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EVALUATION OF PERCOLATION AND NITROGEN LEACHING FROM A SWEET PEPPER CROP GROWN ON AN OXISOL SOIL IN NORTHWEST PUERTO RICO

Eric Harmsen, Joel Colón Trinidad, Carmen Lis Arcelay, and Dionel Cádiz Rodríguez. Department of Agricultural and Biosystems Engineering, University of Puerto Rico, Mayagüez, PR 00681.

ABSTRACT: A study was conducted to evaluate the influence of agricultural lime ($CaCO_3$) on the movement and uptake of inorganic nitrogen for a sweet pepper crop (*Capsicum annuum*) grown on an Oxisol soil (Coto clay) in northwest Puerto Rico. The Coto clay soil, which contains the 1:1 kaolinite mineral, has a low pH (4 to 4.5). The 1:1 type clays are known to possess a net positive charge at low pH, resulting in the adsorption of negatively charged ions such as nitrate. From an environmental standpoint this characteristic of the 1:1 clay is favorable, since nitrate leaching, a major cause of groundwater pollution in many areas, is reduced relative to soils with net negative charge. However, agricultural plants, such as sweet peppers, favor a higher soil pH (approximately 6.5), which can be obtained by the application of agricultural lime. This application, however, may have the negative effect of increasing the potential for nitrate leaching, as the net charge in the soil particles becomes positive with increasing pH. This paper describes the results of a nitrogen leaching analysis for two sweet pepper crop seasons. The analysis was based on multiplying the daily percolation flux through the soil profile by the measured concentration of nitrogen below the root zone. Irrigations were scheduled using the pan evaporation method for estimating crop water requirements. No significant difference in nitrogen leaching was observed for the lime and no-lime treatments. This finding was attributed to the low nitrate retention capacity of this soil, even a low pH. The average percentages of nitrogen leached during the 1st and 2nd season, relative to the amounts applied, were 26% and 15%, respectively. Leaching events were associated with large rainstorms, suggesting that leaching of N would have occurred regardless of the irrigation scheduling method used.

INTRODUCTION

Sweet pepper crops were planted at the UPR Experiment Station at Isabela in northwest PR (Figure 1) March 2002 and January 2003. Harmsen et al. (2002) provided a detailed description of the experimental layout of the field site. The soil at the Isabela Experiment Station belongs to the Coto series. It is a very fine kaolinitic, isohyperthermic Typic Eutrustox. These are very deep, well drained, moderately permeable soils formed in sediments weathered from limestone. The available water capacity is moderate, and the reaction is strongly acidic throughout the whole profile. Consistence is slightly sticky and slightly plastic in the Oxic horizons. A strong, stable granular structure provides these soils with a very rapid drainage, despite their high clay content (Keng et al., 1981). Average values of hydraulic properties published for the Coto clay soil near the study area are as follows: air dry bulk density 1.39 g/cm^3; porosity 48%; field capacity 30%; wilting point 23%; available water holding capacity (AWHC) 9% (Soil Conservation Service, 1967). The AWHC of this soil is low for clay. Typical values for clay are 15 to 20% (Keller and Bliesner, 1990). A small value of AWHC means that there is a greater potential for leaching since the soil moisture content associated with the field capacity is more easily exceeded.

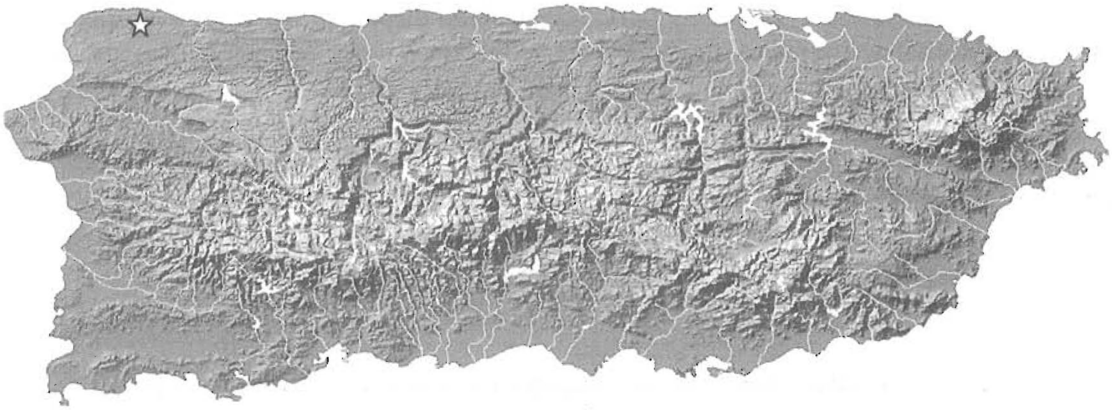

Figure 1. Location of field site at Isabela, PR (☆).

The experimental site of 0.1 ha was divided into four blocks, each block divided into four plots, one for each treatment, for a total of sixteen plots. The plots measured 67 m^2. The treatments included two lime levels (lime and no lime) and two fertigation frequencies (F1 weekly, and F2 bi-weekly). Each plot had four beds covered with plastic (silver side exposed) with two rows of sweet pepper plants per bed. The transplanted sweet peppers were grown in rows 91 cm apart, plants 30 cm apart along rows, with beds 1.83 meter on center. This gave a plant population of approximately 37,000 plants per hectare. There was an initial granular application of triple super-phosphate of 224 kg/ha and 80 kg/ha of 10-10-10 fertilizer. Peppers were planted from 11 March through 13 March 2002 and from 27 January through 31 January 2003. KNO_3 and urea were injected through the drip irrigation system throughout the season at different frequencies (F1 weekly or F2 bi-weekly). The total nitrogen applied during the season was 225 kg/ha. After transplanting, soil samples were taken bi-weekly at 20-cm increments, down to an 80-cm depth from each plot to be analyzed for moisture content and nitrogen concentration. Each date when soil samples were collected, whole plants were harvested for growth data. Periodic pesticide applications were made to control weeds and insects affecting crop growth.

Water Balance

A water balance approach was used in this study to estimate percolation past the root zone. The water balance is shown in the following equation:

$$\text{PERC} = R \cdot RO + IRR - ET_c + \_S \tag{1}$$

where PERC is percolation below the root zone, R is rainfall, IRR is irrigation, RO is surface runoff, ET_c is crop evapotranspiration, and $\_S = S_1 - S_2$, where S_1 and S_2 are the water stored in the soil profile at times 1 and 2, respectively. The units of each term in equation 1 are in mm of water per day.

Rainfall (R) was obtained from a tipping bucket-type rain gauge located on the Experiment Station property. The rain gauge was located within a weather station complex located approximately 0.4 km from the study area. The weather station consisted of a 10-meter (high wind resistant) tower with lighting protection, data logger and radio communication system, and sensors to measure the following parameters: wind direction and speed, temperature, relative humidity, barometric pressure, cumulative rainfall, and solar radiation (Zapata et al., 2001).

Irrigation (IRR) was applied through a drip irrigation system. The inline-type emitters produced a flow of 1.9 liters per hour per emitter at a design pressure of 10 pounds per square inch (psi). Emitters were spaced every 30 cm. Irrigations (IRR) were scheduled on the basis of estimated evapotranspiration rate as determined from the following equation:

$$IRR = ET_{pan} = (K_c\, K_p\, E_{pan}) \qquad (2)$$

where ET_{pan} is the pan evaporation-derived evapotranspiration, K_c is the evapotranspiration crop coefficient for sweet peppers (FAO Paper No. 56, Allen et al., 1998), which varied daily; K_p is the average annual value of the pan coefficient equal to 0.78 for Isabela, PR (Goyal and González, 1989). A cumulative water meter was used to control the gallons of irrigation water applied.

The evapotranspiration term in equation 1 was estimated from the following equation:

$$ET_c = K_c\, ET_o \qquad (3)$$

where K_c is the crop coefficient (dimensionless) and ET_o (mm/day) is the reference evapotranspiration obtained using the Penman-Monteith equation, given below (Allen et al., 1998):

$$ET_O = \frac{0.408\, \Delta\, (R_n - G) + \gamma \left(\frac{900}{T + 273} \right) u_2\, (e_s - e_a)}{\Delta + \gamma\, (1 + 0.34\, u_2)} \qquad (4)$$

where Δ is the slope of the vapor pressure curve (kPa $^oC^{-1}$); R_n is net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}); γ is the psychrometric constant (kPa^{-1}); T is mean daily air temperature at 2-m height (^oC); u_2 is wind speed at 2-m height; e_s is the saturated vapor pressure (kPa^{-1}); and e_a is the actual vapor pressure (kPa^{-1}). Equation 4 applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1} and an albedo of 0.23.

Data required by equation 4 were obtained from the weather station located near the study area. Wind speeds obtained from the 10 m high tower were adjusted to the 2 m wind speed, required by the Penman-Monteith method, by means of an exponential relationship. Initial values of the crop coefficient were obtained from the literature for sweet pepper for the initial, mature and end crop stages (FAO Paper No. 56). Adjustments of K_c were made during the calibration of equation 1 as described later in this section. ET_o was estimated on a daily basis using a spreadsheet program.

The values of S in equations 1 and 2 were obtained from the following general formula: S = _v*Z, where _v is the vertically averaged volumetric soil moisture content over the depth Z, obtained by multiplying the moisture content, mass-basis (_m), by the soil bulk density and dividing by the density of water. The soil bulk densities were obtained from undisturbed soil cores.

Between sampling dates when measured values of $\_{}_{v}$ were not available, daily values were estimated by using equation 1 along with information about the moisture holding capacity of the soil. In this method, if the water added to the profile by rainfall or irrigation exceeds the soil moisture holding capacity (or field capacity), then the excess water was assumed to be equal to PERC and the moisture content was set equal to the field capacity on that day. This approach has previously been used for irrigation scheduling (Shayya and Bralts, 1994), waste landfill leachate estimation (Fenn et al., 1975) and estimation of aquifer recharge rates (Thornthwaite and Mather, 1955; Papadopulos & Associates, Inc., and MathSoft, Inc. 1994). In this study, the effective field capacity of the soil was determined in situ by saturating the soil and obtaining the soil moisture content within 48 hours.

Calibration of the water balance equation was accomplished by adjusting the ratio of runoff to rainfall (RO/R) within reasonable limits, until the measured and estimated soil moisture content were in reasonable agreement. 1 – RO/R represents the fraction of rainfall that infiltrates into the soil bed. This contribution of water can occur in several ways for the plastic covered bed-type system used in this study. Rainfall may enter directly through the holes in the plastic made for the plants. Rainfall that runs off of the plastic into the furrow or that falls directly into the furrow may also be absorbed into the beds. Under flood conditions, which occurred on several occasions during the two crop seasons, water could have entered the beds under a positive water pressure. For non-flooding rainfall events, soil water may move from the furrows into the beds by means of unsaturated flow, which is controlled by the pore water pressure gradient between the furrow and the bed.

Nitrogen Leaching

Nitrogen leaching (nitrate and ammonium) was estimated by multiplying the daily value of PERC by the concentration of nitrogen within the 60-to 80-cm depth of soil. This vertical interval was considered to be below the root zone, since plant roots were not observed within this interval any time throughout the two seasons. The following equation was used to estimate nitrate and ammonium leaching, respectively:

$$L_{NO3} = 0.01\ \_{}_{b}\ NO_3\ PERC / \_{}_{vol} \qquad (5a)$$

$$L_{NH4} = 0.01\ \_{}_{b}\ NH_4\ PERC / \_{}_{vol} \qquad (5b)$$

where L_{NO3} and L_{NH4} are the kg of nitrate and ammonium leached below the root zone per hectare; NO_3 and NH_4 are the nitrate and ammonium soil concentration in mg/kg in the 60-to 80-cm depth interval; PERC is the percolation rate in mm; and $\_{}_{b}$ and $\_{}_{vol}$ are the bulk density (gm/cm^3) and volumetric moisture content (cm^3/cm^3) in the 60-to 80-cm depth interval. Equations 5a and 5b were used on a daily basis. Each measured value of soil concentration used in equation 5a and 5b was based on the average of four replications. Values of NO_3 and NH_4 between sampling dates were linearly interpolated.

RESULTS AND DISCUSSION

The Coto clay soil was analyzed for various physical and hydraulic properties (Table 1). The soil has a relatively high sand content and high hydraulic conductivity in the 0- to 20-cm interval, which accounts for its high water intake capacity. We observed on several occasions the rapid infiltration of water after large rainfall events. In fact, the value of hydraulic conductivity for the 0- to 20-cm interval is similar to that of sand, which averages 900 cm/day (Freeze and Cherry, 1979). Bulk density, porosity, hydraulic conductivity, moisture content at 0.33 and 15 bars pressure, and AWHC were obtained from undisturbed cores in the laboratory.

Measured soil pH soil was between 4 and 5. Laboratory incubation tests were performed to determine the proper amount of lime needed to be applied to the soil to increase the pH to around 6.5 in the limed treatments; this amount was 7.4 tons lime/ha. The first year the pH did not respond as expected in the limed plots; therefore, this may have contributed to there being no significant difference observed in the estimated nitrate losses by leaching between the lime and no-lime treatments. The second year the amount of lime applied to the limed treatments was doubled (14.8 tons lime/ha) and pH levels rose as expected.

Figure 2 shows a comparison of the evapotranspiration derived from pan and Penman-Monteith methods during Year 2. ET_{pan} was observed to have higher variability than ET_c. For reference, Figure 2 also shows the ET_c based on long-term average climate data for Isabela, PR. The seasonal ET for the methods of pan, Penman-Monteith and Penman-Monteith based on long-term data were 447 mm, 402 mm, and 511 mm, respectively.

Table 1. Physical and hydraulic properties of Coto clay in the 0-20, 20-40, 40-60, and 60-80 cm depth intervals.

Depth (cm)	% Sand[1]	% Silt[1]	% Clay[1]	Soil Classification	Bulk Density	Porosity
0-20	35.10	19.35	45.55	silty clay	1.36	0.49
20-40	28.72	1.85	69.43	clay	1.36	0.49
40-60	22.50	5.00	72.50	clay	1.31	0.51
60-80	20.00	5.80	74.20	clay	1.29	0.51

Depth (cm)	Hydraulic Conductivity (cm/day)	In-Situ Field Capacity Year 1 Site	In-Situ Field Capacity Year 2 Site	Moisture Content at 0.33 bar Pressure	Moisture Content at 15 bar Pressure	Available Water Holding Capacity (AWHC)
0-20	1210.06	0.33	0.44	0.44	0.39	0.05
20-40	316.99	0.33	0.37	0.37	0.27	0.10
40-60	70.10	0.37	0.36	0.36	0.31	0.05
60-80	12.19	0.37	0.38	0.38	0.3	0.08

[1] Soil texture data for the 40 to 60-cm and 60 to 80-cm depths were obtained from Soil Conservation Service (1967). All other data were measured during the project.

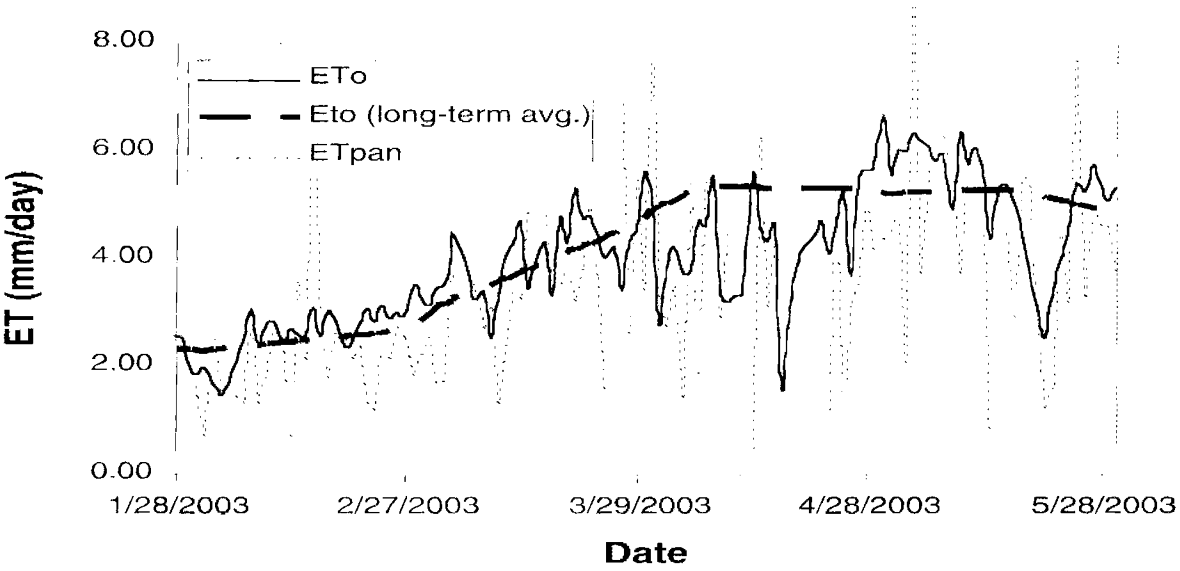

Figure 2. Daily values of evapotranspiration for a sweet pepper crop between 27 January to 12 June 2003, at Isabela, PR. Evapotranspiration was derived from the pan evaporation and Penman-Monteith methods.

The water balance equation (Eqn. 5) was calibrated for the site conditions. Figure 3 shows the simulated and measured average soil moisture content for Year 1 and Year 2. The measured moisture contents shown in Figure 3 represent the vertically averaged moisture content over all sixteen plots. The minimum and maximum measured soil moisture content is also shown in Figure 3. Vertically averaged values of the in situ-measured field capacity equal to 0.39 and 0.35 were used in the Year 1 and Year 2 analyses, respectively (averages from Table 1). It was necessary to use a value of RO/R = 0.25 reasonable agreement between the estimated and measured soil moisture content. During Year 1, the beginning of the season was quite wet. On 6 April 2002, a 176-mm rainfall occurred, which caused severe flooding of the study area. During Year 2, a rainy period occurred from 5 April to 18 April with flooding observed in the field plots. The largest rainfall of the season occurred on April 10, 2003 equal to 97 mm.

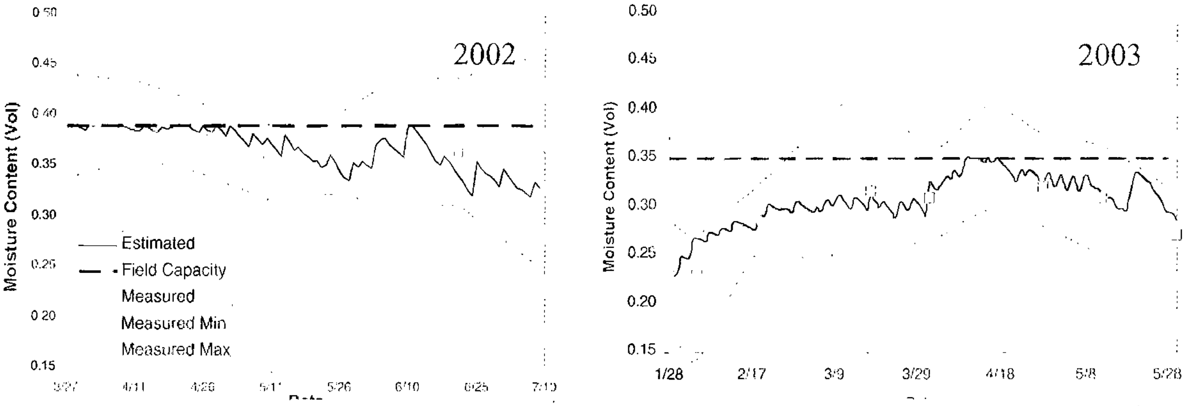

Figure 3. Estimated and measured volumetric soil moisture content between 27 March and 9 July 2002, and 27 January and 12 June 2003.

According to the procedure described above, percolation occurred on those days when the estimated moisture content exceeded the field capacity moisture content (0.39 for Year 1 and 0.35 during Year 2). On those days, the water in excess of the field capacity was assigned to PERC and the moisture content set equal to the field capacity. This can be seen in Figure 3 for those days in which the moisture content curve touched the dashed horizontal line associated with the field capacity moisture content. Figure 4 shows the estimated percolation during Year 1 and Year 2. During the 6 April 2002 rainfall event of 175 mm, 43 mm was converted to percolation. During the 10 April 2003 rainfall event of 97 mm, 31 mm was converted to percolation. Recall that only 25 percent of the rainfall was allowed to infiltrate, which was equal to 44 mm on 6 April 2002, and 24 mm on 10 April 2003. In the latter case 18 mm of irrigation was also applied, which together (24 mm + 18 mm) equaled 42 mm. In this case 31 mm was lost to percolation and 11 mm was stored in the root zone. Table 2 shows the Year 1 and Year 2 seasonal components of the water balance.

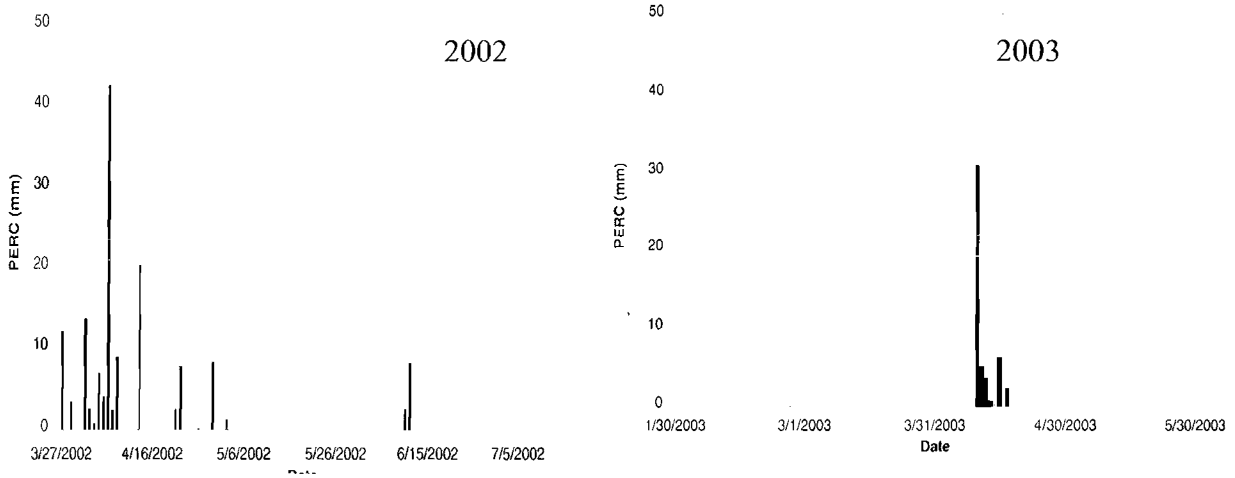

Figure 4. Estimated percolation past the root zone during the Year 1 and Year 2 seasons.

Table 2. Components of the seasonal water balance for Years 1 and 2.

	Year 1 (2002)	Year 2 (2003)
R-RO	175	136
IRR	350	411
ETc	416	441
_S	50	-52
PERC	159	54

Table 3 compares the Year 1 and Year 2 results of the nitrogen leaching analysis. The leached nitrate and ammonium estimates were obtained from equations 5a and 5b, respectively. Figure 5 shows the nitrate concentrations in the 60- to 80-cm depth interval during the Year 1 season. During Year 1 the range of estimated nitrogen leached was between 36 and 67 kg/ha. During Year 2, the range of estimated nitrogen leached was between 27 and 36 kg/ha. Interestingly, the amount of nitrate lost (average of all treatments) on 6 April 2002, and 10 April 2003, was 19.6 kg/ha and 20.1 kg/ha, respectively. For years 1 and 2 this represented 34% and 60% of the total N lost by leaching during the two seasons, respectively. Figure 6 shows the estimated percentage of nitrogen (i.e., nitrate plus ammonium) leached relative to N applied (225 kg/ha) during the Year 1 and Year 2 seasons for the four experimental treatments.

Table 3. Nitrate, ammonium and nitrate plus ammonium (Total) leached during Year 1 and 2 for the four experimental treatments.

		2002				2003			
	Units	LF1	LF2	NLF1	NLF2	LF1	LF2	NLF1	NLF2
NO3	kg/ha	36	50	47	42	34	32	34	24
NH4	kg/ha	10	13	21	11	2	3	2	3
Total	kg/ha	46	63	67	54	36	35	36	27
Total	%	21	28	30	24	16	16	16	12

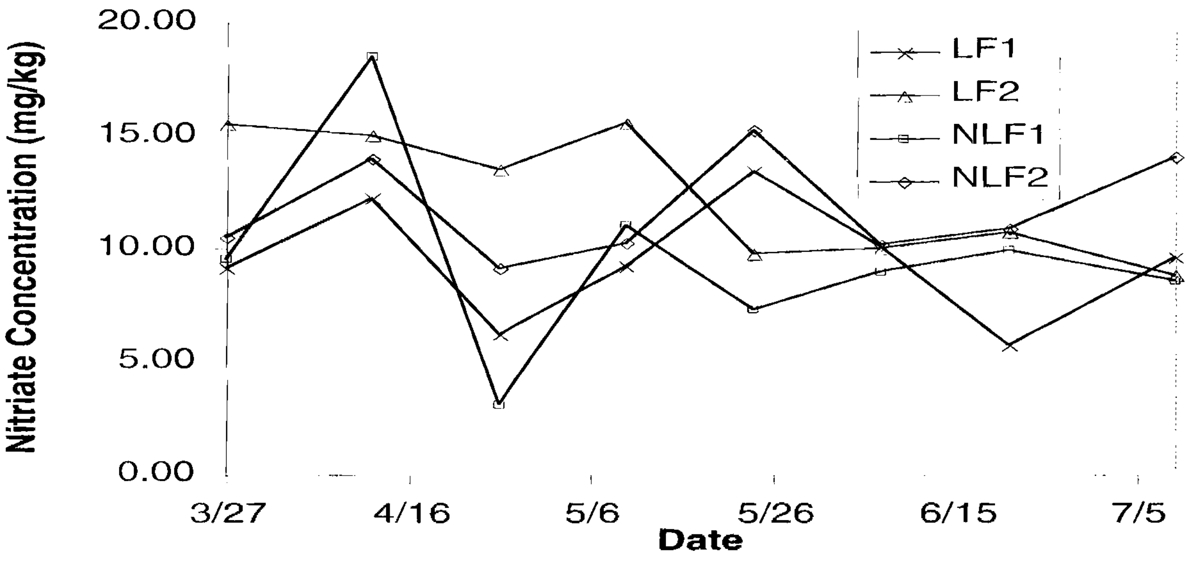

Figure 5. Year 1, Soil nitrate concentrations in the 60- to 80-cm depth interval. Values between the sampling dates were obtained by linear interpolation.

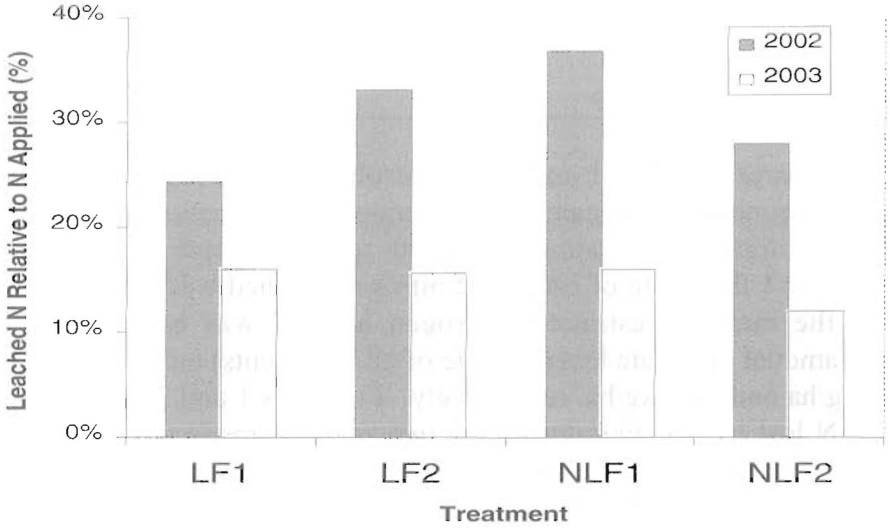

Figure 5. Estimated nitrogen leached during the Year 2 season. LF1 is the Lime-Fertigation 1 treatment, LF2 is the Lime-Fertigation 2 treatment, NLF1 is the No-Lime-Fertigation 1 treatment, NFL2 is the No-Lime-Fertigation 2 treatment.

The smallest amount of nitrogen leaching occurred in the LF1 treatment in 2002 and the NLF2 treatment during the second year. There is no clear difference between either the lime or fertigation treatments. Ammonium leaching was typically much lower than nitrate leaching (Table 3) except in the case of treatment NLF1 in 2002, in which 21 kg/ha ammonium was leached as compared to 47 kg/ha nitrate. The fact that no clear difference was observed between nitrogen leaching for the two lime treatments is consistent with laboratory studies currently being conducted on the Coto clay soil at the University of Puerto Rico Mayagüez Campus, which indicates that the pH at which this soil will possess a net positive charge (< 4) is below the native pH measured in the field (around 4.3).

METHOD LIMITATIONS

There are several sources of uncertainty in the estimates of nitrogen leaching, which include:

- Between sampling dates, soil nitrogen concentrations were derived by linear interpolation. Nitrogen concentrations were measured every two weeks. In some cases, the average nitrate concentration was observed to change as much as 15 mg/kg in the 60- to 80-cm depth interval. The estimated nitrogen leaching would be in error if these concentrations did not change linearly between sampling dates.
- The method of estimating percolation in this study does not account for the leaching that can potentially occur by unsaturated flow. All leaching was assumed to occur when the moisture content of the soil exceeded the soil field capacity. However, significant downward gradients can exist which would result in unsaturated flow. Although not presented in this paper, continuous soil pressure data obtained from vertically spaced tensiometers indicated downward hydraulic gradients throughout most of the season.

SUMMARY AND CONCLUSIONS

This paper described the results of a nitrogen leaching analysis for two sweet pepper crop seasons. The study was conducted on an Oxisol soil in NW Puerto Rico. The analysis was based on multiplying the daily percolation flux through the soil profile by the measured concentration of nitrogen below the root zone. Irrigations were scheduled using the pan evaporation method for estimating crop water requirements. Estimated percolation in 2002 was three times greater than that which occurred in 2003, whereas the nitrogen leached during 2002 was only slightly greater than two times the nitrogen leached during 2003.

No clear difference in nitrogen leaching was observed for the lime and no-lime treatments. This result is consistent with on-going studies of the Coto clay, which indicate that this soil has little to no capacity to retain nitrate. The average percent of nitrogen (nitrate plus ammonium) leached during the 1st and 2nd season, relative to the amounts applied, were 26% and 15%, respectively. Leaching events were associated with large rainstorms, suggesting that leaching of N would have occurred regardless of the irrigation scheduling method used. During the first and second seasons, respectively, 34% and 60% of the total N lost by leaching occurred during a single day (6 April in 2002, and 10 April 2003) when flooding was observed in the study areas.

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