Water Quality Modeling of Fertilizer Management Impacts on Nitrate Losses in Tile Drains at the Field Scale

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Nitrate losses from subsurface tile drained row cropland in the Upper Midwest U.S. contribute to hypoxia in the Gulf of Mexico. Strategies are needed to reduce nitrate losses to the Mississippi River. This paper evaluates the effect of fertilizer rate and timing on nitrate losses in two (East and West) commercial row crop fields located in south-central Minnesota. The Agricultural Drainage and Pesticide Transport (ADAPT) model was calibrated and validated for monthly subsurface tile drain flow and nitrate losses for a period of 1999–2003. Good agreement was found between observed and predicted tile drain flow and nitrate losses during the calibration period, with Nash-Sutcliffe modeling efficiencies of 0.75 and 0.56, respectively. Better agreements were observed for the validation period. The calibrated model was then used to evaluate the effects of rate and timing of fertilizer application on nitrate losses with a 50-yr climatic record (1954–2003). Significant reductions in nitrate losses were predicted by reducing fertilizer application rates and changing timing. A 13% reduction in nitrate losses was predicted when fall fertilizer application rate was reduced from 180 to 123 kg/ha. A further 9% reduction in nitrate losses can be achieved when switching from fall to spring application. Larger reductions in nitrate losses would require changes in fertilizer rate and timing, as well as other practices such as changing tile drain spacings and/or depths, fall cover cropping, or conversion of crop land to pasture.

Hypoxia in the Gulf of Mexico affected an area of 17,500 km^2 during 2006 (LUMCON, 2006). A reduction in nitrate loading by 30% has been recommended to reduce hypoxia in the Gulf of Mexico (Mitsch et al., 1999). Nitrate loadings from the Upper Mississippi River Basin (UMRB) account for roughly 35% of the nitrate entering the Gulf of Mexico (Alexander et al., 1995), yet this area covers less than 20% of the Mississippi River Basin. The UMRB is characterized by an extensive area of Mollisols managed with subsurface tile drainage systems that are used primarily for row crop production. Nitrate concentrations in the Mississippi River are generally greatest in the tributaries emanating from Illinois, Iowa, and Minnesota (Antweiler et al., 1995) where artificially drained soils planted to corn and soybean dominate the landscape (Burkart and James, 1999). Omernik (1977) reported that total N concentrations were nearly nine times greater downstream from agricultural lands than downstream from forested areas, with the highest concentrations being found in the Corn Belt states. It is important to identify and evaluate agricultural management strategies that are capable of reducing nitrate loadings from agricultural systems in the Midwest to attain improved oxygen levels in the Gulf of Mexico.

Management practices to improve water quality can be divided into agronomic management practices and nitrogen removal practices (Dinnes et al., 2002). Considerable agronomic management research has been conducted at the plot scale to evaluate the effects of drain spacing and depth, N fertilizer application rate and timing, crop rotation, or climatic variability on the quality and quantity of drainage (Randall and Mulla, 2001; Dinnes et al., 2002). Nitrogen removal practices include planting buffer strips adjacent to streams and ditches, fall planting of cover crops, restoration of wetlands and wholesale conversion of row cropped fields to perennial cover (Mitsch et al., 2001; Boody et al., 2005). Mitsch et al. (2001) estimated that reductions in nitrate loads to the Gulf of Mexico of 300,000–800,000 metric tonne/yr could be achieved by creating or restoring wetlands and riparian buffers on 0.7–1.8% of the land in the Mississippi River Basin. These reductions compare with their estimates of a 900,000 to 1400,000 metric tonne/yr reduction in nitrate loads as a result of better N fertilizer management throughout the Basin.

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Higher nitrate losses are associated with higher N application rates (Baker and Johnson, 1981), and with fall versus spring application (Baker and Melvin, 1994). Many replicated plot scale studies have been conducted in the Upper Midwestern U.S. to experimentally measure reductions in nitrate losses through tile drains in response to alternative fertilizer management strategies (Randall and Mulla, 2001; Baker and Johnson, 1981; Dinnes et al., 2002; Randall et al., 2003). Weed and Kanwar (1996) demonstrated that the amount of nitrate found in the tile drainage from a loamy soil in Iowa was highly influenced by crop rotation, but not by tillage practice. This is mainly due to application rates of N fertilizer that are greater for grain crops than for legume crops. Randall et al. (2003) concluded in a study on tile-drained Canisteo clay loam soil that nitrate N losses from a corn–soybean rotation with subsurface drainage can be reduced by 13 to 18% by either applying N in the spring or using nitrapyrin (NP) with late-fall applied ammonia.

Attempts have been made to extrapolate experimental results for nitrate leaching at the plot scale to different temporal scales using tile drain simulation models (Davis et al., 2000; Zhao et al., 2000). Davis et al. (2000) calibrated and validated the ADAPT model using tile drainage and associated nitrate losses measured on three long-term experimental plots in Minnesota under continuous corn with conventional tillage. The experimental plots were located on poorly drained Webster clay loam soil (mesic Typic Haplaquols). Davis et al. (2000) found that a decrease in the N application rate from 225 to 175 kg/ha decreased nitrate losses by 48%.

Results from these plot scale studies have been used to estimate regional impacts of alternative fertilizer management practices on nitrate losses at scales that are vastly greater than those at which the studies were conducted (Mitsch et al., 2001). There is a pressing need to evaluate the impact of alternative fertilizer management practices at the field and watershed scales. There have been few studies at the field or watershed scales in the Upper Midwest to evaluate nitrate losses in response to alternative fertilizer management practices. At these scales, replication of experimental treatments is difficult, and spatial and temporal variability make the interpretation of trends in nitrate losses difficult to evaluate. For this reason, researchers attempting to evaluate the impact of N management practices on water quality at coarse scales have often combined experimental and modeling studies. For example, Jaynes et al. (2004) conducted a paired watershed study in Walnut Creek watershed in Iowa as a function of N fertilizer application rate. One portion of the watershed was managed with fertilizer application rates typical of Midwestern corn production, another received split N fertilizer application rates based on a late spring nitrate test (LSNT). Jaynes et al. (2004) showed that use of the LSNT approach reduced nitrate concentrations in tile drainage by 29%. Baksh et al. (2004) used the Walnut Creek watershed data with the Root Zone Water Quality Model (RZWQM) to estimate nitrate losses as a function of N fertilizer application rate. They found that reducing the N application rate from 175 to 125 kg/ha resulted in a 22% decrease in nitrate losses.

Several simulation models have been developed to simulate surface and subsurface agricultural water quality. Examples of such models are AGNPS (Young et al., 1994), SWAT (Arnold et al., 1998), CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), ADAPT (Agricultural Drainage and Pesticide Transport; Chung et al., 1992), LEACHM (Hutson and Wagenet, 1992), RZWQM (USDA-ARS, 1992), and DRAINMOD (Skaggs and Broadhead, 1982). Some of these models do not account for all the major hydrological processes that occur in the Midwestern U.S. such as tile drainage and snow-melt. For example, the simulation models CREAMS, GLEAMS, NLEAP, and LEACHM do not have tile drainage algorithms and the NLEAP and LEACHM models do not account for frozen soil hydrology including snow-melt runoff during the spring. The ADAPT model is a daily time step, field scale water table management model that was developed by integrating GLEAMS, a root zone water quality model, with subsurface drainage algorithms from DRAINMOD. More detailed information about ADAPT can be found in Chung et al. (1992), Ward et al. (1993), Gowda (1996), and Desmond et al. (1996).

Detailed evaluation of simulation models is necessary before their use for practical purposes, and this is often achieved by calibration and validation. This helps to determine whether the model produces rational results compared to observed data. It also provides information on shortcomings of models and additional processes/factors to be considered. Long- term monitoring data are required for calibration and validation of water quality simulation models. The ADAPT model has been calibrated and validated for various hydrologic conditions in the Midwest (Desmond et al., 1995; Chung et al., 1992; Gowda et al., 1999; Sogbedji and McIsaac, 2002a; 2002b; 2006). All of the latter studies, excepting Desmond et al. (1995), evaluated the ADAPT model for situations which involved measured streamflow and/or nitrate loads at the mouth of watersheds in the absence of any experimental fertilizer or tile drainage treatments in the watershed. Limited efforts have been made to evaluate tile drainage flow models in the presence of data involving experimental agricultural management practice treatments applied at the field or watershed scales (Zhao et al., 2000).

The main objectives of this study were to use water quality data collected in south-central Minnesota on two commercially farmed fields with experimental nitrogen fertilizer rate and timing treatments to: (i) calibrate and validate the ADAPT model for monthly subsurface tile drainage and associated nitrate losses, and (ii) determine sensitivity of nitrate losses to fertilizer application rates and timing.

Materials and Methods

Site Description

The calibration and validation of the model for subsurface tile drain flow and nitrate losses were performed using water quality measurements made on two fields of a commercial farm with a corn [*Zea mays* (L.)]- soybean [*Glycine max* (L.) Merr.] rotation. The site is located 8 km southwest of St. Peter, Minnesota (Fig. 1). It is set up such that a 21-ha field is split roughly in half [west field = 11 ha (213 m × 540 m) and east field = 9.3 ha (174 m × 535 m)]. The site is dominated by poorly drained clay loam soils that

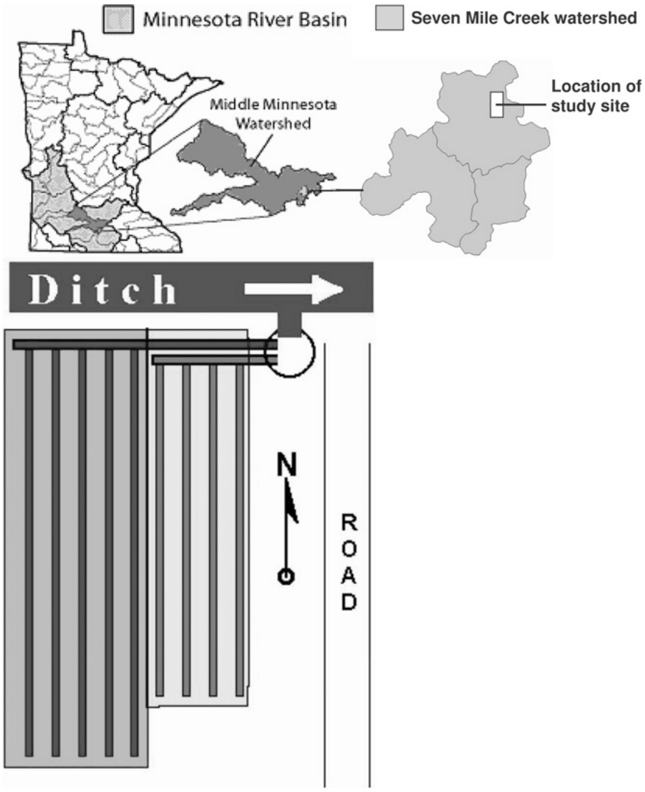

Fig. 1. Location of site in Minnesota.

developed under tall prairie grasses in glacial till. Soils in the study area included Cordova (Typic Argiaquolls), Cordova-Rolfe (Typic Argialbolls), Canisteo (Typic Haplaquolls), Le Sueur (Aquic Argiudolls), Harps (Typic Calciaquolls) and Okoboji (Cumulic Haplaquolls). The site is drained with concrete tile drains installed 15–30 yr ago at 30 m spacings and 1.1 m depths with an average slope of 0.3%. The diameter of tile drains was 152 mm. The average annual precipitation in the region is about 737 mm. Table 1 presents average monthly precipitation, temperature and potential evapotranspiration (PET) data for 1999–2003. Approximately 75% of the total drainage occurs in April, May and early June. The growing season typically lasts from mid/late May until early/mid October. Snow starts to melt in late March or April and high flows are observed at monitoring sites during the April-June period.

The fields were initially owned and operated by a farmer who applied N fertilizer in excess of the University of Minnesota recommendations. In 1995, fertilizer was fall applied by the farmer at a rate of 181 kg N/ha on both-east and west fields. From 1997 to 2001, the Minnesota Department of Agriculture conducted a pilot study at the site to measure the water quality impacts of improved N fertilizer management practices. In the spring of 1997, 1999, and 2001, respectively, 123, 100, and 124 kg N/ha were applied on the east field, and 160, 145, and 124 kg N/ha were applied on the west field, respectively. In 2002, ownership of the farm changed hands and the new owner insisted on switching back to fall N applications and increasing the N application rates to 190 kg/ha on the east field and 225 kg/ha on the west field, respectively. Figure 2 shows measured growing season averaged nitrate concentrations and N fertilizer application rates from 1995–2003. Because of climatic variability, there are both decreases and increases in nitrate losses despite changes in timing and decreases in fertilizer N application rates. In such a situation, long-term modeling can be used to isolate the effects of climatic variability from the effects of changes in application rate and timing of fertilizer.

Table 1. Average monthly temperature, precipitation (standard deviation of precipitation), and potential evapotranspiration (PET) recorded at the experiment site.

	Temperature	Precipitation (SD)	PET
	°C	mm	
January	−9.0	21.5 (13.7)	1.0
February	−5.5	21.5 (18.3)	4.6
March	−1.2	45.8 (22.1)	21.2
April	8.1	78.2 (53.6)	64.4
May	14.8	113.4 (45.1)	105.3
June	19.4	153.7 (74.3)	125.9
July	22.8	92.7 (19.4)	134.8
August	21.6	73.1 (21.6)	114.1
September	16.5	41.1 (25.8)	89.7
October	9.0	48.7 (38.6)	46.0
November	2.4	48.8 (41.4)	13.8
December	−5.7	15.7 (13.7)	3.1
Total		754.5 (85.0)	723.7

Adapt Model

The ADAPT model is a daily time step, field scale water table management model that was developed by integrating GLEAMS, a root zone water quality model, with subsurface drainage algorithms from DRAINMOD. GLEAMS algorithms have been augmented with algorithms for subsurface drainage, subsurface irrigation, and deep seepage and related water quality processes (Desmond et al., 1996). Other enhancements include adding the Doorenbos and Pruitt (1977) potential evapotranspiration method as an alternative to the Ritchie (1972) method; modifying the runoff curve number based on daily soil water conditions; adding a Green-Ampt infiltration model; modeling snow-melt; and accounting for macropore flow. A frost depth algorithm developed by Benoit and Mostaghimi (1985) was incorporated by Dalzell (2000) to enhance the model's capability to predict flow during spring and fall months.

ADAPT uses a detailed pseudo-mechanistic approach for estimating nitrogen fate and transport, including mineralization of soil organic matter, immobilization, nitrification and denitrification, volatilization, crop uptake and N fixation (legumes only), leaching and losses in drainage and runoff. N mineralization is considered as a two-stage process in ADAPT: the first stage being a first-order ammonification process; and the second a zero-order nitrification process. The default potential mineralization rate constant value used in ADAPT is 0.003 kg/ha/day, while the potential nitrification rate constant has a value of 100 mg NO_3–N/kg soil/week. Ammonification occurs from the active soil N, fresh organic N from root and surface residue, and organic N in animal waste. The two soil organic carbon pools are based on carbon:nitrogen (C:N) ratios. Mineralization rates depend on potential mineralization rates, modified by temperature and soil water factors. ADAPT considers mineralization not only from soil organic matter, but also from crop and root residues. Immobilization of nitrogen as nitrate or ammonia is estimated by ADAPT based on fresh residue mass, concentration of nitrogen in the residue and a decay rate which is a function of C to N ratio of the residue, soil water content and temperature. Denitrification is estimated by ADAPT as a function of soil nitrate concentration, a decay coefficient, and temperature and soil moisture factors. Denitrification occurs only when soil moisture content is 10% above field capacity water content.

ADAPT estimates uptake of nitrogen as either nitrate or ammonia based on concentrations of nitrate or ammonia in soil layers, daily nitrogen demand of the crop and root uptake of water from different soil layers. Daily nitrogen demand of the crop is estimated based on total dry matter nitrogen in biomass as a function of concentration of nitrogen in biomass, changes in leaf area index, potential crop yield and the ratio of total dry matter to harvestable yield. For leguminous crops, ADAPT estimates uptake using the same approach described above only when the concentrations of nitrate and ammonia in soil solution exceed 5 mg/L. If the concentrations of nitrate and ammonia are less than 5 mg/L, N fixation occurs in an amount needed to satisfy the daily nitrogen demand. Further details of the nutrient component of the ADAPT model can be found in Knisel et al. (1993). All default N process rate constants in ADAPT were used without any calibration.

Model Inputs

Model simulations were made using climatic data from 1994–2003. Precipitation was measured on site using a tipping bucket rain gauge during 1999–2003 (Table 1). Precipitation data for the remaining years and other climatic data such as daily values of average temperature, solar radiation, wind speed, and average relative humidity were taken from the nearby St. Peter weather station. Subsurface tile drain flows were measured from 1999 onward at a 1-min frequency using an ISCO area-velocity meter (ISCO, Inc., Lincoln, NE) and outputs were 15-min average discharges. Water quality samples were taken from 1999 onward using automated sampling equipment during storm events and grab samples were collected during base flow conditions. Samples were measured for nitrate, total phosphorus, ortho-phosphorus, fecal coliform and E-coli bacteria, turbidity, and total suspended solids. The fields were planted with a corn–soybean rotation under conventional tillage making it very typical of the upper Midwest region cropping system. Since nutrient management data were available at the site from 1994 to 2003, model simulations were conducted starting from 1994.

For corn, di-ammonium phosphate (DAP) and urea were broadcast and anhydrous ammonia was injected. A variable rate N application study (Montgomery et al., 2000) was performed at the site from 1997 to 1999. For this purpose, the field was divided into multiple strips receiving different rates of fertilizer N. For corn, strips received N fertilizer at rates of 61, 101, 146, and 179 kg N/ha. Details of planting and harvesting dates, fertilizer application rates and tillage operations implemented during 1994–2003 are presented in Table 2.

Soil properties required by the ADAPT model for simulation include soil-water release curve data, drained volume and upward flux versus depth, infiltration parameters, and saturated vertical and horizontal hydraulic conductivity. These data were obtained from the Natural Resources Conservation Service Map Unit Use File (NRCS MUUF 2.14 database, Baumer et al., 1987). Table 3 describes some of the key properties derived from the MUUF database and used in the ADAPT model setup.

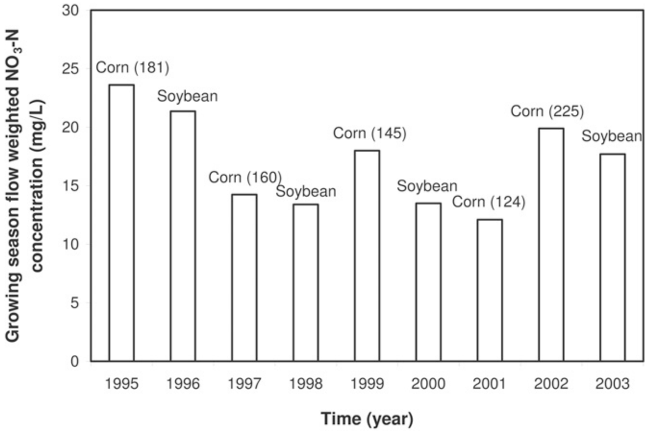

Fig. 2. Measured growing season flow-weighted mean nitrate concentrations in the west field from 1995–2003. Values in parentheses for corn years are N fertilizer application rates. No fertilizer was applied before planting soybeans.

Hydrologic Response Unit Formation

An important step in developing ADAPT model inputs for application is the identification of all hydrologically unique areas within the watershed. This is done by first overlaying GIS layers of hydrologically sensitive parameters such as slope, soil characteristics, land cover/land use, nutrient application rate and timing, and tillage. Each resulting polygon contains hydrologic characteristics that are unique from those around it. These unique areas are referred to as Hydrologic Response Units (HRUs). The number of HRUs that result from this initial definition are usually quite large. However, there are many HRUs in a watershed that have the same hydrologic characteristics and are differentiated by location only. All similar HRUs are then grouped together to form Transformed Hydrologic Response Units (THRUs)– the functional modeling unit. It should be noted that THRUs do not retain the positional information initially present in the HRUs. This data arrangement is based on the assumption that the time of concentration in the study watershed is less than 24 h, the time step resolution of the model. This assumption is valid for relatively small fields such as ours. The THRU formation methodology has been proposed by Kouwen et al. (1993) and extended by Gowda et al. (1999).

In the THRU formation process, spatial data layers of variable N application rates for 1997 and 1999 and soil types were overlaid using ArcView 3.0 GIS software (ESRI, Redlands, CA) to capture the variability in N fertilizer application rate against soil type. Differences in application rates across the field during the variable application rate study were handled in the model setup by treating areas with unique N application rates as separate HRUs. N fertilizer application rates for other years were uniform throughout the fields and were not spatially overlaid for THRU formation. The result was a GIS layer consisting of 11 THRUs for the west (calibra-

Table 2. Crop management operations, nitrogen applications, and tillage operations at the commercial farm study site.

	Crop			NO_3–N			Tillage	
Year	Type	Planting	Harvest	Type	Date	N fertilizer applied to 11-ha field (9.3-ha field)	Operation	Date
						kg N ha^{-1}		
1994	Soybean	1 May 1994	20 Oct. 1994				Chisel	7 Oct. 1993
							Cultivator	17 Apr. 1994
							Planter	1 May 1994
1995	Corn	1 May 1995	20 Oct. 1995	NH_3^+	3 Nov. 1994	169 (169)	Chisel	27 Oct. 1994
							NH_3^+ Applicator	3 Nov. 1994
				DAP	3 Nov. 1994	12 (16)	Cultivator	24 Apr. 1995
							Planter	1 May 1995
1996	Soybean	1 May 1996	30 Sept. 1996				Chisel	18 Aug. 1995
							Cultivator	24 Apr. 1996
							Planter	1 May 1996
1997	Corn	29 Apr. 1997	20 Oct. 1997	NH_3^+	7 Oct. 1996	20 (20)†	Chisel	7 Oct. 1996
							NH_3^+ Applicator	14 Oct. 1996
				Urea	28 Apr. 1997	140 (103)†	Cultivator	22 Apr. 1997
							Planter	29 Apr. 1997
1998	Soybean	7 May 1998	30 Sept. 1998				Chisel	27 Apr. 1997
							Cultivator	30 Apr. 1998
							Planter	7 May 1998
1999	Corn	4 May 1999	20 Oct. 1999	DAP	3 May 1999	145 (100)†	Chisel	7 Oct. 1998
							NH_3^+ Applicator	14 Oct. 1998
							Cultivator	27 Apr. 1999
							Planter	4 May 1999
2000	Soybean	3 May 2000	10 Oct. 2000				Chisel	27 Oct. 1999
							Cultivator	26 Apr. 2000
							Planter	3 May 2000
2001	Corn	11 May 2001	3 Oct. 2001	DAP	10 May 2001	124 (124)	Chisel	17 Oct. 2000
							NH_3^+ Applicator	24 Oct. 2000
							Cultivator	4 May 2001
							Planter	11 May 2001
2002	Corn	20 Apr. 2002	3 Oct. 2002	NH_3^+	10 Nov. 2001	191 (161)	Chisel	3 Nov. 2001
							NH_3^+ Applicator	10 Nov. 2001
				DAP	10 Nov. 2001	34 (29)	Cultivator	13 Apr. 2002
							Planter	20 Apr. 2002
2003	Soybean	3 May 2003	10 Oct. 2003				Chisel	10 Oct. 2002
							Cultivator	26 Apr. 2003
							Planter	3 May 2003

† Weighted average amount of N applied.

tion) field and 15 THRUs for the east (validation) field containing unique combinations of soil type and N fertilizer application rates.

Model Calibration and Validation

Since rigorous sampling methodology for measuring water quality monitoring data were instituted after 1999, the first 3 yr (1999–2001) of high quality monitoring data were used for calibration and the remainder of the data (2002–2003) were used for validation of the ADAPT model using monthly subsurface tile drainage and nitrate losses. The model was validated again using independent flow and water quality monitoring data from the east field. We modified parameters one at a time to check sensitivity of output to their change. We searched for optimum values of parameters in increments of 5% between specific lower and upper bounds, based on literature and default values available. The model was calibrated by varying hydrologically sensitive parameters such as saturated vertical hydraulic conductivity (Table 3), rooting depth, leaf area index, drainage coefficient, and soil moisture retention curves to achieve the closest agreement between predicted and observed subsurface tile drainage and nitrate losses.

Other parameters modified during the calibration of ADAPT, included soil freeze/thaw, soil storage, runoff, and crop growth parameters. These parameters affected the prediction of both ET and surface runoff. It is important to note that there were no observed ET data at the study site. Crop ET was indirectly adjusted by increasing the final leaf area index (LAI) coefficient by 30% (final LAI = initial LAI*1.3). The LAI database built into the ADAPT model is for older cultivars with lower biomass and crop yields that grew in locations different from Minnesota. Table 4 lists the parameters that were adjusted during model calibration.

Table 3. Soil properties used in ADAPT modeling.

Soil name	Horizon	Thickness	Clay	Silt	OM†	K_{sat}	Porosity	WP	FC
		cm	—%—		g/kg	cm/h	cm^3/cm^3	—cm/cm—	
Le Sueur	1	33.0	29.0	37.0	50	5.5	0.5	0.17	0.21
	2	38.1	29.5	36.8	13	2.2	0.4	0.18	0.21
	3	563.9	25.0	36.5	3	2.4	0.4	0.15	0.18
Cordova	1	35.6	28.5	37.3	55	2.1	0.5	0.17	0.21
	2	48.3	31.5	48.5	18	0.4	0.4	0.18	0.21
	3	551.1	24.0	37.0	6	1.0	0.4	0.15	0.18
Cordova-Rolfe	1	43.2	24.5	51.4	40	2.0	0.5	0.15	0.19
	2	48.3	39.5	31.3	15	0.3	0.5	0.28	0.35
	3	543.5	29.5	36.8	5	1.9	0.4	0.17	0.21
Harps	1	40.6	31.0	33.6	45	5.7	0.5	0.18	0.21
	2	25.4	25.0	18.0	25	6.4	0.4	0.16	0.19
	3	569.0	25.0	18.0	5	4.7	0.4	0.15	0.18
Canisteo	1	33.0	31.0	33.6	60	7.4	0.5	0.18	0.22
	2	27.9	27.5	37.8	30	4.3	0.5	0.16	0.20
	3	17.8	22.5	37.7	8	2.8	0.4	0.13	0.16
	4	556.3	27.0	38.1	3	1.7	0.4	0.15	0.18
Okoboji	1	35.6	38.5	43.1	60	0.3	0.6	0.25	0.30
	2	45.7	38.5	54.1	3	0.3	0.6	0.27	0.32
	3	86.4	39.5	53.3	8	0.1	0.5	0.27	0.32
	4	467.3	25.0	36.5	3	2.5	0.4	0.15	0.18

† K_{sat}, saturated conductivity; OM, organic matter; WP, wilting point; FC, field capacity.

Several additional parameters were considered for calibration and ultimately left unchanged because simulation outputs were relatively insensitive to their changes. These parameters included: the thickness of the layer to be used in considering soil moisture effects on runoff (TLRO, 20 mm), initial depth of water table (DTWT, 122 cm), SCS curve number for frozen soils (FCN, 90), kinematic viscosity (KINVIS, 3.7x10^{-4} cm^2/s), the number of days required to develop surface macropore cracks (DACK, 4 d), the percentage of rainfall that penetrates directly to the water table in the event of macropore flow (THRESH, 0.2), and the average daily temperature at which infiltration begins (TCUT, 0°C).

Although the model was continuously run for the entire simulation period (1999–2003), observed data were not available for comparison during winter and fall months of some years (measured data were missing for: Jan., Sept.-Dec., 1999; Jan.-April and Aug.-Dec., 2000; Jan.-Mar. and Aug.-Dec., 2001; Jan.-Mar., Aug.-Sept. and Nov.-Dec., 2002; Jan.-Mar. and Aug.-Dec. 2003). Flow and water quality data are not collected in these months because tile flows are generally low to nonexistent, as a result of either frozen soils or limited rainfall. As a result, measures of model performance are a comparison of the months in which observed data were available. Although the ADAPT model is capable of predicting runoff and subsurface tile drainage during winter and early spring conditions, evaluation of model performance for these events was not possible due to a lack of measured data.

Performance Criteria

Four statistical procedures were used to assess the level of agreement between the predicted and observed data for calibration years:

(i) Observed and predicted means:

$$o = \frac{\sum_{i=1}^{n} o_i}{n}$$

$$p = \frac{\sum_{i=1}^{n} p_i}{n}$$

where n is number of values and p_i is the predicted value and o_i is the observed value

(ii) Nash-Sutcliffe modeling efficiency (E) (Nash and Sutcliffe, 1970),

$$E = 1 - \frac{\sum_{i=1}^{n} \left(o_i - p_i\right)^2}{\sum_{i=1}^{n} \left(o_i - o\ \right)^2}$$

where o_i is the observed value corresponding to p_i. and o is observed mean

(iii) root mean square error (RMSE),

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(p_i - o_i\ \right)^2}{n}}$$

Table 4. Final values of adjusted ADAPT parameters.

Parameter	Description	Final value
ADEPTH	Depth to the impermeable layer	635 cm
UPFLUXHOURS	No. of hours that upflux occurs from water below the drain depth	24 h
SEAL	Surface sealing threshold	15.24 cm
BOTP	Maximum depth of the frost layer	180 cm
KFZONE	Thermal conductivity of frozen soil	251 J m^{-1} h^{-1} K^{-1}
DRYTHW	Heat capacity that converts calories of heat to depth of soil thaw	7.2 x 10^{-6} m^3 J^{-1} h^{-1}
PDENSY	Density of snow	0.3 g cm^{-3}
RKSIMP	Vertical saturated conductivity of the most impermeable layer	0.0002 mm h^{-1}
STOR	Surface storage depth for ponding	2 mm
RKSIMP	Vertical saturated hydraulic conductivity in the impermeable layer	0.0005 cm h^{-1}
DC	Drainage coefficient	0.25 cm h^{-1}
RD	Rooting depth	Corn: 89 cm Soybean: 64 cm
CN2	SCS curve number for antecedent moisture condition II	78

Table 5. Model performance statistics for predicted monthly subsurface tile drainage and nitrate discharge during calibration and validation years.

Statistics		Calibration on west field		Validation on west field		Validation on east field	
		Flow	Nitrate	Flow	Nitrate	Flow	Nitrate
		mm/d	kg/ha	mm/d	kg/ha	mm/d	kg/ha
Mean	Observed	1.1	4.5	0.8	3.0	1.5	3.4
	Predicted	1.2	5.2	1.1	4.4	1.5	4.5
RMSE		0.5	2.9	7.2	2.5	0.8	2.1
E (unitless)		0.75	0.56	0.67	0.67	0.81	0.73
d (unitless)		0.92	0.91	0.91	0.91	0.95	0.93

and (iv) Index of agreement (d) (Willmott, 1981).

$$d = 1 - \frac{\sum_{i=1}^{n} \left(p_i - o_i \right)^2}{\sum_{i=1}^{n} \left(\left| p_i^{'} \right| + \left| o_i^{'} \right| \right)^2}$$

where $p_i^{'} = p_i - p$ and $o_i^{'} = o_i - o$

Index of agreement is a measure of the degree to which the predicted variation precisely estimates the observed variation. The value of d is unity when there is a perfect agreement. Nash-Sutcliffe efficiencies can range from-∞ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match between modeled values and observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < E < 0$) occurs when the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model is.

Nitrogen Fertilizer Application Rate and Timing

Long-term simulations (1954–2003) were made to determine sensitivity of nitrate losses to changes in N application rates and timings. Input parameters used in the simulations for evaluating sensitivity of nitrate losses were the same as those used in the model calibration and validation. Alternative management practices included three different N application rates (0, 123, and 180 kg N/ha) and three different timings- fall, spring pre-plant, and 50% in spring pre-plant and 50% in fall.

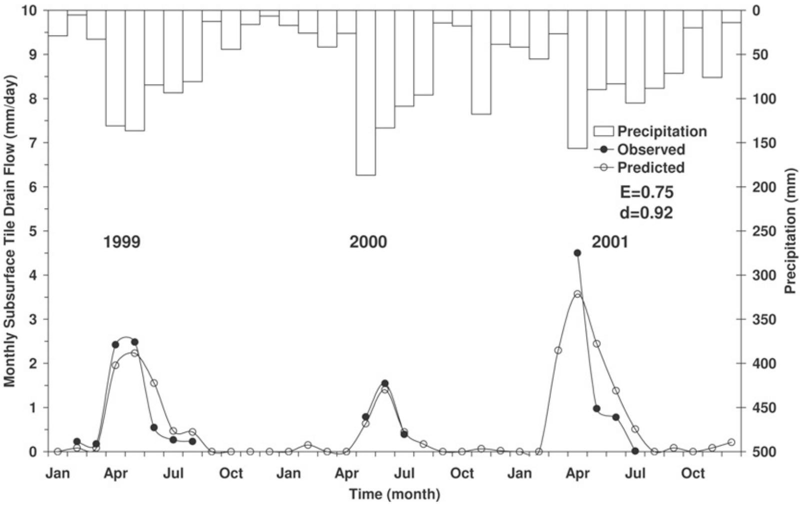

Fig. 3. Comparison between predicted and observed monthly subsurface tile drainage as a function of precipitation for the west field during the calibration period.

Results and Discussion

Model Calibration

Table 5 shows good agreement between predicted and measured subsurface tile drainage and nitrate losses for the calibration and validation periods. In the calibration phase, attempts were made to minimize the RMSE and obtain E and d values closest to unity. Comparison of measured and calibrated values for monthly subsurface tile drainage (Fig. 3) shows that the model underpredicted drainage in early spring. This is primarily due to the difficulty in predicting the onset of subsurface tile drain flow during spring snowmelt runoff. Statistical evaluation of the monthly predicted and observed subsurface tile drain flow gave an E value of 0.75. The index of agreement was about 0.92 and the RMSE was 48% of the observed mean monthly subsurface drainage (Table 5). Table 6 compares monthly observed and predicted subsurface tile drainage and Nash-Sutcliffe efficiencies for the calibration period. For a majority of the months, E values are close to 1, showing good agreement between observed and predicted values. In June, 1999 and May and June, 2001, the E values are negative, suggesting that observed mean drainage is a better predictor than the model. We can conclude from these results that the model performed reasonably well in predicting subsurface tile drainage during the non-snowmelt period.

During the calibration period, predicted monthly nitrate losses were in close agreement with the measured data (Fig. 4). However, the predicted mean monthly nitrate loss was about 16% higher than the measured value. Overprediction of nitrate losses was mainly due to overprediction of flow during snowmelt runoff in 1999 and 2000. Statistical evaluation of the measured and observed nitrate losses gave an E value of 0.56. The index of agreement was about 0.91 and the RMSE was about 36% lower than the measured value (Table 5). Table 6 indicates that a majority of the E values are close to unity, with a few exceptions in June, 1999, May, 2000, and April, May and July, 2001. Overall, the model seems to predict nitrate losses reasonably well when the predicted monthly subsurface tile drain flows were in agreement with the measured data.

In cold climates where soil freeze/thaw occurs, fall soil moisture recharge and climatic conditions during the transition from winter to spring (snowmelt period) determine the timing and magnitude of spring drainage (Sands et al., 2003). Little, if any, subsurface tile drainage occurs during the winter season, while considerable drainage may occur during late March through June. Average daily temperatures from December to March in 1999–2004 were below or close to 0°C as recorded at the weather station. During this period, for days in which the average daily temperature was a few degrees below

0°C, the daily maximum temperature was usually above 0°C. Typically, during this period in Minnesota, snow that melts during the daytime refreezes when the temperature drops in the evening, producing little surface runoff and infiltration. Since the input data for ADAPT uses only a single average daily air temperature value for snow freeze/thaw calculations, the soil freeze/thaw condition is not precisely matched in such periods. This creates inaccuracies in partitioning of drainage between subsurface tile drain flow and surface runoff during spring snowmelt events.

Model Validation

Validation on the West Field

Comparison of measured and predicted values of monthly subsurface tile drainage for validation years (2002–2003) on the west field shows (Fig. 5) that the magnitude and trend in the predicted monthly subsurface tile drainage closely followed that of measured data in most months. There was fair agreement between predicted mean monthly subsurface tile drain flows of 1.1 mm/day and measured subsurface tile drain flows of 0.8 mm/day (Table 5). The model overpredicted subsurface tile drain flows partly due to errors in the prediction of timing and magnitude of snowmelt events in early spring. A comparison of predicted and measured monthly subsurface tile drain flows values gave an E value of 0.67 and the index of agreement was about 0.91. Table 6 indicates that the E values were close to unity for a majority of the period, with some exceptions in May and July, 2002.

There was fair agreement between predicted mean monthly nitrate losses of 4.4 kg/ha and measured losses of 3.0 kg/ha (Table 5). The model overpredicted nitrate losses by 32%, especially during snowmelt events occurring in early spring (Fig. 5). A comparison of predicted and measured monthly subsurface nitrate losses gave an E value of 0.67 and the index of agreement was about 0.91. A comparison of predicted and measured monthly subsurface nitrate losses (Fig. 6) gave an E value of 0.67 and the index of agreement was about 0.91.

Table 6. Observed and model predicted subsurface tile drainage (mm/day), nitrate losses (kg/ha) and Nash-Sutcliffe modeling efficiencies (E) during calibration and validation periods.

			Subsurface tile drainage			Nitrate loss		
	Year	Month	Observed	Predicted	E	Observed	Predicted	E
			——mm/d——			——kg/ha——		
	West field							
Calibration	1999	Feb.	0.2	0.1	0.97	0.7	0.0	0.96
		Mar.	0.2	0.1	0.99	0.5	0.1	0.99
		Apr.	2.4	2.0	0.88	10.9	10.7	1.00
		May	2.5	2.2	0.97	13.7	12.0	0.97
		June	0.5	1.6	−2.34	2.6	9.1	−11.07
		July	0.3	0.5	0.94	0.3	2.8	0.65
		Aug.	0.2	0.4	0.94	0.0	2.3	0.74
	2000	May	0.8	0.6	0.76	5.5	8.0	−5.00
		June	1.5	1.4	0.90	1.6	2.6	0.86
		July	0.4	0.4	0.99	16.1	18.4	0.96
	2001	Apr.	4.5	3.6	0.93	3.4	11.5	−52.05
		May	1.0	2.4	−148.88	2.8	7.0	−5.23
		June	0.8	1.4	−2.62	0.1	2.4	0.74
		July	0.0	0.5	0.79	0.0	4.4	−1.26
Validation-I	2002	Apr.	0.0	0.9	0.75	0.6	3.5	−0.51
		May	0.2	0.7	0.08	15.2	13.6	0.98
		June	2.8	3.8	0.80	0.1	5.6	−2.79
		July	0.1	1.1	−1.74	0.0	0.0	1.00
	2003	Apr.	0.0	0.3	1.00	0.1	1.5	0.76
		May	1.4	1.7	0.86	6.4	8.7	0.55
		June	0.9	0.7	0.89	3.3	4.1	−3.99
		July	0.3	0.3	0.02	0.9	1.5	0.91
	East Field							
Validation-II	1999	Feb.	0.0	0.1	0.99	0.5	0.1	0.98
		Mar.	0.5	0.1	0.85	0.5	0.1	0.98
		Apr.	2.9	2.5	0.92	8.4	7.9	0.99
		May	3.5	2.9	0.90	11.5	8.6	0.87
		June	1.1	1.7	−2.01	2.9	6.5	−46.68
		July	0.3	0.4	0.99	0.0	1.8	0.72
		Aug.	0.3	0.4	0.98	0.0	1.4	0.82
	2000	May	1.2	0.8	−1.96	4.9	5.6	0.77
		June	1.8	1.6	0.74	1.2	1.6	0.97
		July	0.8	0.5	0.79	10.3	11.6	0.96
	2001	Apr.	7.5	5.0	0.82	3.4	7.6	-4.6×10^{-6}
		May	1.5	2.8	−390.37	2.8	4.4	−7.04
		June	1.3	1.5	−0.27	0.1	1.7	0.76
		July	0.1	0.6	0.87	0.0	3.9	−0.35
	2002	Apr.	0.3	1.2	0.47	0.6	2.5	0.53
		May	0.5	0.7	0.96	15.3	13.9	0.99
		June	5.7	5.0	0.97	0.6	4.9	−1.42
		July	0.4	1.1	0.52	0.0	0.0	1.00
		Oct.	0.0	0.0	1.00	0.1	1.6	0.79
	2003	Apr.	0.6	0.3	0.94	6.0	8.3	0.23
		May	1.5	2.2	−76.85	4.3	3.1	−0.81
		June	0.5	0.7	0.96	1.2	1.3	1.00

Validation on the East Field

A second validation of the model was performed on the east field from 1999–2003 (Figs. 7 and 8). Validation results were better for this site compared to the west field (Table 5). Mean

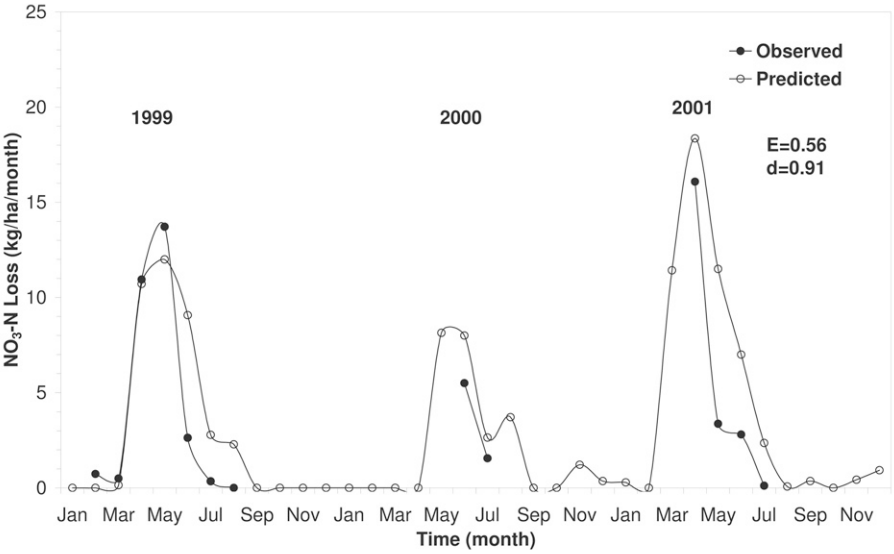

Fig. 4. Comparison between predicted and observed monthly nitrate losses for the west field during the calibration period

subsurface tile drain flows were very close to each other (observed: 1.5 and predicted: 1.5 mm/day), and RMSE values were also smaller for both subsurface tile drain flow and nitrate losses (0.7 mm/day and 0.2 kg/ha). Nash-Sutcliffe modeling efficiencies of 0.81 and 0.73 were observed for subsurface tile drainage and nitrate, respectively.

Measured and Predicted Water and Nitrogen Budgets

The predicted annual subsurface tile drain flows were about 23.2% of the total precipitation, which is comparable to the measured value of 25.3%. The predicted annual ET was 68.8% of the total precipitation, which is comparable with values (64.1% in 1992 and 72% in 1994) measured on a fine-textured tile-drained soil located in central Iowa (Moorman et al., 1999). Measured ET values were not available for our study site. This comparison indicates that the model is partitioning water reasonably well.

The crop nitrogen uptake was 149.5% of the N applied in fertilizer because results presented here are for a corn–soybean rotation with no N fertilizer application in soybean cropping years. N fixed by the soybean crop is not considered applied fertilizer, but can be taken up by the corn crop. Average nitrogen fixation was 109.8 kg/ha which compares well with rates of 80–100 kg/ha determined by Johnson et al. (1975) and more recent estimates of 100 kg/ha for Illinois conditions (Hoeft and Peck, 2002). Soils high in organic matter can mineralize substantial amount of nitrate, which is susceptible to loss in subsurface tile drainage (Randall and Mulla, 2001). The predicted mineralization was 64.4 kg/ha which compares well with 69.8 kg/ha predicted by Davis et al. (2000) on a nearby Minnesota soil with 60 g/kg organic matter. The predicted annual average nitrate loss through subsurface tile drains (59.6 kg/ha) was about 46% of the applied N and about 1.4% higher than the measured nitrate losses (57.8 kg/ha). The predicted nitrate loss by denitrification was about 10.3% of the total N applied, which is comparable to estimated values (10–25%) reported by Meisinger and Randall (1991).

Effects of Alternative Fertilizer Management Scenarios Based on a 50 Year Climate Record

Nitrogen Fertilizer Application Rate and Timing

Decreases in N fertilizer application rate resulted in reductions in nitrate losses (Fig. 9). For example, annual predicted nitrate losses decreased from 50.4 kg/ha to 43.7 kg/ha when fall applied N was decreased from 180 kg/ha to 123 kg/ha. This is a 13% decrease in nitrate losses for a 32% reduction in N fertilizer rate. Further reductions in nitrate losses were predicted when fall N applications were switched to spring or split N application timings. For a N application rate of 180 kg/ha, the model predicted a reduction of 9% (from 50.4 to 45.9 kg/ha) when application timing was changed from fall to spring. Reductions in nitrate losses were also predicted at N application rates other than 180 kg/ha. Averaged across twenty-five rotation cycles, the lowest nitrate losses were found with reduced rates of N fertilizer applied during spring. Overall, reductions in N application rate had a bigger impact on nitrate losses than

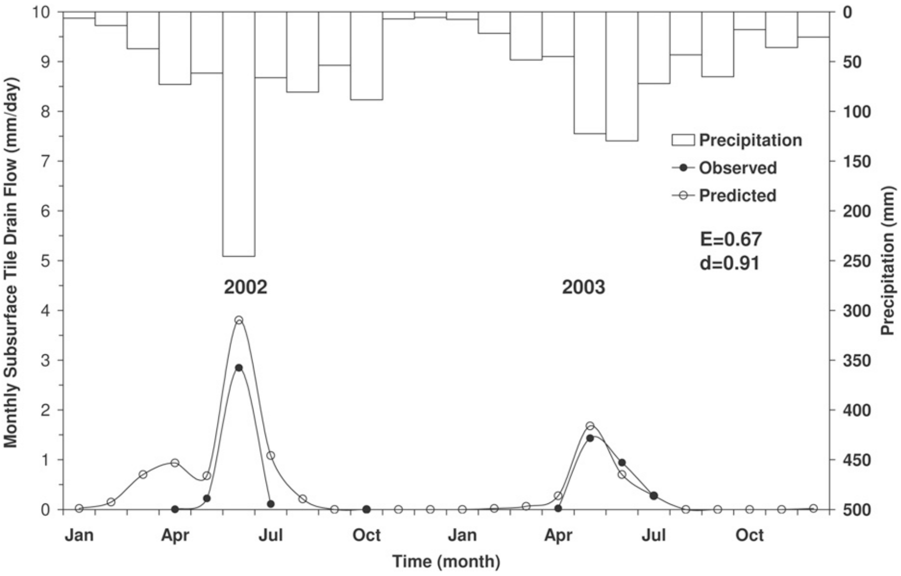

Fig. 5. Comparison between predicted and observed monthly subsurface tile drainage flow as a function of precipitation during validation on the west field.

switching N application from fall to spring.

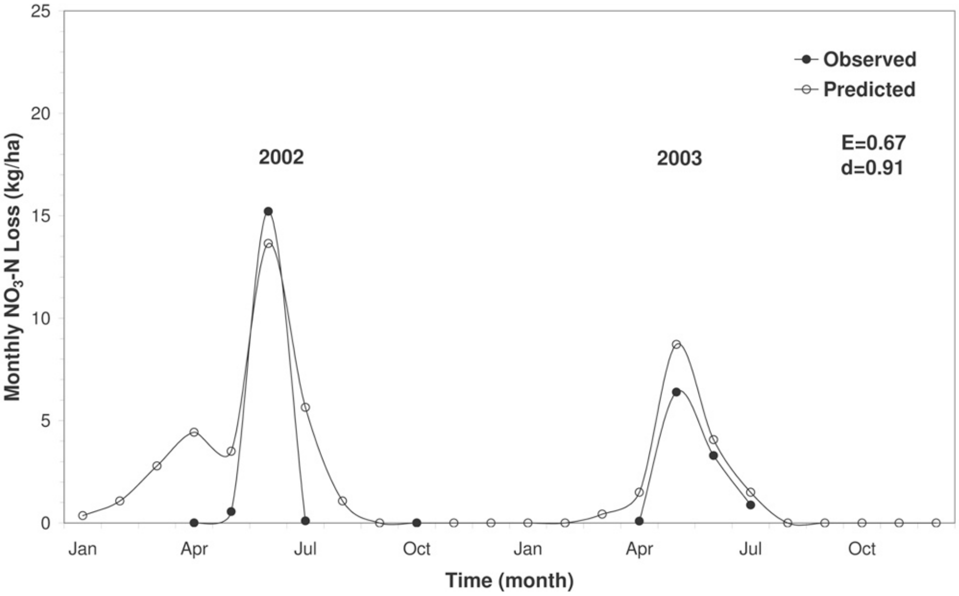

Fig. 6. Comparison between predicted and observed monthly nitrate losses during validation on the west field.

We can use the simulation results to improve the interpretation of the nitrate losses measured in the study site field experiment that involved reductions in N fertilizer rate from 181 kg N/ha to 124 kg N/ha and changes in N application from fall to spring (see Fig. 2). Figure 2 shows a roughly 35% reduction in nitrate concentrations from tile drainage on the west field between 1995 and 2001. During the years of improved N fertilizer management practices (1997–2001), experimental data show nitrate concentrations in tile drainage from the west field varying between 12 and 18 mg/L. Much of this variability is attributable to climatic variability (1999 and 2001 were wet years). In 2002 and 2003, nitrate concentrations increased in response to changes in field ownership and substantial increases in N fertilizer application rates in the 2002 growing season. Using model results based on a 50-yr climatic record, the combination of reduced N applications and changes in N application timing from fall to spring would have caused an 18% reduction in nitrate loads through tile drainage. This comparison indicates that caution must be used in interpreting trends in experimental data for nitrate concentrations from short-term experiments because of variability in factors other than N fertilizer management (e.g., variability in climate and drain flows).

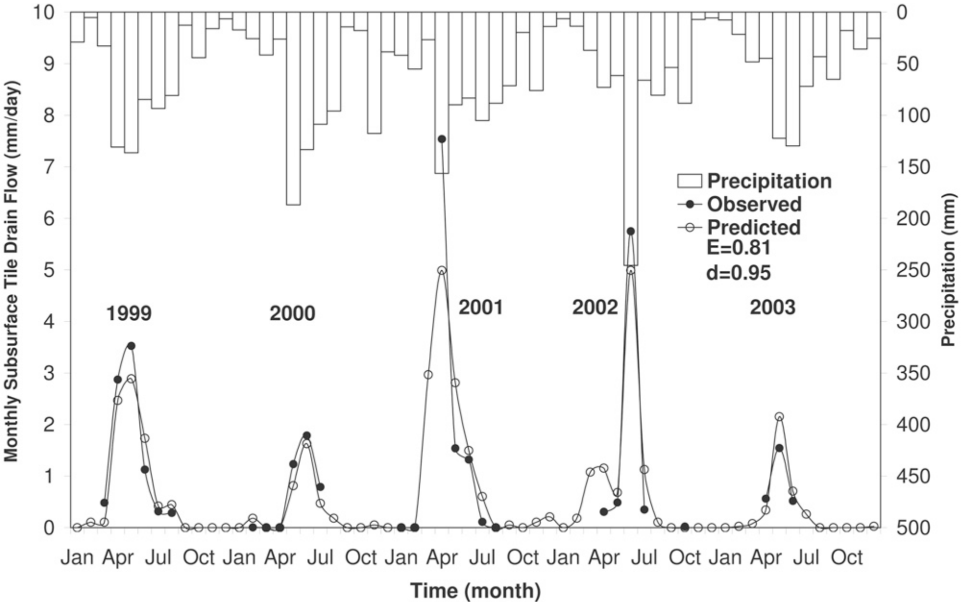

Fig. 7. Comparison between predicted and observed monthly subsurface tile drainage flows as a function of precipitation during validation on the east field.

It is worthwhile to note that reducing N application rates to zero did not eliminate nitrate losses in subsurface tile drainage. Even when no N fertilizer was applied, nitrate losses of about 27 kg/ha were predicted. It appears that losses less than this are not possible for this site and cropping system because the source of this nitrate should be mineralized soil N that was fixed in the soybean portion of the crop rotation.

The results of this modeling study are consistent in trend with those obtained by Davis et al. (2000) and Baksh et al. (2004), who also showed significant reductions in nitrate losses from tile drainage after reducing N fertilizer application rate. In the present study, we obtained a 13% reduction in nitrate losses by decreasing spring N fertilizer application rates from 180 kg N/ha to 123 kg N/ha. In the Davis et al. (2000) Minnesota study, a 93% reduction in nitrate losses was obtained by reducing spring N fertilizer application rates from 175 kg N/ha to 125 kg N/ha. In the Baksh et al. (2004) Iowa study a 22% reduction in nitrate losses was obtained by reducing spring N fertilizer application rates from 175 kg N/ha to 125 kg N/ha.

These different magnitudes of reduction can partly be explained by differences in cropping system, scale and method for collecting experimental data in the two Minnesota studies. The Davis et al. (2000) study involved a continuous corn rotation where N fertilizer is applied every single year,

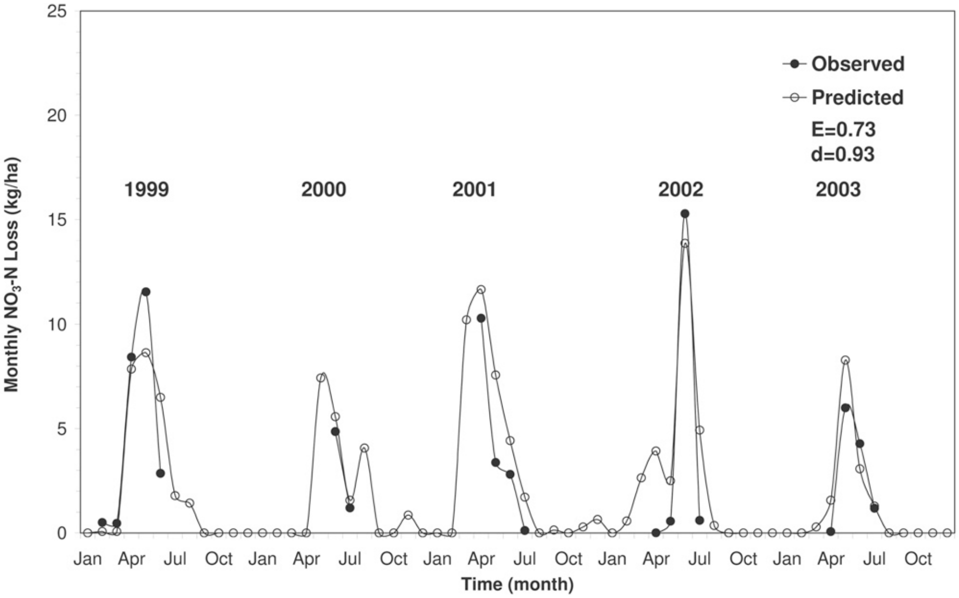

Fig. 8. Comparison between predicted and observed monthly nitrate losses during validation on the east field.

and there is no soybean crop or N fixation. In contrast, the present study is for a corn–soybean rotation in which there is carryover of some N fixed by the soybean crop and N fertilizer is applied every other year. The Davis et al. (2000) study involved experiments at the plot scale (13 m × 15 m), whereas the present study is for measurements collected at the field scale (9–11 ha). The measured values of subsurface tile drain flow and nitrate losses on which the model results in the two studies are based may differ as a result of these scale issues. Finally, the subsurface tile drain flow and nitrate concentration measurements in the two studies were collected using two different methods. In the Davis et al. (2000) study, measurements of nitrate were analyzed from grab samples collected weekly, while flow was measured daily. In the present study, measurements of nitrate were collected using both grab samples and automated samplers during storm events, while flow was measured at 15 min intervals. Thus, the experimental data in the present study includes water quality information during peak flows, whereas the Davis et al. (2000) study does not. For all the reasons mentioned above, results from the present modeling study are an improvement on the results from Davis et al. (2000).

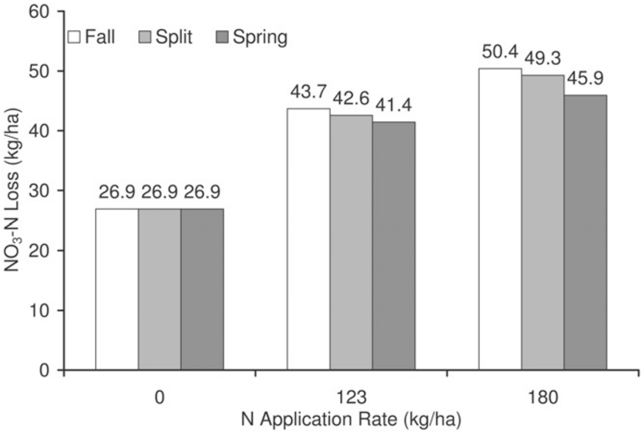

Fig. 9. Comparison of predicted annual nitrate losses for changes in nitrogen application rate and timing.

Conclusions

The ADAPT model was calibrated and validated for monthly subsurface tile drainage and associated nitrate losses on two commercial fields with a corn–soybean rotation under conservation tillage for the period 1999–2003. The predicted monthly subsurface tile drain flows and nitrate losses agreed reasonably well with the measured trends for both calibration and validation periods. Validation results on the east field gave better statistics than validation results on the west field. Comparison of water and nitrogen budgets against measured data and the literature showed that the model accurately partitions water and nitrogen.

The calibrated model was also used to evaluate the effects of changes in rate and timing of fertilizer application on nitrate losses. Simulation results indicated that reductions in nitrate losses are possible by reducing N fertilizer application rate. A 13% reduction in losses was found when fall N application rate was reduced from 180 kg/ha to 123 kg/ha. Further reductions in nitrate losses were obtained by changes in timing of N application. Changing the N application timing from fall to spring at an application rate of 180 kg/ha resulted in a 9% reduction in nitrate losses. Changes in timing and amount of N fertilizer applications may help reduce nitrate loads to the Gulf of Mexico. However, attaining a 30% or greater reduction in nitrate losses to the Gulf may require other alternative management practices such as changes in tile drain spacing and/or depth, planting cover crops in fall, restoration of wetlands, or conversion of cropland to pasture.

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