concept of a saturated buffer is a modification of the edge-of-field drainage system that allows drainage water to flow as shallow groundwater through the buffer's soil. A saturated buffer consists of a shallow perforated drain pipe that extends laterally along the riparian buffer and is connected to the drainage main via a control structure (or diverter box). Gates in this structure can be put in place to force drainage water along the lateral line through the buffer rather than allowing this water to short-circuit the buffer in the original tile pipe. Drainage water seeps from the perforated lateral pipe through the riparian zone where the existing vegetation can uptake both the water and the nitrate in the drainage water. At high drainage flow events, a portion of the drainage water will overtop the structure's gate, and will flow directly to the stream, thus preventing backup of drainage in the field. A three-chamber control structure is not required for this practice, but use of this type of structure (versus a two-chamber structure) allows some additional opportunity for edge-of-field control of drainage water in the field, as well as increased research monitoring capability.

How does a saturated buffer improve water quality?

Allowing the drainage water to seep through the riparian buffer soil provides several natural benefits. The vegetation roots in the buffer can uptake both nitrate in the drainage and the drainage water itself. Secondly, by maintaining saturated soils, the anaerobic conditions required by denitrifying bacteria can be sustained. These microbes can utilize carbon in the soil to denitrify nitrate in the rerouted drainage water. Lastly, by slowing the arrival time of drainage water to the stream, some drain flow reduction may be observed.

How effective are saturated buffers?

This is a new practice with limited performance data available. However, the initial data suggest saturated buffers can be effective, removing 100% of the nitrate load in the water that was routed through the riparian subsurface zone (see the following case study). In the first year of results from this saturated buffer system, 60% of the drainage flow was routed through the buffer, with the other 40% bypassing through the control structure. Coupled with the very high nitrate removal within the buffer, this meant there was an overall 60% reduction in nitrate load to the stream.

Where will saturated buffers work?

Saturated buffers are ideally suited to provide treatment of drainage water where a drain outlets through a buffer area. Conventional drainage pipes short-circuit or bypass this vegetation, but here, the buffer vegetation can be used for treatment of subsurface waters, not just to reduce surface runoff and to provide stream bank stabilization.

Additional benefits

Numerous benefits of riparian buffers within the landscape, such as stream bank stabilization and wildlife habitat, are widely established. It is possible that buffer vegetation could be harvested as a bio-energy crop or for other added-value purposes. In addition to reducing nitrate loads to a stream, a saturated buffer may also help reduce the peak flow in the stream, as drainage waters may be attenuated within the buffer soil.

Level of acceptance

Because this practice is new, there is a low level of adoption at this research-oriented stage. However, there has been great interest in saturated buffers within the drainage community, as this practice would allow combined reduction of subsurface and surface runoff pollutants. Moreover, this practice holds potential because the initial investment may be lower than some other drainage water quality practices and very little maintenance or management is required.

Saturated buffers reduce nitrate loads by:

Increasing denitrification,

increasing plant uptake,

and

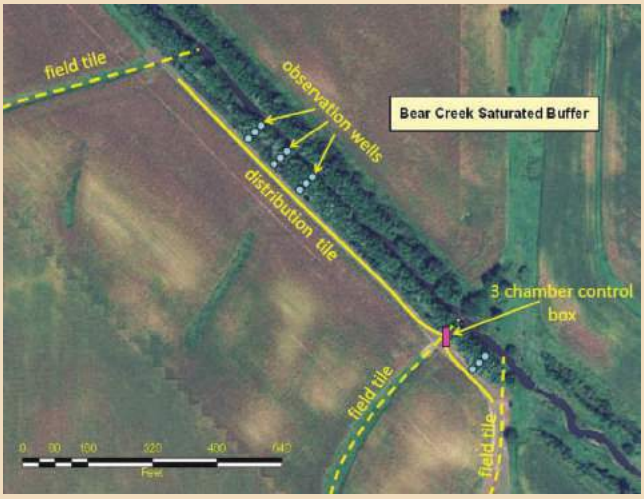
reducing flow to the stream.

Questions and opportunities

Much more research is required to determine the effectiveness and potential negative side effects of saturated buffers under different field conditions and throughout the Midwest.

Saturated Buffer Case Study

One of the first saturated buffers in the Midwest was located along Bear Creek near Story City, Iowa. This saturated buffer was created from an existing riparian buffer that was 60 feet wide and consisted of grasses, shrubs, and silver maple. The lateral perforated drain pipe extended for 1,000 feet between the field and the riparian buffer. The drainage system drained approximately 25 acres of row cropped farmland.



This saturated buffer has been highly effective for nitrate removal in its first year of operation (See "How effective are saturated buffers?"), but much more work is needed to fully understand this novel practice.

Economic Considerations of the Ten Strategies

Implementation of each individual practice will require unique associated costs occurring at different times over the life of the practice. Figures 31 and 32 give general ranges of the cost per area drained and cost per pound of nitrate removed for several of the more established practices in Table 5 (adapted from Christianson, 2011), although such numbers will be highly variable based upon the factors listed below. To compare these practices based upon cost, take a few considerations into account:

1. **When do the major costs of the practice occur?** While some of these strategies have very high up-front costs (such as construction or contractor costs), other practices are done annually, and thus have costs that recur every year.

2. **How effective is this practice for improving water quality?** To get the biggest "bang for your buck," it's important to know the nitrate removal effectiveness of the specific practice in which you are interested. Not only does this effectiveness differ between practices, but the effectiveness of a given practice will depend upon its specific situation (for example, soil type, location within the landscape, climate and precipitation trends) and management.

3. **What size of drained area will be treated?** Like nitrate-removal effectiveness, this differs between practices. For example, bioreactors currently are designed to treat drainage water from field-sized areas (30 to 80 acres), while constructed wetlands may be designed to treat drainage from far larger watershed-scale areas (several hundred to several thousand acres).

4. **What is the lifetime of the practice?** The more construction-based practices have lifetimes upwards of several decades. For example, a wetland may have a design life of greater than 100 years, but it may not be reasonable to assume a cover crop will be grown in a given field consecutively for 100 years.

5. **Are there other benefits of the practice, beyond water quality improvement, that are important to me?** Several of the practices have very important environmental and agronomic benefits, such as improvements in soil quality. The practice of cover crops, for example, is typically not done solely to reduce nitrate in drainage water.

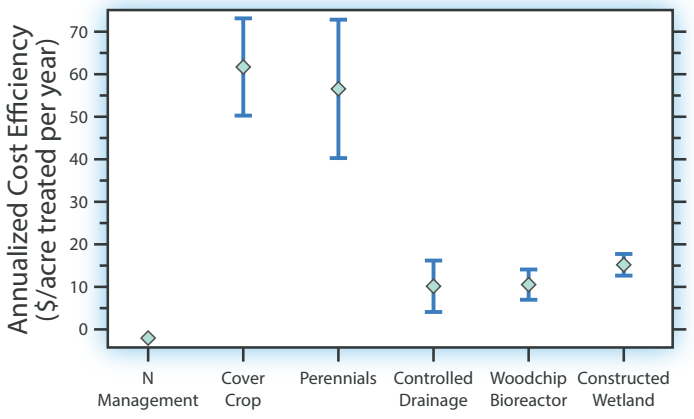


Figure 31: *The annualized cost efficiencies in $ per acre per year for several drainage water quality practices, including initial investment, annual maintenance, and replacement costs projected to occur over 50 years at a 4% discount rate. The N Management practice consisted of application rate reduction from 150 lb N/ac to 125 lb N/ac, and the Perennial practice was based upon a two- year corn rotation followed by three years of alfalfa (from Christianson, 2011).*

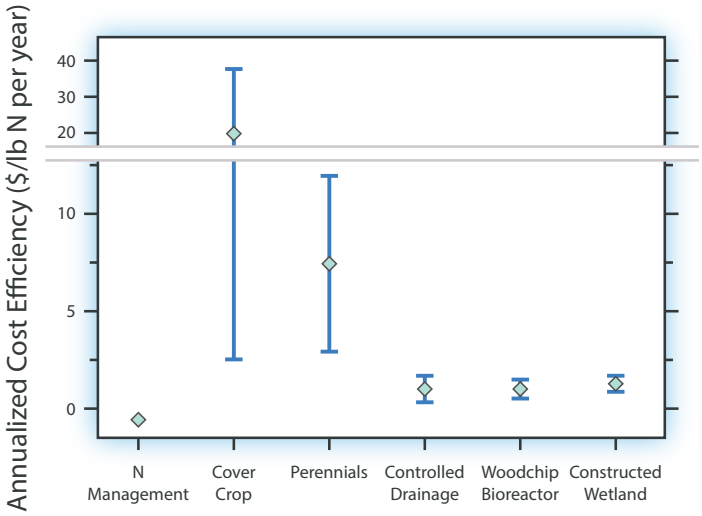


Figure 32: *Annualized cost efficiencies in $ per lb of nitrate-nitrogen removed for several drainage water quality practices; based on total present value costs from Figure 31 and a 50 -year timeline at a 4% discount rate (from Christianson, 2011).*

Table 5: *Major up-front, recurring annual, and other variable costs or benefits of the ten drainage water quality strategies discussed in this publication.*

Practice	Up-Front Costs	Annual Costs	Additional Benefits
Improved N Management	Potential new equipment and extra fertilizer storage requirements	Application costs Fertilizer costs	Potential yield impact
Winter Cover Crops	Potential equipment required for seeding and burn-down/tillage	Seed costs Planting costs (diesel, labor, etc.) Spraying/herbicide or tillage costs if crop overwinters	Potential yield impact Additional long-term benefits, including reduced erosion and improved soil health
Increasing Perennials in the Cropping System	Planting and establishment	Maintenance Harvesting Opportunity cost for land diverted from production of conventional annual crops	Harvested income Additional long-term benefits, including reduced erosion and improved soil health
Drainage Water Management	Design cost Cost of structures Contractor fees	Time to raise/lower gates	Potential yield impact
Reduced Drainage Intensity	Design cost Contractor fees		Potential yield impact
Recycling Drainage Water	Design cost Cost of structures, materials, and/or pumps Contractor fees Land acquisition	Time to manage system Mowing/maintenance Pumping costs Opportunity cost of land out of production	Yield benefit in dry years
Bioreactor	Design cost Cost of structures, woodchips, and materials Contractor fees Seed cost for bioreactor surface	Time to raise/lower gates Mowing/maintenance	
Wetland	Design cost Cost of structures and weir Contractor fees Vegetation and seed cost (wetland and buffer) Land acquisition	Time to maintain Opportunity cost of land out of production	Increased hunting potential from wildlife
Alternative Open-Ditch Design	Design cost Contractor fees Seed cost	Time to mow/maintain	Decreased ditch maintenance for ditches that require frequent cleanout
Saturated Buffers	Design cost Cost of structures and perforated drainage pipe Contractor fees	Time to maintain	

6. **Are there local or seasonal price differences for costs of these practices?** There may be price differences for practice components (seeds, for example, or control structures and their transport) between various midwestern subregions. Charges for labor and construction can vary during the year depending upon availability.

7. **Are government incentives or cost-share programs available?** There are federal and state programs, such as the Environmental Quality Incentives Program (EQIP), specifically intended to help offset the cost of implementing water quality practices. There also may be local funds available in certain watersheds through environmental groups and watershed or drainage associations.

Conclusion

The important agricultural productivity enhancements provided by midwestern agricultural drainage do not come without negative environmental effects. This practice manual describes ten strategies for reducing drainage nitrate loads from conventionally drained row crop-based systems, focusing on ways that either cropping systems or drainage systems could be managed to improve water quality, while maintaining high agricultural productivity and profitability. An attempt has been made to describe the physical, chemical, and biological processes by which these practices reduce nitrate loads to downstream waters. Readers are highly encouraged to seek out additional information about these practices using the suggested information links, the listed references, or through their local extension staff and researchers.

No one practice will be the best option in every situation or location, nor will effectiveness of a given practice be equal in all locations or years.

In most cases, there is no "silver bullet" approach for improving drainage water quality. Each of the strategies presented here provides unique features and characteristics that will be appropriate for some but not all field circumstances and that will experience variable levels of acceptance. No one practice will be the best option in every situation or location, nor will the effectiveness of a given practice be equal in all locations. Excitingly, many of these practices can be used in combination, and several such combinations are very complementary in nature (for example, use of an in-field and edge-of-field practice together). A suite of water quality improvement approaches and efforts will be needed across the landscape to meet our ultimate water quality goals.

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Glossary

Biofiltration	The process where dissolved and suspended pollutants are removed from water by being filtered either by plant materials (for example, sediment filtered by stems and leaves) or through the soil and then are uptaken by microbes or plants.
Control structure	In this context, a structure is installed over a drainage pipe, inside which plates (also called gates, stop logs, or flashboard risers) can be inserted to hold back water behind the plates, thus retaining the water in the field. See the Drainage Water Management, Bioreactors, or Saturated Buffers sections.
Controlled drainage	The use of one or more flow-retarding structures (that is, control structures) placed in the drainage outlet or along drainage pipes that allows the water level in a field to be artificially set. Here, this term is used interchangeably with "drainage water management," and is distinct from, though related to, the practice of subirrigation.
Denitrification	Part of the nitrogen cycle where nitrate is converted to a gaseous form of nitrogen, typically either dinitrogen gas (N_2) or nitrous oxide (N_2O). The soil microbes (denitrifiers) responsible for this process require a carbon source and anaerobic (low oxygen) conditions in addition to a supply of nitrate. If these conditions are not met, many of these microbes will utilize ("breathe") oxygen rather than nitrate, and denitrification will not occur. The production of nitrous oxide may be of concern because this is a greenhouse gas.
Drainage coefficient	The maximum rate at which the drainage system is designed to remove water from a field. This coefficient is expressed as a depth of water over the drainage area, and typical drainage coefficients range from 1/4 inch to 1/2 inch of water per day for field crops, but they can be over 1 inch per day. The drainage coefficient combines drain spacing and depth (see "drainage intensity") along with other characteristics of the drainage system (pipe size and materials, pipe grade, outlet capacity, and contributing drainage area) to serve as a measure of the overall design capacity of the drainage system.
Drainage intensity	This term combines drainage depth and spacing to give a relative indication of how intensively drained an area is. Drainage intensity can be reduced through wider drain spacing or shallower placement (see the Reduced Drainage Intensity practice).
Evapotranspiration	A part of the water cycle or water balance that describes the combined effect of water that is transpired by plants plus water that evaporates from ground and water surfaces.
GPS	Global positioning systems, abbreviated as GPS, use satellites for precise navigation and location applications.
Hypoxic zone, Hypoxia	A water body or an area within a water body experiencing low dissolved oxygen concentrations that can potentially result in harm to aquatic life. Here, this term refers to the seasonally formed hypoxic zone in the Gulf of Mexico. In this case, nitrate loadings in the Mississippi River encourage the growth of algae in gulf waters. These algae eventually die and are decomposed by microbes. During the decomposition process, the microbes utilize the dissolved oxygen in the water, thereby reducing the dissolved oxygen concentrations and leading to hypoxia in the water.
Mineralization	Part of the nitrogen cycle where organic nitrogen, which is not a form of nitrogen that plants can uptake, is transformed into nitrate (NO_3^-) or ammonium (NH_4^+), which are plant-available forms of nitrogen. Soil microbes perform this process as they decompose organic matter.
Nitrification	Part of the nitrogen cycle where ammonium (NH_4^+) is transformed into nitrate by soil microbes under aerobic conditions.
Nitrogen fixation	Part of the nitrogen cycle where atmospheric nitrogen (N_2), which cannot be used by plants and microbes, is converted to ammonia (NH_3). This process can be done biologically by microorganisms (for example, by soil bacteria in symbiotic relationships with legumes such as soybeans), or it can result from lightning strikes and industrial manufacturing processes.
Perennials	Plants that can grow for two or more years without replanting, usually due to regrowth from their existing rootstock. This is in contrast to annual plants, which need to be replanted yearly.
Retention time	The length of time water is retained in a basin (like a wetland or pond) or a reactor (like a bioreactor). Mathematically, this is the structure volume (multiplied by the woodchip porosity, for a bioreactor) divided by the flow rate through the system.
Riparian buffer	Land adjacent to streams or rivers that is managed to grow perennials such as trees, shrubs, and grasses to protect, or "buffer," the water body from pollution originating from upland sources.
Subirrigation	A type of subsurface drainage system designed to allow water to be fed back to the soil through drainage pipes during times of the year when the crop's water demand is not met by existing soil moisture. These systems require additional pumps and a supplementary water supply. This practice is distinct from Drainage Water Management.
Subsurface drainage	The practice of removing excess water from below the soil surface (that is, from the soil profile) through a series of drainage pipes or tubing. This type of drainage is often called "tile drainage" because, historically, clay tile cylinders were used rather than the perforated plastic tubing common today. These pipes are typically installed just below the root zone, at a depth of 30 to 48 inches and at a spacing of 30 to 100 feet.
Surface drainage	The practice of removing standing water from the ground surface by land leveling or through the construction of shallow ditches and grassed waterways.
Two-stage or compound ditch	A form of open-ditch design where the ditch is designed and/or maintained to have two benches or flow stages. The lower stage consists of a small main channel that accommodates base flow occurring under normal drainage conditions, and the higher stage serves as a grassed floodplain for flood conditions.
Watershed	An area of land where all the water falling on it and draining off of it eventually goes to one defined point.

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Notes

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