Soil Nitrogen Balance under Wastewater Management: Field Measurements and Simulation Results

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The use of treated wastewater for irrigation of crops could result in high nitrate-nitrogen (NO_3–N) concentrations in the vadose zone and ground water. The goal of this 2-yr field-monitoring study in the deep silty clay loam soils south of Dodge City, Kansas, was to assess how and under what circumstances N from the secondary-treated, wastewater-irrigated corn reached the deep (20–45 m) water table of the underlying High Plains aquifer and what could be done to minimize this problem. We collected 15.2-m-deep soil cores for characterization of physical and chemical properties; installed neutron probe access tubes to measure soil-water content and suction lysimeters to sample soil water periodically; sampled monitoring, irrigation, and domestic wells in the area; and obtained climatic, crop, irrigation, and N application rate records for two wastewater-irrigated study sites. These data and additional information were used to run the Root Zone Water Quality Model to identify key parameters and processes that influence N losses in the study area. We demonstrated that NO_3–N transport processes result in significant accumulations of N in the vadose zone and that NO_3–N in the underlying ground water is increasing with time. Root Zone Water Quality Model simulations for two wastewater-irrigated study sites indicated that reducing levels of corn N fertilization by more than half to 170 kg ha^{-1} substantially increases N-use efficiency and achieves near-maximum crop yield. Combining such measures with a crop rotation that includes alfalfa should further reduce the accumulation and downward movement of NO_3–N in the soil profile.

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With increasingly limited ground water resources, the reuse of treated municipal wastewater provides an alternative source of irrigation water for crops and landscaping. In addition, utilization of the nutrients in recycled wastewater as fertilizer may decrease the need for commercial fertilizers in a plant system. However, municipal wastewater can contain high levels of nitrogen (N) and other constituents, such as salt, heavy metals, and pharmaceuticals (Pettygrove and Asano, 1985; Toze, 2006; Kinney et al., 2006), that can be detrimental to surface and ground water supplies. Nitrate-N (NO_3–N) leaching into ground water is widespread in the US Central Plains and elsewhere and has been linked to the over-application of commercial fertilizers or animal waste (Bruce et al., 2003). The environmental impact of treated wastewater irrigation practices needs to be evaluated to determine if and when these practices may affect ground water and what management practices can be changed to slow or prevent the downward movement of contaminants such as NO_3–N.

Understanding the losses and transformation processes of wastewater N in the soil are essential for the sustainable use of treated wastewater irrigation in agriculture. This understanding can be achieved by careful field-data collection and analysis in combination with simulation models capable of assessing the consequences of certain factors and farming practices on N losses to the environment.

Bond (1998) pointed out the conflicting requirements of wastewater irrigation, namely that leaching is essential to prevent salinization of the root zone, yet leaching results in the downward movement of salt and nutrients (such as NO_3–N) through the vadose zone and into the ground water. Bond (1998) also pointed out that research challenges in wastewater irrigation include the quantitative prediction of N transformations to evaluate scenarios for N management and the development of specific and more rigorous guidelines for wastewater applications. This paper addresses these research issues.

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Abbreviations: DSSAT, Decision Support for Agrometeorology Transfer; EC, electrical conductivity; NUE, nitrogen-use efficiency; RZWQM, Root Zone Water Quality Model; SAR, sodium adsorption ratio.

The research reported here focused on the use of the Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2000), a deterministic, integrated model developed by the U.S. Department of Agriculture-Agricultural Research Service that simulates the movement of water and nutrients over and through the root zone of an agricultural field. Using the RZWQM, Ma et al. (1998) evaluated soil NO_3–N response to beef-manure application in a corn field in northeastern Colorado. Their calibrated model provided relatively good predictions for NO_3–N and soil-water content, and they concluded that the RZWQM is capable of adequately describing that agricultural system. Ma et al. (2007a) evaluated long-term (26 yr) corn production and water and N balances using the RZWQM in northeastern Iowa and found that although further improvements in simulating plant N uptake and yield were needed, overall the RZWQM adequately simulated year-to-year variations and N loading in tile flow. Malone et al. (2007) evaluated the RZWQM response to different N management strategies on corn yield and NO_3–N concentrations in subsurface tile drainage water. They found that winter wheat sowed after corn and soybean harvest reduced long-term N loss and concluded that RZWQM accurately quantifies the relative effects of corn production and N loss under several alternative management practices. Bakhsh et al. (2004) used an improved version of the RZWQM to evaluate 6 yr (1992–1997) of field-measured data from a field within Walnut Creek watershed located in central Iowa. Simulations of subsurface drainage flow closely matched observed data, but NO_3–N losses with subsurface drainage water, although simulated reasonably well, were not as accurate. For example, during 1993, the model overpredicted the annual amount of NO_3–N drainage losses by 35%. In a comprehensive study of the fate of N in a field soil-crop environment in the Mediterranean region, Cameira et al. (2007) also found that the prediction of residual NO_3–N in the soil presented errors ranging from 19 to 38% using RZWQM. Hu et al. (2006) calibrated and tested the RZWQM to assess N management in a double-cropping system composed of winter wheat and corn in the North China Plain. In general, soil water, biomass, and grain yields were predicted better than plant N uptake or soil residual N. Attempts to rectify that problem through better calibration of the model did not lead to improved results (Hu et al., 2006). In their study, Saseendran et al. (2007) explored whether more crop-specific plant growth modules could improve simulations of crop yields and N in tile flow under different management practices compared with a generic plant-growth module. They calibrated and evaluated the RZWQM with the Decision Support for Agrometeorology Transfer (DSSAT v.3.5) plant-growth modules (RZWQM-DSSAT) for simulating various land-use practices. Data from 1978 to 2003 from a water-quality experiment near Nashua (Nashua experiments), Iowa, were used. They concluded that, considering the uncertainties of basic input data, processes in the field, and lack of site-specific weather data, the results obtained with that RZWQM-DSSAT hybrid model were not much better than the results obtained earlier with the generic crop-growth module.

The above review of the literature indicates that N process-based models are increasingly being used for various N management activities, such as manure/fertilizer management and crop and irrigation management. This testifies to the practical usefulness of such models. However, obtaining consistently good N-related results with the current modeling technology presents serious challenges.

In this study, the latest version of RZWQM, known as RZWQM2 (http://arsagsoftware.ars.usda.gov; see also Ma et al. [2007b] for the current status of RZWQM development and applications), was used as a tool for comparing alternative management and wastewater-irrigation strategies with respect to crop production and soil/ground water quality. A special feature of this applied research was the study of deep vadose zone profiles combined with an examination of the underlying ground water chemistry.

The objectives of this paper are (i) to study the possibility of N leaching to ground water under secondary-treated wastewater application at two sites in the study area and (ii) to model these processes using the recently released RZWQM2 to propose alternatives to current management practice.

Materials and Methods

Background

A long-term crop-irrigation project with secondary-treated wastewater south of Dodge City in semiarid to subhumid southwestern Kansas (Fig. 1), which is underlain by the High Plains aquifer, was the focus of this study. The Dodge City Wastewater Treatment Plant collects wastewater from Dodge City and a meat-packing plant into a collection station. The collected wastewater is piped 17 km south of the city (Fig. 1) into a wastewater treatment facility, which consists of three covered anaerobic digesters and three aeration basins. The treated water is stored in lagoons with a capacity of more than 3454×10^3 m^3. A pumping system, consisting of several centrifugal pumps, distributes the water to irrigate more than 1100 ha of cropland in 25 fields (Fig. 1, circles). The system is managed by CH2M Hill Operations Management International and monitored by the agronomic firm Servi-Tech, Inc., under contracts with Dodge City.

Use of the treated wastewater has resulted in relatively high soil NO_3–N concentrations (10–50 mg kg^{-1}) in the soil profile at the sites irrigated with this treated wastewater (Zupancic and Vocasek, 2002). Although the study area is characterized by a deep water table ranging from 20 to 45 m below ground surface and soils with a silty clay component (predominantly Harney and Ulysses silt loams; Dodge et al., 1965), the evidence suggests that NO_3–N is moving down through the vadose zone, entering the ground water, and exceeding the USEPA safe drinking-water limit of 10 mg NO_3–N L^{-1} (Zupancic and Vocasek, 2002).

Field Monitoring Sites

We established two wastewater-irrigated monitoring sites (N7 and R8 in Fig. 1) and one ground water–irrigated control site (Y8 in Fig. 1). The sites are considered representative of the wastewater-irrigated and ground water–irrigated sites. Site R8 (37°-34’-32” N, 100°-3’-8” W) has been irrigated with wastewater since 1986, before which it was irrigated with ground water. Site N7 (37°-37’-9” N, 100°-2’-19” W) has been irrigated with wastewater since 1998, before which it was dryland farmed. Site Y8 was irrigated with ground water since 1980,

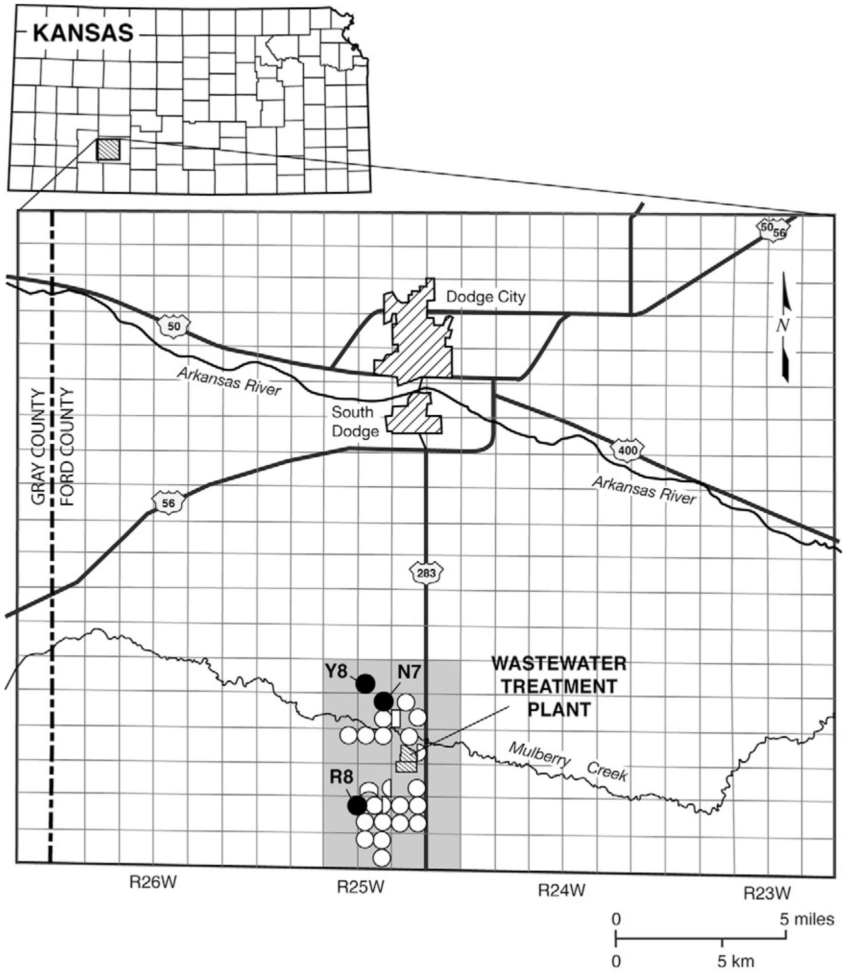

Fig. 1. Location of the study area (highlighted). Circular areas indicate irrigated fields. Black circles are the study sites.

before which it was dryland farmed. Crop-history records indicate corn (*Zea mays L.*) was planted at site N7 each year since 1998 and at site R8 since 2003. From 1997 to 2002, site R8 was planted with alfalfa (*Medicago sativa*). During 2005, the first year of this study, sites N7 and R8 were planted with corn (22–23 Apr. 2005), whereas site Y8 was planted with sorghum (milo). During 2006, the final year of field monitoring, all three sites were planted with corn. The planting history of site Y8 before 2005 is not known with certainty. A LEPA-sprinkler irrigation system applied the treated wastewater at an average rate of 7.3 mm d^{-1} for Site N7 and 6.1 mm d^{-1} for Site R8.

At the beginning of this study (April 2005), we collected three deep (15.2-m) soil cores from each of the sites for a number of physical and chemical analyses using a truck-mounted Giddings probe. Textural, soil hydraulic, and additional physical and chemical analyses were performed by NRCS personnel at the Lincoln, NE, National Soils and Soil Mechanics Laboratories. Nitrogen, carbon, and related analyses were conducted at the Kansas State University and Servi-Tech Soil Analysis Laboratories. The soil bulk density down to 15.2 m was determined from collected cores of known diameter by cutting the core in 15.2-cm increments, weighing them in the field, and oven-drying them in the lab. Table 1 summarizes the measured soil physical properties by layer, which were subsequently used in the simulation model (explained further below), and the experimental methods used to determine those properties.

A neutron probe (503DR Hydroprobe; Campbell Pacific Nuclear Corporation, Martinez, CA) was used to collect moisture-data profiles to 15.2-m depth. Aluminized steel pipe was used as the neutron probe access tube. The neutron probe was calibrated in the field based on core measurements collected from the access tube borehole and on "wet" and "dry" corner plots equipped with neutron probe access tubes that were measured occasionally. Additional details of neutron access tube installation and probe calibration are presented in Sophocleous et al. (2006). Periodic (twice monthly for 2005 and monthly for 2006) measurements of soil water content (at 0.15-m intervals within the upper 1.8 m and at 0.3-m intervals below that) down to 15 m were conducted at one location in each site throughout the growing seasons in 2005 and 2006.

Three suction lysimeters were installed in each site, one at each of three different depths (shallow, 1.6–1.8 m; intermediate, 5.2–8.0 m; and deep, 9–15 m) for collecting pore water samples. A 0.48-MPa vacuum pressure was put on each suction lysimeter 1 wk before sampling. The site R8 shallow-depth and sites R8 and N7 intermediate-depth lysimeters were the only ones to yield pore-water samples in 2005.

All the existing monitoring wells (n = 14) in the area (Fig. 3) were sampled twice a year to measure nitrate-N (NO_3–N) concentrations in ground water, which ranges from depths of 21 m close to the ephemeral Mulberry Creek to >45 m away from Mulberry Creek (Fig. 1). Additional water samples from monitoring, domestic, and irrigation wells and wastewater lagoons were periodically collected.

The Root Zone Water Quality Model

The Root Zone Water Quality Model RZWQM2 is an integrated physical, biological, and chemical process model that simulates plant growth and the movement and interactions of water, nutrients, and pesticides over and through the root zone at a representative area of an agricultural cropping system. It is a one-dimensional (vertical into the soil profile) model designed to simulate conditions on a unit-area basis; it does not address lateral variations in soil properties and water-flow processes. Details on all aspects of the model can be found in Ahuja et al. (2000).

The model uses the Green-Ampt equation to simulate infiltration and the one-dimensional Richard's equation to redistribute water within the soil profile. The hydraulic properties are defined by the soil-water characteristic or retention curves and the unsaturated hydraulic conductivity function. Those relationships are described by functional forms suggested by Brooks and Corey (1964) with slight modifications (Ahuja et al., 2000). In this study, the Brooks-Corey parameters were obtained by fitting the RETC (RETention Curve) program (van Genuchten et al., 1991) to measured soil-water content data.

The soil carbon/nitrogen dynamics module of the RZWQM2 (Shaffer et al., 2000) contains two surface residue pools (fast and slow decomposition), three soil humus pools (slow, medium, and fast decomposition), and three soil microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs). Despite the complexity of this organic matter/N-cycling component, good estimates of initial soil carbon content and nitrogen are generally the only site-specific parameters needed in the model (Ma et al., 1998).

The RZWQM2 is a research-grade, complex tool that was designed to analyze soil and plant processes only within the root zone. Because of model limitations, we had to combine a number of soil horizons into a maximum of 10 layers (Table 1). A downward unit gradient was assumed for the lower boundary condition, set at 10.8 m for site N7 and 4.8 m for site R8 (the lowest depths for which we had detailed soil hydraulic analyses). The first neutron probe soil-water profile measurements before crop planting in April 2005 were used as the initial soil-water depth distribution in the modeling.

The model also requires detailed meteorological data, on a daily basis, and rainfall intensity. Hourly precipitation and other meteorological data (except for solar radiation) were obtained from the Dodge City Municipal Airport weather station 17 km northeast of the study sites; daily solar radiation data were obtained from the Garden City Agricultural Experiment Station 80 km west-northwest of Dodge City, operated by Kansas State University. Due to similar geomorphic, land-use, land-cover, and climatic conditions between Garden City and Dodge City, no significant impacts on calculated water budget components are expected from such climatic-data translocations. This is confirmed by comparing 5 yr (1986–1990) of daily solar radiation data when both Dodge City and Garden City weather stations were collecting such data (M. Knapp, Kansas State Climatologist, written communication, 15 May 2008). A linear regression of the daily average solar radiation values at Dodge City and Garden City during the period 1986 to 1990 yielded an R^2 of >94%. A year-by-year comparison indicated that the Dodge City total solar radiation as a percentage of that from Garden City was 97% for 1986, 99% for 1987, 93% for 1988, and 100% for 1989 and 1990 (M. Knapp, State Climatologist, written communication, 15 May 2008). The model also requires specification of land-use practices such as planting and harvesting dates, specification of irrigation and fertilization events, and the chemical quality of irrigation.

The RZWQM included a generic crop model that can be parameterized to simulate specific crops (Hanson, 2000). However, the latest model version RZWQM2 (version 1.5) incorporated the Decision Support System for Agrometeorology Transfer, DSSAT4.0 suite of crop models (www.icasa.net/dssat/index.html; Ritchie et al., 1998) that can simulate detailed yield components and phenomenological development for specific crops. Of particular interest in our study is the dedicated corn model CERES-Maize, available as part of the DSSAT4.0. The CERES-Maize model has been extensively used worldwide for the development of crop-management applications (Saseendran et al., 2005).

Model Calibration and Evaluation

For accurate simulations, RZWQM2 must be calibrated for soil hydraulic properties, nutrient properties, and plant-growth parameters for the site and crops being simulated (Hanson et al., 1999) because there are significant interactions among the different model components. The available data for 2005 were used in calibrating the model for sites N7 and R8, whereas the available data for 2006 were reserved for verifying ("validating") the model. Due to budget limitations, the control (ground water–irrigated) site Y8 was not instrumented for detailed soil-water content measurements and thus was not modeled in this study. However, soil cores were periodically sampled from that site to compare NO_3–N depth distributions with those of the wastewater-irrigated sites. Calibration targets included the biweekly (during 2005) and monthly (during 2006) neutron soil-water measurements, soil NO_3–N analyses, and harvested corn grain yields. The number of parameters and processes in the RZWQM2 are so numerous that it is exceedingly difficult to decide which ones to optimize and which optimization scheme might be appropriate or even feasible. As a result, Ahuja and Ma (2002) concluded that such agricultural system models as the RZWQM2 are usually parameterized by trial-and-error or iterative processes, although automated calibration methods are increasingly being used. In this paper, we followed the detailed procedures for calibrating the RZWQM2 as laid out by Hanson et al. (1999) and Ahuja and Ma (2002).

A series of sensitivity analyses was conducted (see Results and Discussion) to identify the most important parameters in the soil and plant portions of the model affecting model output and thus to use in model calibration (Sophocleous et al., 2007).

Table 1. Soil physical properties for sites N7 and R8 by layer (in units used in the RZWQM2).

Layer	Soil type	Horizon depth	Bulk density† (*BD*)	Porosity‡ (φ)	Sand fraction	Silt fraction	Clay fraction	K_s§	1/3-bar WC¶,1 (0.03 MPa)	15-bar WC¶,2 (1.5MPa)	TOC#	Air-entry pressure head	Calibrated porosity†† (θ_s)	Calibrated pore size distribution index
		cm	g cm^{-3}	unitless				cm h^{-1}			%	cm	unitless	
1	silty loam	0–23	1.28 ± 0.12‡‡	0.517 ± 0.045‡‡	0.056	0.686	0.258	1.32	0.226	0.131	1.06	−26.28	0.467	0.204
2	silty clay loam	23–74	1.47 ± 0.12‡‡	0.445 ± 0.045‡‡	0.027	0.621	0.352	0.39	0.254	0.169	0.53	−17.53	0.527	0.122
3	silty clay loam	74–168	1.30 ± 0.09	0.509 ± 0.033	0.033	0.624	0.343	0.73	0.271	0.162	0.26	−36.77	0.486	0.169
4	silty clay loam	168–221	1.24 ± 0.14	0.532 ± 0.053	0.114	0.558	0.328	0.98	0.239	0.141	0.24	−113.64	0.425	0.253
5	silty clay loam	221–363	1.38 ± 0.16	0.479 ± 0.060	0.115	0.554	0.331	0.23	0.207	0.122	0.21	−34.36	0.518	0.189
6	silty clay loam	363–625	1.42 ± 0.04	0.464 ± 0.016	0.090	0.610	0.300	0.54	0.231	0.119	0.05	−48.54	0.436	0.199
7	silty loam	625–848	1.35 ± 0.06	0.491 ± 0.022	0.126	0.631	0.243	0.70	0.234	0.107	0.03	−156.25	0.445	0.364
8	silty loam	848–889	1.38 ± 0.08	0.479 ± 0.031	0.141	0.638	0.221	0.70	0.234	0.126	0.02	−98.21	0.431	0.267
9	silty loam	889–945	1.41 ± 0.09	0.468 ± 0.036	0.267	0.513	0.220	0.70	0.248	0.096	0.02	−40.61	0.414	0.300
10	loam	945–1079	1.52 ± 0.03	0.426 ± 0.013	0.344	0.416	0.240	0.15	0.234	0.102	0.01	−98.04	0.446	0.313
								Site R8						
1	silty clay loam	0–16	1.42 ± 0.08‡‡	0.464 ± 0.030‡‡	0.041	0.643	0.316	0.45	0.354	0.150	1.66	−16.38	0.518	0.151
2	silty clay loam	16–29	1.49 ± 0.08‡‡	0.438 ± 0.030‡‡	0.036	0.659	0.305	0.45	0.353	0.142	1.03	−23.61	0.494	0.151
3	silty clay loam	29–50	1.28 ± 0.11	0.517 ± 0.042	0.023	0.599	0.378	0.16	0.380	0.178	0.75	−156.25	0.566	0.269
4	silty clay	50–68	1.21 ± 0.10	0.543 ± 0.039	0.017	0.553	0.430	0.09	0.395	0.201	0.56	−89.29	0.518	0.181
5	silty clay loam	68–90	1.26 ± 0.08	0.525 ± 0.032	0.021	0.592	0.387	0.28	0.382	0.217	0.42	−84.03	0.500	0.216
6	silty clay loam	90–140	1.52 ± 0.10	0.426 ± 0.039	0.030	0.627	0.343	0.85	0.366	0.167	0.34	−67.57	0.513	0.217
7	silty clay loam	140–260	1.62 ± 0.13	0.389 ± 0.050	0.152	0.502	0.346	0.32	0.299	0.131	0.17	−52.63	0.485	0.209
8	silty clay loam	260–300	1.61 ± 0.09	0.392 ± 0.032	0.194	0.483	0.323	0.15	0.280	0.126	0.12	−131.58	0.456	0.238
9	clay loam	300–410	1.53 ± 0.14	0.423 ± 0.053	0.217	0.494	0.289	0.30	0.273	0.119	0	−109.89	0.507	0.314
10	silty clay loam	410–484	1.54 ± 0.14	0.419 ± 0.054	0.188	0.496	0.316	0.13	0.292	0.128	0	−65.36	0.525	0.246

† Core method; value ± 1 SD.

‡ Calculated assuming a particle density (*PD*) of 2.65 g cm^{-3} (φ = 1 − [*BD*/*PD*]); value ±1 SD.

§ Saturated hydraulic conductivity performed on collected core samples according to astm-d5084 Flexible-wall permeability tests.

¶ Soil-water content (wc): [1]pressure-plate extraction; [2]pressure-membrane extraction.

Leco combustion analyzer of acid-treated sample.

†† Within ±2 SD of initially calculated porosity value (φ).

‡‡ Due to the small number of core samples for layers 1 and 2, the samples for both layers were pooled to calculate a common SD.

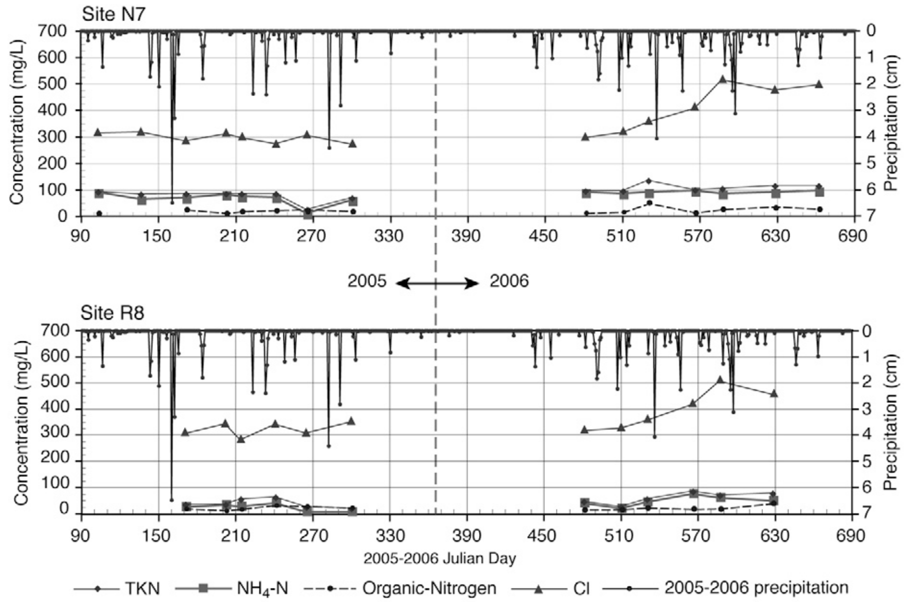

Fig. 2. Treated-wastewater irrigation-water chloride, total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_4–N), and organic nitrogen concentration time series applied to sites N7 (a) and R8 (b) during 2005 and 2006. The nitrate-nitrogen concentration (not displayed) is of the same order of magnitude as organic nitrogen in this graph. Daily precipitation during 2005 and 2006 is also displayed.

For the sensitivity analysis of hydraulic properties, the response variable considered was the soil-water content, whereas for the sensitivity analysis of crop parameters, the response variable considered was the soil NO_3–N. Ahuja and Williams (1991) and Williams and Ahuja (2003) found that the soil water retention curves, as described by the Brooks and Corey equations, could be simply described by the pore-size distribution index, λ. The importance of λ was used for scaling water infiltration and redistribution (Kozak and Ahuja, 2005) and for scaling evaporation and transpiration across soil textures (Kozak et al., 2005). Because of the relatively high sensitivity of parameters θ_s (the saturated soil-water content) and λ, both of which are fitted (as opposed to experimentally measured) parameters, we used the λ and θ_s parameters, which were varied by up to 25% of their originally estimated values, to calibrate the RZWQM2 model. In a few instances, the calibrated θ_s values, which should be considered the calibrated porosity values, were larger than the initially estimated porosity values. Because the porosity (φ) estimates ($\varphi = 1 - [BD/PD]$), derived from the field-measured bulk density (*BD*) and the particle density (*PD*), in our case assumed equal to that of quartz (2.65 g cm^{-3}), contain considerable error, we did not restrict the θ_s values to be less than φ. The RZWQM2 uses θ_s values, not φ values, in its numerical calculations.

The model calibration strategy we used was as follows: The RZWQM2 was first calibrated for soil hydraulic properties, which included the pore-size distribution index (λ) and the saturated soil-water content (θ_s) parameters for each modeled soil layer. The model was then equilibrated with respect to the initial C/N pool sizes for the fast and slow decomposition residue pools; slow, medium, and fast decomposition humus pools; and the three microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs) (Hanson et al., 1999). No laboratory procedures are known to effectively determine the sizes of these pools (Ahuja and Ma, 2002). Therefore, because previous climate and management at a site determines the initial state of a soil in terms of its organic matter and microbial populations, simulations with previous management practices and weather history of the field usually create a better initial condition for those parameters (Ma et al., 1998). After entering all the model inputs and parameters, we estimated the three humus organic-matter pool sizes (based on the measured organic-carbon depth profiles shown in Table 1) at 5, 10, and 85% for fast, medium, and slow pools, respectively, and set the microbial pools at 50,000, 500, and 5000 organisms per gram of soil, respectively, for aerobic heterotrophs, autotrophs, and facultative heterotrophs, as recommended by Ahuja and Ma (2002). This process was facilitated by the RZWQM2 initialization wizard. RZWQM2 was initialized for the organic-matter pools by running the model for 12 yr before the 2005–2006 simulation periods with past management and climate conditions to obtain stabilized sizes for all pools and their distribution with depth in the soil. A 12-yr initialization run was suggested by Ma et al. (1998) to obtain steady-state conditions for the faster soil organic pools.

After initialization and equilibration of the carbon and nitrogen (C/N) pool, the crop parameters were calibrated by trial-and-error adjustments to match observed crop phenology and yield as simulated by the CERES-Maize dedicated corn model incorporated into the latest model version RZWQM2. Corn-calibration parameters included four physiological and two growth parameters as follows: (i) thermal time from seedling emergence to the end of the juvenile phase (P1, expressed in degree days above a base temperature of 8°C, °Cd), (ii) photoperiodism coefficient (P2, expressed as days delay in tassel initiation per hour increase in photoperiod, d h^{-1}); (iii) thermal time from silking to physiological maturity (P5, °Cd); (iv) thermal time between successive leaf tip appearances, known as phyllochron interval (°Cd); (v) maximum possible number of kernels per plant (G2);

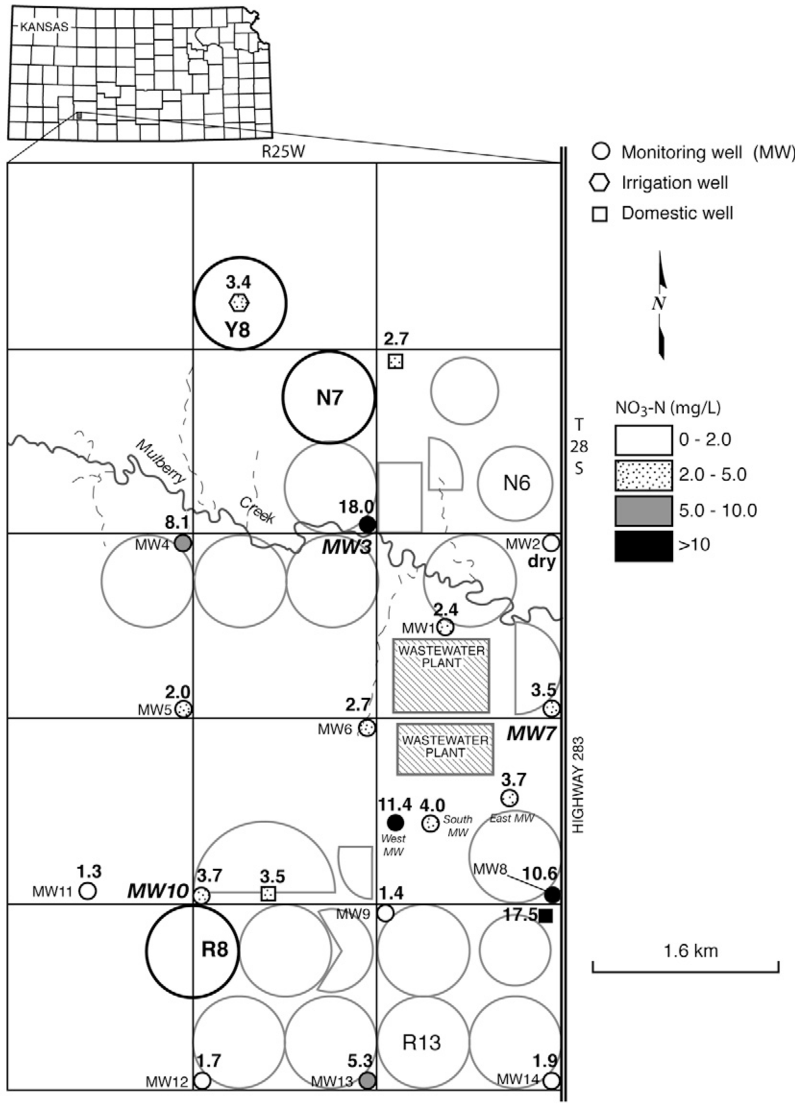

Fig. 3. Ground water nitrate-nitrogen (NO_3–N) concentrations during November 2005. Bold numbers above well symbols indicate ground water NO_3–N concentrations (mg L^{-1}). Circles/semicircles are irrigated fields. The study sites are highlighted. Time series distributions of ground water NO_3–N for monitoring wells MW3, MW7, and MW10 (indicated in bold letters in the Figure) are displayed in Fig. 4.

and (vi) kernel filling rate (G3, mg d^{-1}). We based adjustments of these parameters for corn within the range of values used for Kansas environments (Pachta, 2007; Dogan et al., 2006; Roman-Paoli et al., 2000; Kiniry et al., 1997).

Statistics Used in Model Calibration and Evaluation

Although numerous statistical measures can be used, three statistics were used in this study to evaluate the simulation results: (i) root mean squared error (RMSE) between simulated and observed values, Eq. [1]; (ii) relative root mean square error (RRMSE) (i.e., RMSE relative to the mean of the observed values) Eq. [2]; and (iii) mean relative error (MRE) or bias, Eq. [3].

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \qquad [1]$$

$$\text{RRMSE} = \text{RMSE} \times \frac{100\%}{O_{avg}} \qquad [2]$$

$$\text{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{(S_i - O_i)}{O_i} \times 100\% \qquad [3]$$

where S_i is the ith simulated value, O_i is the ith observed vale, O_{avg} is the average of observed values, and n is the number of data pairs.

The RMSE reflects the magnitude of the mean difference between simulated and experimental results, whereas the RRMSE standardizes the RMSE and expresses it as a percentage that represents the standard variation of the estimator (Abrahamson et al., 2005). The MRE indicates if there is a systematic bias in the simulation. A positive value indicates an overprediction, and a negative value indicates an underprediction.

Alternative Management Simulations and Nitrogen-Use Efficiency

Several management scenarios were simulated using reduced fertilization treatments of 50 and 40% of the actually applied wastewater-N totals at site N7 during 2005 and 2006. Also, reduced irrigation totals of 88, 75, and 50% of actually applied amounts in 2005 were evaluated while maintaining the same irrigation scheduling. In all the above-mentioned management scenarios, the resulting nitrogen-use efficiency (NUE) and grain yields were evaluated.

Nitrogen-use efficiency is a term used to indicate the relative balance between the amount of fertilizer N taken up and used by the crop versus the amount of fertilizer N "lost" and can be defined as follows (Hu et al., 2006):

$$\mathrm{NUE} = \frac{\begin{array}{c}(\text{Plant N uptake for a particular N treatment})\\ -\ (\text{Plant N uptake for zero-N treatment})\end{array}}{(\text{Total amount of N applied})} \qquad [4]$$

To compute NUE, the RZWQM2 model was re-run with a zero-N treatment, and the results were used in Eq. [4].

Results and Discussion

Experimental Observations

The daily precipitation and the general quality of the treated wastewater applied in 2005 and 2006 are shown in Fig. 2. The average electrical conductivity (EC) of the wastewater applied for 2005 was 2.11 mS cm^{-1} for site N7 and 2.07 mS cm^{-1} for site R8 (2.63 and 2.43 mS cm^{-1}, respectively, for 2006), whereas the sodium adsorption ratio (SAR) for 2005 was 5.17 for site N7 and 7.04 for site R8 (6.34 and 5.98, respectively, for 2006). Electrical conductivity and SAR values exceed the Servi-Tech, Inc. agronomic-consulting firm's recommendations of EC <1.5 mS cm^{-1} and SAR <5.0 to avoid salinity problems that may affect crop yields (Zupancic and Vocasek, 2002). Following agronomic recommendations, the farmers averted further salt buildup on crop leaves by converting their sprinklers from higher-pressure overhead nozzles to lower-pressured drop nozzles and by applying gypsum treatments to soils with high exchangeable sodium percentage (Zupancic and Vocasek, 2002).

Figure 3 shows the ground water NO_3–N concentrations from the November 2005 survey sampling. The general ground water flow in the study area is from west to east based on annually measured water levels by the Kansas Geological Survey (www.kgs.ku.edu/Hydro/Levels/). Wells shown in solid black symbols exceed the safe drinking water limit for NO_3–N of 10 mg L^{-1}. Most of the wells have >2 mg L^{-1} NO_3–N in the ground water. This indicates that anthropogenic sources have begun to affect the ground water in the area (Mueller and Helsel, 1996).

The increase in NO_3–N concentration in ground water since 1998 in three of these monitoring wells (MW3, MW7, and MW10, shown in Fig. 3) is shown in Fig. 4. A statistically significant increase in NO_3–N in ground water has occurred, as can be shown by using the Mann-Kendall test for trend (Helsel and Hirsch, 2002). The test statistic, τ, had a positive value (Fig. 4), indicating increasing NO_3–N concentration with time. The calculated probability level, p, (also shown in Fig. 4) was compared with a significance level, α, of 0.10 to indicate a trend if $p < \alpha$, which was the case for the examples shown in Fig. 4.

Figure 5 displays a trilinear diagram with the average water quality (major anions and cations) of the irrigation water applied in R8 and N7 sites marked as the A-circle, the shallow- and intermediate-depth suction lysimeter-sampled pore water from both sites marked as the B-circle, and the sampled (November 2005) domestic, monitoring, and irrigation wells in the area. The sampled populations of applied wastewater, pore water from suction lysimeters, and monitoring and domestic wells form distinct groups in the trilinear Piper diagram. The deeper ground water quality in the general area is a calcium-bicarbonate type water, characterized by relatively low NO_3–N and chloride concentrations (Fig. 5) with specific conductance around 400 µS cm^{-1}. The lysimeter pore water samples plot at a higher sulfate–chloride–nitrate concentration level than the wastewater-reservoir source waters, indicating that evapo-concentration processes and N transformation processes from ammonium-N to NO_3–N may have increased the overall concentration of ions in the lysimeter samples.

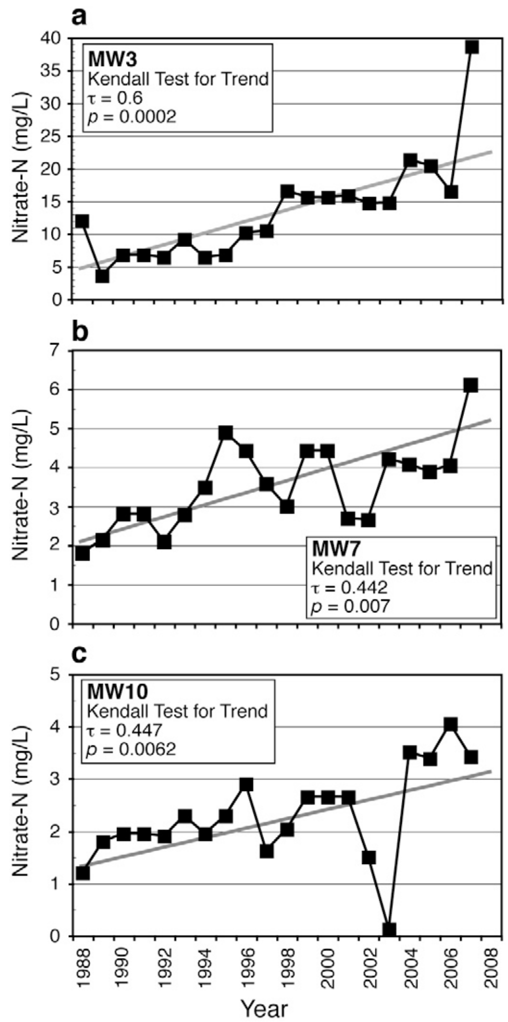

Fig. 4. Ground water nitrate-nitrogen from selected monitoring wells (MW) indicated in Fig. 3. Mann-Kendall trend line and related statistics are indicated, where τ is the nonparametric equivalent of the parametric statistical correlation coefficient, and p is the calculated probability level that is compared with the significance level, α, which was set to 0.10. Depth to water table for wells MW3, MW7, and MW10 were 22.6, 32.0, and 33.5 m, respectively, during the November 2005 measurement survey.

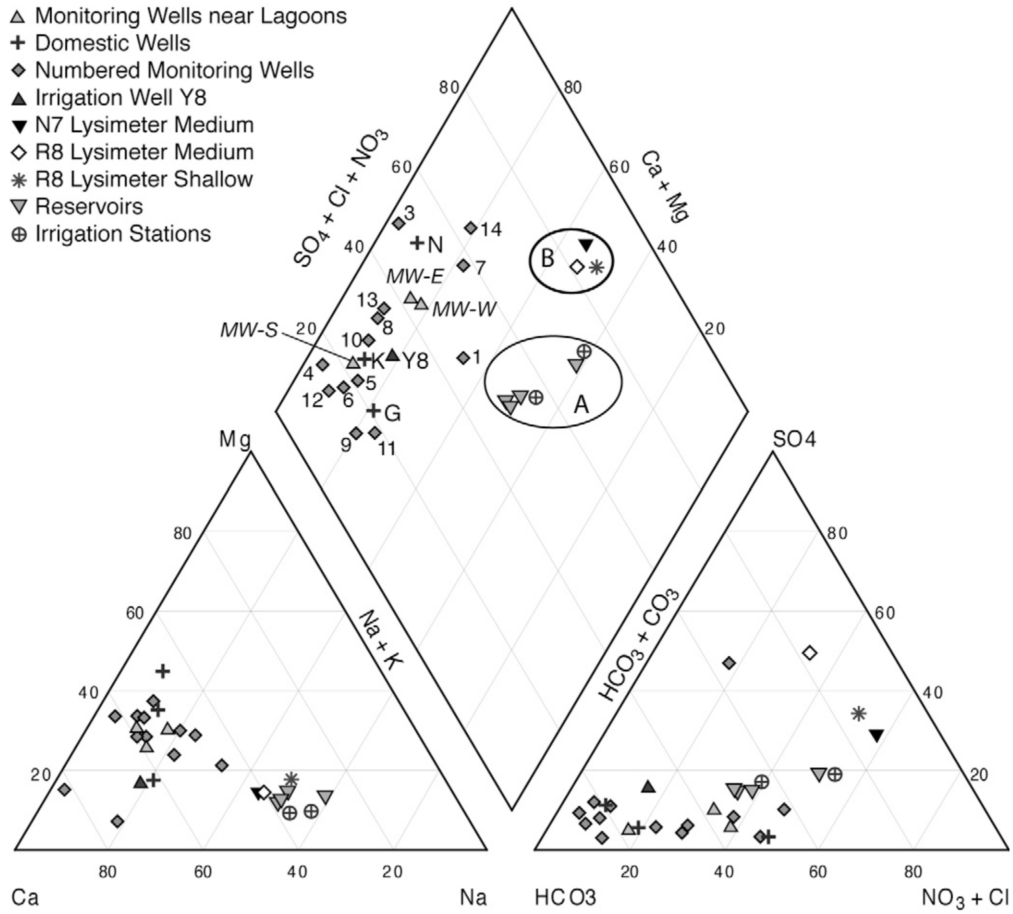

Fig. 5. Trilinear Piper diagram showing the average 2005 quality of irrigation water applied in sites R8 and N7 (circle A), the shallow-and intermediate-depth suction lysimeter-sampled pore water from sites R8 and N7 (circle B), and the domestic, monitoring, and irrigation wells (with their letter/number designations) sampled in the area. The axes numbers represent the percentage of each cation or anion or combination thereof.

High NO_3–N concentrations were found in the soil profile at all sites sampled, as seen in Fig. 6 for sites N7, R8, and Y8. The data for the spring of 2005, which were used as the initial conditions for the RZWQM2, indicated that site R8 (a site with a long-term wastewater-irrigation history since 1986) (Fig. 6a) had a high NO_3–N peak of about 40 mg kg^{-1} around 60 cm, which decreases sharply to 0.7 mg kg^{-1} level in the depth interval of 380 to 580 cm. This decrease is possibly due to previously planted alfalfa roots consuming the NO_3–N at those depths because the R8 site was cropped to the deeply rooted alfalfa perennial from 1997 to 2002. The NO_3–N increases again, reaching a secondary maximum of about 7.2 mg kg^{-1} near the depth of 870 cm, then following a decrease near the 940 cm level to the 3 mg kg^{-1} level. It progressively increases with depth down to more than 1500 cm, reaching the 10 mg kg^{-1} level. It seems that a previous NO_3–N front has reached 1500 cm, with yet older fronts reaching even deeper, indicating that NO_3–N may have already penetrated those depths. When the wastewater-irrigation project began, fertilizer and wastewater were used, resulting in an increased N load above the wastewater concentration. This apparently occurred for several years (1986–1995; F. Vocasek, personal communication, 2008). Before 1986, site R8 was farmed for corn using ground water and fertilizers. For site N7 (with wastewater irrigation history since 1998) (Fig. 6b), a deeper NO_3–N peak (of <28 mg kg^{-1}, i.e., not as high as that at site R8) was observed around the 240-cm-depth level. Then, the NO_3–N concentration progressively decreases with depth to background levels (0.4 mg kg^{-1}) beyond 940 cm, indicating that NO_3–N penetrated to that depth but no further. Before 1998, site N7 was dryland farmed. Finally, for site Y8 (without any wastewater irrigation) (Fig. 6c), a high NO_3–N peak was observed near the 100-cm level, but at the 570-cm-depth level, NO_3–N goes back to background level (1.2 mg kg^{-1}). At site Y8, limited irrigation with ground water occurred since 1980, before which it was dryland farmed.

Historical and current sampling of N in the soil at the studied and nearby wastewater-irrigated sites (N6 and R13; Fig. 3) show increased accumulation of inorganic N in the soil profile with time (Fig. 7; see also Fig. 6), suggesting the inorganic N remaining in the soil at harvest was not taken up completely by the subsequent crop. This residual N is subject to leaching to ground water when rainfall occurs, especially between crop seasons. Numerical simulations indicated consistent increases in N losses due to denitrification, volatilization, and deep seepage as the N-application rate increased.

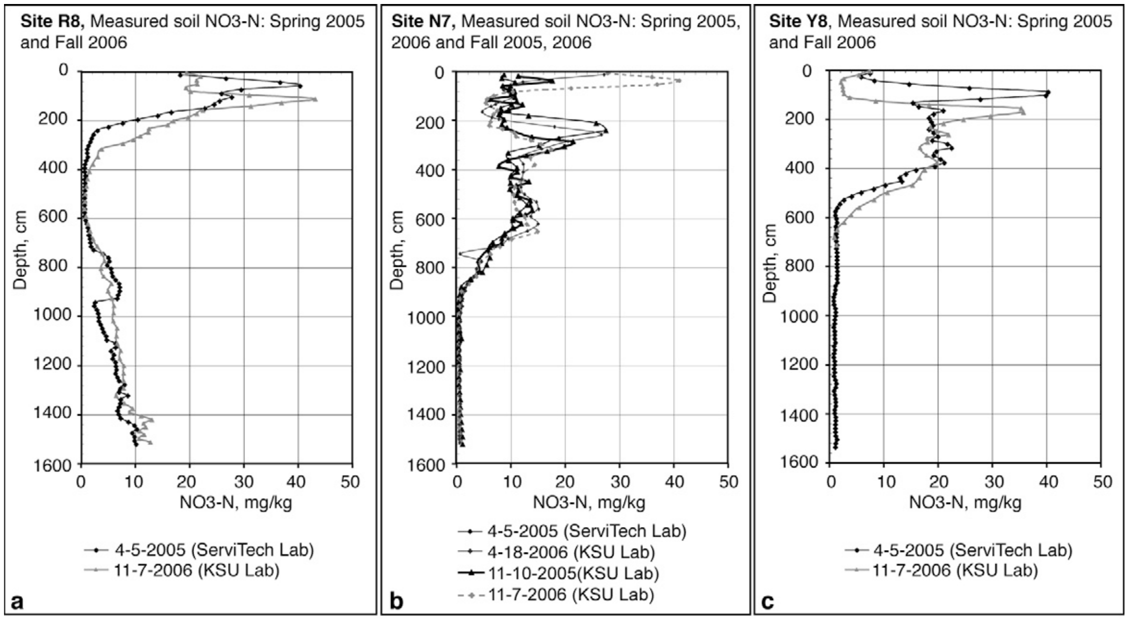

Fig. 6. Measured soil profile nitrate-nitrogen at various times during 2005 and 2006 for the study sites (a, R8; b, N7; and c, Y8).

Sensitivity Analysis

For hydraulic parameters, bulk density, saturation water content (θ_s), and the Brooks and Corey parameters λ (pore-size distribution index) and ψ_a (air-entry or bubbling pressure head) were the most sensitive, whereas saturated hydraulic conductivity (K_s) and residual water content (θ_r) were the least sensitive. As expected, the irrigation and fertilization rates were very sensitive inputs. The hydraulic parameters θ_s and λ were used for model calibration, and the last two columns of Table 1 list the calibrated values of those parameters. The calibrated porosity values (θ_s) were within 2 SD of the initial porosity estimates (Table 1). Additional details on hydraulic and crop-parameter sensitivity analyses for this study site are presented in Sophocleous et al. (2007).

For corn (CERES-Maize) parameters, P1 and P5 were the most sensitive ones from the physiological parameters, followed (in decreasing order of sensitivity) by G2 and G3 from the growth parameters. P2 was the least sensitive from the physiological parameters. The calibrated CERES-Maize parameters are shown in Table 2.

RZWQM2 Model Simulations

Both wastewater-irrigation sites, N7 and R8, were simulated starting from the spring of 2005 and finishing at the end of 2006 (Sophocleous et al., 2007). The simulated and measured water content for the various individual layers for sites N7 (total simulation depth: 10.8 m) and R8 (total simulation depth: 4.8 m) are shown in Fig. 8 for the April to December 2005 simulation period together with the three statistical indicators of model performance (Eq. [1–3]). Although for the upper layers of the soil in both sites the RRMSE and other error measures were relatively high, they improved with soil depth. Using the 2005 calibration parameters, the 2006 simulated and measured soil-water values for the various soil layers for sites N7 and R8 are shown in Fig. 9 along with the three statistical measures. The model seems to satisfactorily predict measured soil-water content, although additional measured data may have further improved this calibration.

The simulated and measured soil NO_3–N profiles in the fall of 2005 in sites N7 and R8, which were planted with corn in April and harvested at the end of September, are shown in Fig. 10 for the 2005 calibration year and in Fig. 11 for the 2006 validation year. The model results for site N7 approximated the main patterns of the November 2005 measured soil NO_3–N profile relatively well (with a relative error of 18.5%), but not the detailed NO_3–N patterns in the soil profile (Fig. 10). For site R8, the November 2005 simulated soil NO_3–N profile had a higher relative error (47.1%). For the prediction year 2006, the site N7 simulated soil profile NO_3–N results for the Spring and Fall sampling dates (Fig. 11a and 11b) had relative errors of 12.8 and 31.1%, respectively, whereas the corresponding relative errors for site R8 simulations (Fig. 11c and 11d) were higher (54.7 and 41.2%, respectively). Obviously, site R8 simulations of soil NO_3–N did not perform very well. Simulating accurate NO_3–N profiles with time is indeed a challenging task.

Besides the measured profile of soil-water content and soil NO_3–N concentration, harvested corn grain yield was used to gauge treatment differences and model performance. For site N7, the corn yield was 14,247 kg ha^{-1} for 2005 and 12,553 kg ha^{-1} for 2006, whereas for site R8 the corn yield was 11,548 kg ha^{-1} for 2005 and 10,105 kg ha^{-1} for 2006. The simulated corn grain yields for site N7 were 15,384 and 11,626 kg ha^{-1} for 2005 and 2006, respectively, whereas for site R8 they were 10,701 and 9102 kg ha^{-1}, respectively. Thus, in all cases, the relative errors in simulated corn yields were well below 10% of measured values.

The model was further analyzed for its response to irrigation and fertilizer management. Although similar results were obtained from both study sites, only results from site N7, which had much higher

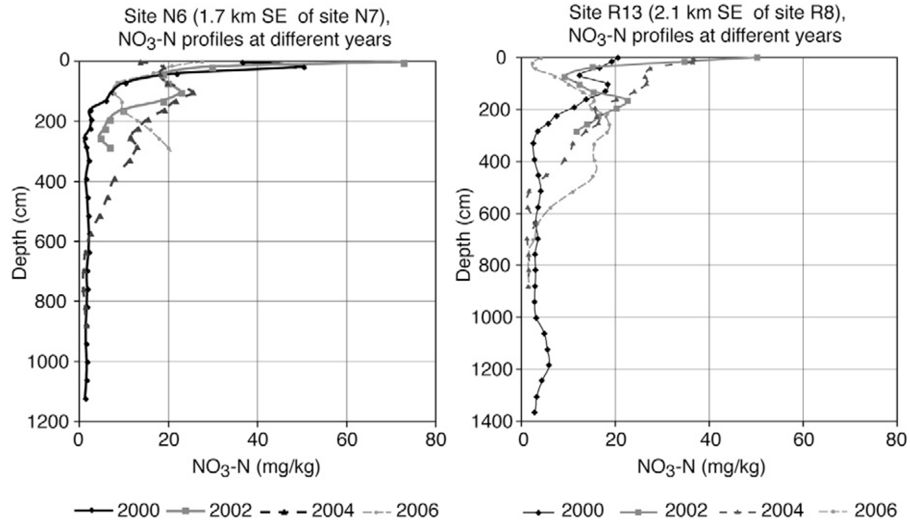

Fig. 7. Time evolution of vadose-zone nitrate-nitrogen profiles for sites N6 and R13, indicated in Fig. 3.

Table 2. Calibrated crop parameters used as input to the Root Zone Water Quality Model for CERES-Maize.

	Maize parameter	Calibrated values
P1	thermal time from seedling emergence to the end of juvenile phase, during which the plants are not responsive to changes in photoperiod (degree days)	245
P2	extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days)	0.52
P5	thermal time from silking to physiological maturity (degree days)	990
G2	maximum possible number of kernels per plant	1100
G3	grain-filling rate during the linear grain-filling stage and under optimum conditions (mg d^{-1})	10.0
PHINT	phyllochron interval (degree days)	38.9

N-fertilization applied than site R8, is presented here. Differences in predicted corn grain yields, plant N uptake, residual soil-profile N, volatilization, and other N losses with different irrigation and fertilization treatments were analyzed using the RZWQM2 model (Table 3). According to Operations Management International lab analyses, the total N applied at site N7 was 427.4 and 520.7 kg ha^{-1} during the 2005 and 2006 irrigation seasons, respectively, both of which were much higher than the total N applied to site R8, which was 230.2 kg ha^{-1} and 252.8 kg ha^{-1} for 2005 and 2006, respectively. The simulated N balance components and NUE for the 2005 and 2006 fertilization totals for site N7 are shown in Table 3. The major source of N is the applied wastewater with additional, secondary sources from dead roots and incorporated residue (Sophocleous et al., 2008), and the major losses of applied N are from plant uptake, with minor losses due to volatilization, denitrification, and deep seepage (Table 3). Mineralization is the major transformation of N, followed by immobilization (Sophocleous et al., 2007; 2008). Large amounts of NO_3–N exist in the unsaturated soil profile (Fig. 6 and 7). The model estimated storage of NO_3–N in the 10.8-m soil profile of site N7 was 1390 kg ha^{-1} in 2005 and 1689 kg ha^{-1} in 2006, suggesting that N leached below the corn root zone and accumulated in the deeper vadose zone and underlying ground water with time (Fig. 4, 6, and 7). The model results indicate that continuing this practice of corn cultivation for the next 20 yr (as a measure of the longer term) will result in NO_3–N accumulation in the deeper vadose zone that will exceed current levels by more than 160% over the 6.8- to 10.8-m-depth interval.

Results suggest that reducing N fertilization by 50% using the same 2005 irrigation scheduling increases NUE significantly while achieving a maximum simulated crop yield, whereas decreasing N fertilization to 40% of the 2005 level achieves maximum NUE while maintaining crop yield within 0.1% of maximum (Table 3). Lowering the wastewater N applications from the 2006 and 2005 applied amounts of 521 and 427 kg ha^{-1}, respectively, to 50 and 40% of those amounts, consistently increased NUE from initially 38.9 and 42.2% to 91.1 and 93.7%, respectively (Table 3). Similar results were obtained for site R8, except that the NUE was lower. For example, the model-estimated NUE for the 2006 fertilization of 252.8 kg ha^{-1} was 36.2%, whereas reducing fertilization by 32.5% (to 170.9 kg ha^{-1}) increased NUE to 54.1% while keeping simulated corn grain yield to within <1% of the normally obtained maximum.

Reducing irrigation total amount for site N7 by various percentages ranging from 12 to 50% (but keeping the same irrigation scheduling) while maintaining N fertilization levels at the near-optimal value of 170 kg ha^{-1} does not result in NUE or grain-yield benefits, which means that the current irrigation practices are efficient and that the used amounts are near optimal (48.55 cm during the 2005 irrigation season; Table 3).

Reducing the fertilization levels at the study sites to around 170 kg ha^{-1} while maintaining currently used irrigation schedules and amounts maximizes the NUE. Such lower fertilization rates can be achieved by blending treated wastewater with freshwater from the underlying High Plains aquifer. This was

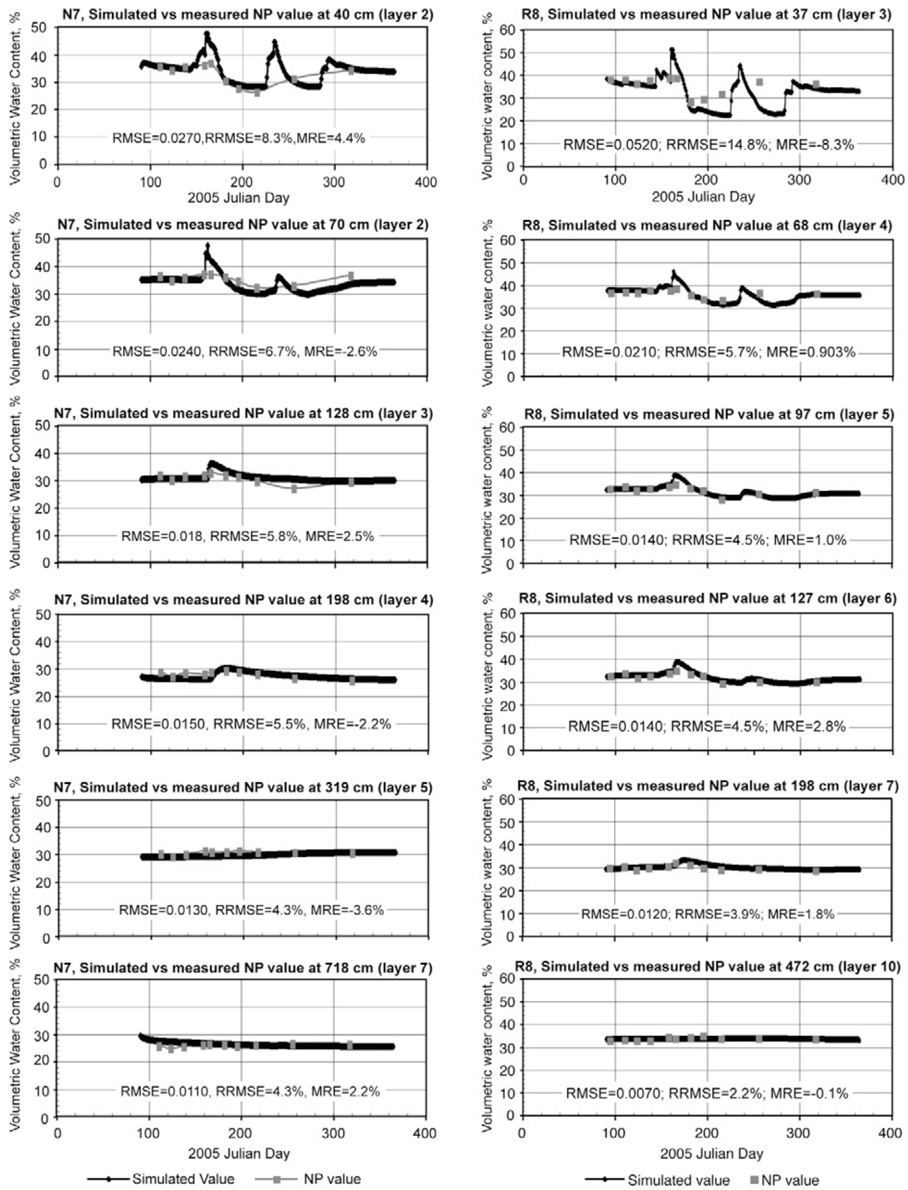

Fig. 8. Comparison of model-simulated and field-measured soil-water contents at various soil depths for sites N7 and R8 during the 2005 calibration period. Three statistical indices, root mean square error (RMSE), relative RMSE (RRMSE), and mean relative error (MRE), are used to quantify the goodness of fit of model parameterization. NP, neutron probe.

practiced during the initial years of the wastewater-irrigation operation, but the practice was later abandoned. The deeper ground water quality is generally good. Implementing a crop-rotation system using leguminous plants, such as alfalfa, will likely decrease the rate of build-up of N in the soil profile, as seen in the profile of site R8 (Fig. 6a), which has a history of alfalfa in the crop rotation.

Conclusions

The analysis performed in this study leads to the following conclusions:

1. Soil coring down to 15.2 m and ground water sampling in the treated-wastewater irrigation area south of Dodge City, Kansas, indicated that NO_3–N is accumulating in the vadose zone and has reached the underlying ground water.
2. Nitrate-N concentrations in the vadose zone and underlying ground water in the wastewater-irrigated areas show increasing trends over time.
3. The RZWQM2 acceptably simulated the observed soil-profile water content but generally overestimated the profile soil NO_3–N and did not simulate its detailed pattern well. In our judgment, better procedures for estimating the humus and microbial pools and plant-growth parameters as well as enhancement of the plant-growth module in the RZWQM2 will further improve the present state of N simulation. Model results may also be improved by increasing the maximum number of soil horizons allowed in the

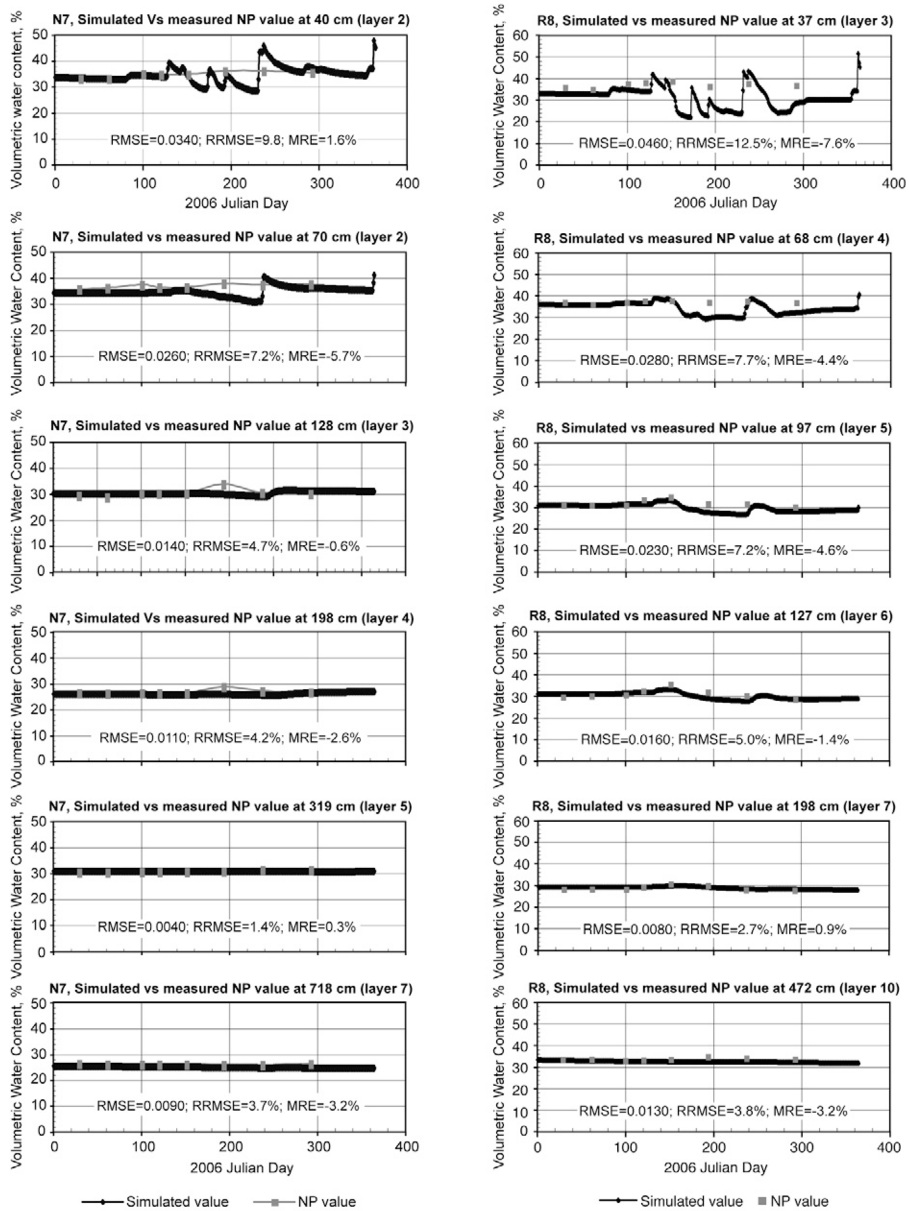

Fig. 9. Comparison of model-simulated and field-measured soil-water contents at various soil depths for sites N7 and R8 during the 2006 prediction period. Three statistical indices, root mean square error (RMSE), relative RMSE (RRMSE), and mean relative error (MRE), are used to quantify the goodness of fit of model parameterization. NP, neutron probe.

model, especially for deep vadose zone profiles, and by obtaining additional soil-hydraulic data.

4. The calibrated RZWQM2 showed that reducing the wastewater N application rates to around 170 kg ha^{-1} increases NUE significantly while maintaining near-maximal crop yield. Adopting this N application rate (170 kg ha^{-1}) would reduce the size of residual NO_3–N stored in the thick vadose zone in the area and slow down its downward migration. Combining such measures with a crop rotation that includes alfalfa should further reduce the amounts of residual NO_3–N in the soil.

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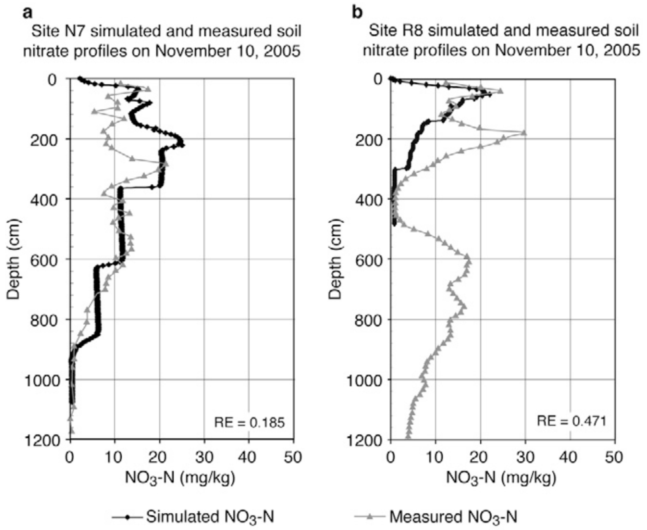

Fig. 10. Measured and simulated soil nitrate-nitrogen profiles at sites N7 and R8 (simulated depths 1080 and 480 cm, respectively) during the soil-sampling date of 10 Nov. 2005.

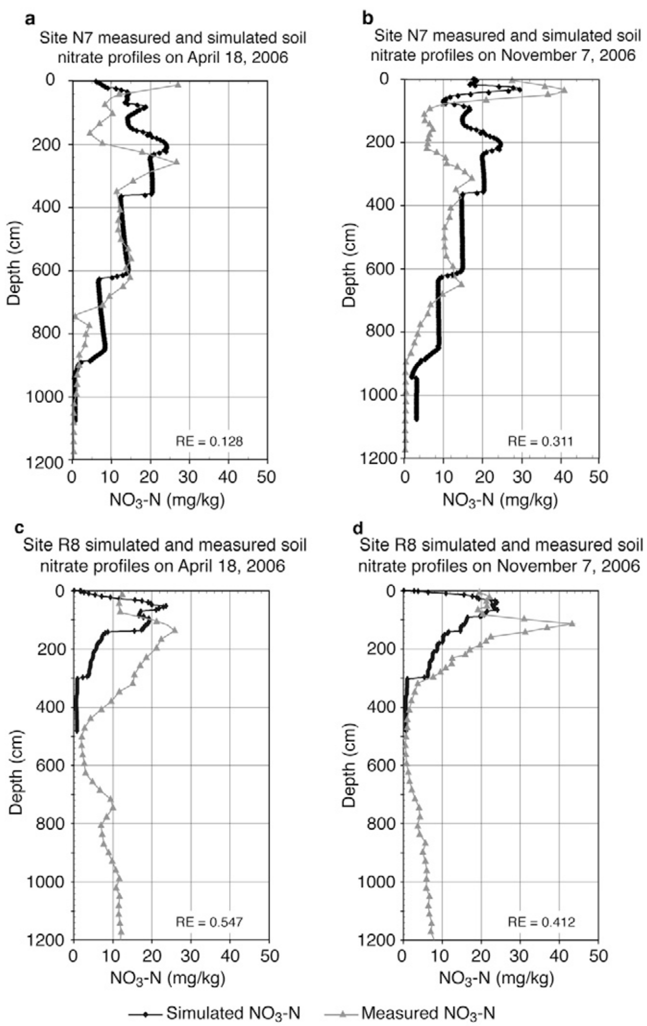

Fig. 11. Measured and simulated soil nitrate-nitrogen profiles at sites N7 and R8 (simulated depths 1080 and 480 cm, respectively) during the soil-sampling dates of 18 Apr. 2006 (a and c) and 7 Nov. 2006 (b and d).

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Table 3. Nitrogen inputs and losses simulated by Root Zone Water Quality Model 2 for the 2005 and 2006 crop seasons for site N7 for current, 50%, and 40% levels of N-fertilization rates and various levels of irrigation reduction through the LEPA system.

Description of method	Crop yield	Percent change in crop yield	Total N input: Storage (10.8m-profile)	Rain	Fertigation[b]	Mineralization	Percent change in mineral ization	Total N losses: Plant uptake	Percent change in plant uptake	Deep seepage	Percent change in deep seepage	Denitrification	Percent change in denitrification	Volatilization	Percent change in volatilization	NUE†
	kg ha^{-1}		kg ha^{-1}													%
								2005								
1. Full rate irrigation‡, full rate N fertilization§	15,384	–	1389.8	9.4	427.4	41.2	–	360.8	–	1.8	–	15.0	–	12.6	–	42.20
2. Full rate irrigation, 50% N fertilization	15,547	1.06	1270.9	9.4	214.4	41.3	0.18	364.0	0.87	1.8	0.01	4.1	−72.93	2.6	−79.63	85.59
3. Full rate irrigation, 40% N fertilization	15,531	0.96	1258.9	9.4	170.4	40.1	−0.57	340.1	−5.74	1.8	0.02	3.7	−75.62	1.5	−88.09	93.70
4. Full rate irrigation, zero fertilization	11,005	−28.46	1251.6	9.4	0	40.9	−0.69	180.5	−49.99	1.8	−0.07	3.2	−78.45	0.0	−99.97	–
5. 88% irrigation, full rate N fertilization	13,654	−11.25	1407.9	9.4	427.4	42.1	2.02	328.7	−8.92	1.8	0.37	17.3	15.18	13.1	4.34	35.04
6. 88% irrigation, 50% N fertilization	14,045	−8.70	1285.6	9.4	214.4	42.3	2.73	337.7	−6.42	1.8	0.38	5.1	−66.35	2.7	−78.54	74.06
7. 88% irrigation, 40% N fertilization	14,090	−8.41	1263.6	9.4	170.4	42.0	1.91	332.1	−7.95	1.8	0.38	3.8	−74.96	1.6	−87.43	89.94
8. 88% irrigation, zero fertilization	10,541	−31.48	1252.5	9.4	0	41.8	1.61	178.9	−50.43	1.8	0.51	3.23	−78.5	0.0	−99.97	–
10. 75% irrigation, full rate N fertilization	11,834	−23.08	1427.5	9.3	427.4	42.8	3.87	294.5	−18.39	1.8	−0.15	19.5	29.82	13.5	7.71	27.68
11. 75% irrigation, 50% N fertilization	11,993	−22.04	1307.0	9.3	214.4	43.1	4.71	299.3	−17.04	1.8	−0.14	6.9	−54.21	2.8	−77.63	56.04
12. 75% irrigation, 40% N fertilization	12,132	−21.14	1280.8	9.3	170.4	43.2	4.82	302.2	−16.26	1.8	−0.15	4.7	−68.56	1.7	−86.71	72.17
13. 75% irrigation, zero fertilization	9866	−35.87	1252.5	9.3	0	43.0	4.49	179.2	−50.34	1.8	−0.19	3.2	−78.60	0.0	−99.97	–
14. 50% irrigation, full rate N fertilization	8005	−47.97	1471.9	9.3	427.4	43.7	6.03	217.4	−39.75	1.7	−1.16	24.4	62.23	15.2	20.76	8.79
15. 50% irrigation, 50% N fertilization	8056	−47.63	1350.8	9.3	214.4	44.3	7.57	220.9	−38.78	1.7	−1.21	11.3	−25.06	3.2	−74.72	19.14
16. 50% irrigation, 40% N fertilization	8128	−47.17	1325.2	9.3	170.4	44.4	7.78	222.8	−38.24	1.7	−1.21	8.6	−43.00	1.9	−84.93	25.23
17. 50% irrigation, zero fertilization	7660	−50.21	1253.7	9.3	0	44.9	8.91	179.8	−50.16	1.7	−1.12	3.2	−78.58	0.0	−99.97	–
								2006								
1. Full rate irrigation¶, full rate N fertilization#	11,626	–	1688.9	11.4	520.7	66.2	–	299.6	–	4.1	–	109.1	–	24.1	–	38.93
2. Full rate irrigation, 50% N fertilization	11,898	2.34	1424.3	11.4	260.7	63.1	−4.66	295.9	−1.23	4.0	−0.60	12.9	−88.13	4.7	−80.34	76.35
3. Full rate irrigation, 40% N fertilization	11,823	1.69	1389.7	11.4	207.9	59.2	−10.50	286.1	−4.48	4.0	−0.78	6.0	−94.46	2.8	−88.46	91.06
4. Full rate irrigation, zero fertilization	5618	−51.68	1374.7	11.4	0	45.4	−31.43	96.8	−67.67	4.0	−1.24	2.4	−97.76	0.0	−100.0	–
5. 88% irrigation, full rate N fertilization	10,068	−13.4	1731.2	11.4	520.7	66.6	0.67	267.6	−10.68	4.1	0.75	122.5	12.24	25.3	5.07	32.82
6. 88% irrigation, 50% N fertilization	10,263	−11.72	1457.4	11.4	260.7	65.2	−1.46	270.8	−9.61	4.1	0.14	20.4	−81.28	5.2	−78.64	66.79
7. 88% irrigation, 40% N fertilization	10,581	−8.99	1409.5	11.4	207.9	61.0	−7.81	264.0	−11.87	4.1	−0.02	8.5	−92.24	3.0	−87.40	80.49
8. 88% irrigation, zero fertilization	5725	−50.76	1379.5	11.4	0	47.8	−27.84	96.7	−67.73	4.0	−0.57	2.6	−97.62	0.0	−100.0	–
10. 75% irrigation, full rate N fertilization	8439	−27.41	1776.9	11.4	520.7	66.3	0.17	233.7	−21.97	4.1	1.36	135.7	24.38	27.0	11.89	26.40
11. 75% irrigation, 50% N fertilization	8720	−25.00	1504.6	11.4	260.7	65.9	−0.48	240.7	−19.64	4.1	0.78	30.5	−72.08	5.8	−75.76	55.41

(cont'd)

Table 3. Continued.

Description of method	Crop yield	Percent change in crop yield	Total N input: Storage (10.8m-profile)	Rain	Fertigation[b]	Mineralization	Percent change in mineral ization	Total N losses: Plant uptake	Percent change in plant uptake	Deep seepage	Percent change in deep seepage	Denitrification	Percent change in denitrification	Volatilization	Percent change in volatilization	NUE†
	kg ha^{-1}		kg ha^{-1}													%
12. 75% irrigation, 40% N fertilization	8826	–24.08	1448.7	11.4	207.9	64.3	–2.80	237.7	–20.66	4.1	0.67	15.2	–86.09	3.4	–86.11	68.02
13. 75% irrigation, zero fertilization	5742	–50.61	1383.0	11.4	0	48.8	–26.32	96.3	–67.86	4.1	0.19	2.7	–97.55	0.0	–100.0	–
14. 50% irrigation, full rate N fertilization	6817	–41.36	1874.6	11.4	520.7	63.7	–3.83	185.0	–38.26	4.2	3.62	143.7	31.63	30.9	28.13	16.70
15. 50% irrigation, 50% N fertilization	6754	–41.91	1607.1	11.4	260.7	64.1	–3.20	183.1	–38.87	4.2	3.08	50.5	–53.68	6.8	–71.91	32.65
16. 50% irrigation, 40% N fertilization	6892	–40.72	1547.7	11.4	207.9	63.6	–3.97	185.1	–38.21	4.2	2.97	31.6	–71.07	4.1	–83.02	41.90
17. 50% irrigation, zero fertilization	5645	–51.45	1391.1	11.4	0	52.9	–20.08	98.0	–67.29	4.2	2.46	2.7	–97.56	0.0	–100.0	–

† Nitrogen use efficiency.

‡ Full rate of 2005-season irrigation = 48.55 cm.

§ Full rate of 2005-season fertigation = 427.4 kg ha^{-1}.

¶ Full rate of 2006-season irrigation = 51.48 cm.

Full rate of 2006-season fertigation = 520.7 kg ha^{-1}.

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