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DRAINMOD-simulated performance of controlled drainage across the U.S. Midwest

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ABSTRACT

Controlled drainage (CD) has recently been proposed as a best management practice for reducing nutrient export from drained cropland in the U.S. Midwest to the Mississippi River and the Gulf of Mexico. We conducted a 25-year simulation study using the hydrological model, DRAINMOD, and the carbon and nitrogen (N) model, DRAINMOD-NII, to evaluate the performance of CD at 48 locations across the U.S. Midwest. Hydrological and Nitrogen predictions of this simulation study were compared to RZWQM-DSSAT predictions by Thorp et al. (2008). Simulation results showed that CD reduced annual subsurface drainage by 86 mm (30%) and annual N drainage losses by 10.9 kg N ha^{-1} (32%), on average over the 48 sites. DRAINMOD predicted highest reductions in drain flow at the south and southeast locations and lowest reductions at the northwest locations. The large reductions in drain flow in the south and southeast locations resulted in a large increase in surface runoff, which could increase soil erosion and sediment transport to surface water. In the north and northwest locations, the smaller amount of water that did not pass through the drainage system because of CD was primarily lost as evapotranspiration. DRAINMOD-NII predictions of annual reductions in N drainage loss followed the same trend of annual reductions in drainage flow. DRAINMOD-NII predictions show that reductions in N drainage loss under CD were mainly attributed to increase in denitrification. The declining trend in predicted annual denitrification from the southern to the northern locations of the Midwest region is most likely attributed to the lower temperature and less precipitation at the northern locations. RZWQM-DSSAT predicted reductions in annual drainage and N loss under CD conditions showed a similar trend to DRAINMOD/DRAINMOD-NII predictions. RZWQM-DSSAT, however, predicted substantially higher reductions in both drain flow (regional average of 151 mm yr^{-1}, 53%) and N drainage losses (regional average of 18.9 kg N ha^{-1} yr^{-1}, 51%). The discrepancies between DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT predictions of annual reductions in drain flow and N loss under CD conditions were caused by differences in model predictions of individual components of the water and nitrogen balances under both free drainage and controlled drainage scenarios. Overall, this simulation study showed that climate variation across the region has a substantial impact on CD efficacy for reducing N drainage loss.

1. Introduction

Agricultural drainage is essential for crop production on over 40 million ha, or about 25% of cropland in the United States. Drainage improves trafficability, providing timely access for performing field operations such as tillage, planting, and harvesting. More importantly, drainage removes excess water in the plant root zone, minimizing plant stress due to excess water and improving crop yield (Evans and Fausey, 1999). Subsurface drainage also reduces surface runoff, sediment losses and the movement of contaminants attached to the sediment, such as pesticides and phosphorus, into surface waters (Skaggs et al., 1994). Drainage, however, significantly alters the hydrology and nitrogen (N) cycling in naturally poorly drained soils. It lowers the water table and increases soil aeration, which increases soil organic matter decomposition (and associated N mineralization/immobilization) and decreases den-

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Table 1
Key input parameters of DRAINMOD model.

Drainage system parameters					
Drain depth (cm)	145				
Drain spacing (m)	27.4				
Drainage coefficient (cm day $^{-1}$)	1.4				
Effective drain radius (cm)	1.1				
Maximum surface storage (cm)	0.5				
Depth to restrictive layer (cm)	299				
Deep seepage parameters					
Restrictive layer thickness (cm)	200				
Piezometric aquifer head (cm)	200				
Restrictive layer conductivity (cm h^{-1})	0.0006				
Soil properties					
Layer depth (cm)	Clay (%)	Silt (%)	θ_s (cm^3 cm^{-3})	θ_{pwp} (cm^3 cm^{-3})	K_{sat} (cm h^{-1})
0–15	45	33	0.56	0.30	3.5
15–60	46	33	0.54	0.29	3.5
60–120	24	29	0.44	0.24	3.5
120–299	25	40	0.32	0.18	3.5
Soil temperature parameters					
Air temperature below which precipitation is snow (°C)	0.0				
Snowmelt base temperature (°C)	1.0				
Critical ice cover at which infiltration stops (cm^3 cm^{-3})	0.2				
Temperature at profile bottom (°C)	9.11				
Snowmelt Coefficient (mm d^{-1} °C^{-1})	5.00				

θ_s, θ_{pwp} are volumetric soil water content at saturation and permanent wilting point, respectively, *K*sat is lateral saturated hydraulic conductivity

itrification. The net result of artificial drainage is an increase in subsurface drainage flow rates and N leaching losses to receiving surface waters.

Nitrogen (N) losses from drained cropland in the U.S. Midwest have been identified as one of the main sources of N leading to the hypoxic conditions in the Gulf of Mexico (Petrolia and Gowda, 2006; Turner et al., 2008; Rabalais et al., 2007, 2014). There are over 16 million ha of artificially drained land in crop production in the Midwest, with five states (Illinois, Indiana, Iowa, Ohio, and Minnesota) accounting for over 50% of the U.S. land planted to corn and soybean (Petrolia and Gowda, 2006). Nitrogen losses from drained corn and soybean fields in the Midwest states make up a significant portion of the estimated 1.6 million metric tons of N discharged annually into the Gulf of Mexico (Scavia et al., 2004; Turner and Rabalais, 2003).

Achieving sustainability of crop production on drained land hinges upon the adoption of effective and economically feasible management practices that minimize nutrient export from drained lands without adversely affecting crop yield or increasing production cost. Drainage water management (DWM), also referred to as controlled drainage (CD), is a promising practice that is recently proposed as a best management practice (BMP) for reducing N export from drained cropland in Midwestern U.S.

Controlled drainage involves the use of an overflow control device (drainage water control structure or flashboard riser) at the drainage outlet that regulates the drainage intensity by raising and lowering the drainage outlet to better match the need for drainage in the agricultural field. This drainage water control mechanism reduces drainage volumes which decreases the edge-of-field mass loss of N to receiving surface waters (Evans et al., 1995; Evans and Skaggs, 2004; Skaggs et al., 2010; Skaggs et al., 2012). Additionally, CD raises the water table increasing anaerobic conditions in the soil profile which favors denitrification (Wesström and Messing, 2007; Skaggs et al., 2010). Lastly, it has been observed that careful management of CD systems during the crop growing season could lead to increasing crop yield and N uptake, especially under dry conditions (Poole et al., 2013). Achieving the yield benefits of CD requires proper management of the drainage systems during the growing season to avoid potential yield losses due to excessive water stresses. The water quality benefits of CD are mostly achieved by managing the drainage outlets during late fall, winter and early spring, when the practice has little or no effect on crop yield. The practice is applicable to both open-ditch and subsurface tile drainage systems.

Research conducted in the late 1970′s and 1980′s have shown that CD can substantially reduce the export of N and P to surface water from drained lands in the North Carolina Atlantic Coastal Plains by over 40% and 25%, respectively (Gilliam et al., 1979; Skaggs and Gilliam, 1981; Evans et al., 1995). As a result of this research, CD was accepted in the mid-1980s as a best management practice (BMP) for reducing nutrient losses to surface waters, with the control structures cost-shared by the state of North Carolina.

Recently, the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture has launched a national initiative for large scale adoption and implementation of CD in the Midwest to reduce N export from drained cropland to the Mississippi River Basin. The performance of CD depends upon several factors, including climatological conditions (precipitation and temperature), soil type (soil texture and organic matter content), topography, cropping system and farming practices (crop rotation, fertilization, tillage), and drainage system design (drain depth and spacing). Thus, the effectiveness of CD is expected to vary from location to location and from year to year. So, the reported performance of CD in the U.S. Southeast cannot be simply extrapolated to other geographic regions such as the U.S. Midwest. Moreover, the magnitude of N losses in drainage water, and the effect of CD on those losses are expected to vary among locations within the Midwest region.

The hydrological and water quality effects of CD are not well documented for the drained cropland of the U.S. Midwest. In Illinois, Pitts et al. (2004) reported 40% reduction in N drainage loss caused by implementing CD practice. In Ohio, Fausey (2005) found that CD reduced drainage outflows by 41% and N losses by 46%. More recently, field experiments have been conducted at several locations across the Midwest to study the effects of CD on N losses from drained croplands to surface waters (e.g. Adeuya et al., 2012; Cooke