Agricultural Water Management 103 (2012) 150–161

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Modeling the effects of controlled drainage, N rate and weather on nitrate loss to subsurface drainage

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ARTICLE INFO

Article history:
Received 4 March 2011
Accepted 5 November 2011
Available online 7 December 2011

Keywords:
Drainage water management
Root Zone Water Quality Model (RZWQM2)
Water and N balance
Conservation practices
Hydrologic modeling

ABSTRACT

Controlled subsurface drainage can reduce nitrate loss to tile flow, but the effects may vary with different N application rates and weather conditions. Interactions between these factors can be understood better via combinations of field experiments and modeling. Using an automated parameter estimation method (PEST), the Root Zone Water Quality Model (RZWQM2) was calibrated with measured monthly tile flow, N loss and flow weighted nitrate-N concentration (FWNC) from 2006 to 2008 in a corn and soybean rotation system with free drainage (FD) management. Similar data from 2006 to 2008 with controlled drainage (CD) management were used to evaluate the model. Changing from FD to CD reduced the annual N loss in tile flow by 22 and 32% based on measured and RZWQM2 simulated results, respectively. The model over-predicted the CD effect possibly because of the slope of the field, which reduces the effect of CD but is not simulated by the model. Long-term RZWQM2 simulations (1996–2008) suggest that N loss can be reduced by about 40% in both FD and CD by decreasing N rate from 245 to 140 kg N ha^{-1} with little effect on corn yield. A further reduction in N loss of 39% (9.3 kg N ha^{-1}) was simulated by implementing CD at the reduced N rate, and the reduced N loss to tile flow was mainly associated with increased N loss to seepage (lateral flow) and crop N uptake. The percent of N loss reduction using CD relative to FD was magnified with increased rainfall (from approximately 20 to 50% with annual rainfall ranging from 600 to 1100 mm), but the reduction varied only between 38 and 40% under different N rates (0–250 kg N ha^{-1}). The results indicate that RZWQM2 accurately responded to CD compared to field measurements, and CD management in combination with reduced N application rates can substantially reduce N loss to the environment with little negative effect on corn yield.

1. Introduction

Subsurface drainage has been practiced widely in the Midwest Corn Belt, USA (Randall et al., 1997; Hatfield et al., 1998; Randall, 1998; Zucker and Brown, 1998; Fisher et al., 1999). This practice shows benefit to both agricultural production and the environment (Baker et al., 2004; Singh et al., 2007). However, studies suggest that nitrate loss through tile drainage was the main source of nitrate in surface water (David et al., 1997; Goolsby et al., 2001; Jaynes and Colvin, 2006) and a leading cause of hypoxia in regions such as the northern Gulf of Mexico (Goolsby et al., 1999; Rabalais et al., 2001).

Many studies have been carried out to investigate the effect of agricultural management practices (e.g., N fertilization, cropping system, buffer crops, and cover crops) on nitrogen (N) loss to subsurface drainage (Randall and Mulla, 2001; Dinnes et al., 2002). In Sweden, research has focused on alternative cropping and soil management practices to reduce nitrate leaching under subsurface drainage conditions (Wesstrom et al., 2001; Wesstrom and Messing, 2007).

An innovative water table management technique, controlled drainage (CD), has been studied and practiced in many countries, such as USA, Australia, Canada and Sweden (Skaggs et al., 1994; Lalonde et al., 1996; Wesstrom et al., 2003; Elmi et al., 2004; Ayars et al., 2006; Zebarth et al., 2009). The practice utilizes a control structure at the end of subsurface drainage lines to vary the depth of the drainage outlet and has potential for improving grain yield and benefiting the environment by reducing tile flow and nitrogen loss. As summarized by Dinnes et al. (2002), controlled drainage management can reduce nitrate loss to the environment by increasing

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doi:10.1016/j.agwat.2011.11.006

denitrification with higher soil anaerobic activity, decreasing tile drainage and soil profile depth. Singh et al. (2007) summarized that controlled drainage could reduce tile drainage discharge volume from 25 to 44%, compared with free drainage (FD). The reductions in nitrate loss by CD varied greatly (13–95%) with soil type, climate (rainfall) conditions, crop system and other management practices (Drury et al., 1996; Lalonde et al., 1996; Amatya et al., 1998; Kroger et al., 2008). The groundwater table depth, drain spacing, time of implementation and duration of the controlled drainage also showed great influence on nitrate loss to tile drainage and crop production (Jacinthe et al., 1999; Kladivko et al., 1999; Fisher et al., 1999; Ale et al., 2010). Thorp et al. (2008) used the Root Zone Water Quality Model (RZWQM2) to estimate that CD reduces nitrate in subsurface drainage by 35–50% across the Midwest, but the model was not tested for CD using field data.

Improper N management has also been considered as a main contribution to increased nitrate load in the Midwest of USA (Dinnes et al., 2002). Improved timing and rates of N application based on weather conditions and crop demand can reduce nitrate loss to tile drainage, but the variation is high with different climate and soil conditions (Randall and Mulla, 2001; Jaynes et al., 2004). Effective combinations of N management may be different among FD and CD due to different soil water availability (Drury et al., 2009). The high temporal and spatial variability in soil and climate results in difficult interpretation of results when experiments are conducted for only a few sites and years. Also few studies were carried out to evaluate the coupled effects of drainage management (FD or CD) and N rate on nitrate losses, soil water, and nitrogen balance across different climate conditions. Such results are essential to adapting better agricultural water and N management practices to reduce nitrate loss effectively to benefit surface waters and the environment.

Combining model simulation and experimental results is an effective method to evaluate the impact of alternative management on water quality at different scales and climate conditions (Youssef et al., 2006; Ma et al., 2007; Nangia et al., 2008). Many system models have been developed and evaluated for simulating nitrate losses in tile flow and crop production such as DRAINMOD (Skaggs et al., 1995; Singh et al., 2006; Youssef et al., 2006; Salazar et al., 2009), ADAPT (Davis et al., 2000; Nangia et al., 2008), CERES-Maize (Garrison et al., 1999), DNDC (Tonitto et al., 2007), GLEAMS (Chinkuyu and Kanwar, 2001; Bakhsh et al., 2000) and RZWQM/RZWQM2 (Kumar et al., 1998; Bakhsh et al., 2001, 2004; Thorp et al., 2007, 2008). Davis et al. (2000) used the ADAPT model to simulate a greater reduction in nitrate loss by reducing N application rate compared to adjusting tile drain depth or spacing. Using the same model, Nangia et al. (2008) predicted a reduction of 13% in nitrate loss by reducing N rates from 180 to 123 kg N ha^{-1} and a further 9% reduction by switching N application time from fall to spring. Singh et al. (2007) applied DRAINMOD in a corn rotation system in Iowa, and found a tradeoff between subsurface drainage and surface runoff under controlled drainage and possible higher excess water stress on crop production. These system model analyses provided useful information on evaluating agricultural management effects on crop, soil hydrology and chemical properties and environment problems, and they improve our understanding of soil water and nitrogen processes under different variations of subsurface drainage systems.

RZWQM2 was utilized for simulating long-term fertilizer effects on crop production and nitrate loss in the Midwest of USA (Ma et al., 2007; Thorp et al., 2008; Malone et al., 2010) and shows promise as a tool for quantifying the relative effects of agricultural management on nitrate losses in drainage flow. Ma et al. (2007) successfully used RZWQM2 to simulate the effects of crop rotation, tillage and controlled drainage on crop yield and nitrate loss in drain flow. Bakhsh et al. (2001) and Thorp et al. (2007) evaluated the model for

Table 1
Management practices at the experiment site from 1996 to 2008 (adapted from Thorp et al., 2007).[a]

Year	Crop	Spring tillage		Planting	Nitrogen fertilizer application					Summer tillage		Harvest	Fall tillage		Drainage management[e]	
		Type	DOY	DOY	Method[b]	DOY	Rate (kg N ha^{-1})			Type	DOY	DOY	Type	DOY	FD (plots 4,5, 6)	CD (plots 1, 2, 3)
							H	M	L						Calibration	Evaluation
1996	Corn	FC	114	115	AA and NPK	109 and 114[c]	210	143	75	RCC	164	307	MP	315	FD	-
1997	Soybean	FC	113	125[d]	-	-	-	-	-	-	-	274	MP	283[d]	FD	-
1998	Corn	FC	115	116	32% UAN	134	172	114	57	RCC	166[d]	264	CP	273	FD	-
1999	Soybean	FC	112	125[d]	-	-	-	-	-	-	-	264	CP	290	FD	-
2000	Corn	FC	115[d]	116	28% UAN	131	199	138	69	RCC	161	265	-	-	FD	-
2001	Soybean	-	-	125[d]	NPK	298[d]	8	8	8	-	-	289	CP	298[d]	FD	-
2002	Corn	FC	109[d]	110	28% UAN	141	199	138	69	RCC	160[d]	287	-	-	FD	-
2003	Soybean	-	-	125[d]	-	-	-	-	-	-	-	281	CP	290[d]	FD	-
2004	Corn	FC	109[d]	110	28% UAN	154	199	138	69	RCC	160[d]	283	-	-	FD	-
2005	Soybean	-	-	125[d]	-	-	-	-	-	-	-	265	CP	274[d]	FD	-
2006	Corn	FC	102	103	28% UAN	143/170[c]	202	134	67/67[c]	RCC	102	276	CP	283	FD	CD
2007	Soybean	-	-	128	-	-	-	-	-	-	-	270	CP	278	FD	CD
2008	Corn	FC	128	125	28% UAN	143/197[c]	157	157	67/90[c]	RCC	123	283	-	-	FD	CD

[a] DOY: day of year; H: high rate (plots 1 and 4); M: medium rate (plots 2 and 5); L: low rate (plots 3 and 6); N: nitrogen; FC: field cultivator; AA: anhydrous ammonia; NPK: nitrogen, phosphorus, and potassium; RCC: row-crop cultivator; MP: moldboard plow; UAN: urea ammonium nitrate; and CP: chisel plow.
[b] Fertilizer was injected into the soil.
[c] AA was applied on DOY 109 at rates of 202 (1), 135 (2), and 67 (3) kg N ha^{-1}; NPK was applied to all plots at 8 kg N ha^{-1} on DOY 114; UAN was applied separately for 3 treatment in 2006 (on DOY 143 and 170) and 2008 (on DOY 143 and 197).
[d] Estimated date.
[e] Drainage management includes free drainage (FD) at plots 4, 5, and 6, and controlled drainage (CD) at plots 1, 2 and 3.