MONITORING AND MODELING THE FATE AND TRANSPORT OF NITRATE IN THE VADOSE ZONE BENEATH A SUWANNEEE RIVER BASIN VEGETABLE FARM

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING

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Chairperson: Dr Wendy Graham
Major Department: Agricultural and Biological Engineering

The Suwannee River basin has received much attention in recent years due to increased nitrogen levels in the groundwater-fed rivers of the basin that could seriously affect the welfare of this ecosystem. Nitrogen levels have increased from 0.1mg/l NO_3-N to more than 5 mg/L NO_3-N in many springs in the Suwannee Basin over the past 40 years. Nitrate concentrations in the Suwannee River itself have been increasing at the rate of .02 mg/L per year over the past 20 years. Suwannee River nitrate loads increased from 2300 kg/day to 6000 kg/day over a 33 mile stretch of the river between Dowling Park and Branford, Florida. Within this stretch of river, 89% of the nitrate loading appeared to come from the lower two-thirds, where agriculture is the dominant land use.

The objective of this research was to monitor and model the impacts of alternative nutrient and water management practices on soil water quality, groundwater quality and crop yield at a commercial vegetable farm in the Suwannee River Basin. Groundwater monitoring wells, suction lysimeters, soil cores and TDR probes were used to monitor water and nitrogen transport at the site. Periodic plant biomass sampling was conducted to determine nitrogen uptake by the plants and to estimate crop yield. Field data show that two-thirds of the nitrogen applied to the spring 2001 potato crop leached to groundwater due to excessive irrigation and poor nitrogen uptake efficiency by the potatoes. The DSSAT35-Potato Crop model and the LEACHM vadose-zone model were calibrated for the spring 2001 potato crop and used to predict nitrogen leaching and crop yield for alternative management practices.

Simulation results show that by reducing the duration of irrigation, reducing the fertilizer application rate, and improving the timing of fertilizer applications, nitrogen leaching can be reduced by approximately 50% while maintaining acceptable crop yields. Results of this project will ultimately be used to develop best management practices (BMPs) and total maximimum daily loads (TMDLs) for vegetable growing regions in the Suwannee River Basin.

CHAPTER 1
INTRODUCTION

Background

The Suwannee River basin has received much attention in recent years due to increased nitrogen levels in the groundwater-fed rivers of the basin that could seriously affect the welfare of this ecosystem. Temporally, nitrogen levels have been increasing steadily in the basin. Katz (2000) found nitrogen levels increased from 0.1 to more than 5 mg/L in many springs in the Suwannee Basin over the past 40 years. Another study found nitrate concentrations in the Suwannee River increasing at the rate of .02 mg/L each year over the past 20 years (Pitman et al, 1997). Spatially, the Suwannee River nitrate loads have increased from 2300 kg/day to 6000 kg/day over a 33 mile stretch of the river between Dowling Park, to Branford, Florida (see Fig 1-1). Within this stretch of river, 89% of the nitrate loading appeared to come from the lower two-thirds, where agriculture is the dominant land use (Pitman et al, 1997). The Suwannee River is used for recreation, fishing, potable water, and provides habitat for a rich and diverse ecosystem. Only through understanding and quantifying the processes that control water and nitrogen movement within the watershed can a solution to this water quality problem be found.

This research is part of a larger Florida Department of Environmental Protection (FDEP)/ Florida Department of Agriculture and Consumer Services (FDACS) funded project to develop Best Management Practices (BMP) in the

Fig 1-1. Suwannee county map (modified from Funk & Wagnalls, 1981).

Suwannee Basin to reduce nutrient loadings to ground water and to evaluate their water quality effectiveness (Graetz et al, 1999). The objective of this research is to monitor and model the nitrogen and water movement through the vadose zone under one 56.7 ha center pivot at a 2020 ha vegetable farm just west of O'Brien, Florida (see Fig 1-1). This farm lies just a few miles from the Suwannee River in the upstream direction of groundwater flow. The sandy soils on this farm are extremely susceptible to leaching nitrogen through the soil and then into the Floridan Aquifer.

Monitoring wells, soil samples, plant samples, and TDR probes were used to obtain on-site nitrogen, plant and soil moisture information over time to track nitrogen movement and validate mathematical models. Soil analysis, crop management and weather information provided inputs necessary for existing vadose zone and crop models. The DSSAT35-Potato crop model and the LEACHM vadose zone model were used to produce an estimate of the load and concentration of nitrogen and the quantity of water leaching through the vadose zone to the Floridan Aquifer. The DSSAT model was also used to predict crop growth, nitrogen uptake and crop yield. These models were calibrated for the spring 2001 potato crop and used to predict nitrogen leaching and crop yield for alternative management practice scenarios to aid in the development of the BMP.

Literature Review

Nitrogen Cycle

The nitrogen cycle is a complex system due to the many oxidations states of N found naturally, and the dynamic nature of the element between its many different forms. Inorganic N can exist in seven oxidation states, however in aquatic environments only a few of these oxidation states dominate: NH_3 (-III), N_2 (0), N_2O_3 (III) and N_2O_5 (V). N_2O_3 and N_2O_5 are acid anhydrides of nitrous and nitric acid and when combined with water produce NO_2^{-1} and NO_3^{-2} ions respectively (Sawyer et al, 1994). Figure 1-2 shows a diagram of the N cycle. Nitrogen is typically introduced into soils by the action of electrical discharge

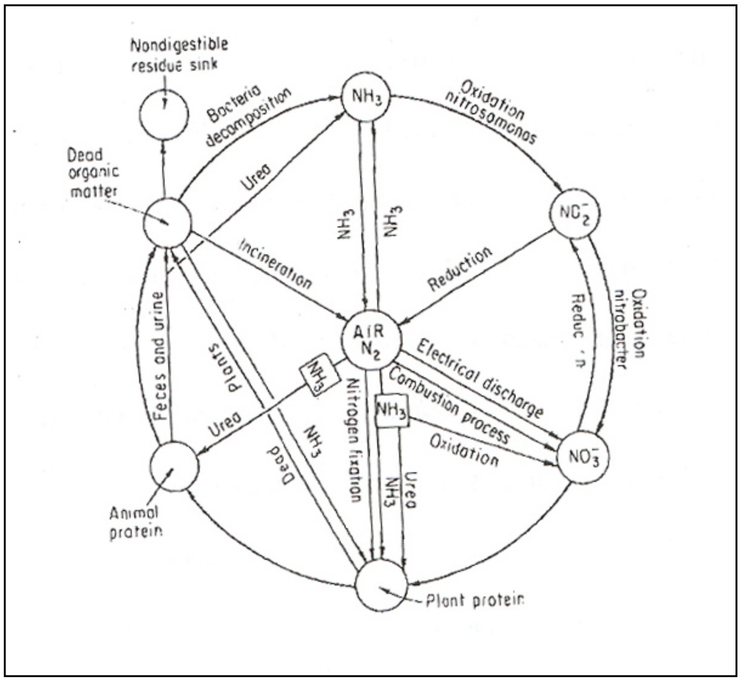


Fig 1-2. Nitrogen cycle (Sawyer et al, 1994).

(lightning), which converts N_2 gas to N_2O_5, or through N fixing plants and bacteria. Other sources of N include dead plant and animal matter, urea and feces.

Urea is hydrolyzed by the enzyme urease into ammonium carbonate.

$$(NH_2)_2CO + H_2O \rightarrow (NH_4)_2CO_3 \tag{1-1}$$

Feces and dead plant and animal matter have N bound up in unassimilated proteins (organic N) that can be converted to ammonia (NH_3) by heterotrophic bacteria.

$$\text{Protein (organic N)} + \text{bacteria} \rightarrow NH_3 \tag{1-2}$$

Some N remains in its organic form and remains as sediments in water (detritus) or in soil (humus). Once converted to ammonia, the N can either be used directly by the plants or oxidized by autotrophic nitrifying bacteria known as Nitrosomonas, into nitrites. Nitrites are than further oxidized by the Nitrobacter group into nitrates.

$$2NH_3 + 3O_2 \rightarrow 2NO_2\text{-} + 2H^+ + 2H_20 \quad (1\text{-}3)$$

$$2NO_2\text{-} + O_2 \rightarrow 2NO_3^- \quad (1\text{-}4)$$

Ammonium's adsorption to soil makes it less susceptible to leaching (Paramasivan et al, 2000) and its rapid conversion to nitrates makes it a suitable fertilizer. Bundy et al. (1986), found significantly higher yields in potato crops using $(NH_4)_2SO_4$ compared to $(NH_4)NO_3$ and attributed it to slower leaching of the NH_4^-. Nitrates are easily dissolved in water and will percolate through the soil and into groundwater. Under anaerobic conditions nitrates and nitrites can be converted back into N_2 gas by bacteria and released into the atmosphere through a process called denitrification (Sawyer, 1994). Some common denitrifying bacteria include species such as Pseudomonas, Alkaligenes and Bacillus (Edinburgh, 2002).

Potato Management

The potato (solanum tubersum) is an arable crop commonly grown in Florida. Unfortunately, sandy soils combined with the potato's inefficient N use makes N leaching from potato production a serious threat to Florida's groundwater. Potatoes are commonly planted in January to February in north central Florida and average potato yield in Florida is currently around 24.7 Mg/ha (Hochmuth et al, 2000). Fertilization rates and irrigation can vary significantly by cultivar and geographic location. Currently the Institute of Food and Agricultural Services (IFAS) recommends fertilization rates of between 196 (Hochmuth and Cordasco, 2000) to 224 kg N/ha (Hochmuth et al, 2000) with two thirds of N applied at planting and the remainder between 30 and 40 days after planting. A survey of fertilization practices by Florida potato growers performed in the 1980's showed average N fertilization rates of about 303 kg/ha (Hochmuth and Cordasco, 2000).

Nitrogen is an important nutrient for potato plants and is typically the most deficient nutrient found in soils (especially sandy soils). Therefore it is often necessary to add large amounts of N as fertilizer (Unlu et al, 1999; Belanger et al, 2000). Since potatoes are very inefficient users of N (Hochmuth et al, 2000; Neetson, 1990), these crops are extremely susceptible to N leaching and subsequent pollution of groundwater. Neetson (1990) found at optimum application rates only about 50% of the fertilizer N is used by the crop and Unlu et al. (1999) found only a 20% efficiency of N use. While fertilizer recommendations vary with geographic location and cultivar (Arsenault, 2001; Veerhagen, 1997; Neetson, 1990), results of potato response to applied N are similar, and recommended fertilizer rates ranged from 200 kg/ha to about 300 kg/ha. However, recommended fertilizer rates tend to be greater for sandy soils compared to clay or loamy soils (Neetson, 1990, Verhagen 1997).

Figures 1-3 shows results for Florida potato experiments performed between 1955-1967 and Figure 1-4 shows results for Florida potato experiments performed between 1962-1998. These figures show that yield generally increases with applications up to approximately 200-225 kg N/ha and then levels off or declines. Experiments conducted in Florida during 1983 and 1984 found no yield advantage and similar N uptake between application rates of 168 and 224 kg/ha of N (Yuan, 1985). Verhagen (1997) reported tuber yield and N leaching for experiments performed at 65 different locations in the Netherlands during the 1995 growing season. Seven different fertilizer rates ranging from 0 to 250 kg N/ha were used and similar yields resulted for the 250, 200 and 175 kg/ha N fertilization rates. Yields dropped off somewhat at the 150 kg N/ha rate and then decreased dramatically for all rates below 150 kg N/ha. Belanger et al. (2000) performed experiments for 12 sites in New Brunswick, Canada, and found optimum fertilization rates ranged from 158 – 233 kg N/ha. Belanger also found that excessive N applied to potatoes can lead to poor tuber quality, delayed crop maturity and excessive N leaching.

Unlu et al. (1999) performed experiments on sandy soils in Turkey using 6 different fertilizer rates of 0, 200, 400, 600, 800 and 1000 kg N/ha. In this experiment fertilizer efficiency produced optimum yields at the 600 kg N/ha rate but only 20% of the N was taken up by the plants. Unlu et al. (1999) suggested that rates could easily be decreased to 400 kg N/ha without significantly affecting yield. While these rates seem at first much higher than optimum rates cited earlier, one must take into account that N in the Unlu et al. study was applied through irrigation sprinklers rather than banded into the rows. This means that the

N per hectare was applied over the entire field (in the rows and in the furrows) effectively cutting in half the amount of N actually reaching the plants in the rows.

Other research suggests that in developing best management practices (BMPs) to determine optimum fertilization rates one must take into account residual N present in the soil at the time of planting (Neetson, 1990; Meyer and Marcum, 1998; Van DerPaauw, 1962). Van Der Paauw (1962) found weak a response of potatoes to N following dry winters, which he attributed to relatively large amounts of mineral N left in the soil. Neetson (1990) developed the N_{min} method to determine fertilization rate recommendations for arable crops based on existing N levels in soils. The N_{min} method was developed in the Netherlands and has since been adopted by Germany, Belgium, Denmark and Sweden. The N_{min} method is based on the amount of soil mineral N in early spring using the equation:

$$N_{rec} = A - B \times N_{min} \qquad (1\text{-}5)$$

where N_{rec} is the recommended N fertilization rate in kg/ha, N_{min} is the amount of soil mineral N (kg/ha) at the end of winter and A and B are determined experimentally for each cultivar. For potatoes A equals 285 kg/ha on clay and loamy soils and 300 kg/ha for sandy soils, and B equals 1.1 and 1.8 for clay/loam and sandy soils respectively. While the N_{min} method is widely used in Europe, its environmental effectiveness for use by crops that are inefficient users of N such as potatoes has shown a need for improvement. Neetson (1990) was able to reduce N_{min} recommended fertilizer rates by 25% with only a 2% decrease in tuber yield. Similarly Verhagen reduced recommended fertilizer rates from 250 kg N/ha to 175 kg N/ha (30% reduction) without significantly affecting yields. Neetson concluded that N_{min} recommendations tended to be aimed at optimum yields and not environmentally optimum rates. Neetson's conclusion could be applied to most N rate research to date, which tends to focus recommendations on yield and not minimizing loss of N to the environment.

Meyer and Marcum (1998) performed experiments on sandy loam soil in the Fall River Valley, California, and further showed the dramatic effects that residual N can play in fertilizer recommendations. In this experiment potatoes were treated with $(NH_4)_2SO_4$ at planting using seven different fertilizer rates of 0, 56, 112, 168, 224 and 448 kg N/ha over two years. Meyer and Marcum found increasing N application rates did not significantly increase yields in any of the first year trials, which followed a relatively dry winter and high soil N levels present at the time of planting. However, increased N application rates significantly increased tuber yield in the second year studies due to heavy rains during the previous winter that caused rapid nitrate leaching and low initial soil N present at the time of planting.

Another important aspect of fertilizer application is proper application timing. Common farming practices for potato crops tend to stress the importance of adding fertilizer early in the season (Hocmuth and Cordasco, 2000). IFAS recommendations call for two thirds of the fertilizer applied at planting and the rest within 35-40 days after planting. Other research cited previously also tended to add fertilizer early on (in some cases all the fertilizer is added at planting). Osaki et al. (1992) performed two experiments to study the effects of fertilizer timing, both of which validate these recommended management practices. In the first of his two experiments Osaki et al. grew potatoes hydroponically adding N fertilizer into the irrigation water on a daily basis. N fertilizer was then stopped at 0, 10, 20, 30, 40, 50, 60, 70, 80 or 100 days after planting, and the plants were then cultured without N until the shoots died. Total tuber weight increased with greater duration of N, however the weight of the primary tuber increased only through 50 days after planting (DAP). Total tuber weight increase in treatments fertilized after 50 DAP was due to growth of lateral and secondary tubers. Osaki et al. defined partial production efficiency of N as the difference in dry tuber weight between two crops grown with different N fertilizer rates and divided by the difference in N added over the same time period. Measurements of the potatoes partial production efficiency were calculated for this experiment and the results show that partial production efficiency deceased rapidly after 50 DAP which is when flowering occurs. In Osaki et al.'s second experiment potatoes were grown in a field. An initial fertilizer application of 100 kg N/ha was added at planting and a second fertilizer application of 200 kg N/ha was added at 0, 14, 28, 42, 56, 70, 84 or 90 DAP. Osaki et al.'s results showed yield did not change significantly when the second application of fertilizer was made between 0-56 DAP but decreased significantly in treatments receiving the second application after flowering (56 DAP). Furthermore, treatments receiving second fertilizer applications after flowering tended to have lower yields than the treatment that received only the basal fertilizer application. Osaki et al. concluded that fertilizer added after flowering may depress some physiological function of the leaves causing tuber growth to be hindered.

Irrigation research is somewhat more difficult to interpret than fertilizer studies due to soil, temperature and precipitation variables involved with developing irrigation recommendations. Currently, the Institute of Food and Agricultural Sciences (IFAS) cites plant water requirements of about 20-40% ET during initial plant growth, 110% ET at peak growth and tuber development, and 70% ET during final growth stages (Hochmuth and Cardasco, 2000). Studies done on Florida soils compared potato yields grown at soil moisture contents of 8%, 10% and 12%, with the highest yields occurring at 10% and lowest yields occurring at 12% moisture content (Hochmuth and Cardasco, 2000). Belanger et al. (2000) found that for potatoes grown on soils with low water holding capacity in New Brunswick, Canada, yields were most strongly affected by water stress during tuber initiation and early to mid-bulking stages. Water utilization by potatoes were found to be primarily taken from the 0-60cm soil depths by Meyer and Marcum (1998) and in the 0-30cm soil depths by Neetson (1990). In determining irrigation management it is important to provide only the minimal amount of water necessary to avoid water stress in order to reduce excess leaching.

Nitrogen Leaching

The rapid movement of N through soil with applied water has been well documented. Model simulations by Verhagen (1997) showed fertilization rates of 250 kg N/ha for potatoes grown on clay and loamy soils leached 75 kg N/ha more N than needed to remain below Netherland's acceptable groundwater nitrate concentration of 11.3 mg N/L. Verhagen further found that reduction of fertilizer rates to 200 kg N/ha had only minor success in reducing the probability of leaching N above government standards, while reduction of fertilizer rates to 175 and 150 kg N/ha both showed dramatic reductions in leached N. Reductions past 150 kg N/ha showed no significant improvement in the probability of reducing N leaching to below acceptable government limits. Unlu et al. (1999) used LEACHM to predict leaching on sandy soils and found N fluxes peaked at about 29 kg N/ha day and averaged around 15 kg N/ha day. Field measurements for this study, performed on the 400 kg N/ha treatment, measured 106 kg N/ha taken up by the plants, 158.6 kg/ha of N left in the top two meters of soil, and 135.4 kg N/ha leached when 843mm of total water was added to the crop.

Controlling nitrate leaching, especially on sandy soils, requires a delicate balance of irrigation, fertilization rates, and maximizing the potato N use efficiency. Verhagen was able to achieve good potato yields with acceptable NO_3 leaching concentrations on loamy and clayey soils but was unsuccessful in creating viable management practices on sandy soil while maintaining acceptable groundwater nitrate concentrations. Neetson (1990) was able to reduce N application rates by 25% below N_{min} recommended fertilization rates with only a 2% loss in yield. However, Neetson also cited the need for higher N rates on sandy soil due to the rapid leaching of N.

The goal for this research on the spring 2001 potato crop was largely one of observation and not optimization of management practices. Little deviation from the farmer's historic irrigation and N management occurred, and research presented in this literature review was not considered in developing the spring 2001 potato management practices. However, studies cited in this literature review suggest that fertilizer rates can be significantly reduced below the current Florida average rate of 303 kg N/ha. Furthermore previous research suggests that at the current average N application rates for potatoes, excessive leaching in sandy soils will likely result in groundwater nitrate concentrations above acceptable drinking water standards.

CHAPTER 2
FIELD EXPERIMENTS

Regional Geology

To understand the complex relationship that nitrate leaching has on water quality in the Suwannee River Basin it is important to understand the regional geology. The research site lies along a physiographic region know as the Cody Escarpment (see Fig 2-1). This region marks the boundary between the Northern Highlands and the Gulf Coastal Lowlands provinces. In the Northern Highlands province the Hawthorn Group (upper clay confining unit of the Floridan Aquifer) is intact causing fewer sinkholes and more surface drainage. In the Gulf Lowlands province the Hawthorn Group has been eroded away leaving a thin sheet of surficial sands covering the Suwannee Limestone and allowing many small sinkholes to be formed. The Cody Escarpment is a transitional zone between these two provinces (see Figures 2-2a & 2-2b) where the surficial sands are relatively thick and the Hawthorne Group is largely eroded leaving a thin and pocketed clay mantle atop the limestone and a topography consisting of large funnel shaped sinkholes (Randazzo and Jones, 1997). The regions along and below the escarpment represent the greatest threats to water quality of the Suwannee River Basin. Surficial sands hold few nutrients and are extremely susceptible to leaching. With little or no clay layer present, applied chemicals move quickly into the groundwater.

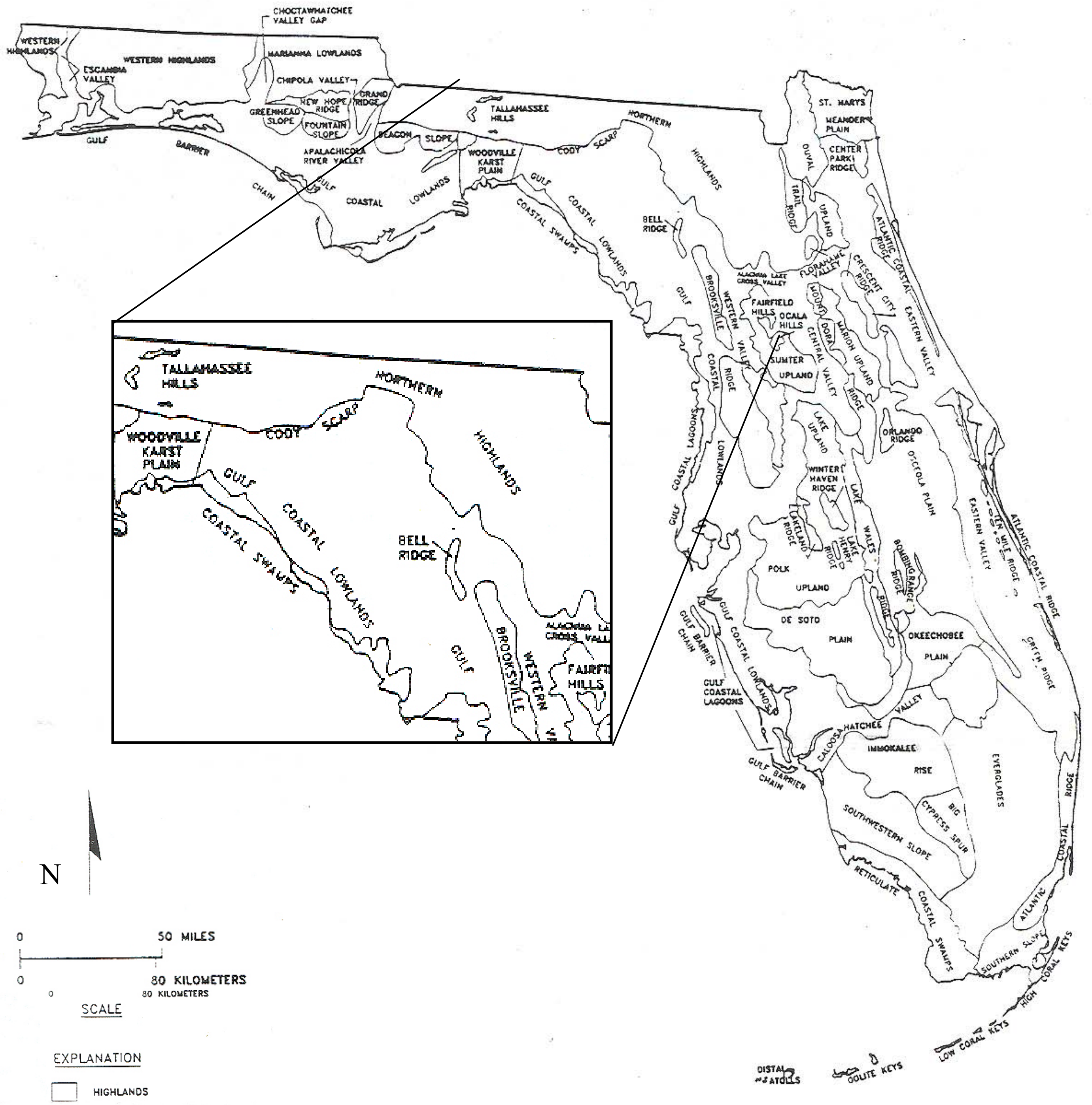
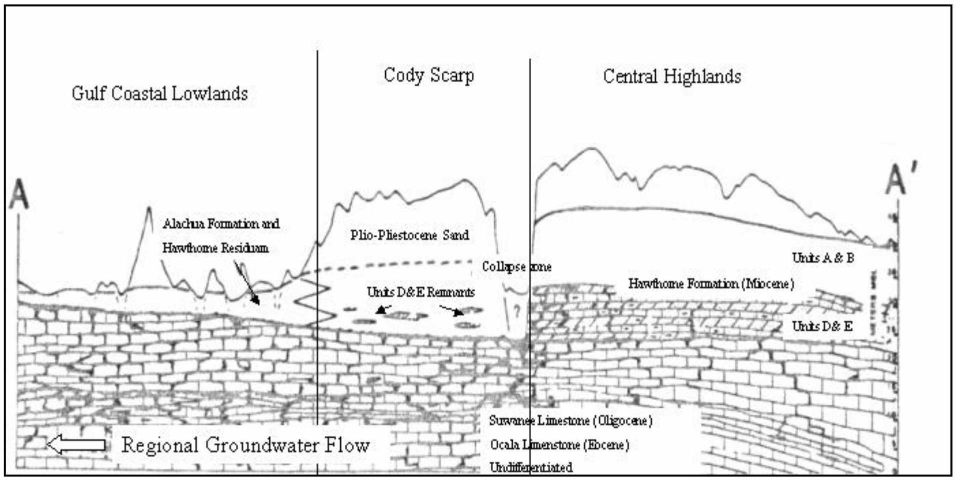
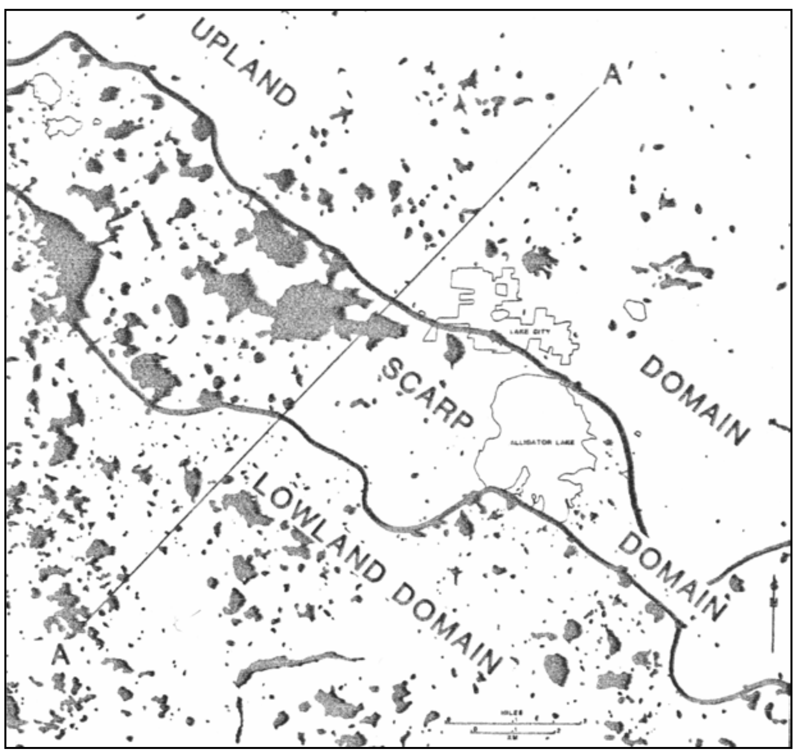


Fig 2-1. Physiographic provinces of Florida (modified from Randazzo and Lones, 1997).



a) Typical cross section across the Cody Scarp (modified from Randazzo and Jones, 1997).



b) Shows the difference in concentration of depressions in the Highlands, along the scarp, and the Lowland physiographic provinces (Randazzp and Jones, 1997)

Fig 2-2. Cody Scarp: a) typical cross section; b) difference in concentration of depressions.

The research site is located in O'Brien, FL, about 20 miles SW of Lake City (see Fig 1-1). Soils located at the research site have been classified as Blanton fine sands (Sodek, 1990). Evidence gathered from use of a Ground Penetrating Radar (GPR) device and geologic cross-sections obtained from monitoring well logs were used to characterize the geology of the site. Table 2-1 shows depth to limestone obtained from the logs of the 13 monitoring wells installed within the research pivot (Figure 2-3); the depth averages 7.0m below the surface. The top of the limestone generally represents the upper boundary of the Floridan Aquifer, although during high water table periods the phreatic surface can rise up into the overlying sands.

Table 2-1. Total depth, depth to limestone and depth of casing of 13 monitoring wells.

Well#	Total Depth	Casing Depth	Depth to Limestone
	(m)	(m)	(m)
1	4.0	5.5	5.5
2	3.4	5.5	5.5
3	3.4	7.6	8.2
4	4.0	7.9	7.9
5	2.1	4.3	4.3
6	1.8	7.6	7.9
7	2.7	3.7	4.0
8	1.2	7.0	7.6
9	1.2	7.3	5.5
10	2.1	8.5	8.5
11	1.8	8.2	7.3
12	3.7	9.8	9.4

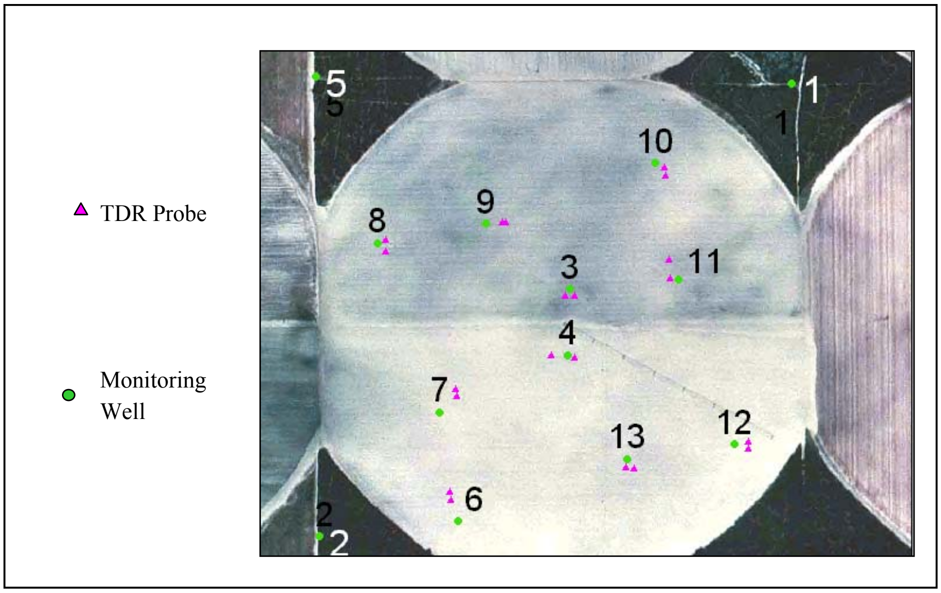


Fig 2-3. Aerial photo of research pivot showing the location of monitoring wells and TDR access tubes.

A GPR is a broad-band impulse radar that radiates shortwave electromagnetic pulses in the earth. (Truman et al, 1988). Increased water content in soil reduces wave velocity, and when there is an abrupt change in water content, such as at the boundary of two soil or rock layers or at a water table, strong changes in wave reflection is detected by the GPR device. Asmussen et al (1986) used a GPR to detect depth of the argillic horizon in 18 soil sites with an r^2=.94.

A GPR was dragged in a grid-like pattern across the research site and the data generated was analyzed to produce a map of the depth to clay. Figure 2-4 shows the GPR transects and depth to clay read off the GPR charts. Ground-truthing was performed by taking field measurements of the depth to clay and comparing them to GPR predicted depth to clay for the same location. An r^2=0.83 was calculated from a linear regression with 15 ground-truthing points

(Figure 2-5). A variogram produced using GPR readings of depth to clay show a variance (C_o+C) of about 0.5m^2, a spatial correlation of about 200m and a nugget (C_o) of 0.175m^2 (Figure 2-6). Thus, although Figure 2-4 suggests there is a continuous clay layer present, this may not actually be the case due to the difficulties of interpreting GPR data and the inaccuracies of spatial interpolation due to the low spatial correlation. It is likely that some of the deepest depth-to-clay readings from the GPR are actually areas absent of any clay layer.

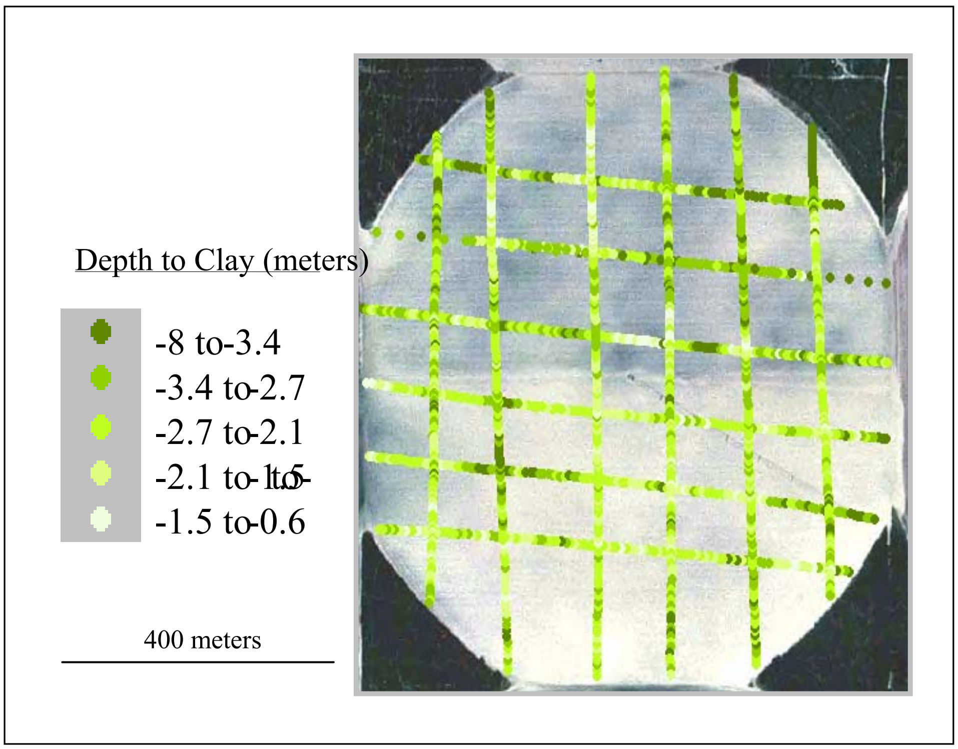


Fig2-4. GPR readings of the depth from surface to clay, overlaying a Digital Ortho-Quad Quarterangle (DOQQ) image of research pivot.

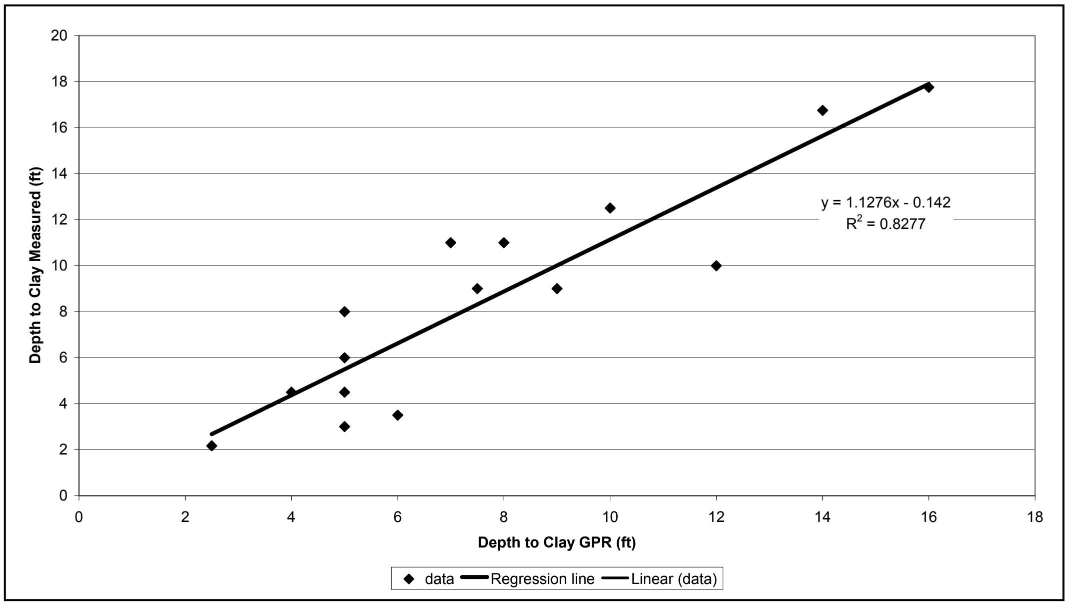


Fig 2-5. Results from the ground-truthing of GPR depth to clay.

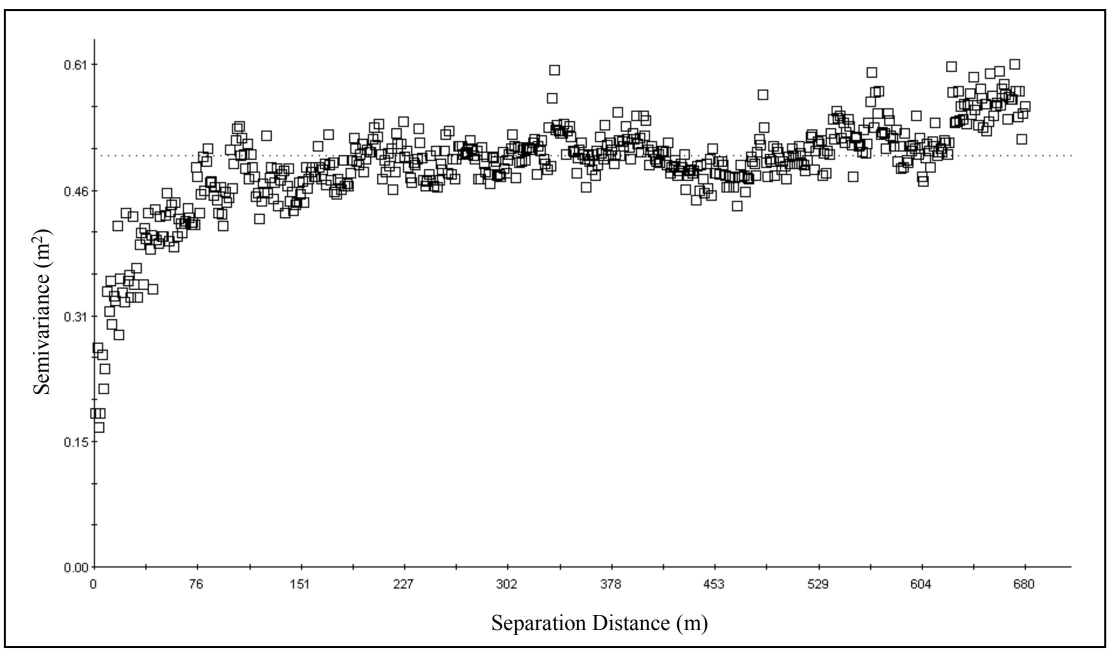


Fig 2-6. Variogram of GPR depth to clay.

Background Sampling

Research at the vegetable farm began in 1999 and includes the biweekly monitoring of groundwater through 13 wells drilled and cased to the top of the limestone (see Figure 2-3 and Table 2-1), and soil samples taken from the ground surface to the top of the clay layer every six weeks. These data are used to monitor long-term trends in groundwater elevation, groundwater nitrate concentrations, and soil water nitrate concentrations beneath the research site. These trends can then be used to compare and track changes in background sampling with changes in farm management and weather trends.

Monitoring wells have been sampled biweekly since April 1999 for nitrate concentrations and groundwater elevations. These groundwater elevations along with elevations collected from the irrigation wells from each of the other 42 center pivots at the research site were used to make a potentiometric surface map for March 29, 1999 (see Figure 2-7). These contours exhibit a southwesterly flow toward the Suwannee River and suggest high potential for nitrate contamination in groundwater to move to the river. Groundwater elevation (averaged over all 13 wells by date) and precipitation over time is shown in Figure 2-8. Figure 2-8 shows the typical patterns for this region of high groundwater elevations following spring and early fall rains. No peaks in groundwater elevation were seen in the spring of 2000 due to an extended drought.

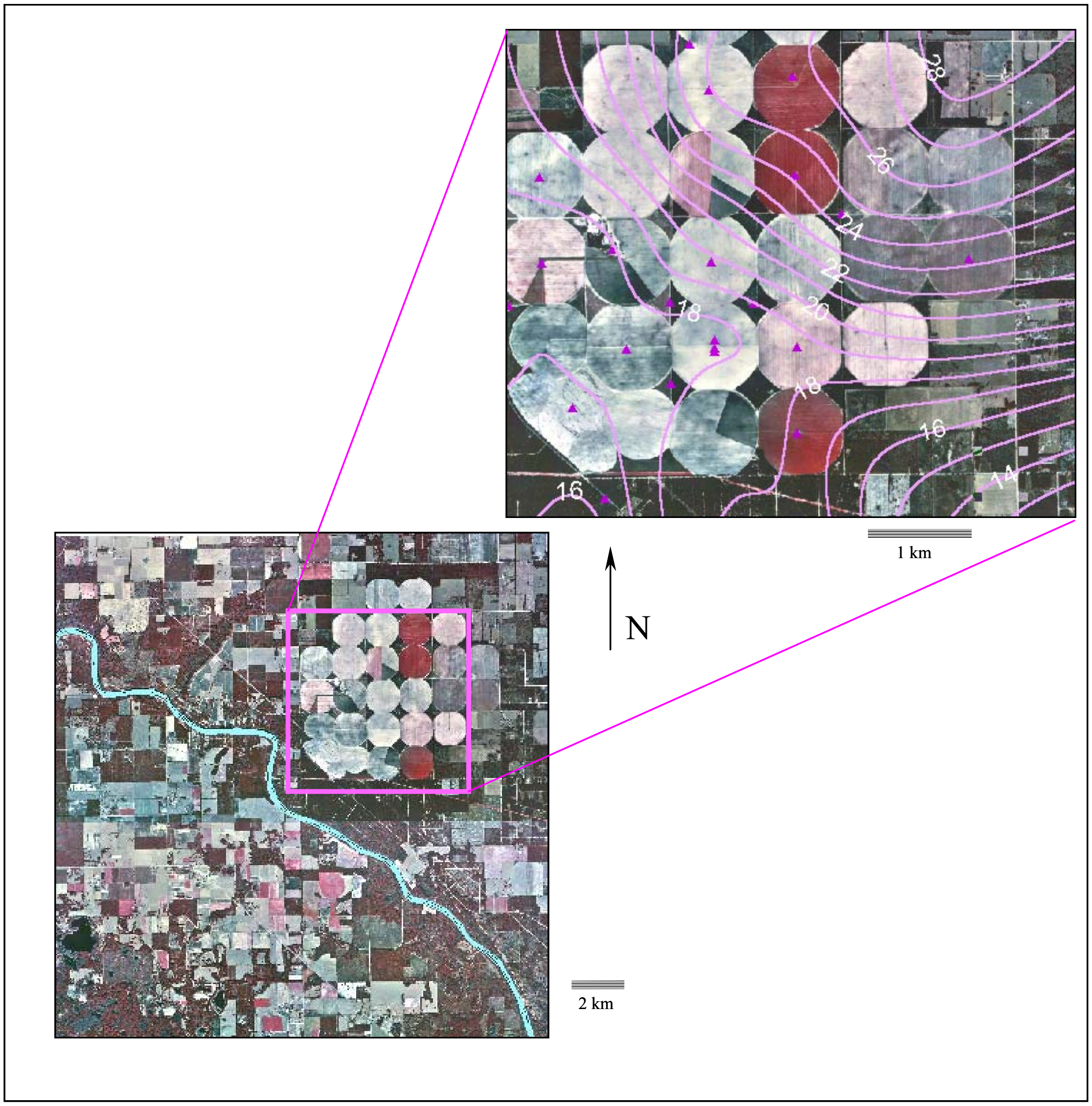


Fig 2-7. Potentiometric Surface drawn using groundwater elevations on 3/29/1999 with center pivot well water elevations

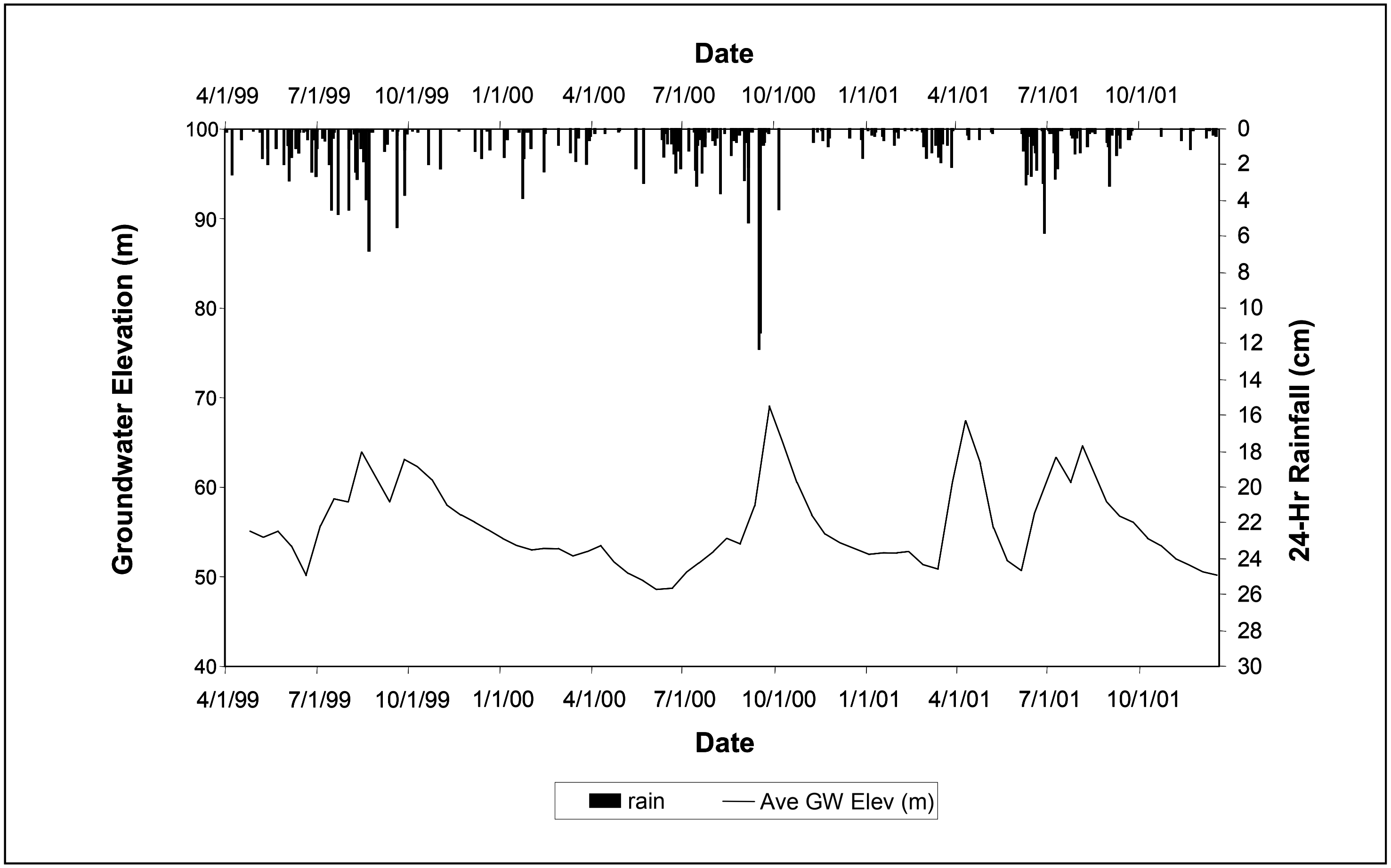


Fig 2-8. Groundwater elevation (MSL) and rainfall with time.

Groundwater nitrate-N levels can be used to illustrate the time response between fertilizer application and groundwater contamination. Figure 2-9 shows groundwater nitrate-N concentrations averaged over all 13 wells over time. A gradual drop in average nitrate concentrations occurred from 32.5 mg/L measured on April 1999, to about 17mg/L prior to the planting of the corn crop in April 2000. During this time only peanuts (a legume which fixes N from the air and requires no additional fertilizer) and cover crops were grown, therefore no N was applied. Between April and May 2000 an application of 387 kg/ha of N was added to the corn crop. Elevated nitrate-N concentrations began to appear in groundwater around July 2000 and eventually peaked in October 2000 at 35mg/L. A second peak in nitrate concentrations occurred in January 2001, about four months after the cotton crop was planted. Nitrate concentrations then declined over spring and early summer then peaked on July 10, 2001 at 32.5mg/L, about 5 months after the potato crop was planted. Figure 2-9 underscores the relationship between rainfall and leaching. It is not until after a series of storm events that the nitrate finally makes its way to the aquifer after application to the ground surface. For instance, the nitrate pulse from the corn crop only takes about 3 months to reach the aquifer (about 7m below land surface) due to a heavy summer rainy season in 2000. However the potato nitrate pulse took approximately 5 months to reach groundwater because the area received less rain after these crops were planted than after the corn crop.

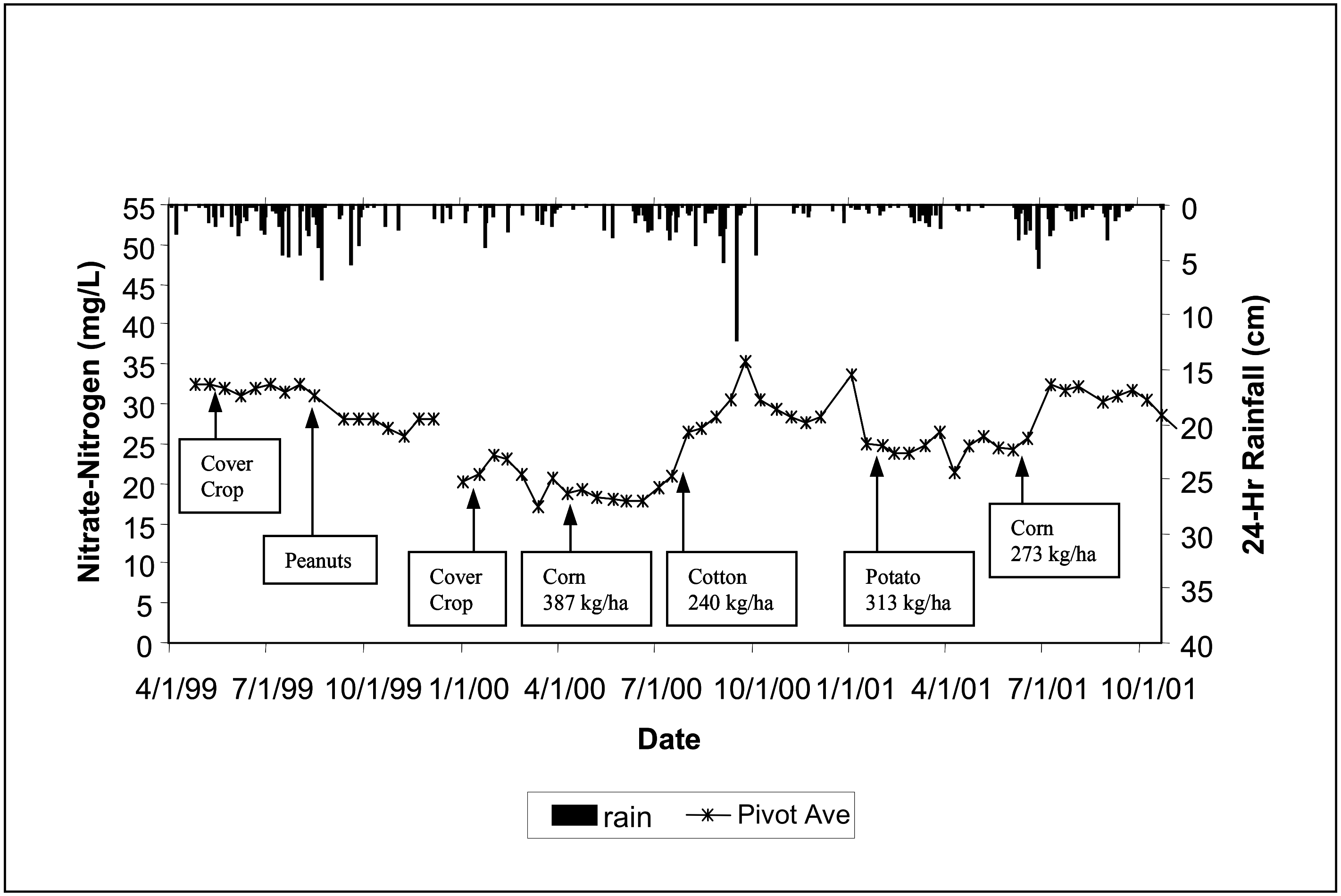


Fig 2-9. Groundwater nitrate concentrations and rainfall with time. Markers indicate crop, time of planting and total nitrogen applied over the entire crop season.

Figure 2-10 shows the distribution of nitrate mass in the top 5.5m of the soil profile obtained from deep soil samples taken from March 15, 2000, to October 8, 2001. Twenty deep soil samples (ten for each center pivot half) were taken approximately every six weeks and analyzed for nitrate-N concentration. These samples were taken in the plant rows at a half-meter interval over the top two meters and then at a one-meter interval down to the clay layer or 5.5m (whichever came first). Nitrate mass tripled in the top 5m of the soil profile, with most of the increase in the top 0.5m interval, during the planting (and addition of 387 kg N/ha of fertilizer) of the corn crop in early April 2000. Nitrate mass remained high through the cotton crop, planted in July 2000, and then slowly declined through the fall 2000 season. Nitrate then increased dramatically to levels over 500 kg/ha by the end of the heavily fertilized potato crop. Note how the trends for the deep soil samples show a preview of the groundwater nitrate response. In both 2000 and 2001 high levels of soil nitrate occur in spring and early summer, then decline throughout the summer rainy season resulting in a peak in groundwater nitrate concentration in the Fall.

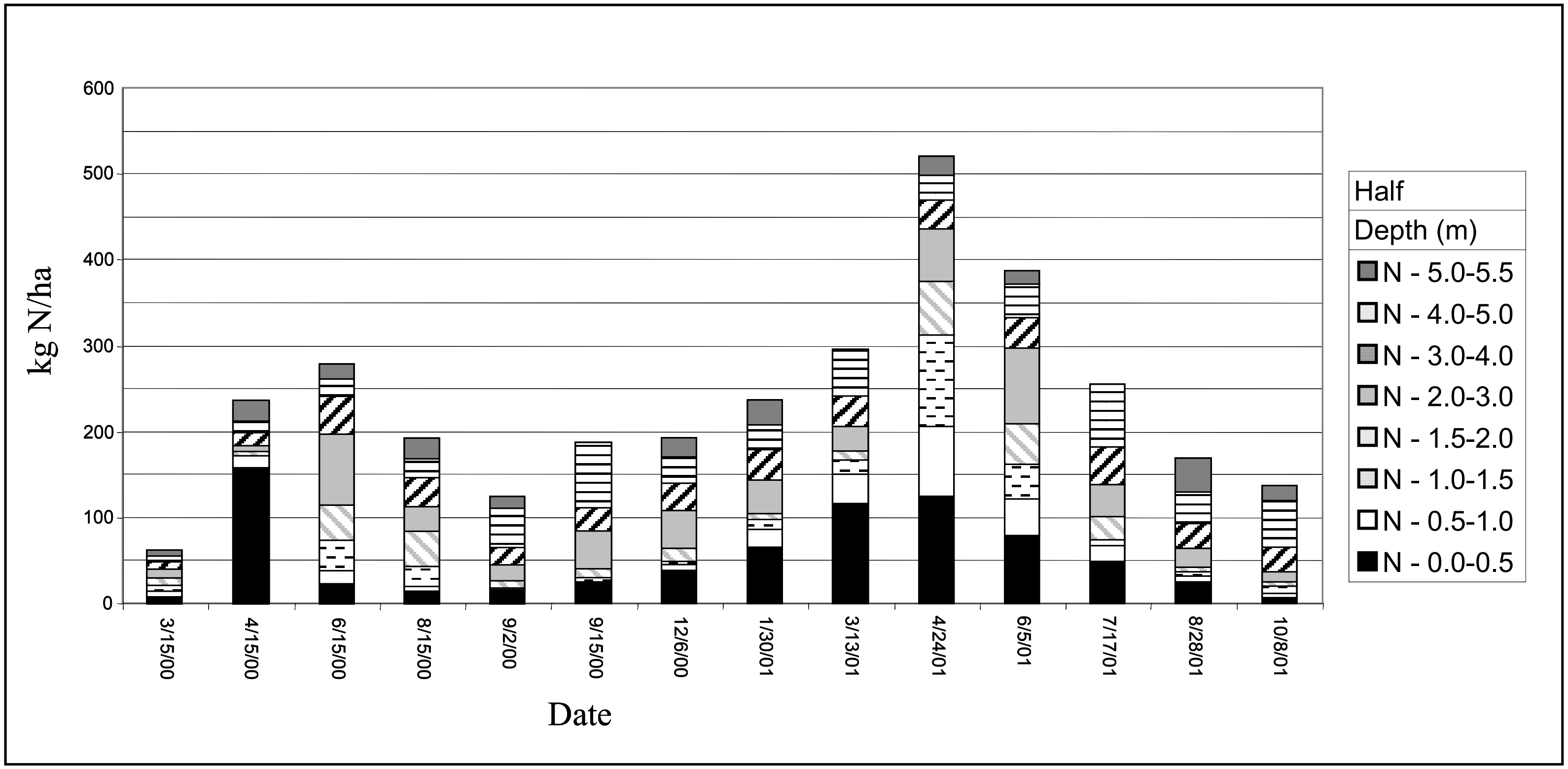


Fig 2-10. Total nitrate-nitrogen mass in top 5.5m of the soil profile. Mass is averaged over 20 samples per depth increment and then the average per depth is summed over all depths.

Figure 2-11 shows a more detailed look at the soil profile response to nitrate fertilizer during the potato crop. At the beginning of the crop season (January 18, 2001, and March 13, 2001), during the period of little rain or irrigation, most of the nitrate is observed in the top 0.5m of the soil profile and concentrations drop significantly over the next meter. As time progresses nitrate concentrations increase significantly in the lower depths of the profile averaging over 100 mg/l in the 1.5-2.0m range on April 24, 2001 and June 5, 2001. No significant increases in nitrate concentrations are seen below the 3.0m range at anytime during the crop. Perhaps through the process of dispersion, nitrate concentrations decrease to around 50 mg/l at a depth of 3.0m. This correlates well with the monitoring well readings in early July, about the time the nitrate pulse is expected to reach that depth.

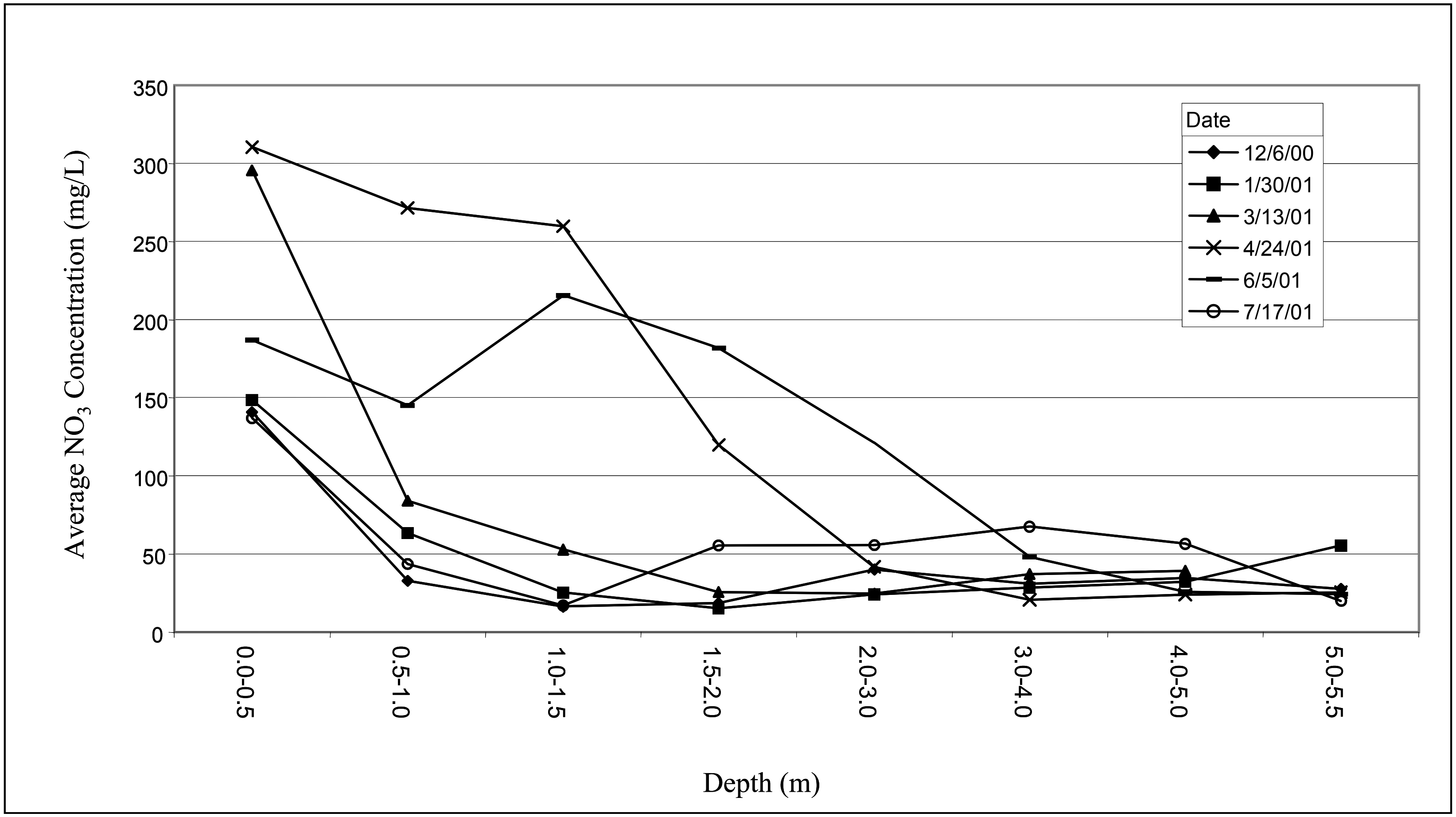


Fig 2-11. Depth profile of NO_3 concentration in soil averaged over 20 soil cores.

Field Methods

Data collection during the spring 2001 potato crop focused on obtaining information that could accurately quantify the movement of nutrients for two different management practices. The research site was located on a 56.7 ha field that was divided into north and south halves, each receiving different fertilizer treatments. Essential information obtained from the farmer is presented in Tables 2-2 and 2-3 and includes the name of the cultivar, planting geometry, and fertilization dates and amounts for north and south half. Irrigation was recorded manually by reading instrument gauges located on the center pivot and can be viewed in the DSSAT input file under the FILEX irrigation section in Appendix C. Actual differences in north and south half fertilizer management were negligible and thus only north half nitrate data will be discussed in this section. An analysis of the south half data is deferred to the modeling results section.

Table 2-2. Plant statistics obtained from farmer.

Cultivar = Red LaSoda		
Previous Crop = Cotton		
Planting Depth =	6	in below ridge of rows
Row Spacing =	40	in rows
Planting Density - 2400 lbs/acre =	10971	seeds/acre
Growing Density (Assuming only 90% of seed pieces sprout plants) =	9874	plants/acre
	24387	plants/ha
Seed Weight =	3.5	oz each seed piece

Table 2-3. Approximate Fertilization Schedule

Applied Nitrogen				
Date	Julian Day	Nitrogen Applied (N Half)	Nitrogen Applied (S Half)	N Fertilizer Type/Method of Application
		kg/ha	kg/ha	
1/18/2001	18	38.2	29.2	34-0-0 preplant, in-bed
2/15/2001	46	16.8	16.8	10-34-0 starter, at planting
3/5/2001	64	112.3	105.5	18-0-0-3, sidedress-liquid N
3/25/2001	84	112.3	94.3	18-0-0-3, sidedress-liquid N
4/28/2001	118	33.7	33.7	30-0-0, applied through pivot

Detailed observations of weather, crop development, plant tissue characteristics, soil characteristics, soil water nitrate concentration and soil moisture information were all obtained to provide a data set that could accurately quantify the movement of water and nutrients through the vadose zone for the spring 2001 potato crop. A weather station was set up at the research site about half a kilometer from the center pivot to record hourly rainfall, temperature and solar radiation. A Texas Electronics TR525 raingauge, a Campbell scientific thermometer and a LiCor LI200X pyranometer were attached to a CR-10 datalogger and downloaded periodically. The potato crop was monitored for biomass accumulation, nutrient uptake and phenological development. Soil cores and deep well monitoring were used to determine soil- and ground- water nitrate concentrations, groundwater elevations, and soil moisture contents. Irrigation and fertilizer management records were obtained from the farmer. Through observation and analysis of these variables a more complete picture of water and N movement beneath the research pivot begins to appear.

Vadose Zone Monitoring

Vadose zone monitoring involved measurements of soil moisture content and soil water N concentration over depth and time. Soil cores were taken only in the rows where all the fertilizer was banded and the plants were located. Soil moisture content and soil water nitrate concentrations were measured using two sets of soil samples. Ten shallow soil samples (five in each center pivot half) were taken biweekly at intervals of 0-15cm, 15-30cm, 30-60cm and 60-90cm to provide detailed information within and just below the root zone of the potato crop. Twenty deep soil samples were taken approximately every six weeks. These were measured at a 0.5m interval over the first two meters and then at a 1m interval down to the clay layer or 5.5m (whichever came first).

Soil samples were weighed wet and then oven dried and re-weighed yielding a gravimetric water content. Gravimetric water content was converted to a volumetric water content using the formulas:

$$\theta_g = \frac{(m_{wet} - m_{dry})}{m_{dry}} \tag{2-1}$$

$$\theta_{vol} = \frac{(\theta_g \times \rho_b \times 100)}{\rho_w} \tag{2-2}$$

where θ_g is the gravimetric and θ_{vol} volumetric water content respectively; m_{wet} is the wet and m_{dry} the oven-dried mass of the soil sample respectively; ρ_b is the bulk density of the soil and ρ_w is the density of water. Bulk density (ρ_b) was measured by the Department of Soil and Water Sciences at the University of Florida from soil samples taken in the field.

Soil moisture measurements were also obtained through weekly TDR measurements using the Trime® FM moisture measuring device developed by MESA Systems Company. Time Domain Reflectometry (TDR) is a technique that uses a high frequency pulse which is propagated along wave guides and reflected back to the source. Transit time between propagation and reflectance is dependant on moisture content of the soil (Trime User Manual, 2001). The TDR probe is a cylindrical PVC tube with wave guides approximately 30 cm long. Twenty TDR access tubes (see Figure 2-3), extending 180cm into the soil, were installed at the field site. Measurements were taken at 30 cm intervals in the access tubes with three measurements taken at each depth, rotating the probe 60° between each reading. TDR measurements are reported as volumetric water content. TDR and soil sample water content measurements are compared over time in Figure 2-12 and with depth in Figure 2-13. Soil moisture values for both the shallow soil samples and the TDR probe show similar trends but the TDR measurements tend to overestimate soil moisture contents and require further calibration to site-specific soil properties.

Water content is highly variable in the top 30cm of the soil due to transient effects of evapotranspiration and irrigation. In general, an increase in moisture content is seen in the 30-60cm range, which corresponds to the bottom of the furrows. This phenomena may be due to water shedding off the beds and into the furrows, or from a possible plough pan created by tightly packed soil just

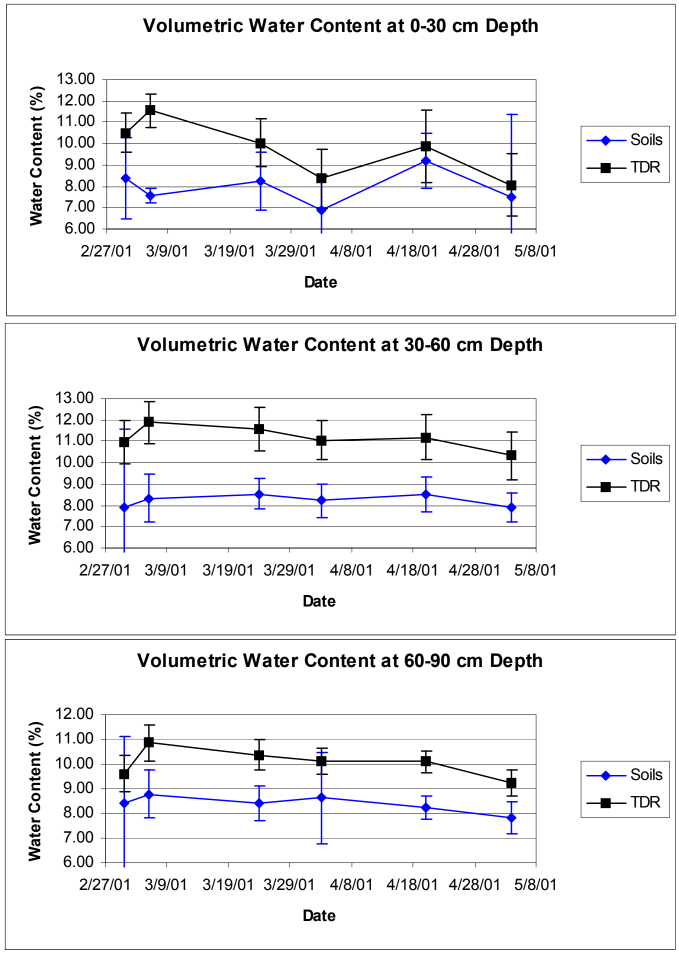


Fig 2-12. Comparison of TDR versus soil moisture content readings over depth. Moisture content is averaged over all sampling locations. Error bars represent one standard deviation around the mean of the measured values.

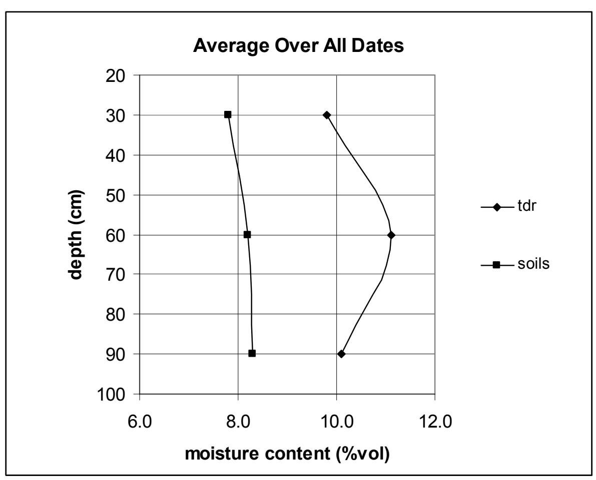


Fig 2-13. Average soil profile of water content with depth for TDRE and oven-dried soil sample measurements.

below the root zone which slows the downward movement of water. The profile below the 60cm range usually becomes drier and then stays constant until just above the clay layer. Figure 2-14 shows a TDR moisture profile of a soil where clay was encountered at the bottom of the profile during installation of the access tube (3W) and one where no clay was encountered (3E). Moisture content rises considerably where readings are taken just above the clay layer. This drainage feature is also seen in moisture content readings from deep soil samples where volumetric water content taken directly above the clay layer averages 17.8% compared to 8.1% for all other samples (data not shown). Although water content does not reach the saturation point of the soil, the clay does seem to slow downward movement significantly.

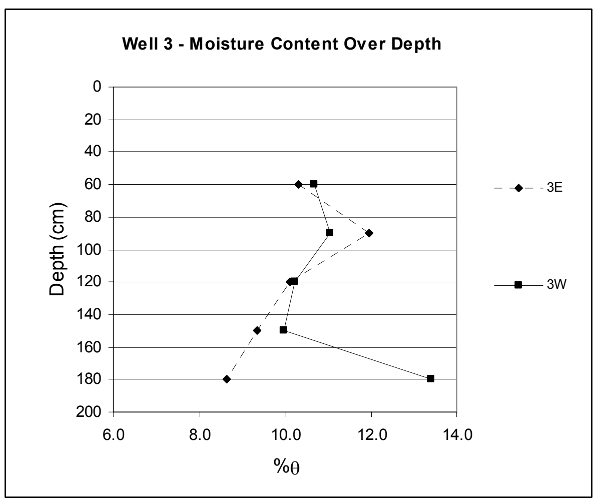


Fig 2-14. Average volumetric water content measured throughout the 2001 potato crop by TDR probes show two different profiles. Well 3W is underlain by clay and has increased moisture content at the 180cm depth.

All of these soil moisture readings seem to indicate ample water in the soil profile. Results from lab measurements of the soil-moisture release characteristics of soil taken from Suwannee Farms indicate volumetric moisture content of 6-7% at a pressure of –345cm and 8-10% at a pressure of –100cm (see Table 2-4). Thus the roots of the potato crop, which only extend about 30-40cm deep, have been provided with ample irrigation to maintain moisture content at field capacity throughout the season. In fact, water content was maintained at or above field capacity throughout the entire profile well below the root zone throughout much of the growing season, indicating excessive irrigation. Since excess irrigation will lead to more N leaching, it is important to provide only the minimum amount of water necessary to prevent plant water stress.

Table 2-4. Saturated hydraulic conductivity, bulk density and retentivity data measured at the research location.

soil tension (cm)	vol MC for 0-50cm	vol MC for 50-100cm
0	38.8	35.3
4	38.8	35.2
20	35.8	34.4
30	29.9	31.2
45	20.3	17.4
60	14.2	12.6
80	11.1	9.3
100	9.7	8.0
150	8.2	6.9
200	7.3	6.2
345	6.6	5.8
15300	1.8	1.8
	cm/day	cm/day
K_{SAT}	4515	3759
	g/cm^3	g/cm^3
Bulk Density	1.48	1.56

Soil samples were transferred to the Department of Soil and Water Science at University of Florida where they were analyzed for KCL extractable nitrate and ammonium concentrations. Appendix A shows the field measurements and detailed calculations. Figures 2-15 and 2-16 depict a column graph in which mass of nitrate-N per area is averaged over north half soil cores for each depth, and that average per depth is summed over all depths to give an estimate of total mass of nitrate in the profile. Total rainfall plus irrigation along with the amounts and dates of fertilization between each sampling are also depicted on the chart. It should be noted that fertilizer dates are only approximate. For instance, the crop was observed being fertilized on March 24, 2001, even though the grower's records indicated that the crop was fertilized on March 25, 2001. Furthermore there is evidence that fertilizer was applied on March 2, 2001, and April 24, 2001, rather than on March 5, 2001, and April 28, 2001, which would correlate better with observed nitrate levels. Also note that although measured nitrate mass in the soil seems high compared to the fertilizer application rate, the fertilizer was banded into the plant rows only, which is where soil samples were taken. Therefore the mass per area values given by the farmer are actually only applied to about half of the area. Residual N from previous crop biomass and leftover fertilizer may also contribute to these high numbers.

Figures 2-17 combines the top 1m of figures 2-15 and 2-16 into one chart and provides insight into how the nitrate was transported through the soil profile over the course of the growing season. Since roots at plant maturity only extend 35 to 40cm deep, it is unlikely that any of the NO_3–N leached below 45cm

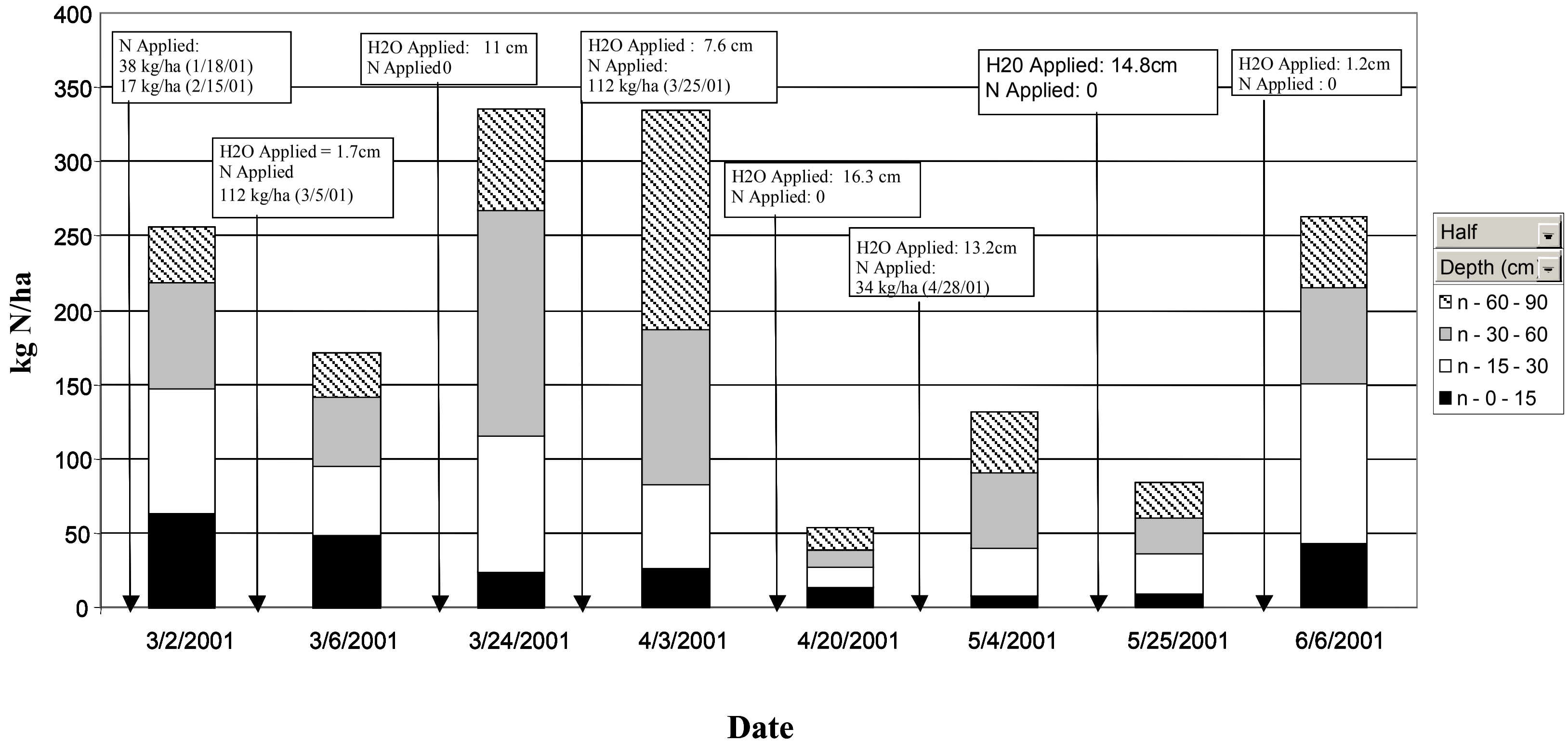


Fig 2-15. N mass in top 90cm averaged over North half soil samples. Each depth increment is averaged over 5 samples.

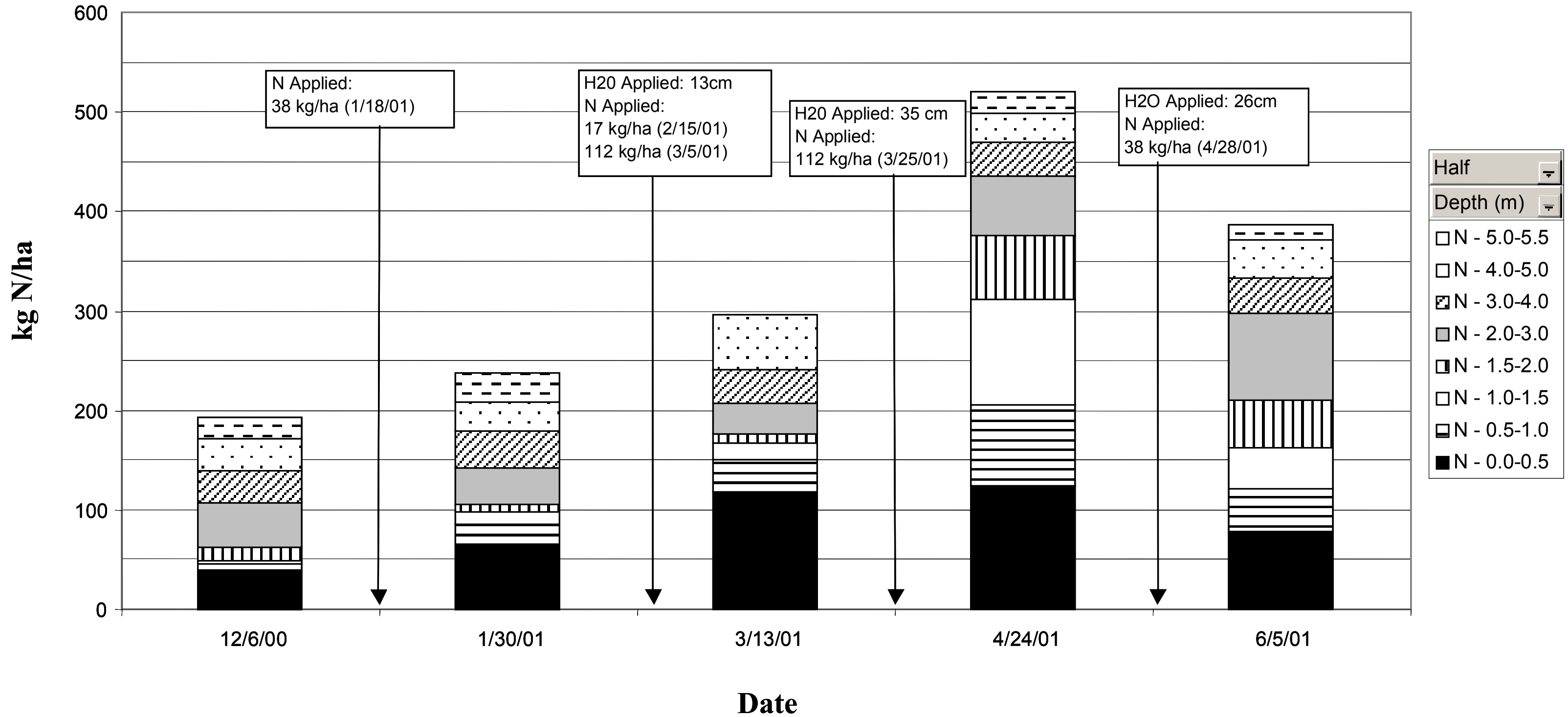


Fig 2-16. N mass in the top 5.5m averaged over North half soil samples. Each depth increment is averaged over 10 samples.

is recoverable by the plants. Thus nutrients below 45cm will eventually leach to the groundwater. A preplant fertilizer treatment of 37 kg N/ha was added to the north half on January 18, 2001. Deep soil samples on January 30, 2001, show approximately 82kg/ha NO_3–N in the top 1m of soil and approximately 225 kg/ha over the top 5.5m of soil. Between January 18, 2001, and the next soil sampling on March 6, 2001, little water was applied to the crop resulting in little leaching. During this time, two fertilizer applications totaling 129 kg/ha for the north half were applied to the field. Nitrate mass measured by shallow soil samples taken on March 2, 2001, showed an increase to approximately 250 kg/ha in the 0-90cm range. Subsequent soil sampling on March 6, 2001, and March 13, 2001, showed steadily declining nitrate mass with no additional fertilizer application and continued leaching through the soil column. The soil sample results for March 24, 2001, show NO_3–N mass increasing to approximately 340 kg/ha in the top 90cm. As indicated previously, fertilizer was applied to the field on that day. Soil samples taken two weeks later on April 3, 2001, showed similar NO_3–N mass in the top 90cm of the soil column. However, mass in the 60 – 90cm interval more than doubled compared to the March 24, 2001 observation while dropping by a third in the 0 – 30cm interval. No new addition of fertilizer occurred during this time and leaching has apparently caused the pulse of the N to move from the surface soil down to the lower depths of the soil column. The NO_3–N mass in the soil profile dropped dramatically by April 20, 2001. The center pivot irrigation system began running 24 hrs/day on April 1, 2001, applying about 8.5mm of water each day to the field. No fertilizer was added between March 24, 2001, and April 20, 2001. The data indicate significant leaching during this intensive irrigation period causing much of the N applied to move below the root zone and become unavailable to the crop. In late April the grower independently observed that plants were deficient in N and a final addition of 68 kg/ha fertilizer was added on approximately April 28, 2001.

The two sets of soil samples taken on June 5, 2001, and June 6, 2001, showed the nitrate mass increased with no addition of fertilizer. The center pivot had been shut off on about May 20, 2001, and herbicides were applied to destroy the plants. This would create a scenario with little leaching and no nutrient uptake. One explanation for the increase in nitrate mass is that an upward flux of water (and nitrates) occurred from a negative pressure gradient caused by evaporation. A second explanation is that the field was re-bedded on June 4, 2001, to cover the potatoes with soil to prevent decaying. During this procedure soil was taken from the furrows and piled over the potatoes. It is possible that N fertilizer that had eroded from the beds into the furrows was returned to the beds during this process.

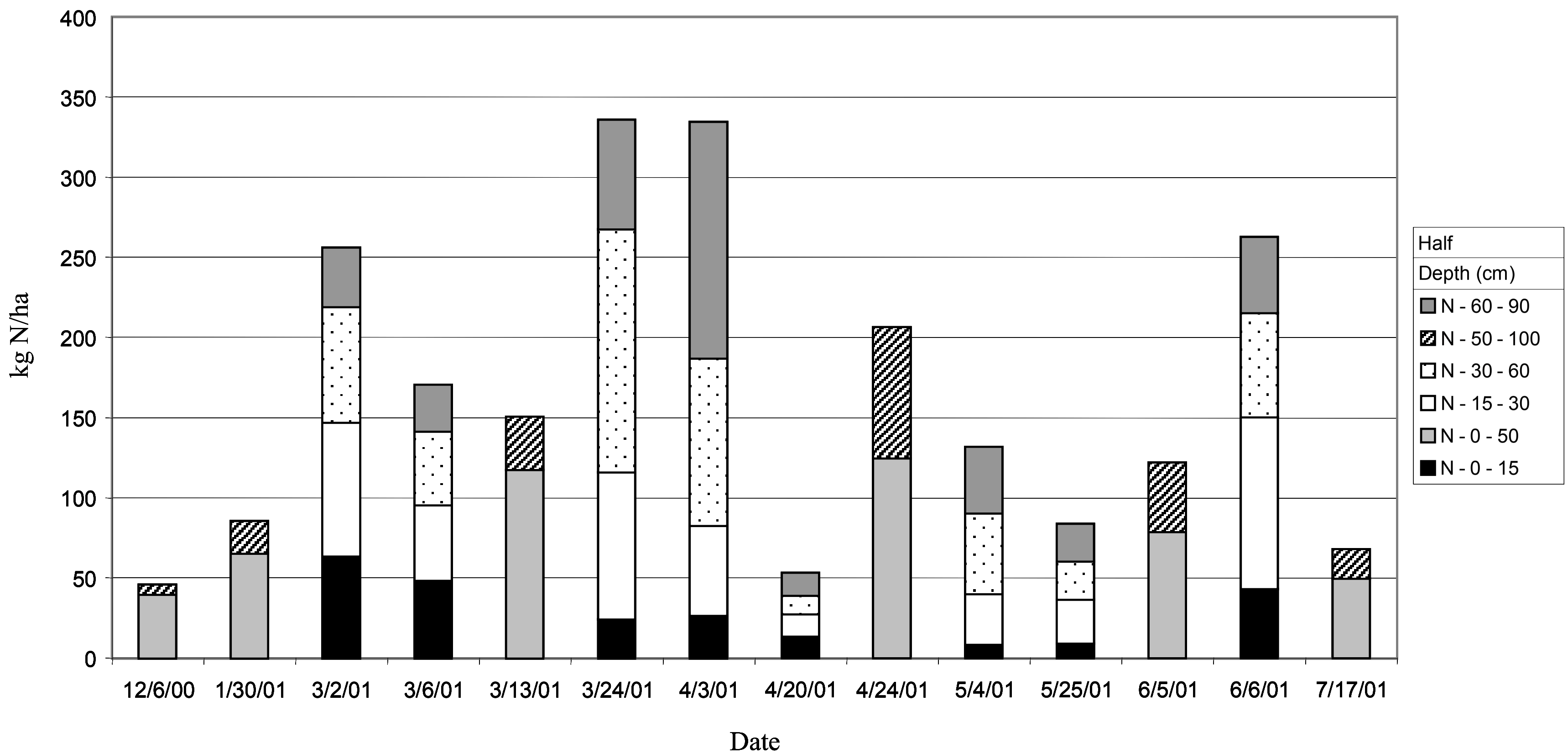


Fig 2-17. Nitrate -N mass for north half shallow -soil samples and the top meter of north half deep -soil samples shown together over the course of the 2001 potato s eason.

Crop Monitoring

Crop monitoring was accomplished by obtaining information from the farmer, taking biomass samples throughout the growing season and through visual observations of the timing of certain phenological growth stages. Crop development (see Table 2-5) was documented during weekly visits to the farm, and times of plant emergence, tuber initiation, date of anthesis (flowering), maximum leaf area and harvest date were noted. These growth stages were used to calibrate the DSSAT model and can be used to compare development of crops from year to year.

Table 2-5. Dates of selected phenological development stages as observed from weekly field visits.

Important Dates		
	Date	Day After Planting
Planting	15-Feb	0
Emergence	07-Mar	20
Tuberization	01-Apr	45
Anthesis	05-Apr	49
Max LAI	20-Apr	64
Killed	21-May	95
Harvest	01-Jun	106

Four biomass samples were taken 37, 40, 47 and 78 days after planting. The DSSAT Manual (Tsuji et al., 1999) suggests taking one biomass harvest at tuber initiation, and again at twenty and forty days after tuber initiation. In this study two biomass samples were taken between emergence and tuber initiation, one at tuber initiation and a fourth and final biomass sampling was done thirty days after tuberization. In each biomass harvest eight plants of average size, two from each quadrant of the field were separated into leaves, stems and tubers. Each plant was then weighed wet, dried in a 75°C oven until a constant weight was achieved, reweighed and sent the Analytical Research Laboratory at University of Florida where the samples were analyzed for Total Kjeldhal Nitrogen. The results of these analyses and the calculations involved are shown in detail in Appendix B. In addition to the biomass harvest, final yield was measured on June 1, 2001. This was done by taking twenty, thirty-foot long sections of a row, 5 from each half of the center pivot, and manually digging up all the potatoes. The potatoes were then divided into three different classes based on size and weighed to determine final tuber yield per acre. Total final yield for all size classes was 38.7 Mg/ha for the north half and 33.7 Mg/ha for the south half.

Using the biomass samples and the final yield data, calculations were then made to estimate total crop N uptake. For the biomass samples N concentrations provided from the plant tissue analysis were multiplied by the dry weight for each plant part and then added together to achieve a total N mass per plant. Average N mass per plant was obtained for all the plants sampled that date and multiplied by the planting density to achieve a N uptake per unit area. At the time the potato plants were sampled for final yield, most of the leaves had senesced thus it was not possible to obtain a final measurement of leaf N mass. Furthermore the tubers had been field dried for about ten days before final harvest measurements were taken, which could cause about a ten percent loss in tuber weight compared to fresh weight measurement (Jones, oral communication). Thus an additional 10%

of the measured weight was added to the final weight of the tubers. Nitrogen concentration of the tubers on May 4, 2001, was used to calculate tuber N mass for the final yield data. To estimate the total N uptake the N mass at maximum leaf area and maximum stem weight (taken on May 4, 2001) and the tuber N at final harvest were added. Nitrogen mass in the roots was not measured, as recommended by Dr K.J. Boote (2001, oral communication), because of the relatively small percentage N mass usually found in the roots. Figure 2-18 compares the N applied on the north half to the total N taken up by the plant, and indicates that approximately one-third of the N applied (101.7 kg/ha) was taken up by the crop.

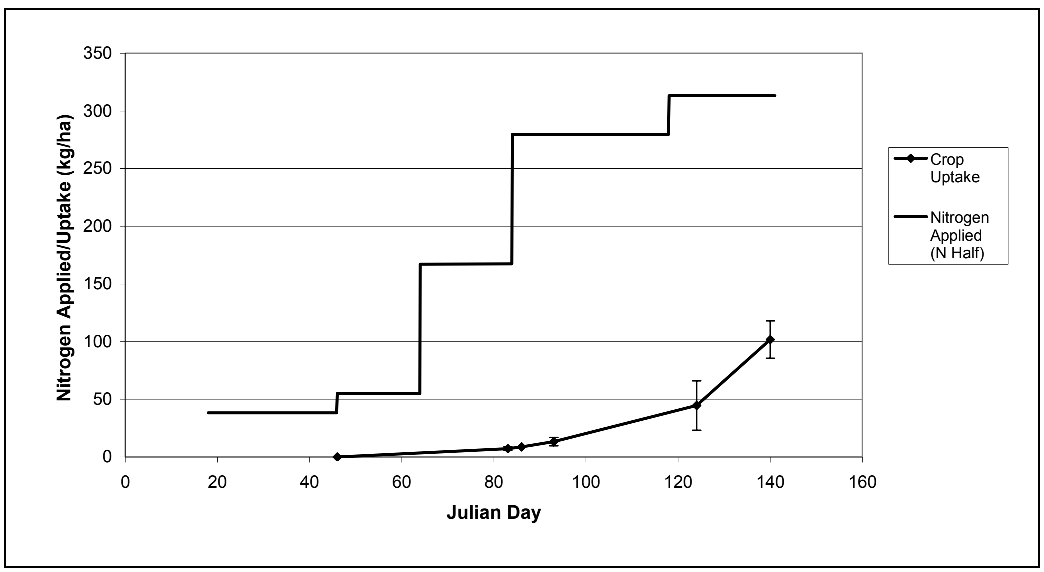


Fig 2-18. Cumulative N applied to the north half and total crop N uptake. Error bars represent one standard deviation around the mean of the measured values.

The field experiments performed in this study provide critical insight into the N uptake and leaching for potatoes, as well as other crops which may be inefficient N users. TDR probes and soil samples indicate that irrigation was more than adequate to maintain field capacity moisture content throughout the season. Soil water nitrate measured from soil samples showed nitrate from fertilizer applications completely leached below the root zone within 2-3 weeks following heavy rain and irrigation. Groundwater nitrate levels taken from monitoring wells below the center pivot showed pulses of high nitrate concentrations about 3-5 months after fertilizer applications. Biomass sampling of the spring 2001 potato crop confirm these observations and suggest only about 30% of the total N applied is being taken up by the plants.

CHAPTER 3
MODELING

Existing crop and vadose zone models were used to predict crop yield and nitrate leaching for the spring 2001 potato crop and to simulate the effect of alternative management practices on crop yield and nitrate leaching. LEACHM (Hutson and Wagenet, 1992) is a well-established vadose zone model capable of simulating soil water and solute transport over a wide range of field conditions. DSSAT (Tsuji et al, 1999) is a well-known crop model that is capable of simulating water and solute transport as well as plant development, yield and N uptake. These two models were chosen to complement each other. LEACHM has more rigorous water and chemical transport algorithms than DSSAT, but lacks DSSAT's ability to predict crop response to changes in weather or farm management. By using these two models to predict crop and soil response to N fertilizer, irrigation practices, and observed weather conditions a more complete understanding is gained of the fate of N at this potato farm.

DSSAT Model Description

The Decision Support System for Agrotechnology Transfer (DSSAT) is actually a shell which allows the user to enter, store and retrieve information needed for running and validating crop models. DSSAT simulates plant processes, development and interactions with its environment, and provides a graphical interface that allows the analyzing and viewing of model results. DSSAT is a DOS based program and provides a windows interface to move between the various programs and models contained within the DSSAT shell. DSSAT contains several crop models including the CERES models for grains (e.g. wheat, maize, soybean, etc.), the CROPGRO model for legumes and a potato model called SUBSTOR. The SUBSTOR model was the only crop model used in this research and will be the main focus of this chapter's discussion. All of these crop models use the same hydrologic and contaminant transport algorithms and differ only in the simulation of the plant's growth and environmental interactions. DSSAT is capable of running sequences of different crops to simulate long-term effects of different weather trends, management practices and soil conditions. A minimum data set is required for use of these models including a weather file (weather can be simulated by the subroutines WGEN or SIMMETEO or measured data can be entered), a soils file, a crop file containing genetic coefficients used to define a cultivar's unique characteristics, and a FILEX (a control file that contains information on management practices and directs the executable file to the proper soil, weather and crop files).

Hydrology

DSSAT's soil water balance routines are described by Ritchie (1998) and are used to predict one-dimensional vertical movement of water under variably saturated conditions for a soil profile consisting of several different layers. Ritchie's model evaluates the soil water budget daily and is capable of predicting plant transpiration, root water absorption, soil evaporation, infiltration, runoff and drainage.

Runoff is calculated using the USDA-Soil Conservation Service (SCS) curve number method with a modification for layered soils. Soil moisture content in the upper layer of the soil profile is used to represent the antecedent moisture condition in determining the curve number. Daily precipitation is used in calculating runoff, but irrigation is assumed not to affect runoff generation. Infiltration is defined as the difference between daily water applied (precipitation plus irrigation) and runoff.

DSSAT uses a cascading drainage routine to describe the movement of water from one soil layer to the next and is initiated with the onset of infiltration. Drainage will only occur in a layer (L) when the soil moisture content (θ_t(L)) is between the drained upper limit (θ_u(L) and saturated moisture content (θ_{SAT}(L)) for that layer. The drained upper limit is usually determined from field measurements and corresponds to soil moisture content at water potentials in the range of –0.1 to –0.33bar (θ_u is similar to field capacity). Saturated moisture content is also measured from field values and is defined as the maximum amount of water a particular soil can hold. The volume per unit area of infiltration from the surface is set equal to FLUX(L) for the uppermost layer. The volume of additional water per area that a soil layer is able to hold (HOLD), is than calculated as

$$HOLD(L) = (\theta_{SAT}(L) - \theta_t(L)) * DLAYR(L) \qquad (3\text{-}1)$$

where DLAYR(L) is equal to the thickness in centimeters of that layer.

If FLUX(L) is less then HOLD(L) soil moisture is updated before drainage is calculated as

$$\theta_t(L) = \theta_t(L) + FLUX(L)/DLAYR(L) \tag{3-2}$$

If $\theta_t(L)$ is less than θ_u than no drainage takes place. If the new $\theta_t(L)$ is greater than the θ_u than drainage is calculated:

$$DRAIN = (\theta_t(L) - \theta_u(L)) * SWCON * DLAYR(L) \tag{3-3}$$

where SWCON is input by the user and is the whole profile drainage rate constant. SWCON is similar to hydraulic conductivity but does not vary with moisture content. After drainage soil moisture is recalculated as

$$\theta_t(L) = \theta_t(L) - DRAIN(L)/DLAYR(L) \tag{3-4}$$

and a new value of FLUX(L+1) representing water moving to the layer below is set equal to DRAIN(L).

If FLUX(L) is greater than HOLD, water in excess of HOLD passes to the layer below and drainage is calculated as in equation (3-3) assuming soil moisture is at saturation. FLUX(L+1) is then recalculated for the water moving to the next layer as

$$FLUX(L+1) = FLUX(L) - HOLD(L) + DRAIN(L) \tag{3-5}$$

Potential evaporation is calculated using a modified Priestly-Taylor equation and requires daily total solar radiation (R_s) and daily maximum and minimum temperatures (T_{max} and T_{min}). Daily weather variables are read from a weather text file. First an equilibrium evaporation (EEQ) is calculated using the following equations:

$$EEQ = R_s(4.88 \text{ x } 10\text{-}3 - 4.37 \text{ x } 10\text{-}3 * \alpha) * (T+29) \quad (3\text{-}6)$$

R_s = daily solar radiation (MJ m^{-2} d^{-1})

α = albedo of crop-soil surface (unitless)

T = .6*Tmax + .4*Tmin = average daily temperature in °C

The albedo value is calculated using the model's estimate of leaf area index(LAI) and the bare soil albedo (SALB) input by the user, using one of two equations depending on the growth stage:

$$\text{for pre-anthesis } \alpha = .23 - (.23 - SALB) * \exp(-.75*LAI) \quad (3\text{-}7)$$

$$\text{for post-anthesis } \alpha = .23 + (LAI - 4) * (2/160) \quad (3\text{-}8)$$

EEQ is then adjusted for the effects of temperature and unsaturated air using the following equations to give the potential evaporation (EO).

$$EO = 1.1 * EEQ \quad \text{for } 5<T_{max}\leq 35°C$$

$$EO = EEQ * (1.1 + .05 * (T_{max} - 35)) \quad \text{for } T_{max}>35°C$$

$$EO = EEQ * .01 * EXP(0.18 * T_{max} + 20) \quad \text{for } T_{max}<5°C \quad (3\text{-}9)$$

DSSAT uses the values calculated for potential evaporation in calculating the potential soil evaporation (EOS) and potential plant evaporation (EOP). EOS is modified by LAI using the following equations:

$$EOS = EO * (1-0.42*LAI) \quad \text{for } LAI < 1$$

$$EOS = EEQ * \exp(-.4 * LAI) \quad \text{for } LAI \geq 1 \tag{3-10}$$

Actual soil evaporation (ES) is then calculated using a user-specified soil upper limit of evaporation as described in Ritchie (1972). Once ES has been determined the equivalent water depth is subtracted from the water content of the uppermost soil layer. If this calculation causes soil water content to fall below air dry conditions ES is reduced to a value that would bring the upper water content to air dry water content. Air dry water content is defined as half the value of the lower limit of soil moisture content(θ_{LL}) of the upper layer.

Potential plant evaporation (EOP) is a function of LAI and is calculated for LAI<3 as

$$EOP = \frac{EO \times LAI}{3} \tag{3-11}$$

Actual plant transpiration is then calculated using root water uptake routines described below. If actual soil evaporation plus actual plant evaporation is greater than potential evaporation then potential plant evaporation is reduced by

$$EOP = EO - ES \tag{3-12}$$

Upward flow of water resulting from evaporation and uptake is calculated using methods described by Ritchie (1998) and are similar to the drainage equations discussed earlier.

Root water absorption, described by Hoffman et al (1990), is calculated by first finding the potential uptake per root length for each layer, provided the uptake does not exceed a maximum daily water uptake assumed to be 0.03 cm^3 of water per cm of root. The hydraulic conductivity, $K(\theta)$ (mm/day), is used in the calculation for root water absorption using the following equations:

$$K(\theta) = 5.0 \times 10^{-5} \text{ mm/day} \quad \text{for } \theta_t = \theta_u$$

$$K(\theta) = 5.0 \times 10^{-5} \exp\left(C_T(\theta_t - \theta_{LL})\right) \quad \text{for } \theta_t > \theta_u \qquad (3\text{-}13)$$

where C_T is a unitless texture coefficient calculated by

$$C_T = 100(1.2 - 2.5\theta_{LL}) \qquad (3\text{-}14)$$

The root water absorption rate q_r is determined using a modification of the following equation:

$$q_r = \frac{4\pi K(\theta)(\psi_r - \psi_s)}{\ln(\frac{c^2}{r^2})} \qquad (3\text{-}15)$$

where Ψ_r and Ψ_s are root surface and bulk soil water potentials respectively, r is the root radius in mm and c is the radius of the soil column through which water is moving. Equation (3-15) is then simplified by assuming that 1) $c=(\pi L_v)^{-1/2}$ where L_v is the root density, 2) r= .2mm and 3) the potential difference between the soil and the roots remains constant at 210 mm water for all water contents. Substituting equation (3-14) for $K(\theta)$ and using the three assumptions equation (3-15) becomes

$$q_r = 0.132 \exp \frac{C_T(\theta_t - \theta_{LL})}{2.07 - \ln(L_v)} \quad (3\text{-}16)$$

Equation (3-16) is used to calculate the maximum water absorption rate of the roots. These maximum absorption rates are converted to a potential uptake rate for each soil layer based on the depth and root length density for that soil layer. By summing the root absorption of each layer a total maximum uptake for the entire soil profile can be obtained and compared to the calculated maximum plant transpiration. If the maximum uptake exceeds the calculated maximum plant transpiration then the absorption rate for each layer is reduced proportionately so maximum uptake equals the calculated plant uptake. If the maximum uptake is less than the maximum transpiration then the transpiration rate is set equal to the maximum absorption rate.

Nitrogen Balance

DSSAT's N balance routines are able to estimate N transformations, nitrate movement through the soil profile, and N uptake by plants. If the plants cannot obtain the N needed to meet their demand, deficiency factors are calculated which can inhibit growth and photosynthetic activity. Nitrogen transformation routines predict mineralization of organic N, nitrification, and denitrification (when anaerobic conditions prevail). Nitrogen transport routines can predict the movement of nitrates and urea from one layer to the next but do not have the capability of transporting organic N or ammonium.

Mineralization of organic N into inorganic forms is simulated using an approach described by Seligman and Van Keulen (1981). Organic N is divided into humic material and fresh organic matter (FOM). FOM is further divided into three pools (carbohydrates, cellulose and lignin), which are each assigned decay constants that represent maximum decay under non-limiting conditions. Limitations due to soil moisture, temperature and the effect of the carbon/nitrogen ratio of the soils are calculated and used to reduce the decay of the FOM. Decay of the humic fraction of the soil into inorganic N generally occurs at a much slower rate than the FOM but is calculated in much the same way except the carbon/nitrogen ratio is not taken into account.

DSSAT calculates nitrification of ammonium using a potential nitrification rate based on the Michaelis-Menton kinetic function. It is dependent on the ammonium concentration, but is independent of soil type. An environmental limit on nitrification capacity (ELNC) is used to reduce nitrification. ELNC is a function of temperature, soil moisture content and soil ammonium concentration and has a value ranging from zero to one.

Movement of nitrate from one layer to the next is dependent on the water flux and soil moisture content calculated in the hydrology routines, and the mass of nitrate in the soil layer (SNO3) in the equation:

$$\mathrm{NOUT} = \frac{\mathrm{SNO3(L)} \times \mathrm{FLUX(L)}}{\theta_t \times \mathrm{DLAYR(L)} + \mathrm{FLUX(L)}} \tag{3-17}$$

where NOUT is the ug N/g of nitrate leached from the layer. If SNO3 is less than 1ug/g, no leaching occurs. These equations assume that all the nitrate in the soil is dissolved in the soil water. Nitrate can move in both vertical directions depending on whether negative or positive potential gradients prevail.

Plant uptake of N depends on the supply of N in the soil and the plant's N demand. In general, plants require a high tissue N concentration early in development and then N concentration slowly decreases as the plant matures and uses N stored in the leaves and stems for further growth of the reproductive organs.

Nitrogen uptake is simulated by first calculating a plant N demand. Plant N demand is calculated separately for the plant vines, roots, and tubers, but uses a similar approach for each. For instance the concentration of N in the plant vines (or tops) is calculated in units of kg N/ha as

$$TNDEM = TOPWT * (TCNP - TANC) \quad (3\text{-}18)$$

where TOPWT is the weight in kg/ha of the tops at that time, TANC is the percent of N mass currently in the vines and TCNP is the critical N concentration, i.e. the minimum concentration at which maximum growth can occur. The value for TCNP is approximated using research from Saffigna et al (1985) and decreases with time as the plants mature. If luxury consumption of N has occurred (TANC>TCNP) then a negative N demand can occur and N uptake will cease until TANC drops below TCNP. This situation will rarely last more than one or two days in the simulation.

After plant N demand is calculated, actual plant N uptake is calculated. Under non-ideal conditions actual plant N uptake can be reduced by low soil moisture content, low soil N concentrations and root length. A soil water factor

(SMDFR) reduces potential uptake based on the soil moisture and takes on a value ranging from zero to one based on the following equation:

$$\text{SMDFR} = \frac{\theta_t(\text{L}) - \theta_{LL}(\text{L})}{\text{ESW(L)}} \tag{3-19}$$

where ESW is the maximum extractable soil water in layer L. Another zero to one factor is introduced based on soil N concentration. FNO3 and FNH4 are nitrate and ammonium concentration factors calculated as

$$\text{FNO3} = 1 - \exp(-.03*\text{NO3(L)}) \tag{3-20}$$

$$\text{FNH4} = 1 - \exp(-.03 * (\text{NH4(L)} - 0.5) \tag{3-21}$$

The actual plant uptake (RNO3U and RNH4U) is then calculated as (only nitrate shown)

$$\text{RNO3(L)} = \text{RLV(L)} * .008 * \text{SMDFR} * 2 * \text{DLAYR(L)} * 100 * \text{FNO3} \tag{3-22}$$

where 100 is a unit conversion, .008 is a coefficient based on the maximum daily potential N uptake of a unit length of root as estimated by Warncke and Barber (1974), and RLV(L) is the root density factor.

The actual plant N uptake is then summed for all the layers and compared to the total plant demand from N. If the sum of actual uptake exceeds plant demand then plant uptake is reduced and N is redistributed proportionally back in the soil profile. The effects of N deficiency on the growth and photosynthetic ability of the plant is described in the crop growth and development section of this chapter.

Crop Growth and Development

The SUBSTOR Potato Version 2.0 crop model was used in this study to simulate the phenological development and biomass accumulation of the Red LaSoda potato and its response to different management practices, soils and climates. Substor-Potato is intended for use over a wide geographic range and for different cultivars. The model is capable of providing a wide range of outputs which include daily measurements of water and N uptake; individual dry matter weights of the plant's roots, stems, tubers and leaves; leaf area index (leaf area subtended per unit area); and phenological growth stage. User inputs into the SUBSTOR Potato model come from weather files, water and N balance routines, a FILEX and a cultivar file. The cultivar file contains five genetic coefficients (G2, G3, PD, P2 and TC) which characterize crop growth and development. These coefficients can be manually input or calculated with the subroutine GENECALC. Due to the large number of variables involved in this simulation a reference table (Table 3-1) provides the names of some of the more essential variables as they appear in the FORTRAN code along with a brief definition.

Table 3-1. Selected DSSAT variables and definitions.

Variable Name	Definition
AMIN1	a factor representing the effecs of temperature, soil moisture and N deficits on plant growth and development
AMIN2	a factor representing the effecs of temperature, soil moisture and N deficits on photosynthesis
G2	genetic coefficient for maximum leaf expansion rate
G3	genetic coefficient for tuber growth rate
ISTAGE5	pre-planting developmental stage
ISTAGE6	planting to sprout germination developmental stage
ISTAGE7	sprout germination to emergence developmental stage
ISTAGE1	emergence to tuber initiation developmental stage
ISTAGE2	tubers initiation to maturity developmental stage
LALWR	leaf area to leaf weight ratio
P2	dimensionless genetic coefficient for the sensitivity of tuber initiation to photoperiod
PD	genetic coefficient for deteminancy
PLA	daily plant leaf area growth
NDEF	nitrogen deficit factor
RTFSOIL	temperature factor for tuber and root growth
RTPAR	partition of assimilate to roots
RTFVINE	temperature factor for vine growth
TEMPM	mean daily soil temp
TEMPMN	minimum daily air temp
TEMPMX	maximum daily air temp
TIND	proportion of potential tuber growth receiving first priority of carbon assimilate

The SUBSTOR Potato model simulates crop growth by dividing the plant's life into different stages of phenological development represented by the variables ISTAGE5 (pre-planting) to ISTAGE2 (maturity) described in Table 3-1. Accumulation and partitioning of biomass are a function of the developmental stage of the plant. The most important environmental variables affecting phenological development and biomass accumulation are temperature, photoperiod (daylength) and intercepted radiation. Temperature effects are represented by thermal time with the use the step functions RTFSOIL and

RTFVINE shown in Figure 3-1. Thermal time is the summation of the daily RTFSOIL or RTFVINE calculations, and is used to calculate growth stage, daily leaf expansion and biomass accumulation. Intercepted radiation is a function of leaf area index and daily solar radiation. Photoperiod is calculated in DSSAT, however, early cultivars such as the crop modeled in this experiment are not very sensitive to photoperiod. Soil water and N levels also play an important role in plant development and biomass accumulation through the use of equation modifiers NDEF and SWDF which are explained in detail at the end of this section.

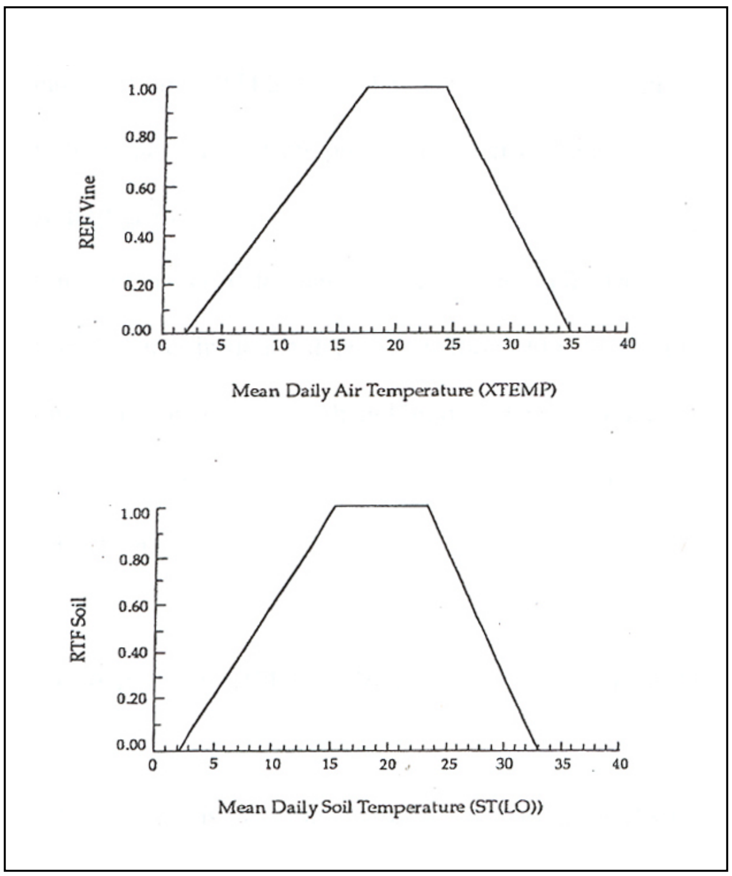


Fig 3-1. Relative thermal time functions for vine growth (RTFVINE) and for tuber and root growth (RTFSOIL) (Griffin et al., 1993).

The pre-emergent growth stage includes all development prior to plant emergence. Observed emergence dates entered into the input file is preferred to the simulation of plant emergence due to the difficulty of reliably obtaining accurate seed piece physiology. In this experiment observed emergence was used based on observations from weekly field trips. If emergence is simulated, germination and sprout elongation is a linear function of RTFSOIL and emergence occurs when sprout length is greater than the depth of planting. During pre-emergent growth the seed piece is the only carbon source to support growth.

Post emergent growth is divided into vegetative (ISTAGE1) and tuber-bearing (ISTAGE2) stages by the tuber initiation date. Estimation of the tuber initiation date is critical since fundamental changes in growth and biomass partitioning occur at this stage. Carbon accumulation, however, is similar for both the vegetative and tuber bulking stages and is estimated by the formula:

$$CARBO = PCARB*AMIN1(PRFT,SWDF1,NDEF1) + 0.5*DDEADLF \qquad (3\text{-}23)$$

where CARBO (g plant^{-1} day^{-1}) is the actual carbon assimilation; AMIN is a unitless modifier ranging from zero to one for temperature factor (PRFT) and soil water (SWDF1) and N deficits (NDEF1); and DDEADLF (g plant^{-1}) is carbon contribution of senesced leaves prior to abscission. PCARB (g plant^{-1} day^{-1}) is the potential assimilated carbon and is calculated as

$$\text{PCARB} = \frac{\text{RUE} \times \text{PAR}}{\text{PLANTS} \times (1.0 \times \exp(-0.55 \times \text{LAI}))} \tag{3-24}$$

where PLANTS is the number of plants per m^2, PAR (MJ m^{-2}) is photosynthetically active radiation and RUE is the radiation use efficiency and equals 3.5 g MJ^{-1} during ISTAGE1 and 4.0 g MJ^{-1} during ISTAGE2 as shown by Sale (1973). Assimilated carbon is obtained from photosynthetic assimilate, seed reserves and carbohydrate reserves. The main difference in growth between ISTAGE1 and ISTAGE2 lies in the difference in carbon partitioning. During ISTAGE1 the proportion of total carbon partitioned to each organ remains constant between stressed and unstressed conditions. During ISTAGE2 partitioning to tubers is given first priority so any deficit in carbon may cause rapid cessation of vine and leaf growth. A greater proportion of total assimilate is allocated to tubers under low temperature, short photoperiod and low to moderate soil water or N levels. Table 3-2 shows the calculations used to simulate daily biomass during both the vegetative and tuber bulking.

Table 3-2.DSSAT plant growth functions.

Variable	Vegetative Growth	Tuber Bulking Growth
Potential Leaf Expansion (PLAG)	= EXP(RLGR)*PLA - PLA	=(G2*RFTVINE/PLANTS)* ÅMIN1(SWDF2,NDEF2)
Relative leaf growth rate (RLGR)	= 0.5*RTFVINE	NA
Leaf Growth (GROLF)	= PLAG (1/LALWR)	= PLAG/LALWR
Stem Growth (GROSTM)	= GROLF	= 0.75*GROLF
Root Growth (GRORT)	=(GROLF+GROSTM)*RTPAR	=(GROLF+GROSTM)*0.2
Potential Tuber Growth (PTUBGR)	NA	= G3*RTFSOIL/PLANTS
Actual Tuber Growth (GROTUB)	NA	=PTUBGR*AMIN1(SWDF2, NDEF2)*TIND

The effect of soil water and N content on the growth of the plants is mainly simulated through the use of three stress factors which are calculated using the conditions reflected from the soil-water and N transport routines. The deficit factors SWDF1 and SWDF2 reflect the effects of water deficit on photosynthesis and growth respectively, and the factors NDEF1 and NDEF2 reflect the effects of N deficit. These factors range in value from zero (most extreme) to one (ideal) and are used as multipliers in several equations to account for these environmental factors. Soil water deficits can cause a reduction in growth and photosynthesis, increase allocation of biomass to the tubers and increase the rate of phenological development. SWDF1 and SWDF2 are calculated as the fraction of actual to potential water uptake and transpiration (see Figure3-2). NDEF1 and NDEF2 are calculated solely on the plant's vine N concentration based on previous research which found this to be a sensitive indicator of N fertility. The following equations are used to calculate NDEF1 and NDEF2:

$$NFAC = \frac{TCNP - TANC}{TCNP - TMNC} \tag{3-25}$$

$$NDEF1 = NFAC \tag{3-26}$$

$$NDEF2 = .95 \times NFAC \tag{3-27}$$

where TCNP is a critical concentration required for maximum plant growth and photosynthesis, TMNC is the minimum concentration below which development ceases, and TNAC, the actual vine concentration.

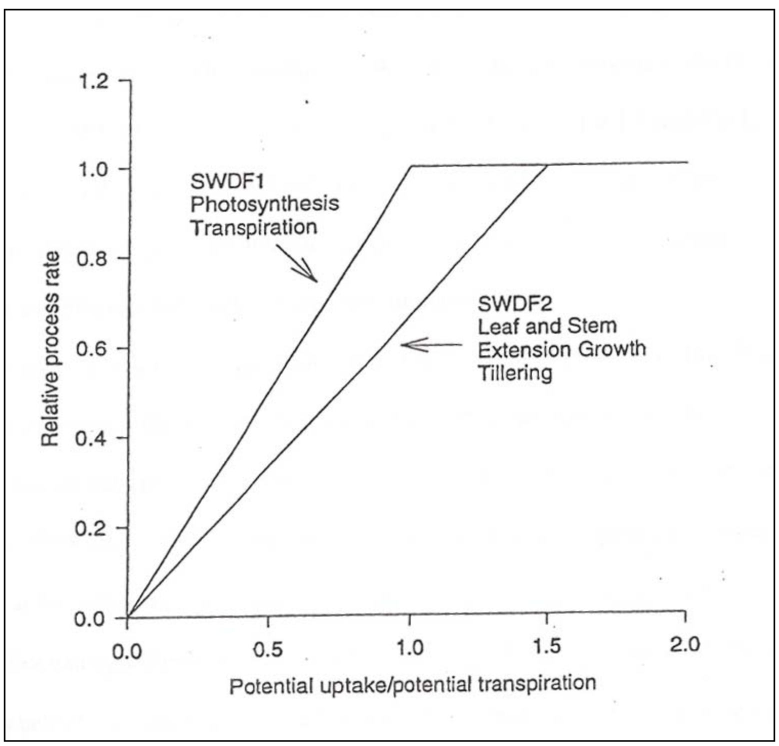


Fig 3-2. Relationship between soil water stress factors and potential transpiration/uptake in the DSSAT model (Ritchie, 1998).

DSSAT Input File

Unlike LEACHM which uses a single input file, DSSAT requires several different input files. The FILEX is the main input file which contains information on crop management, output formats and simulation options. The FILEX is also used to direct the simulation to the proper weather, soil and cultivar files. Each of these files will be explained in detail and the input files are included in Appendix C. DSSAT provides several interactive data management programs that allow properly formatted files to be easily created by proceeding through the necessary windows and answering the prompts. In addition to the files mentioned below, two optional files called FILET and FILEA can be made to compare simulated results to measured data. These two files are not necessary to run the crop models but can be used to calibrate genetic coefficients or to display measured data graphically against the simulated results.

A single FILEX is capable of running many different experiments. FILEX allows simulation of several different treatments which can either all receive completely different management practices, cultivars and environmental conditions, or share similar conditions. This allows easy organization of experiments where separate treatments are imposed on the same crop, or sequences of different crops are grown over several seasons. For example the FILEX shown in the Appendix C has treatments for the north and south half of the center pivot, which differ in the irrigation and fertilizer treatment but use the same cultivar, soil and weather.

After the treatment section of the FILEX, a cultivar section lists the name(s) of the crop being grown and directs the simulation program to the proper file in order to retrieve the genetic coefficients for that cultivar. The potato coefficients are listed in the Appendix C and were obtained by starting with a sample potato cultivar's coefficients from a potato crop grown in Hastings, FL, that is included with the DSSAT software. The values were then manually adjusted to try to more closely fit measured data from Suwannee Farms, however the basis for these adjustments are somewhat difficult to justify. Only one season of potato has been observed and simulated at the research site to date which makes calibration difficult. Therefore the values were adjusted within a reasonable limit based on those observed from other potato experiments to obtain the closest results possible to those measured in this study.

The Fields section of the FILEX is most important from the simulation standpoint for assigning a soils file to experiment. The soils file used in this experiment is listed in Appendix C and information for this file was obtained through field measurements done on site or by the use of a similar soil found in the soil characterization for Florida soils (Sodek et al, 1990). The soil profile can be input using any number of unique soil layers and the code does not necessarily require layers of equal thickness. Drained lower limit, saturated moisture content, bulk density and saturated hydraulic conductivity were obtained from the site measurements. Soil albedo, family name, organic carbon content, pH, particle size information and runoff curve number was found using the Blanton fine sands data (located in Columbia County, FL) from Sodek et al (1990). The value for the drained upper limit was set to 9% for the 0-30cm depths and 8% for 0-60cm, which best represented the observed steady-state, equilibrium water content in the field. The initial conditions of the soil profile at the beginning of the simulation is set in the FILEX and not in the soils files. Initial soil water content, ammonia and nitrate concentrations were set based on results of soil sampling performed on Dec 6, 2000. Initial crop residue and N residue was assigned a value of zero due to the insensitivity of the model to these variables and the lack of field data. Initial organic N was set at about 2100 kg/ha based on input values from another DSSAT soils file for Millhopper fine sands. Transformation of organic N to its inorganic forms is very slow, and of the 2100 kg/ha of organic N specified as the initial condition only 11 kg/ha was transformed over the period of the potato crop simulation.

Planting details such as row spacing, planting depth, planting date, planting method, irrigation and fertilizer management were all obtained from the grower. Emergence date was observed in the field. The plant population at emergence was never measured, therefore the planting density given by the farmer was used to obtain all field totals from the per plant measurements. Weather data are contained in a separate weather file and contains date, daily precipitation, daily maximum and minimum temperatures and daily solar radiation. Other options available in DSSAT include routines which can allow crop rotations, multiple year simulations, automatic water and N management routines that water and fertilize the plants whenever necessary, and automatic harvest at plant maturity.

LEACHM Model Description

The leaching estimation and chemistry model (LEACHM) was developed by Hutson and Wagenet (1992) and is a deterministic model which can simulate water and N transport in unsaturated soils. This model focuses on water transport and chemical processes in the soil rather than crop modeling. LEACHM is comprised of three main executable programs LEACHN (the N and phosphorous model), LEACHP (routines for simulating pesticide movement) and LEACHW (routines for simulating water movement) but only LEACHN will be discussed in this section. Version 3.0 of LEACHM (revised in February 2001) was used in this study.

Hydrology

LEACHM uses a finite-difference form of the one-dimensional Richards' equation to solve transient water flow problems. Richard's equation is derived from the law of mass conservation (3-28) and Darcy's law (3-29):

$$\frac{\partial(\rho\theta)}{\partial t} = -\frac{\partial(\rho q_z)}{\partial z} \qquad (3\text{-}28)$$

$$q_z = -K(\theta)\frac{\partial H}{\partial z} \qquad (3\text{-}29)$$

Where ρ is the density of water, t is time, θ is moisture content, q_z is one-dimensional vertical Darcy flux, z is elevation, H is total hydraulic head, made up of the sum of pressure head and elevation head (H=Ψ+Z), and K(θ) is soil hydraulic conductivity as a function of moisture content. Richards' equation is then obtained by combining equations (3-28) and (3-29):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - U(z,t) \qquad (3\text{-}30)$$

The second term of the right hand side of the equation (3-30) is a source/sink term as a function of time and depth and can account for irrigation and evapotranspiration. A second form of Richards' equation can be obtained by substituting total hydraulic head as the sum of the elevation head plus the pressure head, expressing soil hydraulic conductivity as a function of pressure head instead of moisture content and introducing the term $C(\Psi) = \frac{\partial \theta}{\partial \psi}$, defined as the specific moisture capacity. Equation (3-30) can then be solved in terms of pressure head as

$$C(\Psi)\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\Psi)\frac{\partial(\Psi + z)}{\partial z}\right] - U(z,t) \qquad (3\text{-}31)$$

LEACHM solves for the pressure head in equation (3-31) using a finite difference technique. The soil profile is divided into segments of equal height and an upper and lower boundary is defined with specific boundary conditions. The upper boundary can change with time as water infiltration, evaporation and zero-flux conditions affect the top surface of the profile. The lower boundary can be assigned either as a fixed water table, a free draining profile, a zero-flux boundary or a lysimeter tank boundary condition. Each segment of the soil profile can be assigned a unique set of soil characteristics and initial conditions.

In order to solve equation (3-31) the specific moisture capacity [C(Ψ)] and hydraulic conductivity [K(Ψ)] functions need to be defined. LEACHM uses the Campbell's water retention equation to define the C(Ψ) and K(Ψ) function and to establish the relationship between the fractional water content (θ) and pressure potential (Ψ):

$$\Psi = a\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{3-32}$$

where θ_s is the saturated water content. Variables a and b in Campbell's equation are found by fitting the equation to measured water retention parameters but have no real physically based meaning. Campbell's equation has a sharp discontinuity at $\theta=\theta_s$ (ie h=a). To avoid this discontinuity the function is replaced by another function at high potentials (ie water contents close to saturation). For pressure potentials between zero and h_c,

$$h = \frac{a\left(1-\frac{\theta}{\theta_s}\right)^{1/2}\left(\frac{\theta_c}{\theta_s}\right)^{-b}}{\left(1-\frac{\theta_c}{\theta_s}\right)^{1/2}} \tag{3-33}$$

where (h_c,θ_c) is the point of intersection of the curves and

$$h_c = a\left[\frac{2b}{1+2b}\right]^{-b} \tag{3-34}$$

$$\theta_c = \frac{2b\theta_s}{1+2b} \tag{3-35}$$

The resulting composite water retention curve is sigmoidal, continuous and has a differential water capacity of zero at saturation.

The hydraulic conductivity versus water content function used in LEACHM is

$$K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+2+p} \tag{3-36}$$

In this equation p is a pore interaction parameter and is set to 1 and b is the same as in equation (3-34). A user-input value for at least one point along the K-θ curve is required to match the remaining points of the curve.

Evapotranspiration is an important component in the source/sink term and is computed based on methods of Childs and Hanks (1975). Weekly pan evaporation totals (PAN), a pan factor (f_{pan}) and a crop cover fraction at plant maturity (f_{crop}) are required inputs for calculations of daily evaporation and plant transpiration. Daily potential evapotranspiration (ET_{day}) is calculated as

$$ET_{day} = \frac{f_{pan} \times PAN}{7} \tag{3-37}$$

Daily potential ET is allocated between daily potential transpiration (T_{day}) and daily potential evaporation (E_{day}) by the equations:

$$T_{day} = ET_{day} \times f_{crop} \quad (3\text{-}38)$$

$$E_{day} = ET_{day} - T_{day} \quad (3\text{-}39)$$

where f_{crop} is the crop cover fraction which increases with time as the plant canopy grows to maturity (calculation of f_{crop} is discussed in more detail in the Crop Development section of this chapter). ET is assumed to start at 7:12^{am} and end at 7:12^{pm} during which time evaporation rates vary sinusoidally over time. A potential evapotranspiration flux density (ET_p,mm/d) is distributed over time as

$$ET_p = ET_{max}\sin[(2\pi(t-0.3)] \quad (3\text{-}40)$$

where ET_{max} is ET_p at .55 day and t is time, varying between .3 (7:12^{am}) and .8 (7:12^{pm}) day. E_{day} and T_{day} are then divided, using the same time steps that eq (3-40) is distributed over, into potential evaporation (E_p) and transpiration (T_p) for that time step using the equation:

$$E_p = fE_{day} \quad (3\text{-}41)$$

$$T_p = fT_{day} \quad (3\text{-}42)$$

where f is a function that varies with time and represents the fraction of total evapotranspiration lost during a certain time increment. Actual evaporation (E_a) is calculated by comparing the potential evaporation flux density ($E_p/\Delta t$) during a time interval (Δt) to a maximum possible flux density (q_{max}) (calculated using current water potentials, hydraulic conductivity and an 'air dry' potential described in Hutson and Wagenet (1992)) and the minimum value is taken as E_a. If E_a falls below the potential evaporation flux density ($E_p/\Delta t > q_{max}$) then T_a is increased by the deficit, $E_p - E_a\Delta t$ up to a specified maximum value,

$$T_p = \text{minimum}\ (T_pR_t,\ T_p + E_p - \Delta t E_a) \qquad (3\text{-}43)$$

where R_t is a specified maximum ratio of actual to potential transpiration.

Absorption of water by the plant's roots is calculated using a method by Nimah and Hanks (1973) using a number of coefficients describing root-soil water interactions, a root density factor, hydraulic conductivity and depth of node. Transpiration cannot proceed below water contents corresponding to –1500 kPa and thus actual transpiration can fall below potential transpiration in dry soils.

Solute Movement

Solute transport is predicted by LEACHM by solving the convection-diffusion equation (CDE). In deriving the CDE equation, the principle of mass conservation is used to relate the total solute flux (J_T) with the total concentration of a substance (C_T). Similar to the Richards' equation, described in the hydrology section of this chapter, only a one-dimensional transport is considered with fluxes moving only in the vertical direction.

Since N in the gaseous phase represents an insignificant portion of total flux, a discussion of solute transport is limited to N in the liquid phase only. Total solute flux (J_T) in the liquid phase is given by the equation (3-44):

$$J_T = J_{DL} + J_{CL} \tag{3-44}$$

where J_{DL} and J_{CL} is dispersive and convective fluxes respectively. Diffusive flux in the aqueous phase (J_{DL}) can be represented by Fick's law in terms of the product of a chemical concentration gradient ($\partial C/\partial z$) and a diffusion coefficient

$$J_{DL} = -D_P(\theta)\,\frac{dC}{dZ} \tag{3-45}$$

where $D_P(\theta)$ is the effective diffusion coefficient estimated from Kemper and VanSchaik (1966) using empirical formulas. Convective liquid flux (J_{CL}) can be written in terms of a macroscopic water flux (q) and a hydrodynamic dispersive flux in the following equation:

$$J_{CL} = -\theta D_M(q)\frac{dC}{dz} + qC \tag{3-46}$$

$D_M(q)$ is calculated as

$$D_M(v) = \lambda\,|v| \tag{3-47}$$

where ν is the pore water velocity (ν=q/θ) and λ is the dispersivity, with a range of about 2mm to 80mm. The terms on the right-hand side of equations (3-45) and (3-46) can be combined to give a general equation:

$$J_{DL} + J_{CL} = -\theta D(\theta,q)\,\frac{dC}{dz} + qC_L \tag{3-48}$$

where D(θ,q) is the apparent diffusion coefficient ($mm^2\ d^{-1}$) and is defined as

$$D(\theta,q) = \frac{D_P(\theta)}{q} + D_M(q) \tag{3-49}$$

Using the principle of mass conservation, the mass flux is related to the total concentration of substance by the equation:

$$\frac{\partial C_T}{\partial t} = -\frac{\partial J_T}{\partial z} \pm \phi \tag{3-50}$$

where ϕ is a source/sink term. Equations (3-48) and (3-50) are combined to obtain the general transport equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\theta D(\theta,q)\frac{\partial C}{\partial z} - qC\right] \pm \phi \tag{3-51}$$

LEACHN solves equation (3-51) using a finite difference method using the same soil segments and boundary conditions required for the solution of Richard's equation.

Nitrogen Transformation

The value of the source/sink term in equation (3-51) is determined at the start of each time step and represents the net effects of transformation, degradation and uptake by plants. LEACHN simulates the transformation and flux of N between organic-N, nitrate-N and ammonium-N using concepts described by Johnsson, et al. (1987). The three major transformation processes are mineralization of three major organic pools (feces, litter and humus), nitrification and denitrification.

Mineralization of the three organic N pools are described by a first-order rate law as

$$\frac{dN_i}{dt} = -\mu_{mi} N_i(z) \qquad (3\text{-}52)$$

where μ_{mi} is a rate constant which differs among each of the organic N forms and N_i is the concentration of humus, litter or feces. Nitrification (oxidation of NH_4^+ to NO_3^-) proceeds at a potential rate $\mu_{nit} N_{NH4}$ and decreases as a maximum NO_3^- /NH_4^+ concentration ratio (r_{max}) is approached:

$$\frac{NH_4}{dt} = -\mu_{nit} \max(0, (N_{NH4}(z) - \frac{N_{NO3}(z)}{r_{max}})) \qquad (3\text{-}53)$$

Denitrification follows Michaelis-Menten kinetics with the equation:

$$\frac{dN_{NO3}}{dt} = \frac{-\mu_{denit} N_{NO3}(z)}{N_{NO3}(z) + C_{sat}} \qquad (3\text{-}54)$$

where μ_{denit} is a potential rate and C_{sat} is a half-saturation constant. These three transformation processes are adjusted to account for temperature and water content response which decreases the transformation processes for temperature and water content values lying outside of an optimum range, except for the denitrification process which increases with increased water content.

Nitrogen uptake by plants is based on the Watts and Hanks (1978) approach and requires the input of a total potential N uptake for each crop. Daily potential uptake is then estimated as a fraction of total N uptake (FTNU) based on time as measured by the fraction of the growing season (FGS):

$$FTNU = 8.878FGS^{3.87} \text{ for } 0 \leq FGS \leq 0.3 \qquad (3\text{–}57)$$

$$FTNU = 0.660FGS + 3.485FGS^{2} - 0.930FGS^{3} - 0.899FGS^{4} \text{ for } .3 \leq FGS \leq 1.0$$

Crop Development

Plant growth data are used by LEACHM (1) to partition potential evapotranspiration into potential evaporation and potential transpiration and (2) to define the distribution of roots with depth which is in turn used to determine water and chemical uptake within each soil segment. LEACHM is not a crop model and cannot predict crop yield, plant N uptake, rooting depth or phenological development of the crop. Instead LEACHM relies on user inputs for plant N uptake, phenological development and rooting depth in its calculations of the water and N balance. Three plant growth options are available in LEACHM: no plants, constant root distribution and cover and growing plants. For the growing crop option a crop cover fraction at maturity together with dates of planting, emergence, root maturity, crop maturity and harvest are specified. Equations developed by Davidson et al (1978) for corn growth are used to describe crop cover as a function of time, and root density as a function of time and depth. Fractional crop cover (f_{crop})with time is described empirically by the sigmoidal curve:

$$f_{crop} = \frac{f_{crop@maturity}}{\left(1 + \exp\left[6 - \frac{12t_i}{t_2}\right]\right)} \tag{3-58}$$

where t_i is time elapsed since germination and t_2 is total time between germination and plant maturity. Root density distribution is determined by a relative root depth factor that can expand or compress a default root distribution.

LEACHM Input File

Inputs necessary for running the LEACHM model are all contained in a single text file. Actual values of inputs can be viewed in Appendix D and the source of the input data is explained in this section. Inputs dealing with the format of output files and printing options are left out of this discussion.

A profile depth of 105 cm with 15 cm segments was chosen for easy comparison with shallow soil cores and TDR measurement interval which are both divisible by 15 cm. A free draining lower boundary condition was chosen for this simulation. Initial water content, nitrate and ammonium concentrations for the input file was taken from field conditions measured from deep soil samples in December 2000.

To calculate soil water retention parameters for Campbell's equation measured values of bulk density, saturated hydraulic conductivity and retention data from soil cores taken from the farm during the summer of 2001 were used (see Table 2-4). Campbell constants were initially fit to the measured retention data using the program RETFIT.EXE included with the LEACHM software package. However RETFIT was unable to provide an acceptable fit for the soil pressure experienced in the field due to few data points within this region of the curve. To remedy the situation a series of points were manually input into RETFIT which provided linear interpolation of the water retention measurements within the pressure potentials observed from tensiometer measurements taken in the field to improve the fit in this region. Figure3-3 shows the measured retention data points and the results of the best-fit curve. The best-fit values for AEV and BCAM of –0.869 and 1.72 respectively were used. While bulk density and hydraulic conductivity values changed over depth the Campbell's constants remained constant over depth due to the difficulty of accurately fitting the curves and the similarity of the measured data with depth.

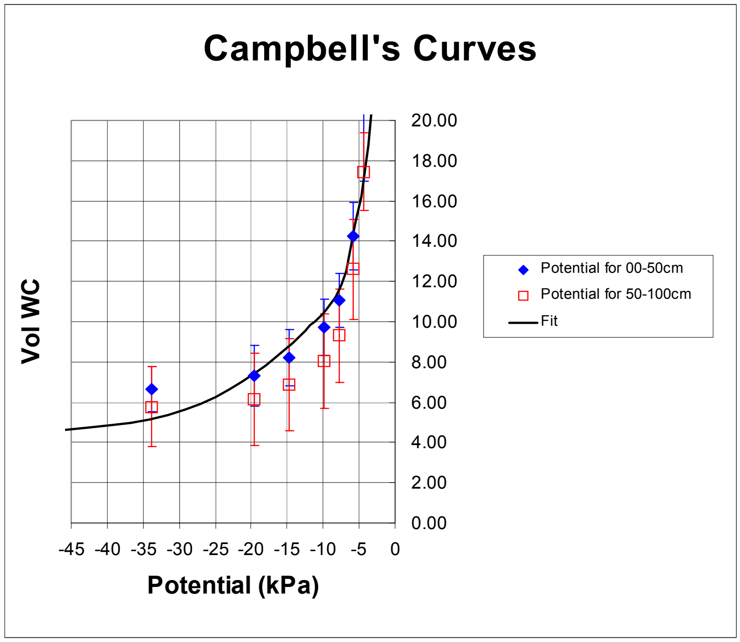


Fig 3-3. Measured retentivity data and the best-fit Campbell curve. Error bars represent one standard deviation around the mean of the measured values.

Well-drained sandy soils and almost no observable slope at the research site create conditions unfavorable for any runoff. A slope of 0% was entered in order to bypass the runoff routine. A curve number of 60 was entered based on acceptable values for sandy soils but since the runoff routine is bypassed due to no slope this value should not have any effect on the simulation.

Crop data inputs were set for a single growing crop with total N uptake and dates of germination, emergence, cover and harvest taken from observed data. Crop cover fraction at maturity was estimated from measured LAI values. Relative root depth was estimated at 0.2 which reflected observed root density.

Root maturity was estimated at 45 days after planting based on DSSAT predictions.

Nitrogen applications were input as kg/ha N based on management practices provided by the grower and listed in Table 2-3. Simulated applications of N were double that of reported fertilizer rates. This is due to the fact that applications were reported as mass per total field area, and since the fertilizer was banded into the rows, which only makeup half the area of the field, actual rates would double. It is important to note however that the results of the total N leached only represents leaching in the rows and would need to be divided in half to obtain an accurate measurement of the leaching rates per field area. Rainfall and irrigation were input based on measured readings from an on-site weather station and irrigation records provided by the farmer. A sample of irrigation water taken in spring 2001 showed 20 mg/L of nitrate-N dissolved in the irrigation water. This value was used as an input in LEACHM. As a result, over the course of the simulation a total of 100 kg/ha of N was added from irrigation water. Weekly potential ET was calculated by summing daily ET values using the modified Priestly Taylor method (explained in the DSSAT model description section). Mean temperatures and amplitude were taken from weather station data. Default values were used for chemical properties, N transformation values and chemical rate constants. These values can be viewed in the input file in Appendix D.

CHAPTER 4
MODELING RESULTS

Calibration and Comparison of Models

In comparing predictions for each model it is important to remember that LEACHM solves more rigorous hydrologic and chemical transport equations but does not have the capability to forecast crop response to different conditions and will predict N uptake and growth based only on the inputs provided by the user. LEACHM input parameters were mostly taken from measured data and required little calibration aside from adjusting the fit of the Campbell water-retention function. DSSAT, on the other hand, uses more empirical hydrologic and chemical transport equations and required more calibration. Model calibration in DSSAT involved adjusting the drained upper limit and crop coefficients to better predict crop dry matter yields (with special attention given to tuber weights) and observed water content. Analysis of both models against measured field data will focus mainly on the soil water content, soil water N concentration, N mass in the soil and, in the case of DSSAT, plant growth.

Figures 4-1(a-i) show a comparison of the measured data and both models' moisture content, soil water concentration and nitrate mass over time for three different depths. Error bars represent one standard deviation around the mean of the measured values. Predicted data for these graphs were obtained from model runs based on north half management practices while measured data

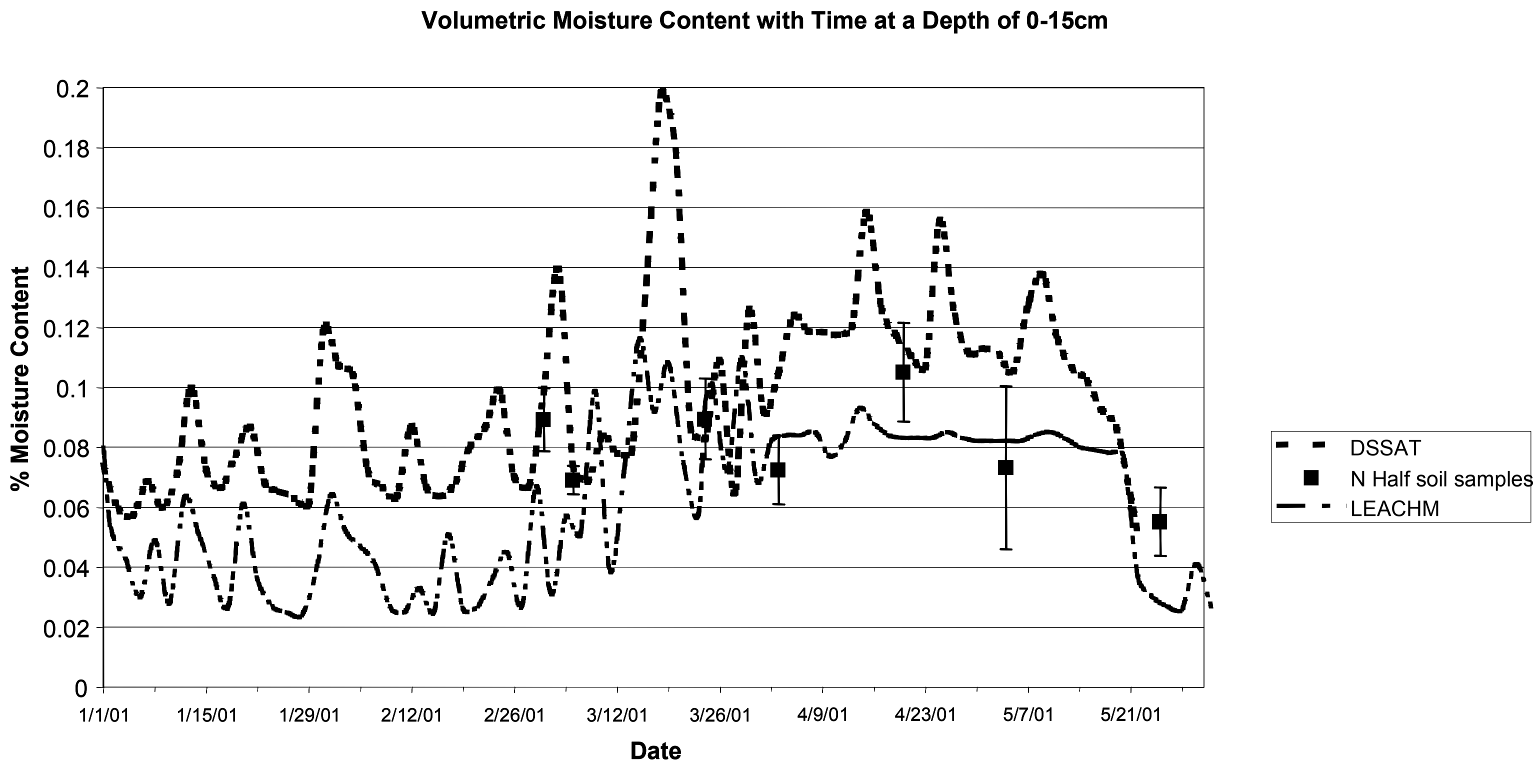


Fig 4-1a. Volumetric moisture content over time comparing LEACHM and DSSAT simulations to measured soil samples for 0-15cm depth.

Fig 4-1. Comparison of DSSAT, LEACHM and measured data for moisture content, nitrate concentration and nitrate mass for selected soil layers.

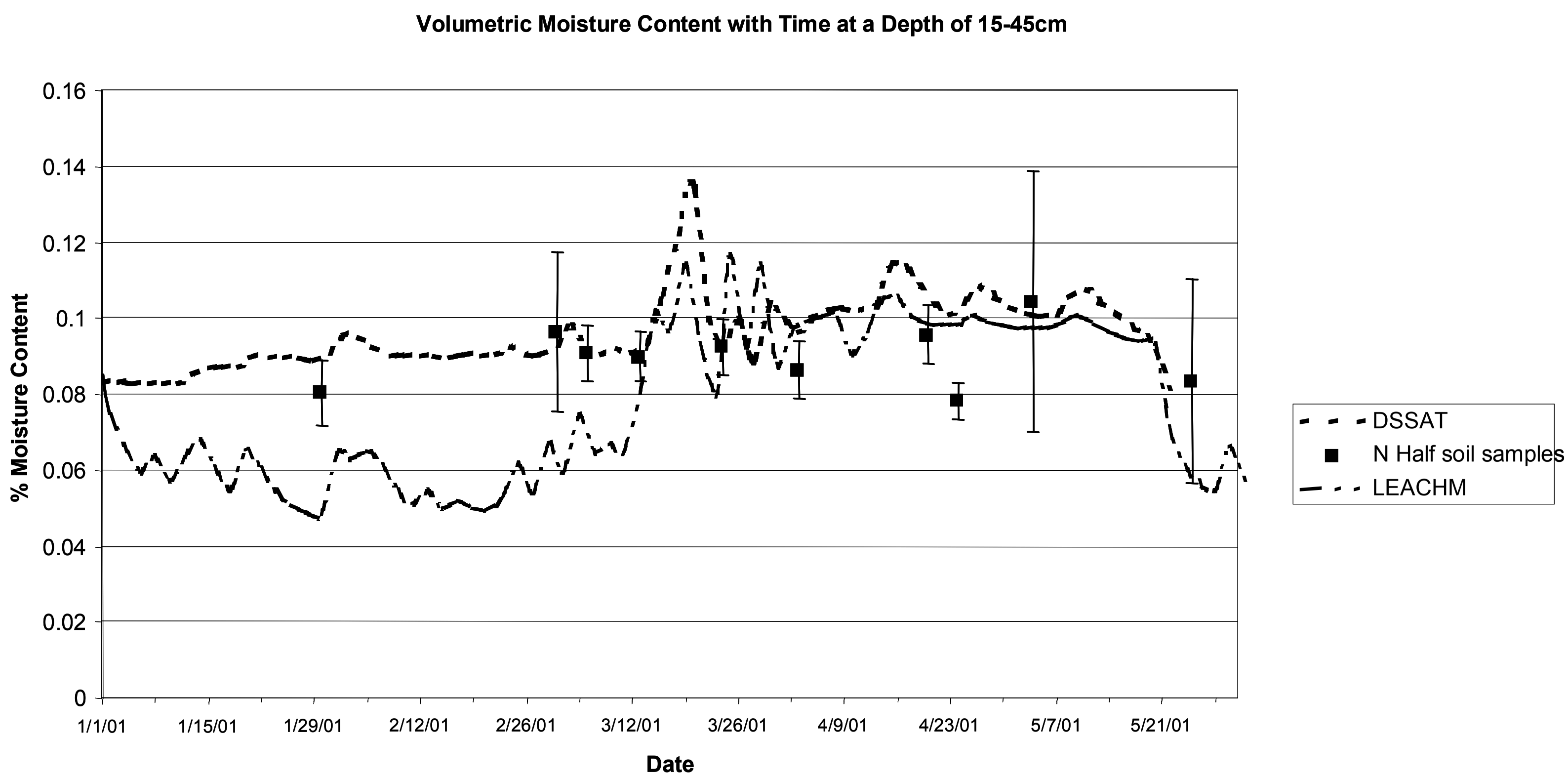


Fig 4-1b. Volumetric moisture content over time comparing LEACHM and DSSAT simulations to measured soil samples for 15-45 cm depth.

Fig 4-1— Continued.

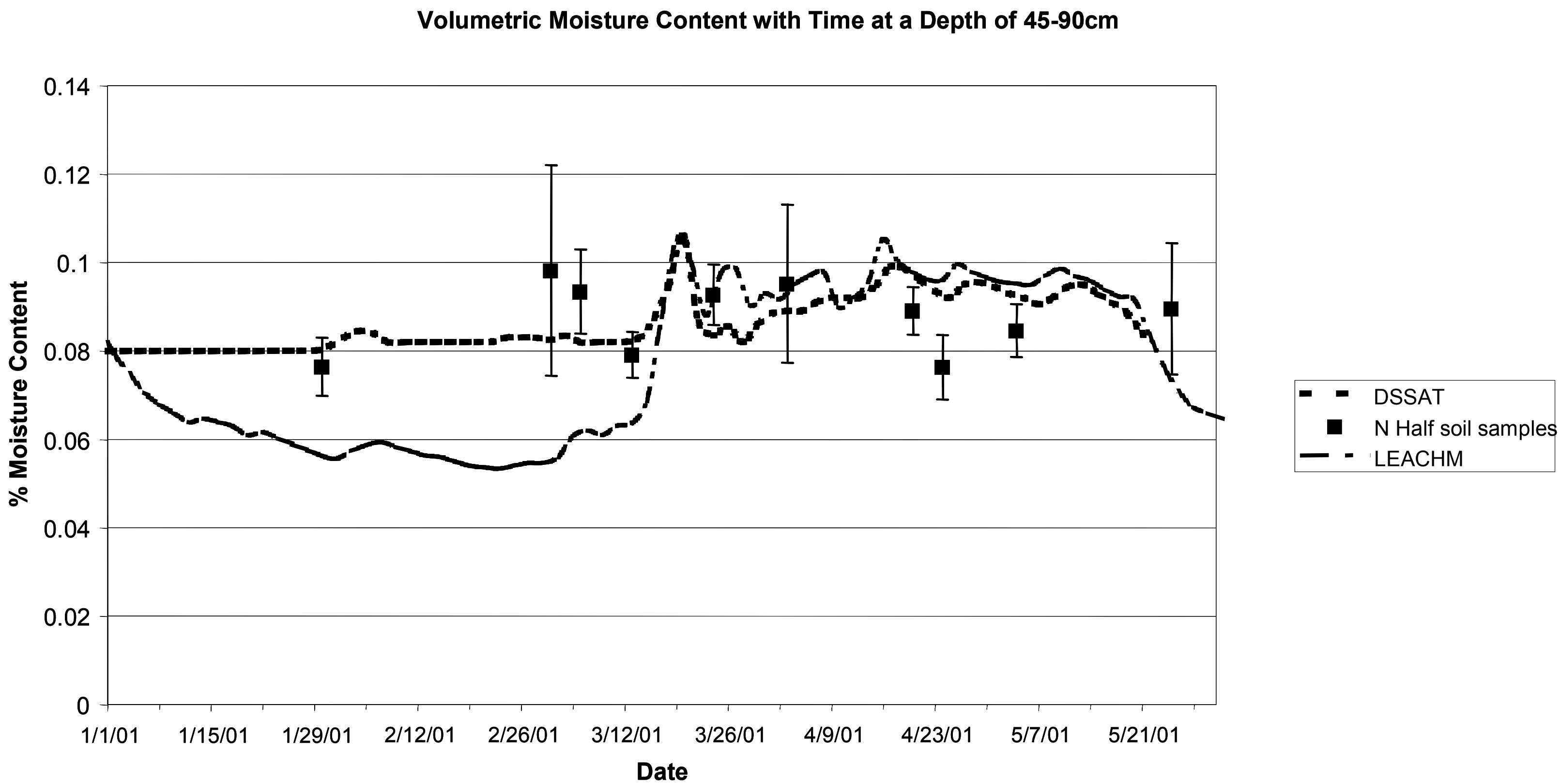


Fig 4-1c. Volumetric moisture content over time comparing LEACHM and DSSAT simulations to measured soil samples for 45-90 cm depth.

Fig 4-1— Continued.

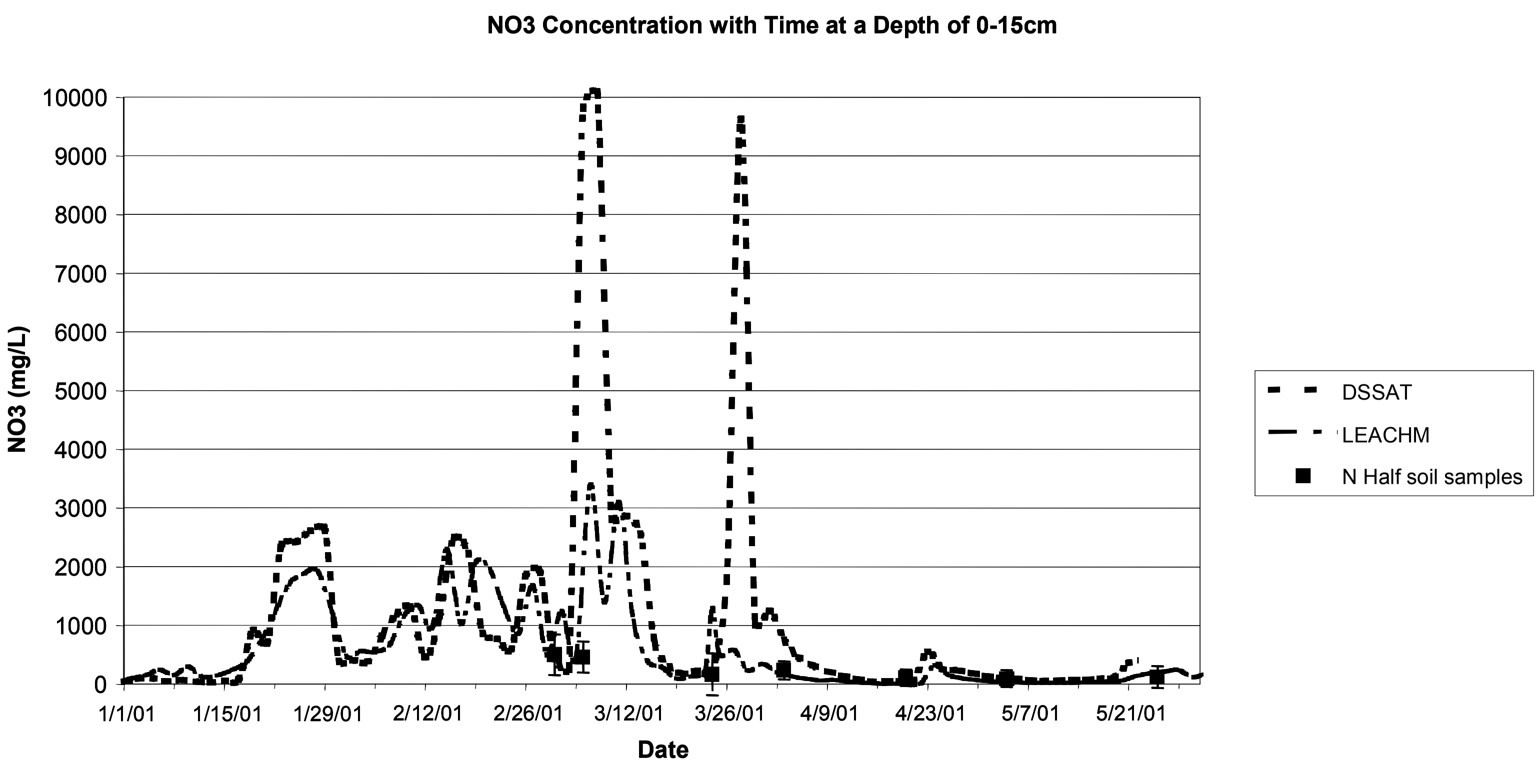


Fig 4-1d. Nitrate concentration over time comparing LEACHM and DSSAT simulations to measured soil samples for 0-15cm depth.

Fig 4-1— Continued.

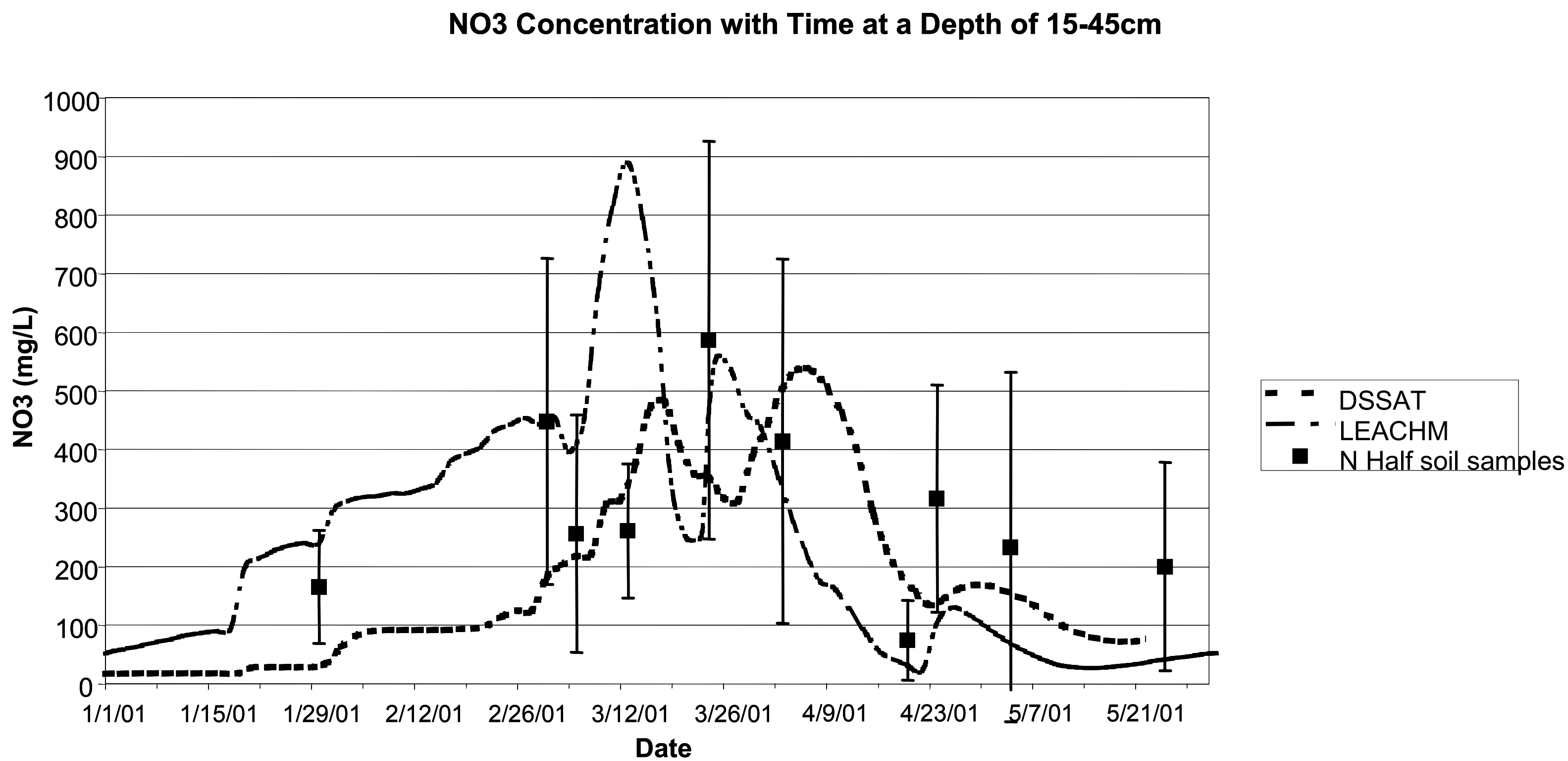


Fig 4-1e. Nitrate concentration over time comparing LEACHM and DSSAT simulations to measured soil samples for 15-45 cm depth.

Fig 4-1— Continued.

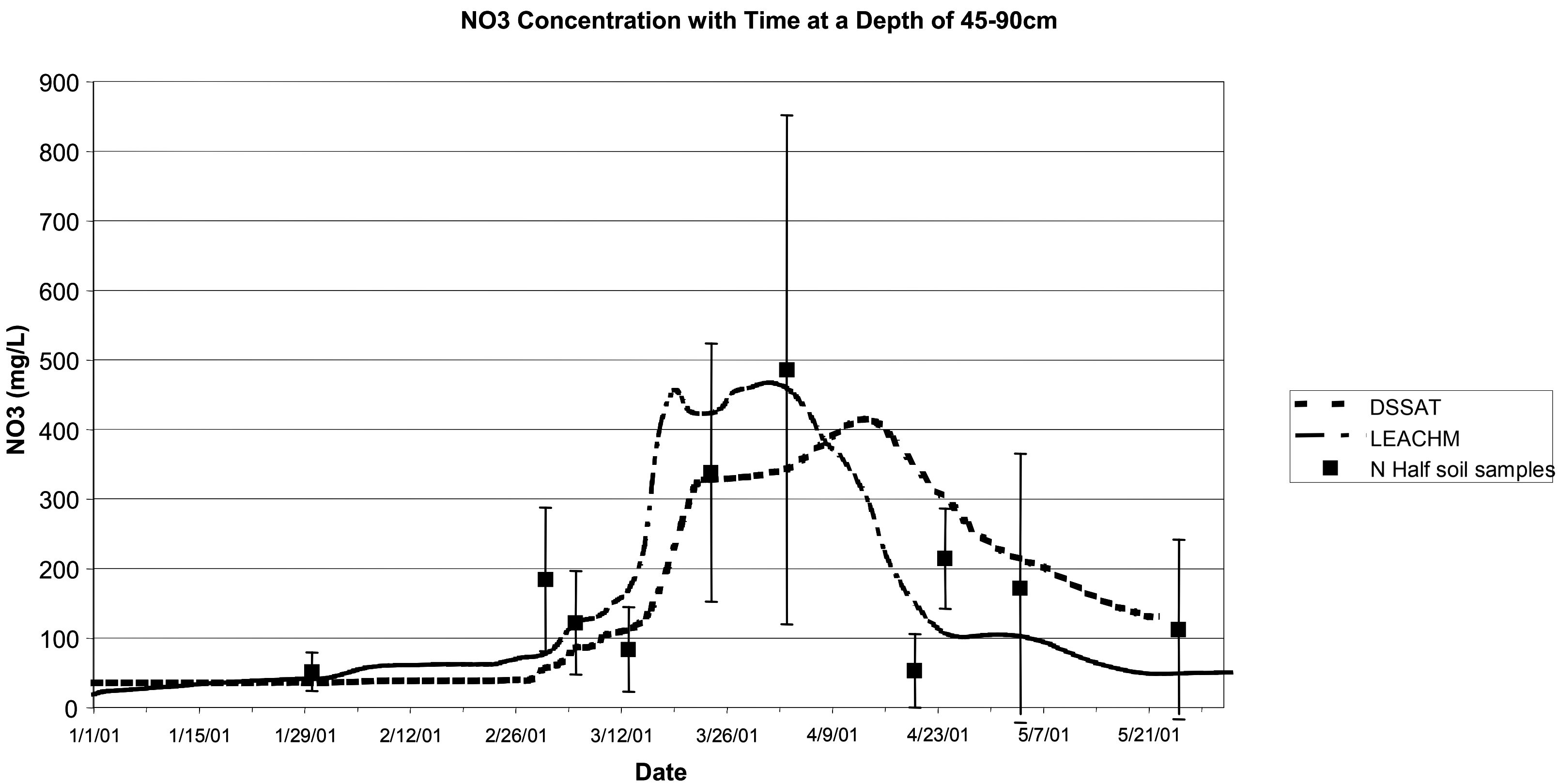


Fig 4-1f. Nitrate concentration over time comparing LEACHM and DSSAT simulations to measured soil samples for 45-90 cm depth.

Fig 4-1— Continued.

NO3 Mass with Time at a Depth of 0-15cm

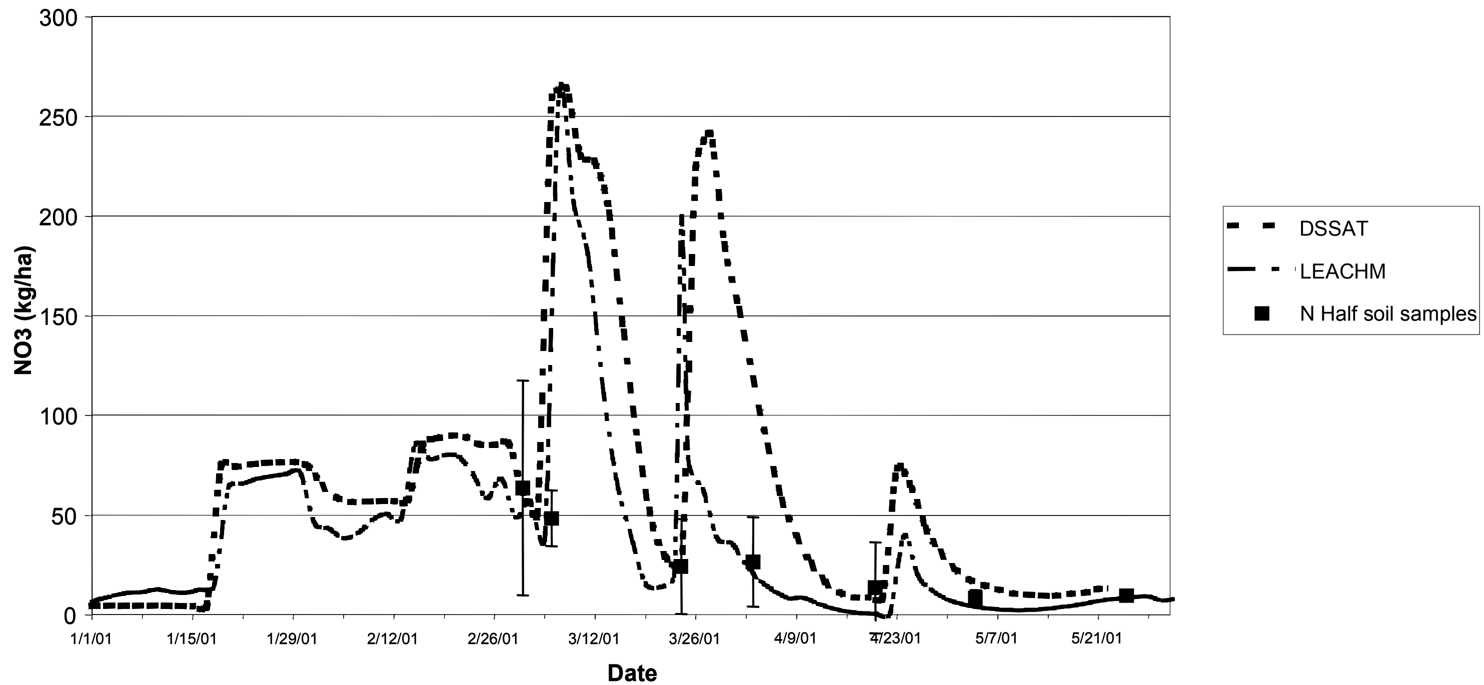


Fig 4-1g. Nitrate mass over time comparing LEACHM and DSSAT simulations to measured soil samples for 0-15cm depth.

Fig 4-1— Continued.

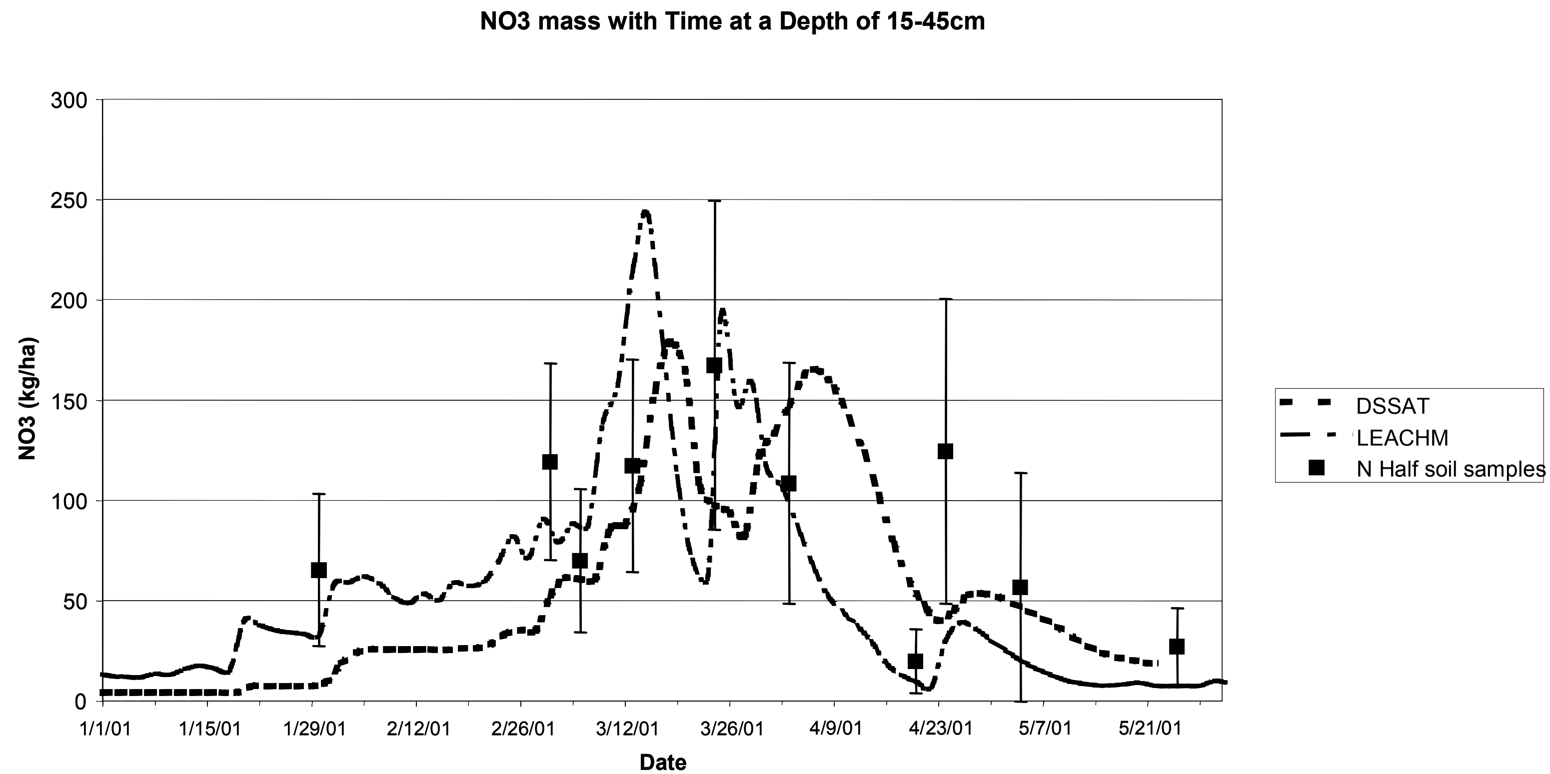


Fig 4-1h. Nitrate mass over time comparing LEACHM and DSSAT simulations to measured soil samples for 15-45 cm depth.

Fig 4-1— Continued.

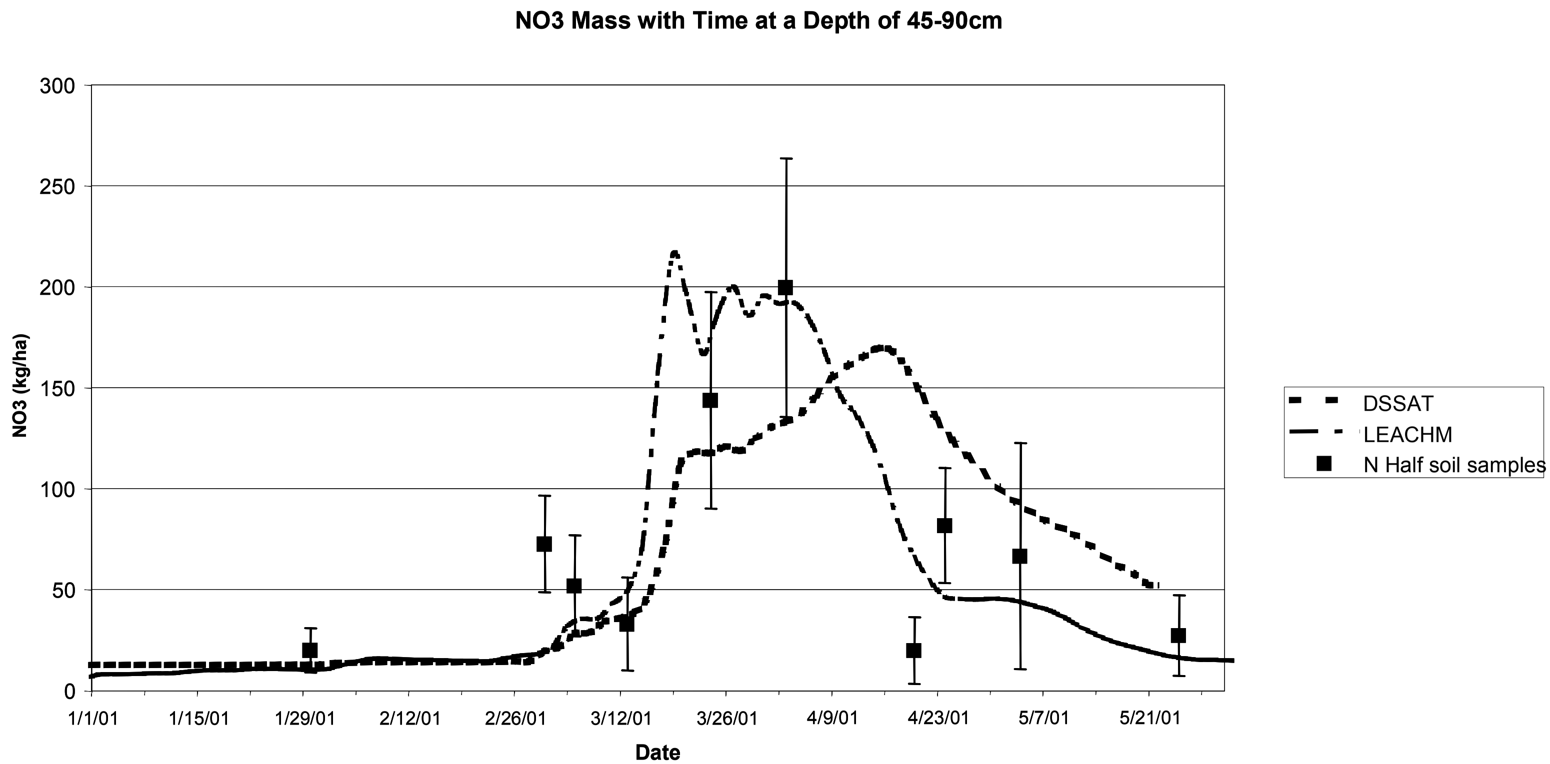


Fig 4-1i. Nitrate mass over time comparing LEACHM and DSSAT simulations to measured soil samples for 45-90 cm depth.

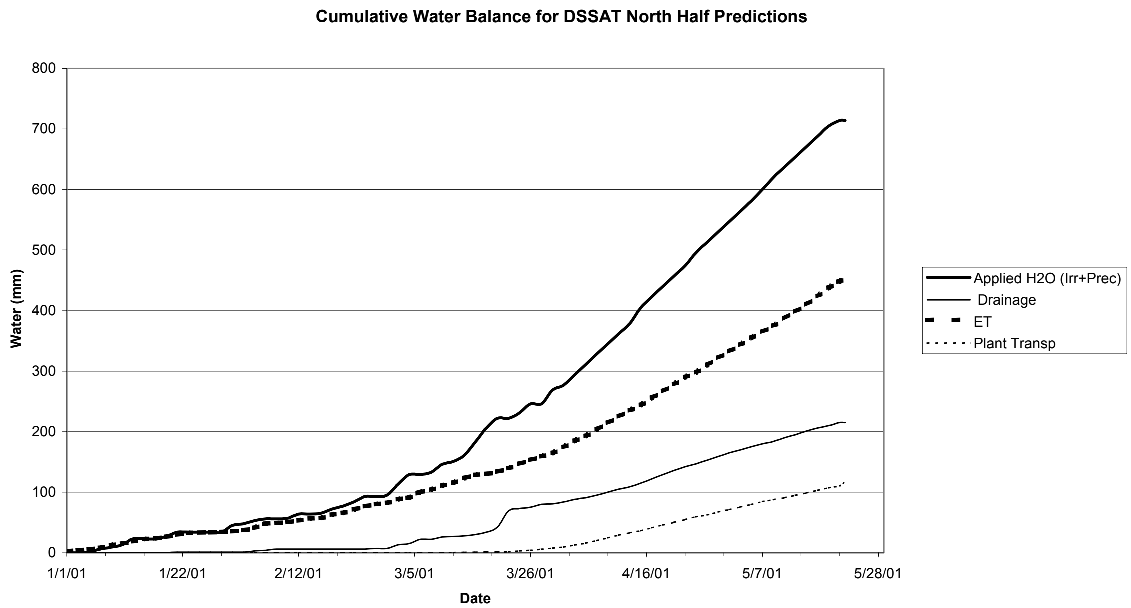
Fig 4-1— Continued.

consist of averages from shallow and deep soil samples over the north half of the field. The three depths (0-15, 15-45 and 45-90cm) were chosen for comparison. The top fifteen centimeters were highly variable due to exposure to surface rainfall, irrigation and evapotranspiration. All measured values for this depth were obtained directly from the 0-15cm shallow soil samples. The 15-45cm depths show moderate variability in both the model and measured results. Measured data on for this depth were obtained either by averaging the 15-30 and 30-45cm shallow soil samples or using the 0-50cm deep soil samples (the 0-50cm deep soil samples did not exhibit the more extreme variability seen in the 0-15cm layer). Finally, the 45-90cm range was the most stable level and was compared by averaging the 45-60 and 60-90cm shallow soil samplings, or using the 50-100cm deep soil sampling intervals. Outputs of the simulations used to produce the graphs were printed every two days. Output for the LEACHM model was printed at 11:00am. The DSSAT model makes predictions on a daily basis and therefore outputs represent daily averages.

In figures 4-1(a-c) volumetric moisture contents are compared over the three depths. Measured moisture content remains fairly constant over time between 8-9%. Model predictions are fairly good for the DSSAT model but not as good for LEACHM. Moisture content in the DSSAT model is easily calibrated by adjusting the drained upper limit (θ_u), which is the controlling factor in DSSAT's drainage equation. DSSAT's water balance routine tends to slow drainage down rapidly after it has reached the θ_u and only falls significantly below that level at the beginning and end of the season when little or no irrigation is applied. Although both models start out with the same initial soil conditions

LEACHM immediately falls well below the measured values, quickly jumps up (almost doubles) in moisture content with the onset of spring rains and increased irrigation (around March 16, 2001), and then quickly falls after irrigation ceases (on May 21, 2001). The rapid moisture content decline at the beginning and end of the season and the high water retention in the middle of the season, are a reflection of the shape of the water retention curve fit in these extremely well-drained soils. Numerous attempts were made to fit Campbell's water retention equation to the observed moisture release data but even the best-fit equation seems to overpredict drainage at high tension (see Figure 3-3). To improve LEACHM's soil moisture calculations in the future the model could be modified to use a different water retention function. Despite LEACHM's moisture retention curve problems at high tensions, the model seems to predict moisture contents quite well near field capacity, and the overall water balance for LEACHM and DSSAT performed similarly (see Figure 4-2).

Figures 4-1(d-f) show N concentrations over time and depth. Soil sampling was only done once every two weeks and was not frequent enough to catch the large peaks predicted by the models, particularly at shallow depths. During the first two weeks of the simulations there is a slow increase in the LEACHM soil-water nitrate concentration even though no fertilizer was applied, while the DSSAT concentration remains relatively constant. This is due to oxidation of the ammonium specified in the initial conditions of the soil, which proceeds at a faster rate in the LEACHM model than DSSAT. In the weeks following the first fertilization on January 15, 2001, up until the 112 kg/ha



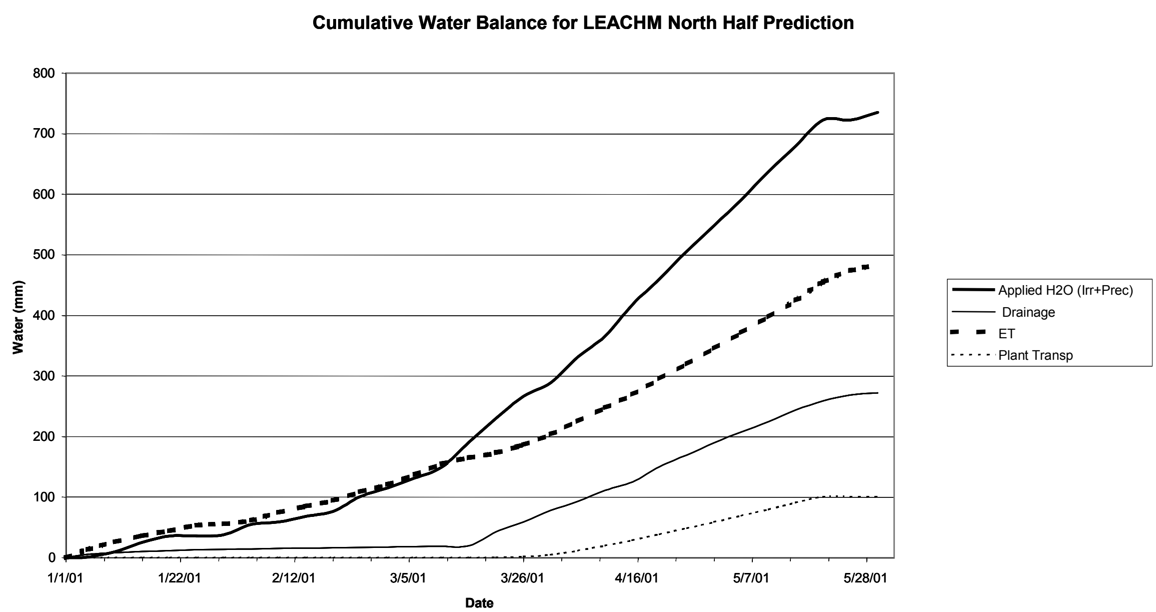


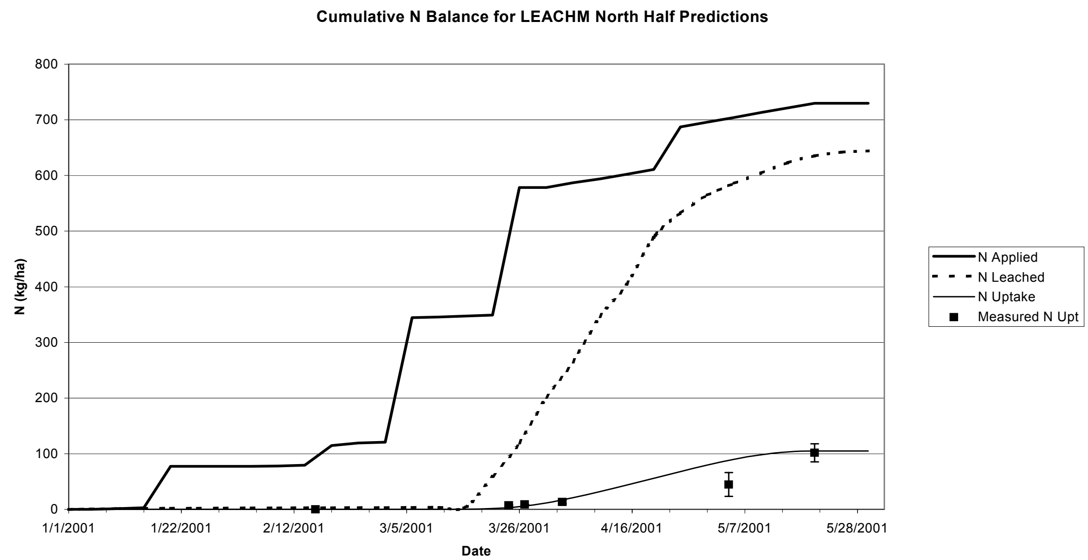
Fig 4-2. A comparison of the DSSAT and LEACHM water balance.

fertilizer application on March 5, 2001, the models perform consistently. Higher nitrate concentrations in the 15-45cm layer are predicted by LEACHM compared to DSSAT during this time period. This trend is not as prevalent in the nitrate mass at the same level due, in part, to a 30% lower moisture content in LEACHM versus DSSAT which would effectively raise nitrate concentration for the same mass. Model predictions are very similar to measured field data through March 5, 2001, although measured results indicate more N leaching with somewhat higher nitrate levels on the March 2, 2001 sampling date and lower nitrate levels on the March 5, 2001 sampling date.

The first major difference between the models is seen after the fertilizer application on March 5, 2001. In the 0-15 layer, DSSAT predicts nitrate concentrations three times greater than the LEACHM concentrations yet the masses in this soil layer are almost identical [see figures 4-1(g-i)]. Another anomaly between the models is observed in the 15-45cm layer from the same N application. Concentration at the nitrate peak is about 50% greater in LEACHM then in DSSAT while mass is only about 30% greater. This may be caused by two reasons: 1) moisture content in the LEACHM model is still much lower than in DSSAT; 2) DSSAT does not leach water and N as fast as LEACHM, and thus the amplitude of the breakthrough curve in the lower depths is smaller. LEACHM's more dynamic transport can be seen by observing the more rapid loss in mass after fertilizer applications, the faster increase of the peaks in the lower layers and the larger amplitude and shorter duration nitrate pulses as compared to the DSSAT breakthrough curves. Measured data taken on March 13, 2001 performs consistently with model predictions for the 45-90 layer but is considerably lower than the LEACHM prediction for the 15-45 layer. Since soil samples were not taken frequently enough to characterize the breakthrough curve for this fertilizer application it cannot be determined whether LEACHM is leaching too fast or too slow.

The response of LEACHM to the second large fertilizer application on March 24, 2001, shows again the effect of moisture content on concentration; the peak of the nitrate concentration for the second application is one-third that of the first application, while the water content is almost three times as much. Both models seem to do an excellent job of matching measured data through the last fertilizer application on April 24, 2001. After this date both models appear to leach both N and water more quickly than indicated by the measured data. Figure 4-3 compares the N balance of the two models. LEACHM leaches more N mass than DSSAT during the simulation period, and thus more mass is left in the soil profile by DSSAT than LEACHM.

Calibrating the crop model was difficult due, in part, to the lack of data for this cultivar (i.e., only one season of data). Calibrations of the DSSAT model were focused on predicting accurate N uptake and tuber yield. By far, the most sensitive variable of the crop model was the drained upper limit of the soil. Crop coefficients were only effective tools for fine-tuning the crop once the plant was able to respond effectively to water and nutrients retained in the soil. Crop management and weather were not adjusted in calibrations since these values



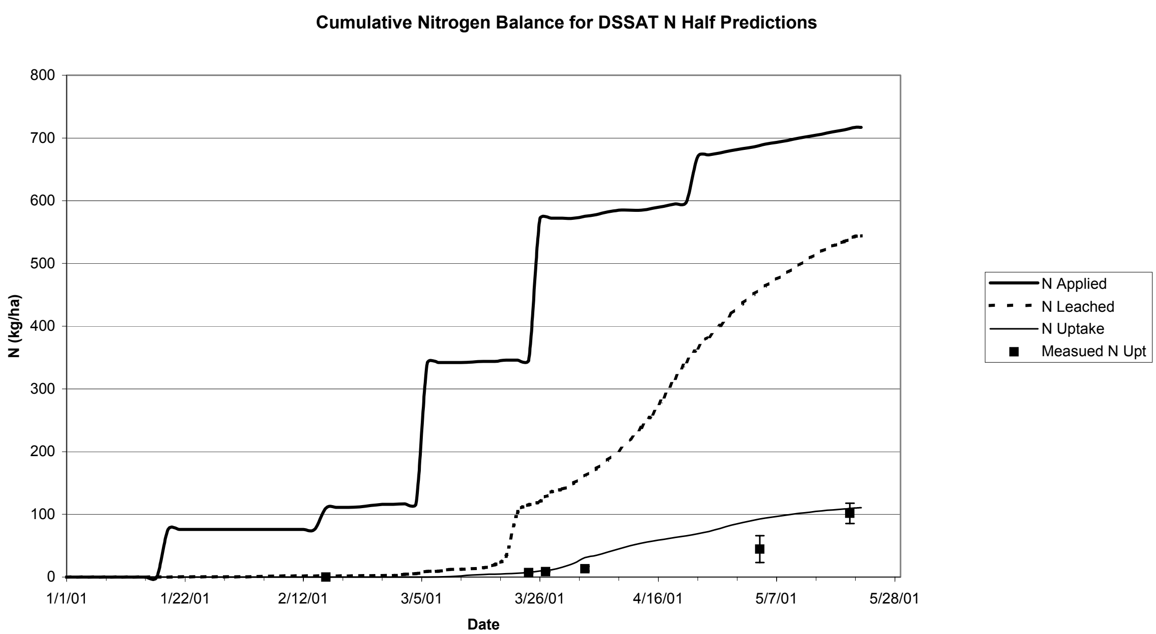


Fig 4-3. Comparison of DSSAT and LEACHM nitrogen balance. Error bars represent one standard deviation around the mean of the measured values.

were accurately measured. The model seemed to have little sensitivity to the soil parameters of saturated hydraulic conductivity, soil albedo, pH, and curve number and seemed to have moderate sensitivity to the drained lower limit, saturated moisture content and organic soil content. Figure 4-4 compares the modeled crop growth to measured data for dry leaf, stem and tuber weight. Measured data, which showed low variability between north and south half data, was averaged over the entire field and simulated results are presented for both north and south half managements. North half dry stem weight predictions underestimated observed values by 24% while estimated final dry tuber weight matched observed data quite well with only a 1% difference. While the final dry tuber yield predictions are accurate, the growth patterns differ in the simulation versus measured data. Measured data seems to follow an exponential growth curve while the simulation predicts a logarithmic path. Table 4-1 compares other predictions with measured results such as time to reach particular growth stages, maximum LAI, plant N content and N uptake. The greatest discrepancy between the model predictions and measured values occurs in the underestimation of leaf mass (Figure 4-4). Griffin et al (1993) (Figures 4-6 & 4-7) also found a much better correlation of model predictions to tuber and stem weights than to LAI, which had relatively poor correlation. Although leaf area trends were accurately recorded, measured LAI values may not be reliable due to difficulties with field LAI measurements. Field leaf area was measured on a per plant basis, multiplied by planting density and divided by total field area which is not as accurate as measuring total leaf area within smaller plots. Furthermore, the plants

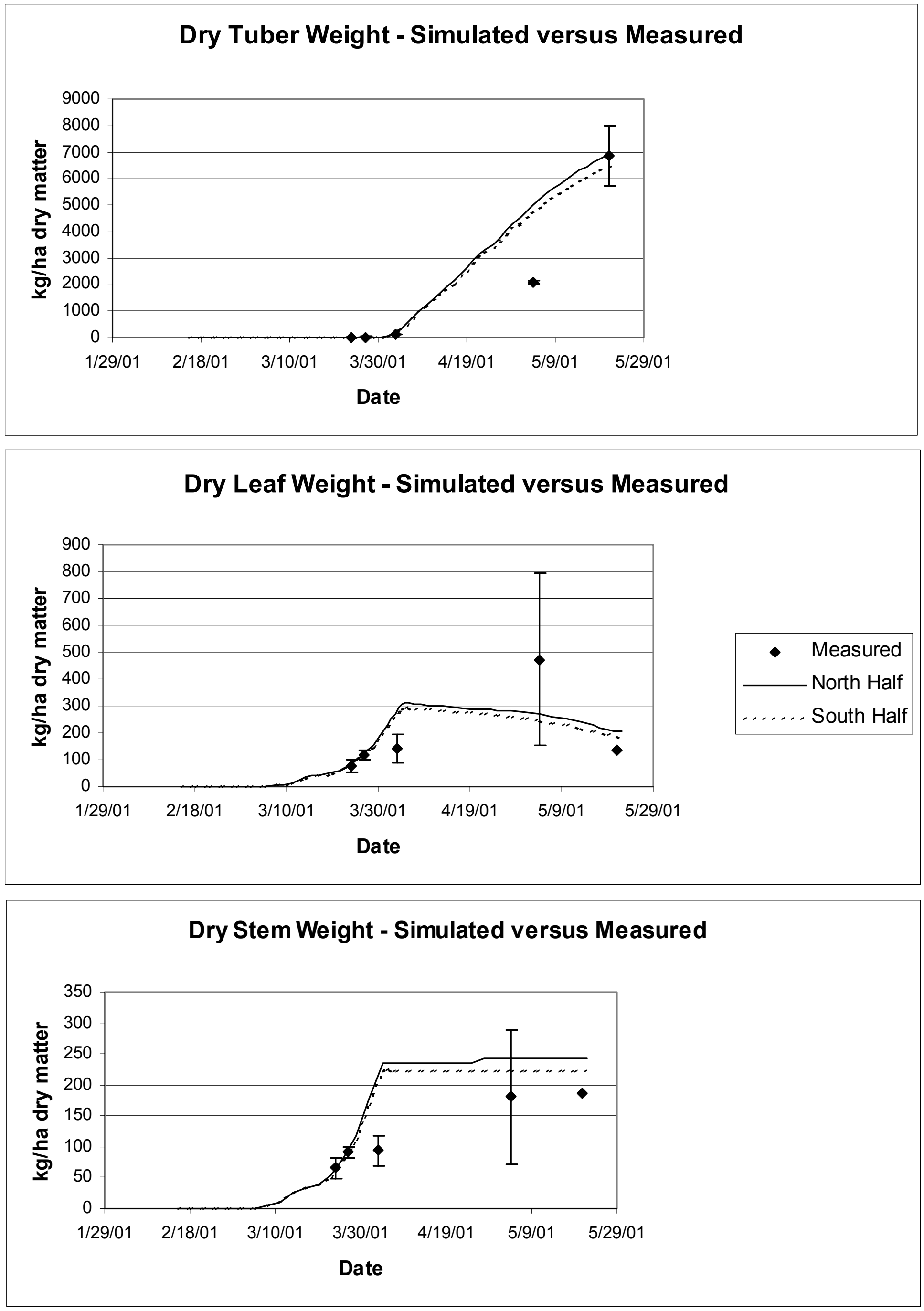


Fig 4-4. Measured versus simulated dry plant matter. Error bars represent one standard deviation around the mean of the measured values.

Table 4-1. Comparison of measured versus simulated values of selected crop characteristics.

	Measured	Simulated North Half	Simulated South Half
Growth Stage [Date]			
Planting	2/15/01	2/15/02	2/15/02
Emergence	3/7/01	3/7/01	3/7/01
Tuberization	4/1/01	3/30/01	3/30/01
Max LAI	4/20/01	4/4/01	4/4/01
LAI			
Max LAI	0.97	0.98	0.93
Nitrogen Concentrations [%]			
Leaves			
3/27/01	4.8	4.7	4.5
4/3/01	5.4	4.7	4.5
5/4/01	3.3	3.6	3.5
5/20/01	3.3	2.7	2.7
Tubers			
3/27/01	2.3	1.5	1.4
4/3/01	2.4	1.5	1.5
5/4/01	1.2	1.4	1.4
5/20/01	1.2	1.4	1.3
Final Mass [kg/ha]	(North/South)		
Dry Tuber Yield	6840/5815	6897	6430
Tuber N mass	83.2/70.8	110.41	102.05
Total N Uptake	101.7	124.47	114.86

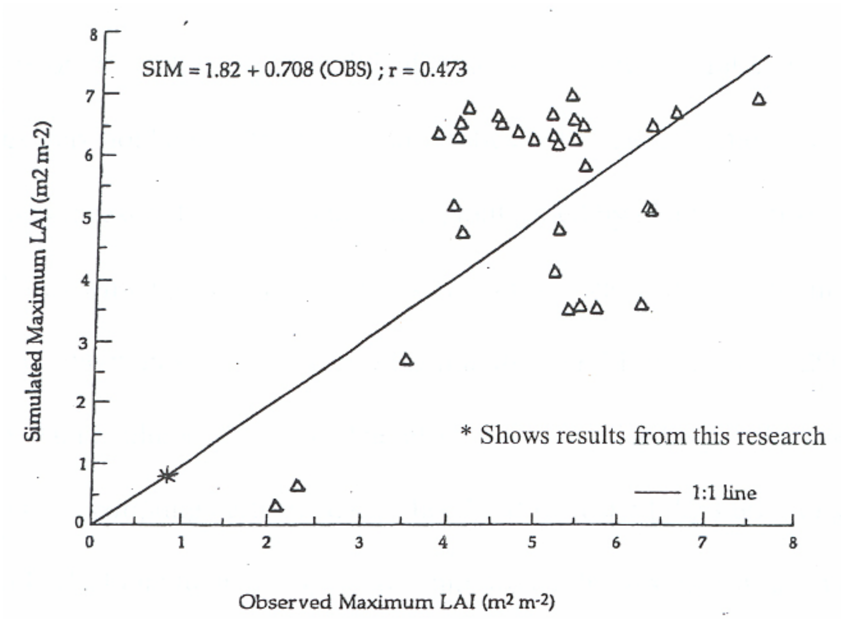


Fig 4-6. Observed versus simulated maximum leaf area index (LAI) (Griffin et al, 1993).

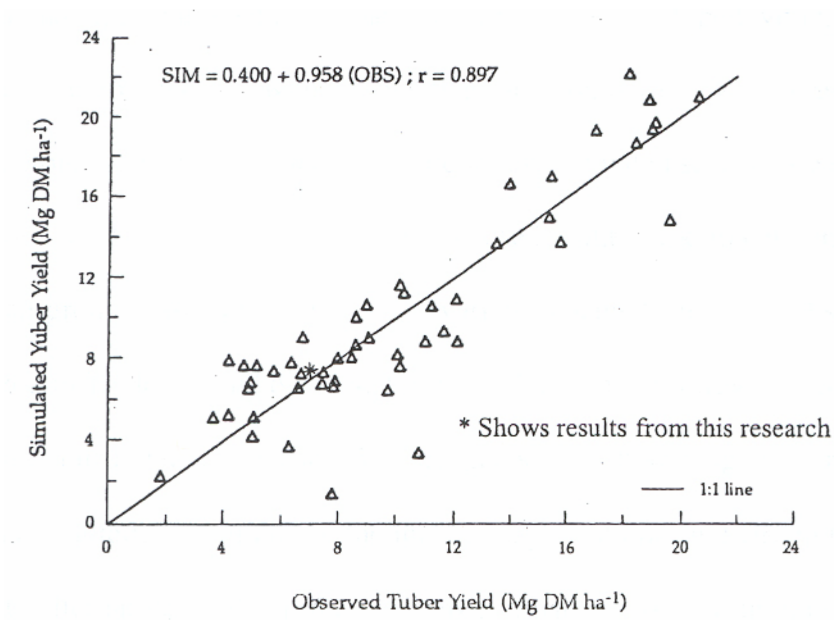


Fig 4-7. Observed versus simulated tuber yield (Griffin et al, 1993).

sampled closest to maximum LAI on April 20, 2001, rotted before any data could be obtained. Therefore maximum LAI was calculated using the fourth biomass sampling performed on May 4, 2001, just 14 days after observed maximum LAI. Final tuber N concentration at harvest is estimated in DSSAT as 1.36% versus the 1.22% observed, and total crop N uptake for DSSAT was 17% greater than that measured in the field.

Evaluation of Alternative Management Practices

After calibration, both models were used to predict the response of a series of alternative management practices. These test runs were developed with the intent of investigating alternative management practices and comparing the differences in the models responses to changing conditions. Fourteen simulated scenarios were chosen for comparison. Table 4-2 describes the test runs used in this experiment, which are broken up into four groups based on the modeling variables being tested. Results of all runs are summarized in Table 4-3 and discussed in more detail in the following sections. Group A shows actual farm practices, Group B investigates alternative irrigation practices, Group C investigates alternative timing of the fertilizer applications, and Group D simulates response to alternative fertilizer rates. In this comparison the optimum irrigation management scenario from Group B was used to investigate the fertilizer timing in Group C. The best irrigation and timing practices were then used to optimize fertilizer rates of Group D. DSSAT runs were performed first and N uptake, dry tuber weight, drainage and N leached were compared for each

Table 4-2. Fertilization rates and times for all DSSAT simulations. Amt applied represents kg N/ha applied per total field area and amt applied x2 represents the amount applied per row area which is the amount used in the simulations.

Fertilization Schedules for Simulation Runs				
Group	Run	Date	Amt Appl	Amt Appl x 2
Group A and Group B	N Half/ 6mm/5mm/AutoIrr	1/18	37	74
		2/15	17	34
		3/5	112	224
		3/24	112	224
		4/23	34	68
	S Half	1/18	29	58
		2/15	17	34
		3/5	106	212
		3/24	94	188
		4/23	34	68
Group C	225_4	1/18	37.5	75
		2/15	37.5	75
		3/6	75	150
		3/27	75	150
	225_A	1/18	37.5	75
		2/15	37.5	75
		3/6	50	100
		3/27	50	100
		4/16	50	100
	225_B	1/18	37.5	75
		2/15	37.5	75
		3/2	62.5	125
		3/20	62.5	125
		4/14	25	50
	225_C	1/18	45	90
		2/15	45	90
		3/2	55	110
		3/22	55	110
		4/16	25	50
	225_7	1/18	30	60
		2/15	30	60
		3/2	41.5	83
		3/14	41	82
		3/22	36.5	73
		4/1	26	52
		4/16	25	50
Group D	275_B	1/18	37.5	75
		2/15	37.5	75
		3/2	87.5	175
		3/20	87.5	175
		4/14	25	50
	225_B	1/18	37.5	75
		2/15	37.5	75
		3/2	62.5	125
		3/20	62.5	125
		4/14	25	50
	202_B	1/18	30	60
		2/15	30	60
		3/2	59	118
		3/20	58.5	117
		4/14	25	50
	182_B	1/18	30	60
		2/15	30	60
		3/2	50.5	101
		3/20	50	100
		4/14	22.5	45
	157_B	1/18	22.5	45
		2/15	22.5	45

Table 4-3. Summary of results from LEACHM and DSSAT simulations.

Group	Treatment	Drainage (mm)		Plant N Uptake (kg/ha)		N Leached (kg/ha)		N In Profile (kg/ha)		Dry Tuber Wt (kg/ha)	Field-Dry tuber yield (Mg/ha)	N Applied (kg/ha)	Leached + Soil	Leached + Soil
		DSSAT	LEACHM	DSSAT	LEACHM	DSSAT	LEACHM	DSSAT	LEACHM	DSSAT	DSSAT	DSSAT	DSSAT	LEACHM
A,B	N Half	215	272.8	110.9	104.9	543.7	644.5	96.9	38.4	6897	38.8	626	640.6	682.9
A	S Half	215	272	102.5	104.9	487	581	96.6	37.7	6120	34.4	560	583.6	618.7
B	N Half_6mm	113	160.3	147	152.7	255.6	514.7	342.7	93.3	7610	42.8	626	598.3	608
B	N Half_5mm	88	124.5	135.1	140.7	162.6	405.4	443.6	200	7101	39.9	626	606.2	605.4
B	Autoirr_50%	66		205.4		120.3		427.2		7808	43.9	626	547.5	
B	Autoirr_75%	80		182.8		162		410		7909	44.5	626	572	
D	275_B	113	160.3	248.9	173.5	270.1	474.7	162	40.1	8291	46.6	550	432.1	514.8
C	225_4	112	160.3	110	111.6	231.2	411.6	236.1	65.4	6407	36.0	450	467.3	477
C	225_5A	111		91.2		196.6		290.2		5050	28.4	450	486.8	
C,D	225_5B	113	160.3	124.3	123.8	230.8	411.3	221.4	53.6	7119	40.0	450	452.2	464.9
C	225_5C	112		117.3		241.1		218		6777	38.1	450	459.1	
C	225_7	111	160.3	101.4	105.2	174.8	368.4	228.6	93.2	5457	30.7	450	403.4	461.6
D	202_B	113	160.3	118.8	119.6	193.3	371.6	224	52.7	6737	37.9	405	417.3	424.3
D	182_B	112	160.3	103.7	106.8	188	344.8	201.1	53.4	6106	34.3	365	389.1	398.2
D	157_B	112	160.3	91.3	94.7	157.7	302	194.1	58.2	5420	30.5	315	351.8	360.2

run. Tuber yield was extrapolated from the dry tuber weight predicted by DSSAT and the measured moisture content at the time of harvest. Nitrogen uptake values obtained from DSSAT runs were then input into LEACHM since LEACHM is not capable of predicting these variables. Note that for all scenarios LEACHM shows more rapid drainage and leaching, and thus a decrease in the N left in the soil at the end of the season when compared to DSSAT predictions.

Group A consists only of simulations for the actual north half and south half management practices. These two simulations are important because they are the only two simulations that have actual field data to verify results. Figure 4-8a shows DSSAT predictions of the fate of N for these simulations. Nitrogen remaining in the soil profile, particularly below 30cm, will most likely be leached eventually. Tuber yield was predicted very accurately for both the north and south half runs. North half tuber yield predictions of 38.8 Mg/ha match closely to the 38.7 Mg/ha measured in the field and south half predictions of 34.4 Mg/ha compare well with the observed value of 33.7 Mg/ha. Ten percent less nitrate was applied to the south half causing an 11% decrease in yield and a predicted 8.9% decrease in N leached to groundwater.

Group B contains simulations testing the crop and environmental response to different irrigation management, and uses the north half fertilization rates and timing. North half irrigation can be viewed in Appendix C under the Filex irrigation section (irrigation is recorded in mm). In the 6mm and 5mm test runs irrigation stayed the same as the north half run in the beginning of the simulation and was adjusted to 6mm/day and 5mm/day during April 1 to May 21, when north half irrigation was being applied daily at the rate of 8.5mm/day. Irrigation prior

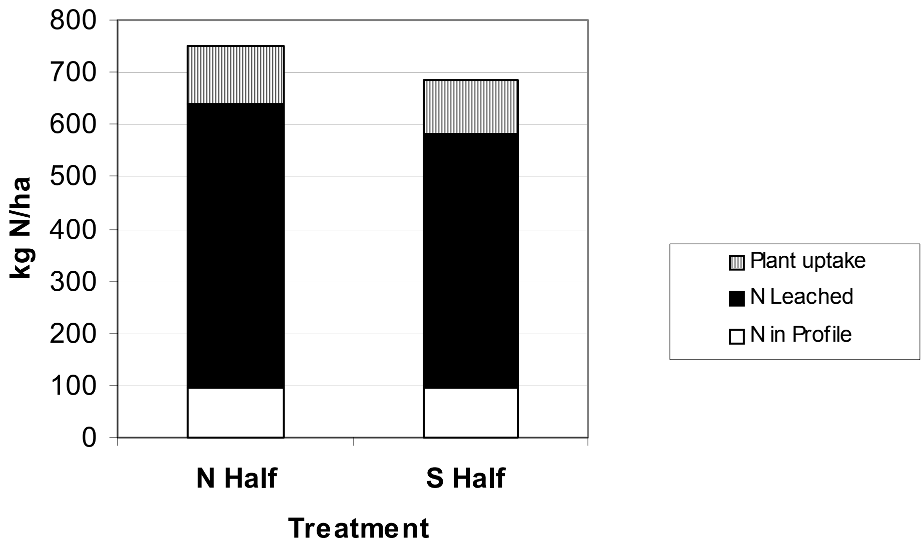


Fig 4-8(a). Simulation results for Group A - Actual management practice.

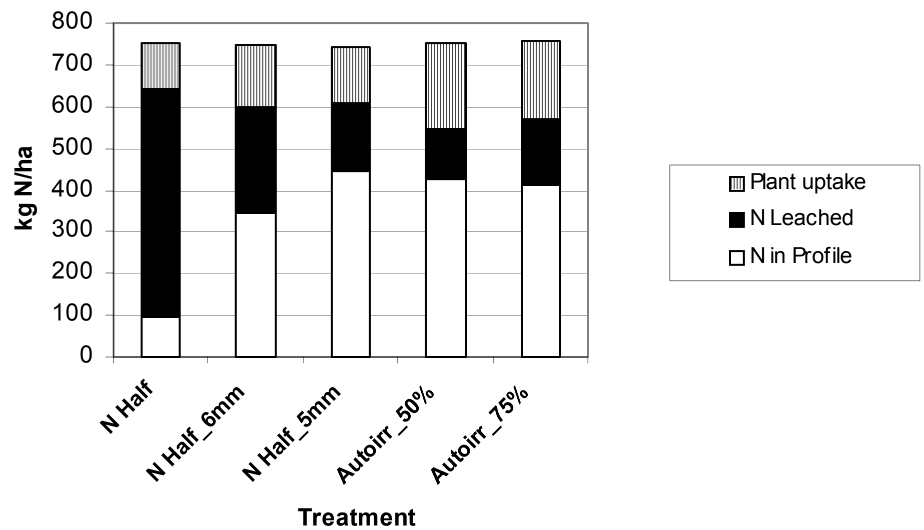


Fig 4-8(b). Simulation results for Group B - Irrigation management.

Fig 4-8. Simulation results for (a) Group A, actual management, (b) Group B, irrigation management, (c) Group C, fertilizer application, and (d) Group D, fertilizer rate.

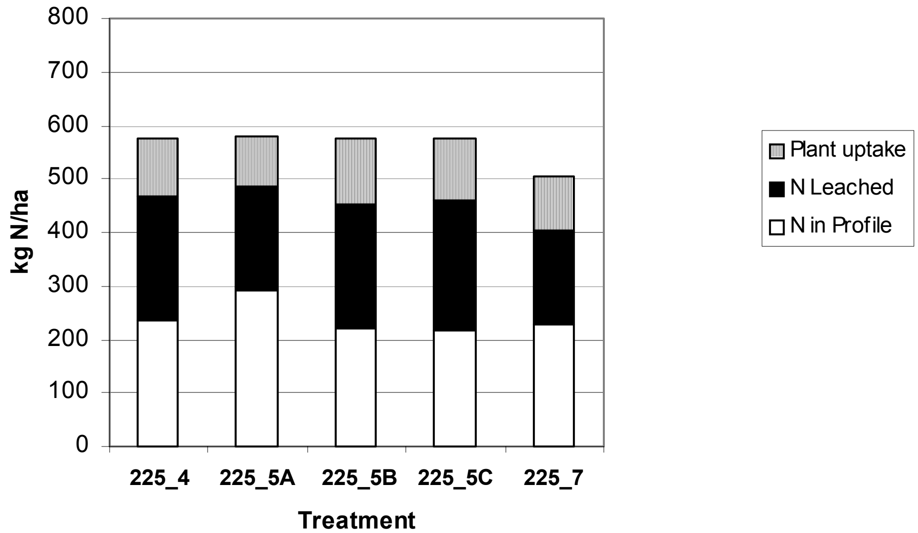


Fig 4-8(c). Simulation results for Group C - Fertilizer Application Timing

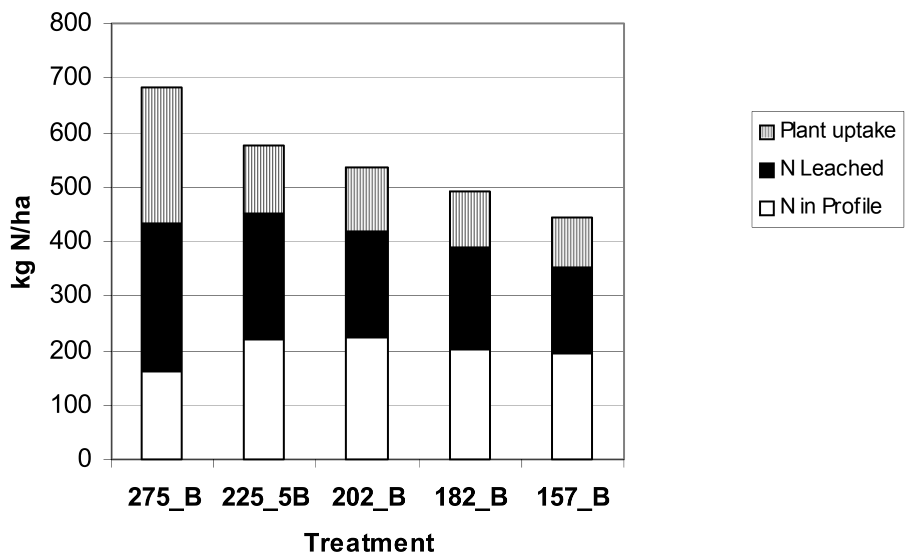


Fig 4-8(d). Simulation results for Group D - Fertilizer Rate

Fig 4-8—Continued.

to April 1, 2001, did not cause excessive nitrate leaching and was thus not altered. The auto irrigation simulation is an option in DSSAT whereby irrigation is applied when soil moisture content at a user-specified depth falls below a user-specified critical moisture content. Critical moisture content is defined as the percent of available water (i.e. moisture content between the drained upper limit and the lower limit of plant extractable water). For instance, if the drained upper limit is 8% and the lower limit is 1%, a critical moisture content of 75% means that irrigation will occur whenever available water drops to 75% of maximum, or when the soil moisture content drops to 6.25%. At a critical moisture content of 100%, irrigation would occur whenever moisture content dropped below 8%. Note that given DSSAT's drainage algorithms, no leaching can occur if the moisture content is kept at or below the drained upper limit, thus this represents an extremely idealized scenario. In the auto irrigation scenario presented, a critical moisture content of 75% monitored at a depth of 30cm was used. Figure 4-9 compares predicted field-dry tuber yields for all simulation runs. The results of Group B simulations show yields increased 9.4% over the actual N-half practices using the 6mm scenario, 2.9% using the 5mm scenario and 12.8% using the auto irrigation scenario. Furthermore the mass of nitrate leached fell by 53%, 70% and 70% respectively, when these scenarios are compared to the north half irrigation treatment (Table 4-3). These N leaching statistics are somewhat deceiving, however, because considerably more N was left in the soil profile for the reduced irrigation` runs, although plant N uptake also increased somewhat (see Figure 4-8b).

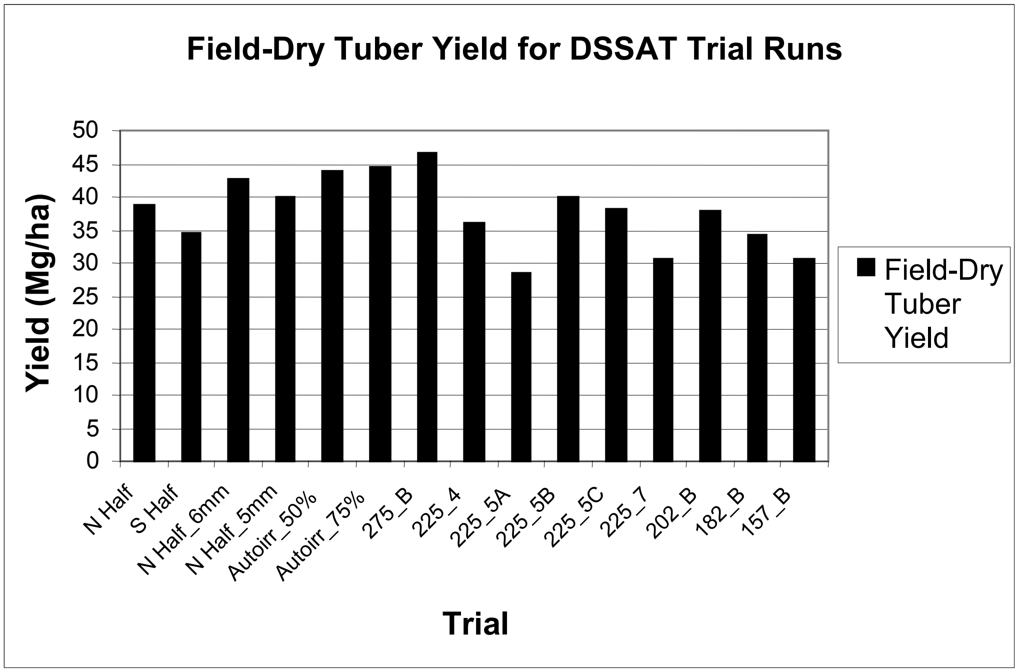


Fig 4-9. Tuber yield results for all DSSAT simulations.

Yields increased in the alternative irrigation runs because excessive irrigation from the N half treatment caused N to leach below the root zone before the plant had a chance to take it up. Figure 4-10 shows there is N stress for the N half run while there was little or no N stress for any of the other three runs in this group. The yields for the 5mm run was lower than for the 6mm run due to water stress during the tuber bulking stage (see Figure 4-11). While the auto irrigation method appears to be the optimum strategy it is unlikely that water could be managed this precisely in actual field operations. In the DSSAT model keeping the moisture content below the drained upper limit completely eliminates leaching. However, in reality, irrigation will not be able to be applied this precisely over both space and time and increased leaching would undoubtedly occur in field trials. Another problem with the auto irrigation scheme is that the plants were only watered every 2-4 days which may cause wilting in the hot Florida sun (Joe Hall, oral communication). Despite these practical matters the

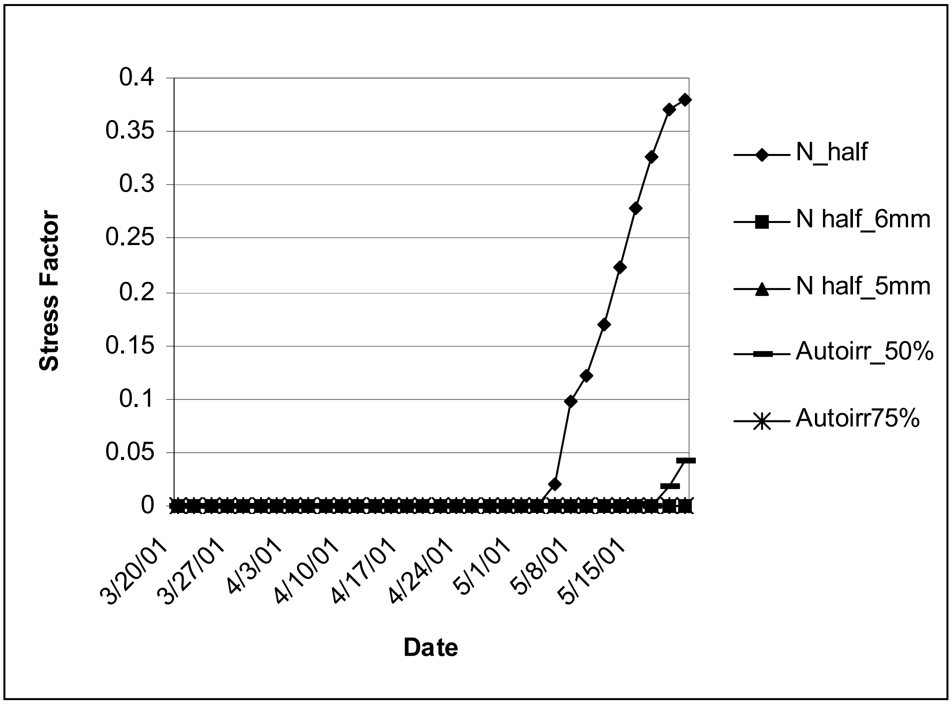


Fig 4-10. Nitrogen stress calculated by DSSAT for Group C.

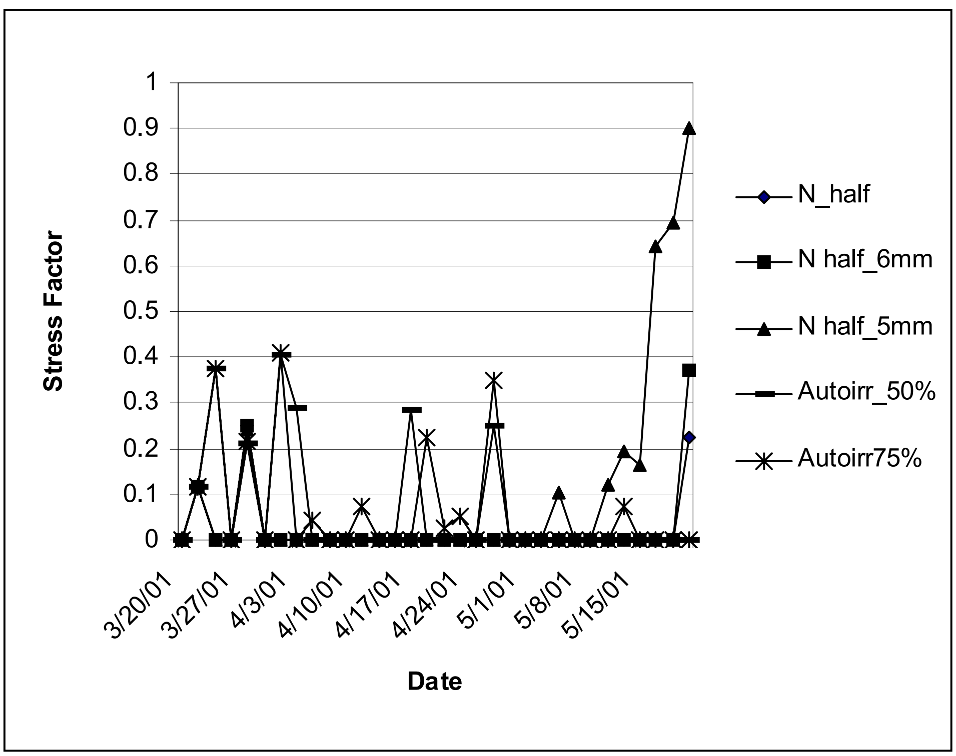


Fig 4-11. Water stress calculated by DSSAT for Group C.

theory behind the auto irrigation method is sound and the idea behind keeping moisture content at or below drained upper limit should be followed. In subsequent treatments the 6mm irrigation schedule was chosen for the most favorable irrigation method because the plants did not undergo water or N stress, leaching was decreased significantly, and the management practice was more feasible and practical than the auto irrigation scheme.

The Group C scenarios all use the 6mm irrigation scheme and a fertilizer application rate of 225 kg N/ha, which is the current IFAS recommendation. Timing and number of applications were varied for these runs, and treatments are summarized in Table 4-2. Simulation results (not shown) showed little difference between runs in which there was a split between pre-plant and at-plant fertilizer versus runs with all initial fertilizer applied at-planting. Therefore all scenarios split the initial fertilizer with 50% applied pre-plant and 50% applied at plant for the sake of consistency. Runs 225_5A, 5B and 5C are runs with a total rate of 225 kg N/ha distributed in 5 applications with each scenario receiving a different distribution of fertilizer. The 225_5A run has the fertilizer applied more heavily late in the season, 225_5B has an emphasis on fertilizer in the middle of the season (but before flowering), and 225_5C has fertilizer applied more heavily in the early part of the season. Results (Figure 4-8c) seem to mirror those found by Osaki (1992) who found little difference in potato yields of treatments in which fertilizer was applied before flowering date but significant decrease in yields in those treatments with late fertilizer applications. Comparison of runs 225_4, 225_5B and 225_7 demonstrates the effect of splitting fertilizer applications. Each run has a pre-plant, at-plant and either two (225_4), three (225_5B) or five

(225_7) additional applications of N applied at times specified in Table 4-2. To minimize the possibility of leaching, the optimal number of applications would be the largest number of applications that could be applied without affecting yield. The larger the number of applications the smaller the mass of N applied per application and therefore the least risk of nitrate leaching due to rainfall. Results in Figure 4-8c shows that 225_5B which has 5 applications has the greatest yield and is therefore the best of these practices. The poor yield predicted for run 225_7 suggests the importance of high nitrate concentration in soil water for optimal plant growth. Although the plants never exhibited N stress during the season for run 225_7, soil water N concentrations were lower than those in run 225_5B and this apparently affected tuber growth. Run 225_4 is clearly sub-optimal because it has higher N lost (Table 4-3), lower yield (Figure 4-9) and fewer split applications.

After finding the most favorable management for irrigation, fertilizer timing, and number of applications the total fertilizer rate was investigated. Since both environmental and economic considerations go into developing best management practices (BMPs), fertilizer rates above current average fertilization rates were not considered. Runs 275_B, 225_5B, 202_B, 182_B and 157_B vary the total mass of N applied, with each run using the optimum irrigation rate of 6mm, and the fertilizer application pattern of 225_B. The results of these simulations (Figure 4-8d) show a steady decline in plant N uptake with fertilizer rates below 275 kg/ha. However the results of these runs show that fertilizer rates can be reduced to as low as 182 kg N/ha and still maintain acceptable yields (only an 11.4% decrease in yield with a 41% decrease in N applied compared to the N half management). Run 225_B predicted a 4% increase in yields compared to the north half with a 28% reduction in N leaching (Figure 4-9).

Run 275_B showed not only a dramatic increase in yield but also a dramatic increase in N efficiency with 45% of the applied N taken by the plants in comparison with the 27.5% efficiency found in the 225_5B run. N efficiency is so high for this run that there is actually less fertilizer leached below the root zone at the 275 kg/ha rate than at the 225 kg/ha rate. Taking a closer look at this run shows a maximum leaf area index of 5.0 as compared with only 0.93 for the measured north half run. Yield increased by 13% compared to the north half run, with a 12% decrease in fertilizer applied. This run does not follow the trend set by all other runs.

Although the realism of the success of run 275_B is highly questionable, valuable insight can be obtained from exploring why this anomaly occurred. Figure 4-12 compares nitrate concentrations at the 15-45cm depth increment over time with the south half run which received 10 kg N/ha more than the 275_B run. Soil water nitrate concentrations are about 50-75 mg/L greater in the 275_B run for the first two weeks after planting (Feb 15). Referring back to Figure 2-18, measured values of N applied versus plant N uptake demonstrate that very little N mass is taken up by the plants within the first month, yet the simulations and research presented in the literature review seems to suggest the

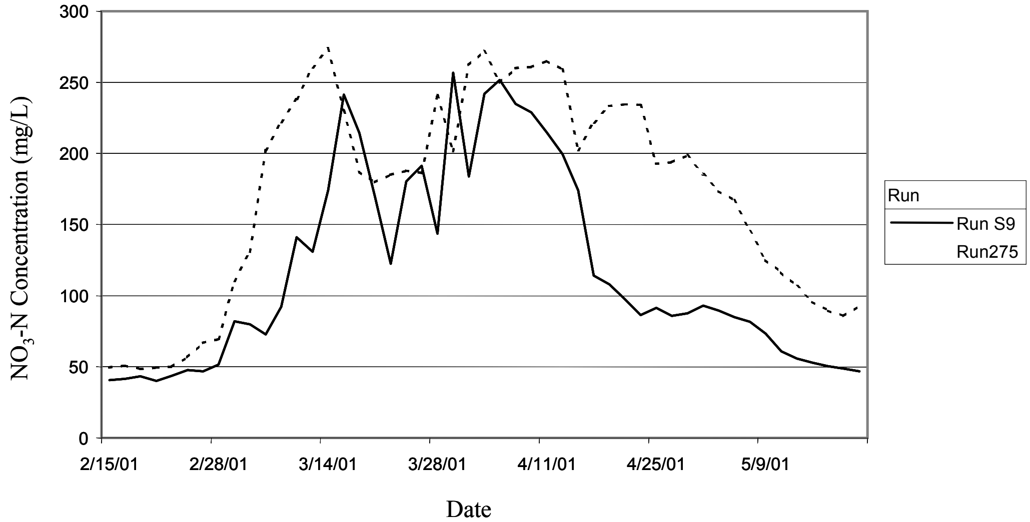


Fig 4-12. Comparison of DSSAT simulated NO3-N in the 15-45cm layer. Higher NO_3 concentration in the second and third week after planting may be the cause of excessively high growth in the 275 simulation.

importance of N early in the plant's development to final yield. Keeping in mind the small mass of the potato plant and limited extent of the roots in the first month, one must conclude that high nitrate concentration and not necessarily high N mass is essential to successful potato growth. This is an important distinction because it demonstrates an area where potato N use efficiency can be greatly increased if high concentrations can be maintained near the roots of the potato without applying a large mass of N fertilizer.

Taking into account the all the information provided by these model runs, run 225_5B appears to provide a good basis for BMP recommendations. The results from these model runs are consistent with previous research and IFAS recommendations. Predictions indicate a moderate amount of N lost (a 29% reduction from N half practices) with good tuber yields and provides a safe margin of error for possible discrepancies between the model predictions and reality.

Figure 4-13 shows soil water nitrate concentrations in the rows at the 60-90cm depth over time for a number of different simulations. Assuming that these concentrations represent values in the rows only, the actual concentrations of nitrate leached to groundwater would be half these values (to account for mixing with water in the furrows which did not receive fertilizer). Leached nitrate concentrations would peak at approximately 100 mg/L of N even at the lowest simulated fertilizer rate (152_B) which is well above the EPA maximum contamination level (MCL) of 10mg/L. However, comparing the north half run and run 225_5B results show a 25% decrease in peak concentration to 146 mg/L while still maintaining similar yields. Table 4-2 shows average nitrate concentrations in leached groundwater over the entire spring 2001 potato season by taking the total mass of leached N and dividing it by the total volume of water drained below 90cm. As with Figure 4-13 these numbers represent concentrations below the rows and can be divided in half to achieve a total field average. Once again nitrate concentrations even with the lowest fertilizer rate exceeds EPA standards.

Table 4-4. Average NO_3 concentrations under potato rows over entire season for selected DSSAT runs.

Run	Average N Conc
	mg/L
N Half	253
Autoirr_50%	182
275_B	239
225_5B	204
202_B	172
182_B	168
157_B	141

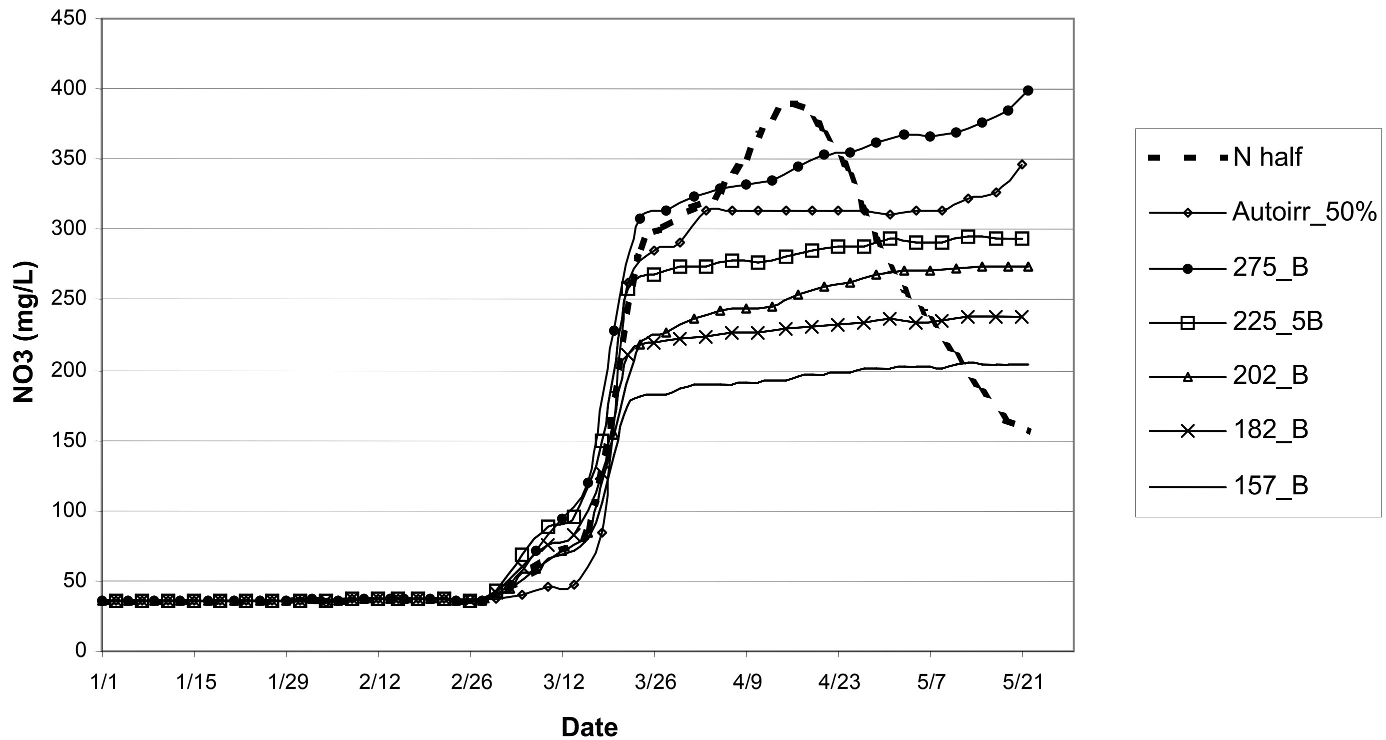


Fig 4-13. NO_3 concentrations in the rows at the 60-90cm depth.

A summary of the results of all the DSSAT simulated runs is presented in Figure 4-14. To optimize management the run that had the greatest yield and least N lost would be chosen. Apart from the anomalous Run275_B, figure 4-14 shows a generally positive trend of increased yield with increased N lost. Note that runs 225_4, 225_5B, 225_5C and 202_B all show yields greater than or equal to south half yields with significantly less N lost (Figure 4-14). In creating a BMP a suitable compromise between yields and N lost must be found.

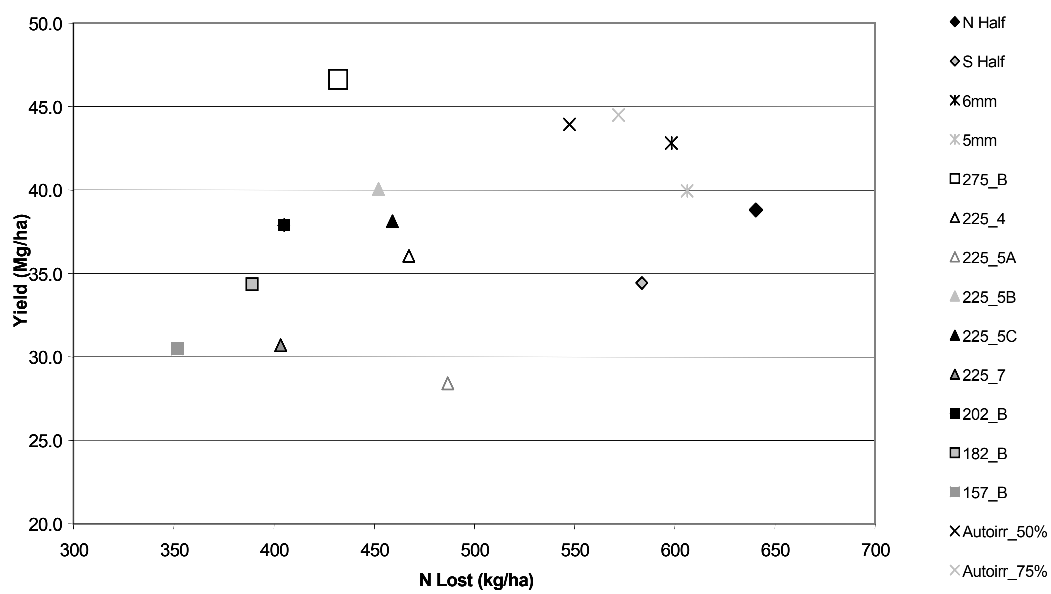


Fig 4-14. Yield versus N Lost (N leached plus N left in soil)

CHAPTER 5
CONCLUSION

This research explored the water and N transport through sandy soils and its relationship to crop growth for a potato crop. The sandy soils present at the research site are characteristic of much of Florida's landscape and the poor N use efficiency of potatoes is characteristic of many other vegetables. Models and observed data were in good agreement with each other. Nutrient and water data collected in the field compared well with observed fertilization dates and rates, and closely matched model predictions for both DSSAT and LEACHM. The crop growth model accurately predicted dry tuber yield, phenological development, and plant N concentration but overestimated stem weight and underestimated leaf weight. Simulations run with the crop model appeared consistent with trends observed in other potato studies and provided much insight into plant –nutrient interactions.

Both model predictions and measured data demonstrated the rapid leaching caused by rains and/or over-irrigation. Fertilizer applied in January and February, during periods of low water application, appeared to remain in the soil profile until heavy rains occurred in March. However, the two largest fertilizer applications were both completely leached out of the soil profile within about two weeks. The first following heavy rains in mid March after the March 5, 2001 fertilizer application, and the second following heavy irrigation beginning a week after the March 24, 2001 application. Rapid leaching due to applied irrigation can be avoided by taking precautions to insure no excess water is applied above field capacity which lies at about 6-7% volumetric water content for soil at the research site. Tensiometer, TDR and soil samples suggest enough water was provided over the spring 2001 potato crop to keep soil at field capacity throughout the entire growing season down to a depth of at least 2m. Concentrations of nitrate-N in soil water at a depth of 1 m peaked at about 400mg/L in the rows suggesting 200mg/L per total field area. Concentrations observed in soil samples taken at a depth of 5m shows peak values of about 68mg/L in the plant rows. Monitoring wells placed inside the center pivot that monitor the top of the Floridan Aquifer, about 5-9 m below land surface, show the leached nitrate took about 2-4 months after the potato harvesting to reach the Floridan Aquifer. Peak values observed July 5, 2001, show nitrate concentrations of about 35 mg/L reaching the aquifer. Model predictions and measured data calculate only about 30% of the N applied was taken up by the potatoes, which is supported by the literature reviewed.

Simulations performed with the DSSAT model suggest that irrigation and fertilizer rates can be reduced while still obtaining acceptable yields. However, environmentally acceptable loads cannot be attained under optimum yield fertilization rates. Yields seem to stabilize at around the 225 kg N/ha fertilizer rate recommended by IFAS (a reduction of 29% from current management practices). Simulations were able to attain north half yields using as little as 182 kg N/ha by using model predictions of soil N concentrations, plant nutrient needs and previous knowledge of the spring 2001 season's weather to time fertilizer and irrigation application. Unfortunately, none of the simulations were able to achieve high yields and maintain environmentally acceptable nitrate concentrations in leached water. The N use efficiency of the potato was never considerably increased. The percent decrease in leached N mass and soil water nitrate concentrations predicted is approximately equal to the percent decrease in fertilizer rates.

The simulations were able to provide insight into possible areas of improvement in management practices. Irrigation can be reduced as much as 30% without stressing the plants. Furthermore, this reduction slowed the effects of leaching considerably, allowing the N to remain in the root zone for a longer period of time. The DSSAT simulations also showed that the potato seems to require high N concentration early in the season, even though there is very little N mass taken up. Early in the season the plant has very little mass and the roots do not extend far. Exclusion of early N applications while potatoes are small could significantly reduce fertilizer rates if a method of maintaining high N concentrations only in the immediate area surrounding the roots can be maintained.

Future models could be improved upon by examining the problem in 2 or 3 dimensions to provide a better understanding of the row-furrow dynamics. The Campbell's water retention function used in the LEACHM model was unable to accurately match soil moisture characteristics at the research site, therefore a new function should be introduced into the model. While the DSSAT model's water transport function accurately describes the observed tendency of the soil to remain at field capacity it should be adjusted to increase the drainage rate. Perhaps one of the most essential improvements necessary for any future crop model is the need for more data. DSSAT has only been tested against one season's worth of crop data using two similar management scenarios. The complicated interaction of DSSAT's many equations and cultivar- specific genetic coefficients require more field experiments to validate this model.

Even with proper irrigation management and lowered fertilizer rates the predicted peak groundwater nitrate levels will not meet acceptable standards. Research published by Verhagen (1997) showed nitrate concentrations could be reduced below acceptable Dutch drinking water standards on clay and loamy soils but not on sandy soils. Given these facts, this research is unable to provide a BMP that will maintain drainage water standards at all times using the irrigation and fertilizer methods studied in this experiment. However, alternative management practices not explored in this research could provide better results.

A successful BMP for Florida's sandy soils will require protecting the N fertilizer from heavy rains. Control release fertilizer which releases N as a function of temperature, or ammonium-N that adsorbs to soil are two alternative N sources that could reduce leaching. Dividing N into more applications of less mass can reduce the damage in the event of heavy rains (although this management practice showed decrease yields in simulations). In some areas of the country farms are using plastic mulch to cover rows and prevent rains from leaching N. Fertilizer timing is important for a BMP as well. Although DSSAT simulations were somewhat sensitive to fertilizer added late in the season, research done by Osaki et al (1992) suggest that potatoes can be stressed for N late in the season without seriously affecting yield. Early in the season, potatoes require high N concentrations but only uptake a small amount of mass. If potatoes can be planted in such a way that early in the season N concentrations are kept high only in the immediate vicinity of the roots and late fertilizer applications are withheld, then a very large portion of the N applied could be eliminated. The use of properly calibrated simulation models can aid in decision-making concerning timing and rates of fertilizer and water that reduce N leaching. Another possible solution lies in working with legislators to define TMDLs for non-point source pollution. If nitrate regulations can be established based on yearly averages then proper crop rotations with legumes or N efficient crops might result in overall average yearly compliance when potatoes or other inefficient N use crops are grown.

APPENDIX A
SOILS DATA

APPENDIX B
MEASURED CROP DATA

APPENDIX C
DSSAT INPUT FILES

APPENDIX D
LEACHM INPUT FILE

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BIOGRAPHICAL SKETCH

Michael Albert was born in 1973 in Allentown, Pennsylvania and grew up in East Windsor, New Jersey. After graduating high school in 1991, he enrolled in the University of Florida where he received a Bachelor of Science in geology. In Fall of 1998 he enrolled at the University of Florida, Department of Agricultural and Biological Engineering where he focused his studies on hydrology.