Agricultural Drainage and Gulf Hypoxia: Economic Targeting of Farmland to Reduce Nitrogen Loads in a Minnesota Watershed

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Selected Paper Prepared for Presentation at the American Agricultural
Economics Association Annual Meeting, Providence, Rhode Island
July 24-27, 2005

Agricultural Drainage and Gulf Hypoxia: Economic Targeting of Farmland to Reduce Nitrogen Loads in a Minnesota Watershed[1]

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Abstract

Agricultural nitrogen losses are the major contributor to nitrogen loads in the Mississippi River, and consequently, to the existence of a hypoxic, or "dead", zone in the Gulf of Mexico. Focusing on two small agricultural watersheds in southwestern Minnesota, simulation results from the Agricultural Drainage And Pesticide Management (ADAPT) model were combined with a linear-optimization model to evaluate the environmental and economic impact of alternative land-use policies for reducing nitrogen losses. Of particular importance was the study's explicit focus on agricultural subsurface (tile) drainage, which has been identified as the major pathway for agricultural nitrogen losses in the upper Midwest, and the use of drainage-focused abatement policies. Results indicate that tile-drained land plays a key role in nitrogen abatement, and that a combined policy of nutrient management on tile-drained land and retirement of non-drained land is a cost-effective means of achieving a 20- or 30-percent nitrogen-abatement goal. Results also indicate that although it is cost-effective to abate on tile-drained land, it is not cost-effective to undertake policies that plug or remove tile drains from the landscape, regardless of whether the land would be retired or kept in production. Therefore, results imply that although tile-drained land is a major source of nitrogen lost to waterways, it is not cost-effective to remove the land from production or to remove the drainage from the land. Because of its value to agricultural production, it is better to keep tile-drained land in production under nutrient management and focus retirement policies on relatively less-productive, non-drained acres.

Introduction

The Mississippi-Atchafalaya River Basin drains 41 percent of the continental United States and accounts for 90 percent of the total freshwater input to the Gulf of Mexico. This water discharges an estimated 1.6 million metric tons of nitrogen each year into the Gulf, with about 61 percent of that as nitrates (the mobile form of nitrogen)

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[1] The authors wish to thank Ford Runge and Steven Taff for reviewing this manuscript.

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(Goolsby, 1999; Rabalais et al., 1999). These nitrates stimulate phytoplankton production in the warm surface waters of the Gulf, which sink to bottom waters where they are decomposed by bacteria. When this oxygen-consuming decomposition outpaces the rate of oxygen diffusion from the surface, oxygen concentration decreases. If oxygen levels fall below 2 milligrams per liter, which is the level at which shrimp and bottom-dwelling fish are not caught by trawlers, then the area is considered "hypoxic". This phenomenon occurs every summer along the northern coast of the Gulf of Mexico, and is currently the world's second-largest such area, covering an area of about 7,700 square miles. In 2001, it covered an area larger than the state of New Jersey but not quite the size of Massachusetts (Rabalais et al., 2002). Such hypoxic areas have become known as "dead zones" because fish vacate them for more oxygen-rich waters and slower-moving bottom-dwellers, such as crabs and snails, are suffocated (Ferber, 2001). The Gulf's dead zone is an economic as well as environmental problem, given that the Gulf accounts for almost one-fifth of the nation's commercial fish landings, and just over one-fifth of the $3 billion total value of these landings. Furthermore, the state most affected by Gulf hypoxia, Louisiana, accounts for over 10 percent of the nation's recreational fish landings alone (Pritchard, 2004).

Increased nitrate levels have been attributed to municipal wastewater, flood control measures, navigational channelization, deforestation, wetland conversion to cropland, riparian-zone loss, expansion of artificial agricultural drainage, and increased nitrogen fertilizer inputs on cropland within the Basin. Of these, the latter two stand out because it is estimated that 90 percent of the nitrate inputs to the Mississippi River derive from non-point sources, of which 74 percent are agricultural in origin. Furthermore, over the past 100 years, the amount of drained land in the Basin has increased from about 5 to 70 million acres (Mitsch et al., 2001), and over the past 50 years, levels of applied nitrogen fertilizer in the Basin have increased from less than 1 million to more than 6 million metric tons per year (Goolsby, 1999). It is no surprise, then, that over half of the nitrate enters the Mississippi north of the confluence with the Ohio River (Rabalais et al., 2002), where over half of the nation's corn and soybean crops are produced.

Given the concern for the Gulf's health, research has been conducted to identify potential remedies for hypoxia. The most widely-cited work is a body of reports issued by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (hereafter referred to as the Task Force), especially that of Doering et al. (1999) for its focus on economic costs and benefits of methods to reduce Gulf hypoxia. They identified nitrogen fertilizer reductions and wetland restoration as the two policies most cost-effective for abating nitrogen loads. Further, they concluded that riparian buffers were not a cost-effective means of abating nitrogen loads, and recommended the restoration of 5 million wetland acres along with a 20-percent reduction in fertilizer use within the Basin to meet a near-20-percent nitrogen-load reduction. The report also implied that abatement beyond the 20-percent level would have severe economic strain on the Basin.

Subsequent work followed, including that of Ribaudo et al. (1999), who concluded that fertilizer-use reductions were more cost-effective than wetland restoration, due to high restoration costs. However, it took a 40-percent reduction in applied fertilizer to achieve a 20-percent reduction in nitrogen load. Other work using a similar framework includes Greenhalgh and Sauer (2003) and Wu et al. (1996).

These studies, indeed, made significant contributions toward identifying potential remedies for Gulf hypoxia. There are, however, some modeling aspects of this research that should be noted. These studies were conducted at a large scale, with regions grouped according to similar physiographic, soil, and climate traits, but that cut across watersheds (ERS, 2004). The Corn Belt region, in particular, contains parts of at least four of the eighteen USGS 2-digit hydrologic units for the continental United States. Segmenting the area under consideration in this manner may be problematic, and Ribaudo et al. (2001) admit that "[b]ecause the…regions do not follow watershed boundaries, the allocation is not precise" (p. 188).

Furthermore, it is apparent that these studies failed to account for agricultural tile drainage. The description of EPIC (the simulation model used) given by Doering et al.(1999) implies that drainage was not adequately accounted for in the analysis: "[T]ile drainage systems impact measured nutrient loads at the watershed outlet but are difficult to account for in the EPIC framework" (p. 76). Note well that Ribaudo et al. (2001), Greenhalgh and Sauer (2003), and Wu et al. (1996) used the same model. Greenhalgh and Sauer (2003) stated that "[n]ot explicitly considered in this analysis were other elements influencing the delivery of nutrients to the Gulf of Mexico, including…tile drains" (p. 8). This conclusion is bolstered by Brezonik et al. (1999), who, speaking about differences in results between basin-wide and regional studies, says that "some studies, notably those on the Minnesota River Basin, involve areas that have significant effects from tile drainage. These effects probably are not fully accounted for in…simulations with EPIC" (p. 3-25).

Why is this apparent omission of tile drainage important? Tile drainage, a series of clay, concrete, or perforated plastic pipes buried a few feet below the field surface, accelerates removal of excess surface and subsurface water from fields, which in turn promotes well-aerated roots that enhances plant uptake of nutrients. Such drainage also allows for timely field operations, promotes earlier plant growth, and improves yields. In addition to these positive on-farm characteristics, tile drainage has been shown to reduce the loss of phosphorus, organic nitrogen, and other pollutants, such as certain pesticides, to waterways (Skaggs et al., 1994). Because the primary method of transport of nitrate-nitrogen is at the subsurface level, however, tile drainage can significantly hasten its movement to the edge of the field, and, thus, into an adjacent stream. Jackson et al. (1973) found that during a three-year study period, subsurface tile drainage accounted for 99.1 percent of all nitrate losses, and Logan et al. (1994) found that during a four-year study period, nitrate losses from surface runoff was between 0.009 and 2.0 lbs/ac, while that of tile drainage was between 0.009 and 76.5 lbs/ac.

How widespread is tile drainage? Consider the number of artificially-drained acres (surface and subsurface) in each of the following Basin states: Illinois (9.8 million), Indiana (8.1), Iowa (7.8), Ohio (7.4), and Minnesota (6.4). Of these drained acres, cropland comprises 90, 85, 90, 80, and 75 percent, respectively (Zucker and Brown, 1998), and tile drainage is the major pathway for nitrate transport in these states.

Further, the combination of tile drainage with row crop production, such as corn and soybeans, can drastically increase nitrate losses. In a four-year study by Randall et al. (1997), average annual nitrate loss via tile drainage was 1.6, and 1.0 lbs/ac for alfalfa and CRP plots, respectively, but 48.5 and 45.2 lbs/ac for continuous corn and corn-soybean-rotation plots, respectively. The five aforementioned states alone account for 51 percent of the nation's acres planted to corn, and 53 percent of acres planted to soybeans (NASS, 2002).

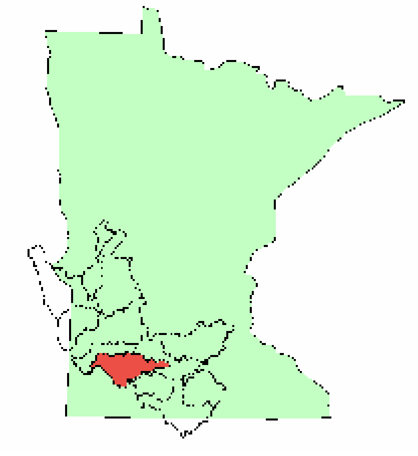
Finally, considering the importance attributed to fertilizer use by the aforementioned studies, it is useful to cite the results of Randall and Mulla (2001), who found that high concentrations of nitrate-nitrogen can be lost through tile drainage from high organic matter soils even if little or no nitrogen is applied, especially in wet years that follow very dry years. In short, significant levels of nitrates can be lost on tiled land regardless of the nutrient management techniques adopted. This result can have grave implications for policies that promote certain production methods, such as Best Management Practices (BMPs).

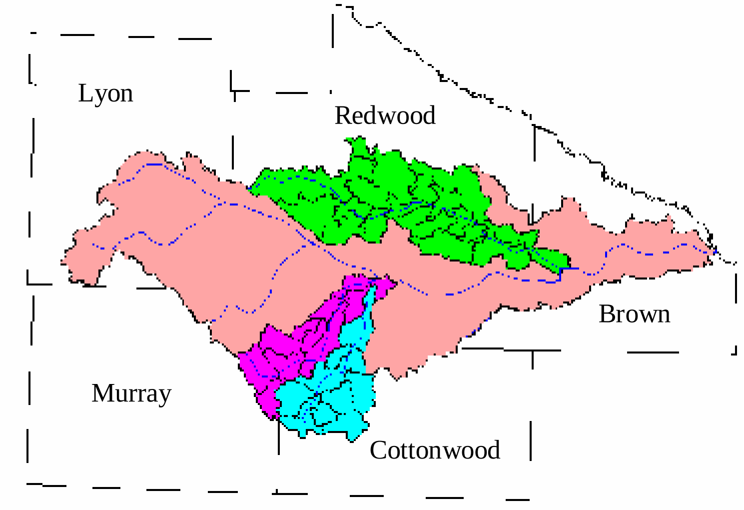
The present work undertook the task of analyzing some of the same land-use policies as mentioned above for reducing nitrogen loads, but did so at the watershed level rather than at a regional or basin scale. Furthermore, this work explicitly accounted for subsurface tile drainage and identified the role it plays in the delivery of nitrates to waterways. Additionally, policies that specifically targeted land with artificial drainage were added to the set of available policies to ascertain whether any efficiencies could be realized.

Study Region

This study addresses the issue of nitrogen loading and agricultural drainage at the watershed scale by focusing on two minor watersheds, the Highwater Creek/Dutch Charlie Creek (HDCC) and Sleepy Eye Creek (SEC) watersheds, comprising 133,058 and 174,180 acres, respectively, of the Cottonwood River Watershed (USGS Cataloging Unit 07020008) in southwestern Minnesota (see Figure 1). The Cottonwood River watershed is dominated by agriculture, with 88 percent of land devoted to row crops and accounts for an estimated 9 percent of nitrate-nitrogen loads to the Minnesota River (Mulla and Mallawatantri, 1997).

Figure 1. Minnesota River Basin and Cottonwood River Watershed





Left: Minnesota River Basin with Cottonwood River watershed highlighted. **Above**: Cottonwood, with Sleepy Eye, Highwater, and Dutch Charlie Creek subwatersheds highlighted (clockwise from top, respectively).

Methods

Land-use[3], climate, and soil data were collected from satellite imagery and an agricultural survey (Strock et al., 2005), the Minnesota Climatology Working Group (2004), and the State Soil Geographic (STATSGO) database (NRCS, 1994), respectively, to conduct simulations over the years 1974-2003, using the Agricultural Drainage And Pesticide Transport (ADAPT) model. ADAPT (Chung et al., 1992) is a daily time step field-scale water table management simulation model that was developed by integrating GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Leonard et al., 1987), a root zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs, 1978), a subsurface drainage model. It has been calibrated at the field scale for a variety of Midwestern conditions. Results from ADAPT were used as input parameters to conduct economic analysis. Economic data were taken from Lazarus and Selley (2003), NASS (2003), and the University of Minnesota's FINBIN database (CFFM, 2004). Physical and economic data were then used as inputs to a linear constrained-optimization model solved using the Generalized Algebraic Modeling System (GAMS, 2004).

The optimization model was used to test the effectiveness of four specific land-use policies for achieving 20- and 30-percent nitrogen-load abatement. These two abatement levels have been recommended by the Mississippi River-Gulf of Mexico

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[3] Land units were developed using a two-part process consisting of the development of Hydrologic Response Units (HRUs), and HRU aggregation into Transformed Hydrologic Response Units (THRUs). In HRU formation, spatial data layers of land cover, soils, and slope (STATSGO map-unit average) were overlain with ARC/INFO GIS software, resulting in a GIS layer consisting of many polygons that each contains hydrologic characteristics that are unique from those around it. Polygons which are similar in every aspect except location were then aggregated into THRUs, the functional modeling unit.

Watershed Nutrient Task Force as necessary for significant reductions in Gulf hypoxia (2001). The first policy was nutrient (fertilizer) management, which called for the adoption of a spring-applied 112 lb. /acre rate of nitrogen fertilizer. Spring application has been established as a Best Management Practice by the University of Minnesota (Randall and Schmitt, 1993), and the rate mentioned was the lowest of the three most commonly used application rates within the study region. The second policy was land retirement, where the current row crop was no longer grown, replaced by pasture. The third policy, labeled "plug and crop" called for land having artificial drainage to be plugged, but for the current crop to be retained. It was assumed that a loss of drainage would reduce crop yields by 20 percent. The last policy, labeled "plug and retire", called for tile-drained land to have its lines plugged in addition to being put to pasture. Because nutrient management has been cited as one the most critical methods of nitrogen abatement, it was first tested alone. All four policies were then tested simultaneously.

Each policy was implemented under three "rules" which governed the way land was chosen for abatement. The first rule required uniform abatement, such that the required percentage of abatement was achieved on each unique land unit, and required that abatement was achieved at minimum cost. In other words, each farmer had to meet the constraint individually, and did it the cheapest way possible. The second rule placed the abatement constraint at the watershed level, and chose land for abatement based on pounds of nitrogen abated per acre. The third rule, also at the watershed level, chose land based on cost per pound of abatement. Thus, the latter two rules represent the decision of a hypothetical watershed manager to abate either using the fewest number of acres or at the lowest cost. For ease of reference, these rules are referred to as the “uniform” rule, the “per-acre” rule, and the “per-dollar” rule, respectively.

Cost, here, refers to foregone net returns to agricultural producers. Net returns on a given acre are defined as crop price per bushel multiplied by yield per acre, minus enterprise cost per acre. Because the role of drainage in nitrogen abatement was of central concern, acreage and abatement levels attributed to tile-drained land were accounted for under each scenario. It was estimated that 10 percent of the land (13,024 acres) in the HDCC watershed contains subsurface drainage, whereas 30 percent (52,255 acres) is tiled in the SEC watershed. Although crop yields were unique to each land unit, the average yields for HDCC were 150 and 43 bushels per acre for corn and soybeans, respectively, and 155 and 43 bushels per acres for SEC. Average enterprise cost was \$270 per acre for corn and \$174 per acre for soybeans. Value per bushel of corn and beans was \$2.19 and \$6.04, respectively. The cost of plugging an acre of tile-drained land was estimated to be \$25, and the cost of switching fertilizer-management practices was assumed to be \$30 per acre.

Results

Under the base case, agricultural net returns were estimated at \$8.3 million in the HDCC and \$12.6 million in the SEC watershed. Base-case nitrogen loads were estimated at 1.2 million pounds for HDCC and 2.8 million pounds for SEC. Fertilizer management alone was not sufficient to achieve a 30-percent reduction in nitrogen loads in either of the watersheds, and was able to achieve 20-percent abatement only in the SEC watershed. Consequently, comparison of the nutrient-management policy under the three rules was impossible. The policy was able to achieve a 7-percent reduction in the HDCC watershed and a 23-percent reduction in the SEC watershed when all relevant acres were nutrient-managed, with an associated $3.3 million and $4.2 million price tag, respectively (see Table 1). The role of tile-drained land was critical under this policy. Although tile-drained acreage comprised only 10 and 30 percent, respectively, of all land in the HDCC and SEC watersheds, it accounted for 99 and 100 percent of abatement, respectively. Therefore, implementing nutrient management on tile-drained land alone resulted in roughly the same level of abatement at a cost of $358,967 and $1.4 million, respectively. Extending the policy to non-drained crop land boosted abatement in HDCC by an additional 1-percent at an additional cost of $2.9 million, and actually reduced abatement in SEC for an additional $2.8 million. (This reduction in abatement was due, in part, to

Table 1. Nutrient-management policy results for the HDCC and SEC watershed.

Nutrient-Management Policy

HDCC

Policy	**Net Return**	**N Load (lbs.)**	**% Abatement on Tile-drained Land**
Base Scenario	$8,291,310	1,233,080	0%
All Land N-Managed	$5,007,233	1,147,522	99%
% N Abated		*(7%)*	
Tile-drained Land N-Managed	$7,932,343	1,148,383	100%
% N Abated		*(7%)*	

SEC

Policy	**Net Return**	**N Load (lbs.)**	**% Abatement on Tile-drained Land**
Base Scenario	$12,627,309	2,777,748	0%
All Land N-Managed	$8,412,698	2,134,301	100%
% N Abated		*(23%)*	
Tile-drained Land N-Managed	$11,219,355	2,134,185	100%
% N Abated		*(23%)*	

the atypical result of some soils whose nitrogen-losses actually increased when fertilizer application was switched from fall to spring.)

Tables 2 and 3 contain the results of implementing the four abatement policies under the three rules in the HDCC and SEC watersheds to achieve 20- and 30-percent abatement, respectively. Because the "plug and crop" policy was not part of any solution, it was omitted from the tables. The per-dollar rule resulted in the highest net returns under 20-percent abatement, saving $1.4 million in the HDCC relative to the uniform-abatement rule, and $2.3 million in the SEC. Differences in net returns were similar under 30-percent abatement. Net returns under the per-acre abatement rule fell between those of per-dollar and uniform abatement. In addition to cost differences, land-use choices were substantially different under the three abatement rules. The uniform-abatement rule required the greatest number of retired acres to satisfy a given constraint, and relied least on tile-drained acreage. When the per-acre rule was followed to achieve

Table 2. Policy results for the HDCC and SEC watersheds with 20% abatement.

20% N-LOAD ABATEMENT

HDCC

Policy Rule	**Net Return**	**Acres Retired**	**Acres Plugged & Retired**	**Acres Nutrient-Managed**	**% Abatement on Tile-Drained Land**
Base Scenario	$8,291,310	0	0	0	0%
Per-Dollar	$7,716,599	22,140	0	5,247	43%
Per-Acre	$6,575,254	7,834	10,693	0	76%
Uniform	$6,317,563	33,657	0	4,760	17%

SEC

Policy Rule	**Net Return**	**Acres Retired**	**Acres Plugged & Retired**	**Acres Nutrient-Managed**	**% Abatement on Tile-Drained Land**
Base Scenario	$12,627,309	0	0	0	0%
Per-Dollar	$11,780,977	3,928	0	31,979	95%
Per-Acre	$11,054,926	18,596	0	0	100%
Uniform	$9,483,958	33,476	0	21,907	50%

20-percent abatement, there was a four-and-a-half-fold increase in the dependence on tile-drained land relative to uniform abatement in the HDCC watershed. In the SEC, it increased abatement from half to all on tile-drained land. Furthermore, the number of retired acres necessary to achieve abatement fell by half in both watersheds.

Additionally, abatement by nutrient management was relatively inefficient under the per-acre rule, and no land followed that policy under that rule. Based on these results, it can be concluded that targeting for tile-drained land was more effective in terms of abatement per acre. It remains to be seen whether it was cost-effective. Thus, hereafter, the discussion will focus on differences between abatement under the per-acre and per-dollar rules.

When the per-dollar rule was followed to achieve 20-percent abatement, the proportion attributed to tile-drained acreage fell from 76 to 43 percent relative to the per-acre rule in the HDCC, and from 100 to 76 percent in the SEC. Also, nutrient

Table 3. Policy results for the HDCC and SEC watersheds with 30% abatement.

30% N-LOAD ABATEMENT

HDCC

Policy Rule	Net Return	Acres Retired	Acres Plugged & Retired	Acres Nutrient-Managed	% Abatement on Tile-Drained Land
Base Scenario	$8,291,310	0	0	0	0%
Per-Dollar	$6,861,092	39,080	0	4,692	37%
Per-Acre	$5,915,503	23,289	11,383	0	52%
Uniform	$5,226,218	47,719	0	6,723	18%

SEC

Policy Rule	Net Return	Acres Retired	Acres Plugged & Retired	Acres Nutrient-Managed	% Abatement on Tile-Drained Land
Base Scenario	$12,627,309	0	0	0	0%
Per-Dollar	$10,617,160	25,714	0	40,214	76%
Per-Acre	$9,915,311	27,510	3,855	0	100%
Uniform	$7,891,215	49,839	0	31,945	50%

retire" policy was not, indicating that nutrient management was cost-effective and the "plug and retire" policy was not. In the SEC watershed in particular, following the per-dollar rule reduced the number of retired acres under 20-percent abatement from 18,596 to 3,928. Thus, nutrient management was relatively ineffective on an abatement-per-acre basis, with no acreage being subject to it under the per-acre rule, but was effective on a per-dollar basis, with 4,700-5,200 acres in the HDCC and 32,000-40,000 acres in the SEC being nutrient-managed. Further, between 93-100 percent of all acres selected for nutrient-management were tile-drained acres.

With regard to the level of abatement, cost differences were of the same magnitude under 20- and 30-percent abatement. Land-uses changes, however, were substantial when abatement increased from 20 to 30 percent. Following the per-acre rule, increasing abatement from 20 to 30 percent increased the number of retired and plug-and-retired acres by 53 percent in the HDCC and by 68 percent in the SEC. Similar results were found under the per-dollar rule, with the increase in abatement requiring an additional 77 percent of retired acreage in the HDCC. In the SEC watershed, the most significant change in land use when abatement was increased was found under the per-dollar rule, where retired acres increased 554 percent.

Discussion of Results

The results of this study indicate that choice of policy and the rule by which that policy is implemented can have a significant impact on the income and land use in a given watershed. Further, the degree to which these differences occur depends, largely, on the characteristics of the watershed in question. These results indicate, as expected, that a watershed with relatively more drainage, such as the SEC watershed, will rely more heavily on tile-drained land to achieve a given level of nitrogen abatement. Results also indicate that abatement is more effective on tile-drained land, and hence focusing attention on land that is tile-drained is a more efficient means of achieving abatement objectives. This conclusion was especially true under the nutrient-management policy. Therefore, the results indicate that close attention should be paid to nutrient practices on tile-drained land, but not on non-drained land.

Furthermore, results indicate that policies that are effective on an abatement-per-acre basis are not necessarily cost-effective. This was true of a policy of plugging and retiring an acre of tile-drained land. Although it was cost-effective to retire tile-drained land from production, it was not at all cost-effective to remove the drainage on that land as well. In other words, it is more cost-effective to address what activity is undertaken on tile-drained land rather than to address the drainage itself. This conclusion is bolstered by the fact that under no policy was it effective to remove drainage on an acre of land but keep it in production. Finally, meeting an abatement constraint of 20 percent required relatively few acres to be retired or managed; however, increasing the abatement constraint, by just 10 percent in this case, required an almost two-fold increase in retired acreage.

The implications of this study are summarized in Table 4, which indicates, based on the results, whether a policy was cost-effective in achieving nitrogen-load abatement on tile-drained and non-drained land, respectively. As the table shows, a combination of nutrient management on row-cropped tile-drained acres combined with land retirement (mostly on non-drained acres) is the most cost-effective means of achieving nitrogen-load abatement, given the tested policy choices. Further, these results indicate that because crop yields are relatively higher on tile-drained land, it is more cost-effective to keep tile-drained acres in production under nutrient management, and to focus most of the land retirement on non-drained acres (tile-drained acreage never comprised more than 15 percent of retired acreage under any scenario following the per-dollar rule).

Table 4. Cost-effectiveness of each policy on tile-drained and non-drained land to achieve nitrogen-load abatement.

	Is the Policy Cost Effective on this Land Type?			
Land Type	**Retire**	**Plug & Retire**	**Plug & Crop**	**Nutrient Manage**
Tile-drained Land	NO*	NO	NO	YES
Non-drained Land	YES	-	-	NO

*Marked as "NO" because tile-drained land never comprised more than 15% of retired acreage under any scenario following the per-dollar rule.

Results also imply that gains from abatement trading may be possible if watersheds abate cooperatively. Under the per-dollar rule policies, the marginal cost per pound of abatement in the SEC watershed was half that of the HDCC watershed. Subsequent research on agricultural nitrogen loading would do well to investigate the benefits of cooperative abatement and abatement trading.

Implications for Gulf of Mexico Hypoxia

The over-arching motivation for this research was Gulf hypoxia. What do the results of this research contribute? First, this research shows that in a small pocket of the Upper Mississippi River Basin, tile-drainage is a major nitrogen contributor and potential major source of nitrogen abatement. Of course, one may argue that these results apply to these watersheds only, because other watersheds have their own unique characteristics.

Although that statement is true, one cannot fail to notice that these two watersheds tucked away in southwest Minnesota are very much like thousands of watersheds throughout the Upper Mississippi River Basin: they are dominated by corn and soybean production; they receive heavy applications of nitrogen fertilizer; they contain soils high in organic matter; they have excess precipitation over evapotranspiration; and they are extensively managed with artificial drainage systems. These characteristics could very well describe any agricultural watershed in Illinois, Indiana, Iowa, or Ohio. Recall that these states, along with Minnesota, contain 39.5 million artificially-drained acres, most of which are in agriculture, and that these five states produce over half of the nation's corn and soybeans. Therefore, given the striking similarities of the study watersheds to the rest of the Upper Midwest, it is very likely that the results here are indeed indicative of what is going on (and what could be done) in other watersheds throughout the Upper Mississippi River Basin. If this is true, and one recalls that the Upper Mississippi River Basin contributes one-third of the total nitrate load to the Mississippi, then it is clear that more work must be done to identify exactly what impact artificial drainage in general, and tile drainage in particular, has on nitrogen loads to the Basin and what the economic gains would be of focusing abatement measures on drained acres. One should also note well that tile drainage is not unique to the Midwest. Drained acres in other Basin states include Arkansas (7 million), Louisiana (7), Mississippi (5.8), Missouri (4.2), and Wisconsin (2.2) (Pavelis, 1987). Therefore, drainage is an issue across the entire Basin, and should be explicitly accounted for in any research that endeavors to address the economics of Gulf of Mexico hypoxia.

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