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Nitrogen Dynamics in Irrigated Forage Systems Fertilized with Liquid Dairy Manure

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ABSTRACT

Optimal manure management that ensures adequate crop nutrition while avoiding pollution problems requires estimates of manure N availability. The present study was performed in the San Joaquin Valley (California) on three dairy forage production fields where liquid manure is applied together with flood irrigation water. The objective of this study was to determine the fate of manure N by combining field measurements with model simulations using the Root Zone Water Quality Model (RZWQM). The average annual N application to corn (*Zea mays* L.) and winter forage (oat [*Avena sativa* L.], triticale [×Triticosecale Wittmack], or Sudan grass [*Sorghum bicolor* (L.) Moench ssp. *drummondii* (Steud.) de Wet ex Davidse]) was 840 kg N ha^{-1}, while 490 kg N ha^{-1} was removed with the harvested crops. The irrigation water input to corn ranged from 45 to 128 cm. The RZWQM described crop yield and N uptake well and accurately simulated the seasonal trends in soil moisture and mineral N content in the top 90 cm of the profile; however, the short-term changes and mineral N estimates for different soil layers were not accurate. For soil nutrient and water dynamics, site-specific calibration was an essential requirement. The model estimated that between 140 and 320 kg N ha^{-1} was leached in a 12-mo period and up to 80 kg N ha^{-1} was volatilized as NH_3, while losses due to denitrification were insignificant in these sandy soils. Field data and model estimates highlight the potential for a more efficient water and N use in the forage systems studied.

Adequate N supply is crucial to obtaining high yields in intensive crop production. While insufficient N application can have serious economic consequences for the farmer, however, excessive fertilization increases the risk of environmental pollution, especially groundwater pollution with NO_3^-, NH_3 volatilization, and emissions of N_2O. Even in well-managed cereal crops, a substantial fraction (typically 40–60%) of N fertilizer inputs can be lost (Galloway et al., 2002). One factor contributing to the low efficiency of N fertilization is the highly dynamic nature of the soil N cycle. A considerable part of the N available to crops may originate from the mineralization of organic material such as soil organic matter, manure, or crop residues. Transformations from one N form into another, including mineralization, are mainly mediated by soil microorganisms, which are affected by a number of factors, including temperature, water content, O_2 availability, pH, supply of nutrients, soil texture, as well as organic matter content and quality (Robertson and Groffman, 2007). These dynamic interactions make it difficult to estimate the amount of N mineralized from organic sources and the temporal pattern of mineralization.

The San Joaquin Valley is one of the top agricultural producing regions in California and the United States, with a high density of large dairy facilities. In the three northernmost counties of San Joaquin, Stanislaus and Merced, more than half a million dairy cows were kept in 2007 at 680 dairies, averaging one cow per hectare of total cropland (National Agricultural Statistics Service, 2009). When intensive animal husbandry is practiced on such a large scale, proper manure management is of utmost importance to minimize negative environmental impacts. A unique characteristic of the dairy manure management in this region is that the manure is first passed through a screen to separate particles larger than a few millimeters from the liquid components. The solid manure is stored in piles and spread in spring or fall, while the liquid is stored in large open ponds (lagoons) and applied multiple times to each crop together with water by flood irrigation. Lagoon water constitutes the major N fertilizer applied to forage crops. In these systems, knowledge of manure N availability to crops is a key to ensuring adequate production while minimizing potential adverse environmental impacts. When fertilizer and manure are applied together with water by flood irrigation, however, studies comparing the water and N use efficiency of different management practices are complicated by the fact that small plots with different irrigation or fertilization practices cannot be easily established. The smallest experimental unit is the irrigation plot or check, which may be several hectares in size. This field limitation to conduct research combined with the uncertainty of N availability from manures has impaired the establishment of accurate manure and fertilizer application rates.

Combining measured field data with model predictions may improve our understanding of the processes taking place and

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Abbreviations: RZWQM, Root Zone Water Quality Model; RMAE, relative mean absolute error; EF, model efficiency; LAI, leaf area index.

allow an assessment of the fate of N in cropping systems (Ludwig et al., 2011). A widely used model in U.S. cropping systems is the Root Zone Water Quality Model (RZWQM), which integrates physical, biological, and chemical processes to model plant growth and movement of water and nutrients through the root zone in agricultural cropping systems (Ahuja et al., 2000; Ma et al., 2011). It is a one-dimensional (vertical into the soil profile) model designed to simulate conditions on a unit-area basis. The RZWQM has been evaluated in a number of areas, representing a wide spectrum of management practices (Ahuja et al., 2000; for reviews, see Malone et al., 2001; Ma et al., 2007). For accurate simulations, however, the model must be calibrated for each site and crop cultivar to which the model is applied (Hanson et al., 1999).

The present study was performed in three fields of different dairy farms located in the northern San Joaquin Valley. The objectives of the present study were (i) to measure the input of N with organic and mineral fertilizers and the N output with harvested crops, (ii) to test the usefulness and limitations of the RZWQM for these forage systems using a sequential calibration procedure, and (iii) to estimate the fate of manure and fertilizer N using the model.

MATERIALS AND METHODS

Site Description and Management

The study was conducted between spring 2007 and fall 2008 in fields of three different dairy farms located in California's Central Valley near Modesto (Stanislaus County). The climate at the location is Mediterranean, with a mean annual temperature of 16.4°C and 310 mm of precipitation (Western Regional Climate Center, http://www.wrcc.dri.edu). While corn relies almost entirely on water supplied by irrigation, the winter forage is only irrigated when the amount of precipitation is insufficient. The soils in the area are formed on alluvium and are relatively sandy (Table 1). The farmland surrounding the dairy facilities is used to produce forage and is fertilized mainly with the manure from the dairy facility. In general, two crops a year are produced on the same field, including corn in summer and wheat (*Triticum aestivum* L.), oat, or triticale in winter. Except for stubble, the entire aboveground biomass of the crops is harvested to produce silage. Flood-irrigated fields are generally divided into irrigation checks or plots. The size of the checks chosen for the present study ranged from 1.2 to 6 ha. The three farms were chosen because their forage crop management and soil types are common in the study area.

The soil on Farm 1 is classified as coarse-loamy, mixed, active, thermic Typic Haploxeralf (Soil Survey Staff, http://soils.usda.gov/technical/classification/osd/index.html). The soil has a sandy texture, with at least 800 g sand kg^{-1} soil in most layers, a slightly acidic pH of about 5.6, and a total soil C content in the topsoil of 18 g kg^{-1} soil (Table 1). No-till management was practiced, allowing the farmer to grow three crops annually: corn in summer, Sudan grass in fall, and triticale as winter forage. In both years, the corn was planted in mid-April and harvested in early August (Table 2). At harvest, the average density was about 106,000 plants ha^{-1}. Corn was irrigated every

Table 1. Soil properties of the three study sites.

Depth	Sand	Clay	Total C	pH	Cation exchange capacity	Bulk density†	Soil moisture at 1500 kPa	Soil moisture at 33 kPa‡	Saturated hydraulic conductivity‡
cm	g kg^{-1} dry soil				$cmol_c\ kg^{-1}$	g cm^{-3}	$m^3\ m^{-3}$		cm h^{-1}
					Farm 1				
0–15	823	43	18.0	5.6	5.5	1.25	0.06	0.16	30.0
15–30	846	35	11.0	5.5	4.2	1.34	0.03	0.13	10.0
30–60	882	30	2.7	5.7	1.9	1.51	0.04	0.12	10.0
60–90	892	39	2.0	5.6	1.8	1.55	0.03	0.10	10.0
90–120	891	43	1.4	5.7	1.7	1.57	0.04	0.12	5.0
120–150	689	90	1.2	5.8	4.0	1.56	0.09	0.26	1.0
150–180	826	48	1.3	5.8	2.9	1.57	0.06	0.17	5.0
					Farm 2				
0–15	736	99	17.7	6.6	8.4	1.29	0.08	0.12	5.0
15–30	741	84	9.9	6.8	7.1	1.39	0.08	0.16	5.0
30–60	737	85	4.6	6.7	5.6	1.50	0.09	0.22	4.0
60–90	682	120	2.6	6.7	6.8	1.57	0.09	0.24	1.5
90–120	578	181	1.7	6.9	10.0	1.53	0.13	0.26	1.0
120–150	669	133	1.1	6.6	6.6	1.60	0.11	0.29	1.5
150–180	660	99	0.7	6.8	6.0	1.56	0.08	0.23	1.5
					Farm 3				
0–15	678	101	12.9	6.4	7.0	1.32	0.08	0.21	2.6
15–30	672	103	6.8	6.5	5.7	1.40	0.08	0.18	2.6
30–60	632	139	3.2	6.6	5.4	1.52	0.09	0.24	0.2
60–90	581	180	1.4	6.6	6.2	1.58	0.12	0.26	2.6
90–120	685	139	0.8	6.8	4.8	1.63	0.11	0.26	2.6
120–150	708	177	0.7	6.8	10.3	1.66	0.14	0.30	2.6
150–180	736	156	0.5	6.9	15.5	1.67	0.19	0.40	2.6

† Estimated based on Rawls (1983).

‡ Adjusted to fit the measured moisture contents in the different layers.

7 to 10 d during the primary growing period. Except for the first irrigation, lagoon water was mixed into the irrigation water with each irrigation event. In addition, commercial fertilizer containing urea, NH_4^+, and NO_3^- was added to the irrigation water. The Sudan grass was irrigated four times with smaller amounts of lagoon water. After the Sudan grass harvest, partially decomposed manure with a C/organic N ratio of 24 was spread on the field. About 170 kg N ha^{-1} was applied as manure, 90% of which was in the form of organic N. The triticale was rain fed, except for one irrigation water application in spring.

On Farm 2, the soil, which is classified as a fine-loamy, mixed, superactive, thermic Typic Argixeroll, had an average sand content of 690 g kg^{-1} soil, a pH of 6.7, and a total C content in the topsoil of 18 g kg^{-1} soil (Table 1). Two crops were grown annually: corn in summer and oat as winter forage. In both years, corn was planted during the first half of May and harvested in late August or early September (Table 2). At harvest, the density was 84,000 plants ha^{-1}. In fall 2007, after the corn harvest, the field was ripped to 90 cm and leveled. In spring 2008, dairy manure composted under aerobic conditions with a C/N ratio of 15 was applied. A total of 300 kg N ha^{-1}, 95% in the form of organic N, was applied with the compost. The compost was tilled in, the field irrigated, and corn planted 2 wk later. Lagoon water was applied with all subsequent irrigations to the corn and winter forage.

The soil on Farm 3 is classified as a coarse-loamy, mixed, active, thermic Typic Haploxeralf. The soil has an average sand content of 670 g kg^{-1} soil, a pH of 6.7, and a total C content of 13 g kg^{-1} soil in the topsoil (Table 1). As on Farm 2, corn was grown in summer and oat as winter forage. In both years, corn was planted after mid-May, irrigated every 10 to 14 d, and harvested early in September (Table 2). The density at harvest was about 77,000 plants ha^{-1}. After the corn harvest, liquid sludge from the bottom of the lagoons was applied to the field. The sludge supplied about 30 kg N ha^{-1}. More than 90% of the N was in the form of NH_4^+, the remainder being organic N. The oat crop had to be irrigated twice, once in fall and once in spring. For both corn and winter forage, lagoon water was applied each time with the irrigation water, except for the irrigation before planting and the first irrigation after planting.

Sampling Procedure

In March 2007, about 15 soil cores from the top 90 cm of the profile were collected in a W pattern from several irrigation checks at each location. The three irrigation checks selected were those with the most uniform soil properties.

For the study, a variety of soil, plant, and water samples were taken from spring 2007 through fall 2008 to characterize N inputs and fate for the three irrigation checks and to provide calibration parameters for the RZWQM model. Soil and plant samples were taken at two sites located at opposite ends of each check. At each site, three plots (10 m long and six rows wide) were marked for soil and plant sampling. The plots were located at a distance of at least 30 m from the border of the check, and the centers of the plots were about 8 m apart. In both years, samples were taken to a depth of 180 cm in spring before corn was planted and in fall after the corn harvest. Because no clear horizons could be distinguished, the soil profile was divided into 30-cm segments, with the top segments split into two 15-cm layers. The samples taken in spring 2007 were used to describe the soil (Table 1) and to initiate the model. During the corn growing season, samples were taken every 3 wk, on average, to a depth of 90 cm. Five cores were collected manually with a soil probe (2-cm diameter) from each plot and combined as a composite sample. The different layers were sampled separately. Soil samples were passed through a 4-mm sieve in the field and kept on ice for transport back to the laboratory.

During the corn growing season, the leaf area index (LAI) was measured with a LI-COR LAI-2000 Plant Canopy Analyzer, and four to six random plants were harvested next to the plots each time the soil was sampled. Before the corn harvest, 4 m of two adjacent rows in each plot was sampled by hand. For Sudan grass and winter forage, an area of 1 and 0.25 m^2, respectively, was harvested in each plot a few days before the crops were harvested for silage. With the exception of the preharvest corn and Sudan grass samples, all plant samples were placed into paper bags and dried at 60°C. The preharvest corn and Sudan grass samples were weighed in the field and a subsample of 8 to 10 plants $plot^{-1}$ was chopped with a garden shredder/chopper (Sears Craftsman). The chopped material was mixed thoroughly

Table 2. Crop management from Spring 2007 to Fall 2008.

Crop	Dates		Water input		N application		N removed with crops	Harvested biomass
	Planting	Harvest	Irrigation	Rainfall	Mineral N†	Organic N		
			cm		kg ha^{-1}			kg DM ha^{-1}‡
			Farm 1					
Corn 2007	10 Apr.	2 Aug.	82	3	281	180	300	19,700
Sudan grass	3 Aug.	17 Oct.	42	0	150	31	139	6,900
Winter forage (triticale)	9 Nov.	11 Apr.	16	21	219	177	220	10,700
Corn 2008	16 Apr.	12 Aug.	128	0	516	110	261	19,900
			Farm 2					
Corn 2007	8 May	24 Aug.	66	0	363	139	314	19,700
Winter forage (oat)	25 Oct.	20 Apr.	39	22	185	97	173	9,100
Corn 2008	14 May	1 Sept.	63	0	368	463	274	20,400
			Farm 3					
Corn 2007	20 May	14 Sept.	46	0	199	114	236	22,200
Winter forage (oat)	7 Nov.	12 Apr.	14	22	59	27	112	11,200
Corn 2008	17 May	5 Sept.	45	0	249	153	259	20,100

† Includes mineral N contained in lagoon water and solid manure.
‡ DM, dry matter.

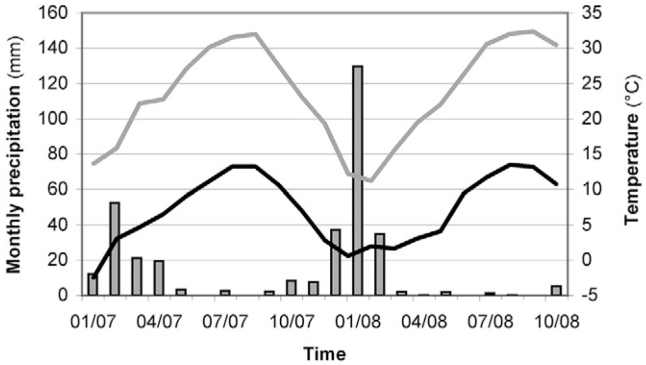

Fig. 1. Weather data of the study area: monthly precipitation (bars) and monthly average of the daily minimum (black line) and maximum (gray line) temperatures.

and about half of it was placed in a paper bag, weighed, dried at 60°C, and weighed again to determine the dry matter content.

During each irrigation event, water samples were taken with 250-mL glass bottles directly at the delivery valve before the water made contact with the soil. When it took <1 h to irrigate the check, one water sample was taken at the beginning and a second at the end of the irrigation. For longer irrigations, an additional sample was taken after the application of about half the water. The duration of the irrigation was recorded. The glass bottles were kept at 4°C and analyzed within 7 d. Water flow was determined with flow meters installed in the irrigation pipes. On Farm 3, flow-rate technical problems did not allow a reliable estimate of the amount of irrigation water applied to the corn in 2007. The average flow rate from 2008 was therefore used to estimate the application rates for 2007.

The weather data required by the RZWQM, including daily values for precipitation, minimum and maximum temperature, wind speed, solar radiation, and relative humidity, were all obtained from two weather stations located within 15 km of the field sites (Fig. 1). The data were available from the University of California's Statewide Integrated Pest Management Program (http://www.ipm.ucdavis.edu/WEATHER).

Physical and Chemical Analyses

The soil samples were kept at 4°C before being processed. Ammonium and NO_3^- were determined in field-moist soil samples within 2 d of sampling. Soils were extracted with 0.5 mol L^{-1} K_2SO_4 (5 L kg^{-1} soil; Mulvaney, 1996) and the suspension filtered (Fisherbrand Q5) for the colorimetric analysis of NH_4^+ and NO_3^-. Nitrate was analyzed using a single-reagent method (Doane and Horwath, 2003). The NH_4^+ concentration was determined using the salicylate method (Verdouw et al., 1978; Foster, 1995). For all other analyses, soil samples were dried at 60°C. Soil texture was determined with the pipette method (Gee and Bauder, 1986). Soil moisture content at 1500 kPa was determined using a pressure plate apparatus (Klute, 1986), pH was measured in a 1:2 soil/water solution following a 30-min equilibration (Thomas, 1996), and the cation exchange capacity was determined with the NH_4OAc method (Sumner and Miller, 1996). Oven-dried and ball-milled soil samples were analyzed for total C and N content by dry combustion on a Carlo Erba NA 1500 Series 2 CNS analyzer (Nelson and Sommers, 1996; Bremner, 1996). Soil moisture content was determined by drying the soil samples at 105°C for 24 h. Bulk density was calculated based on a method developed by Rawls (1983). All results are expressed on a zero-moisture basis.

The dried plant samples were ground with a Wiley mill to pass a 2-mm screen. The ground material was thoroughly mixed and a subsample was ball milled and analyzed for total C and N by dry combustion, as described above.

Irrigation and lagoon water samples were filtered through a 0.3-μm glass fiber filter. The solids were dried and analyzed for total C and N by dry combustion. The filtrate was analyzed colorimetrically for NH_4^+ and NO_3^- using the procedures described for soil samples. Dissolved organic C in the filtrate was analyzed on a UV–persulfate total organic C analyzer (Model Phoenix 8000, Tekmar Dohrmann). Total dissolved N was determined with the alkaline persulfate oxidation method in which the filtrate was mixed with an equal amount of an oxidizing reagent (Cabrera and Beare, 1993), heated in a boiling water bath for 2 h, and analyzed for NO_3^-, as described above. The dissolved organic N was calculated by subtracting N in the form of NH_4^+ and NO_3^- from the total dissolved N.

Model Calibration

The RZWQM, Version 98 (Ahuja et al., 2000), was used for the simulation. Because the soil–plant–atmosphere conditions are highly dynamic and very difficult to characterize in terms of effective parameters, the model must first be calibrated for each site and crop cultivar to which the model is applied (Hanson et al., 1999; Ma et al., 2011). Because soil properties, crop yields, and N uptake were not significantly different at the two sampling sites within a field, only one site per field was used for the model simulations. The calibration procedure consisted of a comparison of simulated vs. observed data for spatial and temporal soil water distribution, crop yield, N uptake, and nutrient dynamics. We calibrated the soil water components first, then the nutrient turnover components, and finally the plant production components, as suggested by Ma et al. (2011). These steps were then repeated until the adjustment of one component no longer had adverse effects on the prediction of the other components. The aim of the calibration procedure was to obtain a good fit between the observed and modeled values for the three sites by adjusting a minimum number of parameter values. When parameters had to be adjusted, the same values were used for all three sites with few exceptions (see below).

Parameters for Soil Water Dynamics

Measured values for soil texture and water content at 1500 kPa were entered into the model for each site and layer (Table 1). Values for bulk density were calculated based on Rawls (1983). To calibrate the vertical soil water distribution for the entire period, the values for saturated hydraulic conductivity and soil moisture content at 33 kPa were adjusted for each site separately, testing a wide range of values to account for the differences in texture (Table 1). For other parameters, default values were used.

Parameters Related to Nutrient Turnover

In the RZWQM, organic matter was distributed across five conceptual pools and was decomposed by three microbial biomass populations. The organic matter pools consisted of slow and fast pools for crop residue and other organic amendments, such as manure, and fast, medium, and slow decaying soil organic matter pools (Shaffer et al., 2000). To establish initial values for the microbial population and the faster soil organic matter pools, the initialization wizard was fed with site-specific data, including tillage operations, climate, and residue properties and a model simulation to cover 30 yr. The resulting sum of the three soil organic matter pools was compared with the measured total soil C in the different layers. The fit between modeled and measured data was very good; the average difference for all layers was 3.1% of the observed values, and the maximum difference was 9.9% (data not shown). The modeled organic matter pools were then used to initiate the model. The modeled distribution of mineral N in the soil profile and the modeled N mineralization rate, however, did not fit the measured data. Two adjustments were found necessary to improve the model accuracy.

Because the RZWQM treats NH_4^+ as immobile in the soil (Ma et al., 2011), modeled NH_4^+, even when applied with the irrigation water, would not move beyond the top 1 cm of the soil profile. For high applications of 50 kg NH_4^+–N ha^{-1} or more, which were not uncommon at our field sites, the modeled NH_4^+ concentration in the top 1 cm would reach levels of >300 mg kg^{-1} soil. Only after being nitrified would the NH_4^+ move down the profile (with the next irrigation water application) and become accessible to crops. In the meantime, predicted losses due to NH_3 volatilization were large. To achieve a more realistic vertical distribution of the applied NH_4^+ in these sandy soils, part of the NH_4^+ was entered into the model in the form of urea. Urea is mobile in the model and is quickly hydrolyzed to NH_4^+. A urea/NH_4^+ ratio of 70:30 resulted in the best description of the measured mineral N distribution at all three sites.

The simulated mineralization rates of the different soil humus and residue pools were adjusted by changing the pools' C/N ratios. The best agreement between simulated and measured mineral N pools in the soil profile resulted for C/N ratios of the fast, transition, and stable soil humus pools set to 12, 10, and 11, respectively, for all three farms. The optimal C/N ratio of the fast residue was 13, while the C/N ratio of the slow residue pool required site-specific adjustment due to the fact that the manures applied at the three sites differed in their C/N ratios and decomposition stage. Optimal values for Farms 1, 2, and 3 were 14, 5, and 16, respectively.

Plant Growth Parameters

The plant production submodel divided plant parameters into more than 80 genetic parameters and 10 site-dependent parameters. For corn and winter forage, we first selected cultivars with characteristics that were most similar to those used in our study and then calibrated individual cultivar coefficients using the observed data (Ma et al., 2011). None of the corn and wheat cultivars supplied with RZWQM adequately described the temporal development of aboveground biomass, N uptake, and LAI. Therefore, seven and three genetic parameters needed to be adjusted for corn and winter forage, respectively, as well as three site-dependent parameters. The same genetic parameters were used to describe crop development at all three sites.

For corn, the generic parameters of the cultivar GPSR, supplied by the model (Ahuja et al., 2000), were used. The number of days needed to complete the different growth stages had to be adjusted to fit the observed development in the field (parameters C1–C4 in Table 3; Fig. 2). In addition, the leaf/shoot ratio was adjusted to improve the fit between measured and modeled values for LAI, the whole-plant N content was increased to reflect the measured N uptake, and the soil water head required for germination was adjusted to ensure successful germination (parameters C5–C7 in Table 3). The following adjustments among the site-dependent parameters were necessary: (i) the rooting depth was set to 2 m; (ii) the plant density was set to the density measured at harvest; and (iii) the leaf density (biomass needed to obtain an LAI of 1) was set to 8.8, 9, and 8 g LA^{-1} for Farms 1, 2, and 3, respectively. All other site-dependent parameters were used as supplied by the model.

For the winter forage, the generic parameters of the winter wheat cultivar at Akron were used (Saseendran et al., 2004). The following adjustments were made: vernalization was not required, and the time needed for plants to complete vegetative and reproductive growth was adjusted to fit the development observed in the field (parameters W1–W3 in Table 3; Fig. 2). The site-dependent parameters were adjusted as follows: (i) the maximum N uptake rate was set to 0.04 g $plant^{-1}$ d^{-1}; and (ii) the plant-density basis for leaf density was set to 400,000 plants ha^{-1} for all three farms. In addition, (iii) the specific leaf density was set to 1.7, 1.2, and 2.2 g LA^{-1} for Farms 1, 2, and 3, respectively.

The model does not provide parameter values for the growth of Sudan grass. Parameters from the corn cultivar GPSR were

Table 3. Plant genetic parameters used to calibrate crop development at all three sites.

Parameter		Default value	Adjusted value
	Corn (differences with cultivar GPSR)		
C1	time needed for plant to germinate, d	5	3
C2	time needed for plant to grow to four-leaf stage, d	3	15
C3	time needed for plant to complete vegetative growth, d	38	40
C4	time needed for plant to complete reproductive growth, d	40	90
C5	leaf/shoot ratio	1.8	0.6
C6	maximum whole-plant N content	0.026	0.036
C7	average 5-d soil water head at which germination is 50%, cm	–6000	–9000
	Winter forage (differences with winter wheat cultivar at Akron)		
W1	vernalization	required	not required
W2	time needed for plant to complete vegetative growth, d	155	80
W3	time needed for plant to complete reproductive growth, d	40	60
	Sudan grass (differences with corn cultivar GPSR)		
S1	stem diameter of the mature plant cylinder, cm	80	30
S2	aboveground biomass at which height is 1/2 max. height, g	60	10
S3	aboveground biomass of a mature plant, g	215	25
S4	biomass of plant at four-leaf stage, g	20	7.5
S5	maximum whole-plant N content	0.026	0.036
S6	leaf/shoot ratio	1.8	6.5

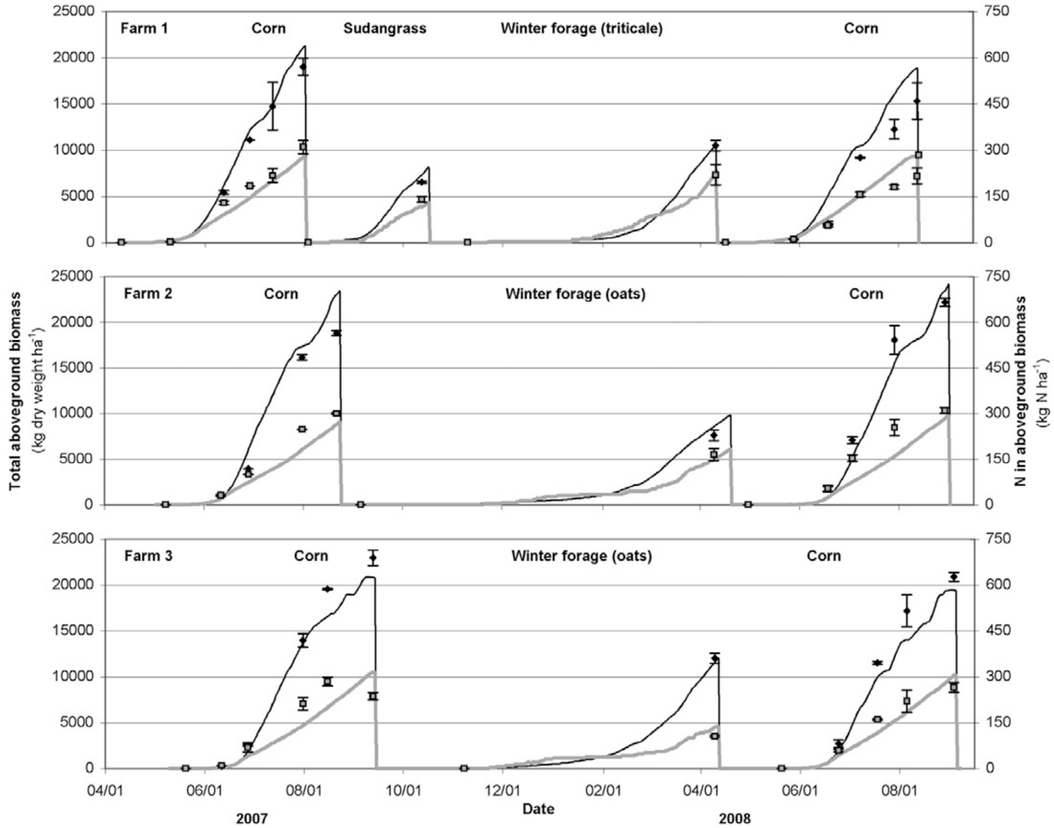

Fig. 2. Simulated (black line) and measured (filled diamonds) aboveground biomass of the crops as well as simulated (gray line) and measured (open squares) N in the aboveground biomass. The measured data shown are means ± standard error of the mean (n = 3).

therefore used and adjusted to simulate the development of Sudan grass on Farm 1. Modifications were necessary to adjust for the higher plant density (parameters S1–S6 in Table 3; Fig. 2). The values used for these adjustments correspond to the values supplied by the model for cereals with the exception of the maximum whole-plant N content and the aboveground biomass at half the maximum height. The latter has a strong effect on plant height. Two adjustments to the site-specific parameters were necessary, namely (i) the plant-density basis for leaf density was set to 400,000 plants ha^{-1} and (ii) the specific leaf density was set to 2.5 g LA^{-1}.

Data Analysis

Three measures were used to quantify the agreement between observed and modeled values. Detailed discussions can be found in Loague and Green (1991), Janssen and Heuberger (1995), and Wallach (2006).

The bias is a simple way to summarize the agreement between predicted and observed values:

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right) \quad [1]$$

where n is the total number of observations, O_i is the observed value for the ith situation, and P_i is the corresponding value predicted by the model. The bias measures the average difference between measured and calculated values. If the model underpredicts, on average, the bias is positive, and conversely if the model overpredicts, on the average, the bias is negative. Bias alone, however, is not sufficient as a summary of model errors. A bias value near zero may be the consequence of very small model errors in all situations or alternatively of large errors that approximately cancel each other between under- and overprediction.

The relative mean absolute error (RMAE) is the average difference between the observed and predicted values as a proportion of the observed values:

$$\text{RMAE} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|O_i - P_i\right|}{\left|O_i\right|} \quad [2]$$

Compared with the more widely used relative mean squared error, the RMAE does not overweigh large differences.

Modeling efficiency (EF) is a measure of the deviation between model predictions and observed values relative to the scattering of the observed data:

$$\text{EF} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad [3]$$

where $\bar{O}$ is the average of the observed values. If the model is perfect, EF = 1. A model that gives EF = 0 has the same degree of agreement with the data as using the average to predict for every situation. A model can be a worse predictor than the average of the observed data (EF < 0).

Linear regression analyses were conducted with SAS (SAS Institute, 1990), using the REG procedure. Normality of the residuals was evaluated graphically and with the Shapiro–Wilk test. When necessary, the data were transformed, using logarithmic and square root transformations.

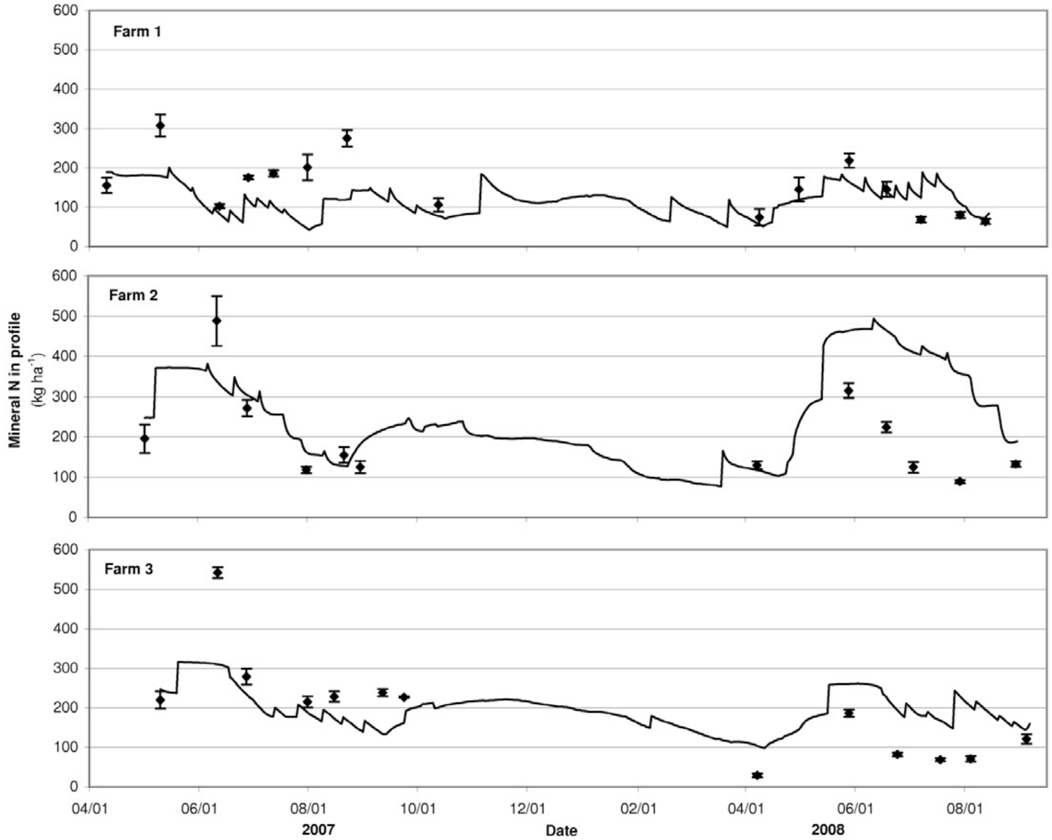

Fig. 3. Simulated (line) and measured (filled diamonds) soil mineral N content (sum of NH_4^+ and NO_3^-) in the top 90 cm of the profile. The measured data shown are means ± standard error of the mean (*n* = 3).

RESULTS AND DISCUSSION

Crop Management and Yield

The three farms differed considerably in the amount of irrigation water and N applied. Irrigation water application between spring 2007 and spring 2008 ranged from 62 to 140 cm. The largest amount of irrigation water was applied on Farm 1 (Table 2) due to three annual crops and sandy soil with a high infiltration rate. The lowest amount of irrigation water was used on Farm 3, where leaching was reduced due to a duripan in some parts of the field and relatively high clay content in some of the soil layers. Most of the irrigation water, between 46 and 82 cm, was applied to corn, with the highest application corresponding to Farm 1. On average, about 9 cm of water was applied with each irrigation. In 2008, the total water application to corn reached 128 cm on Farm 1. For comparison, corn evapotranspiration estimated from the daily values for reference evapotranspiration (from http://www.ipm.ucdavis.edu/WEATHER) and crop coefficients (Snyder et al., 2000), ranged from 50 to 55 cm on the three farms.

When lagoon water was mixed into the irrigation water, the N concentration in the irrigation water ranged from 60 to 130 mg N L^{-1}, with 35 to 45% of the N being in the organic form. Therefore, an average water application of 9 cm resulted in applications of 55 to 120 kg N ha^{-1} with each irrigation. Inorganic N consisted predominantly of NH_4^+. The C/N ratio of the lagoon water ranged from 3.7 to 7.8 (data not shown). Variation in irrigation water properties was more pronounced among application dates than among farms. On average, corn was harvested for silage 113 d after planting. The aboveground dry biomass ranged between 19,700 and 22,200 kg ha^{-1}, and the N in the aboveground biomass ranged between 236 and 314 kg ha^{-1} (Table 2; Fig. 2). Corn yields on the three farms compare favorably with the average yield in Stanislaus County, which was 19,000 and 18,800 kg ha^{-1} in 2007 and 2008, respectively (Stanislaus County Department of Agriculture, 2008). The winter cover crop produced aboveground biomass between 9100 and 11,200 kg ha^{-1}, with an N content ranging from 112 to 220 kg ha^{-1}. On Farm 1, the Sudan grass yielded 6900 kg ha^{-1} and 140 kg N ha^{-1}. Therefore, between 350 and 660 kg N ha^{-1} was removed from the fields with the harvested crops between spring 2007 and 2008. During the same period, the N application ranged from 640 to 1040 kg ha^{-1}, with corn receiving between 310 and 500 kg N ha^{-1} (Table 2). This N application rate is in excess of the average N use for corn in the United States, which has been relatively constant since the 1980s at about 145 kg ha^{-1} (Fixen and West, 2002; National Agricultural Statistics Service, 2006). Nitrogen input exceeded N removed in the harvested crops by 380, 300, and 50 kg ha^{-1} on Farms 1, 2, and 3, respectively.

Nitrogen in the Soil Profile

Mineral N contents in the profiles were greater in 2007 than in 2008, which were partly due to high spring values in 2007 following a dry winter. In general, the mineral N content in the top 90 cm of the profile was greatest in early summer and decreased during the period of maximum N uptake by corn (Fig. 3).

Excess N fertilization did not result in increased mineral N concentrations in the top 180 cm of the soil profile between spring

2007 and spring 2008. On Farm 1, the mineral N content in the total profile (180 cm) was about 260 kg ha^{-1} in spring 2007 and 2008. While in spring 2007 about 65% was in the top 90 cm, however, only 30% was in the same layer in spring 2008 (data not shown). On Farm 2, 380 and 240 kg mineral N ha^{-1} were found in the soil profile in spring 2007 and 2008, respectively. Slightly more than half of the N was found in the top 90 cm in both years. On Farm 3, about 340 kg mineral N ha^{-1} was found in the profile down to 180 cm, 220 kg of which was stored in the top 90 cm in spring 2007. In spring 2008, only a few cores could be taken to a depth of >100 cm due to a hardened duripan at the time of sampling. In the top 90 cm of the profile, the mineral N content had decreased to 30 kg ha^{-1}. Because high N application rates generally coincided with high water application rates (Table 2), it is likely that a large proportion of the excess applied N was leached below the sampling zone.

Model Performance

Crop growth and N uptake were modeled using the same plant genetic parameters for all three sites. On average, the RZWQM slightly overestimated crop yield (negative bias) and tended to underestimate N uptake (Fig. 2; Table 4). The high RMAE, which ranged from 0.17 to 0.41, is mainly the result of large relative differences between measured and modeled values early in the season, while the absolute differences were small (Fig. 2). During the second half of the growing season, the RMAE was generally <0.2. In fact, the average EF of 0.92 for plant biomass and 0.76 for N uptake indicate that the model accurately simulated crop development.

Table 4. Statistical analysis of the predicted moisture and mineral N content in the soil profile, as well as of plant growth and N uptake after model calibration (*n*, number of observations; RMAE, relative mean absolute error; EF, model efficiency; DM, dry matter).

Parameter	*n*	Bias	RMAE	EF	Bias	RMAE	EF
		Yield			N uptake		
Farm		kg DM ha^{-1}			kg ha^{-1}		
Farm 1	12	−1414	0.41	0.89	0.4	0.29	0.85
Farm 2	9	−469	0.25	0.93	42.5	0.29	0.73
Farm 3	10	1351	0.17	0.95	13.8	0.31	0.70
Depth, cm		Moisture			Mineral N		
		m^3 m^{-3}			kg ha^{-1}		
			Farm 1				
0–15	15	−0.02	0.30	0.56	−6.6	0.55	0.19
15–30	15	−0.01	0.19	0.63	11.2	0.45	−0.35
30–60	15	−0.01	0.16	−0.38	19.1	0.37	−0.44
60–90	15	0.01	0.10	0.00	18.6	0.52	−1.21
0–90	15	−0.01	0.09	0.73	40.2	0.35	−0.09
			Farm 2				
0–15	12	0.00	0.23	0.34	−20.2	0.64	−4.08
15–30	12	−0.01	0.12	0.47	2.5	0.83	−0.80
30–60	12	0.00	0.05	0.08	−29.3	1.03	−1.78
60–90	12	0.01	0.05	−0.63	−36.1	1.15	−3.22
0–90	12	0.00	0.05	0.65	−83.0	0.76	−0.87
			Farm 3				
0–15	13	0.02	0.38	−0.91	17.2	0.52	0.38
15–30	13	0.01	0.28	−3.58	2.4	0.93	−0.43
30–60	13	0.02	0.22	−3.86	1.1	1.10	0.08
60–90	13	0.00	0.17	−3.19	−28.5	2.03	−1.00
0–90	13	0.01	0.23	−3.65	−3.8	0.74	0.41

In contrast to plant growth and N uptake, simulation of the soil moisture content was less accurate (Fig. 4; Table 4) despite site-specific calibration, which was done using a wide range of values for saturated hydraulic conductivity and soil moisture content at 33 kPa for the different soil layers. On Farms 1 and 2, a relatively small bias and predominantly positive EF values indicate that the model prediction was acceptable. In contrast, on Farm 3, negative EF values indicate that the average of the observed data would have been a better predictor than the model simulation (Table 4). This is partly due to the fact that the field could only be entered for soil sampling when the soil moisture content had decreased after an irrigation event. Therefore, the samples captured only part of the large fluctuations in soil moisture content that occurred between irrigation events. Under these conditions, the average moisture content may, in fact, better describe the soil moisture content than a model that simulates the large fluctuations. In addition, a spatially heterogeneous subsoil layer on Farm 3, which restricted water infiltration, may have contributed to the difficulties in modeling soil moisture content. This is in line with Malone et al. (2001), who reported in their review that restricting layers have caused difficulties for model parameterization in some studies. It was therefore not possible to model soil moisture dynamics accurately on Farm 3 with the data available. The predictions for the layers below 90 cm were inaccurate as well, using data from only four samplings (data not shown).

Compared with the amount of N applied, the bias of the modeled mineral N contents in the profile was relatively small (Table 4). In general, the simulated mineral N contents were similar to sampled values at planting and when the crops were harvested but less accurate during the corn growing season (Fig. 3). For example, the difference between the modeled and measured soil mineral N content on Farm 2 was 56 kg N ha^{-1} in the top 90 cm of the profile when the corn was harvested in 2008. This corresponds to only 6% of the mineral N and 3.4% of the total N applied during the simulation period. On the other two farms, the difference between measured and modeled mineral N contents in fall 2008 was even smaller. The difficulty in modeling mineral N contents in the profile during the cropping season, which resulted in predominantly negative EF values for the different soil layers (Table 4), may be due to inaccurate prediction of soil water movement and plant N uptake from the different soil layers. In addition, the overprediction of the mineral N content in the soil profile during the 2008 corn growing season on Farm 2 was probably due to an overprediction of N mineralization from the compost applied in spring 2008. The compost had a relatively narrow C/N ratio of 15, resulting in a high modeled mineralization rate. Therefore, to model N mineralization from both lagoon water and compost accurately, an additional residue pool would have been needed. To a lesser degree, the same problem may have existed on the other two farms where lagoon water and either partially decomposed manure or liquid slurry were applied.

Modeling Nitrogen Losses

Simulated N losses accounted for 41, 29, and 15% of the total N applied during the 18-mo simulation on Farms 1, 2, and 3, respectively. According to the model simulation, the main pathway of N loss was by leaching of NO_3^- past 180 cm,

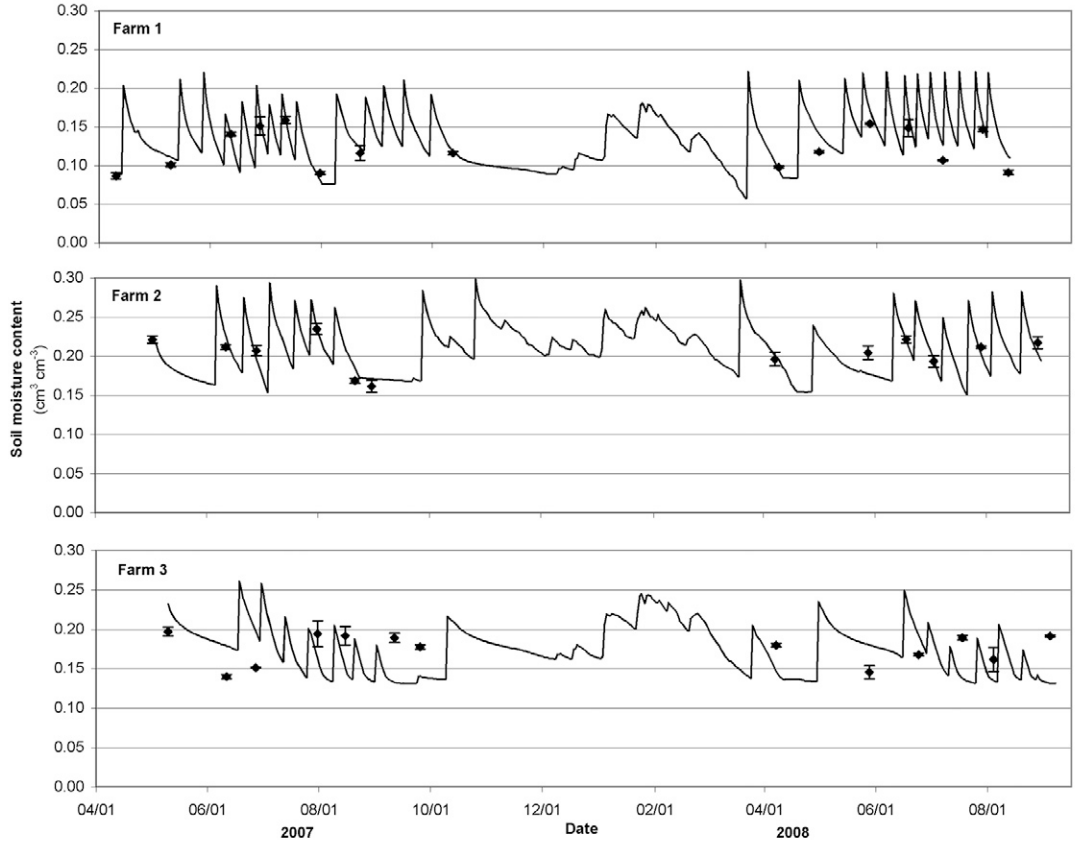

Fig. 4. Simulated (line) and measured (filled diamonds) volumetric soil moisture content in the top 90 cm of the profile. The measured data shown are means ± standard error of the mean (*n* = 3).

accounting for at least 82% of the N lost (Table 5). On Farm 1, most of the leaching occurred in summer. This model prediction is supported by our observation that irrigation water applications exceeded corn demand. In contrast, on Farm 2, leaching was more influential during the winter. Linear regression of the data reported in Table 5 showed a close ($R^2 = 0.82$) and significant ($P < 0.01$) correlation between the amounts of water and NO_3^- leached. High leaching losses are in line with our observation that mineral N concentrations were greater in spring 2007, which followed a winter with less precipitation, than in spring 2008.

The estimated volatilization of NH_3 on Farm 1 reached 82 kg N ha^{-1} during the simulation period, 60% of which was lost during the 2 wk following the application of solid manure in May 2008. This loss corresponds to about 30% of the N applied with the manure. On Farm 2, the total predicted NH_3 volatilization also reached 82 kg N ha^{-1}. High volatilization rates coincided with modeled NH_4^+ concentrations >40 mg kg^{-1} dry soil in the top 1 cm of the profile. In contrast, only 5 kg N ha^{-1} was lost by volatilization during the simulation period on Farm 3. The estimated NH_3 volatilization from lagoon water was greatest from Farm 2, where about 10 and 4% of the NH_4^+–N applied to corn and winter forage, respectively, were lost to volatilization. Values reported in the literature have generally been higher, and NH_3 losses of up to 60% of the NH_4^+ applied with cattle slurry have been reported (Thompson et al., 1990). Dilution with water, low soil pH, high infiltration rates, and physical separation of particles from the liquid fraction, however, have been found to significantly reduce NH_3 volatilization (Bussink and Oenema, 1998; Sommer et al., 2003, 2006). In contrast, high temperatures increase NH_3 losses (Bussink and Oenema, 1998). On our farms, the soil pH was below 7, particles were removed before the slurry was pumped into the lagoons for storage, and the lagoon water was diluted with at least five times the quantity of irrigation water when applied. In addition, the sandy soils allowed high infiltration rates. These factors probably reduced NH_3 volatilization rates from the lagoon water. Therefore, the losses estimated by the model seem to be reasonable despite the high temperatures.

Estimated N losses due to denitrification (N_2O and N_2) were negligible on all three farms, accounting for <0.2% of the N applied. Manures may result in increased N losses due to denitrification compared with mineral fertilizers (van Groenigen et al., 2004; Rochette et al., 2008). Nitrous oxide emissions from manure are related to their content of water-soluble C, especially volatile fatty acids (Paul and Beauchamp, 1989). This readily available C may sustain denitrification and increase O_2 consumption, the latter resulting in anaerobic microsites (Rochette et al., 2000). De Klein et al. (2001) reported annual losses of N_2O ranging from 0 to 5% of the manure N applied. In other studies, the losses ranged from 0.5 to 2.9% (Kaiser and Ruser, 2000; van Groenigen et al., 2004; López-Fernández et al., 2007). Compared with these studies, the simulated losses in our study are low. The infiltration rates in these sandy soils are high, however, resulting in only short periods of high moisture contents after an irrigation event or rainfall. On Farm 3, where a duripan restricted infiltration,

Table 5. Simulated fate of N and irrigation water during the growth of the different crops.

Crop	Mineralization	Plant uptake	NO_3^- leached below 180 cm	NH_3 volatilization	Denitrification	Water leached below 180 cm
	kg N ha^{-1}					cm
			Farm 1			
Corn 2007	62	280	129	8	0	20
Sudan grass	83	130	68	0	0	12
Winter forage	115	217	50	72	1	14
Corn 2008	157	281	345	2	2	68
			Farm 2			
Corn 2007	63	274	90	43	0	7
Winter forage	187	183	229	7	0	18
Corn 2008	362	294	70	32	3	4
			Farm 3			
Corn 2007	51	315	89	0	0	13
Winter forage	121	138	47	1	0	3
Corn 2008	158	304	12	4	1	1

the soil moisture content remained high for several days. Under these conditions, denitrification is generally increased; however, the modeled denitrification losses were not higher than on the other farms, presumably due to lower water and N application rates on Farm 3. Therefore, despite the difficulties in modeling N contents in the different soil layers and the changes during the cropping season, the model prediction that most N was lost through leaching seems reasonable.

CONCLUSIONS

Use of the RZWQM for simulating irrigated forage systems was challenging because high irrigation water applications in combination with high infiltration rates in sandy soils resulted in very dynamic changes in the soil moisture content and because lagoon water and manure in varying stages of decomposition were applied several times a year. While the same crop-specific parameters were used for all three sites, soil moisture and nutrient turnover required site-specific calibrations. Because the model treated NH_4^+ as immobile, the estimated vertical distribution of mineral N would have been highly inaccurate if 70% of the applied N had not been entered into the model as urea. To improve the simulation, more frequent soil moisture measurements may be required. In addition, creation of separate N pools in the model, representing lagoon water and manure N sources, may improve the N mineralization simulation. After calibration, the model adequately estimated seasonal crop yield, N uptake, and soil mineral N in the top 90 cm of the soil profile, but it was relatively weak in estimating short-term changes in mineral N content within the different soil layers. Despite these difficulties, the predicted N losses were reasonable when compared with literature values. Both measured and modeled data highlight the potential for more efficient water and N fertilization management at these dairies.

The implementation of these improvements should result in more accurate model estimates. This will allow use of the model to test a wide range of management practices to select the most promising ones for field trials. Using a model for a pre-selection is especially beneficial in flood irrigation systems, where small plots with different irrigation and fertilization practices cannot be easily established.

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