DRAINMOD-N II: EVALUATED FOR AN AGRICULTURAL SYSTEM IN IOWA AND COMPARED TO RZWQM-DSSAT

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ABSTRACT. *A new simulation model for N dynamics, DRAINMOD-N II, has been previously evaluated for only a few sites. We evaluated the model using ten years (1996-2005) of measured data from a subsurface-drained, corn-soybean agricultural system near Story City, Iowa. Nitrogen fertilizer was applied to plots at low, medium, and high rates (57 to 67 kg N ha*$^{-1}$*, 114 to 135 kg N ha*$^{-1}$*, and 172 to 202 kg N ha*$^{-1}$*, respectively) during corn years, and nitrate (*NO_3*) losses from subsurface drains under each plot were monitored biweekly for ten years. Average annual simulated and measured* NO_3 *losses in drainage water were 21.9 and 20.1 kg N ha*$^{-1}$ *for the low N rate, 26.6 and 26.5 kg N ha*$^{-1}$ *for the medium N rate, and 36.6 and 37.0 kg N ha*$^{-1}$ *for the high N rate, respectively. The model efficiency statistics for DRAINMOD-N II simulations of annual subsurface drain* NO_3 *losses were 0.89, 0.95, and 0.94 for the low, medium, and high N rates, respectively. For the same experimental dataset, a comparison of DRAINMOD-N II simulations to that of another model that simulates hydrologic and N dynamics of agricultural systems, the RZWQM-DSSAT hybrid model, demonstrated that the two models were most different in their simulations of soybean N fixation, plant N uptake, and net N mineralization. Future field investigations should focus on generating better understandings of these processes. The results suggest that DRAINMOD-N II can reasonably simulate the effects of different corn-year N rates on losses of* NO_3 *through subsurface drainage lines and that simulations of subsurface drainage* NO_3 *losses by DRAINMOD-N II are comparable to that of RZWQM-DSSAT.*

Keywords. *DSSAT, DRAINMOD, DRAINMOD-N II, Management, Nitrogen, RZWQM, Simulation, Subsurface drainage.*

Computer simulation modeling and agronomic experimentation are complementary endeavors in agricultural research (Bakhsh et al., 2001; Singh et al., 2006; Youssef et al., 2006; Thorp et al., 2007). Although experimentation can provide detailed datasets that describe the conditions, processes, and management outcomes of agricultural systems, the work is usually expensive, labor-intensive, and time-consuming. Adequate funding and labor over multiple growing seasons are required to capture enough relevant information to adequately characterize the agricultural system responses to environmental conditions and management practices. In contrast, computer simulation models can be rapidly applied to simulate the conditions, processes, and management outcomes of agricultural systems over many years. They are also useful for closing a system's mass balances for water, nitrogen (N), and carbon (C) and for understanding the movement of water and nutrients through pathways that are difficult to measure. However, all simulation models are developed with certain limiting assumptions and must therefore be adequately tested against measured data to ensure that the simulation results are reasonable. The ongoing effort to marry agronomic experimentation with computer simulation is an important objective in agricultural research, especially when either a new simulation model is developed or experimental data are collected at a new field site.

Loss of nitrate (NO_3) to surface water resources is currently one of the greatest challenges facing agricultural production in regions that rely on artificial subsurface drainage, particularly in the Midwestern U.S. (Burwell et al., 1976; Baker and Johnson, 1981; Cambardella et al., 1999; Jaynes et al., 2001). The December 2007 report from the U.S. EPA Science Advisory Board, Hypoxia Advisory Panel (EPA, 2007) called for a 45% reduction in NO_3 discharged to the Gulf of Mexico to effectively reduce the extent of the hypoxic zone, a problem that has been attributed to NO_3 transport down the Mississippi River from regions associated with Midwestern corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr) production (Burkart and James, 1999; Goolsby et al., 2001). Many alternative farm management strategies have been proposed to curtail the levels of NO_3 lost from subsurface-drained agricultural systems in the Midwest (Dinnes et al., 2002), one of which is more efficient use of N fertilizer application rates for corn crops. In an effort to understand this N management option, Jaynes et al. (2001) and Jaynes and Colvin (2006) reported ten years of experimental data on the effect of different corn-year N fertilizer treatments (~200 kg N ha^{-1}, ~135 kg N ha^{-1}, ~70 kg N ha^{-1}, and ~60:60 kg N ha^{-1} split) on NO_3 losses in subsurface drainage at a site near Story City, Iowa. The 10-year dataset includes

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observations of soil hydraulic and physical properties, daily meteorological conditions, hourly precipitation amounts, daily flow from subsurface drains, bi-weekly NO_3 loss from subsurface drains, annual N contents in harvested grain, annual soil N contents at harvest, and annual crop development and yield. This makes the dataset very valuable for computer simulation studies on the cycling of water and N under the treatments imposed on this agricultural system.

Previous efforts to model the hydrology and N dynamics at this central Iowa site have been reported in the literature. Bakhsh et al. (2001) used the Root Zone Water Quality Model (RZWQM) to simulate the effects of the three single-application N fertilizer treatments on corn yield and NO_3 loss in subsurface drainage for years 1996 through 1999. Thorp et al. (2007) reported the use of RZWQM coupled with the Decision Support System for Agrotechnology Transfer (DSSAT) family of crop growth models to simulate the effect of the three single-application N fertilizer treatments on corn yield and N dynamics for years 1996 through 2005, and this study also included the simulation results for N fertilizer treatments over a long-term weather record. Finally, Ma et al. (2008) updated the RZWQM-DSSAT hybrid model to include DSSAT version 4.0, altered the RZWQM soil microbe simulation, and used the model to simulate all four N fertilizer treatments at the Story City, Iowa, site. The study presented herein is the first to use information collected at the site for an evaluation of the DRAINMOD-N II model.

DRAINMOD-N II (Youssef et al., 2005) is a field-scale, process-based computer model that has been recently developed to simulate the C and N dynamics of agroecosystems in response to environmental conditions and management practices. The model is designed to utilize the simulation results from the DRAINMOD water management model (Skaggs, 1978, 1982) along with N management inputs to simulate the transport and transformation processes of C and N within an agricultural system. DRAINMOD-N II has been previously evaluated for a few sites (Youssef et al., 2006; Youssef and Skaggs, 2006; Bechtold et al., 2007; David et al., 2008; Salazar et al., 2009), but the model has not yet been evaluated for conditions in Iowa. Our objectives were: (1) to evaluate DRAINMOD-N II using the 10-year dataset from the experimental field under different corn-year N fertilizer treatments near Story City, Iowa, and (2) to compare the DRAINMOD-N II simulation results to that of the RZWQM-DSSAT hybrid model, previously evaluated using the same measured dataset (Thorp et al., 2007, Ma et al., 2008).

MATERIALS AND METHODS

HYDROLOGY MODEL

DRAINMOD (Skaggs, 1978, 1982) is a one-dimensional, field-scale computer model designed to simulate the effects of artificial surface and subsurface drainage systems on the hydrology of agricultural fields. Simulations are based on a water balance for a soil column of unit surface area centered between adjacent drains and extending from the soil surface to the depth of an impeding soil layer. A second water balance is simulated at the soil surface during rainfall events. A soil profile having up to five distinct horizons can be simulated, each with unique soil water retention and hydraulic conductivity relationships. Infiltration is computed using the Green and Ampt (1911) equation. Precipitation in excess of the infiltration rate is held as surface depressional storage, which generates surface runoff when it exceeds a maximum storage depth. Water flux to subsurface drains is computed using the Hooghoudt steady-state equation with a correction for convergence near the drains (Bouwer and Van Schlifgaarde, 1963). Lateral water movement is assumed to occur only within an elliptically shaped saturated zone between two parallel drainage lines. In the case of ponded surface conditions, where Houghoudt's relationship does not hold, DRAINMOD uses the Kirkham (1957) equation to compute water flux to the drains. Potential evapotranspiration (ET) is either computed using the Thornthwaite (1948) method or calculated separately by the user and read by the model as input data. Daily or monthly correction factors are used to improve Thornthwaite estimates of potential ET for local site conditions. Actual ET depends on the upward flux of water from the saturated zone and on the soil water contents to the depth of a user-specified, temporally variable root zone. If soil water conditions can satisfy the potential ET demand, actual ET is set equal to potential ET. Otherwise, actual ET is the amount that can be supplied given the current soil water conditions. Optionally, DRAINMOD may simulate vertical or lateral seepage using a simple Darcy's law approach. The model can also optionally simulate soil temperature processes and the effects of freezing and thawing on hydrology in cold climates (Luo et al., 2000, 2001)

Based only on soil water conditions, DRAINMOD simulates relative crop yield. The model accounts for yield loss resulting from excess soil water stress, deficit soil water stress, soil salinity, and planting delay caused by trafficability issues. A stress day index approach (Hiler, 1969) is used to simulate the cumulative effect of stresses on the crop throughout the growing season. Computation of the stress day index is based on a stress day factor (indicating the intensity and duration of the stress) and a crop susceptibility factor (indicating the degree to which a crop species is affected by a stress during each stage of development). The DRAINMOD implementation of the stress day index approach is described by Evans et al. (1991) and Evans and Skaggs (1993). The simulated value for the stress day index in a given season is used to compute relative yield, which is actual yield expressed as a percentage of potential yield.

Weather, soil, crop, and drainage system information is required to run DRAINMOD. The model reads hourly precipitation data from a file. Thornthwaite (1948) computations for potential ET require minimum and maximum daily temperature and geographic location. Utility software is available for properly formatting these weather input files. To simulate water movement in the soil profile, DRAINMOD requires the Green and Ampt (1911) infiltration parameters, the soil water retention and hydraulic conductivity parameters, the relationship between volume drained and water table depth, and the relationship between upward flux and water table depth. A utility program is available to define these relationships using the Millington and Quirk (1961) approach. Crop inputs vary based on crop species. Desired planting date, growing season length, parameters for yield loss caused by planting date delay, factors for crop susceptibility to water stress, and parameters relating yield response to stress day index must all be specified uniquely for each crop. Important drainage system design parameters include drain spacing and depth, effective drain radius, depth to the impeding layer, and weir settings for water table management. Additional inputs are also required to characterize deep and lateral seepage and surface storage.

Over the past 30 years, DRAINMOD has been evaluated for many drainage sites around the U.S. (Skaggs et al., 1981; Skaggs, 1982; Chang et al., 1983; Fouss et al., 1987; McMahon et al., 1988; Workman and Skaggs, 1989; Sands et al., 2003; Wang et al., 2006). Of particular interest for our study, Sanoja et al. (1990) and Singh et al. (2006) reported evaluations of DRAINMOD for conditions in Iowa.

NITROGEN MODEL

DRAINMOD-N (Brevé et al., 1997a, 1997b) was the original N model linked with DRAINMOD for simulating N dynamics within artificially drained agricultural systems. This N model had several limitations, including no simulated pool for the ammonium (NH_4) form of N, no simulation of temporal changes in the organic N pool, and consideration of N movement between organic and inorganic pools as merely a one-way net mineralization process involving only NO_3. To overcome these limitations, Youssef et al. (2005) developed a new N model, named DRAINMOD-N II, for simulating N fate and transport using the results of the DRAINMOD hydrology simulation.

DRAINMOD-N II is a one-dimensional, field-scale model that simulates N dynamics using three soil N pools, including NO_3, NH_4, and organic N. If the optional NH_4 pool is ignored, the model simulates mineral N similar to the Brevé et al. (1997a) version. In its higher complexity modes, the model simulates N inputs to the soil system from atmospheric deposition, N fixation by legumes, application of inorganic N fertilizers including urea and anhydrous ammonia, and application of organic N sources including manure and plant residues. Simulated N processes within the soil system include mineralization, immobilization, nitrification, fertilizer dissolution, and urea hydrolysis. Nitrogen movement out of the soil system is simulated through the pathways of plant N uptake, denitrification, ammonia volatilization, surface runoff, subsurface drainage, and deep seepage. Nitrogen transport through the soil profile is simulated using a multiphase form of the one-dimensional advection-dispersion-reaction equation (Hillel, 1982), which is solved numerically using a first-order, finite difference approximation. Since N dynamics in the soil system depend heavily on C dynamics, a submodel for simulating C cycling, similar to that of the CENTURY model (Parton et al., 1987, 1993), is incorporated into DRAINMOD-N II. The C submodel simulates C dynamics between three soil organic matter pools (active, slow, and passive), two above- and below-ground residue pools (metabolic and structural), and a surface microbial pool. Each pool is characterized by its organic C content, potential rate of decomposition, and C:N ratio. DRAINMOD-N II also simulates the impact of several environmental factors that affect N and C dynamics, including soil temperature, soil moisture, and soil pH. This is done by defining a dimensionless response function for each factor and using the response function to modify N process rates when environmental conditions are suboptimal.

STUDY SITE MANAGEMENT

The study area was a 22 ha section of a production crop field near Story City, Iowa (42.2° N, 93.6° W). The soil survey of Story County indicated that the Kossuth-Ottosen-Bode soil association was present at the site. Most of the land area had the Kossuth silty clay loam and Ottosen clay loam soil types (Brevik et al., 2003). Smaller areas of Harps loam and Okoboji silty clay loam were also present. The site was chosen for its uniformity of soils, nearly level terrain, and existing pattern subsurface drainage system (Jaynes et al., 2001). In 1992, subsurface drainage lines with a diameter of 10.2 cm were installed at a depth of 1.45 m. Twelve corrugated plastic drain pipes, each 500 m in length, were laid parallel to each other and were spaced either 27.4 or 36.5 m apart, although this study focused only on the hydrology of the 27.4 m spacing drains. On the east side of the study area, each pipe drained into the main collection lateral, which carried water to a nearby stream within the city limits of Story City. In 1996, each of the 12 drainage lines was intersected immediately prior to the main lateral with a vertical sump made of 0.6 m diameter corrugated plastic culvert. Each sump was equipped with devices for measuring water flow continuously and collecting water samples for analysis of NO_3 content in drainage water.

The original objective for research at the site was to assess the effect of variable N fertilizer application rates on losses of NO_3 though the subsurface drainage system (Jaynes et al., 2001). Starting in 1996, the field was planted using a two-year corn-soybean rotation with corn planted in even years and soybean planted in odd years (table 1). Prior to this time, the field was also managed using a corn-soybean rotation, except for a stint of continuous corn from 1994 through 1996. The study area was divided into twelve plots, each uniquely drained by one of the twelve laterals of the subsurface drainage system. During corn years, three N fertilizer application rates were replicated three times over nine of the twelve plots. The remaining three plots received split N applications, which were not simulated in this study. In 1996, anhydrous ammonia was injected one week before corn planting at rates of 202, 135, and 67 kg N ha^{-1} for the high, medium, and low N treatments, respectively. In 1998, 32% liquid urea ammonium nitrate (UAN) was applied three weeks after planting at rates of 172, 114, and 57 kg N ha^{-1} for the high, medium, and low N treatments, respectively. In the remaining corn years (2000, 2002, and 2004), 28% liquid UAN was applied after planting with application rates of 199, 138, and 69 kg N ha^{-1} for the high, medium, and low N treatments, respectively. In years 1996 and 2001, approximately 8 kg N ha^{-1} was added to all treatment plots as NPK fertilizer. Except for the NPK application in 2001, no fertilizer was applied during any other soybean years. Over the course of the 10-year study period, tillage transitioned from intensive conventional tillage to more conservative tillage practices. A moldboard plow was used after harvest in 1996 and 1997, and a chisel plow was used after harvest in 1998 and 1999. From 2000 to 2005, a chisel plow was used after soybean harvest and no tillage was performed after corn harvest. A field cultivator was used to prepare the seed bed for planting in all corn years and for soybean in 1997 and 1999 only. A row-crop cultivator was also used for weed control in all corn years. A field-plot combine modified to automatically collect grain weight and moisture information (Colvin, 1990) was used to harvest the crop and collect yield information for each plot. Except for N fertilizer applications and harvest, all management decisions were made by the operator of the farm.

Table 1. Management practices at the study site from 1996 to 2005.[a]

					Nitrogen Fertilizer Application									
		Spring Tillage		Planting			Rate (kg N ha^{-1})			Summer Tillage		Harvest	Fall Tillage	
Year	Crop	Type	DOY	DOY	Method[b]	DOY	H	M	L	Type	DOY	DOY	Type	DOY
1996	Corn	FC	114	115	AA and NPK	109 and 114[c]	210	143	75	RCC	164	307	MP	315
1997	Soybean	FC	113	125[d]	--	--	--	--	--	--	--	274	MP	283[d]
1998	Corn	FC	115	116	32% UAN	134	172	114	57	RCC	166[d]	264	CP	273
1999	Soybean	FC	112	125[d]	--	--	--	--	--	--	--	264	CP	290
2000	Corn	FC	115[d]	116	28% UAN	131	199	138	69	RCC	161	265	--	--
2001	Soybean	--	--	125[d]	NPK	298[d]	8	8	8	--	--	289	CP	298[d]
2002	Corn	FC	109[d]	110	28% UAN	141	199	138	69	RCC	160[d]	287	--	--
2003	Soybean	--	--	125[d]	--	--	--	--	--	--	--	281	CP	290[d]
2004	Corn	FC	109[d]	110	28% UAN	154	199	138	69	RCC	160[d]	283	--	--
2005	Soybean	--	--	125[d]	--	--	--	--	--	--	--	265	CP	274[d]

[a] DOY = day of year; H = high rate; M = medium rate; L = low rate; N = nitrogen; FC = field cultivator; AA = anhydrous ammonia; NPK = nitrogen, phosphorus, potassium; RCC = row crop cultivator; MP = moldboard plow; UAN = urea ammonium nitrate; CP = chisel plow.

[b] Fertilizer was injected into the soil.

[c] AA was applied on DOY 109 at rates of 202 (H), 135 (M), and 67 (L) kg N ha^{-1}, and NPK was applied to all plots at 8 kg N ha^{-1} on DOY 114.

[d] Estimated date.

DATA COLLECTION

Ten years of measured information were available for use in this study. From 1996 to 2005, select measurements were collected to characterize the dynamics of the hydrologic and nitrogen cycles at the site. Jaynes et al. (2001) and Jaynes and Colvin (2006) described the equipment and procedures used to automatically measure flow from drainage sumps and to compute the depth of water drained from each plot on a daily basis. Hourly rainfall was measured from 1996 to 2005 with a tipping-bucket rain gauge less than 0.5 km from the site. Missing data and precipitation data for temperatures below 0°C were obtained from a National Climatic Data Center (NCDC) weighing rain gauge 2 km away. Evapotranspiration was not measured at the site. However, ET measurements within the Walnut Creek watershed, 30 km south of our study site (Hatfield and Prueger, 2004), were obtained and used as an estimate of ET. Runoff and seepage measurements were also not available; however, visual observations of runoff at the site were infrequent. To characterize the N balance at the site, water samples were automatically collected from drainage sumps and were returned to the laboratory on approximately a biweekly basis for analysis of NO_3 content in drainage effluent (Jaynes et al., 2001). After harvest each year, grain samples were analyzed for N content, and soil residual N concentrations were measured from soil cores collected to a depth of 120 cm within each N fertilizer treatment plot. Due to difficulty in measurement, many other components of the N cycle at the site, including N fixation by soybean, N mineralization from organic matter, volatilization, denitrification, and N in runoff and seepage, were largely unknown. Grain yield was measured in each plot using the procedure outlined by Jaynes et al. (2001).

In addition to the tipping-bucket rain gauge, a weather station was positioned less than 0.5 km from the site. From 1996 to 2005, the meteorological information necessary for Thornthwaite (1948) estimates of potential ET, including maximum and minimum daily temperature, and other weather data were collected from this station. Five years of weather information from 1991 to 1995 were used for model initialization. Daily maximum and minimum temperature information for 1991 to 1995 was obtained from the Iowa State University AgClimate station at Ames, Iowa, 25 km southwest of our study site. Hourly precipitation measurements for 1991 to 1995 were obtained from a NCDC weighing rain gauge 2 km away from the site.

Efforts to characterize the soil properties at the site were carried out during the earlier years of site monitoring. Bakhsh et al. (2000) described an investigation into the relationship between soil attributes and spatial variability in yield at the site. Soil properties of bulk density, field capacity at 33 kPa, and sand, silt, and clay percentages were measured to a depth of 1.2 m at 42 sampling sites across the 22 ha field. Soil organic carbon (SOC) was measured to a depth of 60 cm with values of approximately 2.5%, demonstrating that levels of SOC were greater in comparison to many soils in the Midwest (Jaynes et al., 2001). Measurements of SOC were used to establish initial conditions for the soil organic matter pools in DRAINMOD-N II.

MODEL PARAMETERIZATION

Both the hydrology and nitrogen simulations were performed using the new DRAINMOD 6.0 graphic user interface. The interface can be used to enter and edit all the model input parameters, to execute both DRAINMOD and DRAINMOD-N II, and to view the output files. The interface also gives access to the utility programs for creating the soil and weather input files.

Hydrology

Drainage system design parameters were set according to the physical dimensions of the drainage system at the site (table 2). The drainage coefficient was set to 1.4 cm d^{-1}, which was the maximum measured daily flow rate from the drains over the 10-year period. The maximum depth of surface depressional storage was a calibrated parameter with the caveat that Kirkham's depth for direct flow to drains during ponded conditions was set to half of the maximum surface storage depth. To simulate deep seepage, the aquifer head and restricting layer thickness were both set to 200 cm, and the restricting layer conductivity was calibrated to improve water balance simulations.

In our previous work with RZWQM-DSSAT (Thorp et al., 2007), we simulated a ten-layer soil profile for this site, but DRAINMOD accepts only a five-layer soil profile. In addition, RZWQM-DSSAT soil water retention and conductivity

Table 2. Drainage system design parameters.

Input Parameter	Value
Drain depth (cm)	145
Drain spacing (cm)	2740
Effective drain radius (cm)	1.1
Depth to impeding layer (cm)	299
Drainage coefficient (cm d^{-1})	1.4
Maximum surface storage[a] (cm)	0.50
Kirkham's depth (cm)	0.25
Piezometric aquifer head (cm)	200
Restricting layer thickness (cm)	200
Restricting layer conductivity[a] (cm h^{-1})	0.0006

[a] Calibrated parameter.

Table 4. Soil temperature parameters.

Input Parameter	Value
Soil thermal conductivity function coefficient A (W m^{-1} °C)	0.39
Soil thermal conductivity function coefficient B (W m^{-1} °C)	1.33
Rain/snow temperature (°C)	0.00
Snowmelt base temperature[a] (°C)	1.00
Snowmelt coefficient (mm d^{-1} $°C^{-1}$)	5.00
Critical ice content to stop infiltration (cm^3 cm^{-3})	0.20
Air temperature phase lag (h)	8.00
Temperature at profile bottom (°C)	9.11

[a] Calibrated parameter.

Table 3. Parameterization of the soil profile.[a]

Layer	Depth (cm)	Clay (%)	Silt (%)	Initial pH	DC (cm^3 g^{-1})	BD (Mg m^{-3})	Soil Water Retention[b] θ_s	θ_{wp}	θ_r	α	n	Lateral K_{SAT} (cm h^{-1})	SOC (%)
1	0-15	45	33	6.7	2.6	1.60	0.56	0.30	0.04	0.0535	1.105	3.5	2.69
2	15-60	46	33	6.7	2.6	1.65	0.54	0.29	0.04	0.0535	1.105	3.5	2.38
3	60-120	24	29	6.7	2.6	1.90	0.44	0.24	0.04	0.0535	1.105	3.5	1.26
4	120-150	25	40	6.7	2.6	1.90	0.34	0.19	0.04	0.0535	1.105	3.5	ND
5	150-299	25	40	6.7	2.6	1.90	0.32	0.18	0.04	0.0535	1.105	3.5	ND

[a] DC = distribution coefficient; BD = bulk density; θ_s = saturated soil water content; θ_{wp} = wilting point soil water content; θ_r = residual soil water content; K_{SAT} = saturated hydraulic conductivity; SOC = soil organic carbon; ND = no data.

[b] Units are cm^3 cm^{-3} for θ_s, θ_{wp}, and θ_r; α is cm^{-1}.

inputs are based on a modified Brooks and Corey (1964) approach, while the DRAINMOD soil file preparation program utilizes Millington and Quirk (1961) methods to determine these model input parameters. Therefore, the number of soil layers was reduced from that used for RZWQM-DSSAT by combing the soil layers with the most similar properties. In addition, we used the Solver tool in Microsoft Excel to identify the Millington and Quirk (1961) parameters for soil water retention and unsaturated hydraulic conductivity curves that minimized error with respect to the Brooks and Corey (1964) soil curves used in the previous RZWQM-DSSAT study. Porosity was calculated from bulk density measurements (Bakhsh et al., 2000) using a particle density of 2.65 g cm^{-3} in each layer, and saturated soil water content was assumed equal to porosity. Residual soil water content was set to 0.04 cm cm^{-3} in all layers, which is the Rawls et al. (1982) mean value for silty clay loam soils. These parameters were then used within the DRAINMOD soil file utility to compute the soil water retention and conductivity relationships for simulating a five-layer soil profile to a depth of 299 cm at our site (table 3). No further adjustment was performed on the relationships for volume drained and upward flux versus water table depth, as outputted by the soil file utility, since these water retention characteristics were based on that from the previous calibration of RZWQM-DSSAT at the site. Saturated hydraulic conductivity (K_{SAT}) was set equal 1.75 cm h^{-1}, which was half of the Bakhsh et al. (2000) measured value, as recommended in the DRAINMOD manual (Workman et al., 1994). Lateral saturated hydraulic conductivity was set to a value of 3.5 cm h^{-1} throughout the entire profile (table 3), twice the amount of the vertical saturated hydraulic conductivity. Default values for the Green and Ampt (1911) infiltration parameters, as outputted by the DRAINMOD soil file utility, were used to simulate infiltration of water into the soil profile. Most of the soil temperature parameters were set using the same values as Singh et al. (2006), who recently used DRAINMOD for a site in Iowa (table 4). One exception was the parameter for average air temperature above which snow starts to melt, which was adjusted slightly to improve simulations of subsurface drainage in the winter months. The soil temperature at the bottom of the profile was set using the long-term average value of daily maximum and minimum temperature measurements at the site.

Thornthwaite (1948) estimates of potential ET were altered by adjusting the monthly correction factors within a reasonable range to improve monthly simulations of subsurface drainage for our site (table 5). Previous DRAINMOD studies by Wang et al. (2006) in Indiana, Northcott et al. (2001) in Illinois, Singh et al. (2006) in Iowa, and Sands et al. (2003) in Minnesota were used to understand the range of correction factors that was reasonable for Midwestern climates. A heat index of 51 was used based on information given for Des Moines, Iowa, in the DRAINMOD manual (Workman et al., 1994), and the latitude for the site is 42° 12′.

To parameterize the crop component of the model, the desired planting date for each of the ten growing seasons was

Table 5. Monthly ET correction factors.[a]

Month	Value
January	2.2
February	1.8
March	1.4
April	1.1
May	0.8
June	0.7
July	1.0
August	1.2
September	1.6
October	1.8
November	2.3
December	2.5

[a] Calibrated parameters.

set to the actual planting date (table 1), and the trafficability parameters were set very loosely to ensure that the model would simulate no planting delay due to adverse soil moisture conditions. The remaining crop parameters for length of growing season, effective rooting depth, excess water stress, and deficit water stress were set in a unique way. In many previous studies, researchers have set these values identically for seasons where the same crop type is grown (Wang et al., 2006; Singh et al., 2006), because DRAINMOD does not simulate year-to-year variability in crop phenological development. However, we had information on crop phenology from previous simulations using the RZWQM-DSSAT hybrid model (Thorp et al., 2007). Therefore, we used the tables of crop susceptibility factors for various corn and soybean growth stages (Evans and Skaggs, 1993; Workman et al., 1994) to create unique temporal crop stress susceptibility schedules for each of the ten growing seasons based on the crop phenology information previously simulated by RZWQM-DSSAT. A similar approach was used to specify the schedule for effective rooting depth in each growing season. For corn, the effective rooting depth was scheduled to increase to 10 cm two weeks after planting and then to increase by 10 cm every two weeks thereafter up to a maximum depth of 40 cm. The effective rooting depth was also decreased by 10 cm every two weeks in the late season, such that it reached a value of 10 cm on the RZWQM-DSSAT simulated crop maturity date. For soybean, the effective rooting depth was scheduled to increase to 5 cm two weeks after planting and then to increase by 5 cm every two weeks thereafter up to a maximum depth of 35 cm. Then on the harvest date for each corn and soybean crop, the effective rooting depth was set to 3 cm, and it remained there for the duration of the winter. Parameters for computing yield reduction percentages from excess and deficit water stress were obtained from the DRAINMOD manual (Workman et al., 1994), and the limiting water table depth for soil excess water (SEW) calculations was set to 35 cm for corn and 30 cm for soybean.

Nitrogen

Management inputs for tillage and fertilizer in DRAINMOD-N II were set according to actual practices at the site over the 10-year study (table 1). Tillage intensity factors for moldboard plow, chisel plow, and field cultivator operations were assumed to be 0.95, 0.6, and 0.25, respectively. Tillage depths were assumed to be 20 cm for moldboard and chisel plow operations and 10 cm for field cultivator operations. The model was set to recycle plant roots and shoots back into the soil after harvest. Potential yields for corn were adjusted to 12000, 11500, and 9000 kg ha^{-1} for the high, medium, and low N rate treatments, respectively. For soybean, a potential yield of 3500 kg ha^{-1} was used for all three corn-year N rate treatments (table 6). Grain N compositions were set to the average of actual measurements at the site: 1.2% for corn and 5.9% for soybean. Other crop biochemical parameters and the N uptake function for corn and soybean were set using the values reported by Youssef et al. (2006) (table 6). The root depth coefficients, which scale the N uptake depth based on the crop rooting depth specified in DRAINMOD, were set to 1.0 for both corn and soybean crops.

Soil properties required by DRAINMOD-N II were obtained from the measurements of Bakhsh et al. (2000), and the distribution coefficient to relate N species concentrations in the solid and aqueous phases (Youssef et al., 2005; 2006)

Table 6. Yield and biochemical composition inputs for corn and soybean.

Input Parameter	Corn	Soybean
High N potential yield[a] (kg ha^{-1})	12000.00	3500.00
Medium N potential yield[a] (kg ha^{-1})	11500.00	3500.00
Low N potential yield[a] (kg ha^{-1})	9000.00	3500.00
Harvest index	0.52	0.40
Root/shoot ratio	0.12	0.10
Grain nitrogen (%)	1.20	5.90
Shoot nitrogen (%)	0.55	2.20
Root nitrogen (%)	0.55	2.20
Shoot carbon (%)	44.00	44.00
Root carbon (%)	44.00	44.00
Shoot lignin (%)	3.50	9.10
Root lignin (%)	8.30	24.70

[a] Calibrated parameter.

Table 7. General DRAINMOD-N II input parameters.

Input Parameter	Value
Longitudinal dispersivity[a] (cm)	25
Tortuosity	0.5
Maximum allowable error	10^{-4}
Minimum time step (d)	10^{-3}
Rain NO_3-N concentration (mg L^{-1})	0.5
Rain NH_4-N concentration (mg L^{-1})	0.5
Air NH_3-N concentration (mg L^{-1})	0.0
Fertilizer dissolution	
Fertilizer dissolution rate (d^{-1})	2.0
Threshold soil water content (cm^3 cm^{-3})	0.36
Ammonia volatilization	
Threshold soil pH	7.5
Maximum soil buffering capacity (pH (kmol OH$^-$)$^{-1}$ (kg soil)$^{-1}$)	10^5
Volatilization resistance factor (s cm^{-1})	50.0

[a] Calibrated parameter.

Table 8. Rate and environmental response parameters for soil N processes.[a]

Input Parameter	UH	NIT	DEN	OCD
Michaelis-Menten parameters				
V_{max} (μg N (g soil)$^{-1}$ d^{-1})	120.0	14.0	0.7[b]	--
K_m[c]	50.0	10.0	40.0	--
Temperature response function				
Shape factor	0.119	0.413	0.186	0.186
Optimum temperature (°C)	51.6	25.0	30.0[b]	30.0[b]
Soil water response function				
Relative rate at wilting point	0.65	0.0	--	0.15
Relative rate at saturation	0.87	0.0	--	0.50
Lower optimum WFPS[c]	0.5	0.5	--	0.50
Upper optimum WFPS	0.7	0.6	--	0.60
Empirical exponent	1.0	1.0	2.0	1.0
Threshold WFPS range	--	--	0.8	--
pH response function				
Minimum pH	4.0	3.5	--	--
Relative rate at min pH	0.2	0.0	--	--
Maximum pH	10.0	10.0	--	--
Relative rate at max pH	0.5	0.0	--	--
Lower optimum pH	7.0	6.7	--	--
Upper optimum pH	8.0	7.2	--	--
Empirical exponent	1.0	1.0	--	--

[a] UH= urea hydrolysis, NIT = nitrification, DEN = denitrification, OCD = organic carbon decomposition, WFPS = water-filled pore space.

[b] Calibrated parameter.

[c] Units are mg urea L^{-1} for urea hydrolysis, μg NH_4 g^{-1} for nitrification, and mg NO_3 L^{-1} for denitrification.

Table 9. Potential decomposition rate (K_{dec}) and maximum, minimum, and initial C:N ratios for each organic matter pool.[a]

Input Parameter	K_{dec} (d^{-1})	C:N Ratio Min.	C:N Ratio Max.	C:N Ratio Initial
AOM pools				
Surface microbial	1.64384E-2	8	20	10
Surface structural[b]	1.06849E-2			
Surface metabolic	4.05479E-2			
Soil structural[b]	1.34247E-2			
Soil metabolic	5.06849E-2			
SOM pools				
Active	2.00000E-2	3	15	8
Slow	5.47945E-4	12	20	16
Passive	1.23288E-5	7	10	10

[a] AOM = added organic matter, SOM = soil organic matter.

[b] Fixed C:N ratio of 150.

was set to 2.6 $cm^3 g^{-1}$ in all soil layers (table 3). The model was set to simulate N transport through the soil profile over a 5 cm uniform grid to a depth of 299 cm. With only a few exceptions, the DRAINMOD-N II transport and transformation parameters (tables 7 and 8) were set identically to those used by Youssef et al. (2006). Differences include the longitudinal dispersivity parameter, which was adjusted to improve simulations of NO_3 losses in tile drainage. In addition, the Michaelis-Menten maximum reaction rate and the optimum soil temperature for denitrification were adjusted to achieve more reasonable simulations of N loss through this pathway. Soil pH was considered to have no effect on denitrification. Parameters for fertilizer dissolution, pH control, and volatilization were set to default values (table 7), as specified by Youssef et al. (2006).

Potential decomposition rates and C:N ratios for the soil organic matter pools and added organic matter pools were set to default values (table 9), which are taken from Parton et al. (1993). Additionally, for the surface microbial pool, the maximum N content of the added organic matter at the minimum C:N ratio was set to 2%. The maximum N content at which organic materials enter the soil organic matter pools at the minimum C:N ratio was adjusted from the default value to improve simulations of NO_3 loss in subsurface drainage. With the exception of the optimum temperature for organic carbon decomposition, all environmental response parameters for organic carbon reactions were set to default values (table 8).

MODEL INITIALIZATION

The model was initialized by simulating five growing seasons prior to 1996. This procedure effectively reduced the dependency of the 1996 to 2005 model output on initial conditions. A corn-soybean rotation was simulated during this initialization period, with the exception that corn was substituted for soybean in 1995 in accordance with the grower's known practices. Crop growth parameters for these initialization years were specified in a similar manner as described above, using phenological data from previous RZWQM-DSSAT simulations to create the temporal schedules for water excess and deficit stress factors and for crop rooting depths. Field cultivator and moldboard plow tillage events were scheduled before planting and after harvest, respectively, in each initialization year. During the 1992 and 1994 corn years, a 202 kg N ha^{-1} fertilizer application was simulated one week before planting. The 1995 corn year was the first year in which N fertilizer treatments were administered at the site, although we do not have subsurface drain NO_3 measurements until the sumps were operational in 1996. Thus, we simulated the N rate treatments in the 1995 initialization year in accordance with known practices at the site.

The first day of the simulation initialization period was 1 January 1991. On this day, 7,500 kg ha^{-1} of organic material, representing the previous year's remaining corn residue, was added to the soil, 5% of which was added to the surface and 95% of which was incorporated at a depth of 20 cm. The material was specified with an organic carbon content of 44%, a lignin content of 3.5%, and a C:N ratio of 80. Initial conditions for SOC were specified based on measurements in the top 20 cm of the soil profile (table 3), since the default decomposition rates (table 9) from Parton et al. (1993) are based on a 20 cm soil depth. The percentages of initial SOC allocated to the active, slow, and passive soil organic matter pools were adjusted by reinitializing the model with the percent contents of each soil organic matter pool on the final day of the simulation. This procedure was carried out several times until all the pools were stable over the entire simulation period. Initial SOC was allocated as 1.8% to the active pool, 34.0% to the slow pool, and 64.2% to the passive pool. Default values were used to specify the initial C:N ratio of organic material in each soil organic matter pool (table 9). A similar reinitialization procedure was used to specify the initial soil NO_3 and NH_4 contents to a depth of 299 cm, although the model was fairly insensitive to initial NO_3 and NH_4 contents after the first few years of the initialization.

MODEL CALIBRATION AND EVALUATION

To calibrate and evaluate the model, the measured dataset was partitioned into two units in the same way as the previous study with RZWQM-DSSAT (Thorp et al., 2007). Data from growing seasons 1996, 1997, 2000, and 2001 were used for model calibration. These growing seasons covered two sets of corn-soybean rotations at the site. In addition, they covered the producer's transition from heavy to more conservative tillage practices after the 1999 growing season (table 1). Using annual precipitation to estimate the range of weather conditions, years 1996 and 2000 represented the extreme cases over the 10-year period with 101.7 cm of precipitation in 1996 and 55.4 cm of precipitation in 2000. Thus, the calibration dataset adequately represented the range of management and weather at the site over the 10-year study period. Datasets from the remaining growing seasons were used to evaluate the performance of the calibrated model. Similar to Bakhsh et al. (2001), the criteria used to calibrate and evaluate the model were both objective and subjective in nature. Graphical comparison of measured and simulated data was useful for locating anomalies in the simulated data and to check the overall performance of the model over the entire 10-year simulation period. Measured and simulated data were also compared quantitatively by computing various common statistics, such as the percent error, relative root mean squared error (RRMSE), and model efficiency (EF) for daily, monthly, and annual data aggregations, although most of the following discussion focuses on the annual results. Percent error and RRMSE measure the overall departure of simulated values from measured values, while EF measures the deviation of simulated and measured values in relation to the scattering of the measured data. The equations for these statistical computations were obtained from Bakhsh et al. (2004).

To calibrate the hydrology component, several parameters were adjusted to reduce error between measured and simulated flow from the subsurface drainage system. Measured subsurface drainage flow was computed as the average daily discharge from all nine drainage lines at the 27.4 m drain spacing, and this averaged time series was used for comparison of measured and simulated subsurface drain flow. Model calibration efforts focused mainly on adjustment of the restricting layer conductivity and the Thornthwaite (1948) potential ET correction factors. The restricting layer conductivity was adjusted to 0.0006 cm h^{-1} (table 2) to improve annual simulations of subsurface drain flow. Adjusting the correction factors for Thornthwaite (1948) estimates of potential ET (table 5) allowed for further improvement in the simulation of monthly subsurface drain flow. After adjusting these parameters, the maximum surface storage depth was adjusted to 0.5 cm (table 2) and the snowmelt base temperature was adjusted to 1°C (table 4) to fine tune the model performance for periods of heavy rainfall and for occurrences of wintertime drainage, respectively.

To calibrate the nutrient component, measured concentrations and loads of NO_3 in subsurface drainage water were averaged across the three replications for each of the three single-application corn-year N treatments. Daily flow data were used to compute daily NO_3 load based on the most recent tile NO_3 concentration measurement. Monthly and annual NO_3 loads were determined by appropriately summing the daily NO_3 loads. Model calibration focused mainly on parameter adjustments for the longitudinal dispersivity, the denitrification reaction, and SOC transformations to improve error metrics between measured and simulated subsurface drain NO_3 mass losses for the high N rate treatment. Transport of solutes through the DRAINMOD-N II soil profile can be made more advective or dispersive by adjusting the longitudinal dispersivity parameter, which can vary between 5 and 30 cm depending on the soil texture and the distance between the soil surface and impermeable layer (Youssef et al., 2006). We adjusted this parameter to 25 cm to improve simulations of NO_3 loss in subsurface drainage (table 7). The denitrification parameters used by Youssef et al. (2006) for conditions in North Carolina initially resulted in high simulated denitrification for our site in Iowa. Denitrifying organisms in colder regions would be expected to have a lower optimum soil temperature for denitrification than those in warmer regions. In addition, different soil textures at the Iowa site would alter the maximum denitrifying capacity of the soil. Therefore, the Michaelis-Menten reaction rate and the optimum soil temperature for denitrification were adjusted to 0.7 μg N (g soil)$^{-1}$ d^{-1} and 30°C to improve simulations of denitrification for our Iowa site (table 8). This reduced the denitrification rate to 15% of N inputs from fertilizer application and rainfall deposition for the high and medium N rate treatments. Follett et al. (1991) reported that denitrification rates for a moderately well drained soil with 2% to 5% soil organic matter should range from 6% to 20% of N inputs from fertilizer and rainfall. Further improvement in the simulations was achieved by adjusting two parameters that govern the SOC transformations. First, the maximum soil N content at which organic materials enter the soil organic matter pools at the minimum C:N ratio was adjusted from the default value of 10 μg N cm^{-3} soil to a calibrated value of 45 μg N cm^{-3} soil. Essentially, this adjustment increased net mineralization in corn years while decreasing net mineralization in soybean years, which resulted in an increase in soybean N fixation as an input to the system and closer agreement between measured and simulated subsurface drainage NO_3 discharge. The optimum soil temperature for soil organic matter transformations was also adjusted to 30°C, identical to the optimum soil temperature for denitrification, to account for cooler soil conditions in Iowa, as compared to the previous model calibration in North Carolina (Youssef et al., 2006). After DRAINMOD-N II was calibrated and evaluated using data from the high N rate treatment, the model was subsequently evaluated for the medium and low N rate treatments using all ten years of data. Nitrogen rates and potential corn yield were the only parameters adjusted to simulate the reduced N rate treatments.

Comparison To RZWQM-DSSAT

After calibrating and evaluating DRAINMOD-N II, simulation results were compared with that of the RZWQM-DSSAT model for the same experimental dataset, as reported by Thorp et al. (2007) and Ma et al. (2008). A comparison of the DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT models is summarized in table 10. With regard to the model design, DRAINMOD and DRAINMOD-N II simulate hydrology and nutrient dynamics separately, whereas RZWQM-DSSAT integrates hydrology, nutrient, and crop growth simulations on a daily time step. As a result, RZWQM-DSSAT allows for feedback between hydrology and nutrient simulations. With regard to their hydrology components, the two models differ in their simulation methods for ET, soil water redistribution, and storage of water on the soil surface. RZWQM-DSSAT does not simulate surface water storage, whereas DRAINMOD does. To simulate ET, DRAINMOD uses the Thornthwaite (1948) method to compute potential ET, or the user can optionally provide potential ET as an input to the model. RZWQM-DSSAT uses the Shuttleworth-Wallace double-layer form of the original Penman-Monteith ET model (Farahani and DeCoursey, 2000). DRAINMOD simulates soil water contents in two zones: saturated and unsaturated. To avoid complex numerical methods for computing soil water movement, the model assumes that unsaturated soil layers are drained to equilibrium, and a dry zone may form within the user-specified root zone if potential ET cannot be satisfied by upward flux from the water table. RZWQM-DSSAT implements a numerical solution of the Richards equation to compute soil water redistribution. Both models utilize the Hooghoudt steady-state equation to compute water flux to the subsurface drains, and DRAINMOD reverts to the Kirkham (1957) equation under ponded surface water conditions. Both models use a Darcy approach to compute seepage and Green and Ampt (1911) methods to compute infiltration. With regard to organic matter simulation, DRAINMOD-N II computes C:N dynamics using approaches based on the CENTURY model by Parton et al. (1987, 1993), whereas RZWQM-DSSAT uses the organic matter and nitrogen (OMNI) module developed by Shaffer et al. (2000). The C:N modules of both models simulate soil organic matter in three pools; however, the implementation with regard to the microbial and residue pools for each model is somewhat different. DRAINMOD-N II simulates one microbial pool that acts only on the surface residue, whereas RZWQM-DSSAT simulates three microbial pools that act

Table 10. Comparison of DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT.[a]

	DRAINMOD/ DRAINMOD-N II	RZWQM-DSSAT
Model design	Separated	Integrated
Surface storage	Yes	No
Infiltration	Green and Ampt	Green and Ampt
ET	Thornthwaite	Shuttleworth-Wallace
Soil water	Drained to equilibrium	Richards equation
Tile drainage	Hooghoudt/Kirkham	Hooghoudt
Seepage	Darcy equation	Darcy equation
C:N dynamics	Modified CENTURY	OMNI
Solute transport	ADR equation	Partial piston disp.
Tillage	Yes	Yes
Crop	Empirical yield model	DSSAT crop models

[a] ET = evapotranspiration; ADR = advection-dispersion-reaction.

within the layers of the soil profile. In addition, DRAINMOD-N II simulates two aboveground and two belowground residue pools, all of which interact in the nutrient cycling algorithm. RZWQM-DSSAT simulates two belowground residue pools; surface residue is quantified and incorporated but is not considered part of the nutrient cycling algorithm. With DRAINMOD-N II, solute transport through the soil profile is achieved with the advection-dispersion-reaction equation, whereas RZWQM-DSSAT uses a sequential partial piston displacement and mixing approach. Finally, whereas an empirical approach is used in DRAINMOD to compute relative yield based on soil water conditions, RZWQM-DSSAT implements the DSSAT family of crop growth models (Jones et al., 2003) for physiologically based crop growth, development, and yield simulations.

RZWQM-DSSAT Simulations

Ongoing developments with the RZWQM-DSSAT model, particularly the update from DSSAT3.5 to DSSAT4.0, warranted some further calibration of RZWQM-DSSAT beyond that reported by Thorp et al. (2007). In addition, Ma et al. (2008) demonstrated the sensitivity of RZWQM-DSSAT to the microbial growth and decay parameters, which were set to default values in the original calibration by Thorp et al. (2007). Thus, the RZWQM-DSSAT results reported in this work represent an updated model calibration that focused mainly on adjustment of the microbial parameters to calibrate the RZWQM nutrient component and readjustment of the DSSAT cultivar coefficients to improve simulations of crop growth, development, and yield with DSSAT4.0. Recalibration of RZWQM-DSSAT began by first accepting the adjustments made by Ma et al. (2008) to the original calibration by Thorp et al. (2007). The adjustments included setting the decay rate of the slow organic matter pool back to the default value of 4.5E−10 s d^{-1} $organism^{-1}$, setting the denitrification reaction rate to 3.0E−13 s d^{-1} $organism^{-1}$, and setting the lateral hydraulic gradient to 5.0E−6 cm cm^{-1}. The RZWQM nutrient component was then calibrated by adjusting the death rate for aerobic heterotrophs to 9.0E−37 s d^{-1} and the death rate for anaerobic heterotrophs to 5.0E−34 s d^{-1}. Aerobic heterotroph populations mainly affect the rate of N mineralization, while anaerobic heterotroph populations mainly affect the rate of denitrification. Simulations of crop growth, development, and yield using the new DSSAT4.0 modules were then improved by adjusting cultivar coefficients. Efforts focused mainly on adjustment of the corn model. The final cultivar parameters used for simulating corn growth at the site were 240 degree days above a base temperature of 8°C (DD_8) for P1 (thermal time from seedling emergence to the end of the juvenile phase), 0.75 d for P2 (extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate), 850 DD_8 for P3 (thermal time from silking to physiological maturity), 725 kernels for G2 (maximum possible kernels per plant), 6.75 mg d^{-1} for G3 (kernel filling rate during the linear grain filling stage and under optimum conditions), and 55 DD_8 for PHINT (phylochron interval). The soybean model was calibrated by adjusting the LFMAX parameter (maximum leaf photosynthesis rate) to a value of 0.7 mg CO_2 m^{-2} s^{-1}. All other soybean model parameters were set equal to that reported by Thorp et al. (2007). RZWQM-DSSAT was initialized by simulating common management practices over 35 years of historical weather (1961 to 1995). Model calibration and evaluation efforts focused on the high N rate treatment at the site, and the recalibrated model was subsequently evaluated for its performance at the two lower rates of N without further calibration.

Results and Discussion

Hydrology Simulation

The calibrated DRAINMOD model simulated the hydrologic balance at the site as shown in table 11. Precipitation ranged from 55.3 cm in 2000 to 100.6 cm in 1996, and simulated subsurface drainage followed precipitation patterns over the 10-year study duration with a minimum flow of 0.9 cm in 2000 and a maximum flow of 32.1 cm in 1996. Differences in the reported precipitation amount used as input for DRAINMOD versus RZWQM-DSSAT are due to rounding errors in the formatting of model input files. RZWQM-DSSAT accepts hourly rainfall data to the ten-thousandth of an inch, whereas DRAINMOD accepts hourly rainfall only to the one-hundredth of an inch. Simulated runoff with DRAINMOD ranged from 0.5 cm in 2003 to 10.4 cm in 1996. Approximately 60% of the runoff in 1996 occurred on day of year (DOY) 168 due to a 16 cm rainfall event on that day. Simulated ET with DRAINMOD ranged from 45.6 cm in 2003 to 53.2 cm in 1996. These simulated values are slightly higher than the ET measurements for a nearby site in central Iowa, where measured ET ranged from 40 to 50 cm $year^{-1}$ during four years of corn production (Hatfield and Prueger, 2004). Simulated deep seepage was not extremely variable, ranging from 3.2 cm $year^{-1}$ in 2000 to 4.2 cm $year^{-1}$ in 1998. Annual changes in soil water storage with DRAINMOD ranged from a net gain of 3.3 cm in 2003 to a net loss of 3.0 cm in 1999. Slight deviations occurred when checking the annual water balance for simulations, which can be attributed to the case where precipitation happens as snowfall in the later part of one year but neither runs off nor infiltrates until snow melt happens in the succeeding year.

Water balance simulations with DRAINMOD and RZWQM-DSSAT over the 10-year period were very similar. The main difference was that DRAINMOD simulated nearly twice as much runoff as compared to RZWQM-DSSAT. However, since runoff was relatively low at the site, the total difference between runoff simulations by the models over the

Table 11. Annual water mass balance for continuous 10-year simulations with DRAINMOD and RZWQM-DSSAT.[a]

	DRAINMOD						RZWQM-DSSAT						Observed
Year	P	RO	ET	SP	SD	ΔS	P	RO	ET	SP	SD	ΔS	SD
1996	100.6	10.4	53.2	4.1	32.1	+0.8	101.7	9.2	48.9	4.7	27.9	+9.4	26.9
1997	70.0	3.6	47.3	4.0	15.0	0.0	69.6	1.6	46.3	5.9	15.0	-0.8	14.7
1998	88.2	2.6	52.7	4.2	30.2	-1.4	87.7	3.9	51.8	6.1	28.6	-1.7	32.5
1999	78.9	5.2	46.2	3.7	26.9	-3.0	77.3	1.6	49.8	4.5	30.9	-9.3	32.3
2000	55.3	1.9	45.9	3.2	0.9	+3.3	58.9	0.2	48.2	2.0	2.0	+3.2	0.1
2001	78.9	5.4	50.5	3.9	19.7	-0.5	76.9	1.0	45.3	4.3	20.8	+8.0	18.9
2002	66.0	3.2	52.6	3.7	7.6	-1.0	65.9	0.2	56.7	4.7	13.1	-8.8	8.5
2003	75.3	0.5	45.6	4.0	21.9	+3.3	75.9	0.3	46.2	3.5	17.3	+8.2	23.2
2004	82.6	1.6	51.8	4.1	26.3	-1.1	82.6	0.4	54.1	5.3	27.2	-4.8	24.4
2005	71.5	1.9	52.2	3.8	14.0	-0.4	73.1	0.5	50.9	4.2	13.2	+2.9	14.3
Sum	767.3	36.3	498.0	38.7	194.6	0.0	769.6	18.9	498.2	45.2	196.0	+6.3	195.8

[a] All values are in cm. P = precipitation; RO = runoff; ET = evapotranspiration; SP = seepage; SD = subsurface drainage; ΔS = change in soil water storage. P - RO - ET - SP - SD (simulated) = ΔS. Slight deviations in the annual mass balance are due to snow effects.

ten years, 17.4 cm, amounts to only 2% of total water inputs through precipitation. To balance the higher runoff simulated by DRAINMOD, RZWQM-DSSAT tended to simulate slightly higher deep seepage and greater soil water storage over the 10-year simulation; however, this result did not hold true for water balance simulations during individual years. Overall, the water balance simulations by both models were very similar.

DRAINMOD simulated annual subsurface drainage for the calibration years with a percent error of 11.93% (table 12). The RRMSE and EF were 17.81% and 0.92, respectively, indicating good agreement between measured and simulated subsurface drainage during model calibration. For the evaluation years, DRAINMOD simulated annual subsurface drainage with a percent error of –6.02%, and the RRMSE and EF statistics were 11.45% and 0.91, respectively. These statistics demonstrate that the model, calibrated for the conditions of this study site, can adequately simulate subsurface drainage for datasets independent of those used for model calibration. On a daily basis, error statistics also demonstrated good agreement between measured and simulated subsurface drainage with an EF of 0.75 over the entire 10-year simulation period. Statistical measures for simulations of subsurface drainage were very similar when comparing the performance of the DRAINMOD and RZWQM-DSSAT models (table 12). From these results, it is difficult to conclude that one model simulated subsurface drainage better than the other. Both the RRMSE and EF statistics demonstrated that RZWQM-DSSAT simulated subsurface drainage better than DRAINMOD in the calibration years, but DRAINMOD performed better than RZWQM-DSSAT in the evaluation years.

Sensitivity analyses with both DRAINMOD and RZWQM-DSSAT demonstrated the possibility of multiple model realizations that would give similar results for subsurface drainage, while water flow through other pathways, particularly deep seepage and ET, were somewhat different. Essentially, if we adjusted the models to simulate higher ET, subsurface drainage simulations could be reasonably maintained by adjusting other model parameters to reduce deep seepage. Here, we have calibrated both models to give similar simulations of ET (table 11), which are also reasonable as compared to ET measurements by Hatfield and Prueger (2004) at a different central Iowa location. However, without direct measurements of ET at our site location, we can only speculate about the accuracy of this aspect of the model simulation. Our situation is not different from that of other researchers who have reported model evaluation studies with limited measured information (Sands et al., 2003; Wang et al., 2006; Singh et al., 2006). However, if we are to be truly confident in the ability of an agricultural systems model to accurately simulate all components of the hydrologic balance within an agricultural field, then these models must be more rigorously tested using more detailed and thorough datasets. For example, layered temporal soil moisture measurements from neutron probes at our site would have been very helpful to further characterize the soil water profile and to calculate estimates for ET and deep seepage, similar to Hunsaker et al. (2005). Estimates of actual ET are particularly important for evaluating simulations with models like DRAINMOD and RZWQM-DSSAT, because relatively small changes in simulated ET can correspond to more drastic changes in simulated

Table 12. Error statistics for annual simulations of water and nitrogen (N) out the subsurface drainage lines for high N rate plots using DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT.[a]

	DRAINMOD/DRAINMOD-N II						RZWQM-DSSAT					
	Calibration[b]			Evaluation[c]			Calibration[b]			Evaluation[c]		
	SD	NM	FWANC[d]	SD	NM	FWANC	SD	NM	FWANC	SD	NM	FWANC
PE (%)	11.93	-11.69	-21.56	-6.02	4.85	13.50	8.59	5.16	1.68	-3.49	-19.04	-14.11
RRMSE (%)	17.81	17.21	22.42	11.45	9.04	17.84	9.57	19.83	16.64	16.46	35.61	20.68
EF	0.92	0.94	-2.73	0.91	0.95	-1.57	0.98	0.92	0.38	0.82	0.21	-2.45

[a] SD = subsurface drainage; NM = nitrate mass in subsurface drainage; FWANC = flow-weighted average nitrate concentration in subsurface drainage; PE = percent error; RRMSE = relative root mean square error; EF = model efficiency.

[b] Years 1996, 1997, 2000, and 2001.

[c] Years 1998, 1999, 2002, 2003, 2004, and 2005.

[d] Year 2000 not included in the computation because of high concentration errors associated with low flow rate in that year.

subsurface drainage. When all other water balance pathways remain equal, a 10% adjustment in ET, which is merely 5 cm year^{-1} at our site (table 11), corresponds to a 25% change in subsurface drainage. Simulation studies of soil water balances with the CERES, WOFOST, and SWAP models (Eitzinger et al., 2004) and with the CROPGRO faba bean model (Sau et al., 2004) have yielded similar results. Thus, efforts to better understand the ET component of the water balance is crucial for improving field-scale hydrology models like those tested in this work. Additionally, instead of merely reporting the results of subsurface drainage simulations, researchers must begin to report the complete mass balance simulated by a model such that better comparisons of the lesser-known water balance pathways can be made between modeling studies in the literature.

CARBON SIMULATION

An important goal of model initialization is to ensure that the SOC pools have reached a quasi-steady state. The term "quasi" is used because changes in SOC occur very slowly and because constantly changing land uses and management practices typically prevent agricultural systems from reaching a complete steady state. Simulations of appropriate SOC dynamics are required for reasonable simulations of N dynamics. Figure 1 demonstrates that the SOC contents in each of the three soil organic matter pools for both models were at a quasi-steady state throughout the simulation period. With the modified CENTURY component used by DRAINMOD-N II, the active, slow, and passive soil organic matter pools were stable containing between 1.4% and 3.5%, between 32.8% and 33.7%, and between 63.5% and 65.6% of total soil organic carbon, respectively. With the OMNI component used by RZWQM-DSSAT, the fast, intermediate, and slow soil organic matter pools were stable containing between 0.3% and 0.5%, between 3.0% and 3.4%, and between 96.1% and 96.7% of total soil organic carbon, respectively. These results highlight the difference in the way the nutrient components of each model handle the steady-state soil organic carbon simulation for this location in Iowa.

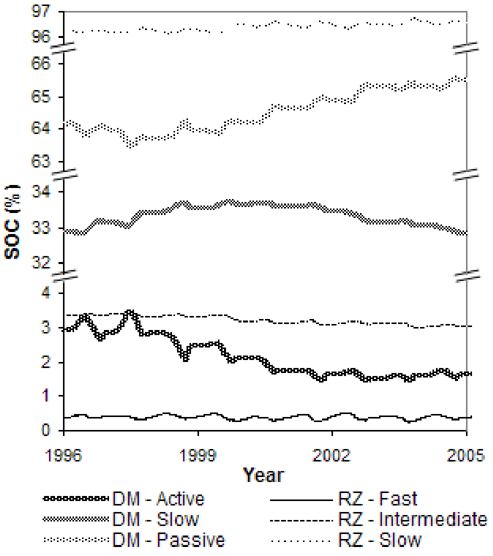

Figure 1. Daily percent soil organic carbon in each of the three soil organic matter pools for DRAINMOD-N II (DM) and RZWQM-DSSAT (RZ) simulations for high N rate plots.

NITROGEN SIMULATION

The calibrated DRAINMOD-N II model simulated the N mass balance for the high N rate as summarized in table 13. Simulated organic soil N storage is currently not outputted by DRAINMOD-N II, making it difficult to verify the complete N mass balance for the model. Values for total soil N storage changes in table 13 were computed by subtracting the total N outputs from the total N inputs annually. Model simulations of net N mineralization are reported in table 13 because of the importance of this process in characterizing plant-available N. However, when considering the total N mass balance of the soil system, net N mineralization is not a critical component since it merely represents a movement of N between organic and inorganic forms but not an overall change in total N stored. The primary N input to the system in corn years was fertilizer applications according to the actual management of the high N rate plots (table 1). During soybean years, DRAINMOD-N II simulated N additions to the system through N fixation in the range of 78 to 207 kg N ha^{-1} (table 13). A secondary pathway for N input to the soil system included incorporation of crop residue. Simulated annual averages of 60 and 119 kg N ha^{-1} were returned to the system through this pathway during corn years and soybean years, respectively. The assumption of a 0.5 ppm concentration of both NO_3 and NH_4 in precipitation added an average of 8 kg N ha^{-1} per year. Simulated denitrification rates ranged from 8.3 to 27.3 kg N ha^{-1} annually, and annual levels of N lost in runoff ranged from 1.2 to 7.2 kg N ha^{-1}. Outputs of N through the subsurface drainage system followed patterns of precipitation over the 10-year simulation at the site. The years with the highest precipitation, 100.6 cm in 1996 and 88.2 cm in 1998, corresponded to the years with highest annual loss of N in subsurface drainage, 59.2 kg N ha^{-1} in 1996 and 61.4 kg N ha^{-1} in 1998. The lowest precipitation of 55.3 cm in 2000 corresponded to the minimum annual N loss, 2.7 kg N ha^{-1}, through subsurface drains. Average simulated N uptake by corn and soybean crops was 172 and 302 kg N ha^{-1}, respectively. Soybean N uptake includes N fixation and N removed from the soil. Annual net mineralization rates ranged from 44 kg N ha^{-1} in 1996 to 165 kg N ha^{-1} in 2001 with an average annual net N mineralization rate of 125 kg N ha^{-1} over the 10-year simulation. Net mineralization rates simulated by DRAINMOD-N II tended to be lower during corn years, probably due to the short-term immobilization that occurs after incorporation of corn residues with high C:N ratios. DRAINMOD-N II also tended to simulate N budget deficits in soybean years and N budget surpluses in corn years at the high N rate, and an N budget deficit of 199 kg N ha^{-1} was simulated over the 10-year period.

Statistical computations showed that DRAINMOD-N II was more effective at simulating variation in annual NO_3 mass lost in subsurface drainage as compared to the annual flow-weighted average NO_3 concentration (FWANC) of subsurface drain effluent (table 12). This is the result of the model being calibrated for NO_3 mass losses rather than FWANC in the subsurface drains. DRAINMOD-N II also tended to greatly overestimate FWANC in subsurface drainage when the drain flow was small, which is why the FWANC value simulated by DRAINMOD-N II in the dry year of 2000 was very high (table 14). FWANC values for year 2000 were not included in the statistical computations given in table 12. Error statistics were better for model

Table 13. Annual nitrogen (N) mass balance for continuous 10-year simulations in high N rate plots using DRAINMOD-N II and RZWQM-DSSAT.[a]

Model	Year[b]	FZ	FX	RI	P	D	V	RO	SD	SP	PU	ΔS	MN
DRAINMOD-N II	1996	210	0	56	10.1	19.3	0.0	4.7	59.2	3.6	161	+28	44
	1997	0	204	130	7.0	10.1	0.0	1.7	23.3	3.7	330	-28	156
	1998	172	0	58	8.8	27.3	0.0	2.1	61.4	4.7	167	-24	135
	1999	0	207	129	7.9	10.8	0.0	6.1	50.2	4.4	326	-54	162
	2000	199	0	54	5.5	8.3	0.0	4.8	2.7	4.0	157	+82	74
	2001	8	78	95	7.9	15.3	0.0	7.2	34.6	5.1	240	-113	165
	2002	199	0	63	6.6	11.4	0.0	5.4	16.2	4.8	182	+49	85
	2003	0	125	111	7.5	16.2	0.0	1.7	45.1	5.4	280	-105	156
	2004	199	0	67	8.3	18.5	0.0	1.2	45.0	6.0	194	+9	106
	2005	0	199	132	7.1	12.1	0.0	2.3	28.2	5.8	333	-43	163
	Sum	987	813	895	76.7	149.3	0.0	37.2	365.9	47.5	2370	-199	1246
RZWQM-DSSAT	1996	210	0	195	9.4	10.6	0.6	1.0	55.8	7.3	236	+105	91
	1997	0	223	66	5.7	5.8	0.0	0.1	35.3	9.4	303	-60	97
	1998	172	0	146	7.6	16.0	0.6	0.4	30.9	9.9	193	+75	91
	1999	0	231	68	7.2	8.4	0.0	0.2	50.2	7.1	320	-78	145
	2000	199	0	162	5.2	15.1	0.5	0.0	2.7	3.2	260	+85	117
	2001	8	156	64	6.1	10.3	0.0	0.0	48.8	6.5	272	-101	124
	2002	199	0	165	6.1	24.4	0.5	0.0	22.0	7.5	250	+66	103
	2003	0	205	84	6.9	13.0	0.0	0.0	30.0	5.6	290	-40	120
	2004	199	0	181	7.4	16.5	0.6	0.0	38.1	8.5	245	+79	85
	2005	0	266	98	6.2	14.4	0.0	0.0	18.9	6.6	354	-22	117
	Sum	987	1081	1229	67.8	134.5	2.8	1.7	332.7	71.6	2723	+109	1090

[a] All values are in kg N ha^{-1}. FZ = fertilizer; FX = fixation; RI = residue incorporation (includes root decomposition); P = precipitation; D = denitrification; V = volatilization; RO = runoff; SD = subsurface drainage; SP = seepage; PU = plant uptake; ΔS = change in soil nitrogen storage; MN = net mineralization. FZ + FX + RI + P - D - V - RO - SD - SP - PU = ΔS.

[b] Corn in even years and soybean in odd years.

Table 14. Measured and simulated values for annual nitrogen (N) balance components in high N rate plots.[a]

	Drain NO_3 Mass (kg N ha^{-1})			Drain FWANC (mg N L^{-1})			Grain N (kg N ha^{-1})			Residual Soil N[b] (kg N ha^{-1})			
Year[c]	OBS	DM	RZ	OBS	DM	RZ	OBS	DM	RZ	OBS	DM	RZ	DOY
1996	64.6	59.2	55.8	24.1	18.4	20.0	98	105	138	53.6	54.4	78.7	318
1997	26.9	23.3	35.3	18.3	15.5	23.5	197	200	180	54.9	32.8	25.3	274
1998	58.4	61.4	30.9	18.0	20.3	10.8	107	109	116	67.3	66.2	59.4	298
1999	49.4	50.2	50.2	15.3	18.7	16.3	204	197	193	37.8	47.6	37.5	288
2000	0.1	2.7	2.7	13.7	29.0	13.7	100	103	154	57.1	97.3	99.6	311
2001	43.9	34.6	48.8	23.3	17.5	23.4	128	145	153	34.4	63.6	43.9	319
2002	15.0	16.2	22.0	17.7	21.3	16.7	144	119	159	48.9	90.3	63.4	319
2003	48.2	45.1	30.0	20.8	20.6	17.3	142	170	148	29.3	45.7	52.9	324
2004	42.5	45.0	38.1	17.4	17.2	14.0	134	127	159	36.2	78.9	44.7	316
2005	21.3	28.2	18.9	14.9	20.1	14.3	ND	202	218	65.3	76.4	32.3	300

[a] FWANC = annual flow-weighted average nitrate concentration in subsurface drainage; OBS = observed; DM = DRAINMOD-N II simulated; RZ = RZWQM-DSSAT simulated; DOY = day of year; ND = no data.

[b] Total inorganic N (nitrate + ammonium) to a depth of 120 cm on the specified measurement date.

[c] Corn in even years and soybean in odd years.

Table 15. Average monthly nitrogen (N) mass losses in subsurface drainage for continuous 10-year simulations in high N rate plots using DRAINMOD-N II and RZWQM-DSSAT.[a]

Month	Observed	DRAINMOD	RZWQM-DSSAT
January	0.3	0.5	0.3
February	1.3	0.9	0.9
March	2.0	2.6	2.3
April	6.4	6.5	6.7
May	9.9	9.1	10.7
June	11.1	11.9	9.0
July	2.9	2.2	1.2
August	0.0	0.0	0.0
September	0.0	0.0	0.0
October	0.4	0.3	0.0
November	1.9	1.4	1.3
December	0.9	1.1	0.7

[a] Units are kg N ha^{-1}.

simulations of annual NO_3 mass lost through the subsurface drain lines with a percent error of –11.69% during calibration years. The RRMSE and EF between measured and simulated annual NO_3 mass losses during calibration years were 17.21% and 0.94, respectively. For the evaluation years, the model simulated annual NO_3 mass loss with a percent error of 4.85%, and the RRMSE and EF statistics were 9.04% and 0.95, respectively. These statistics indicate excellent simulations of annual NO_3 mass losses in subsurface drainage. DRAINMOD-N II was also able to simulate monthly NO_3 mass loss in subsurface drainage with an EF of 0.80 over the entire 10-year simulation. Measurements and DRAINMOD-N II simulations both showed that approximately 75% of the annual NO_3 mass losses were transported through the subsurface drains during the months of April, May, and June with increasing losses from April to June (table 15). Simulations of N removal in grain by DRAINMOD-N II were also excellent (table 14) with a PE of 1.4%, RRMSE of 10.3%, and EF of 0.85 over the entire simulation period. This was an expected result, since the user has great control over the grain yield and grain N removal simulation with this model. Percent error between measured and simulated values for residual soil inorganic N, including NO_3 and NH_4, measured annually after harvest to a depth of 120 cm (table 14) was 34.7% over the entire 10-year simulation period.

Similar to the hydrology results, the results for nitrogen balance simulations suggest that the DRAINMOD-N II and RZWQM-DSSAT models performed relatively similarly with regard to simulations of N loss in subsurface drainage (tables 12 through 15), although DRAINMOD-N II simulated the drainage N losses better than RZWQM-DSSAT in the evaluation years (table 12). These poorer evaluation-year simulations by RZWQM-DSSAT were mainly the result of underestimated subsurface drainage N losses in 1998 and 2003 (table 14). In 2003, this may be the result of overestimated N removal in grain by RZWQM-DSSAT in the three preceding years. Denitrification and volatilization were not substantially different between the two models (table 13). Over the 10-year simulation period, DRAINMOD-N II simulated greater N losses through the pathways of denitrification, runoff, and subsurface drainage by 14.8, 35.5, and 33.2 kg N ha^{-1}, respectively. RZWQM-DSSAT simulated 24.1 kg N ha^{-1} greater losses to the deep seepage pathway. Differences between the simulated losses of N to these output pathways are small in comparison to that of the plant uptake pathway, as RZWQM-DSSAT simulated 353 kg N ha^{-1} more plant N uptake than DRAINMOD-N II. In addition, since N inputs from precipitation and fertilizer are not substantially different between the two models, two other plant-based pathways, N fixation and residue incorporation, remain as the only input pathways that demonstrate substantial differences between the models.

With its physiologically based CROPGRO-Soybean model, RZWQM-DSSAT simulated 268 kg N ha^{-1} greater soybean N fixation than that simulated by DRAINMOD-N II over the 10-year simulation period. Soybean N fixation in DRAINMOD-N II is based solely on the user-specified plant N needs and the daily inorganic N contents within the plant root zone. If soil N contents are sufficient for soybean plant needs, then no fixation is simulated. Since it is not the goal of DRAINMOD-N II to simulate crop growth on a physiological basis, a key modification for DRAINMOD-N II may be to allow the user to specify a baseline level for soybean N fixation such that N flow through this pathway can be more easily adjusted to test its effect on the total N balance. Although the difference in simulated soybean N fixation between the models is substantial, both models simulated soybean N fixation and soybean N uptake within a reasonable range, according to the literature review by Salvagiotti et al. (2008). Thus, this substantial discrepancy between the models highlights a need for better quantification of soybean N fixation in future field investigations. Another interesting difference between the two models was the amount of N returned to the soil in crop residue. DRAINMOD-N II simulated greater return of crop residue N during soybean years, while RZWQM-DSSAT simulated more N returned during corn years. Levels of N returned to the soil with corn root decomposition in RZWQM-DSSAT were found to be highly sensitive to the CERES-Maize radiation use efficiency parameter, which significantly affects root mass growth and subsequently the amount of root-assimilated N later released during root decomposition. Over the 10-year simulation, RZWQM-DSSAT simulated 334 kg N ha^{-1} greater incorporation of residue N, including root decomposition, than that simulated by DRAINMOD-N II. With regard to N outputs from the soil system, RZWQM-DSSAT simulated 353 kg N ha^{-1} greater plant N uptake than DRAINMOD-N II. This result is related to the tendency of RZWQM-DSSAT to simulate greater N fixation by soybean (table 13) as well as the model's tendency to overestimate the amount of N removed in corn grain at the high N rate (table 14). The two models also demonstrated substantial differences in their simulations of soil N storage. RZWQM-DSSAT simulated a 109 kg N ha^{-1} increase in soil N storage, whereas DRAINMOD-N II simulated a 199 kg N ha^{-1} decrease in soil N storage over ten years of simulations. DRAINMOD-N II also simulated higher net N mineralization than that simulated by RZWQM-DSSAT (table 13), which can be attributed to lesser immobilization due to lower amounts of crop residue returned to the soil. In addition, net N mineralization represents a significant time-critical source of inorganic N to the soil profile, as the cycling of C and N through the organic matter pools continually responds to daily fluctuations in soil temperature, soil moisture, and concentrations of inorganic N in the soil profile. Very different simulations of the crop effects on the N cycle between the two models, in addition to differences in the organic N cycling algorithms themselves, introduced substantial variation in how the models simulated net N mineralization.

Since DRAINMOD-N II and RZWQM-DSSAT differed substantially in their simulations of crop N uptake and soybean N fixation, the results highlight the importance of crop growth simulation for characterizing the N cycle of agricultural systems, particularly when N-fixing legumes are present in the crop rotation. Recent simulation results using the APSIM model also suggested that simulations of subsurface drainage N losses were substantially affected by the APSIM crop N uptake simulation (Malone et al., 2007). We calibrated DRAINMOD-N II and RZWQM-DSSAT to give similar results for subsurface drain N losses, but they are less in agreement about from where the source of N to supply the drainage N losses is derived. Simulation results confirm that future field investigations should focus more heavily on characterizing the amount of N that is fixed by soybean as well as the net level of N mineralized from soil organic matter.

CROP YIELD SIMULATION

The calibrated DRAINMOD model simulated crop yield (relative yield × potential yield) for the high N rate treatment at the site as summarized in table 16. For calibration years, DRAINMOD simulated relative corn yield with a percent error of 6.1% and an RRMSE of also 6.1%. Soybean yield was simulated with a percent error −0.1% and an RRMSE of 1.2% for calibration years. For evaluation years, the model simulated corn yield with a percent error of −4.8% and an RRMSE of 6.1%, and soybean yield was simulated with a percent error of −0.9% and an RRMSE of 7.2%. These results demonstrate that the crop component of DRAINMOD was able to respond to water excess and deficit stress for the high N rate plots (table 17).

Table 16. Crop yield simulation results for high N rate plots using DRAINMOD and RZWQM-DSSAT.[a]

Year[b]	DRAINMOD[c]	RZWQM-DSSAT	Observed
1996	8784	9042	8264
1997	3154	3010	3123
1998	9084	9239	9067
1999	3098	3221	3236
2000	8556	8944	8087
2001	2415	2704	2453
2002	9924	9709	10529
2003	2776	2351	2497
2004	10572	11397	11475
2005	3199	3627	3419

[a] Units are kg ha^{-1}.

[b] Corn in even years and soybean in odd years.

[c] DRAINMOD results are based on potential yields of 12000 kg ha^{-1} for corn and 3500 kg ha^{-1} for soybean.

Relative crop yield simulations with DRAINMOD were comparable to that simulated by the more rigorous crop growth models used within RZWQM-DSSAT. However, the DRAINMOD crop component was not able to perform this well without help. First, since the DRAINMOD crop component does not simulate grain weight explicitly, the yield results depend heavily on the calibrated values for potential yield (table 6). Adjustments to these values change the yield results substantially. Second, as discussed in the methodology, we used the simulation results from the RZWQM-DSSAT crop simulations to aid in the parameterization of the DRAINMOD crop component. Specifically, we used the RZWQM-DSSAT phenology simulation to specify the timing of crop susceptibility factors for simulating crop yield responses to deficit and excess soil water stress in DRAINMOD. When we used the standard approach for specifying these factors as given in Workman et al. (1994), the percent error and RRMSE for crop yield simulations was much greater than our reported results (table 17). Although DRAINMOD is not designed to simulate the effects of environmental conditions on the physiology of crop development, this result highlights the importance of carefully considering the crop developmental stage when using soil water conditions to compute crop yield responses to excess and deficit water stress. This is particularly important when using DRAINMOD-N II to simulate N dynamics, since DRAINMOD-N II relies on DRAINMOD simulations of relative crop yield to compute plant N uptake.

RESPONSE TO REDUCED N RATES

After calibration and evaluation for the high N rate treatment, DRAINMOD-N II simulations of annual NO_3 mass lost in subsurface drainage at the low and medium N rate treatments were shown to respond appropriately (fig. 2a), with non-normalized root mean square errors of 4.1, 3.2, and 4.6 kg N ha^{-1} for 10-year continuous simulations at the low, medium, and high N rates, respectively. Average annual simulated and measured NO_3 mass in subsurface drainage over the 10-year study were 21.9 and 20.1 kg ha^{-1} for the low N rate, 26.6 and 26.5 kg ha^{-1} for the medium N rate, and 36.6 and 37.0 kg ha^{-1} for the high N rate, respectively. DRAIN-MOD-N II simulations of annual FWANC in drainage water also responded to reduced N application rates (fig. 2b) with non-normalized root mean square errors of 2.4, 2.6, and 3.8 mg N L^{-1} for 10-year continuous simulations at the low, medium, and high N rates, respectively. Average annual simulated and measured FWANC in subsurface drainage were 11.2 and 10.0 mg L^{-1} for the low N rate, 13.6 and 13.3 mg L^{-1} for the medium N rate, and 18.9 and 18.9 mg L^{-1} for the high N rate, respectively. Annual FWANC values for year 2000 were not considered in these computations because the model tended to output unrealistically high FWANC values when subsurface drainage was very small. Measured versus simulated responses of corn yield to reductions in N rates are not plotted here because DRAINMOD-N II does not simulate crop yield reductions due to N stress. Instead, the user must adjust the potential yield parameter to ensure that the model responds appropriately to N rate reductions. This represents a major difference between DRAINMOD-N II and RZWQM-DSSAT, which uses a physiologically based corn growth model to simulate crop growth and yield responses to N fertilizer treatments. For our simulations with DRAIN–MOD-N II, we adjusted the potential yield parameter for corn (table 6) to minimize error between measured and simulated corn yield at the lower N rates. Potential soybean yield did not require an adjustment, since measured soybean yield at the site did not vary in response to reductions in corn-year N fertilizer treatments.

A comparison of performance statistics for DRAINMOD-N II and RZWQM-DSSAT simulations at the three N rates highlights some important differences between the models (table 18). First, the DRAINMOD water model and the DRAINMOD-N II nitrogen model are separate models that are executed independently of one another (table 10). As such, the effect of different N fertilizer rates in DRAINMOD-N II does not feedback on the hydrology simulation of DRAINMOD. Thus, the subsurface drain flow statistics are identical for all three N rates because the hydrology simulation does not change. With RZWQM-DSSAT, the hydrology, nitrogen, and crop growth components are all integrated on a daily time step, so changes to the N simulation

Table 17. Error statistics for simulations of yield and nitrogen (N) removal in grain for high N rate plots using DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT.[a]

		DRAINMOD/DRAINMOD-N II				RZWQM-DSSAT			
		Calibration[b]		Evaluation[c]		Calibration[b]		Evaluation[c]	
		CRN	SOY	CRN	SOY	CRN	SOY	CRN	SOY
Yield	PE (%)	6.1	-0.1	-4.8	-0.9	10.0	2.5	-2.3	0.5
	RRMSE (%)	6.1	1.2	6.1	7.2	10.0	7.0	4.7	4.8
Grain N	PE (%)	5.2	5.9	-8.1	5.9	47.6	2.3	12.4	-1.6
	RRMSE (%)	5.7	7.4	11.9	11.6	48.1	13.2	13.4	5.3

[a] CRN = corn; SOY = soybean; PE = percent error; RRMSE = relative root mean square error.

[b] Years 1996 and 2000 for corn and years 1997 and 2001 for soybean.

[c] Years 1998, 2002, and 2004 for corn and years 1999, 2003, and 2005 for soybean.

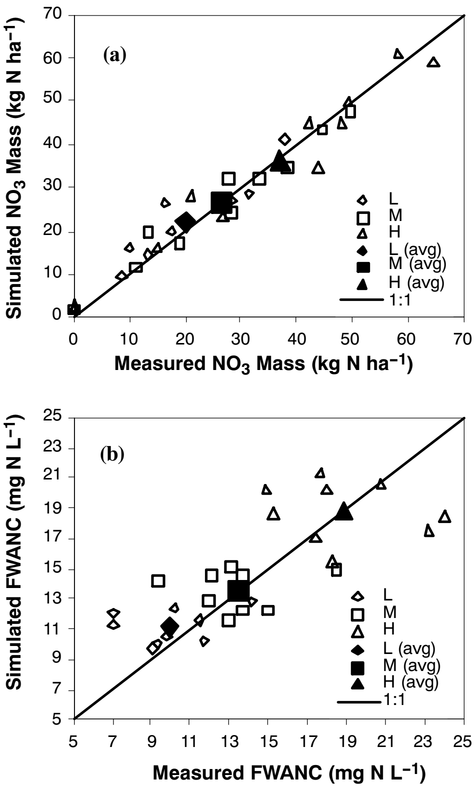

Figure 2. Annual measured versus simulated (a) nitrate mass and (b) flow-weighted average nitrate concentration (FWANC) in subsurface drainage for continuous 10-year simulations with DRAINMOD-N II at the high (H), medium (M), and low (L) nitrogen application rates.

will change both the hydrology and crop growth simulations as well. As such, there were changes in the performance of RZWQM-DSSAT when simulating subsurface drainage at the three N rates, and a slight decline in performance was seen with this model at the low N rate. The integrated nature of RZWQM-DSSAT makes calibration of the model more complicated because the adjustment of one parameter can affect the entire simulation. All the components of RZWQM-DSSAT must be working well together before the overall simulation is satisfactory, and it is easy to overcalibrate one component of the model at the expense of the performance of a different component. With DRAINMOD/DRAINMOD-N II, the hydrology simulation can be finalized before moving forward with calibration of the N component, and the user has much greater control over the crop simulation. These differences indicate a tradeoff between the two models. Whereas RZWQM-DSSAT simulates some processes in greater detail and with fewer required inputs, particularly for the crop component, the model did not simulate subsurface drain NO_3 mass losses as well as DRAINMOD-N II at any of the N rates (table 18). On the other hand, with greater user control over the crop component simulation, DRAINMOD/DRAINMOD-N II was able to achieve much better simulations of subsurface drain NO_3 losses than RZWQM-DSSAT, but the calibrated model cannot respond appropriately to different N fertilizer management practices without further user involvement in the crop component simulation. The advantage of one model versus the other ultimately depends on its intended use.

Table 18. Error statistics for annual simulations at three corn-year nitrogen (N) rates using DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT over a 10-year simulation period.[a]

	N Rate	DRAINMOD-N II		RZWQM-DSSAT	
		RRMSE	EF	RRMSE	EF
Drain flow	H	13.4	0.93	15.4	0.91
	M	13.4	0.93	14.7	0.92
	L	13.4	0.93	19.4	0.85
Drain N mass	H	12.4	0.94	31.3	0.64
	M	12.1	0.95	30.5	0.71
	L	20.5	0.89	35.7	0.66
Drain FWANC	H	20.1	-0.57	18.9	-0.13
	M	19.3	-0.22	23.2	-0.25
	L	24.3	-0.30	39.8	-0.48
Residual soil N	H	54.5	-3.33	47.9	-2.34
	M	49.2	-2.87	43.8	-2.07
	L	55.9	-1.32	54.1	-1.17
Corn yield	H	6.1	0.81	6.7	0.76
	M	5.7	0.79	7.4	0.65
	L	16.5	-0.03	13.7	0.29
Corn grain N	H	10.6	0.57	28.2	-2.00
	M	12.6	0.39	16.0	0.02
	L	21.7	0.12	19.7	0.28
Soybean yield	H	5.8	0.81	5.7	0.82
	M	6.3	0.79	4.9	0.87
	L	7.0	0.77	5.5	0.86
Soybean grain N	H	9.9	0.75	9.9	0.75
	M	10.2	0.73	9.3	0.78
	L	11.4	0.70	10.8	0.73

[a] RRMSE = relative root mean square error (%); EF = model efficiency; H = high; M = medium; L = low; FWANC = flow-weighted average nitrate concentration.

Neither model was able to capture the year-to-year variability in annual FWANC very well (table 18), although both models responded appropriately in their simulations of subsurface drain FWANC at the three N rates (fig. 2). Negative values for EF also demonstrate that neither model was able to effectively simulate the amount of residual soil N after harvest each year (table 18), although this is a difficult process to simulate accurately. In spite of the differences between the crop components of DRAINMOD and RZWQM-DSSAT, the two models did not demonstrate any extreme differences in simulations of crop yield and N removal in grain. Simulations of corn yield by the two models were relatively similar at the medium and high N rates, and both models experienced a decline in corn yield simulation performance at the low N rate. This may indicate a more complex plant response to severe N stress that even the physiologically based crop model of RZWQM-DSSAT is not simulating. RZWQM-DSSAT tended to substantially overestimate N removal in corn grain at the high N rate, but simulations of N removal improved at the reduced N rates. The opposite was true for DRAINMOD-N II, where the best simulations of N removal in corn grain were at the high N rate and performance declined at the lower N rates. The two models also tended to simulate soybean yield and N removal in soybean grain very similarly, although the physiologically based CROPGRO-Soybean model within RZWQM-DSSAT performed somewhat better than DRAINMOD-N II at the medium and low corn-year N rates.

CONCLUSIONS

- After thorough calibration of DRAINMOD/DRAINMOD-N II, the model was able to reasonably quantify the hydrology, nutrient dynamics, and crop yield responses for a subsurface-drained agricultural system near Story City, Iowa.
- DRAINMOD-N II simulations of NO_3 concentration and mass losses through subsurface drains responded appropriately to changes in N fertilizer application rates to corn following soybean.
- DRAINMOD-N II simulated subsurface drain NO_3 mass losses better than RZWQM-DSSAT at three different N fertilizer application rates to corn following soybean.
- Whereas DRAINMOD/DRAINMOD-N II implements simplified approaches for some processes and gives the user greater control over the crop component simulation, RZWQM-DSSAT simulates some processes in greater detail and with fewer required inputs. The advantage of one model versus the other ultimately depends on its intended use.
- Disagreements between model simulations by DRAINMOD/DRAINMOD-N II and RZWQM-DSSAT indicate that future field investigations should more thoroughly characterize soybean N fixation, plant N uptake, net N mineralization, and amounts of N in crop residue returned to the soil.

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