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Subsurface Drainage in Iowa and the Water Quality Benefits and Problem

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Subsurface Drainage in Iowa and the Water Quality Benefits and Problem

Abstract
It is estimated that there are approximately 3.6 million ha of land with artificial subsurface drainage in Iowa, with 2.4 million ha of that within the 3000 organized drainage districts (total land area of the state is 14.6 million ha). This drainage has made otherwise wet soils very productive. Much of this drainage was installed early last century and is reaching the end of its service life. One challenge will be the repair/replacement of these drainage systems. Because subsurface drainage "short circuits" some infiltrating water back to surface water resources, there is also a water quality challenge. Research has shown that during rainfall-runoff events, the presence of artificial subsurface drainage generally delays and reduces the volume of surface runoff. Therefore, total losses of sediment, phosphorus, ammonium-nitrogen, pesticides, and micro-organisms are decreased with subsurface drainage. However, nitrate-nitrogen leaching is increased with subsurface drainage water, and has been implicated as a major factor relative to hypoxia in the Gulf of Mexico. Research has identified several factors relative to soils, weather, and management (cropping, tillage, chemical application practices, and drainage parameters) that influence the nitrate-nitrogen leaching problem. This will be discussed along with implications for possible changes in the drainage systems and land management that may be needed to sustain production while reducing nitrate-nitrogen losses.

Keywords
nitrogen, phosphorus, nonpoint pollution, nutrients, controlled drainage, wetland

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments

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INTRODUCTION

About two-thirds of Iowa’s 14.6 million ha is in row-crops (9.3 million ha), and much of that (about 3.6 million ha) has been artificially drained in the last 120 years, most in the last 95 years. Roughly two-thirds of the drainage area is within organized drainage districts. See Figure 1 for information on historic loss of wetlands in Iowa (Bishop, 1981; Bishop et al., 1998). With the installation of subsurface drainage came conversion of prairies and marshes to productive crop-land. Currently, Iowa ranks first or second in the U.S. every year in the total production of both corn and soybeans. However, with subsurface drainage and these land-use changes, changes in watershed hydrology and water quality have also occurred. In a study by Schilling and Libra (2003), historical trends in discharge were made for 11 streams in Iowa for the 1940 to 2000 period. For nearly all streams, annual baseflow, annual minimum flow, and annual baseflow percentage increased with time. Reasons given for the trends were “improved conservation practices, greater artificial drainage, increasing row crop production, and channel incision.” Switching from perennial grasses and wetland plant species to annual crops certainly decreased total annual evapotranspiration (and increased total drainage volumes), with monthly differences most dominant in early spring and late fall when annual crops are just being established, or have

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SUBSURFACE DRAINAGE IN IOWA AND THE WATER QUALITY BENEFITS AND PROBLEM

J.L. Baker¹, S.W. Melvin¹, D.W. Lemke², P.A. Lawlor¹,
W.G. Crumpton³, and M.J. Helmers¹

It is estimated that there are approximately 3.6 million ha of land with artificial subsurface drainage in Iowa, with 2.4 million ha of that within the 3000 organized drainage districts (total land area of the state is 14.6 million ha). This drainage has made otherwise wet soils very productive. Much of this drainage was installed early last century and is reaching the end of its service life. One challenge will be the repair/replacement of these drainage systems. Because subsurface drainage “short circuits” some infiltrating water back to surface water resources, there is also a water quality challenge. Research has shown that during rainfall-runoff events, the presence of artificial subsurface drainage generally delays and reduces the volume of surface runoff. Therefore, total losses of sediment, phosphorus, ammonium-nitrogen, pesticides, and micro-organisms are decreased with subsurface drainage. However, nitrate-nitrogen leaching is increased with subsurface drainage water, and has been implicated as a major factor relative to hypoxia in the Gulf of Mexico. Research has identified several factors relative to soils, weather, and management (cropping, tillage, chemical application practices, and drainage parameters) that influence the nitrate-nitrogen leaching problem. This will be discussed along with implications for possible changes in the drainage systems and land management that may be needed to sustain production while reducing nitrate-nitrogen losses.

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INTRODUCTION

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matured and been harvested, respectively. Water quality, as measured by nitrogen (N) and phosphorus (P) concentrations, declined with that land-use change and with increased drainage volumes. While total nutrient masses in the root zone of the soil profile from 120 years ago to now have not changed that much (in most cases, because of erosion, masses/amounts are lower today), it is the amounts of the “available” forms that are critical where the term, “available,” relates to the potential to be transported with water, surface runoff and/or subsurface drainage. For N, the form that is most available to be lost is nitrate-nitrogen (NO$_3$-N) because it is a soluble anion and is not adsorbed by most soils. An assessment by McIsaac and Libra (2003), increased row cropping and increased use of N fertilizer since 1945 has increased the NO$_3$-N concentrations in the Des Moines River draining much of north-central Iowa. In a prairie, the grass is very efficient at removing NO$_3$-N from the soil solution in the root zone. Measurements made of the NO$_3$-N concentrations in shallow saturated soils in a railroad right-of-way in native grasses showed concentrations of less than 0.2 mg/L, while in an adjacent row-crop field less than 20 m away, the concentrations in soil water in the saturated zone were over 10 mg/L. The difference is primarily a result of cropping, with the associated fertilization and tillage. Row-crops in particular, with growing seasons of less than 120 days, are “leaky” systems with no water or nutrient uptake two-thirds of the year. In addition, N fertilization of corn is necessary to achieve economic optimum yields, although of the roughly 200 to 220 kg N/ha total plant needs, generally only 50 to 60% is supplied by the producer as inorganic N fertilizer, with the remainder coming from mineralized organic N in soil and plant residues. This leads to the impact of tillage, where with increasing severity of tillage, aeration within soil particles/aggregates increases, resulting in an increase in mineralization. In a study of four tillage systems on crop production and water quality of subsurface drainage in northeast Iowa (Weed and Kanwar, 1996), NO$_3$-N concentrations for moldboard- and chisel-plowed fields were on average about 30-50% higher than for flat and ridged no-till fields. Part of this difference may have been due to the changes in the volume and route of infiltration between tillage systems, but differences in N mineralization are also believed to have been a factor. Variability in weather plays a major role in NO$_3$-N concentrations and losses (and therefore, as an uncontrolled variable, makes it extremely difficult to manage inputs to reduce losses). Precipitation patterns not only affect the timing and volumes of subsurface drain flow, they, along with temperature patterns, affect NO$_3$-N concentrations in soil, and therefore in drainage water, by affecting N transformations and crop uptake. Data are shown in Figure 2 for average NO$_3$-N concentrations in tile drainage from plots in a corn-soybean rotation (with the corn fertilized between 168 to 179 kg N/ha) in north-central Iowa with concentrations in the Raccoon River (draining part of that area) for 15 years (1989-2003). River concentrations are averaged for the April through July periods when over 90% of the subsurface drainage occurred (1989 was the only year when no tile flow was measured from the plots, and 1994, 1997, and 2000 were years of abnormally low flows). These data show that concentrations in both subsurface drainage and the river were high (≥ 10 mg/L), and were generally lower during drier years and higher in wetter years following drier years. In drier years, crop yields were depressed and therefore N uptake/removal was less, and losses by leaching (and denitrification) were also less, leaving more N in the system available to be lost. The year-to-year variability in NO$_3$-N concentrations was at least as great as the variability in concentrations within a year for plots receiving N rates differing by a factor of two. Ammonium-nitrogen (NH$_4$-N) and organic-N, mostly associated with the soil, are not that “available” or mobile. In addition, the amounts of these N forms present in the soil profile at any point in time in crop-land use are not that much different than in the original soil. The one effect that the instituted cropping/tillage system has on these N losses is increased potential for erosion.
Given a soil with 3% organic matter (with roughly 5% of that organic matter being N), each 1 ton/ha soil loss, with an enrichment ratio of 2.0, would represent 3.0 kg N/ha lost. In the “availability” sense then, the cropping/tillage system that is possible because of subsurface drainage does increase the availability or potential for total N loss.

The same is true for P, possibly even more so, because generally most of the P lost from tilled fields is associated with soil loss. At a soil concentration of 500 ppm total-P, each 1 ton/ha soil loss, with an enrichment ratio of 2.0, would represent 1.0 kg P/ha lost. P lost dissolved in surface runoff can be increased by P fertilization as “available P” levels (based on agronomic soil tests) increase, but generally less than 0.5 kg P/ha is lost in solution with 10 cm of surface runoff.

Because of P interactions with soils, particularly with P-deficient subsoils where they exist, P concentrations in subsurface drainage in Iowa are such that less than 0.05 kg P/ha would be lost with 10 cm of subsurface drainage.

As with P, several other potential pollutants such as herbicides, insecticides, other organics, NH$_4^+$-N, micro-organisms, and sediment itself, can be adsorbed and/or “filtered-out” of water passing through the soil to a subsurface drain (Gilliam, et al., 1999). The remainder of this paper will review subsurface drainage water quality studies to assess or quantify these effects, and to consider what is needed in the way of further research and improved management to reduce water quality problems.

**RESEARCH RESULTS**

The one water quality problem that is potentially increased with installation of artificial subsurface drainage systems is NO$_3^-$-N leaching. In addition to allowing more intense cropping, subsurface drainage increases infiltration and the amount of water percolating through the soil profile, and short-circuits that water back to the surface. Thus the carrier volume for NO$_3^-$-N increases, and the time for attenuation, primarily via denitrification, decreases. Many studies have been made to quantify the effects of application rate on NO$_3^-$-N concentrations and losses from N-fertilized cropland, particularly corn.

Considering the law of diminishing returns, i.e. as more N is applied, corn yield response (and the percentage of incremental N taken up) decreases, until it eventually reaches zero, it might be logical to think NO$_3^-$-N concentrations, and losses, in subsurface drainage might go up almost exponentially with application rate. However, given that the amount of N normally supplied as fertilizer (150 kg/ha/yr in Iowa) may only represent 60% of that taken up by the whole plant in a growing season, 100 kg/ha must be available from the soil. Thus two facts are evident, 1) even with no fertilizer applied some loss will occur, and 2) the effect of increasing amounts of unused N at higher application rates is somewhat “buffered” by a large amount of NO$_3^-$-N naturally present in a tilled field.

Data for a four-year study in Iowa of N rate on corn show that NO$_3^-$-N concentrations in subsurface drainage went up roughly linearly with application rate up to 224 kg/ha, with an intercept concentration of about 6 mg/L with no N applied (Figure 3). Furthermore, in a six-year study with manure, doubling the available N rate on corn in a corn-soybean rotation, from 166 to 336 kg/ha did not double the NO$_3^-$-N concentrations in subsurface drainage (Figure 4); it is possible that the organic matter in the manure may have enhanced denitrification, particularly at the higher rare.

One concept being developed and tested to reduce NO$_3^-$-N leaching using improved application/placement methods (Ressler, et al., 1997) is to cut or smear macropores around a line source of applied N (such as that applied with a knife applicator), and then compact and dome the soil over it. The overall desired hydrologic effect is that most of the infiltration and percolating water enter and pass through soil on either side of the line source, but not through it. Early results have been promising (Ressler, et al., 1998a and 1998b).
Improved timing of N applications is also being considered to reduce NO$_3$-N leaching with subsurface drainage, particularly avoiding fall application, and the use of split and/or side-dress applications. With the greatest N need by corn being early to mid summer, logic would indicate that fall application would be bad for both leaching loss and efficiency of use. While some data exist illustrating slightly higher leaching losses and slightly lower yields (Randall, et al., 2003) with fall versus spring application, it does not happen everywhere all the time. Data shown in Figure 5 for corn grown three years in Iowa do not show increased NO$_3$-N concentrations or lower yields for fall-applied N. Split N applications during the growing season have not shown large or consistent reductions in NO$_3$-N concentrations in subsurface drainage (Randall, et al., 2003), although in two Iowa studies, a combination of reduced rate and split application showed lower concentrations compared to a higher single application treatment (Kanwar et al., 1988; Timmons and Baker, 1991 and 1992). In studies of corn yields as affected by timing of N applications, split applications did not show a consistent effect (Baker et al., 1995), and in a series of application timings, including fall and split, the best corn yields were obtained for N applied about the time of planting.

There are also several reviews and studies of the effects of tillage on hydrology and NO$_3$-N concentrations and losses in subsurface drainage (e.g., Baker, 1987; Kanwar et al., 1999; Randall and Mulla, 2001). Data from an extensive study in northeast Iowa (Weed and Kanwar, 1996) given in Table 1 show that concentrations and losses for plowed fields were generally higher than for ridged or flat no-till fields for a corn-soybean rotation. While the same was true for concentrations for continuous corn, losses for no-till were about the same as for moldboard plow because lower concentrations were off-set by increased flow with no-till.

If one needs to dramatically reduce NO$_3$-N leaching from subsurface drained lands, the most effective option is to change the land use from row-crops to alfalfa or other sod-based crops, or possibly small-grains. Data in a water quality review (Baker, 1980) showed that NO$_3$-N concentrations in non-row-cropped lands are usually less than 6 mg/L. In addition, studies in Iowa (Melvin et al., 1993; Kanwar et al, 1999) and Minnesota (Randall et al., 1997) also showed much reduced concentrations for alfalfa, CRP, and small-grains compared to row-crops. In fact, the Minnesota study showed a 90% reduction in NO$_3$-N leaching losses with CRP (from a combination of both reduced concentrations and reduced flows).

Constructed or reconstructed wetlands can be placed within the landscape to intercept subsurface drainage water to reduce NO$_3$-N transport downstream. The primary process for reducing NO$_3$-N concentrations is denitrification when large amounts of biomass created in wetlands by growth of aquatic plants, such as cattails, decompose and use the dissolved oxygen (O$_2$) in the water and drive the system anaerobic. Through seepage into groundwater and evapotranspiration, wetlands can also reduce transport by reducing the volume of the “pass-through” drainage. The efficiency of a wetland to remove NO$_3$-N by the denitrification process is significantly affected by temperature (cooler/freezing conditions reduce the rate), the amount of NO$_3$-N available to the wetland, and the residence time of the water in the wetland. These last two factors lead to the importance of the appropriate site selection and sizing of constructed/reconstructed wetlands in the landscape or watershed. First, they must be sited where they will be exposed to significant concentrations and amounts of NO$_3$-N; thus drainage from larger areas of row-crop land must be allowed to pass through the wetland. Second, in order to have sufficient time for denitrification to take place, the wetlands must be sized to achieve adequate residence times.

In an Iowa field study under natural rainfall/drainage conditions, subsurface drainage from row-crop land in 1996 and 1997 was distributed to nine 0.04-ha individual wetland cells. The drainage was divided such that there were three area-ratio treatments: 1046 to 1, 349 to 1, and 116 to 1. At the higher area ratio, very little flow reduction occurred (on a percentage basis); the water simply passed through quickly. With roughly 38 mm of subsurface drainage each year, the total amounts of water measured entering the wetlands (including about 250 mm of precipitation during the periods of measurement) by area-ratio were about 40,000; 13,000; and 6,000 mm, respectively. Seepage and ET reduced outflows about 6, 28, and 38%, respectively. Average flow-weighted NO$_3$-N concentrations in inflow were 17 mg/L in 1996 and 13 mg/L in 1997. Reductions in NO$_3$-
N concentrations on a percent basis were higher during 1996 and for both years increased as the area ratio decreased, being 9, 22, and 58%, respectively, in 1996; corresponding values for 1997 were 4, 13, and 36%. Combining volume of flow data with concentration data provides the mass balance data shown in Figure 6. The combined effects of reduced flows and reduced concentrations at lower area-ratios resulted in even greater reduction in NO$_3$-N transported (increased % of NO$_3$-N removed), such that at the 116 to 1 area-ratio the reduction was over 50% both years. In terms of absolute amounts of NO$_3$-N removed, in 1996, an average of 900 kg/ha of wetland was removed; in 1997, the value was about 450 kg/ha. Within each year, the amounts removed were fairly constant, decreasing only slightly with decreasing area-ratio. Based on these data, similar data from other studies, and simulation modeling results, constructed/reconstructed wetlands that are 0.5 to 2% of the overall drainage area (200 to 1, to 50 to 1 area-ratios) should result in significant NO$_3$-N reductions in tile drained areas of the Midwest.

Given the physical, economic, and social constraints of using traditional in-field management practices to limit NO$_3$-N leaching, as well as for constructed wetlands to treat subsurface drainage water with high NO$_3$-N concentrations, additional approaches to drainage and water management for water quality improvement are needed. One of those receiving increasing attention is “controlled drainage”, where increasing the outlet elevation and maintaining a higher water table during certain times of the year can potentially reduce NO$_3$-N losses. Some studies (e.g., Evans et al., 1995) have shown that losses have been decreased by as much as 45% due to a combination of decreased flows and decreased concentrations. Most of the overall decrease was due to decreased flow; the decrease in concentrations was believed due to denitrification, which could be enhanced by soil saturation at higher elevations and for longer times, as shown in simulation experiments (Jacinthe et al., 1999).

As the current drainage systems reach the end of their service life, renovation, reconstruction, and new construction of drainage systems provide opportunities to design them for water quality benefits. In addition to possibly providing for controlled drainage, issues of tile depth and spacing need to be considered, although water quality data with respect to these factors and NO$_3$-N leaching are limited. In one study in Indiana (Kladivko et al., 1991), narrow spacing increased some pesticide concentrations, but had little effect on NO$_3$-N concentrations. However, in that study with drain tile at a constant depth, the 5-m spacing had about twice the subsurface flow volume compared to the 20-m spacing, so NO$_3$-N losses were also doubled. In a modeling study for the Minnesota cold climate over an 85-yr simulation period, Jin and Sands (2003) predicted an average of 67 mm of increased subsurface drainage for a 7-m drain spacing compared to 30-m. However, in another Minnesota modeling study, Davis et al. (2000) predicted no difference in NO$_3$-N leaching losses between spacings of 15 and 40 m. In an ongoing Iowa study (personal communication, Greg Brenneman), four tile spacings from 9 to 22 m have had no significant effect on NO$_3$-N concentrations. And although a direct comparison is not possible, NO$_3$-N concentrations for a north-central Iowa research site with 8 m spacing are very similar to concentrations for the central Iowa and northeast Iowa sites with spacing of 36 and 27 m, respectively.

The depth of drainage, perhaps with controlled drainage, may hold some potential for affecting both flow and NO$_3$-N concentrations. Early work by Gilliam et al. (1979) showed at two locations in North Carolina that control structures installed in drainage outlets to raise the water tables over the winter could reduce NO$_3$-N losses by 50% or more. However, NO$_3$-N concentrations in drainage were not significantly reduced with higher water tables, and most of the decreased loss was due to decreased flow volumes. Evans et al. (1995) showed similar reductions with controlled drainage with most of the reduction attributed to reduced flow, although in certain cases, NO$_3$-N concentrations were reduced 10 to 20%. Modeling (Skaggs and Chescheir, 2003) using DRAINMOD indicated lower NO$_3$-N losses (and profitable corn production) may be achieved with a combination of more shallow and closely spaced drains. Companion experimental work (Burchell et al., 2003) on plots in North Carolina with drains 0.75 m deep, spaced 12.5 m apart, showed that outflow was reduced by 42% compared to plots with drains 1.5 m deep, spaced 25 m apart. In this case, the effect of depth must have been dominant over that of spacing. While NO$_3$-
N concentrations in outflow were not reduced by shallow drainage, concentrations in shallow groundwater beneath those plots were reduced (presumably because of denitrification). A field-project underway in southern Minnesota should provide more experimental evidence soon (Sands et al., 2003); preliminary results show that shallow drains (at 90 cm) reduced flow and NO\textsubscript{3}-N loss by 40 and 47%, respectively, compared to the 120 cm depth. In a Minnesota modeling study, Davis et al. (2000) predicted reductions of flow and NO\textsubscript{3}-N loss of 8 and 12%, respectively, for drains at 90 cm compared to 120 cm. Drainage modifications have the potential for decreasing NO\textsubscript{3}-N export, and through the integration of drainage modifications with wetlands, there may be the potential for even further reductions.

Another opportunity provided by reconstruction of our drainage systems is use of “biofilters,” where organic materials provide the carbon to consume the oxygen present and drive the system anaerobic, enhancing denitrification (Cooke et al, 2001). In one ongoing Iowa study (Kaspar et al., 2003), wood chips surrounding a newly installed tile line have significantly reduced NO\textsubscript{3}-N concentrations in subsurface drainage compared to a tile line with no wood chips. Furthermore, redesign of a total drainage system including drainage ditches, and the potential for sites for storage/reuse of drainage water provide additional opportunities for water quality improvement (Fausey et al., 2003).

**SUMMARY**

The benefits of artificial subsurface drainage on crop production in providing improved trafficability and crop growth conditions are substantial. In terms of overall drainage from cropped land, artificial subsurface drainage also benefits water quality with reduced losses of sediment, P, NH\textsubscript{4}-N, pesticides, and micro-organisms. However, the increased infiltration and short-circuiting of that water back to surface water resources with artificial subsurface drainage increases NO\textsubscript{3}-N leaching, particularly for row-cropped lands.

While studies have shown that improved N management practices, in the way of rate, timing, and placement, have some potential to reduce NO\textsubscript{3}-N leaching, that potential is probably limited to a reduction of <25-30%. Reduced tillage, and particularly no-tillage, has the potential for another incremental reduction, but again limited in magnitude. Although alternate cropping, such as small grains, alfalfa, or other sod-based crops/rotations, can cause a major reduction, currently that switch would also have major economic implications. Using off-season cover crops to take up water and NO\textsubscript{3}-N does offer another limited possibility.

Therefore, if environmental problems such as hypoxia in the Gulf of Mexico (Downing, et al., 1999) or more local problems result in N criteria required by the U.S. EPA for flowing and standing waters being set three to five times (or more) lower than current concentrations, in-field N management and tillage practices will not be sufficient to meet them. And if changes in cropping, including cover crops, are not economically feasible, off-site practices in the way of constructed/reconstructed wetlands and/or new water management strategies will need to be devised and implemented to reduce flow volumes and/or concentrations.

One possibility is a coupling of NO\textsubscript{3}-removal wetlands, as a proven technology, with the emerging technologies of drainage modifications to achieve a systems approach. Depending primarily on the source-land-area to wetland-area ratio (which affects the drainage water residence time in the wetland), wetlands should be able to remove 40 to 90% of the NO\textsubscript{3} originally present in the drainage water. Drainage system modifications generally under consideration are “controlled drainage” with the elevation of the outlet used to control water release, and use of shallow drainage tubes (e.g. at 30-90 cm rather than at 120-150 cm). These modifications to the drainage system are expected to have a direct effect on volume of subsurface flow and NO\textsubscript{3} loading from subsurface flow. The flow reductions are expected to improve aquatic habitat and reduce the impacts of hydrologic impairments in receiving streams. In addition, the integration of shallow and controlled drainage systems with NO\textsubscript{3} removal wetlands would significantly increase the
number of wetland sites, push those sites closer to the NO$_3$ source, and enhance wetland performance by increasing the average residence time in the wetlands.

Other possibilities involve water storage/reuse facilities, addition of “biofilters,” and alteration of drainage ditch/systems, for water quality improvement. Much research and demonstration work is needed on the technical and practical feasibility of these designs, with subsequent refinement likely needed, before decisions can be made for wide-spread implementation.

REFERENCES


Table 1. Average NO$_3$-N concentrations and losses with subsurface drainage

<table>
<thead>
<tr>
<th>Crop rotation and tillage</th>
<th>NO$_3$-N concentration</th>
<th>NO$_3$-N loss</th>
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<td>Ridge-till</td>
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<td>Rotation corn</td>
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<tr>
<td>Rotation soybean</td>
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<td>Moldboard plow</td>
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<tr>
<td>Ridge-till</td>
<td>21.3</td>
<td>11.7</td>
</tr>
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</table>
Figure 1. Changes in Iowa wetland area with time, 1860-1998.

Figure 2. Average annual NO$_3$-N concentrations for subsurface drainage from corn-soybean plots and the Raccoon River, at Des Moines, Iowa, April through July, 1989-2003.
Figure 3. Possible relationships between NO$_3$-N concentrations in subsurface drainage and N application rate.

Figure 4. Average NO$_3$-N concentrations in subsurface drainage from corn-soybean plots fertilized with inorganic N fertilizer (first bar) or liquid swine manure (subsequent bars).
Figure 5. Flow-weighted NO$_3$-N concentrations and yield for fall (with and without nitrification inhibitor) compared to spring applications, 2000-2003.

Figure 6. Nitrate-nitrogen inputs and removals by wetlands with various drainage to wetland area ratios.