SIMULATING LONG-TERM EFFECTS OF NITROGEN FERTILIZER APPLICATION RATES ON CORN YIELD AND NITROGEN DYNAMICS

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ABSTRACT. *Thoroughly tested agricultural systems models can be used to quantify the long-term effects of crop management practices under conditions where measurements are lacking. In a field near Story City, Iowa, ten years (1996-2005) of measured data were collected from plots receiving low, medium, and high (57-67, 114-135, and 172-202 kg N ha^{-1}) nitrogen (N) fertilizer application rates during corn (*Zea mays *L.) years. Using these data, the Root Zone Water Quality Model linked with the CERES and CROPGRO plant growth models (RZWQM-DSSAT) was evaluated for simulating the various N application rates to corn. The evaluated model was then used with a sequence of historical weather data (1961-2005) to quantify the long-term effects of different N rates on corn yield and nitrogen dynamics for this agricultural system. Simulated and measured dry-weight corn yields, averaged over plots and years, were 7452 and 7343 kg ha^{-1} for the low N rate, 8982 and 9224 kg ha^{-1} for the medium N rate, and 9143 and 9484 kg ha^{-1} for the high N rate, respectively. Simulated and measured flow-weighted average nitrate concentrations (FWANC) in drainage water were 10.6 and 10.3 mg L^{-1} for the low N rate, 13.4 and 13.2 mg L^{-1} for the medium N rate, and 18.0 and 19.1 mg L^{-1} for the high N rate, respectively. The simulated N rate for optimum corn yield over the long term was between 100 and 150 kg N ha^{-1}. Currently, the owner-operator of the farm applies 180 kg N ha^{-1} to corn in nearby production fields. Reducing long-term N rates from 180 to 130 kg N ha^{-1} corresponded to an 18% simulated long-term reduction in N mass lost to water resources. Median annual FWANC in subsurface drainage water decreased from 19.5 to 16.4 mg N L^{-1} with this change in management. Current goals for diminishing the hypoxic zone in the Gulf of Mexico call for N loss reductions of 30% and greater. Thus, long-term simulations suggest that at least half of this N loss reduction goal could be met by reducing N application rates to the production optimum. However, additional changes in management will be necessary to completely satisfy N loss reduction goals while maintaining acceptable crop production for the soil and meteorological conditions of this study. The results suggest that after calibration and thorough testing, RZWQM-DSSAT can be used to quantify the long-term effects of different N application rates on corn production and subsurface drainage FWANC in Iowa.*

Keywords. *Agricultural systems, DSSAT, Hydrology, Management, Nitrogen, RZWQM, Subsurface drainage, Yield.*

Loss of nitrate-nitrogen (NO_3-N) to surface and groundwater resources is one of the greatest challenges facing production agriculture in the Midwestern U.S. today. Sources of inorganic nitrogen (N) to the agricultural systems of this region, including ammonium-nitrogen (NH_4-N) and NO_3-N, typically include application of synthetic N fertilizers for corn (*Zea mays* L.) crops, N mineralization from soil organic matter and applied animal manure, N fixation from leguminous soybean (*Glycine max* (L.) Merr.) crops, and N deposition from precipitation. Under typical conditions, inorganic N existing as NH_4-N is quickly converted to NO_3-N, which is the most water-soluble form of N in the soil. As a result, movement of NO_3-N out of an agricultural system is linked to the pathways of water flow out of the system. Possible pathways for loss of NO_3-N from agricultural systems to surface and groundwater resources include runoff, leaching, and subsurface drainage (Jackson et al., 1973; Schuman et al., 1973; Burwell et al., 1976; Baker and Johnson, 1981; Spalding and Exner, 1993; Cambardella et al., 1999; Jaynes et al., 1999). Excessive levels of NO_3-N in water bodies have had ecologic and economic impacts throughout the drainage basin of the Mississippi River. Eutrophication of surface waters caused by algae growth responses to increased concentrations of NO_3-N has been noted (Randall and Mulla, 2001), and the city of Des Moines, Iowa, has spent millions of dollars to build a facility for removal of NO_3-N from drinking water when the public health limit of 10 mg NO_3-N L^{-1} is exceeded (Keeney and DeLuca, 1993). Excess NO_3-N in water bodies has caused negative impacts as far south as the Gulf of Mexico, where hypoxia threatens commercial and recreational fisheries. This effect has been linked directly to NO_3-N transport down the Mississippi River from regions associated with Midwestern corn and soybean production (Burkart and James, 1999; Goolsby et al., 2001).

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Reduction of N fertilizer application rates has been suggested as a strategy for reducing losses of NO_3–N from agricultural systems to the environment (Dinnes et al., 2002); however, field research on this matter has only been conducted under limited and relatively short-term conditions. For three years in southern Minnesota, Gast et al. (1978) applied four different N application rates to continuous corn and monitored the NO_3–N concentration in subsurface drainage water. For five years in Iowa, Baker and Johnson (1981) studied how two corn-year N application rates affected NO_3–N contents of drainage water beneath plots of corn grown in rotation with either soybeans or oats (*Avena sativa* L.). Rasse et al. (1999) tested several rates and methods of fertilizer application to corn for five years in Michigan and measured the NO_3–N contents of drainage outflow from field lysimeters. For six years in Minnesota, Randall and Mulla (2001) studied the rate and timing of N applications to continuous corn and measured the NO_3–N concentration of subsurface drainage water beneath the treatments. For four years in Iowa, Jaynes et al. (2001) studied how three corn-year N rates affected NO_3–N contents of drainage water beneath plots of corn grown in rotation with soybeans. All of these studies demonstrated that reductions of applied N generally correspond to reductions of NO_3–N losses in subsurface drainage water. It follows that reduction of N application rates is a potential solution to the environmental problems associated with agricultural N management. However, due to the limited timeframe of these studies, it is not possible to ascertain from them how the agricultural systems would have responded to long-term reductions in N fertilizer application rates.

Agricultural systems models have been a cost-effective tool for rapidly evaluating the long-term effects of N management strategies on crop productivity and loss of NO_3–N to the environment (Bakhsh et al., 2001; Thorp et al., 2006). Many of these models are process-oriented, utilizing water, carbon, and nitrogen mass balance principles to simulate the hydrologic, nutrient, and crop growth and developmental processes that occur within agricultural systems. The Root Zone Water Quality Model (RZWQM) is one example of an agricultural systems model that contains algorithms for simulating the effect of N fertilizer application rate and timing, tillage practices, crop rotations, and controlled drainage on the fate of agricultural N (Ahuja et al., 2000a). RZWQM is known for the strength of its hydrologic and nutrient cycling algorithms and for its applicability to the soil and water quality issues of various cropping systems. The Decision Support System for Agrotechnology Transfer (DSSAT) software is another example of a processed-based agricultural systems model (Jones et al., 2003). DSSAT integrates several models that simulate the growth and developmental processes for unique crop species, such as corn, soybean, and wheat (*Triticum aestivum* L.), within a software framework that facilitates evaluation of crop growth models and application to various agricultural systems. DSSAT is well known for the strength of its crop growth models, many of which have been evaluated for many different climates and soil types around the world. Given the strengths of these two agricultural systems models, recent efforts have focused on developing several of the DSSAT crop growth models, including CERES-Maize and CROPGRO-Soybean, as a replacement of the generic crop growth algorithm originally used in RZWQM (Ma et al., 2005; Ma et al., 2006).

Monitoring of the processes occurring within an agricultural cropping system provides a wealth of data that can be used to evaluate, improve, and apply existing agricultural systems models. With the interest of understanding how N fertilizer rates affect loss of NO_3–N from subsurface drainage lines, the response of a central Iowa agricultural system to variable N fertilizer application rates has been intensively monitored since 1996 (Jaynes et al., 2001; Jaynes and Colvin, 2006). Bakhsh et al. (2001) used data from this site to simulate the effects of variable N application rates on crop productivity and loss of NO_3–N in subsurface drainage between 1996 and 1999; however, long-term simulations were not completed. In addition, since that time, RZWQM has been linked with the DSSAT crop growth models, other improvements to RZWQM have been made, and six more years of data have been collected at the field site. Thus, the objectives of this research were to: (1) evaluate the RZWQM-DSSAT hybrid model using ten years of observed data from a subsurface-drained agricultural system in central Iowa, and (2) use a 45-year weather record to simulate the long-term effects of N fertilizer application rates on crop yield and N dynamics at the site.

Materials and Methods

The RZWQM-DSSAT Hybrid Model

RZWQM is a one-dimensional, field-scale agricultural systems model that can be used to simulate on a unit area basis the physical, chemical, and biological processes that govern movement of water, nutrients, and pesticides and growth of crops at a representative point in the field (Hanson et al., 1998; Ahuja et al., 2000a). A soil profile having up to 12 distinct horizons can be simulated, and a modified Brooks-Corey approach is used to describe soil water retention and hydraulic conductivity relationships in each horizon. Infiltration of water into the soil profile is computed using a modified Green-Ampt equation, and redistribution of water within the soil profile is simulated using a mass-conservative numerical solution of the Richards equation. Precipitation and irrigation water in excess of the infiltration rate enters macropores, if present. Any excess water remaining after macropore infiltration is considered runoff (Ahuja et al., 2000b). Routines for simulating subsurface drainage and fluctuating water tables are also incorporated in the model (Johnsen et al., 1995; Singh et al., 1996). Transfer of chemicals to runoff water is simulated using a non-uniform mixing approach. Transport of chemicals through the soil matrix during infiltration is achieved using sequential partial piston displacement and mixing, applied at 1 cm depth increments. Larger increments are used to compute chemical transport during redistribution (Ahuja et al., 2000b). Nitrate-nitrogen is transported through the soil profile as a non-adsorbing, conservative chemical, and the concentration of NO_3–N in subsurface drainage water is estimated as a function of its concentration in saturated soil layers (Kumar et al., 1998). Potential evapotranspiration (ET) is simulated in RZWQM using the Shuttleworth-Wallace double-layer form of the original Penman-Montieth ET model (Farahani and DeCoursey, 2000), incorporating the modifications of Farahani and Ahuja (1996). In addition to computing transpiration from the plant canopy, the model also partitions the soil surface into bare soil and residue-covered fractions and explicitly computes evaporation from each.

The comprehensive nutrient component in RZWQM includes two residue pools, three organic matter pools, and three microbial pools for simulating the dynamics of carbon and nitrogen within the soil system. Inorganic nitrogen is also simulated in NH_4-N and NO_3-N pools. Given initial conditions for each pool, the model simulates the processes of mineralization, immobilization, nitrification, denitrification, volatilization, urea hydrolysis, methane production, organic matter decay, and microbial growth and decay. Reaction rates are determined by microbial population, efficiency factors, and soil properties, including pH, O_2 content, temperature, water content, and ion strength (Shaffer et al., 2000). The model also simulates soil chemistry processes, pesticide processes, soil heat transport, snowpack dynamics, surface plant residue dynamics, and the effect of management practices on the agricultural system. Simulated management practices include tillage, applications of manure, fertilizer, and pesticide, planting and harvesting operations, and irrigation (Ahuja et al., 2000a).

Originally, a generic plant growth model was incorporated into RZWQM (Hanson, 2000); however, recent efforts have aimed to replace the RZWQM plant growth model with components from the DSSAT family of crop growth models, including CERES-Maize (Ma et al., 2006) and CROPGRO- Soybean (Ma et al., 2005). These models were used because they have the ability to simulate leaf number, phenological development, and other yield components that were not simulated with the original RZWQM plant growth model. RZWQM supplies the CERES or CROPGRO model with weather information, soil water and N contents, soil temperature, and potential ET. The crop growth model then returns simulated results for plant uptake of water and N and other plant growth variables, such as leaf area index and yield, to RZWQM.

Both RZWQM and DSSAT are well-known and widely used around the world. Specifically for agricultural systems in the Midwestern U.S., RZWQM has undergone extensive evaluations as a part of the USDA-ARS Management Systems Evaluation Areas (MSEA) project (Watts et al., 1999). RZWQM has also been widely applied to study how NO_3-N is lost in subsurface drainage in the Midwest, particularly in Iowa (Kumar et al., 1998; Bakhsh et al., 2001; Bakhsh et al., 2004). The CERES-Maize crop model within DSSAT has been rigorously applied to study Midwest corn production in the work of Hodges et al. (1987), and more recently the model has been used to study site-specific crop development and to formulate N fertilizer prescriptions for corn in Iowa (Paz et al., 1999; Thorp et al., 2006). CROPGRO-Soybean has also been developed (Pedersen et al., 2004) and evaluated (Sexton et al., 1998) for simulating soybean growth in the Midwest, and the model has been used to understand water stress effects on observed spatial yield variability (Paz et al., 1998) and to study site-specific soybean variety management in Iowa (Paz et al., 2003). The RZWQM-DSSAT hybrid model has been previously evaluated and applied for other agricultural systems in Iowa in the work of Ma et al. (2007) and Saseendran et al. (2007).

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-N 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-N 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. Corn plant populations were 66,000 plants ha^{-1} through 1996 and 75,000 plants ha^{-1} thereafter. Plant populations for soybean were 370,000 plants ha^{-1} in all soybean years. Row spacing was 76 cm for corn and 18 cm for soybean. 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 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 ten-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 owner-operator of the farm.

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

Year	Crop	Spring Tillage Type	Spring Tillage DOY	Planting DOY	Nitrogen Fertilizer Application Method[b]	DOY	Rate (kg N ha^{-1}) H	M	L	Summer Tillage Type	Summer Tillage DOY	Harvest DOY	Fall Tillage Type	Fall Tillage DOY
1996	Corn	FC	114	115	AA & NPK	109 & 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, and potassium; RCC = row-crop cultivator; MP = moldboard plow; UAN = urea ammonium nitrate; and CP = chisel plow.
[b] Fertilizer was injected into the soil.
[c] AA was applied on DOY 109 at rates of 202 (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 measurement data 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) describe 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 near the site. Missing data and precipitation data for temperatures below 0°C were obtained from a National Climatic Data Center 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. Measurements of the water table depth were available from 2001 through 2005. To characterize the N balance at the site, water samples were automatically collected from drainage sumps and were returned to the laboratory on a biweekly basis for analysis of NO_3-N content in drainage effluent (Jaynes et al., 2001). After harvest each year, grain samples were analyzed for protein content, and soil residual NO_3-N concentrations were measured from soil cores collected 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, other necessary meteorological information, including maximum and minimum daily temperature, wind run, solar radiation, and relative humidity, were collected from this station. Thirty-five years of central Iowa weather information from 1961 through 1995 was used to initialize the model. For 1961 to 1990, maximum and minimum daily temperature, solar radiation, and daily precipitation were obtained from a weather dataset for the Iowa State University Agronomy and Agricultural Engineering Research Center (AAERC), 25 km southwest of our study site. Wind run and relative humidity for 1961 through 1990 were obtained from a National Climatic Data Center (NCDC) weather station at Des Moines International Airport, 75 km south of the study site. For 1991 though 1995, maximum and minimum daily temperatures from AAERC were used, but information on solar radiation, daily precipitation, wind run, and relative humidity were obtained from a dataset for the Walnut Creek watershed located 30 km south of the study 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. Bakhsh et al. (2001) later used these soil properties for simulations in RZWQM, and our study made use of them as well. Soil organic carbon (SOC) measurements at the site indicated 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 three organic matter pools within the nutrient component of RZWQM.

Model Initialization

The soil profile was divided into ten layers and simulated to a depth of 298 cm (table 2). Model inputs for bulk density and saturated hydraulic conductivity (K_{SAT}) were set equal to the values used by Bakhsh et al. (2001) based on the measurements of Bakhsh et al. (2000). Porosity was calculated from bulk density using the default particle density of 2.65 g cm^{-3} in each layer. Necessary parameters to describe the soil water retention curves include the saturated soil water content, residual soil water content, pore size distribution index, and bubbling pressure. 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. Based on previous RZWQM calibrations for similar soils in Iowa (Ma et al., 2007), a pore size distribution index of 0.1 was used in all layers, and values for bubbling pressure were adjusted slightly from those of Ma et al. (2007) to achieve quality simulations of daily tile flow. Other required parameters, including the

Table 2. Parameterization of the soil profile.[a]

Layer	Depth (cm)	BD ($Mg\ m^{-3}$)	Soil Water Retention[b] θ_s ($cm^3\ cm^{-3}$)	θ_r ($cm^3\ cm^{-3}$)	τ_b[d] (cm)	λ	Lateral K_{SAT}[d] ($cm\ h^{-1}$)	Conductivity[c] K_{SAT} ($cm\ h^{-1}$)	τ_{bK}[d] (cm)	SRGF	SOC (%)
1	0-2	1.16	0.56	0.04	−15	0.1	5.0	3.50	−1	1.00	2.69
2	2-15	1.16	0.56	0.04	−15	0.1	5.0	3.50	−15	1.00	2.69
3	15-30	1.22	0.54	0.04	−15	0.1	5.0	3.50	−15	0.30	2.38
4	30-60	1.27	0.52	0.04	−15	0.1	5.0	3.50	−15	0.03	1.09
5	60-90	1.48	0.44	0.04	−15	0.1	5.0	2.00	−15	0.01	1.26
6	90-120	1.56	0.41	0.04	−15	0.1	5.0	1.00	−15	0.00	1.46
7	120-150	1.75	0.34	0.04	−15	0.1	5.0	0.10	−15	0.00	ND
8	150-200	1.80	0.32	0.04	−15	0.1	1.0	0.01	−15	0.00	ND
9	200-250	1.80	0.32	0.04	−15	0.1	0.8	0.01	−15	0.00	ND
10	250-298	1.80	0.32	0.04	−15	0.1	0.6	0.01	−15	0.00	ND

[a] BD = bulk density; θ_s = saturated soil water content; θ_r = residual soil water content; τ_b = bubbling pressure; λ = pore size distribution index; K_{SAT} = saturated hydraulic conductivity; τ_{bK} = conductivity curve bubbling pressure; SRGF = soil root growth factor; SOC = soil organic carbon; and ND = no data.

[b] Other required parameters include A_1 (set to zero) and B (computed using the RZWQM default constraint) for all layers (Ahuja et al., 2000b).

[c] Other required parameters include N_1 (set to zero) and K_2 and N_2 (computed using the RZWQM default constraints) for all layers (Ahuja et al., 2000b).

[d] Calibrated parameters. In addition, the lateral hydraulic gradient was adjusted to a value of 1E-5.

Table 3. Non-default RZWQM parameterization.[a]

Parameter	Value	Source
Hydrology component		
Dry soil albedo	0.2	Bakhsh et al. (2001)
Wet soil albedo	0.1	Bakhsh et al. (2001)
Crop canopy albedo	0.25	Song (1999)
Residue albedo	0.8	Bakhsh et al. (2001)
Effective drain radius	1.1 cm	Youssef et al. (2006)
Bubbling pressure	−15 cm	Calibrated
Lateral K_{SAT}	5 $cm\ h^{-1}$	Calibrated
Lateral hydraulic gradient	1E−5	Calibrated
Nutrient component		
Slow residue to IM-OM TC	0.3	Ma et al. (2007)
Fast residue to fast OM TC	0.6	Ma et al. (2007)
Fast OM to IM-OM TC	0.6	Ma et al. (2007)
IM−OM to slow OM TC	0.7	Ma et al. (2007)
Initial surface corn residue	0.5 $t\ ha^{-1}$	Assumed
Initial age of surface residue	87 d	Assumed
Initial height of surface residue	3 cm	Assumed
Initial residue C:N ratio	60	Assumed
Natural residue incorporation	80%	Assumed
Conc. of NO_3−N in rainwater	1 ppm	Assumed
Denitrification reaction RC	1E−14	Calibrated
Slow OM pool decay RC	2.4E−9	Calibrated
Management		
Corn row spacing	76 cm	Jaynes et al. (2001)
Soybean row spacing	18 cm	Jaynes et al. (2001)
Corn soil planting layer	2	Jaynes et al. (2001)
Soybean soil planting layer	1	Jaynes et al. (2001)
Harvest efficiency	97%	Assumed
Corn stubble height	15 cm	Assumed
Soybean stubble height	2 cm	Assumed
Corn minimum LSR	185 $s\ m^{-1}$	Assumed
Soybean minimum LSR	75 $s\ m^{-1}$	Assumed

[a] K_{SAT} = saturated hydraulic conductivity; IM-OM = intermediate organic matter pool; TC = transfer coefficient; OM = organic matter; C:N = carbon:nitrogen; NO_3−N = nitrate-nitrogen; RC = rate coefficient; and LSR = leaf stomatal resistance.

intercepts and exponents for hydraulic conductivity curves, were computed from the soil water retention parameters using the RZWQM default constraints. A fully saturated soil was assumed when matric suction was less than bubbling pressure. Due to the intensity of tillage at the site and to simplify the model, the macropore and surface crust algorithms were not implemented in this work. Soil layers below the subsurface drains were simulated using the technique of Ma et al. (2007). To maintain a water table in the soil profile, the K_{SAT} of the lower layers was tapered down to 0.01 cm h^{-1} and deep seepage was assumed to be zero. Losses of water below the subsurface drainage system were simulated using the lateral flow algorithm in RZWQM, and the lateral K_{SAT} and lateral hydraulic gradient parameters were adjusted to calibrate this component. Other parameters required for simulating the hydrologic balance are given in table 3.

The nutrient component of the model was initialized using the technique described by Ma et al. (1998) and applied by Jaynes and Miller (1999). For soil layers down to 120 cm, measured SOC (table 2) at the site was divided among the slow (85%), intermediate (10%), and fast (5%) organic matter pools similar to Ma et al. (1998). Because no SOC measurements were available for layers deeper than 120 cm, the final initialization results from another study in central Iowa (Jaynes and Miller, 1999) were used as input for these layers. The Jaynes and Miller (1999) initialization results were also used as input for the residue and microorganism pools in all layers, and inorganic pools were set to zero. These beginning values were then used to initialize the nutrient component of the model by simulating the typical management practices and soil conditions at our study site over 35 years of historical weather data from 1961 through 1995. Organic matter and microorganism pools stabilized in 20 years or less. Nutrient pool values after the 35 year initialization period (table 4) were then used as the initial conditions for model calibration and evaluation simulations and for the long-term simulations of N dynamics. Similar to Kumar et al. (1998) and Jaynes and Miller (1999), rate coefficients for some intrapool organic matter transformations were adjusted to keep simulated organic matter levels similar to measured values. Except for the parameters given in table 3, RZWQM default values were used for all nutrient component parameters, including C:N ratios for the various nutrient pools and initial conditions for all soil water, temperature, and chemical parameters. Rainwater was assumed to have a NO_3−N concentration of 1 ppm.

Table 4. Initial nutrient parameters used for simulations as obtained from the 35-year initialization procedure.

Layer	Depth (cm)	Residue Pools (μg C g^{-1}) Fast	Residue Pools Slow	Organic Matter Pools (μg C g^{-1}) Fast	Organic Matter Pools Inter.	Organic Matter Pools Slow	Microorganism Pools (organisms g^{-1}) Aerobes	Microorganism Pools Autotrophs	Microorganism Pools Anaerobes	NO_3-N (μg N g^{-1})	NH_4-N (μg N g^{-1})
1	0-2	30.8	225.8	462	1714	24738	880001	7087	298800	2.92	0.085
2	2-15	12.3	222.0	469	1714	24738	858602	7097	301981	2.80	0.091
3	15-30	47.3	167.3	209	940	20561	198190	2973	113545	5.58	0.007
4	30-60	26.2	117.8	171	1046	9527	79066	599	51512	10.68	0.002
5	60-90	7.0	13.7	379	1356	11081	14487	237	10254	6.20	0.000
6	90-120	0.0	12.2	518	1547	12063	8775	151	7196	4.02	0.000
7	120-150	4.5	9.3	117	65	210	2798	42	1151	2.69	0.000
8	150-200	3.0	0.9	186	18	208	551	29	102	1.94	0.000
9	200-250	3.3	0.9	186	18	208	495	26	92	2.81	0.000
10	250-298	3.3	0.9	187	18	208	469	24	89	3.18	0.000

Table 5. Simulated management practices used for initializing the nutrient component during model calibration and for applying the calibrated model to simulate the effects of long-term nitrogen (N) application rates.[a]

Crop	Spring Tillage Type	Spring Tillage DOY	Planting DOY	N Fertilizer Application Method	N Fertilizer Application DOY	N Fertilizer Application Rate (kg N ha^{-1})	Harvest DOY	Fall Tillage Type	Fall Tillage DOY
Corn (even years)[b]	FC	112[c]	113[c]	Inject AA	106[c]	202[d]	278[c]	MP	289[c]
Soybean (odd years)	FC	124	125	--	--	--	278	MP	289

[a] DOY = day of year; FC = field cultivator; AA = anhydrous ammonia; and MP = moldboard plow.
[b] As an exception for the nutrient component initialization only, corn was planted in the 1995 growing season.
[c] During leap years, the DOY for these operations must be incremented by one.
[d] To simulate long-term N dynamics, the N application rates were varied from 0 to 300 kg N ha^{-1} at an increment of 50 kg N ha^{-1}.

For model calibration and evaluation purposes, management practices from 1996 through 2005 were simulated in accordance with the producer's actual practices at the site (table 1). For the 35-year nutrient component initialization from 1961 through 1995, a corn/soybean rotation was simulated with corn planted at 66,000 plants ha^{-1} in even years and soybean planted at 370,000 plants ha^{-1} in odd years (table 5). An exception occurred for the 1995 growing season where, in accordance with the producer's known management practices, corn was substituted for soybean in the rotation. During all years of the nutrient component initialization, field cultivation was simulated in the spring, and a moldboard plow tillage operation was simulated after harvest. In addition, a 202 kg N ha^{-1} anhydrous ammonia injection was simulated in the spring prior to planting corn. The management practices given in table 5 were also used for long-term simulations of N dynamics from 1961 to 2005; however, the N application rates were varied to carry out the study. Table 3 gives further details on the parameterization of miscellaneous crop management characteristics, and RZWQM default values were used for the type, intensity, and average effective depth of all tillage operations (Rojas and Ahuja, 2000).

Cultivar parameters for the CERES-Maize and CROPGRO-Soybean components of the RZWQM-DSSAT hybrid model were obtained from the cultivar files packaged with the DSSAT software. In addition, calibration results for other corn (Paz et al., 1999) and soybean (Paz et al., 2003) growth simulations in Iowa and measured information on the developmental progress of corn crops at the study site were available to aid in selection of appropriate cultivar parameters. Preliminary simulations suggested that the generic DSSAT cultivar parameters for a 2750 to 2800 growing degree day corn crop could simulate corn phenological development at the site reasonably well. Phenological parameters for this cultivar resulted in simulated silking dates most similar to the average measured silking date at the site, July 17. In a similar way, the generic cultivar parameters for a late Maturity Group II soybean crop were deemed appropriate for simulating soybean growth at the site. Phenological parameters for this cultivar resulted in simulated soybean harvest maturity dates typical for Iowa, mid to late September. During model calibration, some of the growth and/or yield parameters of these generic cultivars were adjusted slightly to improve crop growth simulations at the site. Default values were used for the ecotype and species parameters required by DSSAT, and soil root growth factors (table 2) were set similar to those used by Ma et al. (2005).

Model Calibration and Evaluation

To calibrate and evaluate the model, the measured dataset was partitioned into two units. 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 ten-year period with 101.7 cm of rainfall in 1996 and 55.4 cm of rainfall in 2000. Thus, the calibration dataset adequately represented the range of management and weather at the site over the ten-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 ten-year simulation period. Measured and simulated data were also compared quantitatively by computing various common statistics used in modeling studies, including the percent error, relative root mean squared error

(RRMSE), coefficient of determination (R^2), model efficiency (EF), and coefficient of residual mass (CRM). The equations and descriptions of these statistical computations were obtained from Bakhsh et al. (2004).

To calibrate the hydrology component, three 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 measured flow from the nine drainage lines at the 27.4 m drain spacing. The bubbling pressure was found to be a sensitive parameter for adjusting the drainable porosity of the soil. This parameter was adjusted within the range given by Rawls et al. (1982) for silty clay loam soils such that the simulated rate of decay in subsurface drain flow, after initial onset, closely matched measured values. The lateral K_{SAT} was also found to be a sensitive parameter and was used to adjust the peak flow rate of subsurface drains at the onset of drainage events. The lateral hydraulic gradient parameter was used to control seepage losses below the subsurface drainage system and was used to adjust the overall subsurface drain flows. Calibrated values of −15 cm, 5 cm h^{-1}, and 1E-5 were used for bubbling pressure, lateral K_{SAT}, and lateral hydraulic gradient, respectively (table 3). These parameters were set equally in all soil layers with two exceptions (table 2). First, in the layers below the tile drain, the lateral K_{SAT} parameter was tapered down to help match measured and simulated water table depths in times of no subsurface drainage. Second, in the top soil layer, the bubbling pressure for the conductivity curve was reduced to limit evaporation from the soil surface and match simulated ET with the measured values from a nearby site (Hatfield and Prueger, 2004).

To calibrate the nutrient component, measured concentrations of NO_3–N in subsurface drain water were averaged across the three replications for each of the three N rate treatments. Two parameters were adjusted to reduce error between measured and simulated NO_3–N concentrations in drain water. First, use of the RZWQM default denitrification reaction rate coefficient was troublesome, because too much N loss through the denitrification pathway resulted in underestimation of N movement through other pathways. The coefficient was adjusted to 1E-14 to achieve denitrification rates between 3 and 17 kg N ha^{-1} $year^{-1}$, as measured by Svensson et al. (1991). Other modelers have also experienced difficulty closing the nitrogen balance with high simulated denitrification rates. For a subsurface drained watershed in Illinois, a denitrification rate of only 4 kg N ha^{-1} $year^{-1}$ was estimated using the ADAPT model to simulate nitrogen cycling (Sogbedji and McIsaac, 2006). Second, the rate coefficient for decay of the slow organic matter pool was also adjusted from the default value to a calibrated value of 2.4E-9 (table 3). This adjustment improved simulations of NO_3–N concentrations in subsurface drain water by increasing the simulated net N mineralization rate to values between 69 and 149 kg N ha^{-1} $year^{-1}$, which were reasonable considering the high SOC measurements at the site (table 2) and previous efforts to characterize rates of N mineralization from soil organic matter (Vigil et al., 2002).

After selecting the set of generic CERES-Maize cultivar parameters to appropriately simulate corn phenological development at the site, the biomass growth and yield parameters were adjusted to improve simulations of corn production. Specifically, the phylochron interval (PHINT) was adjusted to obtain harvest indices around 0.50 (Tollenaar et al., 2006),

Table 6. DSSAT cultivar coefficients used to simulate corn and soybean growth.[a]

Parameter	Description	Value
Corn growth model		
P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod (DD_8)	260
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 (d)	0.75
P3	Thermal time from silking to physiological maturity (DD_8)	800
G2[b]	Maximum possible number of kernels per plant	750
G3[b]	Kernel filling rate during the linear grain filling stage and under optimal conditions (mg d^{-1})	7.8
PHINT[b]	Phylochron interval between successive leaf tip appearances (DD)	60
Soybean growth model		
CSDL	Critical short day length below which reproductive development progresses with no day length effect and above which the development rate is reduced in proportion to hours above CSDL (h)	13.5
PPSEN	Slope of the relative response of development for day lengths above CSDL (h^{-1})	0.267
EM-FL	Time from the end of the juvenile phase to first flower (PD)	17.4
FL-SH	Time from first flower to first pod greater than 0.5 cm (PD)	6.0
FL-SD	Time from first flower to first seed (PD)	13.5
SD-PM	Time from first seed to physiological maturity (PD)	33.0
FL-LF	Time from first flower to the end of leaf growth (PD)	26.0
LFMAX[b]	Maximum leaf photosynthesis rate at saturated light levels and optimal temperature (μmol CO_2 m^{-2} s^{-1})	0.8
SLAVAR	Specific leaf area for new leaves during peak vegetative growth (cm^2 g^{-1})	375
SIZLF	Maximum size of fully expanded leaf under standard growing conditions (cm^2)	180
XFRUIT	Maximum fraction of daily available gross photosynthesis that is partitioned to seed and shell	1.0
WTPSD	Maximum weight per seed (g)	0.19
SFDUR	Seed filling duration for a cohort of seed (PD)	23.0
SDPDV	Average number of seeds per pod under standard growing conditions	2.2
PODUR	Time required for cultivar to add full pod load under optimal conditions (PD)	10.0

[a] DD_8 = degree days above a base temperature of 8°C; DD = degree days; and PD = photothermal days.
[b] Calibrated parameter.

and the kernel number (G2) and grain fill (G3) parameters were adjusted within a reasonable range to reduce the error between measured and simulated corn yield. Similarly, after selecting the set of generic CROPGRO-Soybean cultivar parameters to appropriately simulate soybean phenological development at the site, the maximum leaf photosynthesis rate (LFMAX) was adjusted to improve simulations of soybean production. This parameter was adjusted to achieve harvest indices around 0.38 (Sadras and Calvino, 2001) and to reduce the error between measured and simulated soybean yield. The final cultivar parameters used for simulating corn and soybean growth at the site are given in table 6.

Since the high N rate was most similar to typical N rates currently used for corn production in Iowa, calibration procedures for the nutrient and crop growth components of the model were carried out using data from the three high N rate plots only. After evaluating the model for the high N rate plots, data from the medium and low N rate plots were then used to test how well the calibrated model responded to reductions in N application rates. Errors between measured and simulated crop yield and between measured and simulated NO_3–N concentration in subsurface drain flow were determined using the calibrated model to simulate responses to the reduced N rates in the medium and low N rate plots.

Model Application

The calibrated model was applied to study the long-term effects of N application rates on crop yield and N dynamics for this agricultural system. Management practices given in table 5 were simulated over 45 years of historical weather data at the site. Nitrogen fertilizer was applied as an injection of anhydrous ammonia on April 16 of corn years. Initially, application rates were varied from 0 to 300 kg N ha^{-1} at an increment of 50 kg ha^{-1}. To better understand the system within the expected range of reasonable N application rates, simulations were then run from 100 to 180 kg N ha^{-1} at 10 kg N ha^{-1} increments. Crop yield and the overall N mass balance for the 45-year simulations were assessed to determine how N application rates affected long-term productivity and N cycling within this agricultural system.

Results and Discussion

Calibration and Evaluation

Hydrology

The calibrated model simulated the hydrologic balance at the site as shown in table 7. Precipitation was simulated as the only input of water to the system. Output pathways for water included runoff, ET, subsurface drainage, and seepage below the subsurface drains. Precipitation ranged from 58.9 cm in 2000 to 101.7 cm in 1996, and simulated subsurface drainage followed precipitation patterns over the ten-year study duration with a minimum flow of 2.6 cm in 2000 and a maximum flow of 29.9 cm in 1996. Simulated runoff ranged from 0.2 cm in 2000 and 2002 to 9.4 cm in 1996. Approximately 95% of the runoff in 1996 occurred on day of year (DOY) 168 due to a 16 cm rainfall event on that day. Simulated ET ranged from 43.1 cm in 1996 to 50.4 cm in 2002, both of which were corn years. Little difference was noted in the ET simulations between the corn and soybean models, and simulated ET values for corn followed the measurements of Hatfield and Prueger (2004) for a nearby site in central Iowa. Simulated seepage losses below the subsurface drainage system varied from 4.0 cm in 2000 to 12.5 cm in 1998. These values followed the pattern of subsurface drainage over the ten-year period, indicating the ability of the model to simulate seepage losses in response to water table depth variations. Annual changes in soil water storage ranged from a net gain of 6.6 cm in 1996 to a net loss of 9.8 cm in 1999. The sharp decline in soil water storage and water table depth in 1999 was a precursor for the reduced level of subsurface drainage in the following year. Slight deviations occurred when checking the annual and overall water balance for simulations. For annual simulation data, part of the deficit can be attributed to the case where precipitation happens as snowfall in the later part of one year, but does not either run off or infiltrate until snow melt happens in the succeeding year. Computation of the overall water balance over 10 years indicates a 5.3 cm surplus (0.7% of total precipitation), which may be attributed to sublimation of snow. Small deviations of less than 0.002 cm d^{-1} may also be the result of convergence error in the numerical solution of Richard's equation.

The model simulated annual subsurface drainage for the calibration years with a percent error of 5.44% (table 8). The RRMSE, R^2, EF, and CRM between measured and simulated annual subsurface drainage for calibration years were 15.81%, 0.95, 0.94, and −0.05, respectively, indicating good agreement between measured and simulated values during model calibration. For the evaluation years, the model simulated annual subsurface drainage with a percent error of 10.96%, and the RRMSE, R^2, EF, and CRM statistics were 18.48%, 0.89, 0.78, and 0.11, 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. With an R^2 of 0.77 and a non-normalized root mean square error 0.06 cm d^{-1}, error statistics also demonstrated good agreement between measured and simulated subsurface drainage on a daily basis over the entire ten-year simulation period. Simulations of subsurface drainage were also deemed successful by visually comparing daily measured and simulated values over time (figs. 1 and 2).

Table 7. Annual water mass balance for continuous ten-year simulations (all values in cm).[a]

					SD		
Year	P	RO	ET	SP	OBS	SIM	ΔS
1996	101.7	9.4	43.1	11.0	26.9	29.9	+6.6
1997	69.6	1.5	45.5	10.8	14.7	12.0	−1.8
1998	87.7	4.5	46.0	12.5	32.5	26.4	−0.6
1999	77.3	1.8	48.6	8.4	32.3	28.2	−9.8
2000	58.9	0.2	44.1	4.0	0.1	2.6	+4.7
2001	76.9	1.0	45.2	7.8	18.9	19.3	+6.2
2002	65.9	0.2	50.4	9.4	8.5	11.3	−5.3
2003	75.9	0.3	47.3	6.9	23.2	17.0	+3.9
2004	82.6	0.4	47.8	10.4	24.4	24.9	−1.2
2005	73.1	0.5	50.1	8.4	14.3	12.5	+0.2
Sum	769.6	20.0	467.9	89.5	195.6	184.1	+2.8

[a] P = precipitation; RO = runoff; ET = evapotranspiration; SP = seepage; SD = subsurface drainage; OBS = observed; SIM = simulated; and ΔS = change in soil water storage:

$$P - RO - ET - SP - SD\ (\text{simulated}) = \Delta S.$$

Slight deviations in the annual mass balance are due to snow effects.

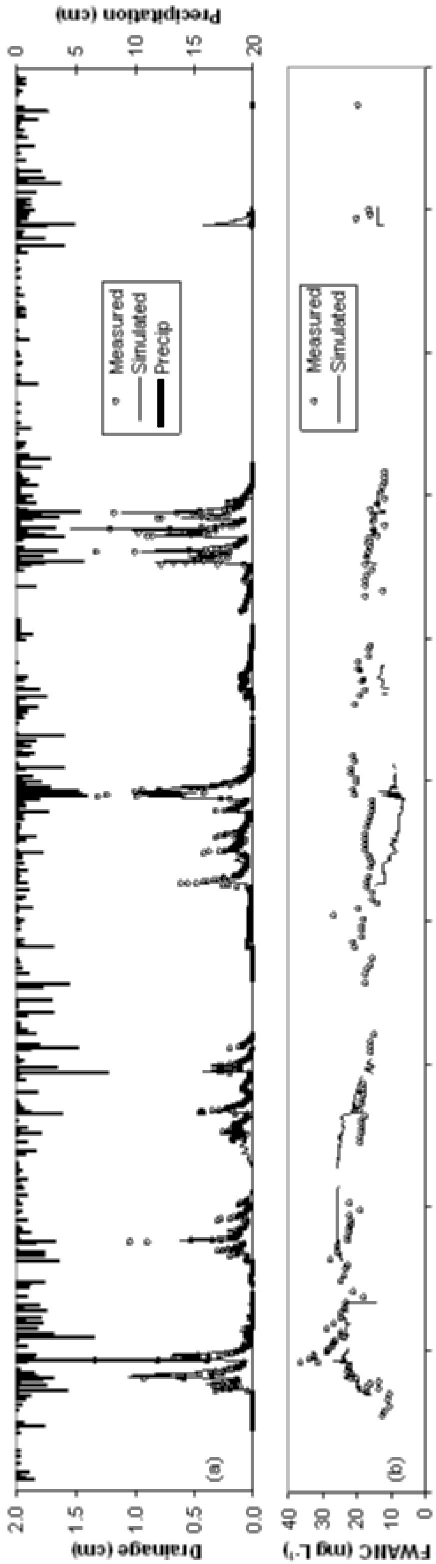

Figure 1. Measured versus simulated (a) subsurface drainage and (b) flow-weighted average nitrate concentration (FWANC) with precipitation for 1996 through 2000 in plots receiving high N rates during corn years (even years).

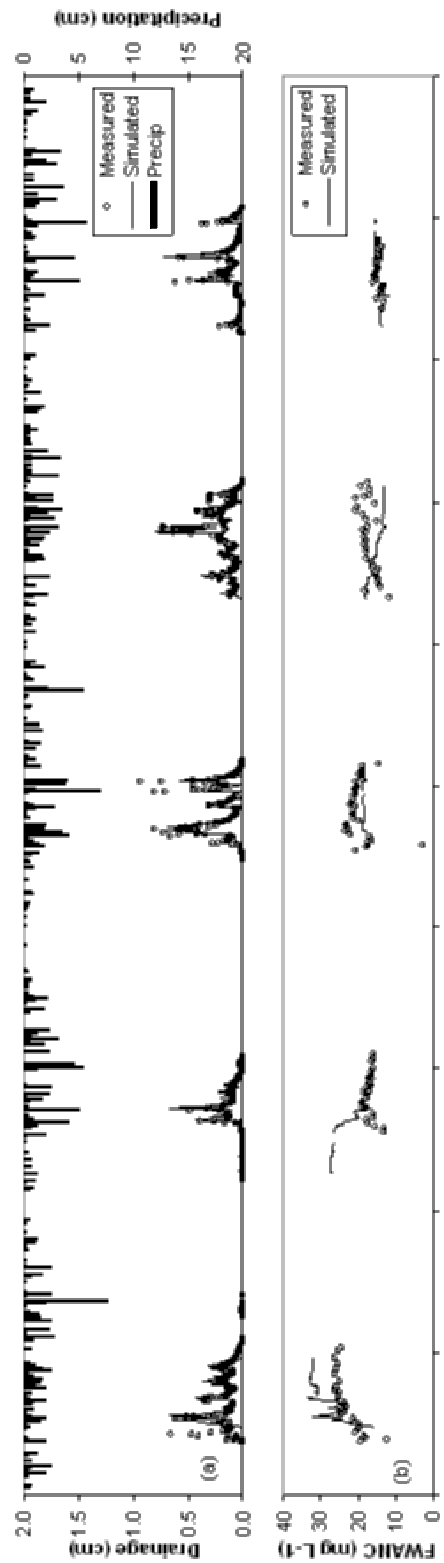

Figure 2. Measured versus simulated (a) subsurface drainage and (b) flow-weighted average nitrate concentration (FWANC) with precipitation for 2001 through 2005 in plots receiving high N rates during corn years (even years).

Table 8. Error statistics for annual simulations of water and nitrogen (N) out the subsurface drainage lines for high N rate plots.[a]

	Calibration[b]		Evaluation[c]	
Statistic	SD	FWANC	SD	FWANC
PE (%)	5.44	1.89	10.96	11.86
RRMSE (%)	15.81	20.70	18.48	22.99
R^2	0.95	0.38	0.89	0.02
EF	0.94	−1.71	0.78	−2.57
CRM	−0.05	−0.02	0.11	0.12

[a] SD = subsurface drainage; FWANC = flow-weighted average nitrate concentration in subsurface drainage; PE = percent error; RRMSE = relative root mean square error; R2 = coefficient of determination; EF = model efficiency; and CRM = coefficient of residual mass.

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

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

Nitrogen

The calibrated model simulated the N mass balance for the high N rate as summarized in table 9. Input pathways included N fertilizer applications, N fixation by soybean, crop residue incorporation and root decomposition, and deposition with precipitation. Output pathways for N included denitrification, volatilization, runoff, subsurface drainage, seepage below the subsurface drains, and crop uptake. Annual changes in simulated soil N storage were computed using the total of all organic and inorganic N present in the soil on the first day of each year. Thus, since net N mineralization merely represents the movement of N between organic and inorganic forms but not an overall change in total N stored, it was not considered as an N input to the soil system for mass balance computations. The primary N input in corn years was fertilizer applications according to the actual management of the high N rate plots (table 1). During soybean years, the model simulated N additions to the system through N fixation in the range of 178 to 276 kg N ha^{-1} (table 9). A secondary pathway for N input to the soil system included incorporation of crop residue and decomposition of crop roots. Annual averages of 91 and 147 kg N ha^{-1} was returned to the system through this pathway during corn years and soybean years, respectively. The assumption of a 1 ppm NO_3-N concentration in precipitation added an average of 7 kg N ha^{-1} per year. Simulated denitrification rates ranged from 1.3 to 18.4 kg N ha^{-1}. Greater amounts of N were lost through denitrification during corn years due to the increased N concentration in surface soil layers from fertilizer applications. Simulated volatilization rates were nearly negligible, with less than 1 kg N ha^{-1} volatilized from fertilizer ammonia during corn years. Levels of N lost in runoff were also negligible. Outputs of N through the subsurface drainage system followed patterns of precipitation over ten years at the site. Maximum precipitation of 101.7 cm in 1996 corresponded to the maximum annual loss of N in subsurface drainage, 70.1 kg N ha^{-1}. Minimum precipitation of 58.9 cm in 2000 corresponded to the minimum annual N loss, 3.6 kg N ha^{-1}, through subsurface drains. Annual loss of N from the soil layers below the subsurface drainage system ranged from 6.4 kg N ha^{-1} in 2000 to 21.0 kg N ha^{-1} in 1998. Average simulated N uptake by corn and soybean crops was 230 and 327 kg N ha^{-1}, respectively. Nitrogen uptake by plants is a difficult process to simulate (Bakhsh et al., 2001). Comparison of measured and simulated N removal in grain indicated that the model tended to simulate too much N uptake, especially for corn (table 10). Annual changes of N storage in the soil, including both organic and inorganic components, ranged from a net gain of 56.4 kg N ha^{-1} in 2003 to a net loss of 67.4 kg N ha^{-1} in 2001. Over the entire ten-year simulation, storage of N in the soil system increased by 66.0 kg N ha^{-1}, indicating that simulated soil N contents in the high N rate plots were relatively stable and unchanging over time. Although this mass balance does not distinguish between organic and inorganic storage of N in the soil, an important factor for management of agricultural systems is the rate at which N is mineralized from organic matter. For this system, simulations showed that N was transferred from the organic to inorganic form at net annual mineralization rates ranging from 69 kg N ha^{-1} in 1996 to 149 kg N ha^{-1} in 1999. Lower net N mineralization rates in 1996 and 1997 are a direct result of the three-year continuous corn management strategy at the site from 1994 through 1996. Corn residue occurs in relatively large quantities but has a moderately high C:N ratio, which corresponds to higher immobilization rates, lower mineralization rates, and thus lower net mineralization rates. Higher net N mineralization rates in 1999 and 2000 are the result of the uncharacteristically warm winter in late 1999 and early 2000. Slight deviations in the N mass balance may be due to convergence error in numerical solutions or due to rounding error in table 9. Convergence error for daily N mass balance computations did not exceed 0.9 kg ha^{-1} d^{-1}.

The model simulated annual flow-weighted average NO_3–N concentration (FWANC) in subsurface drainage for

Table 9. Annual nitrogen (N) mass balance for continuous ten-year simulations in high N rate plots (all values in kg N ha^{-1}).[a]

Year[b]	FZ	FX	RI	P	D	V	RO	SD	SP	PU	ΔS	MN
1996	210	0	98	9.4	6.3	0.95	0.97	70.1	18.2	220	+0.9	69
1997	0	257	148	5.7	1.3	0.00	0.11	25.1	18.2	327	+38.3	75
1998	172	0	60	7.6	8.2	0.85	0.43	25.6	21.0	188	−4.8	99
1999	0	239	127	7.2	2.6	0.00	0.17	43.8	13.6	326	−12.0	149
2000	199	0	77	5.2	10.7	0.75	0.00	3.6	6.4	247	+13.6	130
2001	8	178	106	6.1	3.1	0.00	0.01	56.7	12.4	294	−67.4	107
2002	199	0	130	6.1	18.4	0.72	0.00	21.5	15.8	254	+24.3	122
2003	0	211	192	6.9	3.4	0.00	0.00	31.5	12.0	307	+56.4	116
2004	199	0	92	7.4	9.7	0.99	0.00	36.0	18.2	241	−7.0	99
2005	0	276	161	6.2	3.9	0.00	0.00	19.2	14.6	382	+23.7	131
Sum	987	1160	1191	67.8	67.6	4.30	1.70	333.1	150.5	2787	+66.0	1096

[a] 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; and MN = net mineralization:

$$FZ + FX + RI + P - D - V - RO - SD - SP - PU = \Delta S.$$

Slight deviations in annual mass balance are due to convergence error and rounding error.

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

Table 10. Measured and simulated values for nitrogen (N) balance components in high N rate plots.[a]

Year[c]	FWANC (mg N L^{-1}) OBS	FWANC SIM	Grain N (kg N ha^{-1}) OBS	Grain N SIM	Residual Soil N (kg N ha^{-1})[b] OBS	Residual Soil N SIM	DOY
1996	24.4	23.4	98	124	53.6	46.3	318
1997	17.8	20.9	197	191	54.9	14.0	274
1998	18.5	9.7	107	123	67.3	38.0	298
1999	15.2	15.5	204	190	37.8	21.7	288
2000	20.0	13.9	100	150	57.1	79.2	311
2001	23.8	29.4	128	140	34.4	29.4	319
2002	17.8	19.0	144	162	48.9	46.1	319
2003	21.0	18.5	142	144	29.3	31.9	324
2004	17.9	14.5	134	157	36.2	35.6	316
2005	14.6	15.3	ND	229	65.3	21.4	300

[a] FWANC = annual flow-weighted average nitrate concentration in subsurface drainage; OBS = observed; SIM = 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 11. Crop growth simulation results for high N rate plots.[a]

Year[c]	ABM (kg ha^{-1})	BBM (kg ha^{-1})	LAI	RD (cm)	HI	Yield (kg ha^{-1})[b] OBS	Yield SIM
1996	15855	4552	3.4	67	0.49	8264	7691
1997	8226	1446	5.8	91	0.39	3123	3187
1998	17541	3386	3.4	65	0.54	9067	9470
1999	7869	1399	5.7	92	0.39	3236	3097
2000	17584	3750	3.4	68	0.50	8087	8810
2001	6448	1690	5.3	92	0.37	2453	2384
2002	18972	3832	3.9	72	0.52	10529	9771
2003	7733	1540	6.3	91	0.29	2497	2263
2004	18441	4403	3.3	70	0.54	11475	9975
2005	9252	1493	5.8	90	0.41	3419	3751

[a] ABM = above-ground biomass; BBM = below-ground biomass; LAI = maximum leaf area index; RD = root depth; HI = harvest index, OBS = observed; and SIM = simulated.
[b] Dry weight basis.
[c] Corn in even years and soybean in odd years.

Table 12. Error statistics for simulations of yield and nitrogen (N) removal in grain for high N rate plots.[a]

		Calibration[b] CRN	Calibration SOY	Evaluation[c] CRN	Evaluation SOY
Yield	PE (%)	0.9	0.1	6.0	0.5
	RRMSE (%)	8.0	2.4	9.6	8.1
Grain N	PE (%)	38.5	1.7	14.4	3.6
	RRMSE (%)	40.3	5.9	14.6	6.0

[a] CRN = corn; SOY = soybean; PE = percent error; and 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.

the calibration years with a percent error of 1.89% (table 8). The RRMSE, R^2, EF, and CRM between measured and simulated annual FWANC for calibration years was 20.70%, 0.38, −1.71, and −0.02, respectively, indicating that the model performed more poorly at simulating annual FWANC than annual subsurface drainage. For the evaluation years, the model simulated annual FWANC with a percent error of 11.86%, and the RRMSE, R^2, EF, and CRM statistics were 22.99%, 0.02, −2.57, and 0.12, respectively. Percent error between measured and simulated FWANC was less than 15%, an acceptable value according to Hanson et al. (1999). However, per the definition of the EF statistic, EF values less than zero indicated that the average of FWANC measurements at the site was a better predictor of FWANC than the model. Low values for R^2 resulted from the lower overall variability in annual FWANC in comparison to annual subsurface drainage. With the exception of 2002, FWANC was consistently underestimated in even years when corn was grown (table 10). This result is in agreement with the tendency of the model to overestimate N removal in corn grain. The largest overestimation of FWANC occurred in 2001, which can be attributed to a build-up of NO_3–N in the soil during 1999 and 2000. Higher simulated net N mineralization rates in these years coupled with little precipitation for flushing the soil profile of NO_3–N in 2000 allowed this build-up to occur. Simulations of FWANC in subsurface drain water were also deemed successful by visually comparing measured and simulated values on a daily basis (figs. 1 and 2). Percent error between measured and simulated values for post-harvest soil inorganic N, including NO_3–N and NH_4–N, to a depth of 120 cm was 15.5% for calibration years and 31.6% for evaluation years (table 10). Because of issues associated with N uptake, the model typically had the most difficulty simulating residual soil N in the top 50 cm of the soil profile.

Crop Growth and Yield

The calibrated model simulated crop growth and yield at the site as summarized in table 11. For calibration years, the model simulated corn yield with a percent error of 0.9% and an RRMSE of 8.0%. Soybean yield was simulated with a percent error 0.1% and an RRMSE of 2.4% for calibration years. For evaluation years, the model simulated corn yield with a percent error of 6.0% and an RRMSE of 9.6%, and soybean yield was simulated with a percent error of 0.5% and an RRMSE of 8.1%. These are excellent simulations of crop yield (table 12).

Removal of N in soybean grain was simulated very well with an RRMSE of 6% for evaluation years. Reasonable simulations of both soybean yield and N removal in soybean grain indicate that the percentage of N in soybean grain was simulated appropriately. However, because residual soil N after soybean is underestimated in all years except 2003 (table 10), there may be an issue in the way the model is computing N fixation. The model should perhaps be simulating more soybean N uptake from fixation rather than from extraction out of the soil matrix. Additional evidence for this is seen in the tendency of the model to underestimate subsurface drainage during soybean years (table 7). This underestimation may be indicating an overestimation of soybean transpiration, which would cause more N to flow into the plant from the soil matrix. Even under reduced plant transpiration, soybean N needs could still be met through a simulated increase in N fixation. Overestimation of plant transpiration signals a potential overestimation of soybean leaf area index (LAI) (table 11). Since no data were available for LAI at the site, soybean biomass growth was simulated such that the harvest indices were in good agreement with literature values (Sadras and Calvino, 2001). This strategy resulted in an average maximum LAI of 5.8 for soybean, but the value for corn was only 3.5. Soybean was planted at a higher density, but corn produces twice as much biomass as soybean under normal conditions. Therefore, without measured LAI data, it is unclear whether the simulated maximum LAI values were reasonable or not. As expected, the underestimation of subsurface drainage during soybean years also typically corresponded to an overestimation of FWANC in drainage water (table 10).

Problems with N uptake in the corn model were apparent from the error statistics computed from measured and simulated N in corn grain. The RRMSE for N removal in corn grain was 40% for calibration years and 15% for evaluation years (table 12). Calibration RRMSE is greater than evaluation RRMSE in this case because yield values, not N in grain, was used to tune the corn growth model. Reasonable simulations of corn yield with overestimation of N in grain resulted in a 1.6% simulated N content in corn grain on average. Averaged measured corn grain N content at the site was 1.2%, similar to that measured by other researchers (Singer et al., 2007). With the exception of 1998, subsurface drainage tended to be overestimated in corn years, which may be indicating an underestimation of corn transpiration. Thus, overestimation of N uptake is not occurring as a result of N movement in the transpiration stream. Instead, the algorithms for computing active N uptake must be responsible for the overestimation of N uptake in corn. As expected, overestimation of N uptake typically corresponded to underestimation of both residual soil N and FWANC in subsurface drainage water during corn years (table 10). Underestimation of corn transpiration may also be linked to underestimation of corn LAI (table 11), but no measured data were available to verify LAI simulations.

Another reason for the uptake problems for both crops is that identical soil root growth factors must currently be used for the CERES-Maize and CROPGRO-Soybean components of the RZWQM-DSSAT hybrid model. The user does not have the option to specify soil root growth factors independently for different crop models. The impact of this problem became apparent in the simulations of root growth (table 11). To compensate for the tendency of the corn model to overestimate N uptake, the soil root growth factors were set such that roots would not grow below a depth of 90 cm in the soil profile (table 2). Questionably, this limited corn root growth to depths of less than 70 cm, yet N uptake was still overestimated in corn. These settings also tended to cause too much removal of NO_3-N in the uppermost soil layers, and simulated corn plants rarely experienced water stress (data not shown). On the other hand, the setting for soil root growth factors caused soybean roots to grow to the maximum depth in every year, indicating that the factors had a different effect on growth of soybean roots compared to corn roots. In all years except 1997, soybean growth was simulated with significant levels of water stress even though the roots were growing deeper than corn experiencing no stress. The ability to specify soil root growth factors independently among crop models used in a rotation may improve simulations of N uptake. Further research is also warranted to ensure that each DSSAT crop model responds appropriately under identical soil conditions, such that the models can be effectively united to make continuous simulations of crop rotations.

Temporal Response

In 1996, the first spike in subsurface drainage occurred after a 4.3 cm precipitation event on DOY 130 (fig. 1a), and the model followed this early season drainage trend very well. On DOY 168, a 16.1 cm precipitation event occurred at the site. Measured drainage on the following day was 1.33 cm, the peak value for drainage over the entire ten-year study duration. The model simulated this drainage peak well with 1.27 cm of drainage on DOY 169. Year 1996 experienced more drainage in November and December than any other year in the study. Onset of late fall drainage after a 3.5 cm precipitation event on DOY 296 was simulated very well. However, the model less accurately simulated peak drainage flows after precipitation events on DOY 321 and DOY 349, which may be attributed to issues with simulating freezing rain and/or snowfall. Daily simulated FWANC in 1996 followed the trend of measured values, but the model missed some detail in the daily FWANC variation (fig. 1b). Particularly, the model was unable to simulate the spike in daily FWANC that occurred after the 16.1 cm precipitation event on DOY 168.

In 1997, the model simulated what appeared to be non-measured drainage on DOY 9 through DOY 85 (fig. 1a); however, an equipment malfunction prevented drainage information from being collected during this time period. Simulated drainage followed measured patterns throughout the early part of the growing season in 1997. However, after mid-July, the simulated water table dropped sharply and was unable to recover to simulate drainage from major precipitation events on DOY 205, DOY 285, and DOY 333. This pattern of inability to simulate drainage beyond DOY 200 was evident in all soybean years, although some years exhibited no substantial measured drainage after that time, and annual subsurface drainage was underestimated in all soybean years except 2001 (table 7). This lends further support to the idea that the soybean model overestimated transpiration. Daily FWANC in 1997 (fig. 1b) also showed the annual trend of overestimation (table 10), especially in the first four months of the year. This can be explained in terms of the location of inorganic N in the soil profile. At the end of 1996, there was a significant underestimation of residual soil inorganic N to a depth of 120 cm (table 10). Although no supporting measured data exist for lower layers, the model simulated a significant amount of N mass in the soil layers below 120 cm, including the subsurface drainage layer. Thus, overestimation of FWANC in early 1997 can be attributed to the model's poorly simulated distribution of N in the soil profile at the end of the 1996 growing season. No simulation of FWANC in late 1997 was a consequence of the model's failure to simulate the measured subsurface drainage events during this time.

Unique features of 1998 are continuous measured drainage through the early months of the year and onset of significant drainage events as early as February (fig. 1a). The model had trouble simulating the peak drainage flows resulting from major precipitation events prior to DOY 121, which may be attributed to issues with snowmelt. However, simulated drainage for all of 1998 is an excellent example of the model's ability to simulate the decay in drainage rate after initial onset. Underestimation of FWANC consistently occurred throughout the entire year of 1998 (fig. 1b). An explanation may be that simulated NO_3-N concentrations in the soil profile were overresponding to the effect of growing continuous corn from 1994 to 1996. Significant reductions in simulated net N mineralization in the years following this practice (table 9) as well as the model's tendency to overestimate N removal in corn grain (table 10) may have resulted in simulations of depleted soil NO_3-N concentrations by 1998, and the FWANC in subsurface drainage was lower as a result.

Although the model simulated late fall drainage reasonably in 1998, the simulated water table was not responsive enough to catch measured drainage events in February and March of 1999 (fig. 1a). Onset of simulated drainage in 1999 responded well to the first major precipitation events of the year, which occurred between DOY 93 and DOY 98, and simulated drainage followed measured drainage fairly well throughout the remainder of the year. Daily simulated FWANC also followed the trend of measured values (fig. 1b), indicating that the simulated soil NO_3–N depletions in previous years had recovered by 1999. This recovery is probably due to the unsimulated drainage events in February and March as well as significantly increased simulated net soil N mineralization in 1999 (table 9).

During the first week of July in 1999, the simulated water table began a steady decline and held a low level of 277 cm below the soil surface through May of 2000. The water table did not respond to any precipitation events between July 1999 and May 2000. Several precipitation events between DOY 139 and DOY 163 in 2000 served to raise the water table again, and subsurface drainage was initiated for the only time in 2000 after a 5.0 cm precipitation event on DOY 165 (fig. 1a). It is reasonable to expect that the overestimation of subsurface drainage in 2000 is related to the model's performance in simulating water table fluctuations during periods of low precipitation. Soil profiles in RZWQM can be simulated to a maximum depth of 300 cm; thus, the water table fluctuation to a depth of 277 cm in the spring of 2000 with the resulting overestimation of subsurface drainage in June may have revealed an issue with simulating water table fluctuations in the deepest soil layer. Unfortunately, there was no measured data to verify the actual depth of the water table in 2000.

With significant water table decline after July 2000, the model also missed the measured drainage event that resulted from 4.9 cm of snowmelt infiltration between DOY 74 and DOY 81 in 2001 (fig. 2a). Subsurface drainage was simulated well from DOY 102 through DOY 171, but simulated drainage ceased slightly too early at the end of June in this soybean year. The curve for daily FWANC in drainage water followed a similar shape as measured concentrations; however, an overestimation of FWANC was evident (fig. 2b). The overestimation of residual soil N in the fall of 2000 (table 10) demonstrated why FWANC was overestimated in 2001. With very little subsurface drainage and relatively low seepage levels in 2000 (table 7), two pathways for removal of N from the system were essentially shut down. The model compensated for this by simulating greater rates of denitrification and corn N uptake in 2000 (table 9), and removal of N in grain was grossly overestimated by the model in 2000 (table 10). In spite of this, simulated inorganic N in the upper 120 cm of the soil profile after harvest still exceeded measured values by over 20 kg N ha^{-1} (table 10). These simulation problems in 2000 then resulted in the overestimation of FWANC in subsurface drainage when significant precipitation events in the spring of 2001 flushed the soil profile of NO_3–N. The model's difficulty in simulating the N balance during this period can be linked back further to overestimation of N mineralization during the unseasonably warm winter of 1999 and 2000 (table 9). Because there was very little water to flush the soil profile in 2000, the effects of the overestimation of N mineralization in 1999 did not influence simulations of FWANC in subsurface drainage until 2001.

Throughout the remainder of the simulation from 2002 to 2005, model simulations of daily drainage were very impressive. In 2002, the model responded well to the onset of heavier drainage after 4 cm and 5 cm precipitation events on DOY 117 and DOY 131, respectively (fig. 2a). In 2003, onset of subsurface drainage was simulated fairly well after several precipitation events of less than 1 cm occurred in April; however, the peak drainage rate was not simulated very well during this time. Year 2004 was an excellent year for simulating subsurface drainage, with annual measured and simulated values of 24.4 cm and 24.9 cm, respectively (table 7). Simulated values for daily drainage also tended to closely follow measured values throughout the entire year (fig. 2a). Similar to the 2003 soybean year, onset of drainage in the spring of 2005 was simulated well, but the peak in drainage at onset was not simulated as well. Simulated drainage followed measured values throughout May and June, but the drainage event in July was not simulated as well due to overestimation of soybean transpiration.

Daily FWANC in subsurface drainage was also simulated relatively well from 2002 to 2005. Overestimation of daily FWANC during the first four months of 2002 indicated that the model was still attempting to compensate for poor N balance simulations in previous years (fig. 2b). However, starting in May 2002, the model simulated FWANC very well, and simulations of residual soil N in the fall of 2002 closely matched measured values (table 10). A slight and consistent underestimation of daily FWANC was seen throughout 2003 (fig. 2b). In 2004, daily FWANC was overestimated through DOY 115 and underestimated afterwards. This underestimation was probably associated with the overestimation of N removal in corn grain (table 10) in combination with low N mineralization in 2004 (table 9). Daily simulations of FWANC in 2005 were excellent (fig. 2b).

Response to Reduced N Rates

Although the model was calibrated using data from the high N rate treatment only, use of the calibrated model to simulate the lower N rate treatments demonstrated that the model responded appropriately to shifts in N application rates. Simulations of hydrology at the site were not significantly affected by reduction of N application rates. The average absolute difference between simulated annual subsurface drainage was 0.21 cm when comparing high N rate and low N rate simulations, and it was 0.04 cm when comparing high N rate and medium N rate simulations. Model simulations of annual FWANC in subsurface drainage responded very well to reduced N application rates (fig. 3a), with non-normalized root mean square errors of 3.5, 3.6, and 4.2 mg N L^{-1} for ten-year continuous simulations at the low, medium, and high N rates, respectively. Average simulated and measured FWANC in drainage water over the ten-year study were 10.6 and 10.3 mg L^{-1} for the low N rate, 13.4 and 13.2 mg L^{-1} for the medium N rate, and 18.0 and 19.1 mg L^{-1} for the high N rate, respectively. Similar to high N rate simulations (table 10), years 1998 and 2001 gave the greatest errors between measured and simulated annual FWANC for the low and medium N rate treatments. Model simulations for N removal in grain and for residual soil N also responded to reductions in N rates (data not shown). Soybean yield was not affected by corn-year fertilizer treatments, and the model simulated soybean yield in the low, medium, and high N rate plots with RRMSE of 5.8%, 6.3%, and 6.7%, respectively. Simulated corn yield responded to the three N rate treatments (fig. 3b). The model simulated corn yield with RRMSE of

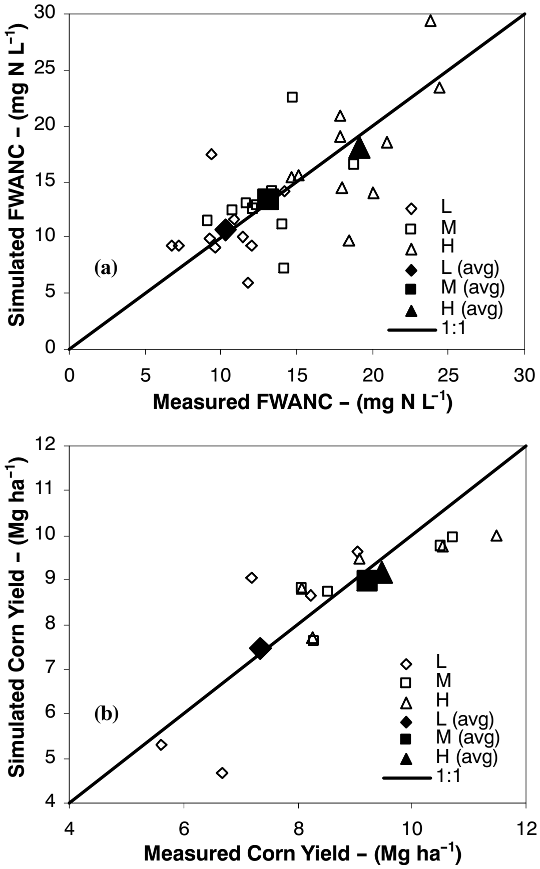

Figure 3. Measured versus simulated (a) annual flow-weighted average nitrate concentration (FWANC) in subsurface drainage and (b) dry-weight corn yield for continuous ten-year simulations at the high (H), medium (M), and low (L) nitrogen application rates.

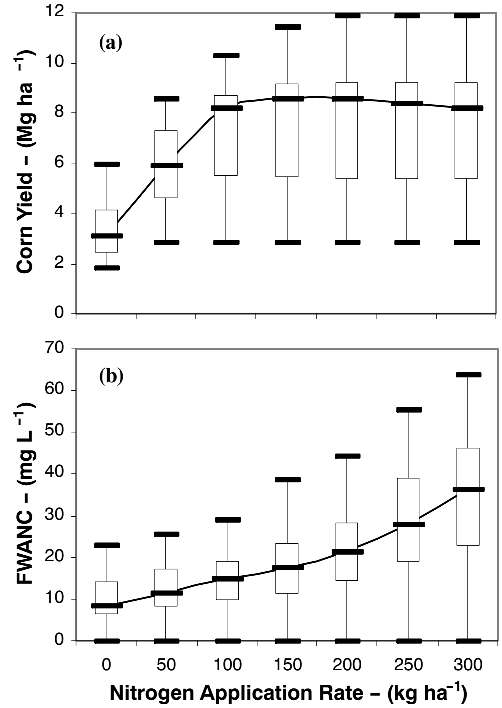

Figure 4. Simulated response of (a) dry-weight corn yield and (b) annual flow-weighted average nitrate concentration (FWANC) in subsurface drainage to variable corn-year nitrogen application rates over 45 years of historical weather information.

17.3%, 7.0%, and 9.2% for the low, medium, and high N rate treatments, respectively. Higher errors for the low N rate treatment resulted from a severe underestimation of corn yield in 1998 and an overestimation of corn yield in 2004. Corn yield simulations in the remaining years were very reasonable for the low N rate treatment. Simulated and measured dry-weight corn yields, averaged over plots and years, were 7452 and 7343 kg ha^{-1} for the low N rate, 8982 and 9224 kg ha^{-1} for the medium N rate, and 9143 and 9484 kg ha^{-1} for the high N rate, respectively. Measured and simulated results both demonstrated that use of N rates higher than the medium rate did not correspond to a significant increase in corn yield. Overall, these results demonstrated that the model was capable of simulating the effect of various N application rates on the processes occurring within this agricultural system.

Long-Term Simulations

Simulations over the long-term weather record from 1961 to 2005 indicated that the N rate for optimizing corn production at this site was between 100 and 150 kg N ha^{-1} (fig. 4a) with median dry-weight corn yields of 8219 kg ha^{-1} and 8584 kg ha^{-1} at these N rates, respectively. Soybean yield was not responsive to corn-year N rates with median values near 2500 kg ha^{-1} regardless of the N rate applied. The FWANC in subsurface drainage water increased exponentially for N rates above 150 kg N ha^{-1} (fig. 4b). Thus, use of N fertilizer in excess of production optimal rates increased the environmental impacts of this management practice.

The simulation results also demonstrate the need for a comprehensive solution to control loss of N from agricultural systems to the environment. Efficient application of N fertilizer is a component of the total solution, but this strategy cannot be used to single-handedly solve the problem. Long-term simulation results suggest that N fertilizer application rates for this agricultural system cannot be reduced below 100 kg N ha^{-1} without a significant reduction in productivity (fig. 4a). Since many producers are reluctant to push the lower limits of N application rate recommendations, 100 kg N ha^{-1} certainly represents a lower bound for possible N rate reductions. Given that the owner-operator of this farm typically applies 180 kg N ha^{-1} to areas of the field not included in this study, the maximum possible reduction in N application rate is 80 kg N ha^{-1}. Reducing N rates from 180 to 100 kg N ha^{-1} corresponded to a moderate reduction in median FWANC in subsurface drainage water, from 19.5 to 14.9 mg N L^{-1} (fig. 4b). The N mass balance for 45-year simulations demonstrated that the 80 kg N ha^{-1} reduction between applications of 180 and 100 kg N ha^{-1} corresponded to a 27% reduction in N lost to water resources. Calculated as the sum of N lost in subsurface drainage, runoff, and seepage, the change in N rates reduced N loss through these pathways from 2531 to 1835 kg N ha^{-1}, a total of only 696 kg N ha^{-1} over 45 years (table 13). If 100 kg N ha^{-1} represents the lower bound rate for optimizing corn yield, then more reasonable expectations for reducing N rates, given producer comfort levels, obviously would lower the potential for reducing N lost to water resources. For example, rate reductions from 180 to 120 kg N ha^{-1} and from 180 to 130 kg N ha^{-1} over 45 years corresponded to 21% and 18% reductions in N lost to water resources, respectively. The January 2001 action plan from the Mississippi River/Gulf of Mexico Watershed

Table 13. Overall nitrogen (N) mass balance for 45-year simulations under variable corn-year N application rates (all values in kg N ha^{-1}).[a]

Rate	FZ	FX	RI	P	D	V	RO	SD	SP	PU	ΔS	MN	G
0	0	4272	4674	326	82	0	7	853	440	8552	–658	5228	4086
50	1100	4175	4948	326	114	0	7	1051	517	9449	–584	5453	4735
100	2200	4092	5215	326	147	2	7	1236	591	10407	–550	5705	5432
150	3300	3925	5395	326	186	7	7	1537	714	11004	–503	5855	5790
180[b]	3960	3828	5513	326	212	11	7	1729	795	11367	–490	5972	5987
200	4400	3756	5577	326	233	15	7	1905	866	11517	–479	6038	6072
250	5500	3594	5656	326	282	29	7	2429	1075	11706	–444	6117	6130
300	6600	3442	5708	326	336	49	7	2978	1295	11814	–396	6171	6156

[a] FZ = total 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; and G = removal in grain:

$$FZ + FX + RI + P - D - V - RO - SD - SP - PU = \Delta S.$$

Slight deviations in annual mass balance are due to convergence error and rounding error.

[b] Current corn production N rate used by the owner-operator of this farm.

Nutrient Task Force (2001) called for a 30% reduction in N discharged to the gulf to effectively reduce the extent of the hypoxic zone, and recent modeling of the gulf has shown that an even larger reduction may be needed. Results of this study indicate that reduction of N fertilizer rates could achieve at least half of the 30% reduction goal without significantly decreasing corn production in the Midwest. However, to effectively combat the problem of hypoxia in the Gulf of Mexico, additional changes in management will be necessary to further reduce losses of N from agricultural cropping systems to water resources in the Mississippi River basin.

The N mass balance of the system for long-term simulations helps identify how N cycling changes with different corn-year N application rates (table 13). First, reductions in N rate during corn years corresponded to increases in N fixation during soybean years and to increases in the amount of N mined from the soil. For the 1100 kg N ha^{-1} reduction in total applied N between the 200 and 150 kg ha^{-1} N rates over 45 years, there is a 169 kg N ha^{-1} increase in N fixation and a 24 kg ha^{-1} increase in N mined from the soil; thus, 18% of the N rate reduction is reintroduced through alternate pathways. Management practices, such as reduced tillage, that aim to sequester nitrogen and carbon in the soil instead of mining N from the soil could be used to reduce this effect. For the 200 kg N ha^{-1} N rate, 1.7%, 19.1%, and 79.2% of N inputs and storage losses were output to gaseous reactions, to water resource pathways, and to plant uptake, respectively. For the 150 kg N ha^{-1} rate, these percentages were 1.4%, 16.8%, and 81.8%. Thus, reduction of N rates tended to increase the percentage of N flowing through the plant uptake pathway and to reduce the percentage of N moving to water resources and to the atmosphere. To be effective in reducing environmental impacts from agricultural systems, other management techniques, such as cover crops (Strock et al., 2004), controlled drainage (Drury et al., 1996), and biological filters (Addy et al., 1999; Romero et al., 1999), must be utilized in addition to efficient N application rates to further increase the percentage of N taken up by plants while reducing the percentage of N lost to the environmental pathways.

Conclusions

After calibration and thorough testing, the RZWQM-DSSAT hybrid model was able to reasonably quantify the hydrology, nutrient dynamics, and crop yield for an agricultural system north of Story City, Iowa. Simulations of corn yield and FWANC in subsurface drainage water responded appropriately to changes in N fertilizer application rates to corn following soybean. In future development of the linkage between RZWQM and the DSSAT family of crop growth models, issues with simulating the interaction of crops and soil should be explored as follows.

- Since root growth differs among crop species (Allmaras et al., 1975) and since root growth simulations with the two crop models were questionable, the soil root growth factors should be allowed to vary independently among crops simulated in a rotation.
- The linked version of the CERES-Maize corn growth model tended to overestimate N removal in grain in spite of questionably shallow rooting depths.
- Simulated residual soil N after soybean was lower than measured values in most years indicating a potential underestimation of N fixation and/or overestimation of N uptake through the transpiration stream.

Long-term simulations of crop yield and FWANC in subsurface drainage indicated that reduction of N fertilizer application rates can significantly reduce N losses from a central Iowa agricultural system; however, this cannot be the lone strategy for solving problems associated with release of agricultural N to the environment. Lowering N application rates to within the production optimum range could achieve half of the N loss reduction goal suggested by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. However, other management strategies must be used in combination with efficient N fertilizer management to fully realize an agricultural system that maintains crop productivity while protecting water resources in the Mississippi River basin and the Gulf of Mexico.

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