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Identifying irrigation and nitrogen best management practices for sweet corn production on sandy soils using CERES-Maize model

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ABSTRACT

Research based crop-specific best management practices (BMPs) must be developed for sweet corn (*Zea mays* L. var. *saccharata*) production to reduce the amount of nitrogen (N) leaching. The objective of this study was to identify irrigation and nitrogen BMPs for sweet corn production on sandy soils in Florida using the calibrated CERES-Maize model of the Decision Support System for Agrotechnology Transfer (DSSAT). A total of 24 irrigation schedules, 21 N fertilizer levels, 30 N application splits, and 20 N application rates per split were systematically evaluated in single factor simulations. Then, a set of 324 management scenarios composed of 6 irrigation timing/amount and 54 N fertilizer application strategies selected in early single factor explorations, was explored in a multifactor analysis.

Irrigation frequency had a strong influence on sweet corn yield. If irrigation events were triggered when maximum allowable depletion (MAD) of soil water content was greater than 60%, corn growth suffered water stress and the simulated yield was reduced. The increase in yield approached zero above 168 kg N ha^{-1}. Splitting N fertilizer applications did not influence yield if there was an N application during the small-leaf stage or large-leaf stage; however, the lowest amount of N leaching occurred when no N was applied during the small-leaf stage. Simulated yield increased when application rates decreased from 100 to 70 kg N ha^{-1} per fertigation event, but changed only slightly at application rates less than 70 kg N ha^{-1} per fertigation. Smaller application rates per fertigation decreased N leaching substantially, especially for rates less than 70 kg N ha^{-1}. Six potential BMPs were selected from the 324 management scenarios as optimizing yield while minimizing N leaching. These BMPs were composed of two irrigation schedules (depths of 5.0 and 7.5 mm with MAD values of 20% and 30%), two N levels (196 and 224 kg N ha^{-1}), two N split plans (0-1/4-3/4 and 0-1/3-2/3 of total N applied in the small-leaf, large-leaf, and ear development stages, respectively), and two N application rates per fertigation (30 and 40 kg N ha^{-1}). It should be recognized that these results are recommendations based on modeling assumptions and should be tested in actual field production for their practical and economic validity.

1. Introduction

Sweet corn (*Zea mays* L.) has typically ranked as one of the five most valuable vegetable crops in Florida. Florida is the dominant producer of sweet corn in the United States, ranking number one both in terms of harvested area (17,050 ha, or 17.0% of the U.S.) and market value (189.2 million US dollars, or 25.2% of the U.S. production) in 2010 (USDA/NASS, 2011). Application of nitrogen (N) fertilizer is necessary for farmers to enhance sweet corn yield. Between 1992 and 2006, 81–100% of sweet corn acreage in Florida received an average of 2.0–10.0 applications of N seasonally. An average range of 46–62 kg N ha^{-1} was used at each application, with a statewide annual total application of 1.64–5.48 million kg N (USDA/NASS, 1993, 1995, 1999, 2003, 2007). However, most of Florida's soils are sand-based with little organic matter and low water and fertilizer holding capacities (USDA/NRCS, 2011), hence nitrate nitrogen leaching is an inevitable phenomenon for sweet corn production in Florida, which is economically and environmentally undesirable (Asadi et al., 2002). A modification to the Florida Fertilizer Law (Florida Statutes Chapter 576) in 1994 established a mechanism to fund projects aiming at protecting the state's water resources by improving fertilizer management practices. In this law, best management practices (BMPs) were defined as practices or combinations of practices determined by research or field testing in representative sites to be the most effective and

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practicable methods of fertilization designed to meet nitrate groundwater quality standards, including economic and technological considerations. Hence, research based BMPs must be developed to reduce N loss in sweet corn production in North Florida.

Traditionally, the development of irrigation and N fertilizer application strategies has been achieved by conducting field plot experiments with controlled influential factors and by applying rigorous statistical procedures. Accordingly, substantial field research on determining optimal N rate and N placement methods for sweet corn production have been conducted in various locations in Florida, e.g. in Gainesville (Rudert and Locascio, 1979), in Quincy (Rhoads, 1990), and in Live Oak (Hochmuth et al., 1992; Kidder et al., 1989) where research was conducted on evaluating N sources, application rates, time of application, and the nitrification inhibitor for their effects on yield and tissue N concentration. Hochmuth and Cordasco (2000) summarized 15 N research projects conducted on sweet corn. Fourteen of the projects resulted in optimum yields with N rates at or below the recommended 168 kg N ha^{-1}. However, most of these experiments did not evaluate the influence of interactions between various N fertilizer application and irrigation levels. For example, Hochmuth et al. (1992) applied sprinkler irrigation to maintain soil water potential at −12 kPa when they were evaluating sweet corn yield response to different N rates. Another drawback of these projects is that they did not consider the amount of cumulative N leaching.

Although they are effective, these traditional BMP development methods based on field experiments are usually expensive, time-consuming, and have limited ability to explore the many management options related to irrigation and fertilization. Furthermore, the results obtained are inherently temporally and spatially specific, i.e. the conclusions drawn on some given field conditions and time, might not be valid any more for other situations. Alternatively, crop models have fallen into the scope of developing potential crop management strategies. Crop models have been described as a "quantitative schemes for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables" (Monteith, 1996). Models can be used to predict crop growth, development and yield as a function of soil, climate, weather, and crop management conditions (Ghaffari et al., 2001). 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, V4.0; Hoogenboom et al., 2003) is a widely used crop model. Since its release in 1986 (Jones and Kiniry, 1986), CERES-Maize has been widely applied under different environments to test the hypothetical consequences of varying management practices or characteristics of cultivars on biomass production and grain yield (Epperson et al., 1992; Boote et al., 2001). In addition, it is well established that once validated for a defined environment, crop models can be used as a valuable tool to propose better adapted crop management strategies (Hook, 1994; Boote et al., 1996; Royce et al., 2001; Jagtap and Abamu, 2003). Duchon (1986) used CERES-Maize to predict corn (*Zea mays* L.) yield during the growing season in Illinois. Observed weather conditions were combined with historical weather data to provide 35 scenarios of future weather conditions. Thorp et al. (2006) used the CERES-Maize model to study the corn (*Zea mays* L.) yield response and the N dynamics in central Iowa, USA. The overall goal of their work was to develop a methodology for directly contrasting the production and environmental concerns of N management in agricultural systems. He et al. (2009, 2010, 2011) calibrated the CERES-Maize model with the generalized likelihood uncertainty estimation (GLUE) method and tested its reliability in predicting sweet corn (*Zea mays* L.) production under various irrigation and N fertilizer application levels.

The successful applications of the CERES-Maize model worldwide provide the possibility to efficiently and comprehensively explore the options of field management strategies composed of different irrigation and N fertilizer application levels and to facilitate the development of BMPs for sweet corn production. The challenge faced in exploring the field management options is akin to the navigation problem faced by early mariners who lacked the means to determine longitude accurately (Hammer et al., 2006). Without proper tools and navigating strategies, they seldom reached their desired destinations and sometimes did not arrive at all. Parallels exist between exploring unknown geographic and agricultural management options. For the general scientific challenge of finding solutions within complex problem spaces, Kauffman (2000) introduced the concept of exploring the "adjacent possible" (i.e. the process of moving from a known part of the problem state-space to a part that is unexplored). The concept of exploring the "adjacent possible" can be used to the problem of BMP development for sweet corn production. Previous research has provided some useful information. For instance, Hochmuth (2000) recommended 224 kg N ha^{-1} for sweet corn production based on field experiments. Then more "adjacent possible" points of total N could be explored around this "known" point with the help of a crop model to see the possibility of N reduction and yield sustainability.

This exploring "adjacent possible" methodology has been adopted by several scientists in similar studies. Fang et al. (2010) used the RZWQM2 model, which is a hybrid model combining the Root Zone Water Quality Model (RZWQM) and DSSAT4.0, to develop strategies to improve the water use efficiency (WUE) of wheat-maize double cropping systems in North China Plain. As one objective of the study, they used the calibrated RZWQM2 model to optimize the distribution of limited available water between wheat and maize productions for high WUE and minimum drainage. They explored six possible water distribution ratios under four different irrigation timings and depths and finally found 80:20 (80% of available water to wheat and 20% to maize) was the optimal choice. Yang et al. (2006) used the calibrated CERES-Wheat model to evaluate the effect of one irrigation strategy at different growth stage on growth and yield production of wheat to reduce groundwater depletion in northern China. They explored the temporal options of 11 different irrigation dates. However, one drawback of their exploration methodology was the arbitrary design of irrigation and N fertilizer treatments. They simulated only a limited number of treatments composed of several influential factors, i.e. a large portion of the possible management options might be neglected. Hence they might only obtain some local optimal solutions though they declared they found the best irrigation schedule for the specific crop production area. There should be a paradigm of systematic exploration to obtain the global optimal solutions.

In previous work, the CERES-Maize model was carefully calibrated and evaluated by He et al. (2009, 2010, 2011). In this current study, an effort was made to set up a kind of systematic exploration paradigm that included single-factor, multi-factor simulations, and multi-objective selection components so as to sufficiently use the calibrated CERES-Maize model to develop irrigation and N fertilizer BMPs for sweet corn on the sandy soils in Florida. The main objectives of this study were: (1) to simulate the response of sweet corn yield and cumulative N leaching to varying methods of N fertilizer and irrigation applications, and (2) to determine alternative N and irrigation management strategies under the environmental conditions of northern Florida with the calibrated CERES-Maize model in DSSAT as potential best management practices.

2. Materials and methods

2.1. Calibration of CERES-Maize model

The CERES-Maize model used in this study is embedded in the Decision Support System for Agrotechnology Transfer (DSSAT) software (Tsuji et al., 1994; Jones et al., 2003), version 4.02 (Hoogenboom et al., 2003). It can simulate corn growth, water, and soil N dynamics at the field scale (Jones and Kiniry, 1986; Ritchie and Godwin, 1989; Ritchie, 1998). Though it has been widely used, the application of CERES-Maize model to solve problems in the real world depends not only on the availability of model, but also on the availability of information that makes it both possible to run the model for particular scenarios and to specify the accuracy of the models for target regions (Hunt and Boote, 1998). It is therefore necessary to calibrate the model for use with crop cultivars and soils of the target regions, and to evaluate the accuracy of the model calculations. In previous studies, the CERES-Maize model was calibrated with the GLUE method (He et al., 2009, 2010) and verified using data collected from a multifactor (various irrigation and N fertilizer rates) field experiment of sweet corn in northern Florida (He et al., 2011).

The most sensitive soil parameters and genotype coefficients that affected total yield and N leaching predictions from the CERES-Maize model were determined by He (2008) using the one-at-a-time (OAT) method (Morris, 1991). The soil parameters SLLL, SDUL, and SSAT influenced the amount of available water in soil profile, while SLRO influenced the amount of water routed to surface runoff. Parameter SLPF represented the effect of micronutrients on yield. CERES-Maize determined yield using six genotype coefficients that differ by variety. Genotype coefficients P1 and P5 control the important phenology dates, such as anthesis date and maturity date of corn. Coefficient PHINT influences both genotype dates and yield. In the DSSAT model, sweet corn varieties were described by these genetic coefficients. However, unlike general field corn varieties, which were harvested when the kernels are dry and fully mature (dent stage), sweet corn was harvested 70–80 days after planting and is picked when immature (milk stage) and eaten as a vegetable, rather than a grain. Thus, the coefficient values of P1, P5, G2, and PHINT were usually smaller than those of field corn varieties. The GLUE method (Beven and Binley, 1992) was used to estimate the values of those sensitive parameters (He et al., 2009), while other parameters were fixed as default values in the DSSAT database. The results of the GLUE method were posterior probability distributions (Beven and Binley, 1992), which were derived based on Bayesian theorem and represented by mean values and standard deviations (STDEV) of the parameters concerned. In this study, the mean values of the posterior distributions of the sensitive parameters obtained from He et al. (2009) were used as default values for model simulations.

According to He et al. (2009), the GLUE method accurately estimated the soil parameters when compared with independent measurements made in the laboratory. Errors in parameters of SLLL, SDUL, and SSAT were 0.009, 0.006, and 0.014 $cm^3\,cm^{-3}$, respectively, with an average relative absolute error (RAE) of about 8.5%. Though there was no direct measurement of genetic parameters in their study, the uncertainties in these parameters were substantially reduced, since the average coefficient of variation (CV) value was reduced from 27% in the prior distribution to 5% in the posterior distribution. After parameters were estimated, the model correctly simulated the dry matter yields, anthesis dates, and harvest dates. The mean values of these variables were similar to field measurements, with RAE values from 2.4% to 4.4%.

2.2. Verification of the calibrated CERES-Maize model

To verify the reliability of the calibrated CERES-Maize model in predicting sweet corn production, a different additional split-plot experiment of two irrigation and three N fertilizer levels was conducted with the same variety of sweet corn (He et al., 2011) on the same type of soil. The calibrated CERES-Maize model precisely predicted phenology dates with only 1 day difference in maturity date for all treatments. Variations in dry matter yield caused by different N and irrigation levels were also correctly simulated with an RAE value less than or equal to 10% for all but one treatment. For cumulative N leaching, He et al. (2011) found that the average RAE value between the simulated N leaching amounts using CERES-Maize model and estimated ones using N balance approach of all six treatments was 15.3%, which was much lower than similar studies (e.g. Wolf et al., 2005; Conrad and Fohrer, 2009), in which the modeled N leaching error was reported to be as high as 71% or more.

2.3. Basic information for model run

Though the CERES-Maize model had been calibrated and verified, some fundamental information was still required to carry out the simulations, including experimental site location, weather, initial soil conditions, and management information. In this study, management data obtained from the fourth and fifth Microwave, Water, and Energy Experiments, MicroWEX-4 and -5 (Casanova et al., 2006, 2007) were used as fundamental inputs to run the model. The experiments were conducted on a 3.65 ha field site at the Plant Science Research and Education Unit, the University of Florida, located near Citra, Florida (29.4094°N, 82.1777°W, 21 m above mean sea level). The site soil is mapped as Lake Sand, Candler Variant, Tavares Variant, and Millhopper Variant 1, which mainly belong to Quartzipsamments (Entisol).

In the MicroWEX-4 and -5 experiments, sweet corn variety 'Saturn SH2' was planted during each of two experimental years on 9th March 2005 and 2006 at a depth of 3.8 cm and a plant population density of 59,000 plants ha^{-1}. The harvest dates were 2nd June 2005 and 1st June 2006, respectively. The N fertilizer used in the experiment was a composite of several N compounds (7.9% nitrate N, 7.9% ammoniacal N, and 16.2% urea N) and was applied weekly by injection through the linear-move sprinkler irrigation system (fertigation) beginning at 4 weeks after planting and ending 1 week before harvest. Other agronomic practices, such as potassium fertilizer, herbicide, and pesticide application followed the recommendations of the Institute of Food and Agricultural Science, University of Florida (Olson and Simonne, 2003).

Historical daily weather data (including solar radiation, maximum temperature, minimum temperature, and rainfall) for 33 years (1958–1990) in Gainesville, Florida were obtained from the McNair Bostick Simulation Lab in the Department of Agricultural and Biological Engineering, University of Florida, and were used as the driving force for the model simulations. The weather in Gainesville is wet and warm, especially in the summer time (June–September). The cumulative rainfall in April and May is comparably low and with high variation, which makes irrigation necessary to guarantee adequate sweet corn yield.

2.4. Systematic exploration of management options of irrigation and N

In this study, CERES-Maize model simulations were designed to systematically and comprehensively explore the possible management options composed of different practical irrigation and N fertilizer application strategies so as to obtain some kind of global solutions that can give the lowest amounts of N leaching and acceptable yields of sweet corn simultaneously. The exploring paradigm consisted of the following steps: (1) single factor simulations with different irrigation schedules to explore the possible irrigation options, (2) single factor simulations with different N fertilizer application timing and amounts to explore the possible N fertilizer application options, (3) multiple factor simulations with

Table 1
Simulated irrigation schedules based on available soil water (ASW) and different values of maximum allowable depletion (MAD).

Treatment	MAD (%)	ASW (mm)	Irrigation depth (mm)
I1	90	25.0	22.5
I2	80	25.0	20.0
I3	70	25.0	17.5
I4	60	25.0	15.0
I5	50	25.0	12.5
I6	40	25.0	10.0
I7	30	25.0	7.5
I8	20	25.0	5.0
I9	10	25.0	2.5

Table 2
Simulated irrigation schedules based on fixed dates and depths.

Treatment	Number of irrigations per week	Irrigation day	Irrigation depth per application (mm)
I10	1	Wednesday	5
I11	2	Monday and Thursday	5
I12	3	Monday, Wednesday, and Friday	5
I13	1	Wednesday	10
I14	2	Monday and Thursday	10
I15	3	Monday, Wednesday, and Friday	10
I16	1	Wednesday	15
I17	2	Monday and Thursday	15
I18	3	Monday, Wednesday, and Friday	15
I19	1	Wednesday	20
I20	2	Monday and Thursday	20
I21	3	Monday, Wednesday, and Friday	20
I22	1	Wednesday	25
I23	2	Monday and Thursday	25
I24	3	Monday, Wednesday, and Friday	25

different combinations of irrigation and N fertilizer schedules, timing and amounts to explore a set of different possible management scenarios, and (4) multi-objective selection to identify some kind of global optimal management strategies from the scenarios explored above.

For the irrigation simulations, the events were scheduled using two approaches. In the first approach, irrigation depth and time were automatically determined based on the maximum allowable depletion (MAD) of total available soil water (ASW) in the soil profile (Panda et al., 2004). The soil profile depth was fixed at 0.5 m because more than 70% of sweet corn roots were concentrated in this region (Bauder and Waskom, 2003). Though the depth of soil profile should ideally change with crop root depth, the constant depth adopted in this study was a simplistic approach used by many irrigation scheduling programs. The ASW was the difference between field capacity (FC) and permanent wilting point (PWP) of the soil. According to the measured FC (or SDUL in DSSAT) and PWP (or SLLL in DSSAT) values, the calculated ASW value of the field was 25 mm. In this study, the value of MAD was varied between 90% and 10% to generate 9 possible irrigation deficit thresholds, identified as I1 to I9 (Table 1). If the MAD value was 50%, it means that when half of the available water in the root zone was depleted, supplemental irrigation was triggered to "refill" the reservoir.

In the second approach, a set of irrigation schedules based on fixed days and depths were tested. Irrigation was simulated with a fixed depth for 1 time (on Wednesday), 2 times (on Tuesday and Friday), or 3 times (on Monday, Wednesday, and Friday) each week during the growing season. This type of schedule was meant to represent a range of irrigation practices that sweet corn growers were capable of in Florida. For a value of ASW of 25 mm, if the depth in each irrigation event was higher than 25 mm, deep percolation or runoff will occur. Thus, the fixed irrigation depths were defined as 20, 40, 60, 80, and 100% of the ASW value, or 5, 10, 15, 20, and 25 mm. Hence, there were 15 possible irrigation scenarios (Table 2), considering both irrigation times and depths. When doing single factor simulations for irrigation, the N application schedule was fixed at a total of 230 kg N ha^{-1} applied evenly in eight applications except for a starter application of 15 kg N ha^{-1}.

The N fertilizer application options were composed of three factors. The first was the total amount of fertilizer N, or N application level. In total, 21 N fertilizer levels were simulated, varying from 0 to 561 kg N ha^{-1} with an increment of 28 kg N ha^{-1}. Among these levels, 224 kg N ha^{-1} was recommended by the Institute of Food and Agricultural Sciences (IFAS), University of Florida (Hochmuth, 2000) and was defined as the standard N level for this study.

The second factor was the time to apply the given amount of fertilizer N. Since inorganic N was mobile in sandy soils, timing of application was very important so that most of the N applied was in the root zone when the crop can most efficiently absorb the N. Corn absorbed the majority of its N during rapid growth between 8-leaf and dough growth stages (Bauder and Waskom, 2003). If N was insufficient during this period, yield loss would occur. Thus, the factor of timing was tested to find the optimal time of N applications to meet the N need of sweet corn growth. In this study, the growth season of sweet corn in northern Florida was divided into three main stages: small leaf stage, large leaf stage, and ear development stage as recommended in the "Vegetable Production Guide for Florida 2003–2004" (Olson and Simonne, 2003). The small leaf stage included the first 4 weeks after planting, or from planting to 12 leaves fully emerged. The large leaf stage roughly included week 5–7, or from 12 leaves to 20 leaves fully emerged (tasseling/silking). The remaining 4 weeks (from tasseling to harvest maturity) was considered as the ear development stage. A nitrogen application split was defined as the proportion of the amount of N applied in each stage to the total N amount except for the starter N application of 15 kg N ha^{-1} which was constant across all scenarios. Overall, 30 plans of N application splits (identified as S1 to S30 in Table 3) were simulated. For example, the split "1:0:0" means applying all N during the small leaf stage and nothing during the later periods, except for the starter N application. In each stage, the given amount of N was distributed evenly in each week. According to the actual N application schedule in field experiments (He, 2008), the split of "0:1/2:1/2" was defined as the standard split.

The third factor was how much N fertilizer should be applied in each fertigation event. For example, 224 kg N ha^{-1} applied with a split of 0:1/4:3/4, results in 56 kg N ha^{-1} applied in the large leaf stage and 168 kg N ha^{-1} in the ear development stage. The N of 168 kg N ha^{-1} could be applied in just one event in week 8, or two events in weeks 7 and 9. It is obvious that a frequent application of a small amount could be a better choice, because less N would be available for leaching and more for crop uptake after any single application. However, the labor cost increases with the number of fertigation events. To determine the optimal N fertilizer application in each fertigation event, a term "application rate" was defined. In this study, 20 application rates ranging from 5 to 100 kg N ha^{-1} with an increment of 5 kg N ha^{-1} were investigated. For instance, when 168 kg N ha^{-1} is applied with a rate of 10 kg N ha^{-1}, there will be 17 fertigation events while only 8 kg N ha^{-1} will be applied in the last event to make the sum equal to the given N amount, and so forth. These application rates were identified as A1 to A20. The application rate of 40 kg N ha^{-1} was set as the standard, because it was close to the application rate per split used in the field experiment through which the fundamental model-run information was obtained.

Table 3
Nitrogen application splits used in single factor simulation.

No.	Split	Description	No.	Split	Description	No.	Split	Description
1	S1	0-0-1[a]	11	S11	1/5-1/5-3/5	21	S21	1/3-2/3-0
2	S2	0-1/5-4/5	12	S12	1/5-2/5-2/5	22	S22	1/2-0-1/2
3	S3	0-1/4-3/4	13	S13	1/5-3/5-1/5	23	S23	1/2-1/2-0
4	S4	0-1/3-2/3	14	S14	1/5-4/5-0	24	S24	2/3-0-1/3
5	S5	0-1/2-1/2	15	S15	1/4-0-3/4	25	S25	2/3-1/3-0
6	S6	0-2/3-1/3	16	S16	1/4-1/4-2/4	26	S26	3/4-0-1/4
7	S7	0-3/4-1/4	17	S17	1/4-2/4-1/4	27	S27	3/4-1/4-0
8	S8	0-4/5-1/5	18	S18	1/4-3/4-0	28	S28	4/5-0-1/5
9	S9	0-1-0	19	S19	1/3-0-2/3	29	S29	4/5-1/5-0
10	S10	1/5-0-4/5	20	S20	1/3-1/3-1/3	30	S30	1-0-0

[a] “0-0-1” means no N fertilizer applied in the small leaf and large leaf stages, and total of the N fertilizer applied in the ear development stage, and so on.

When simulating N treatments, the irrigation schedule was set to the actual field experiment in 2005, which was set up according to daily ET value and water balance in the top soil profile (He, 2008; He et al., 2011). When simulating one factor of N fertilizer application, the other two factors were fixed at their standard levels defined previously. For each of the irrigation and N fertilizer treatments, the model was run for 33 years (1958–1990) of historical weather data at Gainesville, Florida. The average values of the dry matter yield and cumulative N leaching over these 33 years were calculated. In this way, the uncertainties of simulation results (presented as standard deviations) caused by climate variability were considered.

After single factor exploration, several irrigation and N application methods that simultaneously had relatively higher yields and lower N leaching were selected (Table 4) to conduct multi-factor simulations to systematically explore the possible management options composed of the irrigation and N application methods above. For each of the combined management scenarios, the model was also run for the time period of 33 years as previously described and the resulting average values and standard deviations of the dry matter yields and cumulative N leaching were calculated. Then, a multi-objective selection was conducted among these simulated scenarios. First, they were ranked according to their simulated dry matter yields. The strategies that had yields above an “acceptable yield” were selected, while others were eliminated. However, there was no existing “acceptable yield” available in current literature for sweet corn production in Florida. Yield was also influenced by many factors including location, variety, within-row spacing, nitrogen fertilizer levels, etc. (Simonne et al., 1999; Mullins et al., 1999; Hochmuth and Cordasco, 2000; Shuler, 2002). In a companion field experiment (He, 2008), the average fresh yield (ears with husks) was approximately 20.0 Mg ha^{-1}, which was close to the average yield (20.3 Mg ha^{-1}) obtained by Shuler (2002). It was reasonable because the experimental site, variety, and plating time of Shuler’s study were representative in Florida. Thus, a fresh yield (ears with husks) of 21.0 Mg ha^{-1} was selected as an estimate for the “acceptable yield” in this study. The corresponding acceptable dry matter yield was set as 3.4 Mg ha^{-1} with the average ear moisture of about 84.0% (He, 2008).

Next, these selected strategies were ranked again according to their simulated amounts of cumulative N mass leached. The combined management strategies that had the lowest N leaching were selected as potential best management practices. It was also necessary to determine the “acceptable N leached”. In this study, irrigation was designed to match crop plant demands during the season based on the soil water holding ability. Thus, N mass leached into groundwater was mainly caused by rainfall. If a crop was not planted in June after sweet corn harvest, the N stored in soil root zone was prone to be leached. The average cumulative rainfall during the sweet corn production season (March through June) at Gainesville was 448 mm. To arrive at the human health standard of 10 mg N L^{-1} for public water supplies (U.S. Department of Health, Education, and Welfare, 1962), the mass of N leached into groundwater during the growing season should be less than 44.8 kg N ha^{-1}. Dilution was not considered in order to make the amount of N leached conservative. Thus, the “acceptable N leached” was defined as 45 kg N ha^{-1}.

Table 4
Selected irrigation strategies for multifactor simulation.

No.	Title	Description
1	I5	12.5 mm with a MAD of 50%
2	I6	10.0 mm with a MAD of 40%
3	I7	7.5 mm with a MAD of 30%
4	I8	5.0 mm with a MAD of 20%
5	I17	2 irrigations per week with a depth of 15 mm
6	I15	3 irrigations per week with a depth of 10 mm

3. Results and discussion

3.1. Exploration of possible irrigation options

For the possible options of irrigation schedules designed with varying MAD values (Table 1), the exploration results were represented with the response curves of simulated dry matter yield and cumulative N leaching to MAD values (Fig. 1). If the irrigation event was triggered at a threshold MAD value of 30% with an irrigation depth of 7.5 mm (Fig. 1a), the simulated yield reached its maximum value of 3.9 Mg ha^{-1}. If an irrigation event was triggered at a very high level of MAD, e.g. 90%, corn growth suffered from water stress and yield was reduced to only 0.8 Mg ha^{-1}. Under the threshold MAD values of 50% through 80%, water stress likely occurred since the simulated yields were all below 3.0 Mg ha^{-1}. When the irrigation event was triggered at lower levels of MAD, e.g. 10% and 20%, which means frequent irrigations with very small irrigation depths (2.5 and 5.0 mm, respectively), the simulated dry material yields were also lower than the maximum yield obtained at MAD of 30%, which might be caused by more N leaching due to rainfall and less availability for plant uptake. There was a trend of increasing of N leaching if irrigation events were more frequently triggered with lower values of MAD (Fig. 1b). For example, if the irrigation event of 22.5 mm was triggered when MAD was 90%, the cumulative N leaching value was approximately 32 kg ha^{-1}. However, the cumulative leached N was as high as 120 kg ha^{-1} when the event was triggered with a threshold MAD value of 10% or 20% and an irrigation depth of 2.5 or 5.0 mm. This was because when irrigation events were more frequent and with small depths the soil moisture contents were comparably higher. Thus, less rainfall between subsequent irrigation events could be held by the soil matrix and more water moved into deep soil layers. Consequently, more N was leached. Considering both dry matter yield and N leaching, a threshold MAD value of 30 or 40% with an irrigation depth of 7.5 or 10 mm

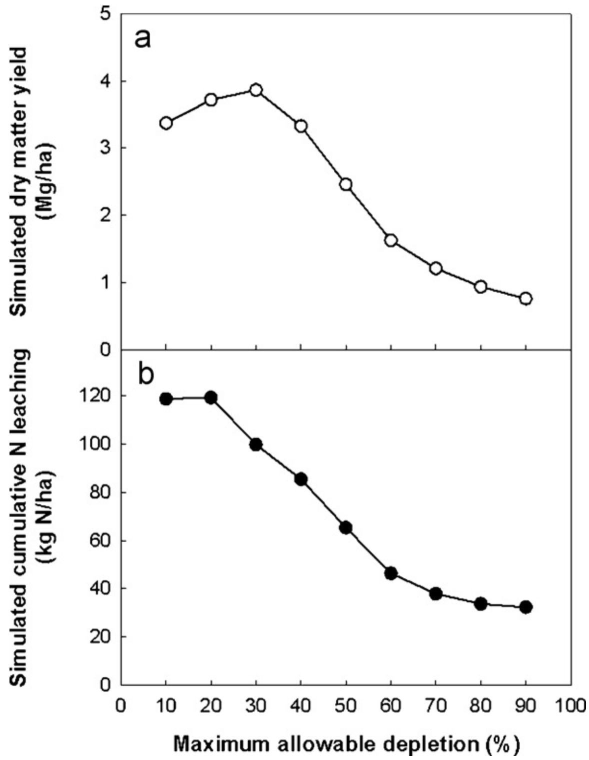

Fig. 1. Response curves of simulated dry matter yield (a) and nitrogen leaching (b) to maximum allowable depletion of soil water. Each point is the mean value over 33-year continuous historical weather data.

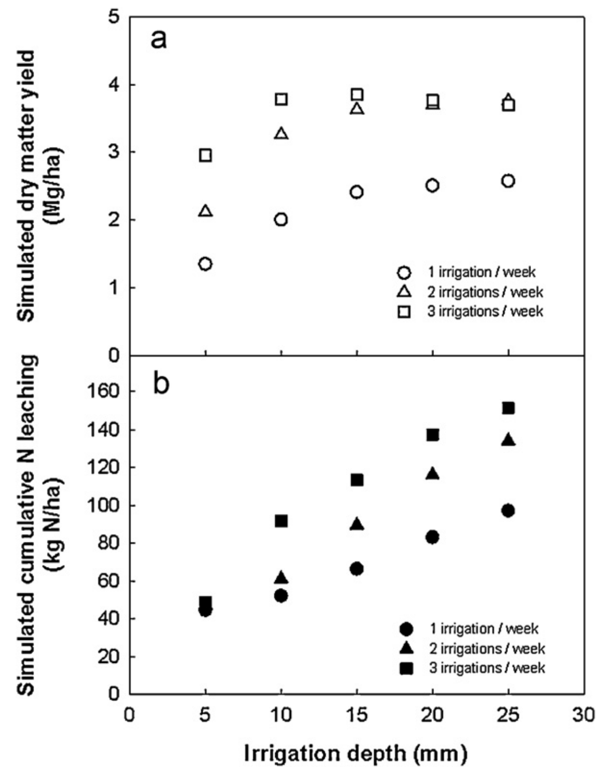

Fig. 2. Response curves of simulated dry matter yield (a) and cumulative nitrogen leaching (b) to different irrigation depths. Each point is the mean value over 33-year continuous historical weather data.

would be a good choice among the irrigation options explored, since these cases resulted in comparatively higher yield though they did not result in the lowest N leaching level.

Next, the possible irrigation options composed of automatic irrigations on fixed days with specific depths were explored (Fig. 2). When enough water was applied, e.g. 2 or 3 irrigations per week with a depth of 15, 20, or 25 mm (Fig. 2a), there was no remarkable difference between the simulated yields. However, dry matter yield was heavily reduced due to water stress when there was only one irrigation event per week. The assumption that when more water was applied more N was leached had been confirmed as shown in Fig. 2b. For example, where there were 3 irrigation events a week with a depth of 25 mm, the simulated N leaching was approximately 150 kg ha^{-1}, or about 65% of the 230 kg N ha^{-1} applied. Considering both yield and N leaching, the methods of 2 irrigation applications per week with a depth of 15 mm and 3 irrigation applications per week with a depth of 10 mm achieved a comparably higher yield and lower mass of leached N in this portion of possible irrigation options explored. Compared with the irrigation schedules with MAD values of 30% and 40%, these two fixed-date-and-depth methods also had similar simulated dry matter yields (3.5–4.0 Mg ha^{-1}) and amounts of N leaching (80–100 kg ha^{-1}). Finally based on the criterion of higher yield and lower N leaching, six irrigation strategies (Table 4) were selected for multifactor simulations.

3.2. Exploration of N application options

3.2.1. Exploration of different amounts of total N

Similar to irrigation, the results of exploration of possible options of N application were also evaluated for the simulated dry matter yields and cumulative N leaching. Above 196 kg N ha^{-1} (open and filled squares in Fig. 3), the yield leveled off at the simulated maximum dry matter yield of 3.4 Mg ha^{-1}. At the same time, N

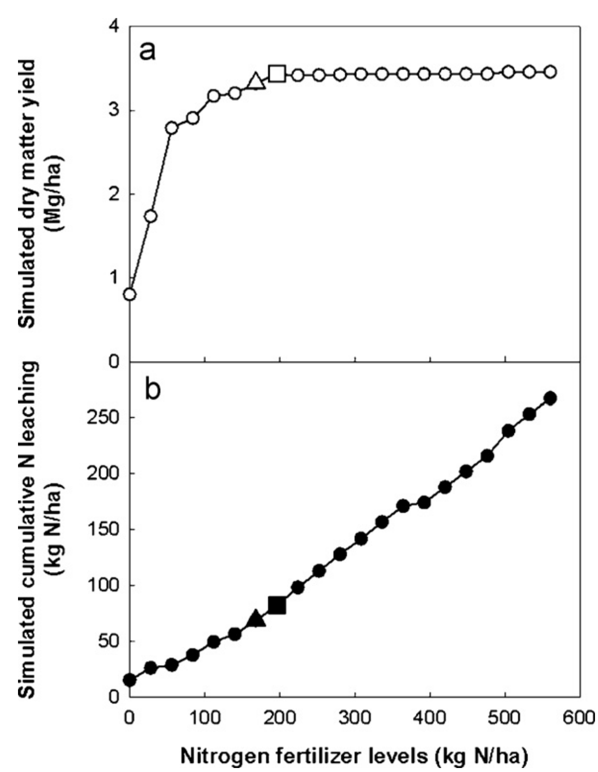

Fig. 3. Response curves of simulated dry matter yield (a) and cumulative nitrogen leaching (b) to different N fertilizer levels. The open and filled triangles indicate the nitrogen fertilizer level of 168 kg N ha^{-1}. The open and filled squares indicate the nitrogen fertilizer level of 196 kg N ha^{-1}. Each point is the mean value over 33-year continuous historical weather data.

Table 5
Ranking of the highest 10 dry matter yields and lowest 10 cumulative nitrogen leaching levels under different N fertilizer application splits.

Dry yield ranking			Nitrogen leaching ranking		
Split	Description	Dry yield ($Mg\,ha^{-1}$)	Split	Description	Nitrogen leaching ($kg\,N\,ha^{-1}$)
S12	1/5-2/5-2/5	3.5	S4	0-1/3-2/3	80
S19	1/3-0-2/3	3.5	S1	0-0-1	82
S4	0-1/3-2/3	3.5	S2	0-1/5-4/5	84
S5	0-1/2-1/2	3.4	S10	1/5-0-4/5	84
S20	1/3-1/3-1/3	3.4	S3	0-1/4-3/4	87
S6	0-2/3-1/3	3.4	S15	1/4-0-3/4	87
S3	0-1/4-3/4	3.4	S5	0-1/2-1/2	88
S16	1/4-1/4-2/4	3.4	S19	1/3-0-2/3	91
S11	1/5-1/5-3/5	3.4	S11	1/5-1/5-3/5	94
S17	1/4-2/4-1/4	3.4	S12	1/5-2/5-2/5	101

leaching steadily increased when more N was applied. For example, the amount of N leached increased from 82 to 266 kg N ha^{-1} when the N application level increased from 196 to 561 kg N ha^{-1}. The leached mass of N was constant at about 45–50% of the total applied N, mainly due to the nature of sandy soils in Florida. Even when no fertilizer was applied after planting there was still some yield and N leaching. The model assumed the N from organic matter present in the soil was 7 kg N ha^{-1}. The initial nitrate-N and ammonium-N concentration was 0.1 g N Mg^{-1} and 0.5 g N Mg^{-1}, respectively, which equal to 1.3 and 6.7 kg N ha^{-1}, respectively. Furthermore there was also a starter N application of 15 kg N ha^{-1} before planting. All of these N resources contributed to the N leaching with no additional N fertilizer applied after planting.

It can be seen that 168 kg N ha^{-1} (Fig. 3) was sufficient for sweet corn to produce yields close to the "acceptable" yield of 3.4 Mg ha^{-1} and comparatively less N leaching. However, it should be recalled the model assumes the fertilizer and water application efficiency is 100%, which means no applied N fertilizer was lost through denitrification, volatilization, and runoff during sprinkler fertigation using the center pivot irrigation. This may not occur in actual production; the efficiency is always less than 100%. For example, when Zhang et al. (2004) assessed the ammonia (NH_3) volatilization, denitrification loss, and nitrous oxide (N_2O) emission on an irrigated wheat-maize rotation field, they found that ammonia volatilization loss could be 26.62% of the applied fertilizer N under maize production. Denitrification losses were 0.67–2.87% and 0.31–0.49% of the applied fertilizer N under maize and wheat, respectively. Furthermore, irrigation was also not always 100% due to conveyance losses and evaporation. Finally, six N amounts as 140, 168, 196, 224, 252, and 280 kg N ha^{-1} (N6 to N11) were selected for the next multifactor simulations.

3.2.2. Exploration of various N fertilizer split

Thirty split strategies identified as S1 to S30 (Table 3) were simulated. The 10 splits that resulted in the highest yields or lowest N leaching amounts were summarized in Table 5. Nitrogen fertilizer split did not show a remarkable influence on yield if there was any application of N during the small leaf stage or large leaf stage, since the simulated dry matter yields were all around the "acceptable yield" of 3.4 Mg ha^{-1}. However, splitting N applications can obviously influence N leaching. The best splits were "0:1/4:3/4", "0:1/3:2/3", because these fertigation schedules coincided best with the N need of sweet corn growth, especially from tasseling to maturity. Three splits S3, S4 and S5 (0-1/4-3/4, 0-1/3-2/3, and 0-1/2-1/2) all ranked in the highest 10 for dry yield and the lowest 10 for cumulative N leaching among the N split options explored. Thus they were selected as optimal N splits for the next multifactor simulations.

3.2.3. Exploration of N application rate

The response curve of dry matter yield to "application rate" (Fig. 4a) showed that if the application of the total N fertilizer was less then 70 kg N ha^{-1} (open triangle on the curve) per fertigation event, the yield would remain the same. The response curve of N leaching to "application rate" (Fig. 4b) was non-linear. The lowest N leaching occurred when applying less than 20 kg N ha^{-1} per fertigation event. In general, the curve trend showed that the cumulative N leaching increased with the increasing of "application rate".

However, applying fertilizer too frequently is economically and logistically impractical for farmers. Thus, the "application rates" of 30, 40 or 50 kg N ha^{-1} were selected as optimal ones among the options of N application rate for multifactor simulations later, considering production cost, yield, and N leaching. The final selected factors as "best" N fertilizer management strategies were summarized in Table 6. For total N amount, six different N fertilizer levels

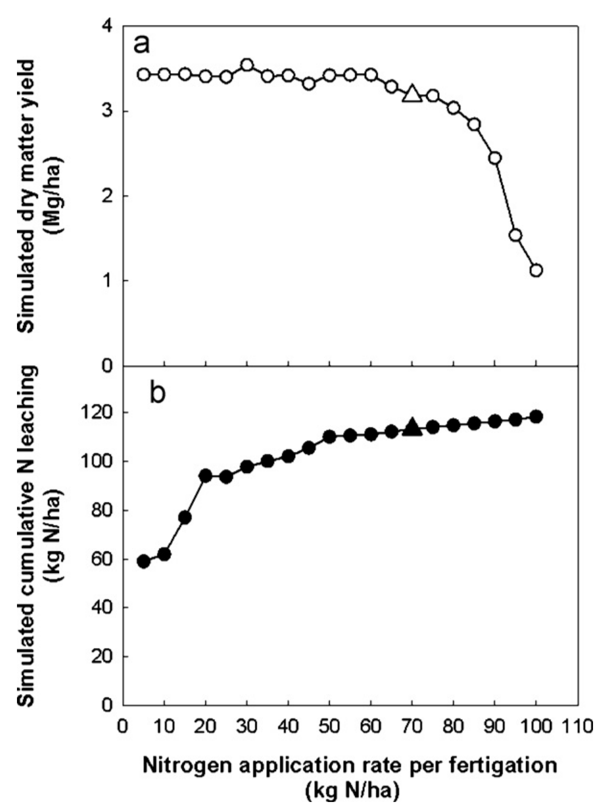

Fig. 4. Response curves of simulated dry matter yield (a) and cumulative nitrogen leaching (b) to different nitrogen fertilizer application rates per fertigation event. The open and filled triangles indicate the nitrogen application of 70 kg N ha^{-1}. Each point is the mean value over 33-year continuous historical weather data.

Table 6
Selected factors of N fertilizer application strategies.

Total amount		Split		Application rate	
Title	Description	Title	Description	Title	Description
N6	140 kg N ha^{-1}	S3	0:1/4:3/4	A6	30 kg N ha^{-1}
N7	168 kg N ha^{-1}	S4	0:1/3:2/3	A8	40 kg N ha^{-1}
N8	196 kg N ha^{-1}	S5	0:1/2:1/2	A10	50 kg N ha^{-1}
N9	212 kg N ha^{-1}				
N10	252 kg N ha^{-1}				
N11	280 kg N ha^{-1}				

ranging from 140 to 280 kg N ha^{-1} were selected. Three different splits and three "application rate" were selected as well. Thus, for a complete factorial experiment design, there were 6 × 3 × 3 = 54 types of fertilizer application options for the later multi-factor exploration, among which the best N fertilizer management practices were assumed to exist.

3.3. Determination of potential BMPs

A management set composed of 324 (54 N options times 6 irrigation options selected) possible management scenarios, was investigated after the explorations of individual management factors. Each management scenario was simulated with the 33-year continuous historical weather data to take the climatic influence into account. The selection of BMPs was based on the "acceptable yield" of 3.4 Mg ha^{-1} dry matter of ears with husks. The scatter plot between simulated cumulative N leaching and dry matter yield (Fig. 5) showed the results of multifactor simulations. Among the management scenarios, the simulated dry matter yield and amounts of N leaching ranged from 2.9 to 3.6 Mg ha^{-1} and 31 to 166 kg ha^{-1}, respectively. Most management strategies failed to achieve a yield greater than the dry "acceptable yield" of 3.4 Mg ha^{-1} or a mass of N leached less than the "acceptable N leached" of 45 kg N ha^{-1}. Only the scenarios or points in the lower right corner fell within the scope of BMP determination. All of the management strategies that had a simulated average dry yield above the acceptable dry matter yield were selected; then these selected treatments were re-ranked according to their simulated average amounts of N leaching. The top 20 of the strategies that had the lowest N leaching amounts were shown in Table 7.

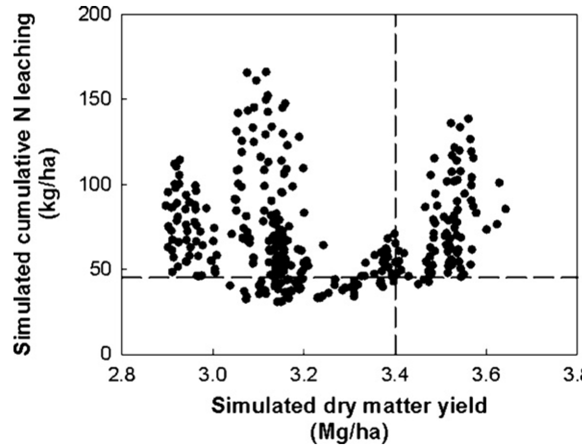

Fig. 5. Simulated cumulative nitrogen leaching vs. dry matter yield in multifactor simulations of 324 scenarios of irrigation and N fertilizer application. Vertical dashed line indicates the "acceptable dry yield" of 3.4 Mg ha^{-1}, while the horizontal dashed line indicates the "acceptable N leached" of 45 kg N ha^{-1}. Each point is the mean value over 33-year continuous historical weather data.

Irrigation strategies of 5.0 mm irrigation with a MAD of 20% and 7.5 mm irrigation with a MAD of 30% dominated the top 20 strategies (Table 7). For N fertilizer, the ranking showed that the optimal total amount of N application was between 196 kg N ha^{-1} and 224 kg N ha^{-1}. The best splits were "0:1/4:3/4" and "0:1/3:2/3". Only one combination with a split of "0:1/2:1/2″ fell in the top-20 strategies. Application rates of 30, 40 or 50 kg N ha^{-1} all appeared in the top 20 strategies, but 30 kg N ha^{-1} was the dominant option. This confirmed the hypothesis that a frequent application of a small amount of N fertilizer might reduce N leaching. In general, it can be concluded from the multi-factor exploration that if growers could apply both irrigation water and N fertilizer in more frequent applications but with smaller amounts in each event, it would result in an "acceptable yield" and "acceptable N leached". Six combination treatments (Table 8) were selected as potential BMPs for future field study. These practices need to be verified in the field since this modeling analysis assumes 100% efficiency in irrigation and fertilizer delivery.

Table 7
The 20 strategies of irrigation and nitrogen fertilizer application that resulted in the lowest average amounts of simulated nitrogen leaching over 33-year (1958–1990) historical weather data.

No.	Irrigation	Total nitrogen kg N ha^{-1}	Nitrogen split	Application rate kg N ha^{-1}	Dry yield Mg ha^{-1}	Nitrogen leaching kg N ha^{-1}	Percent of leaching[a]
1	5.0 mm-MAD 20%	196	0-1/4-3/4	30	3.5	35	18%
2	7.5 mm-MAD 30%	196	0-1/4-3/4	30	3.5	37	19%
3	5.0 mm-MAD 20%	196	0-1/4-3/4	40	3.5	37	19%
4	5.0 mm-MAD 20%	196	0-1/3-2/3	30	3.5	37	19%
5	5.0 mm-MAD 20%	196	0-1/4-3/4	50	3.5	38	19%
6	5.0 mm-MAD 20%	196	0-1/3-2/3	40	3.5	38	19%
7	5.0 mm-MAD 20%	196	0-1/4-3/4	40	3.5	38	19%
8	5.0 mm-MAD 20%	224	0-1/4-3/4	30	3.5	39	17%
9	7.5 mm-MAD 30%	196	0-1/3-2/3	30	3.5	39	20%
10	7.5 mm-MAD 30%	196	0-1/4-3/4	50	3.6	40	20%
11	7.5 mm-MAD 30%	196	0-1/3-2/3	40	3.5	40	20%
12	7.5 mm-MAD 30%	224	0-1/4-3/4	30	3.5	40	18%
13	10.0 mm-MAD 60%	196	0-1/4-3/4	30	3.5	40	20%
14	5.0 mm-MAD20%	196	0-1/3-2/3	50	3.6	41	21%
15	5.0 mm-MAD20%	224	0-1/4-3/4	40	3.6	41	18%
16	5.0 mm-MAD20%	224	0-1/3-2/3	30	3.5	41	18%
17	10.0 mm-MAD 60%	196	0-1/4-3/4	40	3.6	42	21%
18	5.0 mm-MAD20%	196	0-1/2-1/2	30	3.5	42	21%
19	10.0 mm-MAD 60%	196	0-1/3-2/3	30	3.5	42	21%
20	7.5 mm-MAD 30%	196	0-1/3-2/3	50	3.5	42	21%

[a] Percent of leaching is the percentage of nitrogen leached of the total nitrogen applied.

Table 8
Selected potential best management practices (BMPs) for sweet corn production in North Florida.

No.	Irrigation	Nitrogen level kg N ha^{-1}	Nitrogen split	Application rate kg N ha^{-1}
1	5.0 mm-MAD 20%	196	0-1/4-3/4	30
2	5.0 mm-MAD 20%	196	0-1/3-2/3	30
3	7.5 mm-MAD 30%	196	0-1/4-3/4	40
4	7.5 mm-MAD 30%	196	0-1/3-2/3	30
5	5.0 mm-MAD 20%	224	0-1/4-3/4	30
6	7.5 mm-MAD 30%	224	0-1/4-3/4	30

4. Summary and conclusions

The CERES-Maize model of DSSAT was utilized as tool to explore the possible management options composed of different practical irrigation and N fertilizer application strategies so as to develop research-based N-fertilizer BMPs for sweet corn production on the sandy soils in Florida. A total of 24 irrigation treatments, 21 N fertilizer levels, 30 N split combinations, and 20 N rates per fertigation were used to conduct single factor explorations to show the independent influence of these factors on dry matter yield and cumulative N leaching. Then, a combined set of 324 management scenarios that were constructed through a complete factorial experiment design of irrigation and N factors selected from early single factor explorations, was explored to show the influence of interactions among these factors. Finally, six potential BMPs were selected from the management scenarios explored to match the defined "acceptable yield" of dry matter (ears with husks) of 3.4 Mg ha^{-1} and the "acceptable N leached" of 45 kg N ha^{-1}.

Irrigation frequency and amount had a strong influence on corn yield. The trend of increasing N leaching with more frequent and small irrigation depth occurred because less rainfall could be stored when soil moisture content was high. More N applied resulted in more being leached. After 168 kg N ha^{-1} the simulated dry matter yield remained approximately 3.4 Mg ha^{-1}, with negligible increase in yield when increasing N applied. At the same time, N leaching increased steadily as more N was applied. The amount of N leaching increased from 82 to 266 kg N ha^{-1} when the N application level increased from 196 to 561 kg N ha^{-1}, at a constant percentage between 45% and 50% of the total N applied. Nitrogen fertilizer split did not have a remarkable influence on yield if there was any application of N during the small leaf stage, but did have a significant influence on N leaching. Except for a starter N application of 15 kg N ha^{-1}, the optimal splits were "0:1/4:3/4" and "0:1/3:2/3" of total N applied, because these fertigation timing schedules coincided best with the N need of sweet corn growth, especially from tasseling to maturity. A small application rate did not increase yield if it was less than 70 kg N ha^{-1}, but it decreased N leaching. The application rates of 30–50 kg N ha^{-1} were recommended in this study since small application rates (e.g. 5 or 10 kg N ha^{-1}) would greatly increase the number of fertigation events and are impractical for production of sweet corn.

Nitrogen loss is inevitable when growing sweet corn on sandy soils and periodic heavy rainfall. However, the potential BMPs identified in this study may help to reduce the amount of N fertilizer application and consequently reduce nitrate leaching. The CERES-Maize model provided a convenient and economical way to obtain useful information on the interactions between crop, soil, weather and field management strategies. However, it should be recognized that the results obtained in this study were dependent on many model assumptions, for example, the model assumed 100% efficiency and uniformity for irrigation and fertilizer delivery and application, which is usually not the case in practice. These limitations in model simulation need more emphasis when using these results for actual production.

Acknowledgements

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