POTENTIAL WATER QUALITY IMPACT OF DRAINAGE WATER MANAGEMENT IN THE MIDWEST USA

DAN B. JAYNES\textsuperscript{1}, KELLY R. THORP\textsuperscript{2}, DAVID E. JAMES\textsuperscript{1}

\textsuperscript{1} D.B. JAYNES, USDA-ARS-National Laboratory for Agriculture and the Environment, 2110 Univ. Blvd., Ames, IA, USA dan.jaynes@ars.usda.gov.
\textsuperscript{2} D.E. JAMES, david.james@ars.usda.gov.
\textsuperscript{2} K.R. THORP, USDA-ARS-US Arid-Land Agricultural Research Center, 21881 N. Cardon Lane, Maricopa, AZ, USA kelly.thorp@ars.usda.gov.

ABSTRACT Drainage water management (DWM) is a promising technology for reducing nitrate losses from artificially drained fields. While there is an extensive history for the practice in North Carolina, U.S., little is known about the efficacy or cost effectiveness of the practice under Midwest U.S. conditions where artificial subsurface drainage is widely used. In an earlier study, we used a calibrated version of the Root Zone Water Quality Model (RZWQM) coupled with the Decision Support System for Agrotechnology Transfer (DSSAT) family of crop growth models to simulate the impact of DWM on reducing nitrate losses from drained fields across the Midwest. In this study, we use soil and land cover spatial databases to estimate that 4.8 million ha of land used to grow corn within the Midwest would be suitable for DWM. If DWM were adopted on all of this land, nitrate losses in drainage would be reduced by approximately 83 million kg yr\textsuperscript{-1}. Within just the Upper Mississippi River basin and Ohio/Tennessee River basins, DWM has the potential to reduce nitrate losses from drained fields by 52 million kg yr\textsuperscript{-1}. We estimate that with the cost of control structures, redesign of new drainage systems, and payments to farmers to adjust the control structures to reduce nitrate losses, that the cost per kg of nitrate reduced in drainage water for DWM would be US$2.71.

Keywords: Drainage water management, Controlled drainage, Nitrate, Water quality.

INTRODUCTION Drainage water management (DWM), often called controlled drainage, is a potentially valuable management practice for reducing nitrate losses to surface waters in areas of artificial drainage (Evans et al., 1995). DWM differs from conventional free artificial drainage in that a control structure such as a flashboard riser is installed at the drainage outlet. By setting the elevation of the riser, the depth of the water table can be adjusted whenever drainage is occurring. Typically, DWM is used to raise the outlet near the soil surface during the winter or off season when a high water table within a field would not hinder agronomic activity or crop growth. During the planting and harvesting periods, the control structure is set so that the outlet is at the maximum depth of the drainage outlet to drain the field for good trafficability and seed bed tilth. The option also exists with DWM to manage the water table during the growing season to retain some water in the field that would otherwise drain and have it
available for crop uptake. DWM has been found to primarily reduce the annual amount of water discharged at the drain outlet (Evans et al., 1995; Wesström and Messing, 2007) rather than lower the concentration of nitrate in the drainage. This reduction in discharge reduces the loss of agricultural chemicals such as nitrate dissolved in the water by 30 to 50%. While Evans et al, 1995 estimated that DWM is being used on as much as 800,000 ha in the U.S., little is known about the potential impact of this practice for reducing nitrate contamination of the Nation’s surface waters.

Because N fertilizer management alone cannot reduce nitrate losses from drained fields sufficiently to meet water quality goals (Dinnes et al., 2002), additional methods of nitrate removal from subsurface drainage water are needed. DWM may be a viable method for substantially reducing nitrate contamination of Midwestern Rivers, however, there have been few studies using this practice in the Midwest. To help bridge this gap, Thorp et al., 2008 conducted a modeling study of the efficacy of DWM across the Midwest. They simulated the nitrate loss for a typical corn-soybean rotation with either free artificial drainage or with DWM using the RZWQM-DSSAT modeling suite. In this study, we take the modeling simulation results of Thorp et al., 2008 to the next step and estimate the total nitrate reduction potential for DWM if the practice were widely adopted in all suitable locations across the Midwest. We then compare these nitrate load reductions of surface waters to the annual nitrate load in the Mississippi river and estimate the cost of removing nitrate from surface waters using DWM.

METHODS

Simulations Thorp et al., 2008 used the modeling suite RZWQM-DSSAT to simulate DWM across the Midwest. RZWQM is a one-dimensional, field-scale agricultural systems model that can be used to simulate the physical, chemical, and biological processes that govern movement of water, nutrients, and pesticides and growth of crops at a representative point in the field (Hanson et al., 1998; Ahuja et al., 2000a). The Decision Support System for Agrotechnology Transfer (DSSAT) family of crop growth models (Jones et al., 2003), including CERES Maize (Ma et al., 2006) and CROPGRO Soybean (Ma et al., 2005) were used with RZWQM because they have the ability to simulate leaf number, phenological development, and other yield components that were not simulated with the original RZWQM plant growth model and because there is a more extensive literature on the use of these models for crop growth.

Thorp et al, 2008 used 25 years of weather data from the National Solar Radiation Data Base (NREL, 1995) for 48 sites across the Midwest (Figure 1) to create RZWQM-DSSAT input files for daily meteorology and hourly breakpoint precipitation at each location. The RZWQM DSSAT model calibrated in Thorp et al., 2007 was used unaltered for each site. This model was calibrated and evaluated for an artificially subsurface drained agricultural field in central Iowa (Thorp et al., 2007) where corn and soybean were grown in rotation for a range of N fertilizer rates applied to corn only. Ten years of measured yield, soil, and water quality data were used in the calibration of the model. The calibrated model was able to simulate 10 years of annual subsurface drainage with a relative root mean squared error of 18% and a Nash and Sutcliffe (1970) model efficiency of 0.87, regardless of the N fertilizer treatment that was simulated.

Simulations of both conventional and DWM across the Midwest were run using a corn/soybean rotation at each of the 48 sites: corn in even years and soybean in odd years.
Model parameters for crop management, including crop cultivar coefficients, planting dates, and harvest dates, were defined with the aid of state-level National Agricultural Statistics Service (NASS) data for crop development and management across the region (USDA, 2007). For the 48 sites, planting and harvest operations were simulated on the five-year average date (2001-2006) at which the operations were 50% complete in each site's respective state.

Subsurface drain pipes were simulated at a depth of 145 cm with a spacing of 27.4 m. For simulations of DWM, the head gate was lowered to the drain depth of 145 cm three weeks prior to planting. Four weeks after planting, the gate was raised to a depth of 60 cm for the duration of the growing season. This schedule was chosen hypothetically to allow adequate time for pre- and post-emergence management activities. In preparation for harvest, the gates were again lowered to the 145 cm drain depth two weeks before the harvest date. One week after harvest and two days after the fall tillage operation, the gates were raised to 30 cm for the duration of the fall and winter seasons. To simulate conventional drainage, the head gate was set at the drain depth of 145 cm for the entire simulation period.

Model simulations for each of the 48 sites were conducted for 25 yr of weather data from 1966 to 1990 and average nitrogen losses for conventional drainage and DWM over this time period were computed for each site. The differences between conventional and DWM nitrate losses in subsurface drainage across the Midwest are graphed in Figure 1. Thorp et al., 2008 found that DWM could reduce nitrate losses from 7.1 to 49.6 kg ha\(^{-1}\) yr\(^{-1}\) compared to conventional drainage. These represent reductions from 33.3 to 60.9% in nitrate losses across the Midwest. We imported the 48 locations used in the simulations and the simulation results for nitrate losses into a geographic information system (Arcview 3.3, ESRI, Inc.) to estimate the nitrate reduction from DWM for each county within the Midwest using spherical kriging and default parameters.

Figure 1. From Thorp et al., 2008, (a) estimated average annual reduction in nitrate losses through subsurface drains, and (b) long-term percent reduction of nitrate losses through subsurface drains when using Drainage Water Management instead of conventional drainage across the Midwestern U.S.
Estimating Area Suitable for DWM

To estimate the impact of DWM on the total nitrate load leaving artificially drained fields and entering surface waters of the Midwest each year, we estimated the total land used to produce corn that would be suitable for DWM. As a first step, this would include only land that benefits from artificial drainage used for row crop production. Unfortunately, no current estimate of the extent of drained soils exists. The last Census of Drainage to collect systematic drainage information was 30 years ago in 1978. The National Resources Inventory conducted by NRCS (http://www.nrcs.usda.gov/technical/NRIhttp://www.ia.nrcs.usda.gov/programs/NRI/whatisnri.html) collected drainage information in their 1982 and 1992 data collection efforts, but no field data have been collected and released since. In 1987, G.A. Pavelis used land capability class and crop information collected in the 1982 NRI to estimate the extent of drained cropland (Pavelis, 1987). These estimates were published for selected states in the 1987 USDA publication “Farm Drainage in the United States”.

Given that drainage installation has continued since these data were collected, we elected to estimate the prevalence of drained lands from the NRCS STATSGO soils database (http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo). Using the method described in Jaynes and James (2007), we estimated the amount of cropland land benefitting from drainage based on the percentage of each soil making up a STATSGO mapping unit, that soil’s properties, and whether the mapping unit was used for crop production. Soils with a land capability class of II, III, and IV with a “w” or wet limitation were identified by Jaynes and James (2007) as most consistent with earlier drainage estimates and were used here as a surrogate for land benefiting from drainage. We further assumed that only drained soils with slopes $\leq$ 0.5% would be suitable for DWM. Land with slopes $>0.5\%$ would require additional control structures to maintain the water table over more than a few hectares and was not deemed a viable candidate for the practice. To estimate soils having slopes $\leq0.5\%$, we assumed that $\frac{1}{2}$ of the drained soils with slopes of 0-1% and $\frac{1}{4}$ of the soils with slopes of 0-2% fell into this category.

We used the 1992 National Land Cover Database (NLCD) developed by the USGS and USEPA (http://landcover.usgs.gov/natllandcover.php) to estimate agricultural land in crop production. This database was developed from 1992 Landsat thematic mapper imagery and other data. We used the NLCD classifications for Row Crops (82), Small Grains (83), Fallow (84), and Pasture/Hay (81) to represent cropland. Overlaying the STATSGO and NLCD spatial databases, we considered only cropland meeting the land capability class and slope criteria to be land benefitting from artificial drainage.

The RZWQM-DSSAT simulations were for a corn/soybean rotation. We would have liked to estimate the amount of cropland in this rotation, but could not find a spatial dataset for this purpose. Instead, we estimated the fraction of cropland used to grow corn in one year and doubled this number to represent the total area used for corn/soybean rotation. This approach risks over estimating the area used for corn production because some fields are used for continuous corn production. However, nitrate losses are typically greater for continuous corn production than for corn/soybean rotation (Randall et al., 1997), so the nitrate losses estimated by simulation for corn/soybean rotation would tend to underestimate this loss and compensate for the over estimation of corn area. To estimate the fraction of cropland used to grow corn, we used the 2002 NASS county – level data for corn (http://www.nass.usda.gov/QuickStats/Create_County_All.jsp) and total cropland (http://www.nass.usda.gov/Census/Create_Census_US_CNTY.jsp). We
multiplied the corn area by 2 and divided by the total cropland area to give the fraction of cropland in corn. We then used this ratio of corn land to cropland to compute the total area of corn land from the county estimate of cropland of the 1992 NLCD.

Finally, the amount of nitrate reduction caused by switching to DWM from conventional free drainage was computed by multiplying the estimated area of suitable drained cropland by the fraction of cropland that is used to produce corn by the nitrate reduction found from the RZWQM-DSSAT model simulations for each county in the Midwest. All county level data were imported into ArcGIS version 9.2 (ESRI) geographical information system, manipulated as discussed above, and portrayed within the GIS.

RESULTS Average county estimates of the reduction in nitrate losses from the adoption of DWM simulated by Thorp et al, 2008 for the portions of 14 states that make up the Midwest are shown in Figure 2. It is clear from this figure and Figure 1 that the simulations show DWM to be more effective in reducing nitrate losses in the wetter and warmer south eastern regions of the Midwest. DWM is not as effective in the colder drier regions of Iowa, Minnesota, and the Dakotas as there is little winter drainage flow in these regions and less precipitation to drain.

For the Midwest, we estimated from STATSGO soils data that 10 million ha would be suitable for DWM based on the need for cropland to be artificially drained and having slopes < 0.5% (Figure 3). This amounts to about 12.5% of the total cropland in this region. A high fraction of the suitable cropland is in the Red River valley in North Dakota and Minnesota and in the southern Mississippi valley of Arkansas which are dominated by very flat landscapes.

The fraction of cropland in corn production is shown in Figure 4. Much of the corn production is concentrated in the states of Minnesota, Iowa, Illinois, and Indiana where corn is grown, often in rotation with soybean, on nearly all of the cropland in some counties. These states were also found to have an appreciable fraction of their cropland suitable for DWM (Figure 3).

Multiplying the total area of each county estimated to have drained cropland suitable for DWM by the fraction of cropland that we estimated to be used to grow corn gives 4.8 million ha of land used to grow corn suitable for DWM. Multiplying this by the nitrate reduction determined by RZWQM-DSSAT simulations for DWM in that county gives the total reduction in nitrate that would be possible if DWM were applied to all suitable areas within the Midwest states (Figure 5).

For the counties shown in the figure, we compute a total annual reduction of 83.0 million kg of N from the adoption of DWM over conventional free drainage. For comparison, the Upper Mississippi river transports 349 million kg of nitrate each year while the entire Mississippi river transports 813 million kg of nitrate each year. Not all of the area shown in Figure 5 outlets through the Mississippi river. Overlaying the watershed boundaries for the Upper Mississippi and the Tennessee/Ohio watersheds on the counties shown in Figure 5, we compute that about 52 million kg of nitrate could be reduced within these basins each year with DWM. This represents about 8% of the total N load for these watersheds and about 6% of the total load from the Mississippi River entering the Gulf and driving hypoxia each year. This 6% total reduction can be compared to the 45%
reduction called for in the latest Gulf Hypoxia Action Plan (MRGMWNTF, 2008). Thus, wide adoption of DWM would have the potential to meet 6% of the desired 45% reduction needed to reduce the size of the hypoxic area in the Gulf to no more than the target of 5,000 km² each year.

Figure 2. Estimated nitrate reduction by county from adoption of DWM.

Figure 3. Cropland requiring drainage having slopes ≤ 0.5%.
Figure 4. Fraction of cropland used to grow corn.

Figure 5. Reduction in nitrate losses from artificial drainage from using Drainage Water Management on all suitable corn ground.
COSTS In addition to the potential for nitrate removal from the widespread adoption of DWM, it is desirable to estimate the cost of nitrate removal for this practice so that it can be compared to other on- and off-field practices designed to reduce N losses. Considering just the areas shown in Figure 5 that fall within the Upper Mississippi and Ohio/Tennessee river basins, 2.9 million ha of drained corn land is suitable for DWM. We will assume that DWM will be installed as retrofits to existing drainage systems on 20% of these areas and that DWM will be installed on the remainder during new installation of drainage pipe, possibly as farmers move to more intensive pattern drainage. We assume that new installations will be designed with DWM in mind allowing one control structure to control every 8 ha drained, while on systems being retrofitted, one control structure will be required for every 4.8 ha. At a cost of US$1100 per structure, this gives a total of $446 million. We further assume that it will cost an additional $80.36 ha$^{-1}$ for design of new installations for DWM giving a total of $187 million. A 4% annual interest is used for the “time value of money” to compensate for the investment in DWM vs. other possible investments such as stocks or bonds. This adds $754 million over the expected lifetime of the structures of 20 years. Finally, we assume that a management payment will need to be provided to the farmer to close gates in the winter and open again in the spring as this is the time when we would expect the greatest water quality benefit from DWM, but with little agronomic benefit. Currently, the Indiana EQIP program allows a payment of $24.71 ha$^{-1}$ for managing DWM. Applying this number to all of the land potentially suitable for DWM in the basins gives $71.6 million yr$^{-1}$. Summing all of the costs for DWM gives a total cost of $141 million yr$^{-1}$ or about $2.71$ kg-N$^{-1}$ removed. This is a very competitive price when compared to other management practices for reducing nitrate loads to surface waters (Table 1) and may be less expensive than more commonly thought of practices such as constructed wetlands.

Table 1. Cost/benefit analysis of nitrogen removal by DWM in comparison to other approaches for reducing nitrogen.

<table>
<thead>
<tr>
<th>Practice</th>
<th>Cost ($ kg$^{-1}$ N)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Water Management</td>
<td>2.71</td>
<td>This paper</td>
</tr>
<tr>
<td>Constructed Wetlands</td>
<td>3.26</td>
<td>Hyberg, 2007</td>
</tr>
<tr>
<td>Fall Cover Crop</td>
<td>11.06</td>
<td>Saleh et al., 2007</td>
</tr>
<tr>
<td>Bioreactor</td>
<td>2.39 – 15.17</td>
<td>Schipper et al., in press</td>
</tr>
</tbody>
</table>

CONCLUSION Drainage water management (DWM) may prove to be an effective management practice for reducing nitrate loading of surface waters within the artificially drained lands of the U.S. DWM is best suited for artificially drained landscapes having slopes $\leq 0.5\%$. While little field research exists demonstrating the efficacy of this practice in the U.S. Midwest, a modeling study conducted by Thorp et al., 2008 demonstrated that DWM has the potential to reduce nitrate losses from field drains by 7 to 50 kg ha$^{-1}$ yr$^{-1}$ across this region. In this paper, we use assorted spatial databases to estimate that 4.8 million ha of land used to grow corn within the Midwest would be suitable for DWM. If DWM were adopted on all of this land, nitrate losses in drainage would be reduced by approximately 83 million kg yr$^{-1}$. Within just the Upper Mississippi River basin and Ohio/Tennessee River basins, DWM has the potential to reduce nitrate losses from drained fields by 52 million kg yr$^{-1}$. This represents about a 6% reduction in nitrate loading to the Mississippi river and would be a substantial contribution to the
target reduction of 45% likely required to reduce the hypoxic zone in the northern Gulf of Mexico to no more than 5,000 km$^2$ each year. Lastly, we estimate that with the cost of control structures, redesign of new drainage systems, and payments to farmers to adjust the control structures to reduce nitrate losses, that the cost per kg of nitrate reduced in drainage water would be US$2.71 and very cost competitive with other practices for reducing nitrate loadings of surface waters.

We were required to make a number of assumptions and approximations in computing the estimates in this paper. New data sources would greatly improve the estimates if they were to become available. For example, a modern survey of artificially drained land by state and county would be desirable. Also, accurate databases on the extent of corn/soybean rotation vs. continuous corn or corn in rotation with other crops would allow us to more accurately model the contributions of these rotations to nitrate losses and the potential benefits of DWM. High accuracy elevation data, such as being collected by LIDAR surveys by numerous states (e.g. http://www.iowadnr.gov/mapping/lidar/faq.html) would greatly improve our estimate of drained lands with slopes $\leq$ 0.5% that are suitable for DWM and improve our estimate of the number of control structures needed for the practice.

REFERENCES


Ma, L., G. Hoogenboom, L. R. Ahuja, J. C. Ascough II, and S. A. Saseendran. 2006.


