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An Analysis of the Role of Tile-Drained Farmland Under Alternative Nitrogen Abatement Policies

Daniel R. Petrolia and Prasanna H. Gowda

Agricultural nitrogen is a major contributor to Gulf of Mexico hypoxia, and research has shown that agricultural subsurface tile drainage is a major carrier of nitrogen from croplands to streams and rivers. This study compares the results of abating nitrogen under a retired-land minimization policy with those of a net revenue-maximizing policy, paying particular attention to the role of tile-drained land. Findings reveal the retirement-minimizing policy resulted in more tile-drained land being retired and less being fertilizer-managed than was optimal under the net-return maximizing policy. Also, it led to a greater economic burden being shouldered by tile-drained land. Under both cases, tile drainage dominated the abatement process.

Key words: abatement, ADAPT, drainage, hypoxia, nitrogen

Introduction

Agricultural nitrogen loading to rivers and streams has been cited as one of the primary sources of nitrates that lead to hypoxic zones, with the most notable being in the Gulf of Mexico, stretching across coastal Louisiana and Texas (Goolsby et al., 1999; Rabalais et al., 1999). 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).

Research has therefore turned to analysis of agricultural production to determine what impact alternative practices could have on nitrate loading. Such work ranges from field-scale studies (Kladivko et al., 2004; Huggins, Randall, and Russelle, 2001; Davis et al., 2000; Randall et al., 1997; Logan, Eckert, and Beak, 1994) to regional (Dinnes et al., 2002; Randall and Mulla, 2001) and basin-wide studies (Mitsch et al., 2001; Brezonik et al., 1999). Additionally, several studies have attempted to identify the economic feasibility and impact of nitrogen-abatement policies on farm land (Greenhalgh and Sauer, 2003; Ribaudo et al., 2001; Doering et al., 1999; Wu, Lakshminarayan, and Babcock, 1996). Doering et al. found that reductions in applied fertilizer and wetland restoration were the most cost-effective policies for a 20% reduction in nitrogen loads. In contrast, Ribaudo et al. concluded wetland restoration was cost-ineffective, and that only a reduction in applied fertilizer was cost-effective.

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Unfortunately, these latter studies failed to explicitly account for subsurface (tile) drainage. This is a major omission, given that the use of tile drainage on farmland is common throughout the Mississippi River Basin, and that about 90% of all corn and soybeans are produced there [U.S. Department of Agriculture/National Agricultural Statistics Service (USDA/NASS)].[1] In the Midwest in particular, which comprises a large part of the Basin, half of all cropland in Indiana and Ohio is drained, a third of all cropland in Illinois and Michigan is drained, and about a fourth of all cropland in Iowa, Minnesota, and Missouri is drained (Zucker and Brown, 1998).[2]

Tile drainage is the primary carrier of nitrate-nitrogen, and can significantly hasten water and the nitrate contained therein to the edge of field, and thus into adjacent streams (see Jackson et al., 1973; Logan, Eckert, and Beak, 1994). Further, the combination of tile drainage with row crop production, such as corn and soybeans, can drastically increase nitrate losses (see Randall et al., 1997). Finally, the fact that Mitsch et al. (2001) include a minimum spacing standard for farm tile drains along with other essential approaches to reducing nitrogen loads—such as nitrogen fertilizer management, alternative cropping systems, wetland restoration, and river diversions—is clear evidence that farm tile drainage is critical to any discussion of agricultural nitrogen abatement.

Petrolia and Gowda (2006) improve upon prior work by explicitly including drainage characteristics of land in their modeling framework. They found targeting tile-drained land for nitrogen abatement was more efficient relative to a uniformly applied abatement policy. Furthermore, under a targeted scheme, they report tile-drained land accounted for as much as 87% of abatement, even though only 21% of the study area was tile-drained. Their analysis is unique in that policies could be implemented according to the drainage characteristics of each land unit, and the suite of abatement policies included drainage-specific policies such as drain plugging.

Given the above discussion, there is clearly a need for a reduction in agricultural nitrogen loads to the Mississippi River Basin if any significant reductions in the size of the hypoxic zone are to be achieved. Furthermore, it is evident that targeting tile-drained farmland could result in more cost-effective nitrogen-abatement programs within the Basin. However, with the exception of the work described above, no economic analyses have been conducted to explicitly account for the unique role played by tile drainage. Because tile-drained land has consistently higher crop yields relative to non-drained land (and is therefore more profitable), because nitrogen losses from drained land are significantly higher than those of non-drained land, and because tile-drained land behaves fundamentally differently in response to abatement measures compared to non-drained land, we argue that any policy recommendations based on the assumption these lands behave similarly should be considered suspect. It is from this perspective we believe the results of this work should be considered.

It is precisely because of the shortcomings of prior work that this research was undertaken to gain a better understanding of the differences between drained and non-drained farmland, what these differences mean in terms of efficiency of nitrogen abatement efforts, and what they mean in terms of net returns on the agricultural land

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[1] There are roughly 75 million artificially drained acres (surface and subsurface) throughout the Mississippi River Basin (Pavelis, 1987).

[2] Michigan is not part of the Mississippi River Basin, but is included here to emphasize the widespread use of drainage in agriculture.

involved. Although a basin-wide analysis addressing the impact of policy options and market implications (as carried out by prior work) was beyond the scope of this study, the research presented here offers valuable insights into the effectiveness of nitrogen abatement policies at the watershed and farm levels, which is where these policies will ultimately be put into practice.

Study Objective

The primary objective of this study was to compare the impact on on-farm net returns of a watershed-wide nitrogen abatement policy that minimized the number of retired acres with one that maximized net farm returns for a given abatement level. Specifically, this work compares the results of an abatement policy whose goal is to achieve abatement on the fewest possible acres with one whose goal is to achieve abatement with minimal economic impact on farm net returns. For ease of exposition, these policies are referred to as "Retire-Min" and "Return-Max," respectively, and were compared at a variety of abatement levels. In addition to ascertaining the difference in monetary impacts between the two policies, it was also the objective of this work to identify the optimal land-management tools under each policy and to examine the relative importance of tile drainage within this framework.

Nitrogen-Abatement Practices Modeled

Three land-management practices used to achieve abatement were assumed to be available on each acre of row-crop land in the study watersheds. The first practice 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 (BMP) by the University of Minnesota (Randall and Schmitt, 1993), and the rate noted above was the lowest of the three most commonly used application rates within the study region. The second practice was land retirement, where the current row crop was replaced by pasture. The third practice was drain plugging. If a crop continued to be grown on plugged land, then it was assumed a loss of drainage would reduce crop yield by 20%.[3] The latter two policies, retirement and plugging, could be implemented separately or simultaneously.

Study Region, Data, and Methods

A stylized model of the Highwater Creek-Dutch Charlie Creek (HDCC) and Sleepy Eye Creek (SEC) minor watersheds, which comprise part of the Cottonwood River Watershed (USGS 8-digit hydrologic unit 07020008), located in southwestern Minnesota, was developed using a combination of satellite imagery, data from an agricultural survey, climate data, and soil data (see figure 1). The Cottonwood River Watershed drains about 1,310 square miles of land, and the HDCC and SEC minor watersheds themselves drain 133,560 and 175,445 acres, respectively. These watersheds are typical of many agricultural watersheds in the Upper Mississippi River Basin in that they are dominated by

[3] For an analysis of sensitivity to this assumption, see Petrolia (2005).

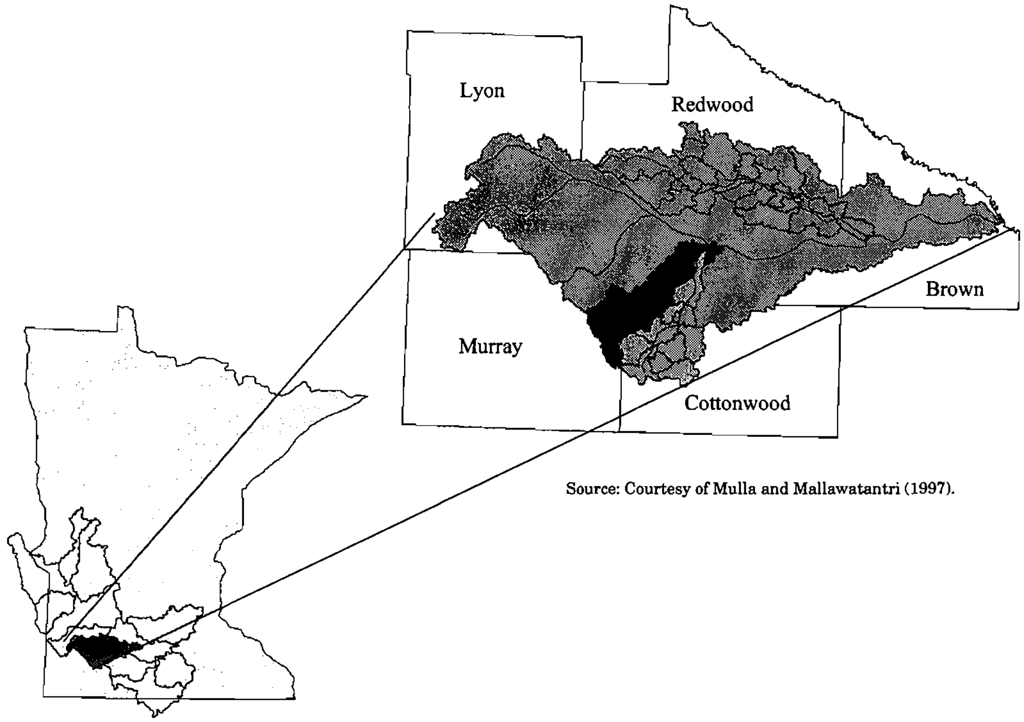

Figure 1. [Bottom left]: Minnesota River Basin with Cottonwood River Watershed highlighted. [Top right]: Cottonwood River Watershed with Sleepy Eye, Highwater, and Dutch Charlie Creek subwatersheds highlighted (clockwise from top, respectively)

corn and soybean production, receive heavy applications of nitrogen fertilizer, have soils high in organic matter content, have a significant excess of precipitation over evapotranspiration, and are extensively managed with artificial tile-drainage systems[4] which rapidly transport nitrogen in shallow groundwater toward surface waterways (Davis et al., 2000).

Modeled 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 et al., 1999), 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 containing hydrologic characteristics that are unique from those around them. Polygons which were similar in every aspect except location were then aggregated into THRUs. These THRUs were then 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 referred to simply as "THRUs").

Climate data for the years 1974–2003 were collected from the Minnesota Climatology Working Group (2004). Soils were represented at the soil-association level using the

[4] Mulla (2004) estimates that tile-drained land comprises approximately 10% of all land in the HDCC watershed and 30% of land in the SEC watershed.

State Soil Geographic (STATSGO) database [USDA/National Resources Conservation Service (NRCS), 1994]. In order to apply these soil associations to ADAPT, it was necessary to choose one soil type as representative of each association. Slopes were a weighted average calculated using the percentage of each soil in each drainage group of each association. STATSGO soil associations present in each watershed were separated into well-drained, poorly-drained, and poorly-drained-improved-by-drainage soils. Crop rotations and fertilizer application methods, timing, and rates were based on Strock et al. (2005). Alfalfa/grass/pasture, forest, and urban/roads acreage was assumed to remain as such throughout all simulations. Drainage spacing and depth specifications for each soil type were taken from Wright and Sands (2001).

Potential corn yield for each soil type present in each soil association was taken from the NRCS Soil Data Mart website (USDA/NRCS, 2004). These yields were then weighted according to percentage of each soil type present in each soil-drainage group, to arrive at a weighted potential yield for each group. Soil-drainage groups were then ranked based on potential corn yield, with the highest ranking group in the study region being assigned a rating of 100. All other groups were rated relative to the high group.

Next, an initial expected yield was assigned to the high group, with other association yields scaled accordingly. Using the high group as the base, yields were adjusted for nitrogen application rates based on expected corn yields reported by Randall et al. (2003). Yields were then further adjusted for differences between fall and spring nitrogen application. It was also necessary to adjust crop yields for fields in need of drainage but not actually drained. Finally, the initial expected yield for the highest rated group was adjusted (and hence all other association yields adjusted relative to it) until the watershed's average yield was equal to the 1999–2003 average yield reported for all corn acres for the relevant counties by FINBIN (University of Minnesota, 2004). Soybean yields were calculated in like manner, except there was no variation in yield due to fertilizer rates and timing because it was assumed that no fertilizer was applied to soybeans.

Enterprise costs for corn and soybeans, with the exception of land rent, were constructed using data from a variety of sources. Fertilizer prices were the 1999–2003 averages reported in *Agricultural Statistics* (USDA/NASS), and equipment costs were the use-related costs documented by Lazarus and Selley (2003). All other costs were the 1999–2003 averages on all land tenure types for the relevant counties as derived from the FINBIN database (University of Minnesota, 2004). Land rent was adjusted to account for soil productivity. Each soil drainage group was assigned a corn yield in the aforementioned manner. These yields were then used to estimate a rent value following a simplified method presented by Lazarus (2004). The intercept term reported in Lazarus was adjusted until the weighted-average rent in each watershed was equal to the 1999–2003 average for cash-rent land for corn and soybeans in the relevant counties, as taken from the FINBIN database.

For per acre revenue, the 2002–2003 mean value per unit reported by FINBIN (University of Minnesota, 2004) over all crop tenure types for the relevant counties was used as the output price per bushel of corn ($2.19/bu.) and soybeans ($6.04/bu.), respectively. Net return for each acre of land in the study was then calculated as:

$$\begin{aligned} \textit{Net Return} = &(\textit{Crop Revenue per Acre} + \textit{Miscellaneous Income per Acre}) \\ &- (\textit{Enterprise Cost per Acre} + \textit{Rent per Acre}). \end{aligned}$$

Therefore, each acre of land had a unique net return value based on its respective soil, production, drainage, and yield characteristics. Because each acre of corn (soybeans) in the watershed was assumed to rotate to soybeans (corn) the following year, per acre net returns from each were combined into a two-year average. The per acre net returns calculated for the base scenario served as the values from which any policy costs were calculated. The difference between the base value and the value associated with an acre of land under an alternative policy was interpreted as the opportunity costs of adopting that policy.

The cost associated with adopting an alternative fertilizer application regime was assumed to be $17.50 per acre, which was half of the weighted-average switching cost calculated over all corn acres that were using either a high or medium application rate, fall application, or both.[5] Annualized per acre drain-plugging costs, based on estimates from Shultz and Leitch (2003), were assumed to be $40 (assuming land would remain plugged for five years).

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, 1992) is a daily time step field-scale water table management simulation model, developed by integrating GLEAMS (Leonard, Knisel, and Still, 1987), a root zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs, 1978), a subsurface drainage model. It has been calibrated and validated at the field scale for a variety of Midwestern conditions.[6] 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. (2000); Randall and Mulla (2001); Randall et al. (1997); and Kladivko et al. (2004). Finally, there is precedence in the economics literature for using ADAPT (e.g., Johansson et al., 2004; Updegraff, Gowda, and Mulla, 2004; Westra, 2001).

It should be noted the watershed was modeled under the assumption that the impacts of drain plugging on one unit of land did not affect an adjacent unit. This assumption, by and large, reflects the reality on the ground because the primary consequences of drain plugging are ponding in low spots within the field and an increase in runoff. Thus, when the drains are plugged, the majority of excess water will not make its way into adjoining fields; it will remain in the field or it will end up in the nearby ditch, just as it would if the drains were operational. The difference is that it will reach the ditch as runoff rather than as subsurface drainage.

The simulated nitrogen load levels for each THRU were then used as input parameters to conduct economic analysis. Per acre nitrogen-load coefficients taken from ADAPT and net-return coefficients estimated as noted above were used as inputs into a linear constrained optimization model which was solved using the Generalized Algebraic Modeling System (GAMS). The objective function was specified in two ways: for the Retire-Min policy, the objective was to minimize the number of retired acres; for

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[5] The cost was halved because the farmer was assumed to produce corn every other year, and thus faced this cost only during those years.

[6] Davis et al. (2000) calibrated and validated ADAPT for tile drainage and associated nitrate-N 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-N losses agreed reasonably with the measured trends for both calibration and validation periods. Additionally, Gowda, Mulla, and Jaynes (2002) calibrated and validated ADAPT for fields in the Walnut Creek watershed in central Iowa, and Gowda et al. (1999) did likewise to evaluate 16 agricultural management practices, with and without tile drainage, on land in a small agricultural watershed in northern Ohio.

the Return-Max policy, the objective was to maximize net agricultural returns in the watershed. The nitrogen-load abatement constraint was applied such that the watersheds, in aggregate, satisfied a range of percentage reductions. In 10% increments, tested abatement constraints ranged 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. (A mathematical exposition of the optimization model is presented in the appendix.) For additional details on data, methods, and programming, as well as sensitivity of results to parameter assumptions, see Petrolia (2005).

Results

Table 1 provides the figures for total cost, cost per acre, and cost per pound of abated nitrogen under each policy at each abatement level. As expected, the Return-Max policy resulted in lower costs at each abatement level. A 10% reduction in nitrogen losses under the Retire-Min policy costs $391,000, whereas costs were negative (–$9,638) under the Return-Max policy. This latter result was due largely to the retirement of unprofitable acres, as well as reduced fertilizer costs on productive acres. The same was true at higher abatement levels, with the largest difference in costs at 30% abatement, where a difference in cost between the two policies was approximately $5.5 million. This difference in cost represents 27% of the base-case total net returns for the entire watershed. Costs per acre tell the same story: at 30% abatement, the cost per acre under the Retire-Min policy was $26.34, and for the Return-Max policy this cost was $8.29. Furthermore, in terms of abated nitrogen, the cost per pound of N under the Return-Max policy was less than one-third the cost under the Retire-Min policy.

Table 2 presents the breakdown of acreage into each management practice under the two policies at each abatement level. Under the Retire-Min policy, up to 20% abatement could be achieved without retiring any additional land. Furthermore, the Retire-Min policy relied more heavily on fertilizer management and drain plugging, although it still required substantial retired acreage at higher abatement levels. The Return-Max policy, however, relied more on fertilizer management at lower abatement levels, and on retirement at higher abatement levels. This policy did not implement any drain plugging whatsoever. This latter result suggests drain plugging may be a means of abatement that helps to mitigate land retirement, yet it is wholly cost-ineffective. Overall, as observed from the general pattern under both policies, the number of fertilizer-managed acres increased as abatement increased, reached a peak at 30% abatement, and declined thereafter, whereas the number of acres retired increased throughout as abatement increased.

Implications of Tile Drainage

Because this study differentiated between tiled and non-tiled land, it was possible to analyze what role tile drainage played in the implementation and consequences of these policies. Figure 2 plots the total cost data for each policy found in table 1 (solid curves) along with the corresponding portion of total cost attributable to tile-drained land only, at each abatement level. The difference in total cost between the two policies is represented by the vertical distance between the two solid curves, and the difference in cost attributable to tile-drained land between the two policies is represented by the vertical distance between the two dashed curves.

Table 1. Total Cost, Cost per Acre, and Cost per Pound of Abated N Under Each Policy at Each Abatement Level

PANEL A. Retirement Minimization (Retire-Min) Policy

Abatement Level	Total Cost ($)	Cost/Acre ($)	Cost/lb. N Abated ($)
10%	391,308	1.27	0.98
20%	2,952,476	9.61	3.68
30%	8,092,557	26.34	6.73
40%	9,806,604	31.92	6.11
50%	13,940,943	45.38	6.95
60%	16,429,096	53.47	6.83
70%	19,982,527	65.04	7.12

PANEL B. Net Farm Return Maximization (Return-Max) Policy

Abatement Level	Total Cost ($)	Cost/Acre ($)	Cost/lb. N Abated ($)
10%	−9,638	−0.03	−0.02
20%	629,123	2.05	0.78
30%	2,547,732	8.29	2.12
40%	5,201,669	16.93	3.24
50%	8,777,313	28.57	4.38
60%	13,407,533	43.64	5.57
70%	18,928,200	61.61	6.74

Table 2. Number of Acres Assigned to Each Land-Use Policy Under the per Acre and per Dollar Rules at Each Abatement Level

PANEL A. Retirement Minimization (Retire-Min) Policy

Abatement Level	N-Managed Acres	Retired Acres	Plugged Acres
10%	19,949	0	1,450
20%	38,486	0	28,676
30%	148,965	37,374	33,284
40%	121,353	84,202	16,667
50%	92,250	132,284	16,667
60%	64,559	189,309	20,050
70%	18,957	253,414	20,051

PANEL B. Net Farm Return Maximization (Return-Max) Policy

Abatement Level	N-Managed Acres	Retired Acres	Plugged Acres
10%	17,689	7,181	0
20%	54,327	13,616	0
30%	57,320	57,384	0
40%	32,647	103,335	0
50%	8,034	152,805	0
60%	3,229	202,639	0
70%	451	257,116	0

At 20% abatement, 92% of the difference in total cost between the two policies was attributable to tile-drained land. At 30% abatement, it accounted for 70%, and at 40% abatement, it accounted for 50%. Thus, tile-drained land, which comprised only 21% of the total land area in the watershed, accounted for the bulk of the cost difference between the two policies. In other words, between one-half and nine-tenths of the cost difference between the two policies could be attributed to the management of just one-fifth of the total acreage in the watershed—the drained acreage.

Figure 3 shows the percentage of retired acres (solid curves) and fertilizer (N)-managed acres (dashed curves) that were tile-drained acres under each policy at each abatement level, respectively. Note that the curve for retired tile-drained acres under the Retire-Min policy begins at the 30% abatement level because there is no retirement of any land at the lower abatement levels, and thus a reported percentage of "zero" would be misleading. Under the Return-Max policy, none of the acres retired at 10% and 20% abatement were tile-drained acres, and at 30% abatement, less than 10% of retired acres were tile-drained. At 40% abatement and beyond, tile-drained acres comprised between 25% and 37% of total retired acreage. Under the Retire-Min policy, no land was retired at 10% or 20% abatement. At 30% and 40% abatement, however, tile-drained acres made up more than half of all retired acres. At 50% abatement and beyond, the share of retired acres followed closely that of the Return-Max policy. Specifically, figure 3 reveals that at 30% and 40% abatement, the majority of the acres retired under the Retire-Min policy were tile-drained acres, whereas the majority of those retired under the Return-Max were *non*-tile-drained acres.

With respect to the percentage of fertilizer-managed acres that were tile-drained acres under each policy at each abatement level, under the Return-Max policy, 98% or more of the fertilizer-managed acres were tile-drained acres, up to the 40% abatement level. At 50% and 60% abatement, tile-drained acres made up 88% and 71% of the total, respectively. Under the Retire-Min policy, similar results were found at the 10% and 20% abatement levels, with tile-drained acres comprising 89% or more of the total. However, between 30% and 60% abatement, tile-drained land made up less than 10% of the total, and only at 70% abatement did it break the 10% mark. Between the 30% and 60% abatement levels, these two policies clearly implemented fertilizer management practices very differently with respect to land drainage type. The Return-Max policy implemented this practice almost solely on tile-drained land, whereas the Retire-Min policy implemented it almost exclusively on *non*-tile-drained land.

Finally, although the above results show the choice of rule can significantly affect the optimal abatement method, more sobering results were found regarding on what land that method is implemented, and on what land the economic burden falls: tile-drained land dominated the abatement process, regardless of the policy chosen. Under the Retire-Min policy, tile-drained land accounted for 99% or greater of total abatement between 10% and 20% abatement levels, for 75% of total abatement or greater between 30% and 40% abatement, and for 54% of total abatement or greater between 50% and 60% abatement. Under the Return-Max policy, tile-drained land represented 87% of abatement between 0% and 20% abatement, and accounted for more than 60% of abatement between 20% and 50% abatement. Even at the 70% abatement level, tile-drained land was associated with 47% of total abatement under both policies, even though it comprised only 21% of the total land area in the study watershed.

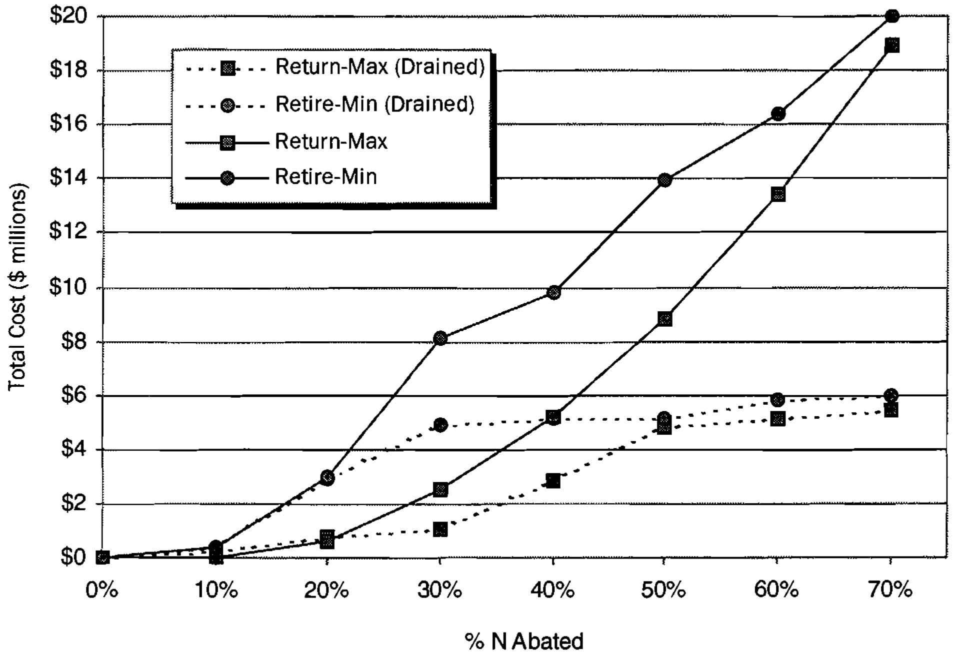

Figure 2. Total cost of abatement for all acres and for drained acres only, under each policy for each abatement level

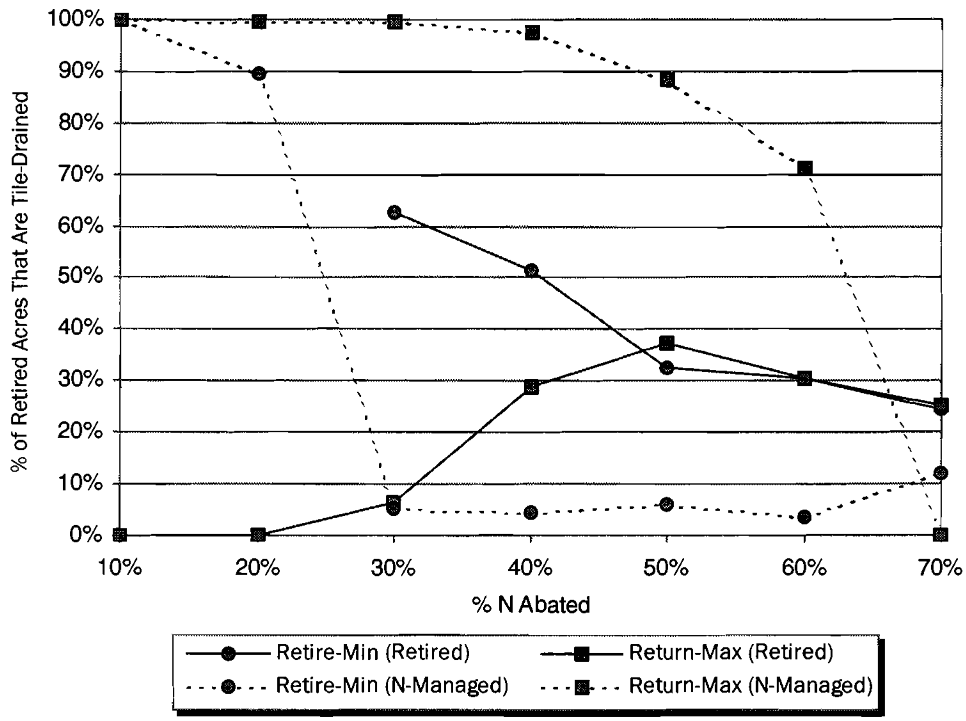

Figure 3. Percentage of retired and N-managed acres that are tile-drained acres, under each policy for each abatement level

Discussion

The motivation for this work was to inform the ongoing debate on nitrogen abatement with particular regard to the role of tile drainage. As discussed earlier, tile drainage is common on agricultural land throughout the Mississippi River Basin, and in particular, common on corn and soybean acres throughout the upper Midwest, where nitrogen fertilizer use is widespread. The watershed modeled here was selected (among other reasons) because it is remarkably similar to many agricultural watersheds throughout this region. Moreover, commenting on the 2001 *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*, prepared by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, Rabalais, Turner, and Scavia (2002) note: "Because 74% of the nitrate load is from agricultural nonpoint sources, and because 56% of the total nitrate load originates north of the mouth of the Ohio River [i.e., the Upper Mississippi River Basin], it is clear that nitrogen reductions in the subbasins of the upper Midwest will be crucial to effective implementation of the plan" (p. 140).

In 2005, there were 39.1 million acres planted to corn in the Upper Basin states of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. If it is assumed that the same proportion of tile-drained crop acres in the study watershed applies to these states (21%), and that the results of our study are indicative of agricultural watersheds throughout the Upper Basin, then only 8.2 million of the 39.1 million acres should even be considered for fertilizer management (i.e., a 79% reduction in the number of acres to consider). Further, only the remaining non-drained acres (i.e., a 21% reduction) should be considered for retirement under a Return-Max type of policy. These results hold for abatement up to 20%; the fertilizer-management result also holds up to 40% abatement, although for land retirement, some tile-drained acres would need to be considered at this higher level. In short, an abatement program that accounted for tile drainage and whose intent was to minimize its impact on farm returns could more efficiently direct abatement resources to where they were most effective, and with respect to fertilizer management, the efficiency gains could be huge.

As an example, Ribaudo et al. (2001) found that a 30% reduction in nitrogen losses would require a basin-wide 60% reduction in applied fertilizer. The present model, however, achieved the same reduction by implementing a 25% reduction in applied fertilizer (on average) on just 38% of corn acres (i.e., the equivalent of a 10% reduction watershed-wide).[7] As the results of this study indicate, implementing this abatement practice on non-tile-drained land is completely ineffective, and may help to explain the results reported by Ribaudo et al.

However, one of the objectives of this study was to determine how a change in the objective of a policy which explicitly accounted for tile drainage would impact the optimal suite of abatement practices, especially with regard to tile-drained land. Petrolia and Gowda (2006) showed that failing to account for tile drainage would result in too little abatement taking place on tile-drained land. By contrast, our analysis found that utilizing tile-drained land strictly for its abatement capabilities (i.e., following the Retire-Min policy) can result in *too much* abatement on such land, leading to unnecessary retirement and drain plugging of the most productive, and usually, the most

[7] The present model's scenario also required that 21% of total cropland be retired as well (greater than 90% of which was non-drained land), but under their scenario, Ribaudo et al. (2001) report 20% of cropland within the Basin also went out of production.

profitable, acres in farming. Tile-drained land consistently has higher yields than its non-tile-drained counterpart, and thus it would be optimal, from an agricultural production standpoint, for this land to remain in production. This point also explains why, under the Return-Max policy, it was not optimal to plug any tile drains.

Although the Retire-Min policy reduced the total number of retired acres by 20,500 relative to the Return-Max policy, in order to achieve 30% abatement (which is the level of abatement called for by the *Action Plan*) it increased the number of retired *tile-drained* acres by 19,819, plugged over 33,000 tile-drained acres, and still had to implement fertilizer management on an additional 91,645 acres. Thus, almost 53,000 (81%) of the most productive acres in the watershed were either removed from production altogether or had their yield potential significantly reduced in order to save less than half as many less-productive acres from being retired. If such a policy were carried out across the Upper Basin, then these results would translate into 16.9 million of the region's best farm acres being retired or compromised for the sake of 7.3 million less-productive acres, with a potential cost of an additional $1.8 billion in net farm returns.[8]

Thus, the results of this study indicate that an optimal nitrogen abatement policy may fall somewhere in between our Retire-Min and Return-Max scenarios—one in which the nitrogen-abatement advantages of drained land are recognized and balanced with the benefits of keeping this land in production. If such a policy were followed on a basin-wide scale, there could be great potential to identify land that is better suited for nitrogen abatement and achieve the desired reductions in nitrogen loads to the Mississippi River and Gulf of Mexico on fewer total acres and at a lower total cost to agriculture. Ultimately, a basin-wide analysis explicitly accounting for the widespread use of tile drainage and its unique environmental and economic impacts is needed. It is hoped this work will encourage further research on other watersheds and at larger scales that take into account the issues highlighted here.

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[8] Fifty-three thousand is 81% of the total number of tile-drained acres in the watershed, and 20,500 is 7.4% of the total number of corn-soybean acres in the watershed. Applying these percentages to the Upper Basin, 16.9 million is 81% of the total number of assumed tile-drained acres, and 7.3 million is 7.4% of the total number of crop acres. The total cost difference between the two policies for the study watershed was $5.5 million; the study watershed represents 0.3% of the total cropland in the Upper Basin. Thus, $5.5 million divided by 0.003 is $1.8 billion. Of course, this calculation does not account for changes in prices and production, so it is likely an upper bound.

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Appendix: Mathematical Exposition of Optimization Model

The Return-Max policy can be represented mathematically as follows:

(A1) $$\underset{x_{ijk}}{\text{Max}}\ WNR = \sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K}\left(r_{ijk} - tech_k\right)x_{ijk}$$

subject to:

(A2) $$\sum_{k}^{K} x_{ijk} = a_{ij},\ \forall i, j,$$

(A3) $$\sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K} n_{ijk}x_{ijk} \le abate\left(\sum_{i}^{I}\sum_{j}^{J} n_{ijB}a_{ij}\right),$$

(A4) $$x_{ijk} \ge 0,\ \forall i, j,$$

where *WNR* is watershed net returns, I is the set of watersheds, J is the set of THRUs, and K is the set of land-use policies. Variable x_{ijk} is the number of acres in THRU j of watershed i assigned to policy k. The coefficients n_{ijk} and r_{ijk} are nitrogen-loss and net-return coefficients, respectively, for each x_{ijk}. The parameter $tech_k$ is the technical cost of policy k, which is common to all i and j. Parameter a_{ij} is the fixed number of acres in THRU j in watershed i, and *abate* is the percentage of the base nitrogen load that a given environmental constraint allows.

Equation (A1), the objective function, is the sum of net returns across all agricultural land in the study watersheds. Equation (A2) represents the $i \times j$ constraints that restrict the sum of acres across all management practices k in THRU j in each watershed i to equal the fixed number of acres x_{ij}. Equation (A3) restricts the sum of all nitrogen losses across all watersheds i, THRUs j, and management practices k to be no greater than the sum of base-case ($k = B$) nitrogen losses across all watersheds i and THRUs j. Equation (A4) restricts the level of acres assigned to management practice k to be nonnegative. Note that only on row-crop acres can abatement take place. Therefore, total abatement is $x\%$ of losses on *total* acres.

Under the Retire-Min policy, the above formulation holds with the substitution of the following objective function for (A1):

(A5) $$\underset{x_{ijk}}{\text{Min}}\ RA = \sum_{i}^{I}\sum_{j}^{J} x_{ijR},$$

where *RA* is the sum of retired acres across watersheds i and THRUs j. (The subscript $k = R$ indicates the land-retirement practice.)

The above constrained optimization problems were solved using the linear-programming solver OSL in the Generalized Algebraic Modeling System (GAMS) (GAMS Development Corporation, 2004), version 2.50, distribution 21.4.