IMPACT OF ALTERNATIVE CITRUS MANAGEMENT PRACTICES ON GROUNDWATER NITRATE IN THE CENTRAL FLORIDA RIDGE: II. NUMERICAL MODELING

C. B. Harrison, W. D. Graham, S. T. Lamb, A. K. Alva

ABSTRACT. *Long-term impacts of alternative citrus nitrogen and water management practices implemented at grower cooperator sites on the Central Florida Ridge were modeled using the nitrogen component of the Leaching Estimation and Chemistry Model (LEACHN). A bromide tracer test was conducted at one representative cooperator site to parameterize and validate the model. Following validation, 50-year simulations of the historic management practices at each site were conducted. These simulations confirmed field observations that groundwater nitrate-nitrogen concentrations below mature citrus groves that receive 246 kg/ha/yr nitrogen (N) as three split applications of dry soluble fertilizer can be expected to exceed the Environmental Protection Agency's (EPA's) Maximum Contaminant Level (MCL) of 10 mg/L a majority of the time. Fifty-year simulations of alternative nitrogen and water management practices implemented in the field study predicted that in all cases reducing the rate and increasing the frequency of N application, and improving irrigation management, will increase N uptake by plants and reduce average groundwater nitrate-nitrogen concentrations to within EPA standards. Modeling results support conclusions of the field study that showed that, of the BMPs tested on mature citrus, applying 142 kg N/ha/yr as fertigation/foliar spray should be the most effective, while applying 180 kg N/ha/year as slow release/dry soluble BMP should be the least effective at reducing groundwater nitrate-nitrogen concentrations. Modeling results further suggest that, to maintain the average groundwater nitrate-nitrogen concentration below the EPA MCL in this region, the N rate should not exceed 172 kg/ha/yr if the fertilizer is to be applied in three split applications of dry soluble fertilizer; 208 kg/ha/yr if the fertilizer is applied in three applications of slow release/dry soluble fertilizer; or 231 kg/ha/yr if the N is to be applied in 18 split fertigation applications. If 64 kg N /ha/yr is applied as foliar spray, modeling results suggest that an additional 187 kg/ha/year may be applied in 18 split fertigation applications (for a total N application rate of 251 kg/ha/yr) while maintaining the average concentration of the leachate below the EPA MCL.*

Keywords. *Citrus, Best management practices, Groundwater quality, modeling, Nitrate-nitrogen.*

A field research project was recently conducted to evaluate the impact of alternative citrus nitrogen and water management practices on groundwater quality beneath vulnerable sandy soils in the ridge citrus growing region of Central Florida (Lamb et al., 1999). Alternative nitrogen and water management practices were implemented on commercial citrus groves in the region, and groundwater sampling was conducted to assess the impact of these practices on groundwater nitrate for a period of approximately five years. Results of the groundwater sampling indicated that all of the nitrogen and water management practices adopted had the potential to lower the groundwater nitrate concentrations to within EPA standards for drinking water.

Article has been reviewed and approved for publication by the Soil & Water Division of ASAE.

The authors are **Catherine B. Harrison**, Graduate Student, **Wendy D. Graham**, ***ASAE Member Engineer***, Professor, and **Scott T. Lamb**, Engineer (presently with St. Johns River Management District, Melbourne, Florida) Department of Agricultural and Biological Engineering, P.O. Box 110570, Rogers Hall, University of Florida, Gainesville Florida; and **A. K. Alva**, Associate Professor, University of Florida Citrus Research and Education Center, Lake Alfred, Florida. **Corresponding author:** Dr. Wendy Graham, University of Florida, Agricultural and Biological Engineering Dept., P.O. Box 110570, Gainesville FL 32611-0570, voice: (352) 392-9113, fax: (352) 392-4092, e-mail: graham@agen.ufl.edu.

In this study, long-term impacts of the alternative citrus nitrogen and water management practices implemented by Lamb et al. (1999) were modeled using LEACHN, the nitrogen component of the Leaching Estimation and Chemistry Model (LEACHM; Hutson and Wagenet, 1992). The model simulates water flow using the Richards equation, evapotranspiration, nitrogen transport using the advection-dispersion equation, nitrogen sorption and transformations, nitrogen uptake by plants, and plant growth for some crops. The LEACHN model was selected for use in this study, over other commonly available nitrogen leaching models such as NTRM (Shaffer, 1985), GLEAMS (Leonard et al., 1987), NLEAP (Shaffer, 1991), RZWQM (Ahuja et al., 1993) or SOILN (Hoffman and Johnsson, 1999), because it provided the best physical representation of the flow, transport, and transformation processes of interest in this study. In addition LEACHN is readily available, well documented, well supported, and has been validated in a variety of field situations (Wagenet and Hutson, 1986; Pennell et al., 1990; Hutson and Wagenet, 1991; Clark, 1994; Jabro et al., 1995).

The purpose of the model simulations was to extend conclusions from the field study beyond the climatic and management conditions that existed for the field experiment. This was accomplished by (1) examining long-term (50 year) impacts of the alternative practices implemented by Lamb et al. (1999) on groundwater quality, and (2) examining the impacts of additional nitrogen and water management practices not implemented in the field study due to cost and time constraints. Simulations were conducted for all the ridge citrus groves included in the field studies (Sites B through E). Simulations were not conducted for the flatwoods grove nor the native vegetation site, where groundwater nitrate-nitrogen concentrations were found to be below the EPA MCL.

METHODS

In order to extend the conclusions of the field study beyond the climatic conditions that existed during the field experiments, 50-year LEACHN simulations of the pre-BMP and post-BMP practices examined by Lamb et al. (1999) were conducted for all the ridge citrus groves included in the field studies (Sites B through E). Fifty-year simulations for several additional nitrogen management practices were also conducted to extend the conclusions beyond the management practices that were implemented in the field.

Data from a vadose-zone tracer experiment conducted at one of the cooperator sites (Site B) in Highlands County, Florida, was used to parameterize and validate the LEACHN model for predicting water flow and solute transport in excessively drained Astatula sand (hyperthermic, uncoated Quartzipsamments), which is the dominant soil type at all cooperators' sites on the ridge. Pertinent information regarding the field experiment is summarized below. Further details on the field experiment may be found in Graham and Alva (1997).

FIELD TRACER EXPERIMENT

The tracer test was conducted in a 20 ha block of Site B, a mature citrus grove in Highlands County, Florida, which was planted in 1963. Valencia oranges on rough lemon rootstock, planted at a density of 212 trees per hectare, are grown at this site (see Lamb et al., 1999). The bromide tracer was applied in the central portion of the 20 ha block, located on Astatula fine sand. The Astatula series consists of nearly level to moderately sloping, excessively drained soils found mostly within the ridge part of the county (Carter et al., 1989).

An aqueous solution containing 125 kg potassium bromide was applied over an area of approximately 1.88 ha using a tractor-mounted herbicide-boom sprayer to achieve an application rate of approximately 44.5 kg Br/ha (4.45 g/m^2) over the treated area. The bromide was applied from tree-trunk to tree-trunk, i.e., in the row middles as well as under the tree canopy, on 16 July 1996. Post-treatment soil samples were taken approximately weekly for the first six weeks after bromide application, biweekly through the end of the summer rainy season, and monthly thereafter. On each sampling date six to ten locations within the application zone but outside the irrigated area (i.e., in row middles outside the tree canopy) were randomly selected. Sampled locations were clearly marked to avoid repeated sampling at the same locations.

Soil samples were taken at 30 cm increments using a 5.0-cm-diameter bucket auger, from the land surface down to the saturated zone. The field moist soil samples were stored in an ice cooler and during transportation to the laboratory. Twenty grams of moist soil was weighed into a 50 mL centrifuge tube and 20 mL of deionized water was added. The suspension was shaken for 30 min and filtered through no. 42 filter paper. The filtrate was ultracentrifuged and the concentration of bromide in the extract was determined using an ion chromatograph (DX300, Dionex Corporation, Sunnyvale, Calif.) Gravimetric soil-water content was also determined for each depth increment to converted the bromide concentration to a soil-water basis. Further details on the sampling and analytic procedures can be found in Graham and Alva (1997).

MODEL PARAMETERIZATION

Soil Physical Properties. Soil physical properties, including percent clay, silt, and organic carbon were obtained from the soil characterization database at the University of Florida (Carlisle et al., 1989). Data for an Astatula fine sand soil core from a citrus grove in Highlands County analyzed by Carlisle et al. (1989) were used to characterize the soil profile for all ridge sites. Table 1 shows the depth of the soil profile and the soil physical properties used in the simulations. Carlisle et al. (1989) provides information only to a depth of approximately 2 m. Therefore, soil properties for the 2 m depth were assumed to extend to just above the top of the capillary fringe which was located at approximately 6 m below land surface at the field site.

Retentivity constants for Campbell's (1974) water retention equation were estimated using the measured water contents at various potentials for each soil layer as reported by Carlisle et al. (1989). A stand-alone program, RETFIT, that accompanies the LEACHN model was used to determine best-fit retention parameters from this data (see table 1). A value of 20 mm was used for the soil dispersivity for all layers, as recommended by Hutson and Wagenet (1992).

Citrus root distribution in each soil layer was estimated from the literature. Based on Boman (1996), as well as studies conducted by McNamee (1955) and Nemec et al. (1982), the following root distribution was estimated as typical for a ridge citrus grove: 50% of the roots in the top 0.3 m, 40% in the next 0.3 m, and the remaining 10% of the roots evenly distributed over the next 3 m (see table 1). A constant mature crop was assumed to be present

Table 1. Soil physical parameters

Soil Layer No.	Depth (mm)	Clay (%)	Silt (%)	Organic C (%)	Roots (%)	Soil Bulk Density* (kg/dm^3)	Air-entry Value* (kPa)	Exponent in Campbell's Equation*	Conductivity* (K) (mm/d)	Dispersivity† (mm)
1	300	1.4	0.3	0.29	50	1.59	–0.815	1.068	18624	20
2	600	1.6	0.0	0.08	40	1.61	–0.690	1.210	21312	20
3	900	1.6	0.0	0.08	1	1.61	–0.690	1.210	21312	20
4	1200	1.5	0.7	0.07	1	1.61	–0.814	0.990	28080	20
5	1500	1.5	0.7	0.07	1	1.61	–0.814	1.000	28080	20
6	1800	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
7	2100	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
8	2400	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
9	2700	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
10	3000	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
11	3300	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
12	3600	1.5	1.1	0.08	1	1.60	–0.790	1.000	22872	20
13	3900	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
14	4200	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
15	4500	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
16	4800	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
17	5100	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
18	5400	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
19	5700	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20
20	6000	1.5	1.1	0.08	0	1.60	–0.790	1.000	22872	20

* Carlisle et al., 1989.
† Hutson and Wagenet, 1992.

throughout the simulation period, and the crop cover fraction (fraction of land covered by the crop and thus subject to ET) was assigned a value of 1. Bromide was assumed not to be taken up by citrus trees in the transpiration stream. A free-draining lower boundary was assumed to occur just above the capillary fringe at a depth of 6 m. Additional soil- and crop-related parameters used in the simulation are summarized in table 2.

Weather Data. Figure 1 shows weekly rainfall and pan evaporation for Site B during the tracer test study period. No surface runoff was observed by either the grower or research personnel; thus measured rainfall was used as the surface flux boundary condition in the LEACHN model. A pan factor of 0.7 was utilized to correct pan evaporation to potential evapotranspiration, and the annual average crop coefficient determined by Jones et al. (1984) for ridge citrus was assumed (see table 2). Daily minimum and maximum air temperatures recorded at the nearby Archbold Biological Station were averaged to obtain mean weekly temperatures and temperature ranges needed for the model.

Model Performance

As pointed out by Pennell et al. (1990), the ability to model field-scale flow and transport in the unsaturated zone is an ambitious goal. Pennell et al. (1990) asserted that it is reasonable to expect simulations to predict the amount of mass remaining in the soil profile, and the depth of the solute center of mass in the profile, within approximately 50% of the actual value. However, they also suggested that accurate predictions of field-scale solute concentration distributions may be unrealistic due to high variability of soil, weather, and source characteristics affecting solute transport. In this study, the zero*th* spatial moment (M_0) and the first normalized spatial moment (M_1') were used to provide estimates of total mass in the soil profile and depth of the center of mass in the soil profile, respectively. These moments provide a convenient means for summarizing, analyzing, and interpreting solute transport behavior in the field experiment, and a reasonable means for comparing model predictions to field measurements (Freyberg, 1986; Pennell et al., 1990; Garabedian et al., 1991).

A comparison between the mass of tracer applied per unit area (4.45 g/m^2) and mass recovery per unit area (M_0) provides a measure of both the efficacy of the experimental technique and the mass of bromide remaining in the vadose zone. Figure 2 shows the average mass of bromide recovered from the soil cores, with the horizontal lines indicating plus/minus one standard deviation around the averaged value. Mass recovery fell within one standard deviation of the applied value for the first 36 days of the experiment. On these sampling days the majority of the bromide plume remained in the vadose zone. Deviations in mass recovery around the applied value on these days may be the result of spatial variability in the bromide application rate, rainfall and evaporation patterns, or soil properties. From Day 50 through Day 246 bromide mass recovery averaged approximately 53% of the applied value, indicating either some loss of bromide to the saturated zone or bromide uptake by the crop. The extremely low mass recovery on Days 295 through 408 indicated that most of the bromide had moved out of the vadose zone by this time. The wide standard deviation bands around the estimated mass recovery for all dates suggests that more sampling locations may be needed to average the effects of this variability. Also shown in figure 2 are LEACHN predictions of the amount of bromide mass remaining in the profile. These data support the hypothesis that there may have been some bromide uptake by the crop, since the

Table 2. Crop related parameters

Parameter	Value	Reference
Wilting point, soil (kPa)	–1500	Highlands County Soil Survey (Carter et al., 1989)
Minimum root water potential (kPa)	–3000	Hutson and Wagenet,1992
Crop cover fraction	1.00	Hutson and Wagenet,1992
Root resistance	1.00	Hutson and Wagenet,1992
Crop coefficients:		Jones et al., 1984
Bromide experiment*	0.84	
Nitrate simulations†	0.53	

* Based on Pan Evaporation.
† Based on Blaney Criddle PET.

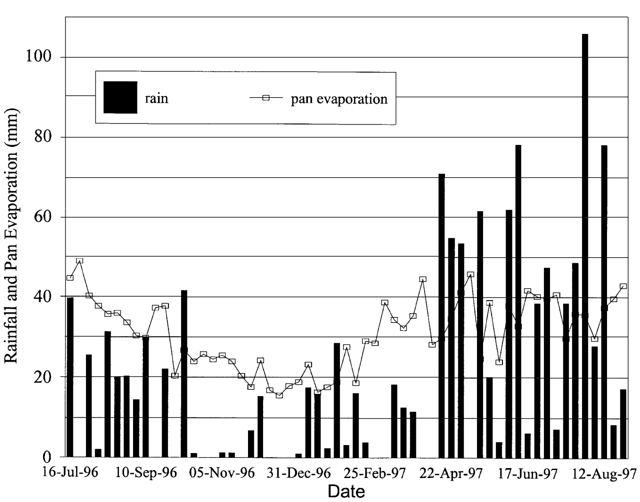

Figure 1–Weekly rainfall and pan evaporation at Site B during the bromide tracer experiment.

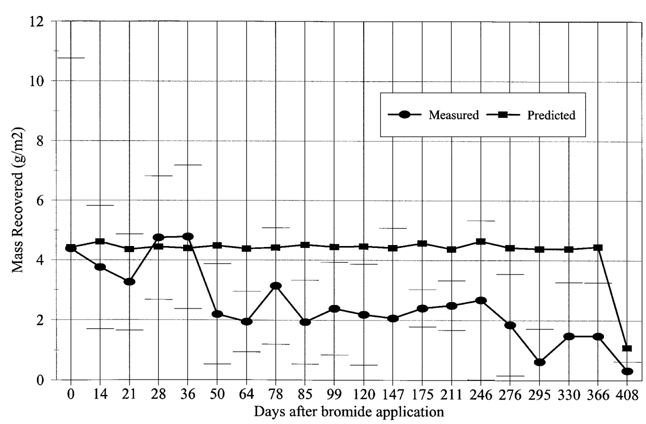

Figure 2–Comparison of measured and predicted bromide mass recovery.

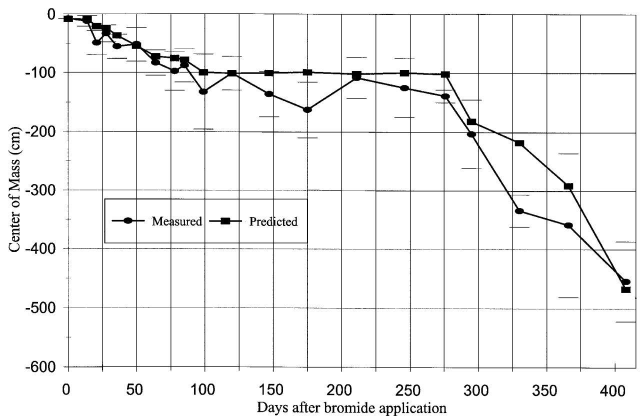

Figure 3–Comparison of measured and predicted movement of the bromide center of mass.

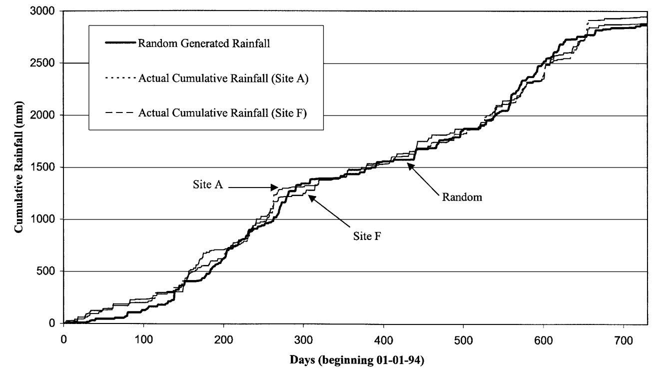

Figure 4–Comparison of randomly generated rainfall versus measured rainfall at Sites A and F.

model does not predict any loss of bromide to the saturated zone until after day 366.

Figure 3 shows simulated depth of the center of bromide mass (M_1') compared with depth of the center of bromide mass calculated from field-measured data. Results for the tracer simulation were very close to those measured in the field, and fell within one standard deviation of the measured values on 16 of the 20 the sampling dates. The regular movement of the center of bromide mass in response to net applied water (i.e., rainfall minus evapotranspiration) is clearly evident in this figure for both the simulated and field-measured data. The bromide center of mass showed a downward trend for the first 100 days of the experiment, which corresponded to the 1996 summer rainy season (see fig. 1). During the dry season from Day 99 (23 October 1996) to Day 276 (16 April 1997) the center of bromide mass remained at approximately 1.3 m below land surface. Between Day 276 and Day 408 (28 August 1997), the center of mass again began to move downward, in response to the 1997 summer rainy season. On Day 408 the center of bromide mass was close to the water table, at approximately 4.5 m below the ground surface. Agreement between the model-simulated and field-measured positions of the center of mass indicates that the soil, crop and weather parameters incorporated into the model (summarized in tables 1 and 2) are representative of actual conditions in the study area.

Model Inputs for BMP Simulations

Soil Physical Properties. Since Astatula sand is the dominant soil type at all of the ridge citrus sites, the soil physical properties and related parameters discussed above and summarized in tables 1 and 2 were utilized for all pre-BMP and post-BMP simulations.

Climatic Data. A weather generator program, WGEN, was used to create one 50-year sequence of randomly generated daily rainfall, potential evapotranspiration (PET), and maximum and minimum temperatures that was used in all pre-BMP and post-BMP simulations. The WGEN model is designed to generate weather sequences that preserve the temporal correlation, and the seasonal and statistical characteristics, of actual observations of these variables for the location of interest (Richardson and Wright, 1984). Appropriate precipitation, PET, and temperature records needed to generate the input statistics for WGEN were obtained from a NOAA weather station at Avon Park, Florida.

WGEN uses a first-order Markov model to generate wet or dry days based on historic transition probabilities. Daily precipitation amounts are then generated using a two-parameter gamma distribution (Richardson and Wright, 1984). A representative two-year sequence of the daily rainfall generated by WGEN is shown in figure 4. This figure shows that the randomly generated weather sequence compared well to measured data from Sites A and F (Lamb et al., 1999). In all model simulations, rainfall was assumed to occur at midday at an intensity of 4.2 mm/h during the dry season when frontal storms predominate (October through May) and 16.6 mm/h during the rainy season when convective storms predominate (June through September).

WGEN generates PET values for a reference grass cover crop using the Blaney-Criddle method; thus the PET rates must be adjusted for citrus. Actual annual ridge citrus ET rates reported by Jones et al. (1984) were divided by average annual grass PET rates calculated from the 50 years of daily PET data generated by WGEN, to obtain an appropriate crop coefficient. The crop coefficient used for the BMP simulations is lower than the coefficients used with the pan evaporation data to model the bromide experiment. This is due to the fact that the Blaney-Criddle method typically overestimates potential evapotranspiration in Florida, because it neglects effects of cloud cover in reducing incoming solar radiation (Jones et al., 1984).

Chemical Properties. Chemical properties required by LEACHN to simulate the transport and transformations of urea, ammonium, and nitrate were obtained from the literature, since detailed site-specific data were unavailable. Table 3 summarizes values used for the simulations as well as literature sources for these values. Most of these parameters were also used by Clark (1994) and fall within the range of values recommended by Hutson and Wagenet (1992). Detailed definitions of these parameters and their significance can be found in Hutson and Wagenet (1992).

Nitrogen Uptake. Potential annual uptake of nitrogen by the citrus crop was estimated based on a field study of components for the typical ridge citrus nitrogen (N) budget (Ashok Alva, unpublished Citrus N budget). In Alva's study, an accounting of all N inputs, changes in storage of N in the root and tree growth, and removal of N due to fruit harvesting showed that average uptake for oranges

Table 3. Chemical properties

Parameter	Value	Reference
K_d, partition coefficient (L/kg):		
Urea	1.0	Clothier et al., 1988
NH_4-N	2.6	
NO_3-N	0.0	
Molecular diffusion coefficient in water (mm^2/day)	120	Hutson and Wagenet, 1992
Bresler's equation adjustments		
a	0.001	Hutson and Wagenet, 1992
b	10	
Synthesis efficiency factor	0.5	Johnsson et al., 1987
Humification fraction	0.2	Johnsson et al., 1987
Carbon : Nitrogen ratio	10	Stevenson, 1982 Hutson and Wagenet, 1992
Minimum matric potential for transformations (kPa)	–1500	Hutson and Wagenet, 1992
Mineralization rate constants (day^{-1}):		
Litter-N	0.01	Clark, 1994
Manure-N	0.02	
Humus-N	0.00007	
Other rate constants (day^{-1}):		
Denitrification	0.001	Clark, 1994
Nitrification	0.2	
Ammonia volatilization	0.6	Hutson and Wagenet, 1992
Denitrification half-saturation constant (mg/L)	10.0	Hutson and Wagenet, 1992
Limiting NO_3/NH_4 ratio in solution for nitrification, r_{max}	8.0	Hutson and Wagenet, 1992
Urea hydrolysis rate constants (day^{-1}):		
Top 0.3 m	0.36	Clark, 1994
2nd layer (0.3-0.6 m)	0.18	
3rd layer and deeper (0.6-6 m)	0.16	

receiving 270 kg/ha/yr N fertilizer is approximately 220 kg N/ha/yr. The potential annual crop uptake needed for LEACHN was calibrated so that, under nitrogen inputs similar to those in Alva's field study, the modeled crop would remove approximately 200 to 240 kg/ha/yr. This method of estimating potential annual N uptake yielded a potential rate of 400 kg/ha/yr that was used as input for all simulations.

Nitrogen Inputs. Table 4 summarizes the pre- and post-BMP nitrogen and water management practices simulated for each site. For the pre-BMP simulations at the mature citrus sites (Sites B, D and E) nitrogen was added at a rate of 82 kg/ha dry soluble ammonium nitrate (41 kg/ha ammonium-nitrogen and 41 kg/ha nitrate-nitrogen) on days 46, 166, and 258, for a total of 246 kg/ha/yr for each simulation year. For the pre-BMP simulations at the young citrus site, nitrogen was added at a rate of 56 kg/ha dry soluble ammonium nitrate (28 kg/ha ammonium-nitrogen and 28 kg/ha nitrate-nitrogen) on days 46, 166 and 258, for a total of 167 kg/ha for each simulated year. These pre-BMP application rates are based on actual five-year average N applied to these sites prior to BMP implementation (Lamb et al., 1999).

To account for fertigation in the post-BMP simulations, equal parts of dissolved ammonium and nitrate were added to irrigation water in the appropriate amounts on days 5, 25, 36, 41, 46, 51, 64, 69, 74, 79, 100, 110, 130, 145, 249, 263, 279, 293 of each simulation year. In practice, foliar spray is applied as urea directly to the leaves. Under optimum conditions none of the urea should be available for leaching; however, some unavoidable losses to the soil surface may occur by drift or washoff. As a very conservative estimate of washoff, it was assumed in the post-BMP simulations that all of the foliar spray was washed off the leaves and available to infiltrate the soil. Thus to account for foliar spray, 21.3 kg/ha urea was added to the soil surface in dry broadcast form on days 74, 259, and 349 of each simulation year.

Table 4. Pre- and post-BMP nitrogen and water management practices

Practice	Sites B,D&E Pre-BMP	Site B Post-BMP	Site D Post-BMP	Site E Post-BMP	Site C	
					Pre-BMP	Post-BMP
Nitrogen management	246 kg/ha/yr dry soluble (3 applications)*	142 kg/ha/yr fertig./foliar spray (18/3 applications)†‡	180 kg/ha/yr dry sol./slow release (3/1applications)§	180 kg/ha/yr fertigation (18 applications)†	168 kg/ha/yr dry soluble (3 applications)*	168 kg/ha/yr fertigation (18 applications)†
Water Management	SCS schedule	Tensiometers	Tensiometers	Tensiometers	SCS schedule	Tensiometers

* Three dry soluble applications in January, April, September.
† Eighteen fertigation applications in January-May, September-October.
|| Three foliar sprays in March, September, December.
§ Jan (45 kg dry, 45 kg slow release), Apr (45 kg dry), Sept (45 kg dry).

For the dry soluble/slow-release BMP nitrogen was applied as 44.8 kg/ha of urea with a release rate of 0.006 day^{-1} [to simulate the slow-release characteristics of the sulfur coating (Lamb, 1996)]. In addition dry soluble fertilizer was added in the amount of 22.4 kg/ha ammonium and 22.4 kg/ha nitrate on days 16, 106 and 258 of each simulated year for the dry soluble/slow release BMP. To account for nitrogen introduced through organic matter additions from leaf litter, 22 kg/ha of litter-N was added to the soil surface every 2 months during all simulations (Ashok Alva, unpublished Citrus N budget). Since each model simulation period was 50 years, initial estimates of nitrogen and carbon in the profile were not critical and were assumed to be zero throughout the profile for all pre-BMP simulations. Soil water nitrate-nitrogen concentrations predicted at the end of 50-year pre-BMP period were assumed as initial conditions for the post-BMP simulations.

Irrigation Management. For the pre-BMP simulations, irrigation water was added to the randomly generated rainfall record in accordance with a rainfall-driven SCS irrigation schedule that was developed for the cooperator sites in 1994. For the post-BMP simulations, the LEACHN code was modified so that irrigation water could be added whenever the soil water potential at a specific depth in the profile exceeded a certain level of dryness. For the post-BMP simulations, irrigation was triggered whenever the soil water potential dropped below –10 kPa at the 15 cm depth during January through June, and whenever the soil water potential dropped below –15 kPa at the 15 cm depth during July through December.

Results and Discussion

Pre-BMP Simulations

Table 5 summarizes the 50-year average nitrogen budget, and table 6 summarizes the 50-year average water budget, for the pre-BMP simulations. Dividing the average kg/ha NO_3-N leached by the average volume of water leached, and making the appropriate unit conversions, gives an average pre-BMP groundwater concentration of 16 mg/L for the mature citrus sites. This is in good agreement with the range of pre-BMP nitrate-nitrogen concentrations measured at Sites B, D, and E by Lamb et al. (see fig. 4, Lamb et al., 1999). The average simulated pre-BMP groundwater concentration of 10 mg/L calculated for the young citrus site is also in the range of the field-measured pre-BMP data for Site C shown in figure 4 of Lamb et al. (1999). Thus, numerical model simulations confirm the field observations that groundwater nitrate-nitrogen concentrations below mature citrus groves receiving 246 kg/ha/yr N as three split applications of dry soluble fertilizer can be expected to exceed the EPA MCL. Furthermore, the simulations confirm that groundwater nitrate-nitrogen concentrations below young citrus groves receiving an average of 167 kg/ha/yr as three split applications of dry soluble fertilizer will be well above background levels (less than 1 mg/L NO_3-N for this region).

Table 5. Pre- and post-BMP nitrogen budget for all sites

Nitrogen Budget (kg/ha/year)	Sites B, D & E Pre-BMP	Site B Post-BMP	Site D Post-BMP	Site E Post-BMP	Site C Pre-BMP	Site C Post-BMP
Applied						
NO_3-N	123.00	39.30	67.20	89.76	84.00	84.17
NH_4-N	123.00	39.30	67.20	89.76	84.00	84.17
Litter-N	132.00	132.00	132.00	132.00	132.00	132.00
Urea-N	0.00	63.90	44.80	0.00	0.00	0.00
Total	378.00	274.49	311.20	311.52	300.00	301.34
Leached						
NO_3-N	153.66	25.80	59.56	51.95	91.80	44.05
NH_4-N	0.00	0.00	0.00	0.00	0.00	0.00
Litter-N	0.00	0.00	0.00	0.00	0.00	0.00
Total	153.66	25.80	59.56	51.95	91.80	44.05
Uptake by Plants						
NO_3-N	186.48	222.40	220.11	236.56	172.68	233.25
NH_4-N	13.60	15.90	15.22	12.23	14.27	12.54
Litter-N	0.00	0.00	0.00	0.00	0.00	0.00
Total	200.08	238.30	235.33	248.79	186.95	245.79
Volatilization Losses						
NO_3-N	1.83	0.36	1.28	0.59	1.12	0.52
NH_4-N	9.34	7.87	8.13	8.10	7.35	7.75
Litter-N	0.00	0.00	0.00	0.00	0.00	0.00
Total	11.17	8.23	9.41	8.69	8.47	8.26

Note: Total mass error for each site is no greater than 0.47 kg/ha/yr.

Table 6. Pre- and post-BMP water budget for all sites

Water Budget (m/yr)	Sites B, D & E Pre-BMP	Site B Post-BMP	Site D Post-BMP	Site E Post-BMP	Site C Pre-BMP	Site C Post-BMP
Total *	1.87	1.77	1.66	1.77	1.87	1.77
Drainage	0.96	0.87	0.77	0.87	0.96	0.87
ET	0.91	0.89	0.89	0.89	0.91	0.89

Note: Total numerical error for each site is no greater than 0.006 m.
* Average annual rainfall for all sites is 1.39 m/yr.

Post-BMP Simulations

Site B. The effect of reducing nitrogen application to 142 kg/ha/yr applied as a combination of fertigation and foliar spray, in conjunction with tensiometer scheduling of irrigation, was studied at Site B. Table 5 shows that leached nitrogen decreased from about 154 kg/ha/year to about 26 kg/ha/year when the fertigation/foliar spray combination was used instead of dry soluble fertilizer. This is in spite of the conservative assumption that 100% of the foliar-applied urea was washed off and available to infiltrate the soil. Plant uptake of N increased by about 38 kg/ha/year in the post-BMP simulation, suggesting that the improved practices cause the nitrate to be more accessible to the trees. Table 6 shows that the total amount of water applied to the soil at Site B decreased from an average of 1.87 m/year to 1.77 m/year after BMP-

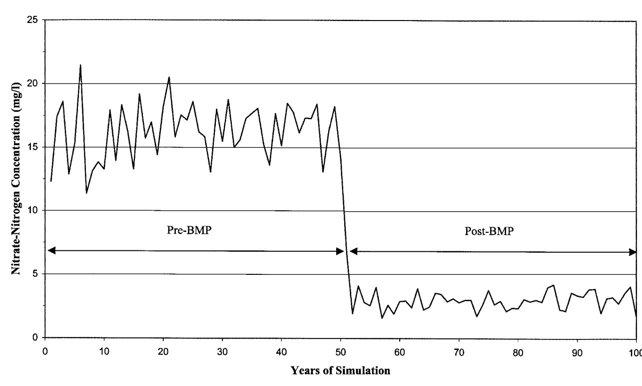

Figure 5–Comparison of pre-BMP and post-BMP annual average nitrate-nitrogen concentrations in leachate at Site B.

implementation. Since the rainfall record was the same for pre- and post-BMP simulations (an average of 1.39 m/year), these results indicate that the amount of water applied as irrigation decreased by 0.1 m/year under irrigation scheduling using tensiometers.

Figure 5 shows the simulated annual leachate concentrations for pre- and post-BMP situations, calculated by dividing the annual mass of nitrate-nitrogen leached from the profile by the annual volume of water leached from the profile for each year of simulation (50 years total for each simulation). This figure shows that the annual leachate nitrate-nitrogen concentrations ranged from approximately 12 mg/L to 22 mg/L, and averaged 16 mg/L in the pre-BMP period. The average value and the variability of annual leachate concentrations were both reduced significantly after BMP implementation, when nitrate-nitrogen concentrations ranged from approximately 2 to 4 mg/L, and averaged 3 mg/L. For convenience the pre- and post-BMP data have been plotted as continuous times series on the same graph. However, the purpose of figure 5 is to demonstrate the effect of weather variability on annual leachate concentrations, and not sequential changes over time. Furthermore the transition of pre- to post-BMP concentrations is dependent on the particular pattern of the weather series during this transition period and therefore not of particular interest.

Figure 6 shows the cumulative distribution of the daily leachate concentrations for the 50-year pre-BMP and post-BMP simulations. Daily leachate concentrations were calculated by dividing the daily mass of nitrogen leached from the profile by the daily volume of water leached from the profile for each day of simulation (18,250 days total for each simulation). These daily concentrations were then sorted from smallest to largest, then plotted against their rank to provide an experimental cumulative distribution function. To avoid the impacts of initial conditions, the first year of data from both the pre- and post-BMP simulations were not included in the calculation of the cumulative distributions. For comparison purposes, the experimental cumulated distribution function for the four years of post-BMP field-measured nitrate-nitrogen concentrations obtained from the uppermost port of the multilevel samplers (i.e., the top of the water table) at Site B is also shown in figure 6. For the pre-BMP simulations the nitrate-nitrogen concentration leaching from the vadose zone exceeds the EPA MCL 76% of the time. For the post-BMP simulations exceedence of the MCL did not occur after the first year of BMP implementation. The cumulative distribution function for the nitrate-nitrogen measured in the water samples from the top of the water table fell significantly below the simulated pre-BMP cumulative distribution function and appeared to be approaching the simulated post-BMP cumulative distribution function.

Site C. Fertigation at a total rate of 168 kg/ha/yr, in conjunction with tensiometer irrigation scheduling, was recommended for Site C. Post-BMP nitrogen and water balances for the Site C simulations are included in tables 5 and 6. The total amount of nitrate-nitrogen leached decreased from about 92 kg/ha/year to 44 kg/ha/year after BMP implementation. Plant uptake increased by about 60 kg/ha/year, suggesting that frequent fertigation allows the nitrate to be more accessible to the tree before leaching can occur. As with Site B, the total amount of irrigation water applied decreased by 0.1 m/year due to irrigation scheduling.

Annual leachate concentrations for both the pre- and post-BMP periods are shown in figure 7. This figure shows that the annual leachate nitrate-nitrogen concentrations ranged from approximately 7.5mg/L to 12.5 mg/L, and averaged 10 mg/L in the pre-BMP period. The average value and the variability of annual leachate concentrations were both reduced significantly after BMP implementation,

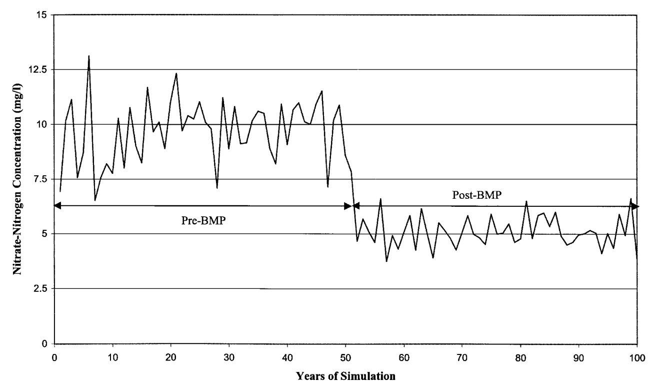

Figure 7–Comparison of pre-BMP and post-BMP annual average nitrate-nitrogen concentrations in leachate at Site C.

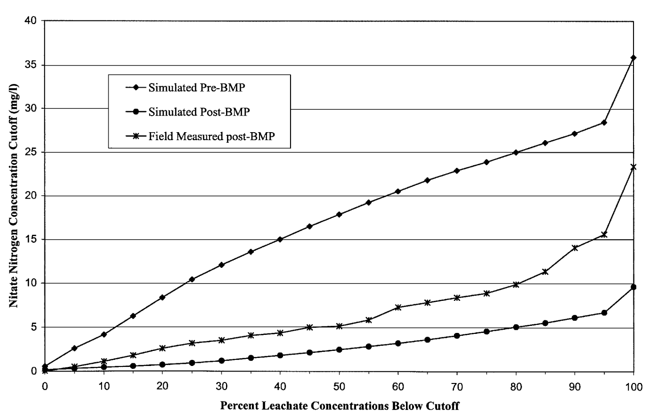

Figure 6–Comparison of daily simulated pre-BMP, simulated post-BMP, and measured post-BMP nitrate-nitrogen concentration frequency distributions at Site B.

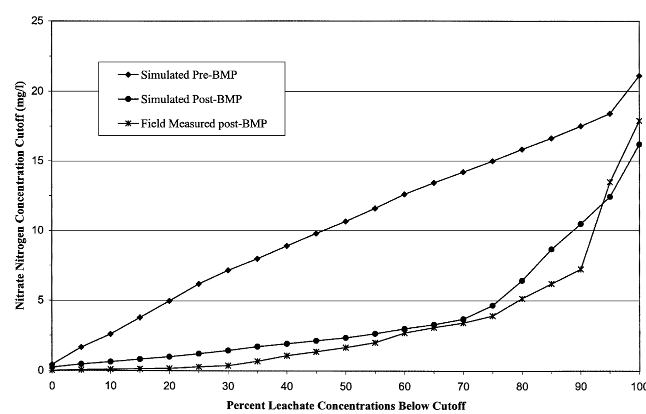

Figure 8–Comparison of daily simulated pre-BMP, simulated post-BMP, and measured post-BMP nitrate-nitrogen concentration frequency distributions at Site C.

when nitrate-nitrogen concentrations ranged from approximately 4 to 6 mg/L, and averaged 5 mg/L.

The cumulative distribution functions for simulated (leachate) and measured (top of the groundwater) concentrations for Site C are shown in figure 8. The model predicted that under the pre-BMP scenario the MCL would be exceeded 54% of the time but that, under the post-BMP scenario, the MCL would be exceeded only 11% of the time. Note that the measured concentration cumulative distribution function was much lower than the simulated pre-BMP cumulative distribution function, and was very close to the post-BMP cumulative distribution function.

Site D. A combination of slow-release and dry soluble fertilizer at a total rate of 180 kg/ha/yr was recommended for Site D, in addition to tensiometer irrigation scheduling. Post-BMP nitrogen and water balances for Site D simulations are included in tables 5 and 6. The total amount of nitrate-nitrogen leached was predicted to decrease from about 154 kg/ha/year to about 60 kg/ha/year. Plant uptake increased by about 35 kg/ha/year, again suggesting that improved nitrogen and irrigation management allows the nitrate to be more accessible to the tree before leaching can occur. For Site D the amount of irrigation water applied decreased by about 0.21 m/year due to irrigation scheduling. Note that increased efficiency of irrigation at Site D compared to the other sites is due to the fact that there is no fertigation at Site D and thus there are fewer prescribed irrigation events.

Figure 9 shows 50 years of annual nitrate-nitrogen concentrations in the leachate for both the pre- and post-BMP simulations. Under pre-BMP management the simulated annual average nitrate-nitrogen concentration in the leachate concentrations ranged from approximately 12 mg/L to 22 mg/L, and averaged 16 mg/L. The predicted annual post-BMP leachate concentration ranged from about 6 gm/L to 12 mg/L, and averaged approximately 8 mg/L. The cumulative distribution function for the daily nitrate-nitrogen concentrations leaching from the profile for Site D is shown in figure 10. The model predicted that the MCL would be exceeded 76% of the time under pre-BMP management, but only 33% of the time under simulated post-BMP management. The simulated pre-BMP nitrate-nitrogen concentration cumulative distribution function showed much higher nitrate-nitrogen concentration than either the simulated

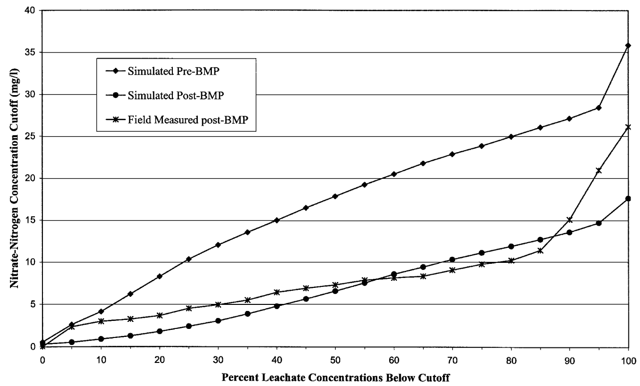

Figure 10–Comparison of daily simulated pre-BMP, simulated post-BMP, and measured post-BMP nitrate-nitrogen concentration frequency distributions at Site D.

post-BMP distribution or the field-measured MLS concentration distribution, which are very similar.

Site E. Fertigation at a total rate of 180 kg/ha/yr, in conjunction with tensiometer irrigation scheduling, was recommended for Site E. The post-BMP nitrogen and water balances for Site E simulations are included in tables 5 and 6. The total amount of nitrate-nitrogen leached was predicted to decrease from about 154 kg/ha/year to 52 kg/ha/year. Plant uptake was predicted to increase by about 49 kg/ha/year, and the total amount of irrigation water applied decreased by 0.1 m/year due to irrigation scheduling.

Figure 11 shows that the average annual leachate concentration concentrations ranged from approximately 12 mg/L to 22 mg/L, and averaged 16 mg/L in pre-BMP period. The average value and the variability of annual leachate concentrations were both reduced significantly after BMP implementation, when nitrate-nitrogen concentrations ranged from approximately 5 to 8 mg/L, and averaged 6 mg/L. Figure 12 shows the cumulative distribution function for the average daily leachate concentrations for the pre-BMP and post-BMP simulations, and for the field-measured nitrate-nitrogen concentrations obtained from the uppermost port of the multilevel samplers at Site E. Measured concentrations from the uppermost MLS port fall below the simulated pre-BMP concentrations and are quite close to the post-BMP

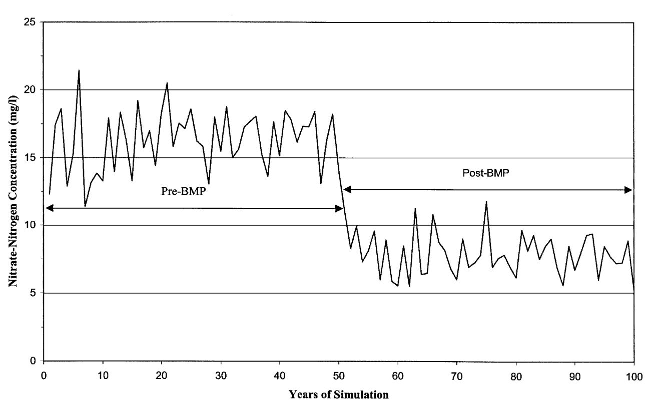

Figure 9–Comparison of pre-BMP and post-BMP annual average nitrate-nitrogen concentrations in leachate at Site D.

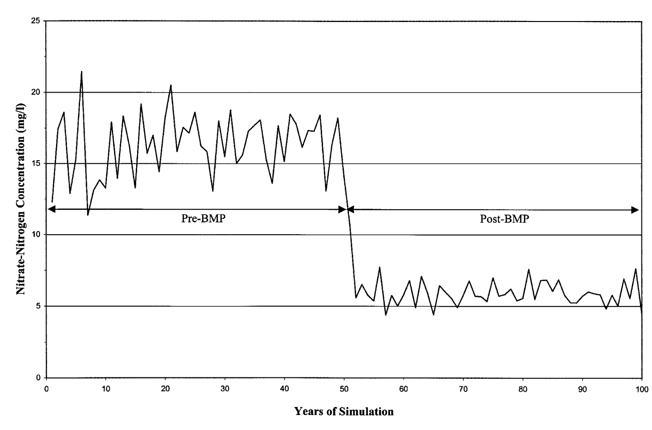

Figure 11–Comparison of pre-BMP and post-BMP annual average nitrate-nitrogen concentrations in leachate at Site E.

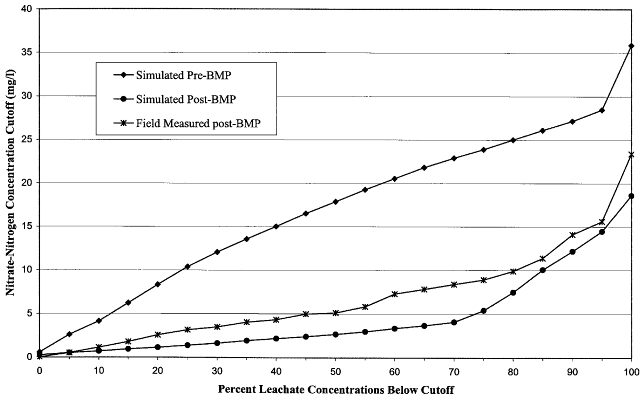

Figure 12–Comparison of daily simulated pre-BMP, simulated post-BMP, and measured post-BMP nitrate-nitrogen concentration frequency distributions at Site E.

concentrations. LEACHN predicted that the MCL would be exceeded 76% of the time under pre-BMP nitrogen and water management, but only 15% of the time under post-BMP management. The MCL was exceeded in approximately 20% of the measured concentrations for the upper-most port of the MLS during the four-year field-sampling period.

Additional Simulations. Additional modeling runs were conducted to estimate the maximum rates of N application allowable under the dry-soluble, dry-soluble/slow release, fertigation, and fertigation/foliar spray application frequencies outlined above, while maintaining the average annual N concentration in the leachate below 10 mg/L. Figure 13 shows the cumulative distribution functions of the daily leachate concentrations for these four modeling runs. This figure shows that dry-soluble N rates should not exceed 172 kg/ha in three applications if an average leachate concentration of 10 mg/L is to be maintained. Under this scenario, the MCL would be exceeded 52% of the time. Dry-soluble/slow release N rates should not exceed to 208 kg/ha/yr in three applications to maintain an average leachate concentration of 10 mg/L; however, this practice would exceed the MCL 44% of the time. Fertigation N rates should not exceed 231 kg/ha/yr in 18 applications to maintain an average leachate concentration of 10 mg/L. This practice would exceed the MCL 24% of the time. If 64 kg N/ha/yr were applied as foliar spray, figure 13 shows that an additional

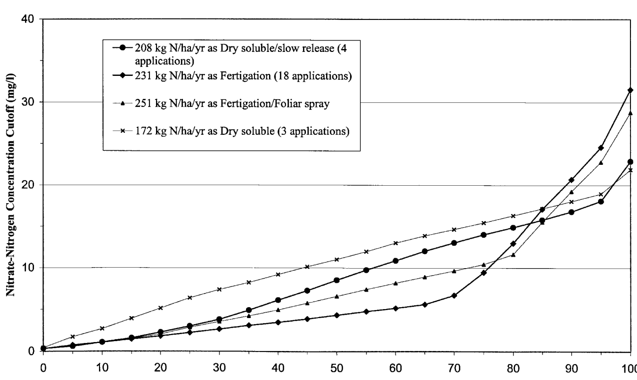

Figure 13– Nitrate-nitrogen concentration frequency distributions for maximum N application scenarios.

187 kg/ha/year could be applied in 18 split fertigation applications (for a total N application rate of 251 kg/ha/yr) while maintaining average leachate concentrations below the EPA MCL. Under this scenario, the MCL would be exceeded at 28% of the time.

Conclusions

The Leaching Estimation and Chemistry Model (Hutson and Wagenet, 1992) was parameterized and validated for predicting water and solute transport in excessively drained Astatula sand on the Central Florida ridge using data from a vadose-zone tracer experiment conducted at a citrus grove in Highlands County, Florida. Subsequent simulations of nitrogen transport with the LEACHN model showed that the amount of nitrate-nitrogen reaching the surficial aquifer beneath Central Florida citrus groves can be significantly reduced under improved irrigation and fertilizer management practices. Fifty-year simulations of the BMPs recommended by Lamb et al. (1999) predicted that reducing the rate and increasing the frequency of N application, and improving irrigation management, should both increase N uptake by plants and reduce average groundwater nitrate-nitrogen concentrations to within EPA standards

Modeling results supported the conclusions of Lamb et al. (1999) that (1) all of the BMPs implemented in the field project should, on average, meet the EPA MCL for groundwater; (2) of the BMPs tested on mature citrus groves, applying 142 kg N/ha/yr as fertigation/foliar spray should be the most effective at reducing groundwater nitrate-nitrogen concentrations; (3) applying 180 kg N/ha/yr split into 18 fertigation applications should produce slightly lower average groundwater nitrate-nitrogen concentrations that applying 180 kg N/ha/yr split into 3 applications of dry soluble/slow release fertilizer; and (4) if 180 kg N/ha/yr is applied to mature citrus groves periodic exceedences of the EPA MCL can be expected.

Additional modeling runs were conducted to estimate maximum rates of N application that should, on average, maintain groundwater nitrate-nitrogen concentrations below the EPA MCL at these sites. These simulations suggest that these maximum N rates are approximately (1) 172 kg/ha/yr if the fertilizer is applied in three split applications of dry soluble fertilizer; (2) 208 kg/ha/yr if the fertilizer is applied in three split applications of dry soluble/slow release fertilizer; (3) 231 kg/ha/yr if the N is applied in 18 split fertigation applications; and (4) 251 kg/ha/yr if 64 kg N/ha/yr is applied as foliar spray, and an additional 187 kg/ha/year is applied as 18 split fertigation applications. However it must be recognized that, even if average nitrate-nitrogen concentrations leaching to groundwater are maintained below 10 mg/L, the EPA MCL can be expected to be violated from 24% to 56% of the time under these practices.

The validity of LEACHN model predictions is highly dependent on the rate of nitrogen uptake assumed by the model. In the simulations conducted for this study, potential nitrogen uptake was calibrated so that the modeled crop would remove approximately 200 to 240 kg/ha/yr (Ashok Alva, University of Florida Citrus Research and Education Center, unpublished Citrus N budget). In the current model this potential rate is a constant that is not adjusted seasonally for root growth, shoot growth, young tree development, or fruit harvest. Further studies on the rate and timing of N uptake by citrus are needed to refine the citrus N uptake and growth mechanisms incorporated into the LEACHN model. Similarly, nitrogen application and uptake mechanisms should be enhanced to more appropriately account for the application and uptake of foliar applied urea. Due to these and other model limitations more confidence should be placed on the relative effectiveness of the BMPs, rather than the precise concentrations of nitrate-nitrogen, predicted by the model.

Acknowledgments. The authors would like to thank the Highlands County, Florida, citrus grower cooperators for allowing long-term and frequent access to their groves; Rick Edwards, Joseph Ayers, David Graves, David Flowers, and Paul Stark for their faithful execution of the bi-weekly field sampling; and Ashie Akpoji for his help with database management and data analysis. Financial support for this work was provided in part by the Florida Department of Agriculture and Consumer Services. This article is Florida Agricultural Experiment Station Journal Series No. R-06740.

References

Ahuja, L. R., D. G. Decoursey, B. B. Barnes, and K. W. Rojas. 1993. Characteristics of macropore transport studied with the root zone water quality model. *Transactions of the ASAE* 36(2): 369-380.

Boman, B. 1996. Citrus: Understanding its irrigation requirements. *Irrig. J.* 46(2): 8-12.

Campbell, G. L. 1974. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Sci.* 117(6): 311-314.

Carlisle, V. W., F. Sodek, M. E. Collins, L. C. Hammond, and W. G. Harris. 1989. Characterization data for selected Florida soils. Soil Science Research Report No. 89-1. Gainesville, Fla.: Institute of Food and Agricultural Sciences.

Carter, L. J., D. Lewis, L. Crockett, and J. Vega. 1989. *Soil Survey of Highlands County, Florida.* Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service.

Clark, J. 1994. Evaluation of nitrogen movement beneath a leatherleaf fernery. M.S. thesis. Gainesville, Fla.: University of Florida.

Clothier, B. E., T. J. Sauer, and S. R. Green. 1988. The movement of ammonium nitrate into unsaturated soil during unsteady absorption. *Soil Sci. Soc. Am. J.* 52: 340-45.

Freyberg, D. L. 1986. A natural gradient experiment on solute transport in a sand aquifer. 2. Spatial moments and the advection and dispersion of nonreactive tracers. *Water Resour. Res.* 22(13): 2031-2046.

Garabedian, S. P., D. R. LeBlanc, L. W. Gelhar, and M. A. Celia. 1991. Large scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 2. Analysis of spatial moments for a nonreactive tracer. *Water Resour. Res.* 27(5): 911-924.

Graham, W. D., and A. K. Alva. 1997. Ridge Citrus Water Quality Project, Annual Progress Report (1996-1997). Submitted to the Florida Department of Agriculture and Consumer Services Division of Agricultural Environmental Management, Tallahassee, Fla.

Hoffman, M., and J. Johnson. 1999. A method for assessing generalized nitrogen leaching estimates for agricultural land. *Environ. Monitor. & Assess.* 4(1): 35-44.

Hutson, J. L., and R. J. Wagenet. 1991. Simulating nitrogen dynamics in soils using a deterministic model. *Soil Use & Manage.* 7(2): 74-78.

Hutson, J. L., and R. J. Wagenet. 1992. *Leaching Estimation and Chemistry Model: A Process-Based Model of Water and Solute Movement, Transformations, Plant Uptake and Chemical Reactions in the Unsaturated Zone*. Ithaca, N.Y.: Water Resources Institute, Cornell University.

Jabro, J. D., J. D. Toth, Z. Dou, R. H. Fox, and D. O. Fritton. 1995. Evaluation of nitrogen version of LEACHM for predicting nitrate leaching. *Soil Sci.* 160(3): 209-217.

Johnsson, H., L. Bergstrom, P. E. Jansson, and K. Paustian. 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agric. Ecosys. & Environ.* 18(4): 333-356.

Jones, J. W., L. H. Allen, S. F. Shih, J. S. Rogers, L. C. Hammond, A. G. Smajstrla, and J. D. Martsolf. 1984. Estimated and measured evapotranspiration for Florida climate, crops and soils. Florida Agricultural Experiment Station Technical Bulletin 840. Gainesville, Fla.: University of Florida.

Lamb, S. T. 1996. Monitoring and modeling the impacts of alternative nutrient and water management practices on groundwater quality in the Central Florida Ridge. M.S. thesis. Gainesville, Fla.: University of Florida.

Lamb, S. T., W. D. Graham, C. B. Harrison, and A. Alva. 1999. Impact of alternative citrus management practices on groundwater nitrate in the Central Florida Ridge: Part 1. Field Investigation. *Transactions of the ASAE* 42(6): 1653-1668.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. *Transactions of the ASAE* 30(5): 1403-1418.

McNamee, J. M. 1955. Root distribution of Hamlin orange on three major rootstocks in Arredondo fine sand. M.S. thesis. Gainesville, Fla.: University of Florida.

Nemec, S., H. C. Burnett, and M. Patterson. 1982. Root distribution and loss on blighted and healthy citrus trees. *Proc. Soil & Crop Sci. Soc. Florida* 41: 91-96.

Pennell, K. D., A. G. Hornsby, R. E. Jessup, and P. S. C. Rao. 1990. Evaluation of five simulation models for predicting aldicarb and bromide behavior under field conditions. *Water Resour. Res.* 26(11): 2679-2693.

Richardson, C. W., and D. A. Wright. 1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture, Agricultural Research Service, ARS-8. Washington, D.C.: GPO.

Shaffer, M. J. 1985. Simulation model for soil erosion-productivity relationships. *J. Environ. Qual.* 14(1): 144-150.

Shaffer, M. J., A. D. Halverson, and F. J. Pierce. 1991. Nitrate leaching an economic analysis package (NLEAP): Model description and application. In R. F. Follett, D. R. Keeney, and R. M. Cruse, eds. *Managing Nitrogen for Groundwater Quality and Farm Profitability*, 285-322. Madison, Wis.: Soil Science Society of America.

Stevenson, F. J. 1982. Origin and distribution of nitrogen in soil. In *Nitrogen in Agricultural Soils*, ed. F. J. Stevenson, 1-42. Madison, Wis.: ASA/CSSA/SSSA.

Wagenet, R. J., and J. L. Hutson. 1986. Predicting the fate of nonvolatile pesticides in the unsaturated zone, *J. Environ. Qual.* 15(4): 315-322.