EVALUATION OF SWEET CORN YIELD AND NITROGEN LEACHING WITH CERES-MAIZE CONSIDERING INPUT PARAMETER UNCERTAINTIES

J. He, M. D. Dukes, G. J. Hochmuth, J. W. Jones, W. D. Graham

ABSTRACT. *A study was conducted to evaluate the ability of the CERES-Maize model in the Decision Support System for Agrotechnology Transfer (DSSAT) to simulate sweet corn (*Zea mays *L. var.* saccharata*) yield and nitrogen leaching in Florida, considering input parameter uncertainties. In this type of biological system modeling, uncertainties in predictions with respect to input parameter uncertainty are often not reported. Thus, the result of model verification could be misleading if there are large uncertainties in field observations, since single model prediction values cannot comprehensively represent heterogeneous field conditions. Instead, comparisons between the distributions of model simulations and field observations were recommended in this study. A two-factor split-plot field experiment was conducted with three nitrogen fertilizer levels (185, 247, and 309 kg N ha^{-1}) and two irrigation levels (I1 and I2; I2 = 1.5 × I1, where I1 is the irrigation demand calculated based on a daily soil water balance). Yield response to different nitrogen fertilizer and irrigation management levels was evaluated, and the cumulative nitrogen leaching was estimated for each of the treatments based on a nitrogen balance. Next, the field experiment treatments were simulated with the calibrated CERES-Maize model using parameter sets generated from parameter distributions derived with the generalized likelihood uncertainty estimation (GLUE) method in a previous study. Simulated dry matter yields and cumulative nitrogen leaching were compared to field-measured or estimated values. Measured total and marketable yields were not affected by irrigation level. Estimated nitrogen leaching increased significantly with higher levels of irrigation and nitrogen fertilizer application. The calibrated CERES-Maize model accurately predicted the phenology dates, with an error of 0 and 1 day for anthesis and maturity dates, respectively. The prediction uncertainties (due to uncertain input parameter values), as measured by the standard deviation (SD) in predicted anthesis and maturity dates, were only 1 and 2 days after planting, respectively. The model also accurately predicted the changes in dry matter yield caused by different nitrogen and irrigation levels, with a relative absolute error (RAE) less than 12% for all but one treatment. Due to the uncertainties in soil and genetic parameters, the prediction SD of simulated dry yields ranged from 655 kg ha^{-1} at I1 to 960 kg ha^{-1} at I2, while the observation SD ranged from 220 to 463 kg ha^{-1} for measured dry yields. The uncertainties in simulated dry yield were higher than the uncertainties of measured values due to relatively high variations in estimated genetic coefficients. The model performance could be improved further if the variations in estimated genetic coefficients could be reduced. The difference between the simulated and estimated nitrogen leaching amounts was significant and complex, ranging from -31 to 43 kg N ha^{-1} with an average absolute difference of 15.3%. This discrepancy was probably due to both the errors in estimation of potential nitrogen leaching in the field experiment using a mass balance approach and the inaccuracy of model predictions. Nevertheless, the increase in nitrogen leaching resulting from higher nitrogen fertilizer levels was correctly predicted. The uncertainties in simulated N leaching covered more than 67% of the uncertainties of estimated leaching for all but one treatment, indicating that estimated soil parameters via the GLUE method were able to represent the heterogeneity of field soil. In general, the CERES-Maize model is able to simulate sweet corn production under different management conditions sufficiently to allow exploration of tradeoffs between crop yield and nitrogen leaching for sweet corn production in Florida.*

Keywords. *CERES-Maize, DSSAT, Irrigation, Nitrogen leaching, Sweet corn, Yield.*

Sweet corn (*Zea mays* L. var. *saccharata*) is typically ranked as one of the five most valuable vegetable crops in Florida. During the seasons of 2006-2007 and 2007-2008, sweet corn was ranked first in terms of vegetable crop acreage (20.2% and 22.9% of the state's total vegetable acreage, respectively) and fourth in total vegetable value (10.9% and 10.2% of the state's total vegetable value). Almost all sweet corn produced in Florida is for the fresh market rather than processing (USDA-NASS, 2009). The application of nitrogen (N) fertilizer is necessary to obtain a profitable yield on sandy Florida soils. However, high

Submitted for review in June 2010 as manuscript number SW 8609; approved for publication by the Soil & Water Division of ASABE in July 2011.
The authors are **Jianqiang He,** Associate Professor, College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shaanxi, China; **Michael D. Dukes, ASABE Member,** Professor, Department of Agricultural and Biological Engineering, **George J. Hochmuth,** Professor, Department of Soil and Water Science, **James W. Jones, ASABE Fellow,** Distinguished Professor, Department of Agricultural and Biological Engineering, and **Wendy D. Graham, ASABE Member,** Professor, Water Institute, University of Florida, Gainesville, Florida. **Corresponding author:** Michael D. Dukes, Department of Agricultural and Biological Engineering, University of Florida, P.O. Box 110570, Gainesville, FL 32611-0570 phone: 352-392-1864, ext. 205; e-mail: mddukes@ufl.edu.

levels of nitrogen fertilizer application cause risk both to human health and the environment when the mobile N leaches or runs off into water bodies. The U.S. Environmental Protection Agency (EPA) has set a drinking water nitrate maximum concentration of 10 mg NO_3-N L^{-1} (USDHEW, 1962). Additionally, high nitrate levels in groundwater that discharges into N-limited surface waters can contribute to long-term eutrophication of these water bodies (Asadi et al., 2002). As an example, in recent years the nitrate concentration has increased in the Suwannee River basin of northern Florida (Ham and Hatzell 1996; Pittman et al., 1997; Katz et al., 1999). In addition, groundwater accounted for nearly 62% of freshwater withdrawals in Florida, and 14.3 million people (80%) of the state's 17.9 million residents obtained their drinking water from groundwater sources in 2005 (Marella, 2005).

The proactive, incentive-based program of developing crop-specific best management practices (BMPs) began in Florida as a result of the Florida Watershed Restoration Act (FWRA, 1999) to reduce nitrogen leaching and maintain acceptable crop yields. Modeling and experimental studies on nitrogen fate are needed to lead the implementation of these policies for sweet corn and other crop production systems in Florida. Although N fertilizers have made a large contribution to increase crop yield in the past 50 years, typically no more than half of all N fertilizer inputs are recovered in the aboveground biomass of harvested crops (Smil, 1999). Although the ultimate fate of unutilized N fertilizer is uncertain, it is clear that a major fraction is lost to the environment as reactive N species. Input-output budgets or balances are often used to assess the effects of agricultural production on the environment and to develop suitable N management methods to minimize the environmental impact (Leach et al., 2004; Schroder et al., 2003). For example, Pathak et al. (2004) used a mass balance approach to estimate the contribution of N mineral fertilizer to N leaching to shallow groundwater in a tropical paddy in Thailand. The N inputs to the experimental site came from commercial fertilizer, precipitation, irrigation water, and soils. Outputs of N from the site were N leached into groundwater, in harvested crops, in surface runoff, stored in soils, and other loss from the field. The leaching loss was calculated from daily fluxes of water percolation and soil water N concentrations extracted by vacuum lysimeter. They found that the loss of N into surface water and groundwater accounted for 19% of the total N applied. However, they did not try to compare the calculated amounts of N leaching based on mass balance with the measured N leaching.

Previous research on optimum N fertilizer rate and placement method, which are two main factors in N BMP development, for sweet corn production has been conducted in several experiments in Florida, e.g., in Gainesville (Rudert and Locascio, 1979), Quincy (Rhoads, 1990), and Live Oak (Hochmuth and Donley, 1992; Kidder et al., 1989). All of the experiments provided information about how much N fertilizer should be used to optimize sweet corn yield. However, these projects were inevitably expensive and time-consuming, and they did not evaluate all possible fertilizer management strategies. In addition, N fate was not assessed in these studies. With the development of computer technology, crop models have become a useful tool for exploration of possible management strategies in crop production.

The CERES-Maize corn growth and yield model (Jones and Kiniry, 1986; Tsuji et al., 1994) in the Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al., 2003), V4.0, is a popular crop model that has been widely used for many different applications throughout the world. The model has been used to assess agrochemical fate, such as herbicide (e.g., atrazine) leaching (Gerakis and Ritchie, 1998), and nitrate leaching from wheat and maize fields (Kovacs and Nemeth, 1995) and maize fields (Pang et al., 1998). Bowen et al. (1993) tested the CERES-Maize model for its ability to simulate N mineralization, nitrate leaching, and N uptake by maize following the incorporation of ten different legume green manures. There also have been numerous applications of the model to field corn growth simulation, e.g., to simulate phenology dates of maize under N-stressed conditions (Gungula et al., 2003), to characterize corn yield variability (Paz et al., 1999), and to study the corn yield response and the N dynamics of a cornfield (Thorp et al., 2006). For the applications in sweet corn production, Lizaso et al. (2007) modified the CERES-Maize model to predict fresh market yield of sweet corn using experimental data obtained in northern Florida; Garcia et al. (2009) used the CERES-Sweet Corn model, which was a modification of the CERES-Maize model, to determine the impact of weather and soil moisture conditions on water use and water use efficiency of sweet corn; and He et al. (2009) optimized input parameters to predict dry matter yield, soil moisture dynamics, and N leaching based on the Generalized Likelihood Uncertainty Estimate (GLUE) (Beven and Binley, 1992) method, but information about the application of CERES-Maize model on sweet corn production is generally limited compared with its application in field corn.

In many studies, the uncertainties in input parameters have been neglected (e.g., Soler et al., 2007; Thorp et al., 2008; Timsina et al., 2008); these uncertainties contribute to model output uncertainties. In these studies, traditional searching methods such as conjugate gradient-descent search, stochastic search, etc., were used to find a single parameter set that minimized errors of predictions for all of the observations. This approach could be inadequate in model verification where the single-value model simulation results (e.g., dry matter yield) are compared with field observations. However, variability always exists in field observations. Model users usually compare the model output values with the mean values of field observations so as to calculate the goodness-of-fit. However, if the uncertainties in field observations are large, this kind of comparison might be misleading since the model did not comprehensively represent the actual heterogeneity of the field measurements. Limitations in the optimal parameter set concept have also been discussed by Beven (1993, 2006), Beven and Binley (1992), and Beven and Freer (2001). They suggest that there is inherent uncertainty in parameters and that a number of parameter sets may be equally accurate and appropriate for use in simulating the system. Given the observations available, there may be no rigorous basis for differentiating between these parameter sets. Thus, Bayesian methods are becoming increasingly popular for estimating parameters for complex mathematical models (e.g., Campbell et al., 1999) because this approach provides a coherent framework for dealing with uncertainty (Makowski et al., 2006). One such methodology, GLUE (Beven and Binley, 1992), allows information from different types of observations to be combined to estimate probability distributions of parameter values and model predictions (Lamb et al., 1998). Thus, when taking the input parameter uncertainties into account in model simulations, information about model simulation uncertainties will be available. If both the mean values and standard deviations of model simulations, or the distribution patterns can be compared with the corresponding field observations, then more confidence will be obtained for the model performance and its future applications.

The CERES-Maize model, which was calibrated with the GLUE method in an earlier study (He et al., 2009), may be used as a tool to develop N BMPs for sweet corn production in Florida. It should be noticed that the CERES-Sweet Corn model (Lizaso et al., 2007) was not adopted in this study because the field experiment and model simulations were finished before this new model was released. The main objective of this study was to evaluate the ability of the CERES-Maize model to simulate sweet corn production on the sandy soils of northern Florida with respect to yield and cumulative N leaching over different N fertilizer and irrigation levels, considering the model simulation uncertainties due to input parameter uncertainties.

Materials and Methods

Field Experiment Design

A field experiment was conducted during spring 2006 at the University of Florida Plant Science Research and Education Unit located in Citra (29.4094° N, 82.1777° W; 21 m above mean sea level), Marion County, Florida. The experiment was a two factor split-plot design, since the two factors (irrigation and nitrogen fertilizer levels) can simultaneously affect corn yield and N leaching. There were two irrigation levels, I1 and 1.5×I1 (I2), where I1 is the irrigation schedule based on a daily soil water balance. Three fertilizer application levels were established as 185, 247 and 309 kg N ha^{-1}, labeled as N1, N2, and N3, respectively. Thus, there were six combined treatments (N1I1, N2I1, N3I1, N1I2, N2I2, and N3I2) with four replicates each resulting in a total of 24 experimental plots. Each plot (15.2 m long) consisted of eight rows of sweet corn with a row spacing of 76 cm. The sweet corn cultivar 'Saturn' shrunken (sh_2) (Seedway Company, Hall, NY) was planted at a depth of 3.8 cm and a planting density of 59,000 plants ha^{-1} on March 14, 2006.

Nitrogen Fertilizer Application

Nitrogen fertilizer was applied uniformly across the soil surface through a micro-irrigation system with tubing evenly spaced across the soil surface. This placement of the tubing was done to simulate fertigation from a center-pivot irrigation system commonly used for sweet corn production in northern Florida. The N fertilizer solution was injected into the system with a peristaltic pump. In each plot, the N solution was distributed to sweet corn plants with drip tapes (Turbulent Twin Wall, 0.2 m emitter spacing, 0.25 mm thickness, 3.72 L min^{-1} at 69 kPa, Chapin Watermatics, Inc., Watertown, N.Y.).

When arranging the drip tapes in each row, uniformity was considered so as to ensure that the experimental results would not be impacted. The uniformity depended on the number of drip tapes in the row. A simulation was conducted with the HYDRUS-2D model, version 2.0 (Simunek et al., 1999), to determine the minimum number of drip tapes in each row required to obtain adequate uniformity of soil wetting across the plot. The simulation dimensions were 76 × 50 cm, where 76 cm was the row width and 50 cm was the soil profile depth. Each emitter of a drip tape was represented as a point with a constant pressure of 0 bar. Initial soil pressure was set as -0.2 bar, and the bottom of the profile was set as free drainage. Simulations were conducted with the scenarios of one through four drip tapes delivering solution to the plots. The simulated soil water contents at different horizontal positions along the row width and at three specific soil depths (10, 20, and 30 cm) were recorded. Then the lower quarter distribution uniformity (DU_{lq}), which is a measure of the uniformity with which irrigation water is distributed to different areas in the field, was calculated for each of the scenarios using the following equation (Burt et al., 1997):

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \tag{1}$$

where

$\overline{D}_{lq}$ = average of lower quarter of soil water contents at different horizontal positions and a specific soil depth

$\overline{D}_{tot}$ = average of the corresponding total soil water contents.

After 30 min, the DU_{lq} ratios of simulated water contents at the soil depth of 10 cm were 0.58, 0.66, 0.82, and 0.97 for the four drip tape arrangements, respectively. The highest DU_{lq} ratio of 0.97 was obtained when four drip tapes were evenly arranged between rows, which is higher than the maximum DU_{lq} ratio of 0.89 reported by Baum et al. (2005) for residential irrigation systems of turf in various counties in Florida. Thus, the arrangement plan with four drip tapes was adopted in this study to guarantee the distribution uniformity of fertigation solution.

In the field experiment, there were eight rows in each plot, but only the central six rows were arranged with drip tapes in the furrows; the outer two rows were used as borders. The N fertilizer used in the experiment was a composite of several N compounds. The total N mass concentration was about 32%, including 7.9% nitrate N, 7.9% ammoniacal N, and 16.2% urea N. Details of the three N levels are shown in table 1. Level N2 was about 10% higher than the N fertilizer level recommended by the Institute of Food and Agricultural Sciences (IFAS) at University of Florida, which is about 224 kg N ha^{-1} (Hochmuth, 2000). N1 was 75% of N2, while

Table 1. Levels of nitrogen fertilizer applied to plot experiment in 2006.[a]

Date (2006)	N1 (kg N ha^{-1})	N2 (kg N ha^{-1})	N3 (kg N ha^{-1})
14 March	15	15	15
7 April	27	41	55
12 April	21	28	35
19 April	21	28	35
26 April	21	28	35
3 May	21	28	35
10 May	21	28	35
17 May	21	28	35
24 May	17	23	29
Total	185	247	309

[a] N2 was 10% higher than the nitrogen fertilizer level of 224 kg N ha^{-1} recommended by Hochmuth (2000); N1 was 75% of N2; N3 was 125% of N2.

N3 was 125% of N2. The first N application was carried out during planting, while all other applications were conducted with weekly fertigations beginning three weeks after planting.

Irrigation

In this study, the irrigation level I1 was scheduled using a daily water balance of the effective root zone. The water content was estimated with the following equation:

$$WC_t = WC_{t-1} + IRR + RAIN - ET_C - (DP + RO) \quad (2)$$

where
- WC_t = soil water content at time t (mm)
- WC_{t-1} = soil water content at time t-1 (mm)
- IRR = irrigation depth since time t-1 (mm)
- $RAIN$ = rain since time t-1 (mm)
- ET_C = crop evapotranspiration since time t-1 (mm)
- DP = deep percolation since time t-1 (mm)
- RO = runoff since time t-1 (mm).

Irrigation depths based on the soil water balance were assumed not to result in drainage below the root zone and runoff on the soil surface; therefore, *DP* and *RO* were assumed to be zero in equation 2. Thus, the irrigation depth can be estimated as:

$$IRR = (WC_t - WC_{t-1}) + ET_C - RAIN \quad (3)$$

When the depth of rainfall was known, the daily irrigation depth could be determined by daily ET_C and soil water contents at time t and t-1. The daily ET_C value was determined using the following equation:

$$ET_C = ET_0 \times K_C \quad (4)$$

where ET_0 is the reference ET, and K_C is the crop coefficient.

The daily values of ET_0 and rainfall were obtained from the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu), which had a weather station approximately 750 m from the experimental site. In the FAWN system, ET_0 values were calculated with the IFAS Penman method (Jones et al., 1984). The crop coefficients were based on Simonne et al. (2003) and Bauder and Waskom (2003) information for sweet corn (table 2).

Soil water content was calculated using soil water holding characteristics. First, the total available water (AW) for crop uptake was determined by the maximum allowable depletion (MAD) of the available water capacity (AWC) in the root zone. The AWC was defined as the difference between field capacity (FC) and permanent wilting point (PWP) of the soil. The MAD is the fraction of the available water that was used to meet ET demands, which was set as 50% in this study according to the recommendation of James et al. (1982) and Simonne et al. (2003). Once AWC was known, the total depth of AW can be obtained by multiplying AWC by MAD and the crop effective root zone depth. Since the root depth increased as the corn grew during the season, the depth of the root zone was treated as a step function of growth stage, ranging from 0 cm at planting to a maximum value of 50 cm at maturity because more than 70% of sweet corn roots have been reported to be concentrated in the top 50 cm soil layer (Bauder and Waskom, 2003).

Table 2. Crop coefficient (K_C) of sweet corn at different stages of development (based on Simonne et al., 2003, and Bauder and Waskom, 2003).

Growth Stage	Time (weeks after planting)	K_C
1	Planting to 2 weeks	0.15
2	3 to 4 weeks	0.30
3	5 to 6 weeks	0.50
4	7 to 8 weeks	0.65
5	9 to 10 weeks	1.00
6	11 weeks to harvest	0.90

To determine the values of soil FC and PWP, soil samples were collected in the experimental field and analyzed in the lab of the Department of Soil and Water Science, University of Florida. The soil in this study was sandy and mapped as Lake Sand, Candler Variant, Tavares Variant, and Millhopper Variant 1, which mainly belongs to Quartzipsamments (Entisol). The FC was measured as the volumetric soil moisture at a soil pressure of 0.1 bar, while PWP was measured as the volumetric soil moisture at 15.3 bars (Klute, 1986). The measured average values of FC and PWP were 0.11 and 0.05 cm^3 cm^{-3}, respectively.

The starting point for irrigation scheduling was 15 March 2006 (or the first day after planting), on which the first irrigation of 11.4 mm was applied. This brought the soil reservoir to full capacity so that WC_t was equal to AW. Then daily estimated ET_c was subtracted from the available water until the soil water storage was reduced to the allowable depletion level. At that point, an irrigation was applied with a net amount equivalent to the accumulated ET losses since the late irrigation. The soil reservoir was thus recharged to full capacity, and the depletion cycle began again. In this way, the date and amount for each irrigation event were estimated. In this study, a linear-move sprinkler irrigation system was used to supply irrigation water to the plots by altering system speed to achieve target levels of irrigation. The cumulative amounts of I1 and I2 are shown in figure 1.

Soil and Biomass Sampling

Biweekly soil sampling was conducted during the growth season. Samples were collected with an auger in the center part of each plot at four depths: 0-15 cm, 15-30 cm, 30-60 cm, and 60-90 cm. The samples were analyzed for soil moisture, KCl extractable soil nitrate and ammonium concentrations in the Department of Soil and Water Science, University of Florida, using the methodologies provided by Klute (1986) and Page et al (1982). Biweekly biomass sampling was conducted simultaneously at the locations within 1 m of the soil sampling locations. A whole plant that had an average height and growth in the sampling area was collected at each sampling. The samples were stored on ice and then processed in the Department of Agricultural and Biological Engineering, University of Florida. Each plant was divided into leaves, stems, husks, cobs, and kernels. Plant sample analysis included measurements of moisture and total Kjeldahl nitrogen (TKN) of different plant tissues. Biomass moisture was determined by drying the samples in an oven at a constant temperature of 60°C for 48 h. The dry samples were then processed with the Kjeldahl procedure (Page et al., 1982) to determine TKN concentration in the Analytical Research Laboratory (ARL) at the University of Florida.

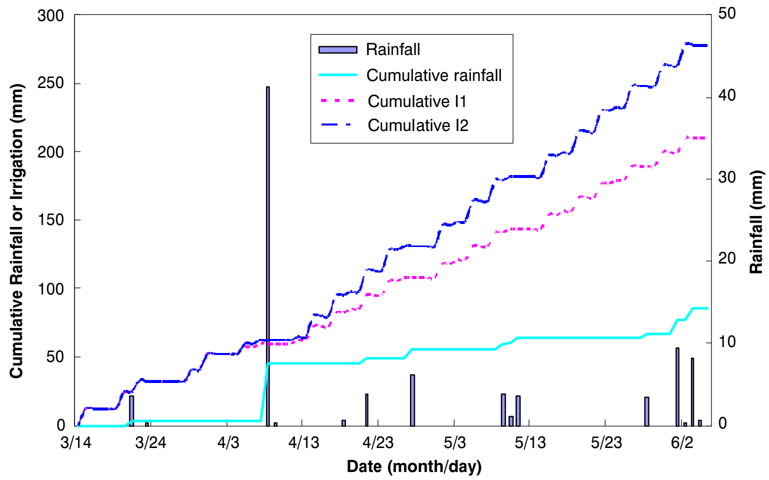

Figure 1. Daily rainfall and cumulative rainfall (solid line), irrigation, of I1 (dotted line), and I2 (dash-dotted line) during the growth season of sweet corn in 2006.

Yield Analysis

Yield sampling was conducted when the sweet corn reached fresh market maturity, about 80 days after planting. Ears in a sampling zone, which consisted of a 6.1 m section of two center rows in each plot, were completely collected, whether the kernels were fully filled or not. The total plants in this zone were counted. Then the collected ears (plus husks) were weighed for fresh yield. The collected ears were classified into three classes, U.S. #1, U.S. #2, and Cull, according to the USDA sweet corn classification standards (USDA, 1997). Several corn ears were separated into husks, kernels, and cobs and dried in an oven at 60°C for 48 h to measure the dry weight.

In this study, the sweet corn total yield was defined as the fresh mass of all ears (plus husks) collected in a unit area. The total weight of U.S. #1 and U.S. #2 yields was defined as the marketable yield. An analysis of variance (ANOVA) was performed to determine the influences of different nitrogen fertilizer and irrigation levels on the two yields using SAS (SAS, 1996), and Duncan's multiple range test was used for means separation.

Nitrogen Leaching Estimation

The nitrogen balance equation provided by Meisinger and Randall (1991) was used to estimate long-term potentially leachable total N (N_{pl}) for each treatment of the field experiment. The equation is as follows:

$$N_{pl} = N_{in} - N_{out} - \Delta N_s \qquad (5)$$

where N_{in} and N_{out} are N input and output of the crop system defined between the top of crop canopy and the bottom of soil profile (90 cm below the soil surface), respectively, and ΔN_s is the net balance of N in the soil at the end of the season, which was also available for leaching eventually. N_{pl} was the mass-balance-based estimation of N leaching to groundwater during a crop growth season. Each component on the right side of equation 5 was investigated before the estimation.

There were five possible N inputs in the sweet corn cropping system. The first was the N fertilizer applied (table 1), which was the largest N contributor in this crop system. The second source was the corn seeds, because they contained organic N such as protein, amino acids, and nucleic acids. According to Meisinger and Randall (1991), the sweet corn seeds supply 0.3 kg N ha^{-1} to the overall N budget. The third source is the N from atmospheric deposition. According to Li et al. (2002), the annual atmospheric N deposition rate in Florida is about 11 kg N ha^{-1} year^{-1}. Since the growth season of sweet corn in this study was 80 days, the atmospheric N deposition in the experiment was estimated as about 2.4 kg N ha^{-1}. However, this value is likely overestimated due to the low number of storm events in this growing season compared with the summer time. The fourth N contributor to the system was the N dissolved in irrigation water. There were four water table wells in a nearby field to monitor the nitrate and ammonium concentration in the surficial groundwater. Thus, the N concentration data collected from these wells during the experiment was used to estimate the N concentration for irrigation water. (Note that this could also be an overestimate since the irrigation wells are significantly deeper than the surficial water table monitoring wells.) The average NO_3-N concentration was 3.65 mg L^{-1}, while the average NH_4-N concentration was about 0.22 mg L^{-1}. The cumulative depth of irrigation level I1 was around 21.0 cm. The cumulative irrigation depth of I2 was about 27.8 cm. Thus, the total nitrogen contained in irrigation water of I1 and I2 were approximately 8.1 and 10.8 kg N ha^{-1}, respectively. The last possible N input was the biochemically fixed N in the soil by specialized micro-organisms, including bacteria, actinomycetes, and cyanobacteria. Since the field was kept fallow before the experiment and no legume crop was planted during the experiment in this study, this N source was considered negligible.

Nitrogen outputs indicate removal of N from the crop system. The most significant N output was the N in corn biomass. This mass of N was estimated with TKN concentrations of corn tissue, weight of corn biomass, and plant density at harvest. The next possible N output was the gaseous loss. It included several physical and chemical processes, such as volatilization of ammonia and denitrification of nitrate. Since no instruments were installed during the field experiment to directly measure these N losses, estimates based on literature values were used. According to Liu et al. (2003), the miscellaneous gaseous N loss was about 4% to 7% of the total N fertilizer application as urea in maize production. In this study, urea nitrogen was 51% of total nitrogen applied, i.e., about 3% of the total applied nitrogen might be lost through urea volatilization. Considering other gaseous losses of nitrate and ammoniacal nitrogen through denitrification and NH_3 volatilization, the total gaseous loss in this study was estimated as 6% of total N fertilizer applied.

The net balance of soil N at the end of the season (ΔN_s) was estimated as the differences in nitrate and ammonium N concentrations between the initial and final soil samples, which were collected on the day of planting and the day of harvest, respectively.

CERES-Maize Model Simulation

Crop growth and development were simulated by the CERES-Maize model with a daily time step from planting to maturity and are based on physiological processes that describe the response of maize to soil and environmental conditions. Potential growth is dependent on photo-synthetically active radiation and its interception, whereas actual biomass production on any day is constrained by suboptimal temperatures, soil water deficits, and N deficiencies (Ritchie and Godwin, 1989; Ritchie, 1998).

There are four groups of model input data: weather, crop, soil, and management. The weather inputs are daily sum of global radiation (MJ m^{-2}), daily minimum and maximum air temperatures (°C), and daily sum of precipitation (mm). Crop parameters and physiological characteristics are given in the form of genetic coefficients, which describe physiological processes such as photosynthesis, respiration, and others for individual crop varieties. The soil inputs are given as soil characterization parameters, which describe the physical, chemical, and morphological properties of the soil surface and each layer. The crop management information includes planting density, row spacing, planting depth, irrigation, application of fertilizer, etc. (Ritchie, 1998).

As mentioned previously, daily weather data were obtained from the weather station (FAWN) at the experimental site. Crop management information was collected from on-site observation. The genotype coefficients and soil parameters were estimated with the GLUE method with independent field experiment data obtained in 2005 and 2006, which were reported by He et al. (2009). These independent experiments used the same sweet corn cultivar as the current study on an adjacent field. Thus, the results of genotype coefficients and soil parameter estimation in He et al. (2009) can be directly used to simulate this current experiment of sweet corn production. Unlike traditional parameter estimation methods aimed at finding an optimal parameter set within some particular structure, the GLUE method uses observed data, including anthesis date, maturity date, dry matter yield (kg ha^{-1}), leaf nitrogen content (%), soil nitrate content (mg kg^{-1}), and soil moisture (cm^{-3} cm^{-3}), and prior information about parameter distributions obtained from the DSSAT database (Hoogenboom et al., 2003) and then calculates a posterior probability distribution of the input parameters including means and standard deviations. The posterior distribution (table 3), computed using Bayes theorem, is used to estimate the uncertainties of parameters and model outputs. According to He et al. (2009), the uncertainties in selected parameters were substantially reduced using the GLUE method, since the average CV value of the parameters was reduced from 27% in the prior distribution to 5% in the posterior distribution. Consequently, the uncertainties in model outputs were also significantly reduced.

Table 3. Distributions of the selected genotype coefficients and soil parameters obtained with the generalized likelihood uncertainty estimation (GLUE) method used in the present study (from He et al., 2009).

Parameter	Mean	SD	Unit
P1	99	8	°Cd
P5	577	10	°Cd
PHINT	40	0.20	°Cd
SLDR	0.73	0.006	fraction d^{-1}
SLRO	78	10	--
SDUL	0.10	0.002	cm^3 cm^{-3}
SLLL	0.06	0.002	cm^3 cm^{-3}
SSAT	0.30	0.02	cm^3 cm^{-3}
SLPF	0.87	0.04	--

All six treatments (N1I1, N2I1, N3I1, N1I2, N2I2, and N3I2) were simulated with the CERES-Maize model under the weather and management conditions of the field experiment in this study. The three N levels (N1, N2, and N3 in table 1) and two irrigation levels (I1 and I2) were set up on the dates when they were actually applied in the input file. For each treatment, simulations were conducted with 3,000 different parameter sets that were randomly generated from the parameter posterior distribution (table 3). Thus, the uncertainties in input parameters were counted into the uncertainties of various model predictions. In previous research, this number of simulations was confirmed sufficient to result in stable model outputs (He, 2008). The means of dry matter yield, anthesis date, maturity date, and accumulative nitrogen leaching of each treatment were compared with the measured or estimated values from the field experiment. The relative absolute error (RAE) was used as a measure of differences in comparisons except for estimated accumulative N leaching, which was defined as follows:

$$\text{RAE} = \frac{|Y' - Y|}{Y} \times 100\% \tag{6}$$

where Y is the measured variable value and Y' is the model prediction value. The difference (Y' - Y) was used in the comparison of accumulative N leaching since this output variable was only based on estimation in the field experiment.

Moreover, uncertainties of model predictions, which were quantified by standard deviation (SD) among the 3000 simulations, were also compared with the observation errors as expressed by the SD among the measurements.

Results and Discussion

Sweet Corn Yield

The influence of irrigation and N treatment on total yield and marketable yield are shown in table 4. Neither irrigation rate nor the interaction between irrigation and N levels had a significant influence (95% confidence level) on total yield or on marketable yield. However, increasing the N application from 185 to 247 kg ha^{-1} resulted in a significant (95% confidence level) increase in average total yield from 17,182 to 20,181 kg ha^{-1}, and average marketable yield

Table 4. Effect of irrigation (I) and nitrogen (N) fertilizer levels on sweet corn total and marketable yield in field experiment; p-values for the main effects and their interactions are also reported.

Factor	Level	Total Yield (kg ha^{-1})	Marketable Yield[a] (kg ha^{-1})
Irrigation Level	I1	18,618	16,681
	I2	20,091	18,431
Nitrogen Level**[b]	N1	17,182 b	15,255 b
	N2	20,181 a	18,584 a
	N3	20,701 a	18,828 a
		p-Values	
Main Effect	I	0.107	0.056
	N	0.010	0.007
Interaction	I × N	0.743	0.405
	CV (%)	11	12

[a] Marketable yield was defined as the sum of U.S. #1 and U.S. #2 ears.
[b] ** = F-test significant, $p < 0.01$. Means within a nitrogen level followed by the same letter are not significantly different ($p \leq 0.05$) according to Duncan's multiple range test.

Table 5. Components of nitrogen balance (kg ha^{-1}) of treatment N1I1 in the field experiment.

Component	Item	Part	Average
Input	N fertilizer		185
	Seed		0.3
	Atmospheric deposition		2.4
	Irrigation water nitrate		7.7
	Irrigation water ammonium		0.5
		Subtotal	195.9
Net residual	Soil nitrate	0-15 cm	-0.5
		15-30 cm	-0.9
		30-60 cm	0.3
		60-90 cm	-0.2
		Subtotal	-1.3
	Soil ammonium	0-15 cm	-3.2
		15-30 cm	-3.6
		30-60 cm	-3.5
		60-90 cm	3.3
		Subtotal	-7.0
Output	Gaseous loss (volatilization and denitrification		11.1
	Plant uptake	Cobs	7.7
		Husks	3.8
		Kernels	42.5
		Leaves	20.3
		Stems	3.8
		Subtotal	78.1
Potential leaching	--	--	115.0

increased from 15,255 to 18,584 kg ha^{-1}. There was no significant difference between N2 and N3; thus, increasing N fertilizer beyond 247 kg N ha^{-1} did not significantly increase yield.

Nitrogen Balance Estimation

For the different components of N balance of treatment N1I1 (table 5), the average total nitrogen in corn tissue was 78.1 kg ha^{-1}. The nitrogen use efficiency (NUE), which was defined as the ratio between crop biomass N and applied fertilizer N, was about 42%, i.e., most applied nitrogen was lost and mainly as nitrogen leaching. According to Raun and Johnson (1999), the worldwide NUE for maize prediction is about 33%. Cassman et al. (2002) reported that despite the improvement in efficiency since 1980, the best estimate of average NUE in U.S. maize cropping systems was only 37%. Thus, 42% is a reasonable estimation of the NUE of the system if considering the precise fertigation method and schedule in this study.

Table 6. Estimated nitrogen leaching across the factorial nitrogen and irrigation levels of the field experiment.

Treatment	Mean (kg ha^{-1})	SD (kg ha^{-1})	CV (%)
N1I1	115	23	20
N2I1	140	15	11
N3I1	196	13	7
N1I2	133	18	14
N2I2	154	19	12
N3I2	214	15	7

Table 7. Effect of irrigation (I) and nitrogen (N) fertilizer levels on estimated nitrogen leaching in the field experiment; p-values for the main effects and their interactions are also reported.

Factor	Level	Cumulative Nitrogen Leaching (kg ha^{-1})
Irrigation Level*[a]	I1	150 b
	I2	167 a
Nitrogen Level***[a]	N1	124 c
	N2	147 b
	N3	205 a
		p-Values
Main effect	I	0.043
	N	<0.0001
Interaction	I × N	0.962
	CV (%)	22.6

[a] * = F-test significant, $p < 0.05$, *** = F-test significant, $p < 0.001$. Means within irrigation or nitrogen levels followed by the same letter are not significantly different ($p \leq 0.05$) according to Duncan's multiple range test.

The same estimation procedure based on N mass balance was conducted for all four replicates of each of the six combined treatments. The final estimated amounts of potential N leaching of the six treatments are summarized in table 6 with variability across the replicates. The interaction between irrigation and N levels did not significantly influence N leaching (table 7), but increased irrigation levels resulted in a significant increase in estimated N leaching from 150 kg ha^{-1} at I1 to 167 kg ha^{-1} at I2. Increasing N rate also resulted in significant estimated N leaching, with an increase of 124 to 205 kg ha^{-1} as N level increased from N1 to N3.

CERES-Maize Model Simulation

Phenology Dates

The calibrated CERES-Maize model performed very well in predicting the anthesis and maturity dates. The mean value of simulated anthesis date was 51 days after planting, identical to the field experiment. The uncertainty of anthesis date caused by input parameter uncertainties was one day. The mean value of simulated maturity date was 81 days after planting, in contrast to the observed 80 days. The prediction uncertainty of maturity date was two days. Both the uncertainties of simulated anthesis and maturity dates were also very close to the observations. The close agreement between mean values and standard deviations of predicted and observed phenology values was not surprising because the model was calibrated using data from previous independent experiments with the same sweet corn cultivar, soil type, N fertilizer, etc. (He et al., 2009). In general, the model correctly simulated the phenology dates of the field experiment, since the distribution patters of model simulations and field observations are very close to each other according to their individual means and standard deviations.

Dry Matter Yield

The simulated dry yield standard deviations ranged from 655 kg ha^{-1} at I1 to 960 kg ha^{-1} at I2 (table 8). These results showed that the prediction SD increased with irrigation amounts, but the SD for different N levels did not vary much at a particular irrigation level. The SD values of measured dry yield ranged from 220 to 463 kg ha^{-1}, and they were also different for various N levels even at the same irrigation level. The SD values of simulated yields were higher than those of observed yields, indicating that more uncertainty was contributed by the variations in estimated cultivar and soil properties than the actual heterogeneity in field cultivar and soil conditions. Thus, opportunity exists for more model calibration to more reduce the input parameter uncertainties. The RAE values between measured and simulated mean yields were less than 12%, except for treatment N1I2, where the simulated yield was 29% higher than the measured yield. The errors of predicted yields were all within one standard deviation of the predicted yields, and most were also within or close to one standard deviation of the measured yields, except for treatment N1I2. For N1I2, the error between simulated and measured yields was 756 kg ha^{-1}, which was three times greater than the SD of measured yields (231 kg ha^{-1}). The source of discrepancy in N1I2 is not known but could have been due to the uncertainties in initial soil N and organic matter, which were not considered in this analysis.

The model also correctly simulated the variations in dry matter yields caused by higher nitrogen and irrigation levels. When N increased from 185 to 247 kg N ha^{-1} at I1, the simulated average dry yield increased from 2,843 to 3,023 kg ha^{-1}. Therefore, an increase in N fertilizer could improve the yield when the N level was low. However, when N increased from 247 to 309 kg N ha^{-1}, the simulated average dry yields were almost the same, indicating that adding N beyond 247 kg N ha^{-1} did not improve sweet corn yield when the crop N requirement was satisfied, which matched the experimental observations as shown previously. Similar results were seen under I2.

Table 8. Comparison between DSSAT CERES-Maize simulated and measured dry yield for the six nitrogen and irrigation treatments.

Treatment	Simulated Mean (SD) (kg ha^{-1})	Simulated CV (%)	Measured Mean (SD) (kg ha^{-1})	Measured CV (%)	RAE[a] (%)
N1I1	2843 (664)	23	2533 (276)	11	12
N2I1	3023 (655)	22	2902 (389)	13	4
N3I1	3024 (655)	22	2943 (220)	7	3
N1I2	3377 (933)	28	2621 (231)	9	29
N2I2	3419 (949)	28	3152 (463)	15	8
N3I2	3447 (960)	28	3268 (324)	10	5

[a] RAE = relative absolute error, defined in equation 6.

Potential Nitrogen Leaching

Before comparing the simulated and estimated amounts of N leaching, it was necessary to analyze the N balance components of the model simulation. The main N inputs of model simulation included: inorganic N applied (identified as NICM in DSSAT) or N fertilizer, initial nitrate-N in the soil profile, initial ammonium-N in the soil profile, and nitrogen from senesced plant matter. In this study, the N fertilizer application amount (table 1) was used as the value of NICM for each treatment. The initial nitrate-N and ammonium-N concentrations were 0.1 and 0.5 g N Mg^{-1}, respectively, which equal about 1.3 and 6.7 kg N ha^{-1}. The N obtained from organic matter was calculated as 7 kg N ha^{-1} by the model. The main N output of model simulation included three main components: N uptake during the season (NUCM), N leached during the season (NLCM), and inorganic N at maturity in the soil (NIAM).

From the components of simulated N balance with CERES-Maize for treatment N1I1 (table 9), it can be seen that 94 kg N ha^{-1} from the total application of 184 kg N ha^{-1} was simulated to have been utilized in production of sweet corn biomass. The NUE value was about 51%, which is higher than the previously estimated field NUE value of 42%. It can be seen that among the three components of N output in the system, N uptake during the season (NUCM) had the largest portion (94 kg N ha^{-1}, or 47% of total N output), while N leached during the season (NLCM) only accounted for a relatively small portion (32 kg N ha^{-1} or 16% of total N output). A significant part of N output was credited to inorganic N at maturity (NIAM) in the soil profile, which covered an average proportion of 68% of the total potential nitrogen leaching. NLCM represented the N that had already been leached into groundwater, while NIAM represented the inorganic N (nitrate and ammonium) that was still in the soil profile at corn maturity. Thus, only considering NLCM as the value of potential N leaching in this study might be misleading. The NIAM would also be subject to leaching after harvest due to rainfall. From a long-term point of view, the total potential N leaching should be the sum of NLCM and NIAM. The same N balance calculations were also conducted for the other treatments (table 10).

Simulated and estimated amounts of potential N leaching were compared (table 11). The variability of simulated potential N leaching ranged from 10 to 16 kg ha^{-1} as irrigation increased from I1 to I2, which indicates that uncertainties increased with irrigation level. The variability in estimated N leaching ranged from 13 to 23 kg ha^{-1}, which was mainly

Table 9. Example of DSSAT CERES-Maize simulated components of nitrogen balance (kg ha^{-1}) of one experimental treatment, N1I1.

Component	Item	Value
Input	Inorganic N applied or N fertilizer (UNIM)	184
	Initial soil nitrate-N	1.3
	Initial soil ammonium-N	6.7
	N from senesced plant matter	7
	Subtotal	199
Output	N uptake during season (NUCM)	94
	N leached during season (NLCM)	32
	Inorganic N at maturity (NIAM)	73
	Subtotal	199
Potential N leaching	NLCM + NIAM	105

Table 10. DSSAT CERES-Maize simulated nitrogen leaching with the six nitrogen and irrigation treatments.

Treatment	N Leached during Season (NLCM) (kg ha^{-1})	Inorganic N at Maturity (NIAM) (kg ha^{-1})	Potential N Leaching (NLCM + NIAM) (kg ha^{-1})	
	Mean	Mean	Mean	SD
N1I1	32	73	105	10
N2I1	33	145	178	10
N3I1	33	206	239	10
N1I2	55	47	102	16
N2I2	66	97	163	16
N3I2	76	148	224	16

due to uncertainties in measured soil N and biomass N concentrations. For all treatments except N1I1, the uncertainties of simulated N leaching covered a large portion (>67%) of the uncertainties of estimated leaching. This result is because N leaching was mainly controlled by soil properties related to water holding capacity, and the soil parameters were well estimated with the GLUE method. Thus, the uncertainties in estimated soil parameters largely represented the heterogeneity of the field soil. An interesting finding in table 11 is that the standard deviations of simulated nitrogen leaching were the same for each specific irrigation level, but there was some difference for the estimated values. This outcome was because the soil was supposed to be homogeneous in the horizontal extent in the model, but that was not the case in the field. The discrepancies between the simulated and estimated N leaching amounts were complex, ranging from -31 to 43 kg N ha^{-1}. For treatments N1I1 and N1I2, the model simulations were smaller than the estimations, but the simulations were greater for the other treatments. On average, the relative absolute difference between simulated and estimated amounts of nitrogen leaching was about 15.3%. The reason for the difference was probably due to both the uncertainties in potential nitrogen leaching estimation in the field experiment and the inaccuracy of model predictions

The discrepancy in soil N leaching modeling due to the complexities and difficulties in N dynamics modeling found in this study is not surprising. Conrad and Fohrer (2009) simulated N leaching under a complex winter wheat and red clover crop rotation in a drained agricultural field with the CoupModel. The measured and simulated nitrate nitrogen leaching were 5.9 and 10.1 kg N ha^{-1}, with an RAE value of 71%. During a later time period, the measured and simulated results were 10.9 and 5.9 kg N ha^{-1}, with an RAE value of 46%. Wolf et al. (2005) used the ANIMO and STONE models to simulate N leaching in sandy soils in a number of plots at the 'De Marke' experimental dairy farm in The Netherlands. Their simulated values of N leaching at the 100 cm depth with ANIMO and STONE in 1992 were 60 and 43 kg N ha^{-1} year^{-1} respectively, but the measured value was only 3 kg N ha^{-1} year^{-1}. Therefore, in this project, the average relative difference of 15.3% between model simulation and estimation appears better than comparable studies. As shown by He et al. (2009), the model was not specifically calibrated with respect to nitrogen leaching; only soil nitrate content and soil moisture were involved in the calibration process. By comparing the estimated and simulated amounts of N leaching in the plot experiment, the model did a relatively good job in simulating N leaching by essentially calibrating the parameters associated with soil water storage and movement.

Table 11. Comparison between DSSAT CERES-Maize simulated and field-estimated potential nitrogen leaching with the six nitrogen and irrigation treatments.

Treatment	Simulated Mean (SD)[a] (kg ha^{-1})	Simulated CV (%)	Estimated Mean (SD)[a] (kg ha^{-1})	Estimated CV (%)	Difference (kg ha^{-1})
N1I1	105 (10)	10	115 (23)	20	-10
N2I1	178 (10)	6	140 (15)	11	38
N3I1	239 (10)	4	196 (13)	7	43
N1I2	102 (16)	16	133 (18)	14	-31
N2I2	163 (16)	10	154 (19)	12	9
N3I2	224 (16)	7	214 (15)	7	10

[a] The source of variability in SD of simulated nitrogen leaching was mainly due to uncertainties in input soil parameters; for estimated nitrogen leaching, the variation was mainly due to the soil heterogeneity and measurements errors.

The CERES-Maize model also correctly simulated the variation in nitrogen leaching caused by higher nitrogen levels. When nitrogen increased from 185 to 309 kg N ha^{-1}, the simulated amounts of nitrogen leaching kept increasing from 105 to 239 kg N ha^{-1} at I1. This confirmed the estimation that as more nitrogen was applied, more was leaching. Similar results were seen for I2.

Summary and Conclusions

A field plot experiment and model simulations were conducted to evaluate the ability of the CERES-Maize model to predict the yield and nitrogen leaching of sweet corn production on the sandy soils in northern Florida under different irrigation and nitrogen fertilizer levels, taking into account uncertainties in parameters determined from a prior study. In contrast with the typical model verification process in which single values of model output variables are compared with the corresponding mean values of field observations, the distributions of model simulations and field observations were compared both for their means and standard deviations in this study. This distribution comparison provides a more comprehensive understanding of model performance in predicting sweet corn production.

The results show that the previously calibrated CERES-Maize model predicted the anthesis and maturity dates within 1 and 2 days, respectively, of observed field values. Thus, for phenological events, the observations fell within the simulated uncertainties of those variables. The model correctly predicted the variations in dry matter yield caused by different N and irrigation levels, with an RAE value of less than 12% for all but one treatment. The differences between the predicted and measured yields were all within one standard deviation of the predicted yields, while most were also within one standard deviation of the measured yields. However, the uncertainties in model-simulated yield were higher than those in field observations, indicating that uncertainties were introduced into the model simulations by the variations of estimated parameters, especially the genetic coefficients. Thus, the model performance can be further improved if the variations in genetic coefficients can be further reduced in the model calibration process with the GLUE method.

The model also correctly predicted the trend of increased N leaching caused by higher N fertilizer levels. However, the difference between the simulated and estimated N leaching amounts was much higher than the difference between the simulated and observed yields. Three of the six treatments had relative absolute differences greater than 20%. This discrepancy in soil N leaching modeling could be due to the complexities and difficulties in N dynamics modeling. However, the uncertainties of simulated N leaching covered more than 67% of those of estimated N leaching for all but one treatment, which means that the soil parameters related to water holding capacity were well estimated with the GLUE method, and variations in these estimated soil parameters represented the heterogeneity of the field soil to a large degree. In the simulated N balance of CERES-Maize, both N leached during the season (NLCM) and inorganic N at maturity in the soil (NIAM) should be considered as potential nitrogen leaching. Otherwise, the calculated potential nitrogen leaching would be much less than the estimated value. Generally, the model can do a comparably good job in simulating N leaching since the average absolute difference between simulated and estimated amounts of nitrogen leaching was about 15.3%, which is much lower than in other published research, by essentially calibrating the parameters associated with soil water storage and movement.

As shown in this study, the N use efficiency of sweet corn production was less than 45%, although sweet corn had a high demand for nitrogen. Fertilizer recovery typically decreases with an increase in N application rates, while timing of fertilizer application also affects fertilizer uptake efficiency in corn (Subedi and Ma, 2005). At the same time, overall N recovery and efficiency of corn also seems to be impacted, to a large extent, by irrigation management practices (Kirda et al., 2005) and climate conditions. Matching N fertilizer and irrigation rates and scheduling with crop demands is thus required to minimize N leaching on the poorly buffered sandy soils in Florida. The CERES-Maize model showed its ability to accurately simulate sweet corn production under different N fertilizer and irrigation management conditions, which allows the exploration of tradeoffs between yields and N leaching for sweet corn production in Florida. Undoubtedly, this kind of model-based research will be very efficient and time-saving. Many kinds of management strategies can be tested, and various climate conditions can be involved in the study.

Acknowledgements

This article was partially supported by the Office of Natural Resources Management and Office of Agriculture in the Economic Growth, Agriculture, and Trade Bureau of the U.S. Agency for International Development under the terms of Grant No. LAG-G-00-97-00002-00, and by the Florida Department of Environmental Protection and the Florida Agricultural Experiment Station. Special appreciation is expressed to the Plant Science Research and Education Unit, University of Florida. The authors thank Dr. M. Annable, Dr. J. Judge, and D. Burch of the Department of Agricultural and Biological Engineering, University of Florida, for their help on this project.

References

Asadi, M. E., R. S. Clemente, A. D. Gupta, R. Loof, and G. K. Hansen. 2002. Impacts of fertigation via sprinkler irrigation on nitrate leaching and corn yield in an acid-sulfate soil in Thailand. *Agric. Water Mgmt.* 52(3): 197-213.

Bauder, T., and R. Waskom. 2003. Best management practices for Colorado corn. Cooperative Extension Bulletin XCM574A. Fort Collins, Colo.: Colorado State University.

Baum, M. C., M. D. Dukes, and G. L. Miller. 2005. Analysis of residential irrigation distribution uniformity. *J. Irrig. and Drainage Eng.* 131(4): 336-341.

Beven, K. 1993. Prophecy, reality, and uncertainty in distributed hydrological modeling. *Advances in Water Resources* 16(1): 41-51.

Beven, K. 2006. A manifesto for the equifinality thesis. *J. Hydrol.* 320(1-2): 18-36.

Beven, K., and A. Binley. 1992. The future of distributed models: Model calibration and uncertainty prediction. *Hydrol. Proc.* 6(3): 279-298.

Beven, K., and J. Freer. 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modeling of complex environmental systems using the GLUE methodology. *J. Hydrol.* 249: 11-29.

Bowen, W. T., J. W. Jones, R. J. Carsky, and J. O. Quintana. 1993. Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. *Agron. J.* 85(1): 153-159.

Burt, C. M., A. J. Clemmens, T. S. Strelkoff, K. H. Solomon, R. D. Bliesner, L. A. Hardy, T. A. Howell, and D. E. Eisenhauer. 1997. Irrigation performance measures: Efficiency and uniformity. *J. Irrig. Drain. Eng.* 123(6): 423-442.

Campbell, E. P., D. R. Fox, and B. C. Bates. 1999. A Bayesian approach to parameter estimation and pooling in nonlinear flood event models. *Water Resour. Res.* 35(1): 211-220.

Cassman, K. G., A. Dobermann, and D. T. Walters. 2002. Agroecosystems, nitrogen use efficiency, and nitrogen management. *Ambio* 31(2): 132-140.

Conrad, Y., and N. Fohrer. 2009. Modeling of nitrogen leaching under a complex winter wheat and red clover crop rotation in a drained agricultural field. *Phys. and Chem. of the Earth* 34(8-9): 530-540.

FWRA. 1999. Florida Watershed Restoration Act. *Florida Statutes*, section 403.067. Tallahassee, Fla.: State of Florida.

Garcia y Garcia, A., L. C. Guerra, and G. Hoogenboom. 2009. Water use and water use efficiency of sweet corn under different weather conditions and soil moisture regimes. *Agric. Water Mgmt.* 96(10): 1369-1376.

Gerakis, A., and J. T. Ritchie. 1998. Simulation of atrazine leaching in relation to water table management using the CERES model. *J. Environ. Mgmt.* 52(3): 241-258.

Gungula, D. T., J. G. Kling, and A. O. Togun. 2003. CERES-Maize predictions of maize phenology under nitrogen-stressed conditions in Nigeria. *Agron. J.* 95(4): 892-899.

Ham, L. K., and H. H. Hatzell. 1996. Analysis of nutrients in the surface waters of the Georgia-Florida Coastal Plain Study Unit, 1970-1991. USGS Water Resources Investigations Report 96-4037. Reston, Va.: U.S. Geological Survey.

He, J. 2008. Best management practice development with the CERES-Maize model for sweet corn production in North Florida. PhD diss. Gainesville, Fla.: University of Florida, Department of Agricultural and Biological Engineering.

He, J., M. D. Dukes, J. W. Jones, W. D. Graham, and J. Judge. 2009. Applying GLUE for estimating CERES-Maize genetic and soil parameters for sweet corn production. *Trans. ASABE* 52(6): 1907-1921.

Hochmuth, G. J. 2000. Nitrogen management practices for vegetable production in Florida. Circular 1222. Gainesville, Fla.: University of Florida, Florida Cooperative Extension Service.

Hochmuth, G., and M. Donley. 1992. Nitrogen fertilization of sweet corn on a sandy soil in northern Florida. Research Report Suwannee Valley AREC 92. Gainesville, Fla.: University of Florida, Florida Agricultural Experiment Station.

Hoogenboom, G., J. W. Jones, C. H. Porter, P. W. Wilkens, K. J. Boote, W. D. Batchelor, L. A. Hunt, and G. Y. Tsuji, eds. 2003. *Decision Support System for Agrotechnology Transfer, Version 4.0. Volume 1: Overview.* Honolulu, Hawaii: University of Hawaii.

James, L. G., J. M. Erpeneck, D. L. Bassett, and J. E. Middleton. 1982. Irrigation requirement for Washington: Estimates and methodology. Research bulletin XB0925. Pullman, Wash.: Washington State University, Agricultural Research Center.

Jones, C. A., and J. R. Kiniry. 1986. *CERES-Maize: A Simulation Model of Maize Growth and Development*. College Station, Tex.: Texas A&M University Press.

Jones, J. W., L. H. Allen, S. F. Shih, J. S. Roger, L. C. Hammond, A. G. Smajstrla, and J. D. Martsolf. 1984. Estimated and measured evapotranspiration for Florida climate, crops, and soils. Bulletin 840 (Tech). Gainesville, Fla.: University of Florida, IFAS.

Jones, J., G. Hoogenboom, C. Porter, K. Boote, W. Batchelor, L. Hunt, P. Wilkens, U. Singh, A. Gijsman, and J. Ritchie. 2003. The DSSAT model cropping system model. *European J. Agron.* 18(3-4): 235-265.

Katz, B. G., H. D. Hornsby, J. F. Bohlke, and M. F. Mokray. 1999. Sources and chronology of nitrate contamination in spring waters, Suwannee River basin, Florida. USGS Water Resources Investigations Report 99-4252. Prepared in cooperation with the Suwannee River Water Management District. Reston, Va.: U.S. Geological Survey.

Kidder, G., E. A. Hanlon, and G. J. Hochmuth. 1989. IFAS standardized fertilization recommendations for vegetable crops. Spec. Ser. SS-SOS-907. Gainesville, Fla.: University of Florida, Florida Cooperative Extension Service.

Kirda, C., S. Topcu, H. Kaman, A. C. Ulger, A. Yazici, M. Cetin, and M. R. Derici. 2005. Grain yield response and N-fertilizer recovery of maize under deficit irrigation. *Field Crops Res.* 93(2-3): 132-141.

Klute, A. 1986. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. 2nd ed. Number 9 (Part 1) in the series. Madison, Wisc.: ASA, CSSA, SSSA.

Kovacs, G. T., and T. Nemeth. 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. *Agric. Systems* 49(4): 385-397.

Lamb, R., K. Beven, and S. Myrabo. 1998. Use of spatially distributed water table observations to constrain uncertainty in a rainfall-runoff model. *Advances in Water Resources* 22(4): 305-317.

Leach, K. A., K. D. Allingham, J. S. Conway, K. W. T. Goulding, and D. J. Hatch. 2004. Nitrogen management for profitable farming with minimal environmental impact: the challenge for mixed farms in the Cotswold Hills, England. *Intl. J. Agric. Sustain.* 2(1): 21-32.

Li, Y. C., A. K. Alva, D. V. Calvert, and D. J. Banks. 2002. Atmospheric deposition of nitrogen in a high lightning intensity area. *Commun. Soil Sci. Plant Anal.* 33(9-10): 1671-1677.

Liu, X., X. Ju, F. Zhang, J. Pan, and P. Christie. 2003. Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain. *Field Crops Res.* 83(2): 111-124.

Lizaso, J. I., K. J. Boote, C. M. Cherr, J. J. Casanova, J. Judge, J. M. Scholberg, J. W. Jones, and G. Hoogenboom. 2007. Developing a sweet corn simulation model to predict fresh market yield and quality of ears. *J. American Soc. Hort. Sci.* 132(3): 415-422.

Makowski, D., J. Hillier, D. Wallach, B. Andrieu, and M. H. Jeuffroy. 2006. Parameter estimation for crop models. In *Working with Dynamic Crop Models*, 101-150. D. Wallach, D. Makowski, and J. Jones, eds. Amsterdam, The Netherlands: Elsevier.

Marella, R. L. 2005. Water use in Florida, 2005 and trends 1950-2005. USGS Fact Sheet 2008-3080. Reston, Va.: U.S. Geological Survey. Available at: http://pubs.usgs.gov/fs/2008/3080/.

Meisinger, J. J., and G. W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. In *Managing Nitrogen for Groundwater Quality and Farm Profitability*, 85-124. R. F. Follett, ed. Madison, Wisc.: ASA, CSSA, SSSA.

Page, A. L, E. H. Miller, and D. R. Keeney. 1982. Part 2: Chemical and microbiological properties. In *Methods of Soil Analysis*, 595-673. 2nd ed. Madison, Wisc.: ASA, CSSA, SSSA.

Pang, X. P., S. C. Gupta, J. F. Moncrief, C. J. Rosen, and H. H. Cheng. 1998. Evaluation of nitrate leaching potential in Minnesota glacial outwash soils using the CERES-Maize model. *J. Environ. Qual.* 27(1): 75-85.

Pathak, B. K., F. Kazama, and I. Toshiaki. 2004. Monitoring of nitrogen leaching from a tropical paddy in Thailand. *Agric. Eng. Intl.: CIGR J. Sci. Research and Development*, Vol. VI: Manuscript LW 04 015.

Paz, J. O., W. D. Batchelor, B. A. Babcock, T. S. Colvin, S. D. Logsdon, T. C. Kaspar, and D. L. Karlen. 1999. Model-based technique to determine variable rate nitrogen for corn. *Agric. Systems* 61(1): 69-75.

Pittman, J. R., H. H. Hatzell, and E. T. Oaksford. 1997. Spring contributions to water quality and nitrate loads in the Suwannee River during base flow in July 1995. USGS Water-Resources Investigations Report 97-4152. Reston, Va.: U.S. Geological Survey.

Raun, W. R., and G. V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. *Agron. J.* 91(3): 357-363.

Rhoads, F. M. 1990. Sweet corn research in north Florida. Research report. Gainesville, Fla.: University of Florida, Florida Agricultural Experiment Station.

Ritchie, J. T. 1998. Soil water balance and plant water stress. In *Understanding Options for Agricultural Production*, 41-54. G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton, eds. Dordrecht, The Netherlands: Kluver Academic.

Ritchie, J. T., and D. C. Godwin. 1989. Description of soil balance. In *Modeling the Growth and Development of Sorghum and Pearl Millet*, 14-16. S. M. Virnami, H. L. S. Tandon, G. Alagarswamy, eds. Research bulletin 12. Pradesh, India: ICRISAT.

Rudert, B. D., and S. J. Locascio. 1979. Growth and tissue composition of sweet corn as affected by N source, nitrapyrin, and season. *J. American Soc. Hort. Sci.* 104: 520-523

SAS. 1996. *SAS Statistics User's Guide.* Release Version 6. Cary, N.C.: SAS Institute, Inc.

Schroder, J. J., H. F. M. Aarts, H. F. M. Berge, H. van Keulen, and J. J. Neeteson. 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. *European J. Agron.* 20(1-2): 33-44.

Simonne, E. H., M. D. Dukes, and D. Z. Haman. 2003. Principles and practices for irrigation management. In *2003-2004 Vegetable Production Guide for Florida*, 33-39. S. M. Olson and E. H. Simonne, eds. Lenexa, Kans.: Vance Publishing.

Simunek, J., M. Sejna, and M. T. van Genuchten. 1999. The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media, Version 2.0. Golden, Colo.: Colorado School of Mines, International Ground Water Modeling Center.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. *Global Biogeochem. Cycl.* 13(2): 647-662.

Soler, C. M. T., P. C. Sentelhas, and G. Hoogenboom. 2007. Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *European J. Agron.* 27(2-4): 165-177.

Subedi, K. D., and B. L. Ma. 2005. Effects of N deficiency and timing of N supply on the recovery and distribution of labeled ^{15}N in contrasting maize hybrids. *Plant Soil* 273(1-2): 189-202.

Thorp, K. R., W. D. Batchelor, J. O. Paz, B. L. Steward, and P. C. Caragea. 2006. Methodology to link production and environmental risks of precision nitrogen management strategies in corn. *Agric. Systems* 89(2-3): 272-298.

Thorp, K. R., K. C. DeJonge, A. L. Kaleita, W. D. Batchelord, and J. O. Paz. 2008. Methodology for the use of DSSAT models for precision agriculture decision support. *Computers and Electronics in Agric.* 64(2): 276-285.

Timsina, J., D. Godwin, E. Humphreys, Yadvinder-Singh, Bijay-Singh, S. S. Kukal, and D. Smith. 2008. Evaluation of options for increasing yield and water productivity of wheat in Punjab, India, using the DSSAT-CSM CERES-Wheat model. *Agric. Water Mgmt.* 95(9): 1099-1110.

Tsuji, G. Y., J. W. Jones, and S. Balas, eds. 1994. *Decision Support System for Agrotechnology Transfer, Version 3*. Vols. 1-3. Honolulu, Hawaii: University of Hawaii.

USDA. 1997. United States standards for grades of sweet corn for processing. Effective 15 May 1962 (reprinted January 1997). Washington, D.C.: USDA Agricultural Marketing Service.

USDA-NASS. 2009. Florida: Acreage, yield, production, and value of Florida vegetables, melons, potatoes, blueberries, and strawberries: 2006-2007, 2007-2008. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov/Statistics_by_State/Florida/Publications/Vegetables/index.asp. Accessed 15 June 2011.

USHEW. 1962. Public health service drinking water standard. Publ. 956. Washington, D.C.: U.S. Department of Health, Education, and Welfare.

Wolf, J., M. J. D. Hack-ten Broeke, and R. Rötter. 2005. Simulation of nitrogen leaching in sandy soils in The Netherlands with the ANIMO model and the integrated modeling system STONE. *Agric. Ecosyst. Environ.* 105(3): 523-540.