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RESEARCH
INTRODUCTION

Drainage water management

R. Wayne Skaggs, Norman R. Fausey, and Robert O. Evans

This article introduces a series of papers that report results of field studies to determine the effectiveness of drainage water management (DWM) on conserving drainage water and reducing losses of nitrogen (N) to surface waters. The series is focused on the performance of the DWM (also called controlled drainage [CD]) practice in the US Midwest, where N leached from millions of acres of cropland contributes to surface water quality problems on both local and national scales. Results of these new studies are consistent with those from previous research reported in the literature that DWM can be used to reduce N losses (primarily in the nitrate nitrogen [NO_3-N] form) from subsurface drained fields. The measured impact varied over a wide range (18% to more than 75% reduction in N loss to surface waters), depending on drainage system design, location, soil, and site conditions. Crop yields were increased by DWM on some sites and not on others, with the year-to-year impacts of DWM on yields dependent on weather conditions, as well as the above factors. Papers reporting advances in the development of datasets and models to predict the impact of drainage intensity and DWM on hydrology and water quality at watershed and basin scales are also included in this collection (Moriasi et al. 2012; Heilman et al. 2012).

Drainage is necessary for agricultural production on about 25% of cropland in the United States and Canada (Pavelis 1987; Shady 1989). Globally, about 33% of the world's cropland requires drainage (Smedema et al. 2004). Without drainage, farming would not be possible on many of these lands; with drainage, they are among the most productive in the world. Drainage ditches or subsurface drains (tile or plastic drain tubing) are used to remove excess water and lower water tables, improve trafficability so that field operations can be done in a timely manner, prevent water logging, and increase yields. Drainage is also needed to manage soil salinity in irrigated arid and semiarid croplands.

Drainage has been used to enhance crop production since the time of the Roman Empire, and probably earlier (Luthin 1957). Until recent years, the focus of drainage research and development was to improve its efficiency and increase crop yields and profits. Research beginning in the 1970s (e.g., Baker et al. 1975; Gambrell et al. 1975) showed that agricultural drainage has significant impacts on surface water quality. Subsurface drainage reduces surface runoff, sediment losses, and the movement of contaminants attached to the sediment into surface waters. However, it increases the losses of N (Gilliam et al. 1999; Dinnes et al. 2002) and is cited as one of the major sources causing algal blooms and hypoxia in major water bodies. Nitrogen losses from intensively drained cropland in the US Midwest are considered a major contributor to excessive N and hypoxic conditions in the Gulf of Mexico (Mitsch et al. 2001; Rablais et al. 2002; David et al. 2010). By the end of the last century, the development of methods to reduce off-site environmental impacts had become an important objective of drainage researchers and engineers.

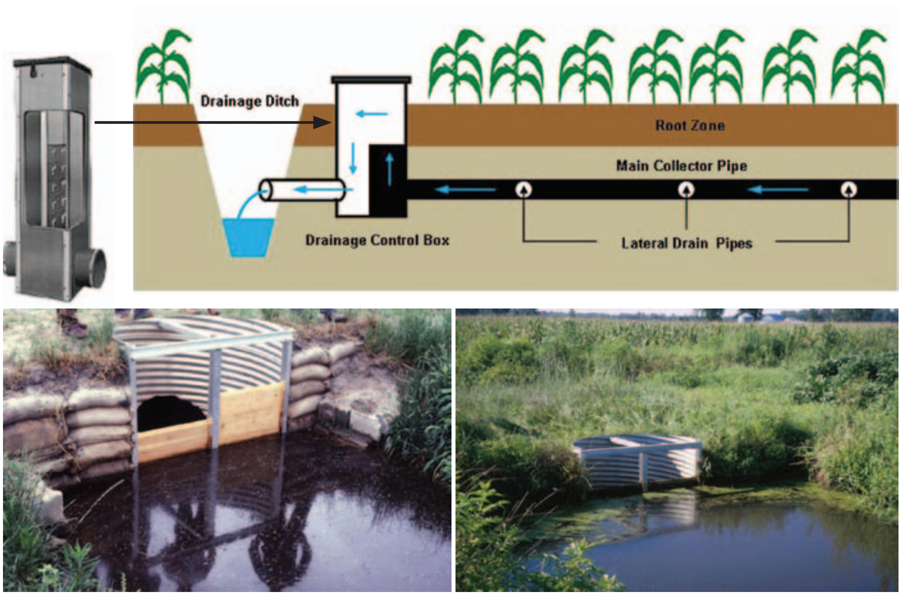
The development of methods to reduce losses of N in drainage waters has become a primary objective in addressing the environmental impacts of agricultural drainage. Reducing N losses is difficult because the nitrate form is mobile in soil solution and may be readily leached with subsurface drainage water. A number of methods may be used to reduce losses (Dinnes et al. 2002; Heilman et al. 2012). They include source reduction by fertilizing at appropriate rates, cover crops, routing drainage water through wetlands, use of biofilters, and DWM. All are needed. Drainage water management, or controlled drainage, emerged as an effective practice for reducing losses of N in drainage waters in the 1970s and 1980s. The practice is inherently based on the fact that the same drainage intensity is not required all the time. It is possible to dramatically reduce drainage rates during some parts of the year, such as the winter months, without negatively affecting crop production. Drainage water management may also be used after the crop is planted to reduce drainage intensity and conserve water for crop use during the growing season. Drainage water management is typically applied by installing a structure in the drainage ditch or subsurface drain that allows the outlet water level elevation to be adjusted or managed (figure 1).

Drainage water management, or controlled drainage, has been used for many years to reduce subsidence of drained organic soils in the Florida Everglades and other locations (Clayton and Jones 1941; Stevens 1955). The first experiments showing that this practice could be effective for reducing N losses in drainage water were conducted on drained irrigated lands in California (Meek et al. 1970; Willardson et al. 1972), but the practice was not applied. Gilliam et al. (1979) determined that CD could be used during the winter months in North Carolina to reduce N losses from drained agricultural (corn–wheat–soybean rotation) lands by 40% to 50%. This was followed by a number of additional research studies and field trials (Skaggs and Gilliam 1981; Doty et al. 1987; Evans and Skaggs 1989; Evans et al. 1989, 1995) in the coastal plain, where excessive N in drainage waters had been cited as a significant contributor to algal blooms and fish kills in the coastal streams and estuaries. The practice was accepted as a best management practice by the state of North Carolina with cost sharing for the control structures. It was heavily promoted by the USDA Natural Resources Conservation Service (NRCS), the Cooperative Extension service, and other federal and state agricultural and environmental agen-

R. Wayne Skaggs is William Neal Reynolds Distinguished University Professor and **Robert O. Evans** is professor and Department Head at the Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina. **Norman R. Fausey** is research leader and supervisory research soil scientist at the Soil Drainage Research Unit, USDA Agricultural Research Service, Columbus, Ohio.

Figure 1

Drainage management structures for subsurface drains and open ditch outlets.



cies as a recommended practice for water conservation and improved water quality (Evans and Skaggs 2004). More than 4,000 structures have been installed since the program began in 1984. This application of CD (now referred to as DWM) was the subject of a special issue of the Journal of Soil and Water Conservation in 1992 (Stone et al. 1992; Evans et al. 1992).

Research conducted in glacial-derived soils in colder climates—Ontario (Lalonde et al. 1996; Tan et al. 1998; Gaynor et al. 2002; and Drury et al. 2009), Ohio (Fausey 2005), and Sweden (Wesstrom and Messing 2007)—showed that DWM was effective in reducing losses of N in drainage waters in those areas. Collectively, the above results supported the potential use of DWM in the US Midwest.

AGRICULTURAL DRAINAGE MANAGEMENT SYSTEMS TASK FORCE

Concern about the extent of hypoxia in the Gulf of Mexico and evidence to support the contribution of soluble nutrients (especially NO_3-N) from the Mississippi River Basin to nourish the algal bloom heightened in the early 2000s. Discussions within USDA about possible sources and solutions led the Partnership Management Team (USDA Agricultural Research Service [ARS]; USDA NRCS; Cooperative State Research, Education, and Extension Service/National Institute of Food and Agriculture) to establish an interagency task force identified as the Agricultural Drainage Management Systems Task Force. The Task Force was formally established in early 2003 as a technical work group to assist in addressing and resolving water quality issues on drained agricultural lands. The Task Force developed a Charter and an Action Plan through meetings and discussions that included state and federal agencies, nongovernment organizations, and industry representatives. The Action Plan ultimately led to recommendations to USDA to encourage additional research throughout the Midwest to document the environmental benefits of DWM, revise the Practice 544 standard nationally and for individual states, seek Conservation Innovation Grant proposals to demonstrate and evaluate Practice 544 Drainage Water Management, offer cost-share incentives to encourage adoption of the practice, and develop a strategy to promote adoption of the practice.

Formation of the Task Force by USDA created a realization among the drainage-affiliated industries that they had expertise and incentive to contribute in assisting the agricultural and environmental communities in improving water quality and increasing yields for food and energy producers. Thus, the Agricultural Drainage Management Coalition (ADMC) was organized in 2005. ADMC works at the local and state level to educate farm, drainage, and conservation groups as well as local, state, and federal authorities to build understanding of the latest drainage water management systems and technologies. ADMC was awarded and managed the five-state USDA NRCS funded national DWM Conservation Innovative Grant project involving land-grant university, state agency, and ARS personnel. Five of the seven papers in this issue report results obtained in this project.

Drainage water management (Practice 554) was identified as a priority practice in the USDA NRCS Mississippi River Basin Initiative initiated in 2009. Adoption of the practice was negligible during the first 2 years leading NRCS to establish a National Agricultural Water Management Team to assist states in the voluntary conservation efforts to reduce nitrates leaving drained farmland, with an initial focus to address the intensively drained farmlands in the Upper Mississippi River Basin. A Phase I Team was formed in September 2010 to provide recommendations for strategic actions the NRCS should take to increase successful producer adoption of DWM within the Mississippi River Basin Initiative. The team was charged with assessing the current use of the practice, identifying barriers to the adoption of DWM, determining and considering lessons learned through past experience, and developing strategic action recommendation that will increase adoption of DWM. Based on the Phase I Team report, a Phase II Team was charged to increase the adoption of agricultural DWM for conservation benefits. An Action Plan has been developed to guide the Team in achieving its goals. The Team organized and held a National Summit in Minnesota in October 2011 to increase the nationwide adoption of DWM as part of a conservation system through understanding of past history, current situation, and future opportunities.

POTENTIAL FOR DRAINAGE WATER MANAGEMENT IN THE US MIDWEST

Jaynes et al. (2010) evaluated the potential water quality impact of DWM in the

US Midwest. They used USDA NRCS, United States Geological Survey, and US Environmental Protection Agency databases to determine that approximately 10 million ha (25 million ac) of cropland in the region are suitable for DWM (soils normally drained with slopes <0.5%). The Root Zone Water Quality Model, coupled with Decision Support System for Agrotechnology Transfer crop growth models, were used to simulate the impact of DWM on reducing nitrate losses from drained fields across the Midwest. Results indicated that application of DWM on 4.8 million ha (12 million ac) used to grow corn in the region would reduce NO_3-N losses from drained fields to surface waters by 83 million kg y^{-1} (180 million lb yr^{-1}). When the expenses for control structures, installation, and management were considered, the cost per kilogram of removing NO_3-N from surface waters, or of preventing its entry, was among the least expensive of alternative methods. Benefits due to drainage water conservation and increased yields would further lower the effective cost of reducing N loads to surface waters.

Control structures (figure 1) can be fitted to the outlets of existing drainage systems. DWM will be most effective on relatively flat lands where one structure will affect the outlet water level and drainage rates from relatively large areas (Strock et al. 2011). For new systems, the network of lateral and main drains can be designed to accommodate DWM by following contours and breaking the field into management zones such that a single structure can be used to manage drainage water levels and rates from relatively large areas. This would allow DWM to be applied to a larger percentage of subsurface drained lands and would greatly increase its efficiency (Pitts 2008).

FIVE-STATE DRAINAGE WATER MANAGEMENT PROJECT

Five of the seven papers in this special section report results from the five-state drainage water management project referenced above. The project was organized by the ADMC in close cooperation with USDA ARS researchers, Land Grant university faculty, and state agency personnel and funded by USDA NRCS through the Conservation Innovation Grant program. The project resulted in the demonstration of DWM on a total of 20 sites in the states of Indiana, Illinois, Iowa, Minnesota, and Ohio. Collectively, these sites provided opportunities for hundreds of farmers, land owners, conservation and environmental professionals, and the general public to see DWM first hand and learn about its operation and benefits. The DWM sites were located adjacent or close to conventionally drained sites with the same soil series, crops, and farming practices. Drainage outlets were instrumented to measure flow rates and determine N losses in the drainage water, and the paired watershed approach was used to determine the effect of DWM on subsurface drainage volumes, N loads, and crop yields.

Collecting research quality data on demonstration projects is notoriously difficult as the time required to get sites selected, instrumented, and treatments established often limits the time available to collect a dataset of appropriate length and quality to test the hypothesis. In some cases (Jaynes 2012; Helmers et al. 2012), the demonstration sites were established consistent with a field research approach, where the effect of DWM could be compared to conventional drainage in well-instrumented, field-scale, replicated plots. In others (Cooke and Verma 2012; Ghane et al. 2012; Adeuya et al. 2012), paired DWM and conventionally drained sites were established on farmer-operated, production-scale fields, located on a range of soils and conditions across a wide region of a state. There are advantages and disadvantages to both approaches. Overall, results of this project provide valuable information and greatly expand our database on the effectiveness of DWM, especially in the large area of subsurface drained cropland in the US Midwest.

EFFECT OF DRAINAGE WATER MANAGEMENT ON NITROGEN LOSSES IN DRAINAGE WATER

Results contributed by papers presented in the special section of this journal issue add significantly to our knowledge on the effectiveness of DWM in reducing N losses to surface waters. A summary of results of published studies on effect of DWM on N losses in drainage water is given in table 1. Examination of results of individual studies indicates that N losses in drainage water are almost entirely in the nitrate form. Thus, the effects of DWM shown in table 1 on N losses may be interpreted as the effect on NO_3-N losses. The table was originally presented by Skaggs et al. (2010). Results from papers published since that time, including those presented in this issue, have been added. Because our focus is on the effect of DWM, or CD, on water conservation and N losses, the table does not include studies on subirrigation. Nor does it include the results of modeling studies. Such studies have been very useful in understanding how DWM functions under different weather conditions, system designs, and operational strategies and in projecting the potential impact of DWM on N loads if applied at state or regional scales (Jaynes et al. 2010). In addition, models would logically play a critical role in evaluating the effect of DWM on annual N loads for purposes of nutrient trading or related incentives to promote N loss reduction to surface waters (Skaggs et al. 2012). However, table 1 includes only those studies in which effects of DWM on annual drainage volumes and N losses have been determined from field measurements and observations.

Studies presented in this issue increased our database on the impact of DWM on N loss from 12 to 20 sites. DWM reduced measured average annual drainage volumes from 18% to over 85%, depending on site and year. Consistent with observations in previous studies, DWM did not greatly affect NO_3-N concentrations. So, its effect on N loads, on a percentage basis, was similar to its effect on drainage volumes, with reductions of NO_3-N loads among the sites from 18% to 79%. The ranges in response to DWM, for both drainage volume and N loads, are similar to those obtained in previous studies, some of which were conducted on very different soils, cropping systems, and climatological conditions (table 1).

In addition to showing that DWM substantially reduced drainage outflows and N loads in the drainage water in all studies conducted, a review of results in table

Table 1

Summary of results of field studies of effectiveness of drainage water management in reducing drainage volumes and nitrogen loads (modified from Skaggs et al. 2010).

Reference	Location	Soil	Years observed	Area (ha)	Drain spacing (m)	Drain depth (m)	Control depth* (m)	Percent drainage	Reduction nitrogen loss
Gilliam et al. 1979	North Carolina	Portsmouth sandy loam	3	5 to 16	30 and 80	1.2	0.3 to 0.5	50	50
	North Carolina	Goldsboro sandy loam	3	3	30	1	0.3	85	85
Evans et al. 1989	North Carolina	Ballanhack sandy loam	2	4	18	1	0.6	56	56
	North Carolina	Wasda muck	2	4	100	1.2	0.6	51	56
	North Carolina	Wasda muck	2	4	18	1	0.6	17	18
Lalonde et al. 1996	Ontario	Bainesville silty loam	2	0.63	18.3	1	0.75	49	69
							0.5	80	82
Breve et al. 1997†	North Carolina	Portsmouth	1.2	1.8	22	1.2	0.4 to 0.5	16	20
Tan et al. 1998	Ontario	Brookston clay loam	2	2.2	9.3	0.65	0.3	20	19
Gaynor et al. 2002‡	Ontario	Brookston clay loam	2	0.1	7.5	0.6	0.3	16	
Drury et al. 2009§	Ontario	Brookston clay loam	4	0.1	7.5	0.6	0.3	29	31 to 44||
Wesstrom and Messing 2007	Sweden	Loamy sand	4	0.2	10	1	0.2 to 0.4	80	80
Fausey 2005	Ohio	Hoytville silty clay	5	0.07	6	0.8	0.3	41	46
Jaynes 2012	Iowa	Kossuth/Ottosen	4	0.46	36	1.2	0.6	18	21
Helmers et al. 2012	Iowa	Taintor/Kalona	4	1.2 to 2.4	18	1.2	0.3	37	36
Adeuya et al. 2012	Indiana	Rensselaer	2	3	21	1	0.15 to 0.6	19	23
	Indiana	Rensselaer	2	6 to 9	43				18
Cooke and Verma 2012	Illinois	Drummer	2	15	30	1.15	0.15	44	51
		Drummer/Dana	1 to 2#	8.1	15	1.15	0.15	44	52
		Orion Haymond	1 to 2#	5.7	18 to 21	1.15	0.15	89	79
		Patton/Montgomery	1 to 2#	16.2	12	0.85	0.15	38	73

* Control typically removed during seedbed preparation, planting, and harvesting periods.

† Controlled drainage (CD) during the growing season only. CD reduced subsurface drainage volume by 16%; Nitrogen loss from subsurface drain + runoff by 20%.

‡ CD reduced subsurface drainage by 35%, increased surface runoff by 28%, and reduced total outflow by 16%. Nitrogen results were not reported and effects on pesticide loss were reported.

§ CD reduced subsurface drainage by 29%, increased surface runoff by 38%, and reduced total outflow by 11%.

||CD reduced nitrogen loss by 44% for recommended nitrogen application rates and by 31% for elevated nitrogen rates.

Drainage volume measured for two years and nitrogen losses measured for one year for these locations.

1 raises questions as to what happens to the water that was not removed by drainage and why the response to DWM was so different between the different sites and soils represented. This question was discussed in detail by Skaggs et al. (2010). They concluded that DWM reduces subsurface drainage volumes by increasing evapotranspiration, increasing seepage, and increasing surface runoff. The impact of DWM on each of these hydrologic components depends on weather, soil properties, site conditions, drainage system design and management, and crops.

What happens to the N? The effectiveness of DWM in reducing N losses to surface and ground waters depends on both its effect on hydrology and on N dynamics in the soil profile. Some of the N may be taken up by the crop in response to increased evapotranspiration. In cases where the bottom of the profile remains saturated and anaerobic (reduced) or where seepage water passes through reduced zones, N may be converted through denitrification and lost from the profile as nitrogen gas. For moderately well drained soils, DWM may be equally or more effective in reducing drain flows, but have limited effectiveness in reducing N losses as seepage water containing NO_3-N may eventually make its way to surface waters through different paths.

EFFECT OF DRAINAGE WATER MANAGEMENT ON CROP YIELDS

The effect of DWM on yields depends on soil properties, site conditions, drainage system design, and management strategy. For a given year, the effect of DWM on yields is very dependent on weather conditions during the growing season. DWM can potentially increase yield by retaining drainage water in the profile so that it is available to supply crop needs during subsequent dry periods. During unusually dry growing seasons, there may be little or no drainage water to conserve, so the effect of DWM in such years might be nil. Conversely, in seasons when rainfall occurs at about the right time to satisfy crop evapotranspiration requirements, drainage water conserved by DWM is not needed to satisfy evapotranspiration demands and would likely have little effect on crop yield. DWM will have maximum effect on crop yields in years when a wet period during the growing season is followed by a moderately long dry period, followed by another wet period, etc. Such conditions provide the best opportunity for DWM to conserve soil water that can subsequently be used by the crop. Such sequences of weather events would logically happen in some locations more than in others and in some years more than in others. Thus, long-term studies (records) are needed to determine average effects of DWM on crop yields. If other factors are equal, DWM would be expected to have the greatest effect on conserving water and increasing yields where subsurface drains are deep and drainage intensity is high. In systems where drains are relatively shallow and far apart, or the hydraulic transmissivity of the soil profile is low, DWM must be carefully managed to avoid negative impacts on crop yields.

Effects of DWM on crop yields as measured in field experiments and demonstration sites are summarized in table 2. Note that results presented in this issue constitute a significant percentage of results published on this subject. While there were substantial positive effects of DWM on measured yields in some cases, there were negligible or not statistically significant effects in others. The relatively short period of observation in many of the studies may have contributed to the failure to detect effects of DWM on yields in some cases. In only one case was DWM reported to have a negative effect on yield, and, in that case, for only one of the two crops studied (Helmers et al. 2012). More work is clearly needed to determine the effect of DWM on crop yields for a range of soils, drainage system designs, management strategies, and weather conditions.

A review of both previous studies and those reported in this issue revealed no instances when DWM during the winter and early spring months had a negative impact on crop yields. This is important as management of drainage outlets during the fallow season has the greatest impact on reducing drainage volumes and N losses to the environment. While DWM may result in yield increases in some cases and not in others, its effect in reducing N losses to surface waters has been found to be significant in all cases.

Table 2

Summary of measured effects of drainage water management (DWM) on crop yields.

Reference	Location	Years observed	Number of sites	Crop	Effects of DWM on crop yield
Tan et al. 1998	Ontario	2	1	Soybean	No effect
Drury et al. 2009	Ontario	2	1	Corn	No effect
		2	1	Soybean	No effect
Wesstrom and Messing 2007	Sweden	4	1	Cereals	2% to 18% increase
Fausey 2005	Ohio	5	1	Corn	No effect
	Ohio	5	1	Soybean	No effect
Poole et al. 2011	North Carolina	6	2	Corn	11% increase
	North Carolina	5	2	Wheat	No effect
	North Carolina	6	2	Soybean	10% increase
Delbecq et al. 2012	Indiana	5	2	Corn	5.8% to 9.8% increase
Jaynes 2012	Iowa	2	1	Corn	No effect
	Iowa	2	1	Soybean	8% increase
Helmers et al. 2012	Iowa	4	1	Corn	Reduced yield
	Iowa	4	1	Soybean	No effect
Cooke and Verma 2012	Illinois	2	4	Corn	No effect
		2	3	Soybean	No effect
Ghane et al. 2012	Ohio	1 to 2	7	Corn	1% to 19% increase in 6 of 9 observations
		1 to 2	7	Soybean	1% to 7% increase in 7 of 11 observations

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