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NITRIFICATION, DENITRIFICATION, AND SORPTION-DESORPTION OF NH_4-N IN SANDS DURING WATER MOVEMENT TO SUBSURFACE DRAINS

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ABSTRACT

Isotopically labelled (^{15}N-depleted $(NH_4)_2SO_4$) N fertilizer was applied at a rate of 115 kg N/ha to a Florida citrus grove located in a subsurface drained Spodosol in order to determine the fate of applied N. The fertilizer was applied to one 0.22-ha field plot each of shallow-tilled (ST), deep-tilled (DT), and deep-limed/tilled (DTL) soil. Analyses of soil, soil solution, drainage water, and citrus leaf samples revealed that much of the NH_4-N was nitrified to form NO_3-N during the first 42 days after application of fertilizer. Partially because of a local drought, most of the applied N was absorbed by plant roots during the first 134 days and leaching losses in drainage water were less than 4% of the amount applied. Rates of nitrification and N uptake by roots were highest for DTL and lowest for ST treatments. Selective deep tillage with lime incorporation of Spodosols appears to be an effective means to manage fertilizer and water resources for citrus and possibly other agricultural crops without contaminating groundwater supplies.

Chapter 1: Introduction

Acid, sandy soils with shallow water tables are commonly utilized in Florida for intensive production of high-value vegetable, fruit, and horticultural crops. Productivity of these soils using the definition by Hillel (1981) may be severely restricted by limiting levels of both "chemical fertility" and "physical fertility". High contents of silica sand and low contents of colloidal material provide porous soil matrices that primarily have only short-term capacity to supply water and nutrients to active plant root systems. Relatively large pores and low ion exchange capacities of the solid particles also result in potential leaching losses of fertilizer applied to such soils. During rain storms or when excess irrigation is applied, soluble nutrients from applied fertilizer may easily be displaced from the rooting zone of the soil profile and be transported into underlying groundwater. Obviously, careful management of fertilizer and soil water for crops growing in these soils is needed to simultaneously minimize chemical contamination of groundwater supplies, maximize the use-efficiency of crop roots for nutrients applied in chemical fertilizer, and optimize the water use-efficiency of crop roots.

Although the average annual rainfall in Florida is high (1.3 to 1.5 meters) the distribution during the year is highly nonuniform giving a relatively dry period during the winter and spring months and a relatively wet period during the summer and fall months. For crops growing in sandy soils with an impermeable layer located in the profile at some depth less than 2 m, ditch or subsurface drainage systems are frequently installed so as to prevent development of anaerobic soil conditions in the rooting zone during the wet season. These systems are particularly needed to remove excess water during intense thunderstorms from soil areas with nearly flat topography. However, during the dry period the accelerated removal of drainage water may well decrease the effectiveness of rainfall events and the water use-efficiency of the crop. Leaching loss of soluble fertilizer nutrients may also be increased as a result of accelerated water discharge from ditches or subsurface drain tubes (Mansell, Wheeler and Calvert 1980; Mansell et al. 1977). Such enhanced leaching of applied fertilizer should be most evident during the wet period but also would be expected for large storms even during the dry period. On the one hand artificial drainage tends to enhance use-efficiency of crops for water and fertilizer by permitting active growth of the root system during the wet season, but accelerated leaching loss of nutrients due to the drainage system tends to restrict the use-efficiency of applied fertilizer. During the dry period, the limited water-holding capacity of these coarse-textured soils requires that irrigation be used to maintain economically profitable crop yields. Insufficient irrigation will limit yields whereas excess irrigation enhances leaching loss of fertilizer. Thus effective soil water management for crops growing in shallow sands must of necessity include both irrigation and drainage practices. The effectiveness of soil water management practices for these soils will ultimately be reflected in the magnitude of crop yields and in the quality of groundwater.

Results from a 3-year investigation (Mansell et al. 1977, Rogers et al. 1977, Calvert et al. 1981) of fertilizer leaching losses from an experimental citrus grove located on a Spodosol at the University of Florida Agricultural Research Center near Ft. Pierce show that significant quantities of NO_3-N and PO_4-N were removed from the soil through discharge of drainage water. These losses occurred despite a management practice of applying small quantities of fertilizer frequently (every 3 months) to minimize leaching losses. As much as 22% of 169.52 kg/ha of N (55% of fertilizer N was NH_4-N and 45% was NO_3-N) applied in 4 split applications during a 12-month period was lost as NO_3-N in the drainage water. However, for treatments which had been deep-tilled to a depth of 105 cm prior to planting of citrus trees the average annual loss of NO_3-N in the drainage water was equivalent to only 3% of the total N applied as fertilizer. The effectiveness of the deep tillage plots in minimizing the leaching loss of N was attributed to increased retention of applied NH_4-N in the top soil due to upward transport of colloidal material from subsurface horizons and to increased potential for denitrification of NO_3-N in the soil profile due to slower drainage rates which resulted in generally higher water contents following rainfall events.

A major limitation of the interpretation of some of the results from this study however was that the applied fertilizer N was not labelled with a tracer such as ^{15}N or ^{14}N.

Thus a field investigation was performed to quantitatively evaluate the fate of ^{15}N-depleted NH_4^+ applied as fertilizer to a subsurface-drained sandy soil in an experimental citrus grove in South Florida. Isotopically labelled fertilizer N was applied to plots of a Spodosol which had previously received shallow- and deep-tillage treatments.

The primary objective of this investigation was to determine the influence of movement (leaching), ion exchange, and transformations (nitrification, denitrification, etc) upon ^{15}N- depleted NH_4^+ applied as a single fertilizer application to a tube-drained sandy soil in a citrus grove. A secondary objective was to evaluate the influence of 3 soil modifications --- shallow tillage ST, deep tillage DT, and deep tillage with initial incorporation of limestone into the profile DTL --- upon the fate of applied ^{15}N- depleted NH_4^+. Both objectives require evaluation under field conditions.

A brief review of the use of ^{15}N and ^{14}N isotopes as a tracer for fertilizer nitrogen in soil-plant systems will be given before presenting a description of experimental methods and results.

Chapter 2: Isotopic Tracer Methods for Nitrogen in Soil-Plant Systems

The recovery of fertilizer N applied to a given soil is commonly determined by both difference (non-tracer) and isotope tracer methods. Results from these two methods (Kowalenko 1980) may however lead to different conclusions. The difference method gives a measure of the net recovery of fertilizer N after several processes (denitrification, nitrification, ion exchange, leaching, immobilization, etc.) have exchanged with and transformed the fertilizer N. Broadbent and Carlton (1980) have shown that the assumption in difference method calculations that plant uptake of unlabeled N is the same in fertilized and unfertilized plots is not valid. In contrast, ^{15}N and ^{14}N tracer techniques give a measure of the actual fate of the applied N (Kowalenko 1980) as well as provide more accurate results than the difference method (Broadbent and Carlton 1980). Tracer methods permit actual measurement of fertilizer recovery as well as the distribution of recovered N in various chemical fractions.

Nitrogen tracer techniques (Hauck and Bremner 1976) are based upon the observation that naturally occurring N compounds contain about 0.366 atom % ^{15}N and 99.634 atom % ^{14}N. Addition of a fertilizer with an unusually high (^{15}N-enriched) or low (^{15}N-depleted) concentration of ^{15}N to a soil-plant system can thus be used as a tracer. Measured changes of $^{15}N/^{14}N$ ratios in samples removed from the system provide a means to investigate transformations of the added fertilizer. The magnitude of the change in the isotope ratio R from the background level R_o can be used to calculate the extent to which the tracer N has interacted with and become part of the system. The percentage of N present in a sample of soil or soil water initially from either ^{15}N-depleted or ^{15}N-enriched material can be calculated using the relationship

$$\beta = \frac{R_o - R}{R_o - R_i} \qquad (1)$$

where R_i is the isotopic ratio for the tracer material.

Hauck and Bremner (1976) state that isotope tracer methods offer much potential for studying ways to maximize the efficiency of fertilizer nitrogen in crop production. They state that movement of N into, within, and from soil can accurately be obtained only by the use of ^{15}N-depleted or ^{15}N-enriched fertilizers. Isotopically labelled fertilizer is particularly needed in soil-plant systems (Broadbent and Carlton 1980) which contain a background of large amounts of indigeneous N. Although ^{15}N-enriched materials have been used in most nitrogen tracer studies, use of ^{15}N-depleted material has gained in popularity due to the lower cost of those materials. However, the use of ^{15}N-depleted materials (Hauck and Bremner 1976) is restricted to experiments where excessive dilution does not occur in the soil-plant system. Thus studies of plant uptake or movement of applied nitrogen should be performed for single- rather than multiple-seasons.

Kowalenko (1980) used ^{15}N-enriched $(NH_4)_2SO_4$ to investigate transport and transformation of fertilizer NH_4^+ in eight micro-size (20-cm diameter) fallow field plots of a sandy soil in Canada. The ^{15}N-enriched (5.5% enrichment) fertilizer was applied to the soil at a rate of 184 kg N/ha in June 1977. Net fertilizer recoveries (as determined by differences between extracted N in fertilized and unfertilized plots) from the upper 75 cm of the soil profile were determined to be 117 and 19% of that originally applied, respectively, for 35 and 102 days after application of the fertilizer. Measurements of total ^{15}N concentrations however revealed that recoveries of fertilizer N were actually 73 and 25% for 35 and 103 days after fertilization. Almost all (93%) of the fertilizer NH_4^+ initially applied was nitrified within 35 days. If the nitrification was assumed to have occurred at a constant average rate, then that rate for this sandy soil would have been 4.89 kg N/ha/day which was considerably higher than a rate of 2.30 kg N/ha/day obtained previously by the same author for a clay loam soil. Both soils had been in fallow prior to the experiments such that neither soil had crop residues to influence microbial processes. Although relatively low organic matter content of the sandy soil suggested limited microbial activity, tracer data showed the microbial process for nitrification to be rapid. Leaching, denitrification, clay fixation of

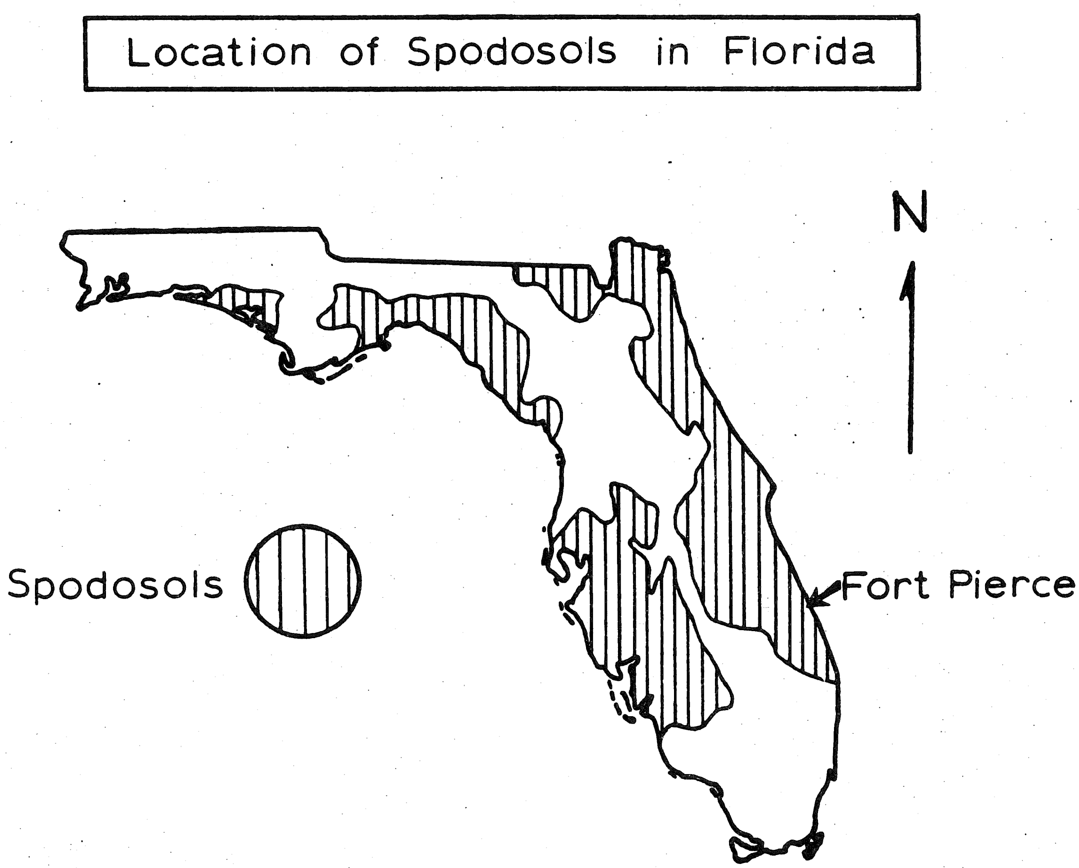
NH_4^+, mineralization, and immobilization all were important in the transport and transformation of fertilizer NH_4^+ applied to a sandy soil.

Chapter 3: Experimental Methods and Procedure

An experimental citrus grove originally developed (Knipling and Hammond 1971) in 1970 on 9 hectares of flatwood land at the University of Florida Agricultural Research Center (A.R.C.) near Fort Pierce was selected as the location for this investigation. The location of the experimental site as well as the distribution of Spodosols over the land area of Florida is shown in Fig. 1. The grove was established as a cooperative venture between the University of Florida Institute of Food and Agricultural Sciences (IFAS) and the Agricultural Research Service (ARS) of the United States Department of Agriculture. The IFAS-ARS effort was designated as the Soil, Water, Atmosphere, and Plant Relationships Project (SWAP). The original purpose for the SWAP grow was to evaluate the influence of deep tillage, with and without incorporation of limestone into the profile, upon subsurface drainage and growth of citrus in a Spodosol. The SWAP grove was chosen as the site for this work partially because of the background information on chemical and physical characteristics that has been accumulated (Mansell et al. 1977; Mansell, Wheeler and Calvert 1980; Calvert et al. 1981; Rogers et al. 1977) for the acid, sandy soils in the grove. Another reason for that choice was the fact that it is one of the best designed Coastal Plains experimental drainage sites in the Southeastern United States.

Figures

Fig. 1: Map of Florida showing major land areas of Spodosols and the location of the experimental site.



Three 0.5-hectare plots of citrus were selected for this research. One plot was selected for each of the three soil profile modification treatments: (i) shallow-tilled (ST) to 15-cm depth, (ii) deep-tilled (DT) to 105-cm depth, and (iii) deep-tilled (DTL) to 105 cm depth with an initial incorporation of 56 metric tons per ha of dolomitic limestone into the profile. All treatments received annual applications of 2.24 metric tons per ha of limestone to the soil surface. During the initial deep tillage operation, a trenching machine incorporated and mixed spodic and underlying sandy clay loam material with sandy soil material from the A horizons. The primary soil type at the site is Oldsmar fine sand (a member of the sandy siliceous, hyperthermic family of Alfic Arenic Haplaquods). In undisturbed profiles, the A horizon of the acid sand has an average (Calvert et al. 1981) depth of 82 cm and contains about 1% organic matter. Underneath the A horizon a nearly impermeable spodic layer ranging in thickness from 10 to 20-cm contains about 3.5% organic matter. A layer of sandy clay loam, also with low permeability to water, occurs beneath the spodic horizon.

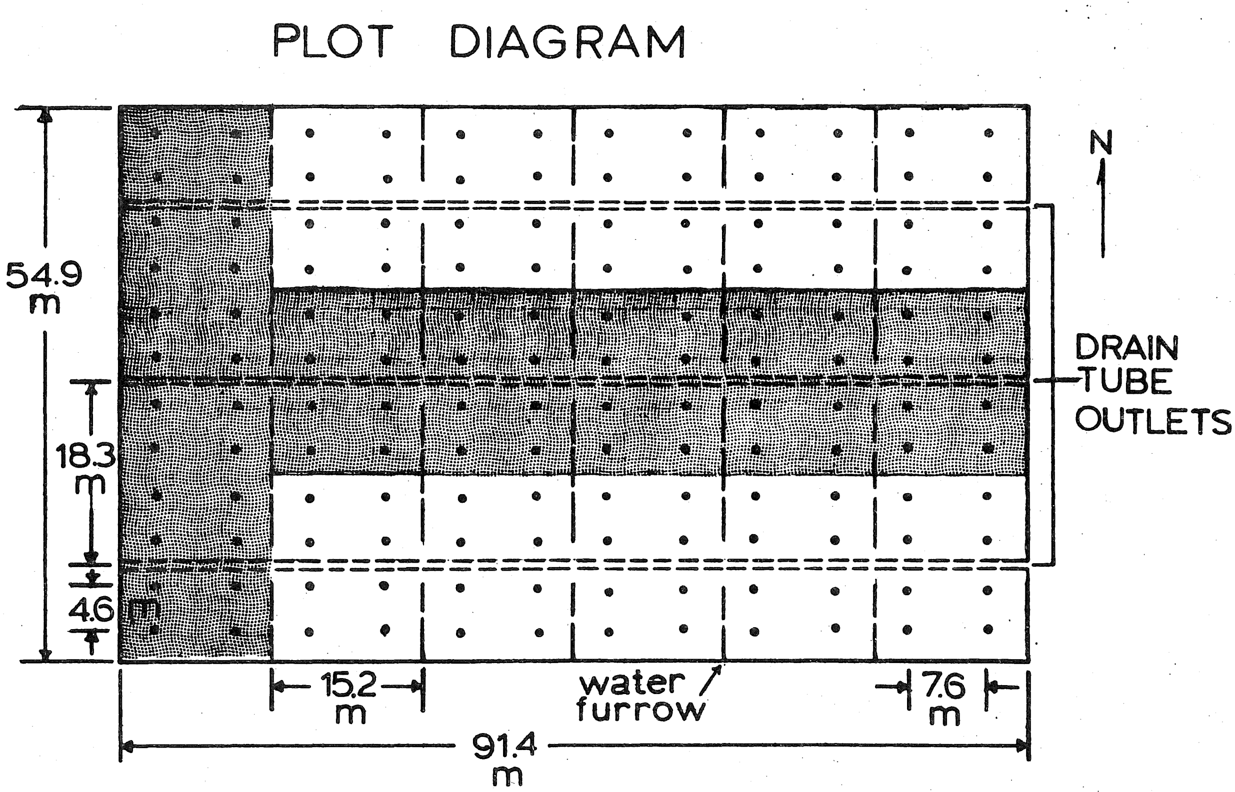
Surface drainage in each plot was provided by a system of elevated beds (38 cm height of bed crown above the bottom of water furrows) separated by parallel water furrows. The width of the beds as measured from centers of adjacent water furrows was 15.2 m. During very intense rain storms any surface drainage water from each plot was removed by collection ditches at the end of the water furrows. Subsurface drainage was provided by a system of 10-cm corrugated plastic tubes buried beneath the soil surface at an average depth of 107 cm and spaced 18.3 m apart. The drain tubes were located perpendicular to the elevated soil beds. Two rows of citrus 7.6-m apart with a spacing of 4.6 m between trees were planted along the top of each bed in 1970. Water from the center tube in each plot discharged into a concrete manhole where flow was measured with 30.5 cm, 30 degree, V-notch weirs and Stevens type F, Model 68 waterstage recorders. Pensacola bahiagrass was seeded to each plot in 1970. A strip of surface along each tree row was maintained bare of bahiagrass and weeds.

In order to investigate the fate of N in fertilizer applied to these coarse-textured acid soils, ^{15}N-depleted NH_4-N was applied as $(NH_4)_2SO_4$ in an otherwise complete fertilizer to shallow-tilled (ST) and deep-tilled (DT and DTL) plots. On June 5 (Julian Day 157) of 1980, ^{15}N-depleted 8-2-8 (% N - % P_2O_5 - % K_2O) fertilizer was applied at a rate of 115 kg N/ha to selected areas (The shaded area in the plot diagram in Fig. 2 indicates the fertilized area.) for each of ST, DT, and DTL plots. A batch of the isotopically labelled fertilizer (625 kg) was prepared by mixing 232 kg of ^{15}N-depleted $(NH_4)_2SO_4$ (courtesy of Dr. R. D. Hauck, Tennessee Valley Authority, Muscle Shoals, Alabama) with 63 kg of ordinary superphosphate, 84 kg of muriate of potash, and 246 kg of powdered dolomite. Isotopically labelled fertilizer was broadcast by hand to the elevated beds (but not to the water furrows) in the shaded area shown in the plot diagram (Fig. 2) centered about the drain field for the center drain in each of the three plots. Dots in Fig. 2 designate the locations for citrus trees. Approximately 0.22 ha in each plot received labelled fertilizer. The remainder of each plot was fertilized with the same rate of non-labelled 8-2-8 fertilizer.

Irrigation was applied immediately after the fertilizer application to prevent volatilization of NH_4-N due to previous annual applications of limestone to the surface soil. One gallon cans containing open bottles of sulfuric acid were placed at selected locations in the treatment plots in order to trap any gaseous NH_3 released to the atmosphere. The acid solutions were later analyzed for N concentration.

During an 8-month period following the application of ^{15}N-depleted fertilizer, concentrations of NO_3-N and NH_4-N were determined in subsurface drainage water, samples of soil solution, in soil cores, and in selected leaf samples from citrus trees. When nitrogen concentrations in water, soil and tissue samples were sufficiently high, ratios of ^{15}N-to-^{14}N concentrations were determined. The central drain in each of the selected ST, DT and DTL plots was continually monitored for water flow rates (Data provided by Dr. J. S. Rogers, Agricultural Engineer, USDA, University of Florida) and intermittently monitored for water quality samples. Automated water samplers (ISCO Model 391) were used

Fig. 2: Schematic diagram (scale: 1-to-695 cm) of experimental citrus plots for ST, DT, and DTL treatments.



to take samples from weirs at the outflow of each drain. Samples were taken most frequently during periods of drain discharge after rainfall events. All water samples were frozen and stored for later analysis.

Soil solution samplers were constructed of medium porosity Pyrex glass discs permanently glued to the bottom end of various lengths of 3/4 inch PVC pipe. Rubber stoppers were placed in the top end of the pipes to provide an air pressure seal. The fritted disc samplers were placed at 4 soil depths - 60, 75, 90, and 105 cm - and at 6 horizontal distances from the central drain - 5, 50, 100, 350, 500, and 900 cm - along one row of citrus in each plot. Hand-operated air pumps were used to apply approximately 80 cm of water to each solution sampler during sampling periods. The samplers were stoppered for 4 to 6 hours to enable extraction of 25 to 100 cm^3 of water depending upon the water content of the soil. Solution samples were taken 57 (August 1), 69 (August 13), and 76 (August 20) days after fertilizer application. Samples were frozen and stored before analysis.

Soil water suction was determined from mercury manometer-type tensiometers located at 4 soil depths - 30, 60, 90, and 105 cm - and 6 horizontal distances - 5, 50, 100, 350, 500, and 900 cm - from the central drain in each treatment. The tensiometers were located along one row of trees in each plot. Water inside the tensiometers made hydraulic contact with water in soil pores through a porous ceramic cup at the bottom of each tensiometer. Mercury manometers permitted measurements of water suction of soil water.

A hydraulic coring machine was used to take continuous soil cores down to a depth of 70 cm in the ST plot and to a depth of 100 cm in each of DT and DTL plots. The holes in the soil profile were later refilled with inert builders sand to prevent preferred water flow to drain tubes. Each core was divided into subsamples corresponding to depths of 0-8, 9-23, 24-38, 39-53, 54-70, 71-84, and 85-100cm. The subsamples of soil were frozen and stored until analysis could be perform. Twelve cores were removed from each of the tree plots on dates corresponding to 12 (June 15-16), 42 (July 16-17), 75 (August 19-20), and 134 days (October 16-17) after the initial surface application of labelled fertilizer. Six of the twelve cores from each plot were taken near each drain and the remaining cores were taken from 450 cm lateral distance from each drain. A total of 912 soil samples were collected and analyzed for this investigation.

Leaf samples were collected from six rootstock varieties for both grapefruit and orange trees once during July and again in October. The samples were ground in a Wiley mill and frozen until analysis could be performed.

All water samples were thawed and analyzed for pH using a glass electrode, NO_3-N concentration using a nitrate specific ion electrode, NH_4-N concentration using the phenolate

(EPA 1976) method, and soluble salts using an electrical conductivity meter. The remaining volume of each sample was measured and analyzed for NH_4-N and NO_3-N using a macrokjeldahl procedure (Bremner 1965). Soil samples were also thawed, extracted with water and 1 N KCl and both extracts analyzed similarly to that for the water samples. Leaf samples were dissolved in concentrated H_2SO_4 for total analyses and the solutions analyzed for NO_3-N and NH_4-N. After titration, samples containing more than 1.0 mg N were redistilled by microkjeldahl apparatus into 5 ml of 4% boric acid and 1 ml of 0.08 N sulfuric acid. Reagent grade ammonium sulfate was added to all other samples in order to increase the N content to 1.0 mg per sample. These solutions were analyzed in duplicate for isotopical ratios $^{15}N/^{14}N$ by an automated mass spectrometer at the Los Alamos National Laboratory near Los Alamos, New Mexico. Isotopic ratios for reagent grade $(NH_4)_2SO_4$, ^{15}N-depleted $(NH_4)_2SO_4$, and for soil samples taken from soil that had only been fertilized with unlabelled N materials were used along with the ratios from the samples to calculate the percentages of N derived from the ^{15}N-depleted fertilizer. Approximately 1300 samples of water, soil extracts, and leaf extracts were analyzed for isotopic N ratios. Concentrations of labelled and total N were expressed as mg N/liter of effluent.

Chapter 4: Results and Discussion

The shallow tillage (ST) treatment of the Spodosol located at the SWAP citrus grove is representative of agricultural management practiced on vast areas of similar acid, sandy soils in Florida. Water and nutrient retention capacities of soil in the ST plot (Mansell et al. 1977) have been demonstrated to be very limited. Recommended cultural practices for agricultural crops growing on this and similar soils include split application of fertilizer throughout the growth season and frequent application of relatively small quantities of water during periods of drought or limited rainfall. Because of subsurface horizons with low permeability for water and relatively flat terrain, artificial drainage is often needed to maintain an aerobic root zone during periods of high rainfall. Because of the high values of hydraulic conductivity when these soils are water-saturated (Mansell, et al. 1980) rapid rates of drainage tend to enhance leaching losses of fertilizer nutrients such as nitrogen.

Deep tillage (DT and DTL treatments) of this soil has been observed (Mansell et al. 1977) to increase the nutrient retention capacity by increasing the cation exchange capacity, to increase the water retention capacity by incorporating colloids from an underlying Spodic horizon, and to decrease rates of nutrient leaching loss by decreasing drainage discharge rates. Although this treatment is expensive and requires the presence of a subsurface layer high in colloid content, selective deep tillage over limited soil zones only in the vicinity of crop rows offers a potential conservation practice for applied irrigation water and fertilizer.

As expected, the subsoil pH in the ST plot was observed during this study (Fig. 3) to be considerably lower than the DTL plot but higher than the DT plot. The pH of the top 9 cm of the DTL soil profile was relatively uniform with a value of about 6.1. The higher pH of the DTL soil is attributable to the original incorporation of limestone prior to the deep tillage operation. Annual applications of limestone however were shown to result in pH values near 6.0 for the surface soil of all three treatments. These acid, sandy soils have a predominance (Fiskell and Calvert, 1975) of variable-charge colloids such as organic matter, iron oxides, and aluminum oxides; therefore application of limestone tends to raise the cation exchange capacity. The higher pH of the surface soil of ST and DT plots and the higher pH of both surface and subsurface soil zones in the DTL plot should therefore preferentially favor microbial nitrification of applied fertilizer NH_4-N as opposed to the more acid subsoil conditions of ST and DTL plots.

During the period of this study soil water content generally was higher between 60 to 90 cm depths (Fig. 4) than in the uppermost 30 cm of the profiles for all three tillage treatments. During periods of drainage discharge this was particularly true and the subsoil of the deep-

Fig. 3: Distributions of soil pH with depth measured on June 18, 1980 for ST, DT, and DTL tillage treatments.

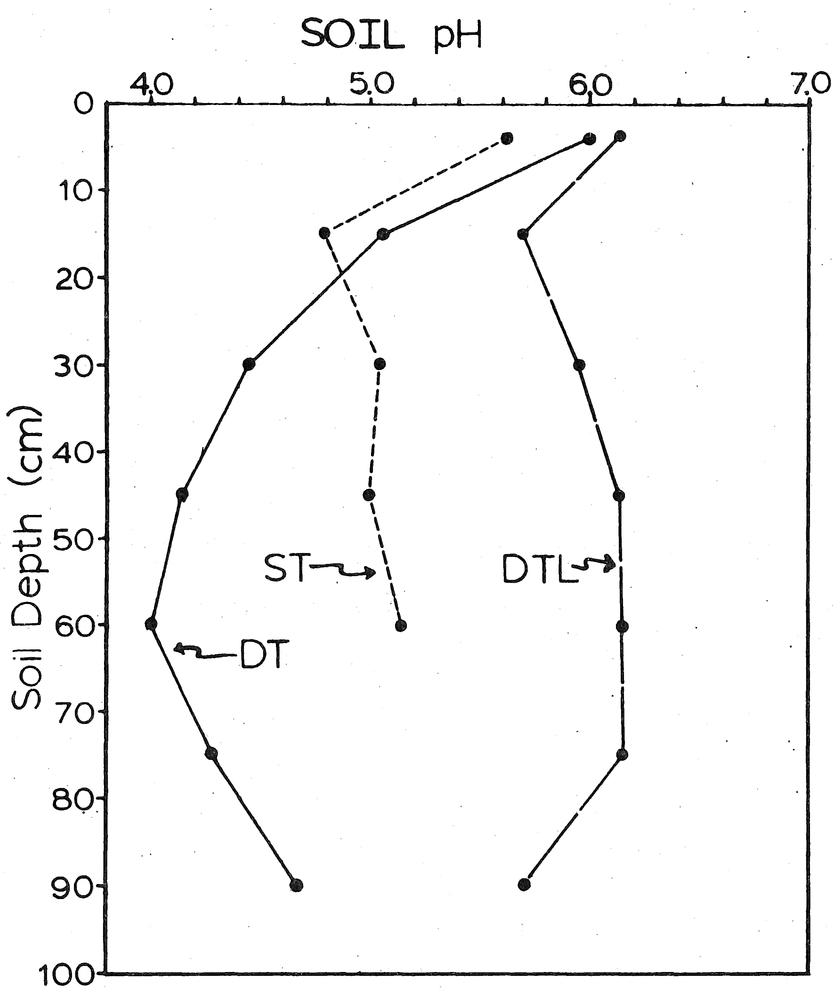
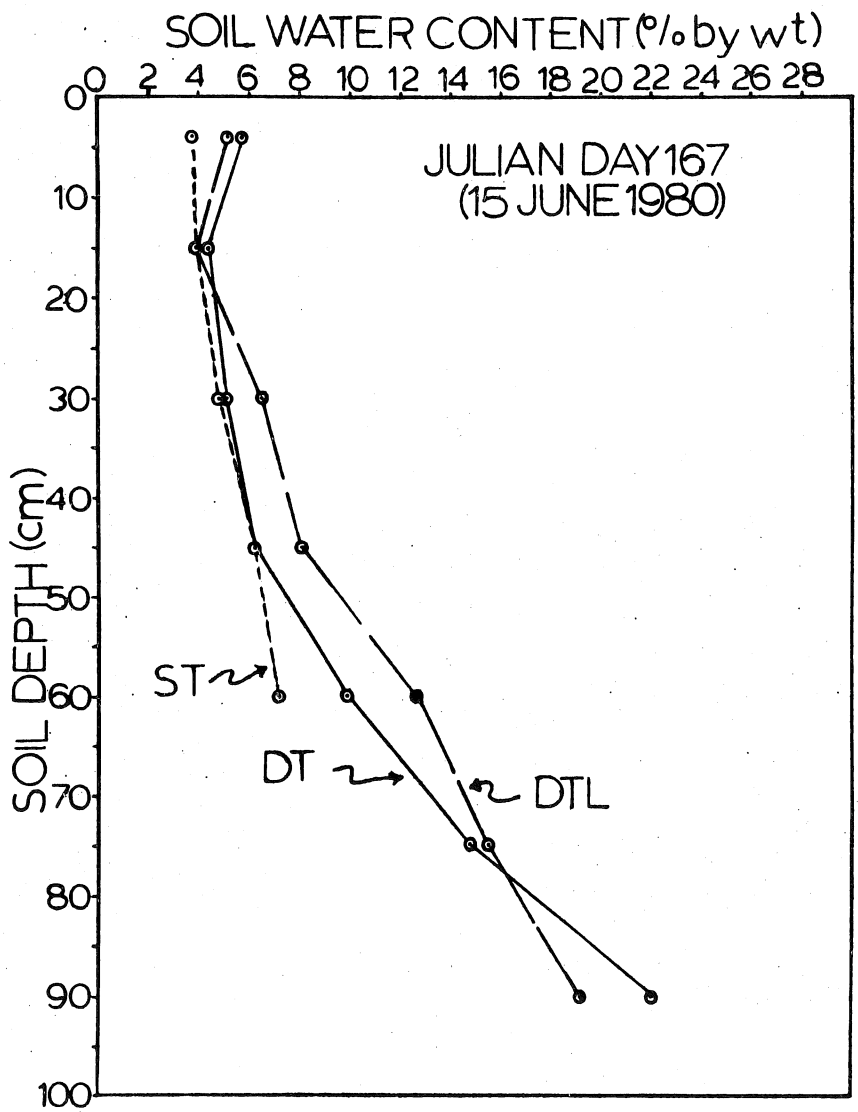


Fig. 4: Distributions of soil water content (% by weight) with depth on June 15, 1980 for ST, DT, and DTL tillage treatments.



tilled plots had generally higher water contents than did the shallow-tilled plot. The water-unsaturated condition of the surface soil in all of the treatments however should tend to enhance nitrification of applied fertilizer. Previous research (Mansell et al. 1977) has also shown that the actual water retention capacity of the shallow tilled soil in the ST plot is generally much less than that in deep-tilled soil in DT and DTL plots.

Soil water pressure head values for a 10-day period in October also indicate that the soil at 90 cm depth was drier in the ST (Tables 1, 2 and 3) plot versus the DTL plot. Pressure head values were generally slightly negative in ST whereas the values were positive in DTL. Negative pressure heads in the DT soil however indicated that DT soil was drier than the DTL soil.

Volatilization losses from applied fertilizer (Table 4) averaged approximately 0.31 kg/ha of NH_4-N for all 3 plots during the first two months after application of fertilizer. Losses were 0.24, 0.25, and 0.42 kg/ha of NH_4-N respectively for ST, DT and DTL plots. Based upon this information we conclude that volatilization losses of N were sufficiently small to be insignificant.

The original intent of this investigation was to evaluate leaching loss of fertilizer N during a typical summer rainy period when large quantities of water moved through the soil to subsurface drains. However, an unexpected drought occurred during 1980 such that the summer and fall

Table 1: Soil water pressure head (cm of water) at 0.9 m depth and lateral distances of 0, 0.5, 1.0, 3.5, 5.0, and 9.0 m from the center drain tube in the ST plot for 10 days in October 1980.

Date	Lateral Distances: 0	0.5	1.0	3.5	5.0	9.0m
	- - - - - - - (cm of	water)	- - - - -			
October 20	-6	-8	0	0	-	-12
" 21	-9	-8	0	0	-	-12
" 22	-8	-10	-1	+1	-	-12
" 23	-3	-8	0	-1	-	-1
" 24	-6	-8	0	-1	-	-12
" 27	+14	+24	+2	+9	-	-
" 28	-10	-12	-4	-2	-	-12
" 29	-14	-14	-6	-4	-	-12
" 30	-13	-15	-6	-4	-	-13
" 31	-16	-17	-8	-6	-	-16

Table 2: Soil water pressure head (cm of water) at 0.9 m depth and lateral distances of 0, 0.5, 1.0, 3.5, 5.0, and 9.0 m from the center drain tube in the DT plot for 10 days in October 1980.

Date	Lateral Distance:	0	0.5	1.0	3.5	5.0	9.0m
		- - - - -	(cm of	water)	- - - -	- - -	- -
October 20		-5	-15	-14	-10	-6	-5
" 21		-5	-15	-15	-10	-10	-5
" 22		-3	-15	-14	-	-8	-5
" 23		-3	-14	-14	-	-9	-5
" 24		-3	-15	-14	-	-8	-4
" 27		-2	-16	-14	-	-10	-7
" 28		-2	-15	-16	-	-10	-8
" 29		-2	-16	-18	-	-12	-10
" 30		-4	-	-16	-	-12	-10
" 31		-4	-	-20	-	-14	-10

Table 3: Soil water pressure head (cm of water) at 0.9 m depth and lateral distances of 0, 0.5, 1.0, 3.5, 5.0, and 9.0 m from the center drain tube in the DTL plot for 10 days in October 1980.

Date	Lateral Distance:	0	0.5	1.0	3.5	5.0	9.0m
October 20		+16	+8	+9	+16	+14	+16
" 21		+26	+16	+9	+16	+14	+16
" 22		+16	+8	+10	+14	+11	+16
" 23		+17	+8	+10	+16	+14	+17
" 24		+17	+6	+10	+14	+14	-
" 27		-9	-12	+9	0	-	-
" 28		+16	+3	+2	+8	+8	-
" 29		+14	+4	+10	+8	+6	-
" 30		+14	+12	+2	+8	+5	-
" 31		+14	0	0	+8	+4	-

Table 4. Volatilization of NH_3 from surface-applied fertilizer during 1980 as measured by sorption of NH_4-N in containers (cross-sectional surface area of 178 cm^2 per container). Effective volatilization losses of NH_4-N are given as averages for each plot.

Starting Date	Sorption Period	Treatment Plots* ST	DT	DTL	Mean
	(days)	------- (kg NH_4-N/ha)			------
June 6	4	0.0455	0.0371	0.0680	0.0500
June 10	8	0.1219	0.1191	0.2427	0.1612
June 18	6	0.0197	0.0230	0.0331	0.0253
June 24	7	0.0191	0.0169	0.0208	0.0185
July 1	20	0.0185	0.0157	0.0197	0.0180
July 21	7	0.0185	0.0416	0.0404	0.0337
Total		0.2432	0.2534	0.4247	0.3067

*These values were calculated by dividing measured amounts of NH_4-N sorption per container (g NH_4-N/178 cm^2) by the conversion factor 1780.

periods received less rainfall than during normal years. Total rainfall plus irrigation was only 84 cm during the 196 day (Fig. 5) period between June 18 and December 3. The rainfall distribution (Figs. 6-11) was such that periods of net drainage discharge were intermittent during the time of this study. For the ST, DT, and DTL plots, discharge occurred during the periods from June 21 to July 3 (Julian Days 173 to 185), July 13 to August 2 (Julian Days 195-215), November 10 to December 5 (Julian Days 315 to 340), and December 20 to 30 (Julian Days 355 to 365). Water discharge occurred from the drains for approximately 67 days of the 196 day period. Drainage rates were obviously highest for the shallow tillage plot. Total drainage from ST was 30.7 cm (Fig. 6) which amounts to only 37% of the total amount of rainfall plus irrigation. Thus roughly 63% of the input water for the 196 day period was assumed to be used during evapotranspiration. Total drainage amounts for DT and DTL deep-tilled plots were however much less than for ST being only 5.6 (7%) and 8.5 (10%) cm, respectively. Evapotranspiration was therefore assumed to account for roughly 93 and 90% of the input water for DT and DTL plots. The evapotranspiration estimates assume no vertical deep seepage water loss and only small changes in soil water storage.

Water fluxes or drainage rates were much greater for the shallow-tilled plot than the deep-tilled plots. For all drains the maximum water fluxes occurred during November (Figs. 9, 10, and 11) with values of 3.0, 0.6, and 1.5

Fig. 5: Accumulative amounts (cm) of rain and irrigation between June 18 (Julian Day 170) and December 31 (Julian Day 366).

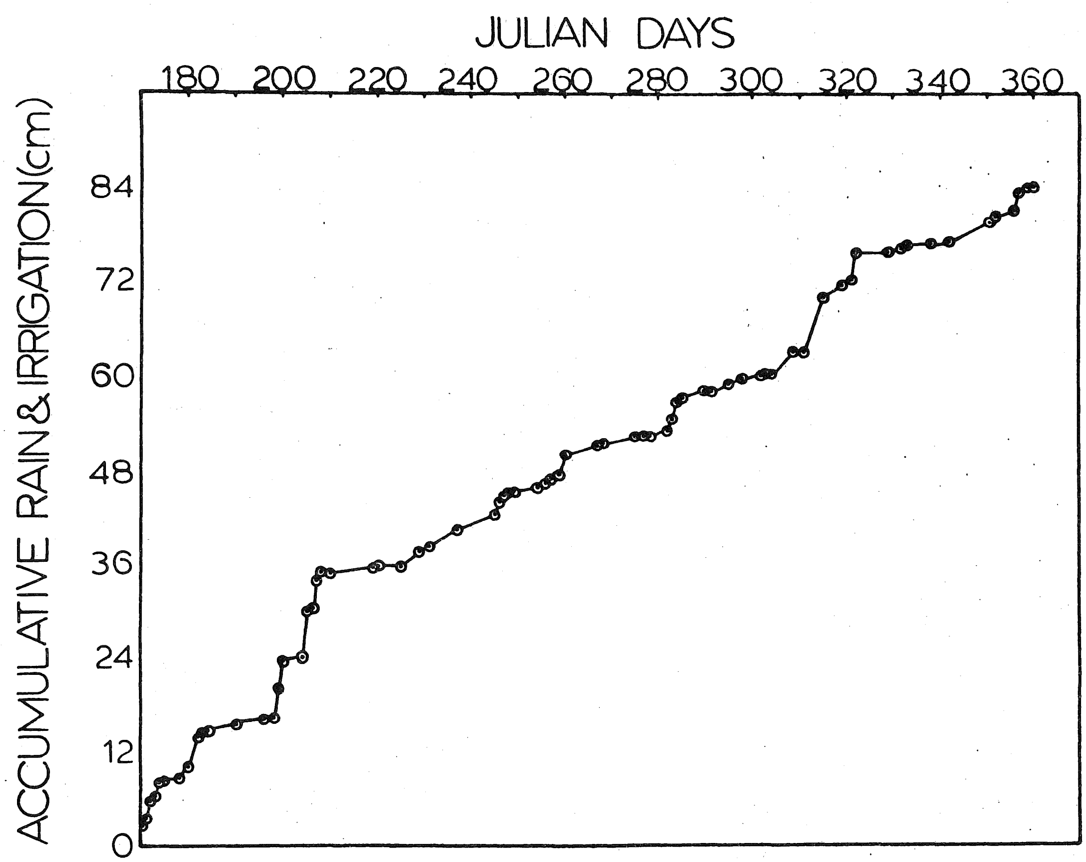


Fig. 6: Accumulative drainage (m^3/ha) from the ST tillage treatment over the period from June 18 to December 31, 1980.

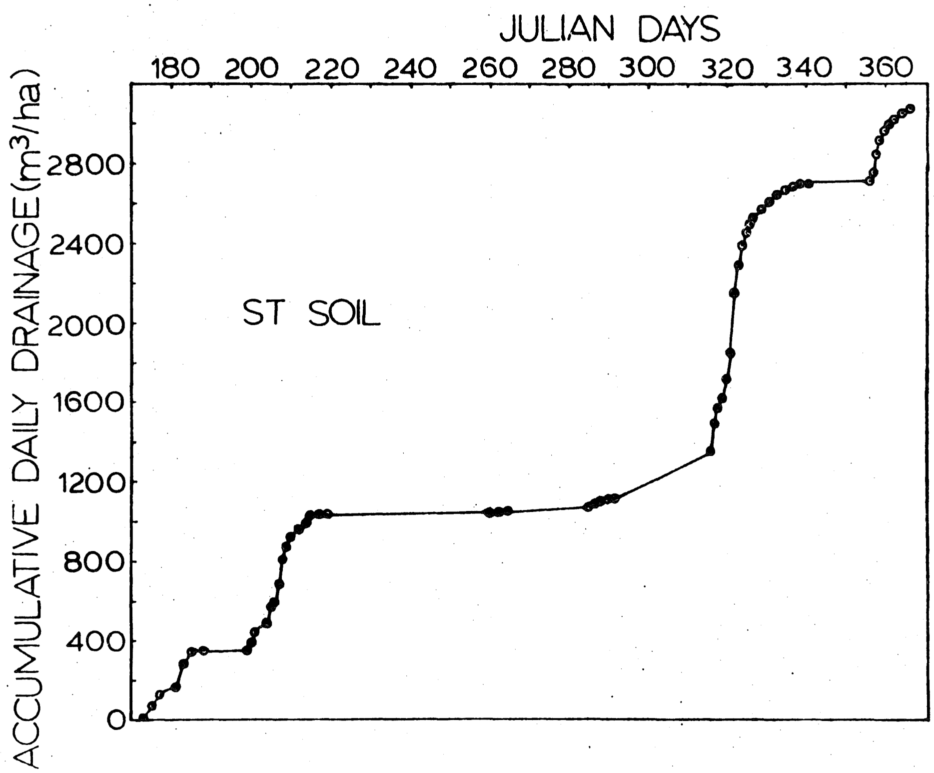


Fig. 7: Accumulative drainage (m^3/ha) from the DT treatment over the period from June 18 to December 31, 1980.

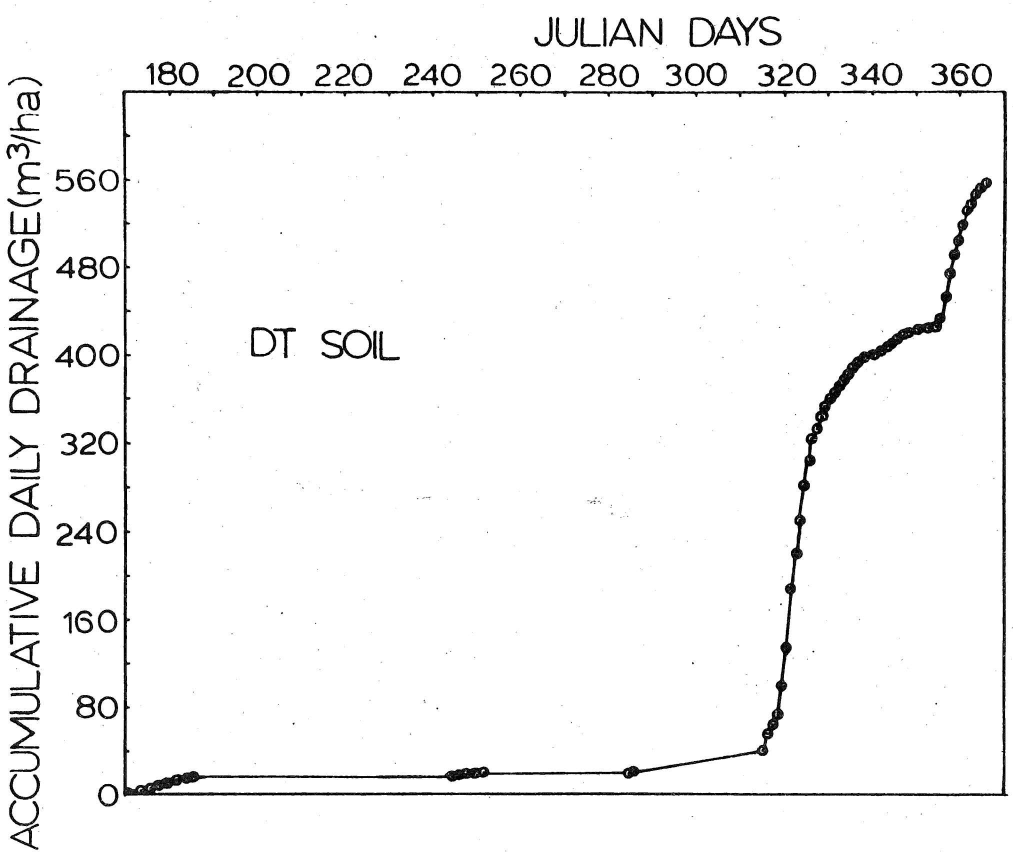


Fig. 8: Accumulative drainage (m^3/ha) from the DTL treatment over the period from June 18 to December 31, 1980.

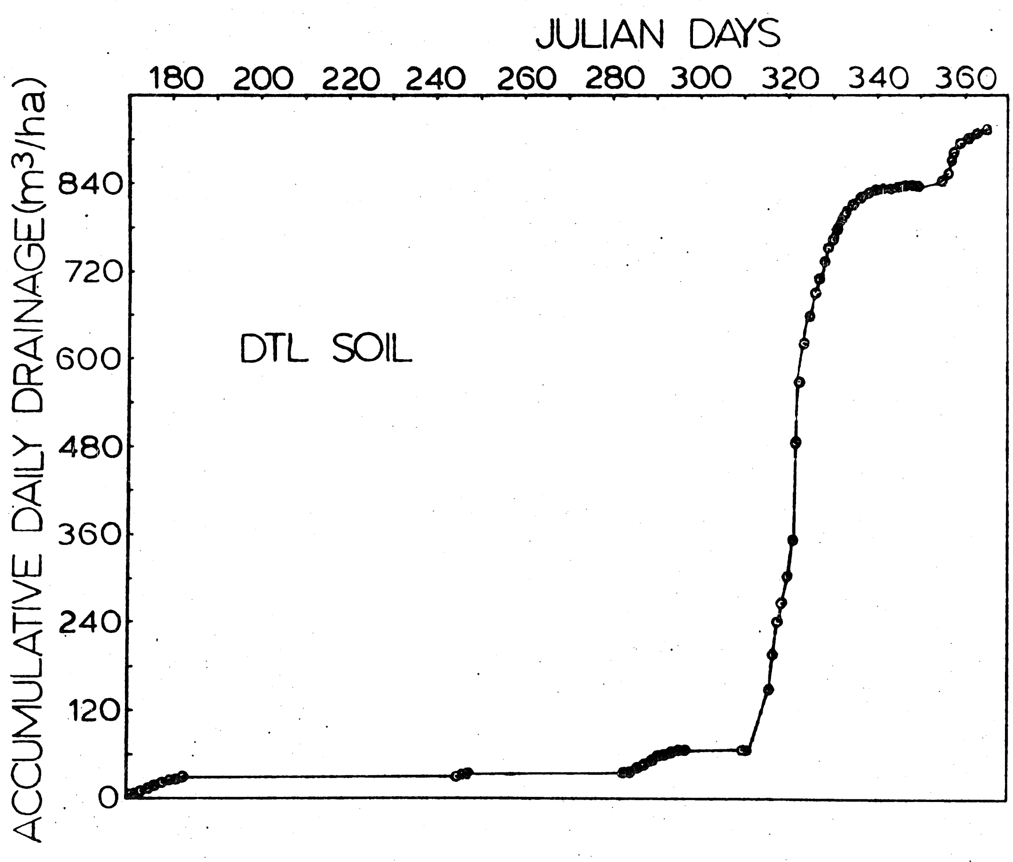


Fig. 9: Drainage flux (m^3/ha/day) from the ST treatment over the period from June 18 to December 31, 1980.

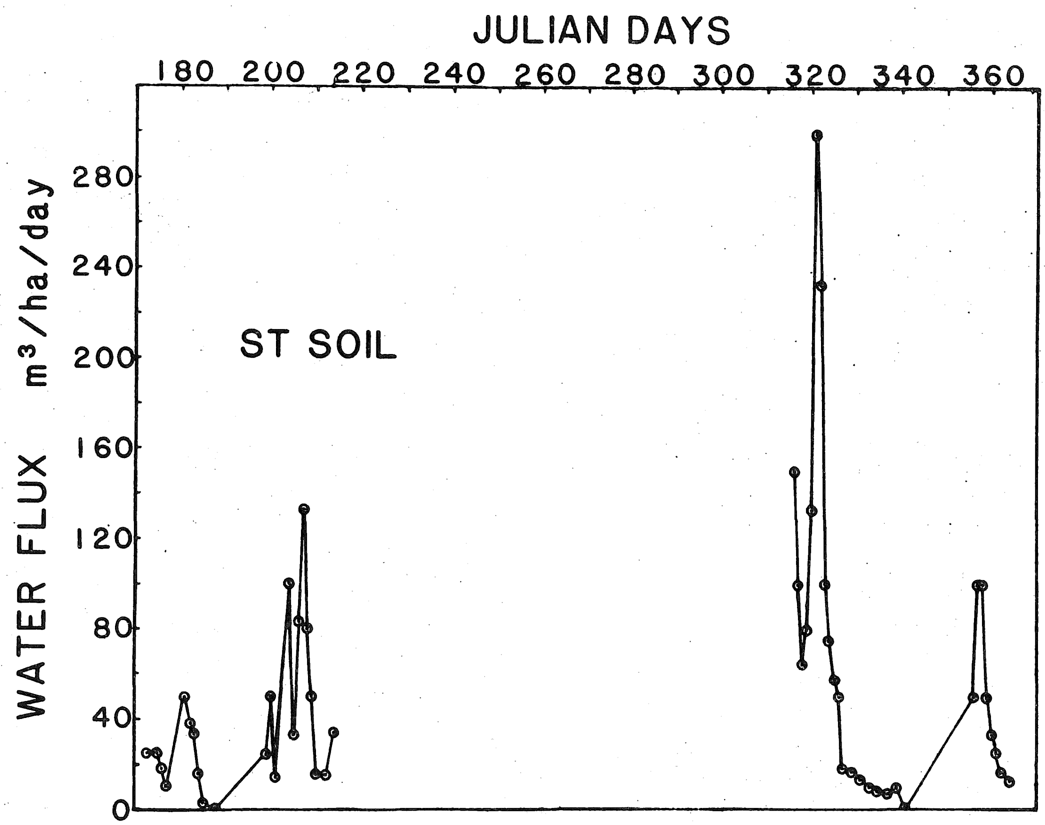


Fig. 10: Drainage flux (m^3/ha/day) from the DT treatment over the period from June 18 to December 31, 1980.

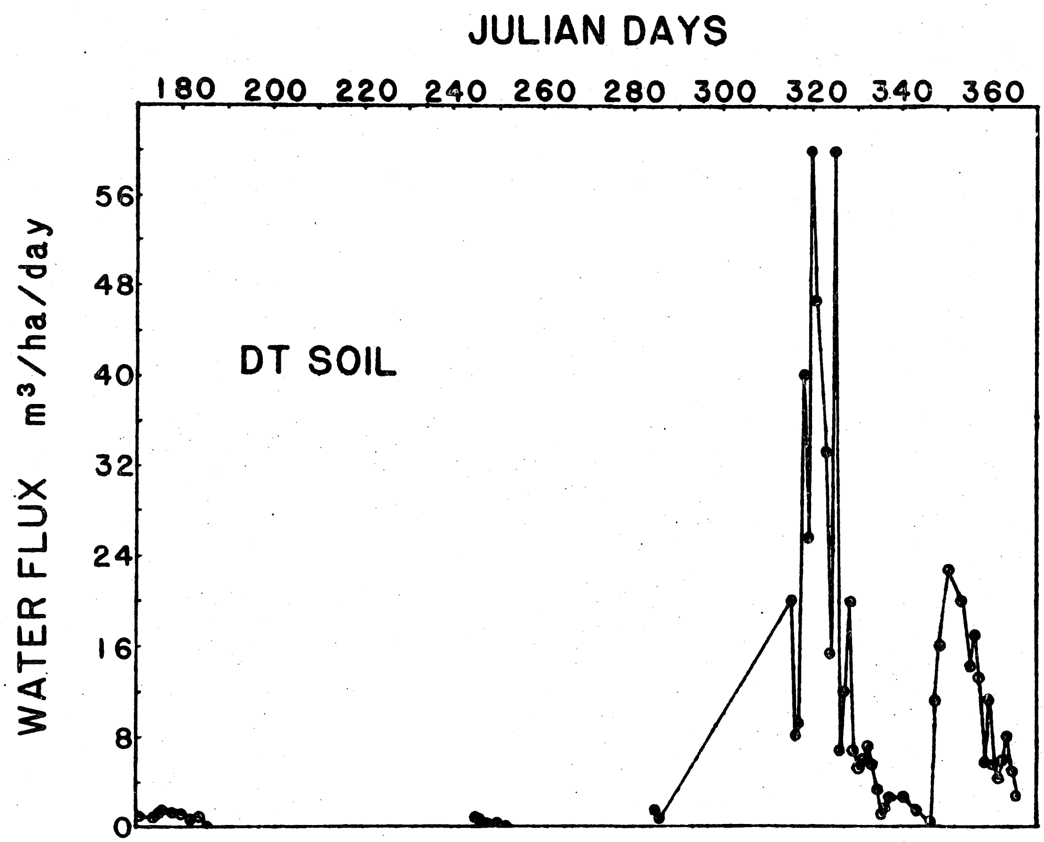
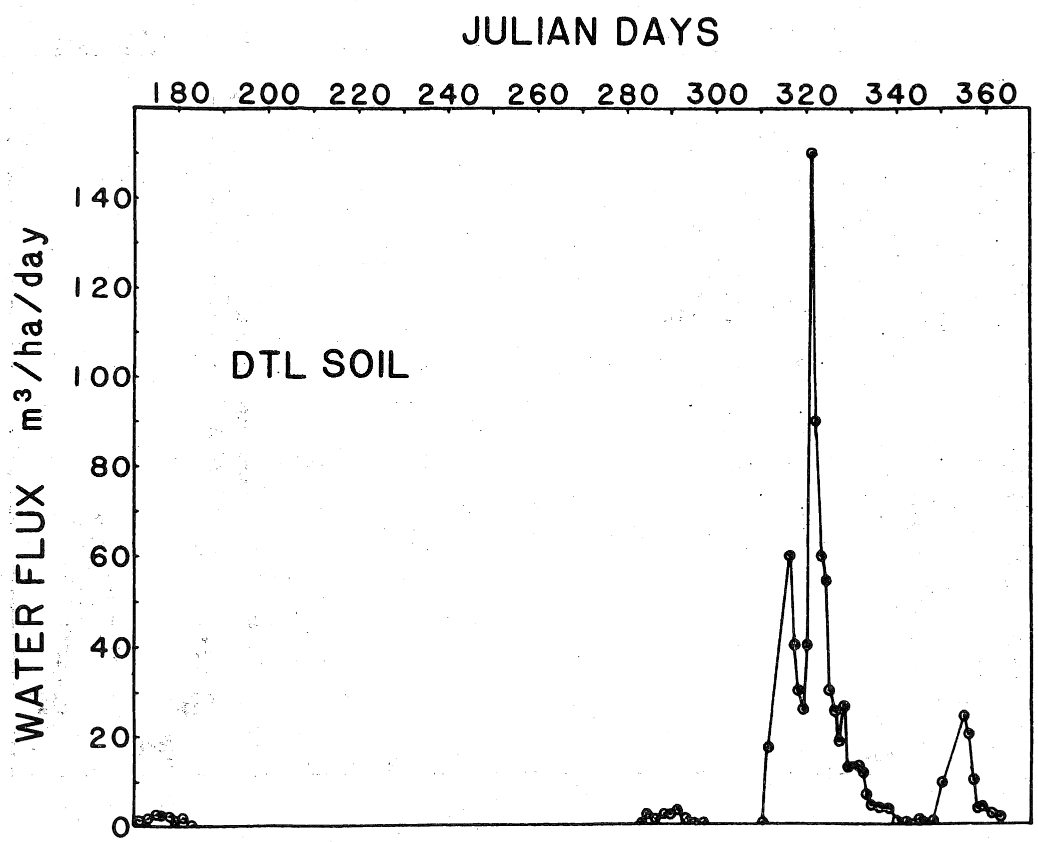


Fig. 11: Drainage flux (m^3/ha/day) from the DTL treatment over the period from June 18 to December 31, 1980.



cm/day respectively for ST, DT, and DTL plots. Drainage was very small during the summer period for the deep tillage plots.

Drainage outflow through subsurface tubes has been consistently greater for all shallow tillage (ST) treatments at the SWAP citrus grove than from both deep tillage (DT and DTL) treatments. Mean annual drainage discharges over the 10 year period from 1971 through 1980 (Dr. J. S. Rogers. 1982. private communication.) for ST, DT, and DTL treatments were 55.4, 33.3, and 28.9 cm.

As expected, the highest concentrations of N (the sum of NH_4-N plus NO_3-N) in the drainage water occurred during the first 2 months after application (Figs. 12, 13, and 14) of fertilizer. For ST drainage water, maximum N concentrations of 25 and 11.7 mg/l occurred during 25 and 48 days after fertilization. For DT soil, maximum N concentrations of 8.2 and 10.3 mg/l occurred during 20 and 27 days after fertilization. For DTL soil, maximum N concentrations of 6.0 and 13.4 mg/l occurred 20 and 26 days after fertilization. Thus N concentrations in drainage water were generally higher in ST (Mansell, et al. 1980) than for the deep-tilled plots (DT and DTL). The higher N concentrations in the drainage is largely attributable to the low cation exchange capacity of this soil. Concentrations of N were lower during the fall versus the summer for DT and DTL drainage waters. This observation was true except for an unexplainable peak that occurred during the latter part of December.

Isotopic N analysis indicated (Figs. 12, 13, and 14) that N from the ^{15}N-depleted fertilizer accounted for as much as 50% of the N in drainage water that occurred during the summer. This was true for all three plots. The percentage of N attributable to the labelled fertilizer decreased with time during the season. For example on November 15 (163 days after application of the fertilizer) percentages of N due to the ^{15}N-depleted fertilizer were 20, 17, and 25% respectively for ST, DT and DTL soils. This data implies that much of the N being discharged through the drains was due to residual N from mineralization of soil organic matter and from previous applications of fertilizer.

Values of nitrogen flux through the drains were calculated by multiplying water flux and N concentrations for each day that drainage occurred. This data (Figs. 15, 16, and 17) indicate that rates of N discharge were greater in the summer than in the fall for the shallow tillage treatment, but were greater in the fall than in the summer for the deep tillage plots. For the ST plot, rates of nitrogen leaching losses as high as 0.850 kg/day were observed for 2 drainage events during the summer. Much smaller rates of 0.012 and 0.015 kg/day were observed for single summer drainage events in each of DT and DTL plots. This information further substantiates (Mansell et al. 1977) the effectiveness of deep tillage in decreasing N leaching loss in these acid sandy soils. Measurements of the area beneath the curves in Fig. 15 shows that total leaching losses of

Fig. 12: Concentration (mg/l) of extracted and labelled N (NH_4-N plus NO_3-N) in drainage water from the ST plot over the period from June 18, 1980 to February 14, 1981.

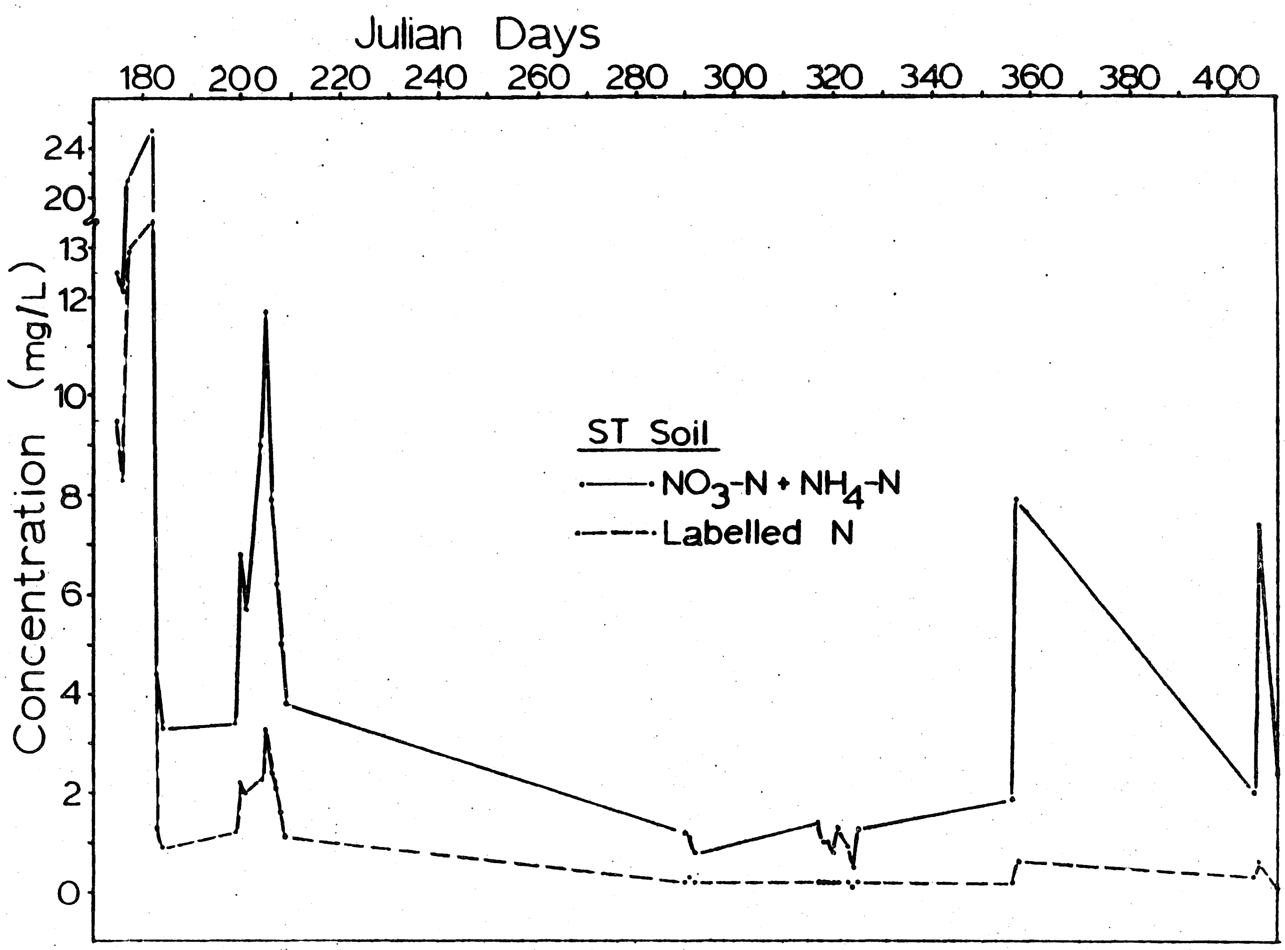


Fig. 13: Concentration (mg/l) of extracted and labelled $N(NH_4\text{-}N$ plus $NO_3\text{-}N)$ in drainage water from the DT plot over the period from June 18, 1980 to February 14, 1981.

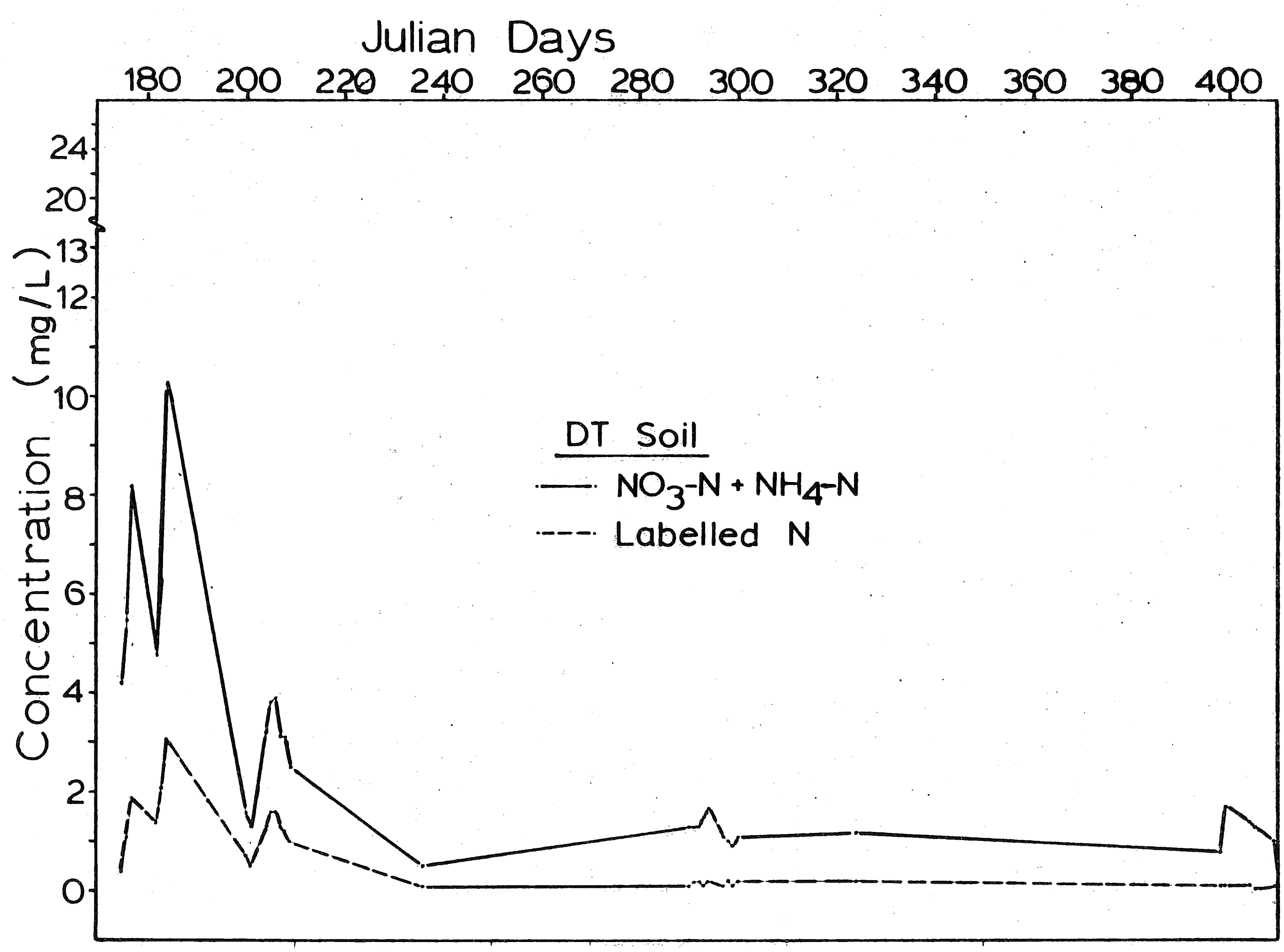


Fig. 14: Concentration (mg/l) of extracted and labelled $N(NH_4\text{-}N$ plus $NO_3\text{-}N)$ in drainage water from the DTL plot over the period from June 18, 1980 to February 14, 1981.

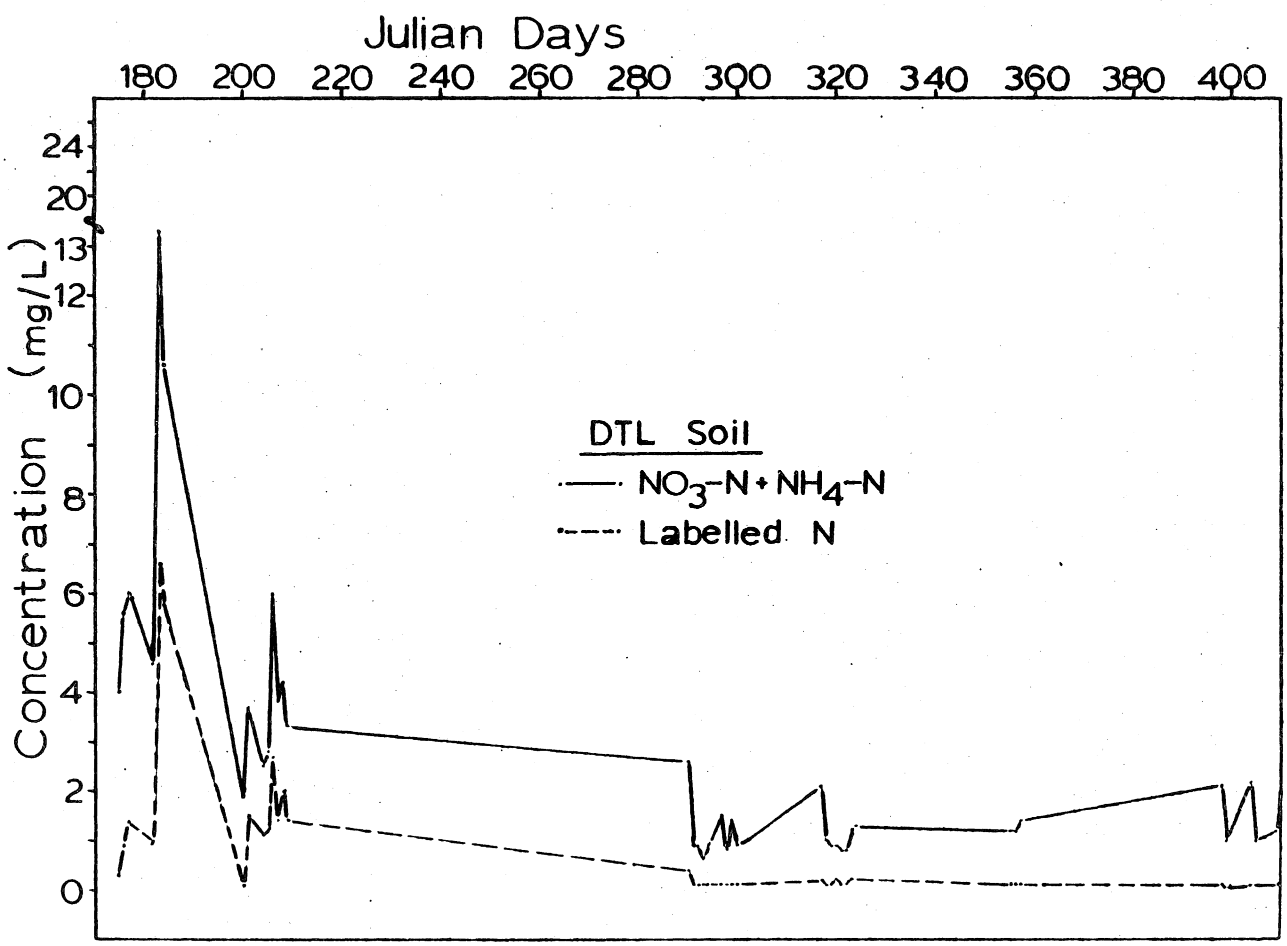


Fig. 15: Flux (g/ha/day) of extracted and labelled N(NH_4-N plus NO_3-N) in drainage water from the ST treatment over the period from June 18 to December 31, 1980.

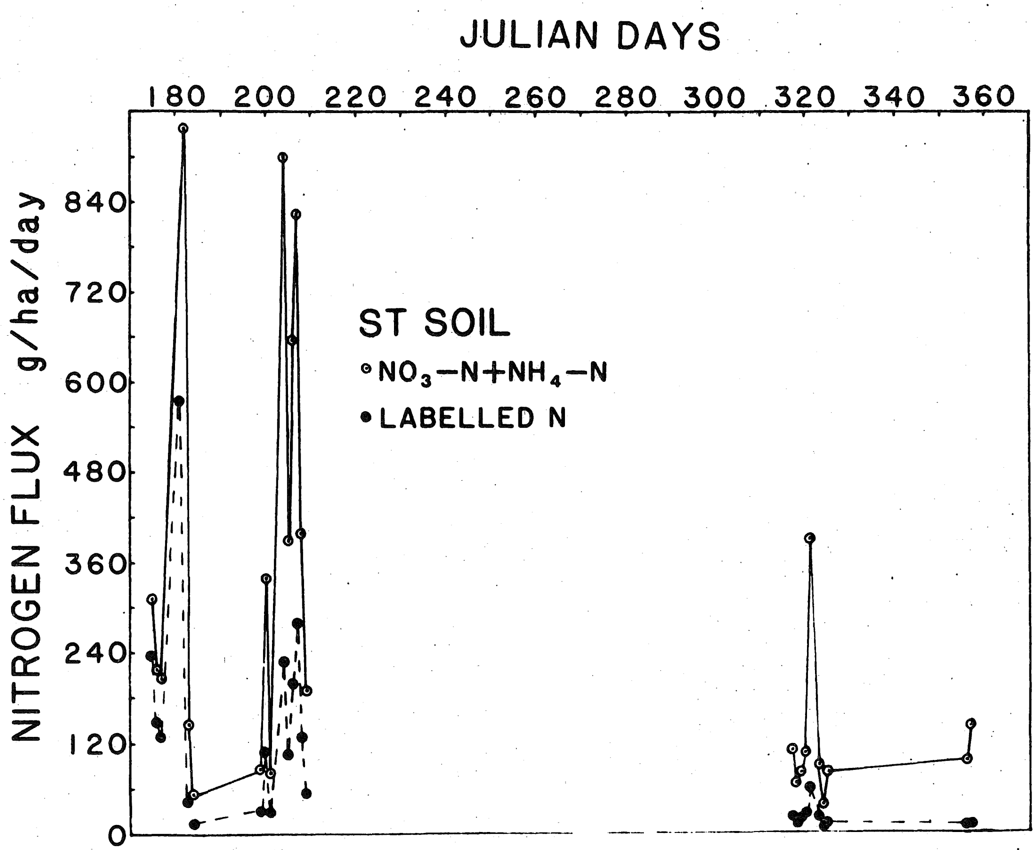


Fig. 16: Flux (g/ha/day) of extracted and labelled N(NH_4-N plus NO_3-N) in drainage water from the DT treatment over the period from June 18 to December 31, 1980.

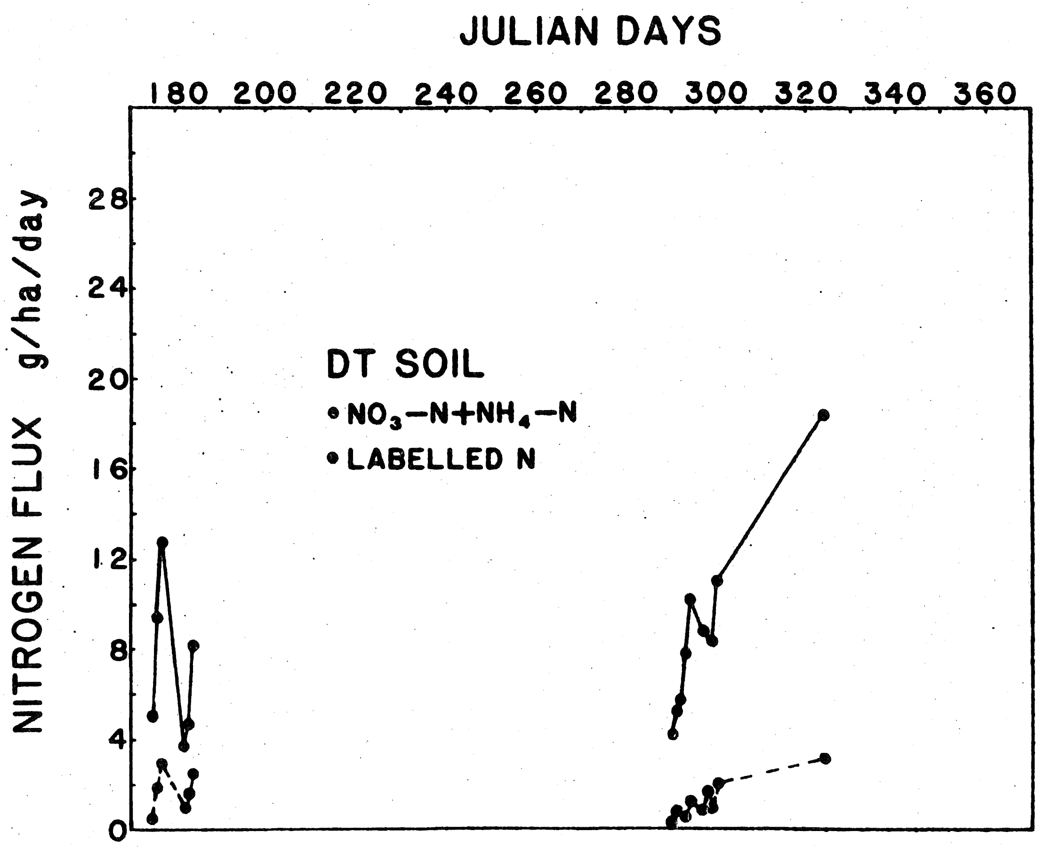
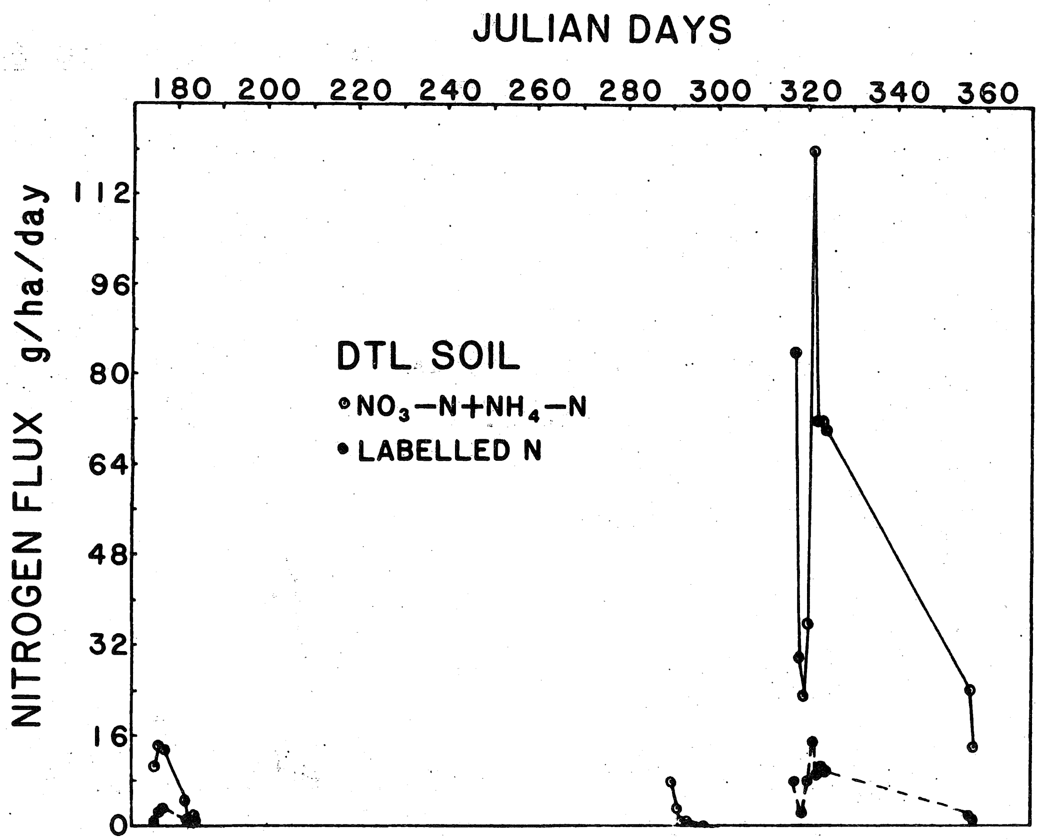


Fig. 17: Flux (g/ha/day) of extracted and labelled N(NH_4-N plus NO_3-N) in drainage water from the DTL treatment over the period from June 18 to December 31, 1980.



total and labelled N were 9.10 and 4.34 kg/ha, respectively, for the first 196 days after application of the fertilizer. Thus 48% of the N discharged from the ST drain was attributable to the ^{15}N-depleted $(NH_4)_2SO_4$. Total leaching losses of N in drainage from the deep-tilled plots were extremely small.

Distributions of total and labelled NH_4-N with soil depth are shown for each of the three plots in Figs. 18, 19, and 20 for dates corresponding to 12, 42, 75, and 134 days after application of the fertilizer. For the deep-tilled plots, NH_4-N contents in the soil profile were low in comparison to those for the shallow-tilled plot. Total NH_4-N quantities in the soil 12 days after fertilization (Table 5) were 142.0, 25.9, and 71.4 kg/ha, respectively, for ST, DT, and DTL plots. After 42 days from fertilization quantities of NH_4-N had decreased to 57.3, 8.5, and 19.3 kg/ha for ST, DT and DTL plots. This data suggests that much of the NH_4-N applied to the deep-tilled plots was either converted to NO_3-N during nitrification and/or absorbed by plant roots from citrus or bahiagrass since volatilization and leaching losses of N were extremely small. Distributions of total and labelled NO_3-N in the soil (Figs 21, 22, and 23) do in fact suggest that nitrification of applied NH_4-N occurred. A sandy soil in British Columbia, Canada with relatively low organic carbon content was shown by Kowalenko (1980) to support suprisingly high microbial activity for N transformations. Between 12 and 42 days after fertilization, quan-

Fig. 18: Distributions of extracted and isotopically labelled NH_4-N in the ST soil profile during 1980 for dates corresponding to 12, 42, 75 and 134 days after fertilization.

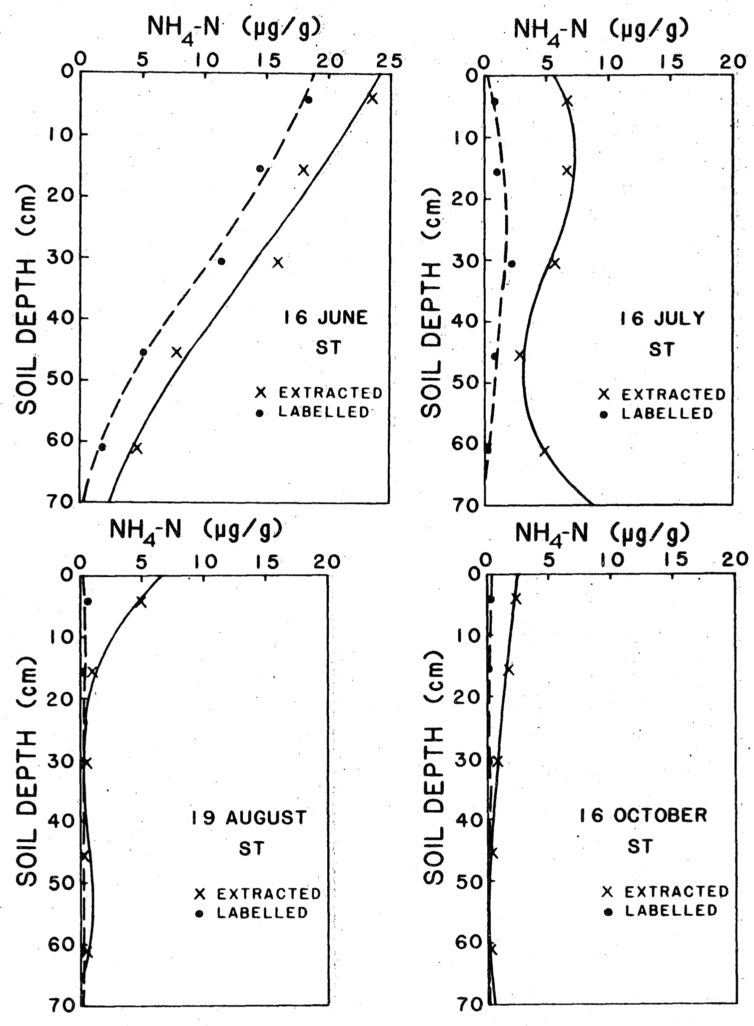


Fig. 19: Distributions of extracted and isotopically labelled NH_4-N in the DT soil profile during 1980 for dates corresponding to 12, 42, 75, and 134 days after fertilization.

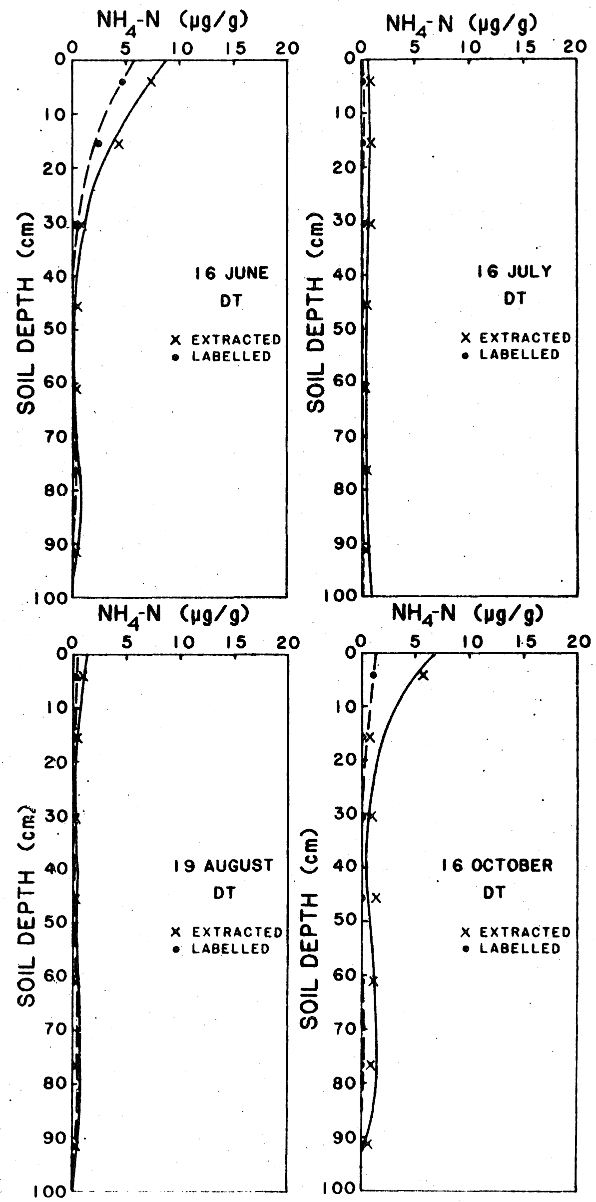


Fig. 20: Distributions of extracted and isotopically labelled NH_4-N in the DTL soil profile during 1980 for dates corresponding to 12, 42, 75, and 134 days after fertilization.

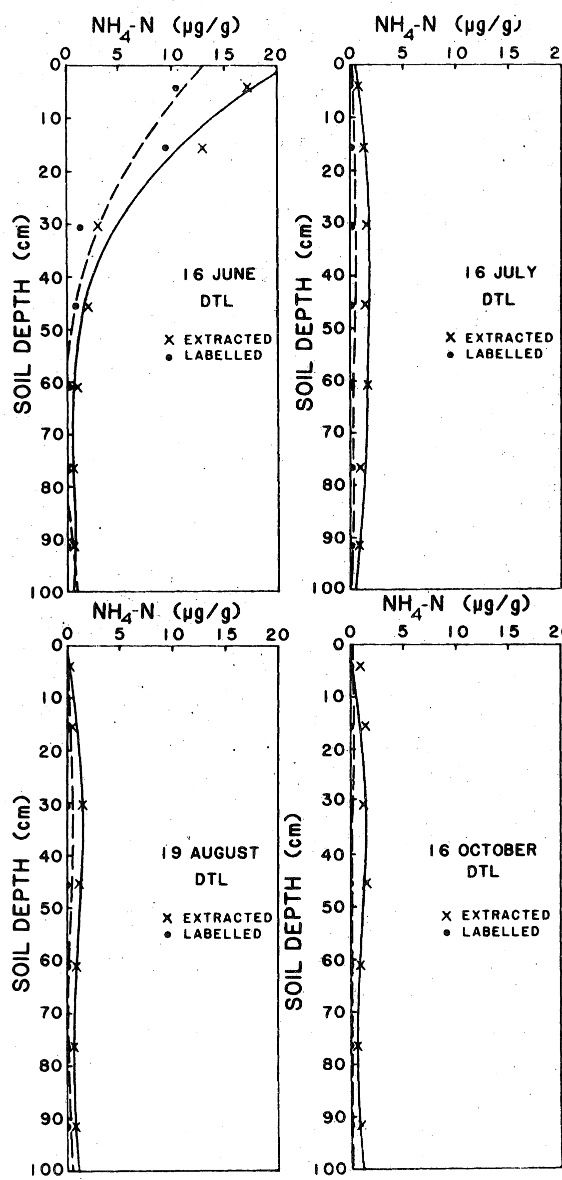


Fig. 21: Distributions of extracted and isotopically labelled NO_3-N in the ST soil profile during 1980 for dates corresponding to 12, 42, 75, and 134 days after fertilization.

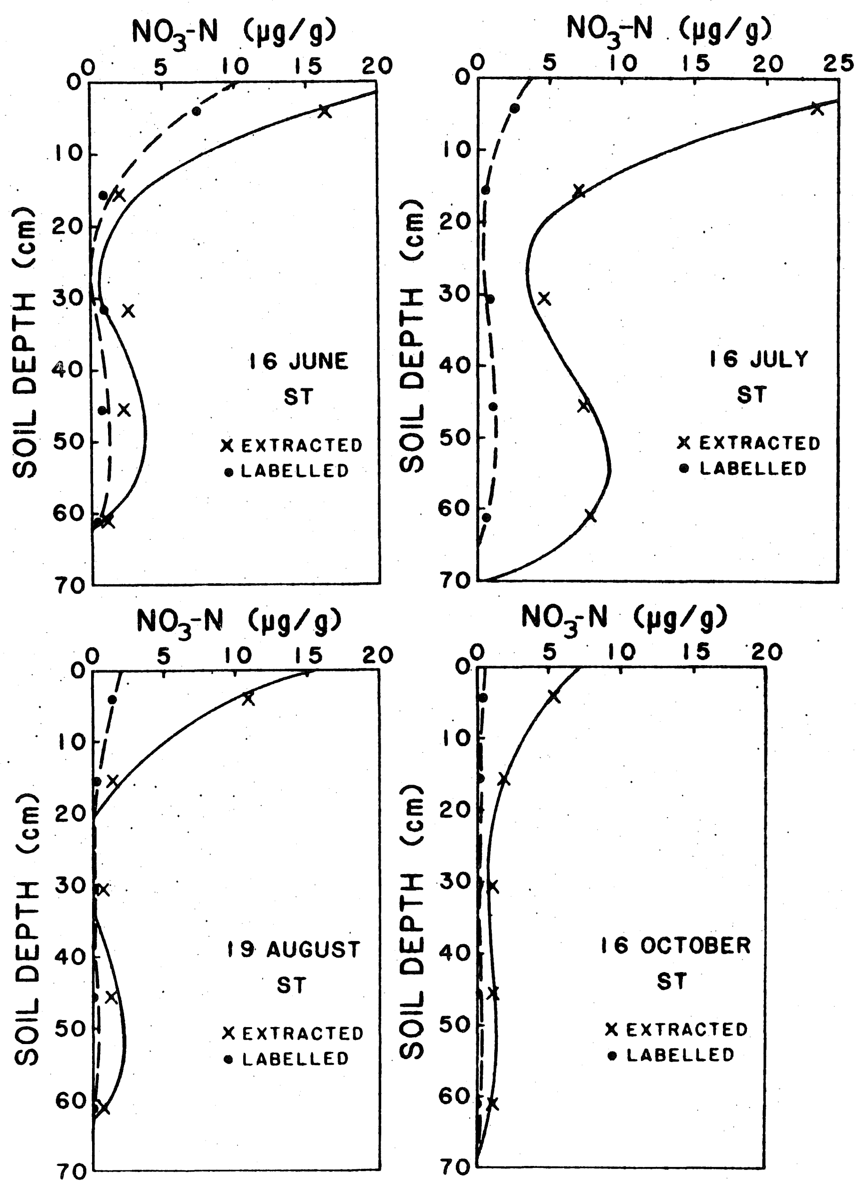


Fig. 22: Distributions of extracted and isotopically labelled NO_3-N in the DT soil profile during 1980 for dates corresponding to 12, 42, 75 and 134 days after fertilization.

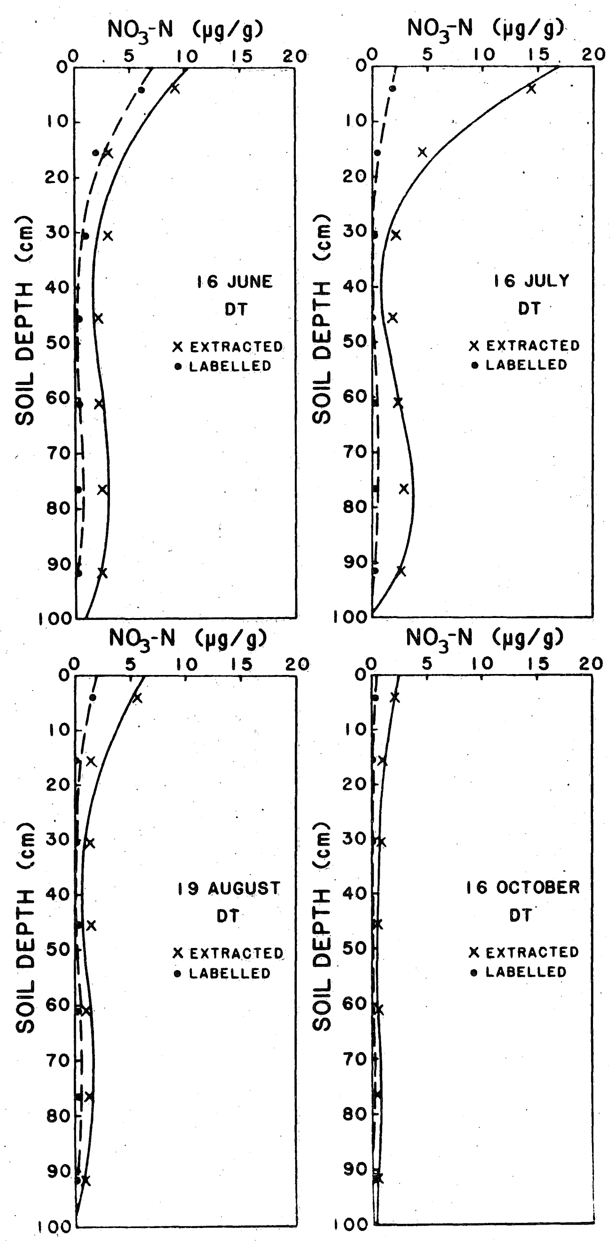
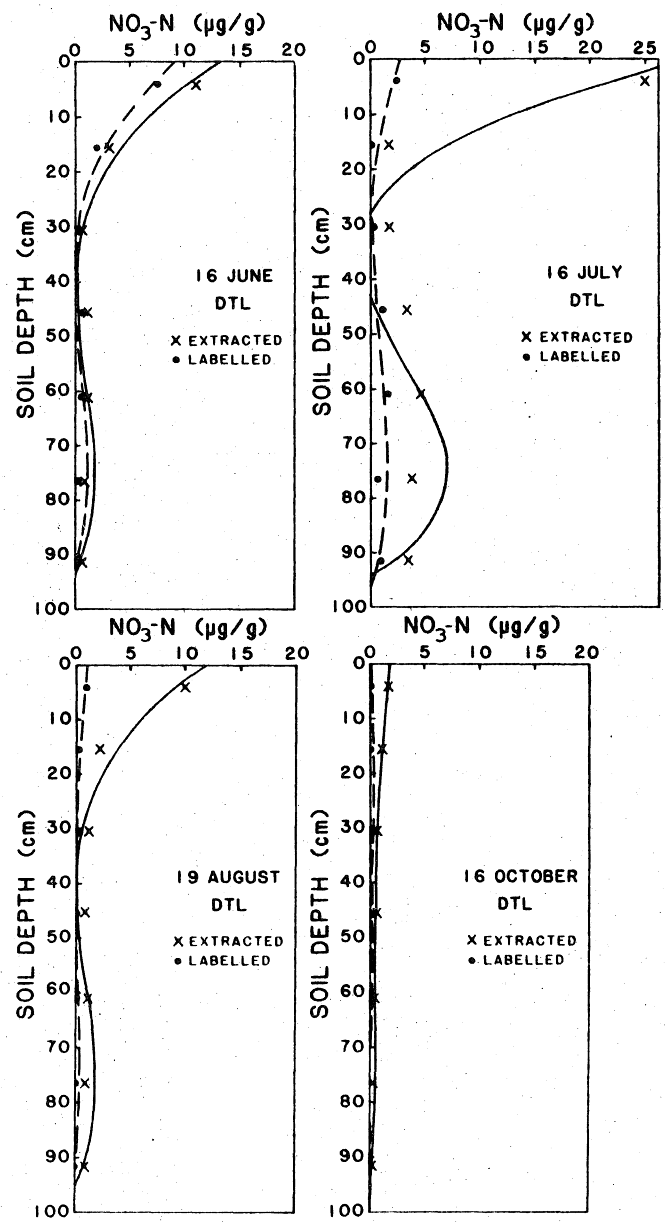


Fig. 23: Distributions of extracted and isotopically labelled NO_3-N in the DTL soil profile during 1980 for dates corresponding to 12, 42, 75, and 134 days after fertilization.



tities (Table 5) of total NO_3-N in the soil increased considerably for all treatment plots in this study but less dramatically for the DT soil. After 42 days, the NO_3-N quantities decreased with time for all treatments probably due to uptake by plant roots.

Quantities of the soil N due to the applied ^{15}N-depleted fertilizer are given in Table 6. Twelve days after fertilization the sum of the labelled NH_4-N and NO_3-N in the soil represented 105, 28, and 54% of the fertilizer, respectively, for ST, DT and DTL plots. The low recoveries of labelled N in the deep-tilled soils imply that root uptake of N was much faster during the first 12 days after fertilizer application than in the ST soil. This deduction assumes the extraction procedure was 100% effective for DT and DTL soils. The ratios of NO_3-N to NH_4-N for the labelled N in the soil were 0.2, 1.5, and 0.5 respectively for ST, DT, and DTL plots. The larger ratios for the DT and DTL plots suggest that nitrification occurred more rapidly in the deep-tilled soils than in the shallow-tilled soil during the first 12 days after fertilization. After 42 days of elapsed time these ratios were 1.0, 7.8, and 7.2 for ST, DT, and DTL plots. These dramatic increases of the NO_3-N/NH_4-N ratios over a 30-day period indicate that nitrification occurred in all soils. After 134 days of elapsed time, quantities of labelled N in all soils were less than 3% of the applied fertilizer, and the ratios of NO_3-N/NH_4-N for ST, DT and DTL plots were 1.9, 0.6, and 0.9 respectively.

Table 5. Mean quantities of extracted NH_4-N and NO_3-N in soil profiles from ST, DT, and DTL tillage treatments on dates corresponding to 12, 42, 75, and 134 days after application of 115 kg/ha of ^{15}N-depleted NH_4-N on June 5, 1980.

	NH_4-N			NO_3-N			NH_4-N + NO_3-N		
Time (elapsed days)	ST	DT	DTL	ST	DT	DTL	ST	DT	DTL
	(kg/ha)			(kg/ha)			(kg/ha)		
12	142.0	25.9	71.4	40.8	50.6	33.4	182.8	76.5	104.8
42	57.3	8.5	19.3	96.3	58.1	77.3	153.6	66.6	96.6
75	12.2	5.6	14.4	23.9	26.0	30.7	36.1	31.6	45.1
134	10.5	20.5	17.4	19.7	12.1	9.5	30.2	32.6	26.9

Table 6. Mean quantities of isotopically labelled NH_4-N and NO_3-N in soil profiles from ST, DT, and DTL tillage treatments on dates corresponding to 12, 42, 75, and 134 days after application of 115 kg/ha of ^{15}N-depleted NH_4-N on June 5, 1980.

	NH_4-N			NO_3-N			NH_4-N + NO_3-N		
Time (elapsed days)	ST	DT	DTL	ST	DT	DTL	ST	DT	DTL
	-----(kg/ha)-----			-----(kg/ha)----			-----(kg/ha)-----		
12	102.6	13.2	42.7	17.6	19.2	19.7	120.2	32.4	62.4
42	11.9	0.8	2.0	11.5	6.2	14.3	23.4	7.0	16.3
75	1.8	1.0	1.1	3.7	5.6	3.5	5.5	6.6	4.6
134	1.1	1.9	0.9	2.1	1.1	0.8	3.2	3.0	1.7

The distributions of total NO_3-N content in the soil (Figs. 21, 22 and 23) imply that some downward movement occurred through the profile during leaching but that a sink possibility uptake by plant roots had extracted fertilizer N from the soil of each of the tillage treatments. Distributions of the sum of NO_3-N and NH_4-N (Figs. 24, 25 and 26) also support that hypothesis. Results from the drainage discharge of N however show that the leaching loss was quite small during the 6-month period of this study. Previous investigators (Calvert et al. 1977) have shown that citrus root systems are generally shallower and less extensive in the profile for shallow-tilled versus deep-tilled DTL soil. Thus one should expect more extensive N uptake from citrus trees growing in DTL soil profiles compared to ST.

Due to the lack of rain and the corresponding lower water content of the shallow-tilled soil compared to the deep-tilled soil, only a very limited number of soil solution samples were collected during August. Despite the very small number of samples reported in Tables 7-9, NO_3-N was definitely the predominant form of N in the ST soil solution. The decrease of the geometric mean concentration of labelled N with time over this 19-day period implies that nitrification occurred. The decrease of the geometric mean concentration of labelled N implies that plant uptake of N actively occurred during this period. Samples were more easily extracted from the generally wetter DT and DTL soils as shown by the N concentrations in Tables 10-15. Geometric

Fig. 24: Distributions of extracted and labelled NH_4-N plus NO_3-N in the ST soil profile during 1980 for 12, 42, 75, and 134 days after fertilization.

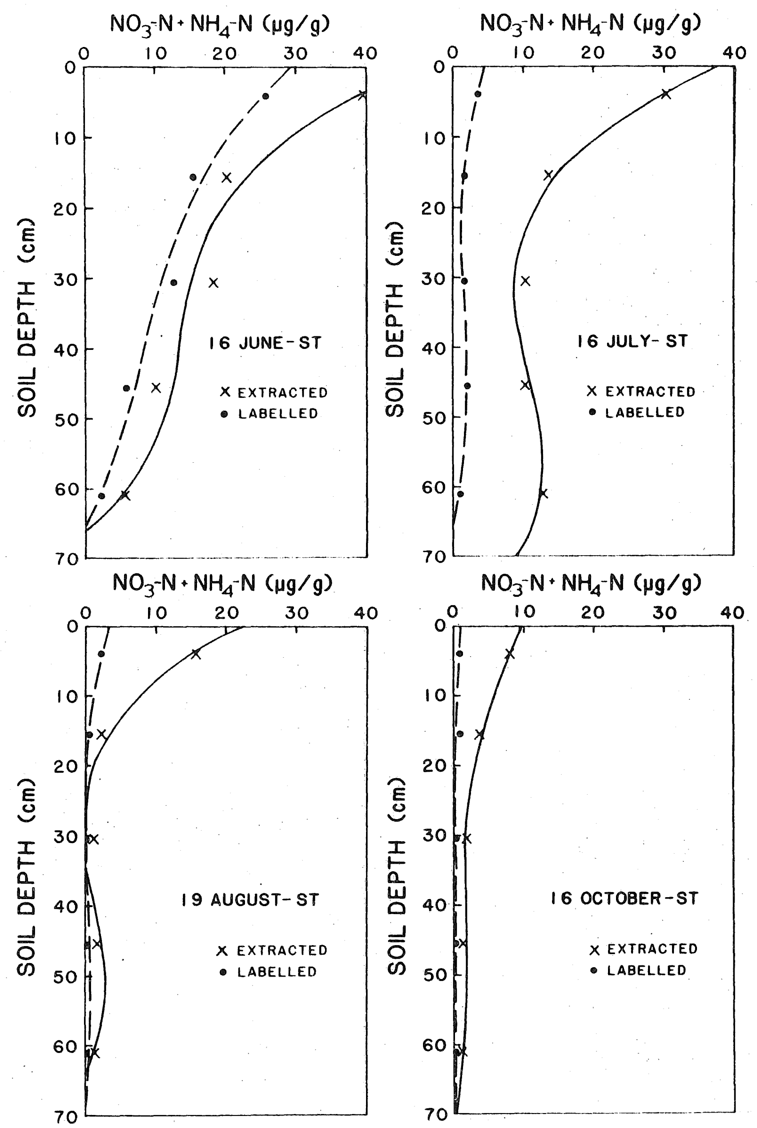


Fig. 25: Distributions of extracted and labelled NH_4-N plus NO_3-N in the DT soil profile during 1980 for 12, 42, 75, and 134 days after fertilization.

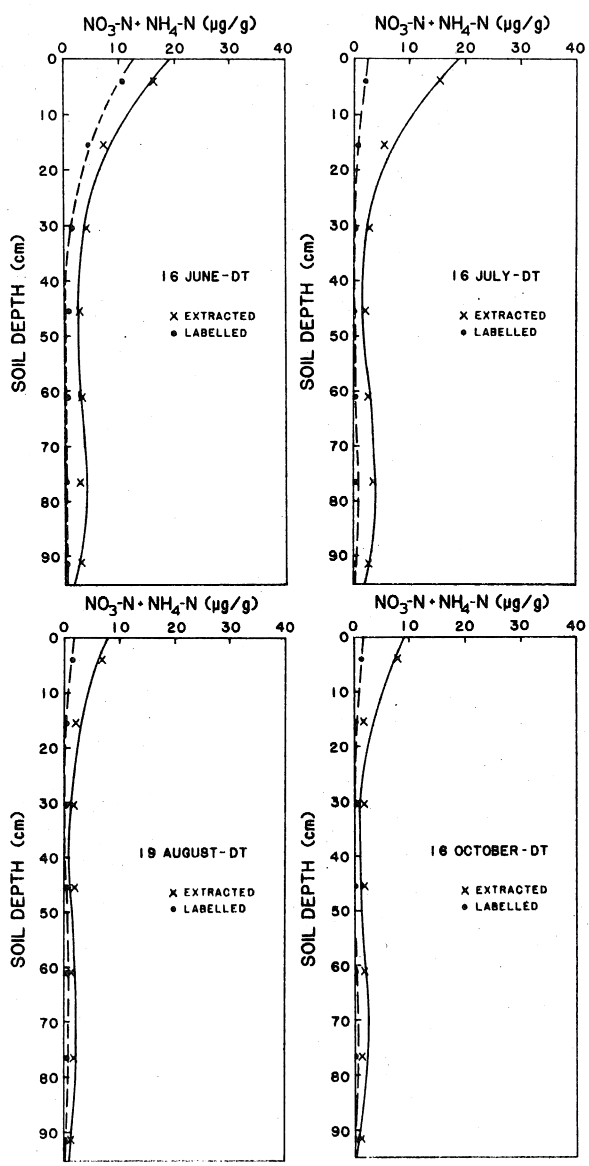


Fig. 26: Distributions of extracted and labelled NH_4-N plus NO_3-N in the DTL soil profile during 1980 for 12, 42, 75, and 134 days after fertilization.

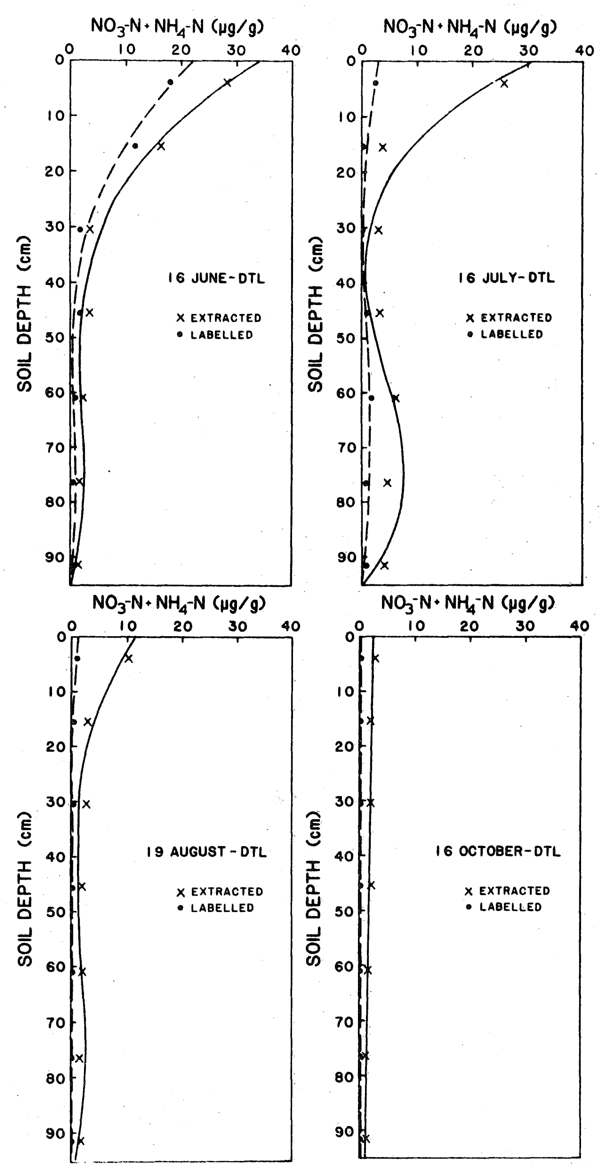


Table 7. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the ST plot on August 1, 1980 (Julian Day 214). Geometric means are shown in parentheses.

	Total NH_4-N (0.15 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	-	-	-	-	-	-
105	0.38	-	-	-	-	0.06

	Total NO_3-N (12.90 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	-	-	-	-	-	-
105	10.60	-	-	-	-	15.70

	Labelled NH_4-N + NO_3-N (7.89 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	-	-	-	-	-	-
105	4.70	-	-	-	-	13.26

Table 8. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the ST plot on August 13, 1980 (Julian Day 226). Geometric means shown in parentheses.

	Total NH_4-N (0.32 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	0.12	-	7.97	0.95
75	-	0.01	-	-	-	0.33
90	-	-	-	-	-	-
105	0.34	-	-	-	-	-

	Total NO_3-N (12.78 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	11.00	-	21.0	3.80
75	-	84.0	-	-	-	10.00
90	-	-	-	-	-	-
105	5.90	-	-	-	-	-

	Labelled NH_4-N + NO_3-N (0.52 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	0.65	0.16
75	-	-	-	-	-	0.35
90	-	-	-	-	-	-
105	0.52	-	-	-	-	-

Table 9. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the ST plot on August 20, 1980 (Julian Day 233). Geometric means shown in parentheses.

Total NH_4-N (0.11 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	-	-	0.98	0.25
75	-	-	-	-	-	0.01
90	-	-	-	-	-	-
105	0.07	-	-	-	-	-

Total NO_3-N (1.19 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	-	-	1.2	2.70
75	-	-	-	-	-	3.30
90	-	-	-	-	-	-
105	0.19	-	-	-	-	-

Labelled NH_4-N + NO_3-N (0.38 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	-	-	0.54	0.74
75	-	-	-	-	-	0.83
90	-	-	-	-	-	-
105	0.06	-	-	-	-	-

Table 10. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DT plot on August 1, 1980 (Julian Day 214). Geometric means are shown in parentheses.

	Total NH_4-N (0.50 mg/l)					
Soil Depth (cm) / Lateral Distance(cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	0.60	0.49	-	0.12	-	0.33
105	0.83	0.93	-	0.48	-	0.91

	Total NO_3-N (8.79 mg/l)					
Soil Depth (cm) / Lateral Distance(cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	14.40	8.70	-	5.50	-	9.10
105	9.60	9.60	-	8.70	-	7.10

	Labelled NH_4-N + NO_3-N (4.80 mg/l)					
Soil Depth (cm) / Lateral Distance(cm):	5	50	100	350	500	900
60	-	-	-	-	-	-
75	-	-	-	-	-	-
90	8.30	7.25	-	3.28	-	5.51
105	5.77	8.31	-	5.36	-	4.68

Table 11. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DT plot on August 13, 1980 (Julian Day 226). Geometric means are shown in parentheses.

	Total NH_4-N (0.12 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	0.30
75	0.01	0.09	0.01	0.01	0.01	0.01
90	-	1.34	0.01	2.49	-	0.22
105	6.17	0.01	0.60	1.63	0.14	1.74

	Total NO_3-N (9.62 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	6.20
75	14.50	44.50	68.00	38.00	9.40	8.00
90	-	55.00	29.00	6.20	-	3.80
105	8.50	39.00	12.50	8.10	5.25	3.65

	Labelled NH_4-N + NO_3-N (1.71 mg/l)					
Soil Depth (cm) / Lateral Distance (cm):	5	50	100	350	500	900
60	-	-	-	-	-	0.16
75	3.47	17.78	29.56	1.87	0.79	0.20
90	-	22.46	12.61	0.43	-	0.10
105	3.51	15.55	5.69	0.48	0.45	0.13

Table 12. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DT plot on August 20, 1980 (Julian Day 233). Geometric means are shown in parentheses.

Total NH_4-N (0.02 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	0.01	-	-	0.01
75	-	0.01	0.01	0.01	0.01	-
90	-	0.01	0.01	0.01	0.01	0.13
105	-	0.01	0.01	0.54	-	0.74

Total NO_3-N (4.03 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	1.05	-	-	1.90
75	-	18.00	40.00	1.60	1.60	-
90	-	23.50	52.50	5.75	2.00	0.61
105	-	7.00	10.00	0.81	-	0.67

Labelled NH_4-N + NO_3-N (0.51 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	-	-	0.57	-	-	0.01
75	-	9.31	21.56	0.08	0.17	-
90	-	12.16	28.30	0.29	0.21	0.01
105	-	3.63	5.39	0.07	-	0.01

Table 13. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DTL plot on August 1, 1980 (Julian Day 214). Geometric means are shown in parentheses.

	Total NH_4-N (0.18 mg/l)					
Soil Depth (cm) Lateral Distance (cm):	5	50	100	350	500	900
60	0.05	0.07	0.06	0.29	0.38	0.28
75	0.22	0.04	0.24	0.36	0.41	0.23
90	0.04	0.08	0.43	0.39	0.33	0.34
105	0.06	0.09	0.27	0.38	0.32	0.33

	Total NO_3-N (6.87 mg/l)					
Soil Depth (cm) Lateral Distance (cm):	5	50	100	350	500	900
60	11.2	18.0	7.1	5.0	4.3	4.3
75	14.3	15.7	6.7	5.0	3.5	4.5
90	13.9	15.0	7.4	6.1	4.1	4.1
105	12.8	13.6	5.2	4.1	4.0	3.3

	Labelled NH_4-N + NO_3-N (3.10 mg/l)					
Soil Depth (cm) Lateral Distance (cm):	5	50	100	350	500	900
60	7.2	11.5	4.6	2.2	1.7	0.7
75	9.3	10.1	4.4	2.2	1.4	0.8
90	8.9	9.6	5.0	2.7	1.6	0.7
105	8.2	8.7	3.5	1.9	1.6	0.6

Table 14. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DTL plot on August 13, 1980 (Julian Day 226). Geometric means are shown in parentheses.

Total NH_4-N (0.18 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	0.01	-	0.01	0.12	-	0.62
75	0.01	0.24	1.08	3.04	2.90	5.51
90	0.10	0.20	0.01	0.01	0.49	3.63
105	0.55	0.01	0.10	0.01	1.53	2.20

Total NO_3-N (14.76 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	10.50	-	10.00	32.50	-	10.50
75	10.00	12.50	42.00	29.00	16.00	34.00
90	10.50	9.40	17.00	17.00	27.50	21.00
105	8.10	20.00	13.50	14.50	21.00	16.00

Labelled NH_4-N + NO_3-N (0.97 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	1.19	-	0.85	2.67	-	0.29
75	1.13	1.11	3.66	2.62	3.65	0.95
90	1.20	0.84	1.45	1.39	5.41	0.64
105	0.98	1.75	1.16	1.19	4.35	0.48

Table 15. Concentrations (mg/l) of total and labelled N in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DTL plot on August 20, 1980 (Julian Day 233). Geometric means shown in parentheses.

Total NH_4-N (0.13 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	0.01	-	0.01	0.01	-	0.28
75	0.82	-	-	0.96	-	-
90	0.01	0.06	0.23	0.58	0.27	0.26
105	0.43	-	0.04	0.14	0.72	0.73

Total NO_3-N (4.14 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	2.10	-	2.60	5.30	-	18.00
75	1.85	-	-	29.00	-	-
90	4.00	1.40	3.70	7.50	11.00	8.00
105	1.00	-	3.20	1.50	5.30	3.20

Labelled NH_4-N + NO_3-N (0.09 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	0.06	-	0.07	0.03	-	0.42
75	0.07	-	-	0.19	-	-
90	0.11	0.04	0.10	0.05	0.71	0.19
105	0.04	-	0.08	0.01	0.38	0.09

means for DT soil solution were only 0.50, 0.12, and 0.02 mg/l of NH_4-N respectively for 57, 69, and 76 days after fertilizer application; however, geometric means for NO_3-N were 8.79, 9.62, and 4.03 mg/l on these same dates. These concentrations were much higher however than those observed in drainage water (Fig. 13) after those dates. This observation was probably due to plant uptake combined with a limited number of subsurface drainage periods. This data also shows that NO_3-N constitutes the predominant form for N in the soil solution. Geometric means for labelled N for 57, 69, and 76 days after fertilization were 4.80, 1.71, and 0.51 mg/l respectively. Thus the concentration of solution N attributable to the ^{15}N-depleted $(NH_4)_2SO_4$ was observed to decrease more than 9 times within the 19-day period. This information is also consistent with the reasoning that N uptake by plant roots was very significant in this deep-tilled DT soil. The slight increase in NO_3-N in soil solution between 57 and 69 days after fertilization further suggests that some nitrification occurred, but was probably limited in rate due to acid subsoil conditions.

Geometric mean concentrations of NH_4-N in DTL soil solution were 0.18, 0.18, and 0.13 mg/l respectively for 57, 69, and 76 days after fertilization; however geometric means for NO_3-N were 6.87, 14.76, and 4.14 mg/l on these same dates. As with DT soil, the N concentrations in soil solution were considerably higher than in the drainage (Fig. 14) water essentially for the same reasons. Nitrate was the dominant form of N in solution and the large increase in NO_3-N concentration between 57 and 69 days after fertilization implies nitrification had occurred. Geometric means for labelled N for 57, 69, and 76 days after fertilization were 3.10, 0.97, and 0.09 mg/l respectively. For this deep-tilled treatment, the concentration of solution N attributable to the ^{15}N-depleted $(NH_4)_2SO_4$ was observed to decrease more than 34 times during the 19-day period. This observation suggests that rates of N uptake by plant roots were higher in DTL soil in comparison to DT soil, probably due to higher pH values in the subsoil. Calvert et al. (1977) have shown that citrus yields were higher and that root systems were deeper in DTL soil compared to DT soil.

Concentrations for selected cations in the DTL soil solution are presented in Table 16 for 57 days after application of fertilizer. Geometric mean concentrations for K^+, Ca^{+2}, and Mg^{+2} were 9.2×10^{-4}, 2.15×10^{-3}, and 2.47×10^{-3} m.e./l, respectively. The presence of these relatively high cation concentrations in the soil solution implies that the ion exchange sites in this soil are predominantly occupied by divalent Ca^{+2} and Mg^{+2} cations which are more competitive than NH_4^+ ions for the exchange sites.

Citrus leaves (Table 17) sampled during the summer and fall had 2.28 to 2.69% N and 12 to 15% of the tissue N was attributable to the ^{15}N-depleted fertilizer. Essentially no difference were observed between the 3 plots.

Table 16. Concentrations (mg/l) of K^+, Ca^{+2}, and Mg^{+2} in soil solution samples from 4 depths and 6 lateral distances from the central drain in the DTL plot on August 1, 1980 (Julian Day 214). Geometric means shown in parentheses.

K^+ (36 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	41	43	26	33	35	31
75	29	25	60	46	41	47
90	52	27	27	41	29	55
105	21	27	48	53	28	32

Ca^{+2} (43 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	44	41	44	42	56	46
75	39	37	44	39	61	31
90	62	28	44	40	44	29
105	46	43	29	63	46	59

Mg^{+2} (30 mg/l)

Soil Depth (cm)	Lateral Distance (cm): 5	50	100	350	500	900
60	29	26	29	27	48	30
75	27	24	29	28	56	22
90	51	19	29	28	31	21
105	26	28	20	55	30	50

Table 17. Mean percentages (%) of N in leaf tissue and percentages (%) of leaf N that was labelled for foliage samples taken in July and October of 1980. Mean values represent 12 rootstock-scion combinations of citrus.

	Percentage N in Leaves			Percentage Labelled N		
Date	ST	DT	DTL	ST	DT	DTL
July	2.69	2.50	2.50	13.33	15.07	14.73
October	2.30	2.28	2.30	13.68	13.06	12.67

Chapter 5: Summary and Conclusions

During the summer of 1980, 115 kg/ha of N in the form of ^{15}N-depleted $(NH_4)_2SO_4$ was applied to portions of a 10-year old experimental citrus grove in South Florida for the purpose of determining the fate of fertilizer N applied to an acid, sandy soil (Spodosol). The influence of deep tillage upon the disposition of the applied N was determined by applying the labelled fertilizer to shallow-tilled (15 cm depth) ST, deep-tilled (105 cm depth) DT, and limed (56 metric tons/ha) plus deep-tilled (105 cm depth) field plots of a Spodosol with a 10-20 cm thick spodic layer located at approximately 80 cm depth. All plots have received annual applications of 2.24 metric tons per ha of limestone. The ST plot is typical of tillage and liming practices for agricultural crops growing in Florida Spodosols. The citrus grove was surface-drained by elevated beds and subsurfaced-drained by 10-cm diameter plastic tubes placed 107 cm deep and 18.3 m apart. Elevated beds with 2 rows of citrus trees were oriented perpendicular to the drain tubes, and the area between tree rows supported a thick Bahiagrass sod. Soil, soil solution, drainage water, and citrus leaf samples were taken at selected times during the first six months following the application of fertilizer. Chemical analyses were performed for NH_4-N and NO_3-N concentrations and isotopic $^{15}N/^{14}N$ ratios were determined. A local drought during the summer and fall restricted the quantities of drainage as well as the sampling frequency for soil solution. During typical years as much as 90% of the total annual rainfall often occurs during the summer and fall seasons.

Accumulative leaching losses of NH_4-N and NO_3-N in drainage water discharge from the deep-tilled DT and DTL plots were extremely small during the first 196 days after the application of fertilizer. The small leaching losses for DT and DTL plots were due to low N concentrations in the water but more importantly to small water discharge rates. Drainage water from the shallow-tilled ST plot resulted in a slightly larger loss of 4.76 and 4.34 kg/ha respectively of unlabelled (residual) and labelled nitrogen. Thus the labelled N leached from the ST soil represented only 4% of the quantity ^{15}N-depleted fertilizer nitrogen. Concentrations of residual plus labelled N in ST drainage water were as high as 25 mg/l during a drainage event which occurred within the first month after fertilization but decreased to about 1 mg/l within 4 months after fertilization. The relative influence of N in the drainage water from ST upon water quality of the downstream canal was small because of the small volumes of drainage that occurred during 1980. Nitrogen discharged in drainage water from all plots was predominantly in the form of NO_3-N with lesser amounts as NH_4-N.

Analyses of soil cores to a depth of 70 cm in the ST plot and 100 cm in the deep-tilled plots revealed that the ^{15}N-depleted NH_4-N was largely nitrified to the NO_3-N form within the first 30 days. During the first 12 days nitrification appeared to proceed at faster rates in the deep-tilled plots as compared to the shallow-tilled plot possibly due to slightly higher water retention capacity and higher pH of the DTL subsoil.

Initially, larger quantities of residual and labelled N (NO_3-N plus NH_4-N) were present in the soil profile for the ST plot (182.8 kg/ha) than for DT (76.5 kg/ha) and DTL (104.8 kg/ha) plots. The quantities of labelled N in the soil at that date were equivalent to 105, 28, and 54% of the applied ^{15}N-depleted $(NH_4)_2SO_4$ for ST, DT, and DTL plots respectively. These data indicate that within 12 days after fertilizer application, 72 and 46% of the labelled fertilizer N, respectively, had been removed from the profiles for DT and DTL plots. Virtually all of the labelled N was present in the shallow-tilled ST soil, however. Since leaching losses for the deep-tilled soils were extremely small and denitrification losses of NO_3-N were most unlikely due to the infrequent rainfall during that period, the unaccounted for N appears to have been absorbed by root systems of bahiagrass and citrus. Volatilization losses of the applied $(NH_4)_2SO_4$ were less than 0.5% for all three plots. Earlier results by Calvert et al. (1977) showed that fruit yields were significantly higher and root development more extensive in the soil profile for the DTL treatment than for ST treatment. Yields and root development for the DT treatments was intermediate. Shallower root systems in the shallow-tilled plot would thus be expected to have lower rates of absorption of soil N by actively growing roots than either of the deep-tilled plots.

Total quantities of N measured in ST, DT, and DTL soil profiles for 12, 42, 75, and 134 days after fertilization showed dramatic decreases in labelled as well as residual N from previous applications of fertilizer. After the first month, much of the soil N appeared to be coming from non-fertilizer sources of N, presumably from mineralization of soil organic matter. By 134 days after fertilization, less than 3% of the ^{15}N-depleted fertilizer N was still present in the soil. These data also imply that most of the applied fertilizer N was utilized by citrus trees and bahiagrass within 4.5 months after application. Previous investigations with non-labelled N (Mansell et al. 1977) and with higher rainfall amounts during summer months revealed that an average of 20% of the fertilizer applied to the shallow-tilled plot of this same citrus grove was leached over a three-year period. Average leaching losses for the deep-tilled plots however were much less (5%). As seen from the current investigation where high residual concentrations of soil N occur from previous fertilizer applications, the use of ^{15}N-depleted fertilizer N provides a more effective means to study the fate of applied N under field conditions. Thus results from this study show that fertilizer use efficiency for labelled N was higher in deep-tilled plots than in the ST plot. Even the N use efficiency for citrus growing in ST soil however was relatively high due to the low frequency of drainage events during 1980.

As expected, soil solution samples taken 57, 69 and 76 days after fertilizer application showed that NO_3-N was the predominant N form in solution in all plots. Concentrations of N in solution decreased during this 19-day period indicating that plant roots were actively absorbing N. Mean concentrations of solution N attributable to the ^{15}N-depleted $(NH_4)_2SO_4$ in the DTL soil were observed to decrease more than 34-fold during this 19-day period. Compared to the DT plot, rates of N uptake by plant roots appeared to be higher for the DTL plot during that period probably due to higher pH values observed for the subsoil.

Isotopic analyses of citrus leaves during the summer and fall showed that 12 to 15% of N in the tissue was attributable to the ^{15}N-depleted fertilizer. Concentrations of N in the tissue did not vary greatly between plots.

Results from this study using labelled N confirm earlier investigations (Mansell et al. 1977) that deep tillage plus lime incorporation into the profile of a Spodosol is an effective means to enhance root absorption of fertilizer N, minimize N leaching losses, and thus minimize contamination of water resources with NO_3-N. Shallow development of root systems, low cation and water retention characteristics, and high values of saturated hydraulic conductivity of shallow-tilled Spodosols provide these acid, sandy soils with potential for leaching loss of fertilizer N during periods of soil drainage. Establishment of narrow (1.0 m wide) zones of deep tillage with lime only in the vicinity of the soil where citrus or other agricultural crops are to be located offers an effective means to increase fertilizer- and water-use efficiencies for newly developed Spodosols. Restriction of the deep tillage operation to only the soil near the crop rows decreases the cost to a fraction of that required to deep till entire fields.

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Appendix: Synopsis from Master of Science Thesis (August 1982) for Miss Ko Hui Liu in the Soil Science Department, University of Florida.

Title: Miscible Displacement of Aqueous Solutions of NH_4-N through Columns of Sandy Soil.

A. Summary

Ion exchange for K^+ and NH_4^+ during miscible displacement was studied using water-saturated soil columns of ST and DTL soils. The soil in each column was initially "saturated" with 0.03 N KCl prior to each displacement experiments. During the displacement experiments steady pore water velocities of 7.8 and 30.1 cm/hr were maintained in the columns. Potassium in the soil was exchanged with either 0.03 N NH_4Cl or 0.01 N NH_4Cl + 0.02 N KCl, and NH_4^+ in the soil was exchanged with either 0.03 N KCl or 0.01 N NH_4Cl + 0.02 N KCl.

Adsorption isotherms for NH_4^+ were determined and retardation R values were computed for each soil These R values were slightly less than those calculated from BTC's (solute breakthrough curves). Because of the presence of lime in the soils, Ca^{2+} and Mg^{2+} were continually leached out of the soil columns. The presence of these divalent cations in the soil solution suppressed the sorption of NH_4^+ and K^+. The zero point of charge ZPC of both soils were determined and found to be 4.8 and 6.1 for ST and DTL soils respectively. A time study of NH_4^+ exchange revealed that ion exchange was instantaneous.

B. Conclusions

Based on the results in this study, the following conclusions were made for ion exchange during transport through ST and DTL soil under water-saturated conditions: (1) The ZPC of DTL soil was higher than that for ST soil due to a lower content of organic matter and higher contents of Fe and Al oxides in the mixed soil. Thus ion exchange in these soils is dependent both on pH and ionic strength of the solution. (2) Ion exchange was shown to be instantaneous and thus the use of a kinetic model for ion exchange in these soils is not justified. (3) Because of the dissolution of lime during displacement experiments, the presence of Ca^{2+} and Mg^{2+} in the system and changes in pH affected the sorption of K^+ and NH_4^+. (4) For these soils, which have been receiving lime for the last 10 years, it is difficult to establish a homo-ionic soil. During these laboratory experiments, the soils were apparently never completely saturated with either K^+ or NH_4^+. Thus the ion exchange obtained was not only for K^+ and NH_4^+ but included other ions such as Mg^{2+} and Ca^{2+}. Due to these considerations, adsorption isotherms rather than ion exchange isotherms were measured and used to calculate the retardation factors.
(5) Since ion exchange was shown to be instantaneous the BTC's in these soils should not have been affected by the flow velocity imposed. A small apparent velocity effect on the translation of BTC's for both K^+ and NH_4^+ was attributed to a change in the chemical environment in the system due to

changes in pH, ionic strength, and ionic composition all of which affect the retardation of ionic species in these soils. (6) The ST soil showed no selective adsorption for either K^+ or NH_4^+. This was anticipated from the similar properties of these ions such as ionic radii and charge. (7) Due to the presence of vermiculite in the DTL soil however, K^+ was fixed during ion exchange and transport. This study shows that even if an ion is fixed or consumed in the system it is still possible to predict its front during transport if it is not completely removed from solution. (8) For the ST soil the displacement studies showed that ion exchange was reversible for ST soil since all the input amount of either K^+ or NH_4^+ were recovered. (9) although the application of lime to these soils has raised the pH, the presence of Ca^{2+} and Mg^{2+} in the soils will inhibit the leaching of either NH_4^+ or K^+ when applied to these soils as fertilizer.