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Missing the Boat: Midwest Farm Drainage and Gulf of Mexico Hypoxia

Daniel R. Petrolia and Prasanna H. Gowda

Research addressing Gulf hypoxia has failed to account for agricultural drainage, the major pathway of nitrate loads in Upper Midwest states. Focusing on two Minnesota watersheds, simulation results were combined with a constrained-optimization model to evaluate the cost-effectiveness of nitrogen-abatement policies, with explicit focus on drainage. Results indicate that drained land dominates in nitrogsen abatement, and has substantially lower abatement costs relative to nondrained land. However, policies that remove drainage were not cost-effective. Further, it was found that nutrient management, a policy strongly recommended by prior research, is relatively cost-ineffective as a means of abatement on non-drained land.

The Mississippi–Atchafalaya River Basin drains 41% of the continental United States and accounts for 90% 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% of that as nitrates (the mobile form of nitrogen) (Goolsby et al., Rabalais et al.). 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, 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 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, Turner, and Scavia). Such hypoxic areas have become

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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). 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% of the nation's recreational fish landings alone (Pritchard).

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% of the nitrate inputs to the Mississippi River derive from nonpoint sources. Seventy-four percent of these nonpoint sources 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.). Levels of applied nitrogen fertilizer in the Basin have increased from less than 1 million to more than 6 million metric tons annually over the past fifty years (Goolsby et al.). It is no surprise, then, that over half of the nitrate enters the Mississippi north of the confluence with the Ohio River (Rabalais, Turner, and Scavia), where more than 50% 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, especially that of Doering et al. 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 restoring 5 million wetland acres along with reducing fertilizer use by 20% within the Basin to meet a nearly 20% nitrogen-load reduction. The report also implied that abatement beyond the 20% level would place severe economic strain on the Basin.

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

These studies 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 cutting across watersheds (U.S. Department of Agriculture, Economic Research Service). The Corn Belt region, in particular, contains parts of at least four of the eighteen USGS two-digit hydrologic units for the continental United States. Segmenting the area under consideration in this manner may be problematic, and Ribaudo et al. 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. 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). Ribaudo et al., Greenhalgh and Sauer, and Wu, Lakshminarayan, and Babcock used the same model. Greenhalgh and Sauer 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., who, speaking about differences in results between basin wide and regional studies, say 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" (pp. 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, tile drainage has been shown to reduce the loss of phosphorus, organic nitrogen, and other pollutants, such as certain pesticides, to waterways (Skaggs, Brevé, and Gilliam). 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. found that during a three-year study period, subsurface tile drainage accounted for 99.1% of all nitrate losses. Logan, Eckert, and Beak report that during a four-year study period, nitrate losses from surface runoff were between 0.009 and 2.0 lbs/acre, while that of tile drainage was between 0.009 and 76.5 lbs/ac.

Higher nitrogen losses from tile-drained land relative to non-tile-drained land are due to increased outflows of mobile constituents such as nitrate-nitrogen. According to Randall, tile drainage removes excess water thereby creating a more aerobic soil profile above the depth of the tile lines. This phenomenon allows mineralization and nitrification to occur, but more importantly, restricts denitrification. Thus, instead of nitrogen being lost solely to the atmosphere as dinitrogen (atmospheric nitrogen) or nitrous oxide via denitrification (as happens in a water-logged, poorly drained no-ntile-drained soil), the nitrogen is lost primarily through the tile lines as nitrate when drainage occurs. In addition, some nitrate can be lost via denitrification in a tile-drained soil depending on drainage intensity and rainfall amount and duration. Although Randall was referring specifically to poorly-drained soils, his conclusion is supported by many studies and is robust across a variety of soil types, climates, and regions (see Skaggs, Brevé, and Gilliam).

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 million), Iowa (7.8 million), Ohio (7.4 million), and Minnesota (6.4 million). Of these drained acres, cropland comprises 90%, 85%, 90%, 80%, and 75%, respectively (Zucker and Brown), and according to Mulla, 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., 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. Illinois, Indiana, Iowa, Ohio, and Minnesota account for 51% of the nation's acres planted to corn, and 53% of planted soybean acres (U.S. Department of Agriculture, National Agricultural Statistics Service 2002).

Finally, considering the importance attributed to fertilizer use by the aforementioned studies, it is useful to cite the results of Randall and Mulla, 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.

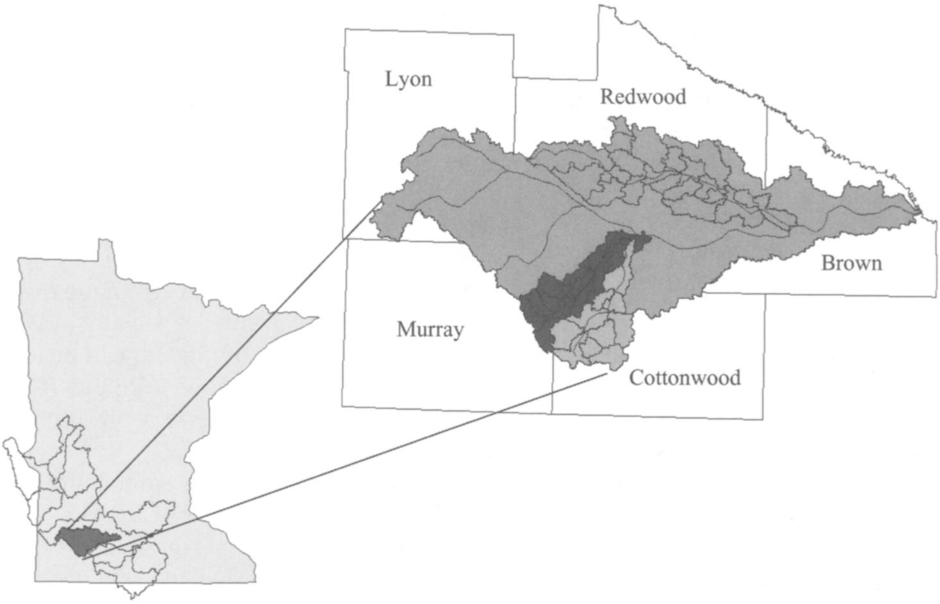
The present work undertook the task of analyzing some of the same land-use policies cited in previous work for reducing nitrogen loads, but did so at the watershed level rather than at a regional or basin scale. Furthermore, this work explicitly accounted for subsurface tile drainage and identified the 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 focused on an area in Minnesota not far from the great river's headwaters, a long way from the southeastern tip of Louisiana, where the mouth of the Mississippi opens into the Gulf. In addition to being the birthplace of the Mississippi River, Minnesota is also home to the Minnesota River, a major tributary of the Upper Mississippi River Basin. The Minnesota River Basin is similar to many basins in the Upper Mississippi River Basin in that it is dominated by corn and soybean production, receives heavy applications of nitrogen fertilizer, has soils high in organic matter content, experiences a significant excess of precipitation over evapotranspiration, and is extensively managed with artificial drainage systems (Davis et al.).

This study focused on the Highwater Creek/Dutch Charlie Creek (HDCC) and Sleepy Eye Creek (SEC) minor watersheds, comprising 133,058 and 174,180 acres, respectively, of the Cottonwood River Watershed (USGS Cataloging Unit 07020008) in southwestern Minnesota, which is a subwatershed of the Minnesota River Basin (see figure 1). These watersheds are dominated by agriculture, with 88% of land devoted to row crops (Mulla and Mallawatantri). About 10 and 30% of the total land area in the HDCC and SEC watersheds are tile-drained, respectively.

Figure 1. Bottom-left: Minnesota River Basin with Cottonwood River Watershed highlighted; top-right: Cottonwood River Watershed with Sleepy Eye, Highwater, and Dutch Charlie Creek Subwatersheds highlighted (clockwise from top, respectively)



Nitrogen-Abatement Policies Tested

Four policies were tested on cropland in the study watersheds to ascertain their relative cost-effectiveness of achieving a range of nitrogen-abatement levels. The first policy was nutrient (fertilizer) management, which called for the adoption of a spring-applied 112 lbs/acre rate of nitrogen fertilizer. Spring application has been established as a Best Management Practice by the University of Minnesota (Randall and Schmitt), 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 replaced by pasture. The third policy, labeled "plug and crop" called for land having artificial drainage to be plugged, but allowed for the current crop to be retained. It was assumed that a loss of drainage would reduce crop-yields by 20%. The last policy, labeled "plug and retire," called for tile-drained land to have its lines plugged in addition to being put to pasture. The latter two policies would thus restore the land to its natural drainage capabilities.

Data Description and Methods

A stylized model of the study watersheds was developed using a combination of satellite imagery, data from an agricultural survey of the study watersheds (Strock et al.), climate data from the Minnesota Climatology Working Group, and soil data from the NRCS State Soil Geographic (STATSGO) database (U.S.

Department of Agriculture, National Resource Conservation Service, 1994). Land units were developed using a three-part process consisting of the development of Hydrologic Response Units (HRUs), HRU aggregation into Transformed Hydrologic Response Units (THRUs, Gowda, Mulla, and Jaynes), then differentiation of THRUs into Modified THRUs. In HRU formation, spatial data layers of land cover and STATSGO soil associations were overlain with ARC/INFO GIS software, resulting in a GIS layer consisting of many polygons, such that each contains hydrologic characteristics that are unique from those around it. Polygons that are similar in every aspect except location were then aggregated into THRUs. These THRUs were further differentiated according to drainage characteristics (tile drainage and slope), nitrogen fertilizer application rate (high, medium, or low), and timing (spring or fall). The resulting unique land units, called Modified THRUs, were the functional modeling unit (hereafter they are referred to simply as "THRUs").

The Agricultural Drainage and Pesticide Transport (ADAPT) model was used to simulate field-scale nitrogen loads for each THRU under each abatement policy. ADAPT (Chung, Ward, and Shalk) is a daily time-step field-scale water table management simulation model that was developed by integrating GLEAMS (Leonard, Knisel, and Still), a root zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs), a subsurface drainage model. It has been calibrated and validated at the field scale for a variety of Midwestern conditions.[1] Additionally, the ADAPT simulation results obtained for this study were consistent with experimental field results pertaining to tile-drained agricultural land, including Davis et al., Randall and Mulla, Randall et al., and Kladivko et al. Finally, there is precedence in the agricultural-economics literature for using ADAPT, including Johansson et al.; Updegraff, Gowda, and Mulla; and Westra.

The simulated nitrogen load levels for each THRU were used as input parameters to conduct economic analysis. Economic data were taken from Lazarus and Selley, *Agricultural Statistics* (U.S. Department of Agriculture, National Agricultural Statistics Service, 2002, 2003, 2004), and the University of Minnesota FINBIN database to construct crop enterprise budgets for corn and soybeans for each fertilizer rate and timing combination. Although enterprise costs varied from one THRU to the next, the average enterprise cost was $270 per acre for corn and $174 per acre for soybeans. ADAPT was not used to estimate crop-yields; rather yields on each THRU were based on NRCS county-level soil-specific yields (U.S. Department of Agriculture, National Resource Conservation Service, 2004) adjusted for drainage and fertilizer-application rates and timing. Although crop-yields were unique to each land unit, the average yields in the stylized HDCC watershed were 150 and 43 bushels per acre for corn and soybeans, respectively, and 155 and 43 bushels per acre for the SEC watershed.

Values per bushel of corn and beans, $2.19 and $6.04, respectively, were the 2002–2003 mean values reported by FINBIN (University of Minnesota) over all crop-tenure types for the study watersheds. Miscellaneous income per acre for each crop was also taken from FINBIN (University of Minnesota). Land rent for each THRU was based on the 1999–2003 mean values reported by FINBIN (University of Minnesota) for the study region and adjusted for crop-yield using Lazarus' method. It was also necessary to include "technical" costs associated with adoption of a particular abatement policy in the calculation of net returns.

Per acre drain-plugging costs, based on estimates from Shultz and Leitch, were assumed to be \$200, and the per acre switching cost associated with adoption of the alternative nutrient-management scheme was estimated to be \$30.[2] The average per acre net return for each THRU, therefore, was calculated as NR = (per acre crop revenue + per acre miscellaneous income) − (per acre enterprise cost + per acre rent + per acre technical cost).

Nitrogen-load abatement constraints were tested in two ways: uniformly, such that each THRU was required to meet the percentage reduction independently, and targeted, such that the watersheds, in the aggregate, satisfied the percentage reduction. Tested abatement constraints ranged, in 10% increments, from 10% to 70% of the base-case load. It was infeasible to achieve abatement beyond 70% of the base under any combination of the tested policies in these watersheds.

Per acre nitrogen-load coefficients taken from ADAPT and net-return coefficients estimated as mentioned above were used as inputs into a linear constrained-optimization model that was solved using the Generalized Algebraic Modeling System (GAMS Development Corporation). The optimization model was used to solve for the optimal combination of abatement policies such that agricultural net returns in the watershed (minus technical costs) were maximized subject to a range of nitrogen-load abatement constraints.

Results

Table 1 contains the percentage changes in net returns under the uniform and targeted policies, respectively, for each abatement level. Targeted abatement resulted in higher net returns for the watersheds at all abatement levels. Returns were 11% higher at the 10% abatement level, and as much as 24% higher at the 40% abatement level. Furthermore, targeted abatement was able to achieve abatement at the 60% and 70% levels, which was infeasible under uniform abatement. Thus, targeting not only resulted in substantially higher net returns for a given abatement level, it was able to abate at levels unattainable under the uniform policy.

Both the uniform and targeted abatement schemes relied solely on nutrient management and land retirement to achieve the required abatement; under no

Table 1. Change in net returns from the base case for the uniform and targeted policies at each abatement level

	% Change in Net Returns from Base	
% N-Load Abated	Uniform	Targeted
Base	\$20,918,619	\$20,918,619
10%	−12%	−1%
20%	−24%	−6%
30%	−37%	−15%
40%	−50%	−26%
50%	−64%	−42%
60%	Infeasible	−64%
70%	Infeasible	−91%

Table 2. Number of acres N-managed and retired under uniform and targeted policies, respectively, at each abatement level

	Uniform		Targeted	
% N-Load Abated	N-Managed	Retired	N-Managed	Retired
10%	13,333	37,157	17,546	7,384
20%	26,667	67,133	43,407	19,018
30%	38,668	97,558	42,546	58,852
40%	45,378	129,956	16,050	100,360
50%	46,258	165,241	2,012	153,529
60%	Infeasible		247	203,585
70%	Infeasible		0	257,226

scenario was it optimal for acreage to come under either the plug-and-crop or plug-and-retire policies. Table 2 contains the distribution of acres under the uniform and targeted schemes for each abatement level. Uniform abatement relied substantially more on land retirement at all abatement levels, retiring 30,000 more acres at the 10% abatement level, and as much as 48,000 more at the 20% abatement level relative to the targeted scheme. Under uniform abatement, the number of nutrient-managed acres equaled about one-third of the number of retired acres. Targeted abatement, however, relied more on nutrient management, assigning as much as 29,000 more acres to this policy relative to uniform abatement.

Nutrient management as a policy tool dominated at lower abatement levels, with the number of such acres equaling more than twice that of retired acres. However, as abatement increased under the targeted scheme policy, reliance on nutrient management peaked at 30% abatement, then declined to zero. At the same time, the number of retired acres rose steadily as abatement increased under the targeted scheme, but there was still less reliance on retirement at all abatement levels relative to the uniform policy. Targeting, therefore, not only altered which land was chosen for abatement, but also the balance of optimal abatement activities. Targeting allowed for more land to remain in production under the same abatement constraint than did the uniform scheme.

The Role of Tile Drainage

The above section gave an overview of the optimal solution under nitrogen-load abatement; and in terms of the optimal policies, results did not differ greatly from previous literature. However, the results conceal the importance of explicitly differentiating between nondrained and tile-drained land in such analyses. This section details the role played by tile-drained land in the optimal solution; it is here that clear distinctions are made between the cost-effectiveness of abating on land that is drained and on land that is not. Keep in mind throughout the following discussion that tile-drained land comprised no more than 21% of all land in the study watersheds.

Table 3 contains the percentage share of abatement on tile-drained land under the uniform and targeted schemes, respectively. Under uniform abatement,

Table 3. Share of N-load abatement on tile-drained land for the uniform and targeted policies at each abatement level

	Share of Abatement on Tile-Drained Land	
% N-Load Abated	Uniform	Targeted
10%	37%	87%
20%	39%	84%
30%	40%	67%
40%	40%	71%
50%	41%	65%
60%	Infeasible	55%
70%	Infeasible	47%

tile-drained land never accounted for more than 41% of total abatement under any abatement level. Nevertheless, the share on tile-drained land was disproportionately greater than the share of total tile-drained acres in the watershed. When targeting was used, the share of abatement on tile-drained land more than doubled at initial abatement levels, to 84% and 87%, respectively. As abatement levels increased, the dependence on tile-drained land declined, but this was due to the fact that the number of tile-drained acres available for abatement was exhausted, and thus further abatement was necessarily achieved on nondrained land.

It is important to realize that almost 90% of initial abatement was achieved on tile-drained land, indicating that on the whole, selecting this land type for abatement is more cost-effective. Figures 2 and 3 testify further to this conclusion. Figure 2 plots the number of tile-drained acres assigned to the nutrient-management policy at each abatement level. Note that *only* tile-drained acres were

Figure 2. Optimal number of tile-drained nutrient-managed acres under uniform and targeted policies at each abatement level

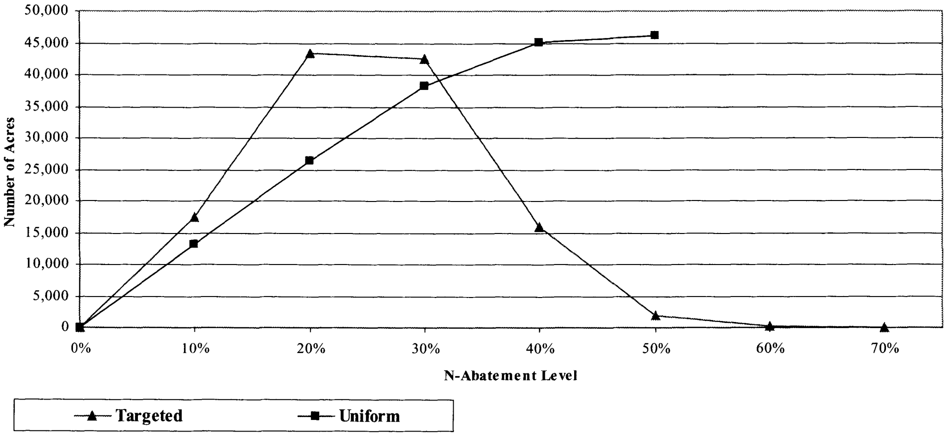
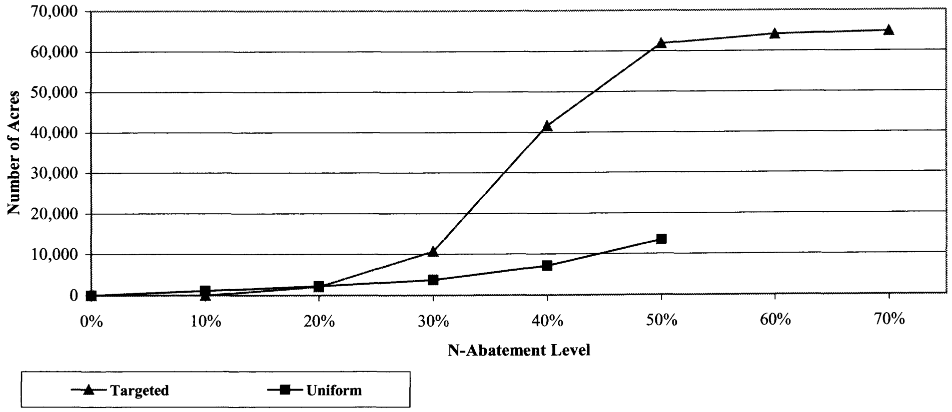


Figure 3. Optimal number of retired tile-drained acres under uniform and targeted policies for each abatement level



assigned to this policy, that is, it was not cost-effective to implement nutrient-management practices on *any* nondrained land. As the figure shows, at least at initial abatement levels, nutrient management on tile-drained land played a larger role under the targeted scheme than under the uniform scheme. At 20% abatement, the difference between the uniform and targeted schemes was almost 20,000 acres. Beyond 30% abatement, dependence on nutrient management on tile-drained acres declined and there was a shift to more reliance on land retirement.

Figure 3 tells the same story with regard to the land-retirement policy. Although the differences were small at lower abatement levels, there were substantial differences in reliance on tile-drained land for retirement at higher abatement levels. At 30% abatement, the targeted scheme assigned about 5,000 more tile-drained acres to retirement than the uniform scheme. At 40% abatement, the difference was more than 30,000 acres, and at 50% abatement, more than 40,000 acres. Note also that at abatement levels of 50% or more, almost all tile-drained land was retired (there are 65,600 total acres of tile-drained land in the study watersheds).

The differences between nondrained and tile-drained land can be seen even more clearly by comparing the results from implementation of a nutrient-management policy on all cropland to those on tile-drained cropland alone (table 4). When all cropland was enrolled, there was an 18% reduction in nitrogen loads with a corresponding 36% reduction in net returns. When only tile-drained cropland was enrolled, however, the same abatement level was achieved with only an 8% drop in net returns. These results indicate, therefore, that there were no abatement gains from adopting nutrient management on nondrained land. In fact, abatement was actually slightly higher when nondrained land was *not* enrolled, due to the fact that some nondrained lands' nitrogen loads actually increased when fertilizer applications were moved from fall to spring. The costs per pound of abatement tell the story: on tile-drained land the average cost was $2 per pound of nitrogen abated; on nondrained land it was $90 per pound.

Table 4. Percentage change in net returns and N-load from base when all cropland and only tile-drained cropland, respectively, come under nutrient management

	% Change in Net Returns from Base	% Change in N-Load from Base
Base	$20,918,619	4,010,828
All Cropland	−36%	−18%
Only tile-drained cropland	−8%	−18%

Discussion

The above results show clearly the differences in abatement capability and cost between nondrained and tile-drained cropland, and hence, the importance of explicitly modeling land as such. When results were segregated according to drained and nondrained land, it was shown that when land is economically targeted for abatement, tile-drained acreage accounted for almost all initial nitrogen abatement, and accounted for more than half of abatement at subsequent levels. Thus, tile-drained land accounted for the lion's share of abatement in the study watersheds even though it comprised no more than 21% of all land in these watersheds.

Prior work concluded that a nutrient-management policy was the most cost-effective method of achieving nitrogen-load abatement, but these results indicate that there is a significant qualification to such a statement. The results here show that certain policies, such as nutrient management, are *only* cost-effective on tile-drained land, but completely cost-*in*effective on nondrained land. Additionally, prior work found that a 45% reduction in applied nitrogen was necessary to achieve a near 20% reduction in nitrogen loads. The present study, however, achieved the same reduction with half the reduction in applied nitrogen. The difference may be attributed to modeling differences; however, it is more likely, and the results here indicate that the difference is due to the explicit modeling of tile-drained land and its relatively greater abatement capabilities. What this means is that because abatement capabilities may be greater on some land than previously estimated, reductions beyond the 20% level may not have as severe consequences on the farm economy as prior work predicted.

Additionally, something must be said about the cost-ineffectiveness of the plug-and-crop and plug-and-retire policies. These policies, which coupled the plugging of drainage with either continued production or retirement, were not selected for use on a single acre of land. One may conclude that the cost of plugging made such a policy prohibitive, but this does not tell the whole story. It is true that the reason a plug-and-retire policy was not cost-effective was because the additional abatement gains from plugging land *after* it had been retired were minimal, and hence the benefits of plugging were outweighed by the cost of plugging. Thus, the cost of plugging did play a role. However, the model was tested by allowing plugging costs to fall from the estimated rate of $200 per acre to as low as $20 per acre before plugging was optimal on even a few acres. Hence, cost was an issue, but the results were not very sensitive to it. Costs would need to be an order of magnitude lower before such a policy was optimal (coincidentally, a $20-per-acre plugging cost would be $10 cheaper than the assumed technical cost associated with the nutrient-management policy, which was quite cost-effective).

Furthermore, the main reason why a plug-and-crop policy was not optimal was because tile-drained land is prime agricultural land. Yields on flat tile-drained soils are consistently higher than that of their steeper nondrained counterparts. Thus, costs notwithstanding, the act of plugging entails a substantial *opportunity cost* to agricultural production, and hence, returns. The more cost-efficient alternative was to adopt nutrient-management policies on the land, so that it remained in production and thus retained the yield benefits of drainage. It was only at higher abatement levels that such a policy became less cost-effective, and it was necessary to begin removing these acres from production as well.

Implications for Gulf of Mexico Hypoxia

The overarching 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 others 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 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 million), Mississippi (5.8 million), Missouri (4.2 million), and Wisconsin (2.2 million) (Pavelis). 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.

Endnotes

[1] Davis et al. calibrated and validated ADAPT for tile drainage and associated nitrate-nitrogen losses using long-term monitoring data measured on three experimental plots of a Webster clay loam under continuous corn with conventional tillage treatment. Their predicted tile-drain flows and nitrate-nitrogen losses agreed reasonably with the measured trends for both calibration and validation periods. Additionally, Gowda, Mulla, and Jaynes calibrated and validated ADAPT for fields in the Walnut Creek watershed in central Iowa, and Gowda et al. did likewise to evaluate sixteen agricultural management practices, with and without tile drainage, on land in a small agricultural watershed in northern Ohio.

[2] Results were not at all sensitive to variations in plugging costs. Also, variations in nutrient-management switching cost levels did change results somewhat, but only in degree. In short, the conclusions reached in this paper were not sensitive to either parameter.

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