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*Movement of Fertilizer and Herbicide Through Irrigated Sands*

*By*

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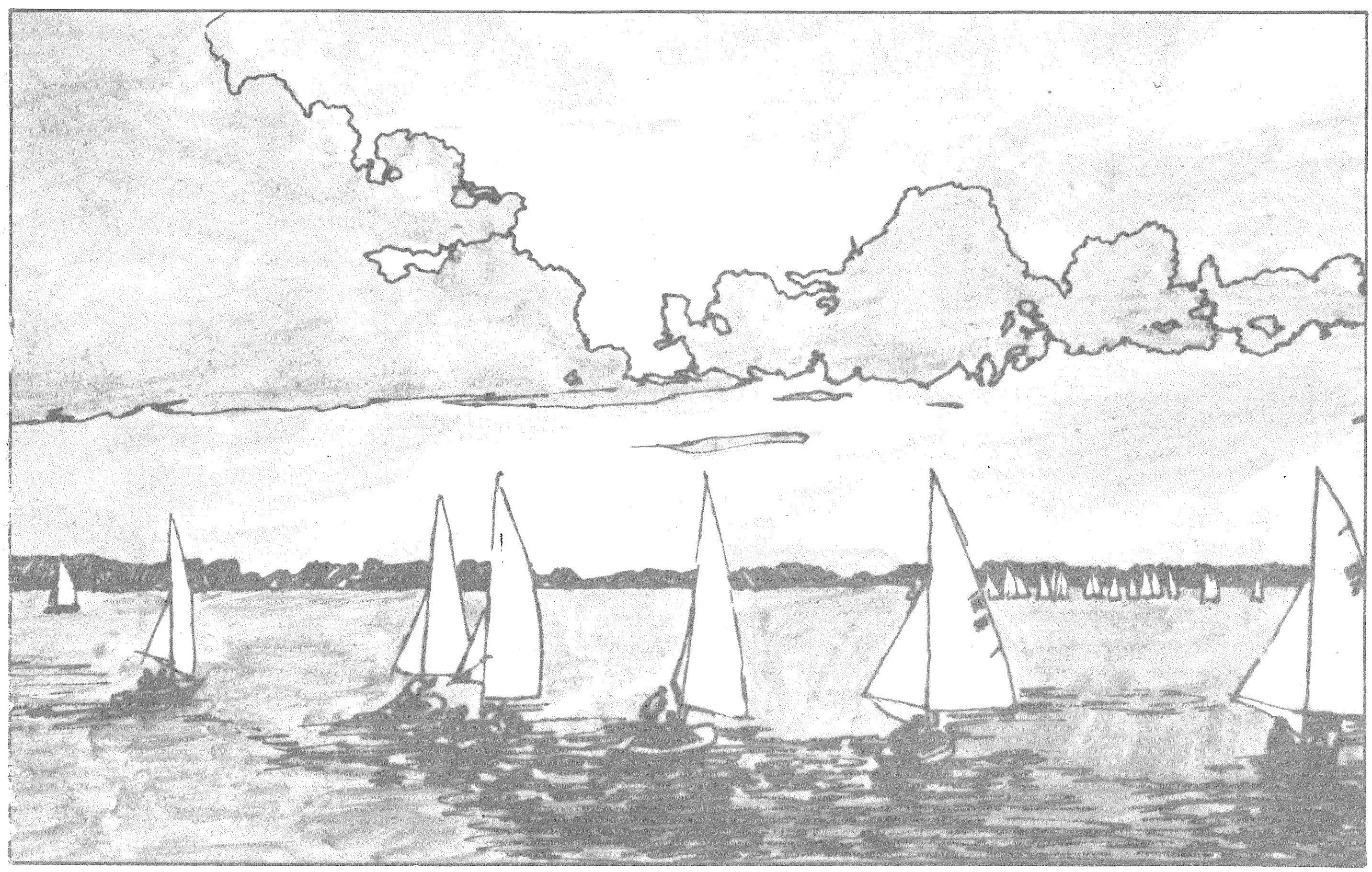

UNIVERSITY OF FLORIDA

TABLE OF CONTENTS

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# ABSTRACT

The simultaneous movement of water and selected agrichemicals (fertilizer nutrients and herbicide) through sandy soils is of particular importance to the efficient use of fertilizers and irrigation water by agricultural crops. Efficient use of fertilizers and herbicides applied to Florida's sandy soils is desirable for maintaining optimum growth of plants and for minimizing groundwater contamination.

Laboratory and field experiments as well as mathematical models were used to study water and solute (potassium and phosphorus nutrients and 2,4-D herbicide) transport in two representative Florida soils: Wauchula sand and Troup sand. In an irrigated and fertilized corn experiment, grain yields and efficiency of water use were observed to be mutually related to both the irrigation and the fertilizer application treatments. Leaching of applied nutrients and irrigation water from the soil "rooting zone" resulted in decreased water use efficiency in these soils. Mathematical models were developed and used to simulate transport and chemical-physical reactions for potassium, phosphorus and 2,4-D herbicide in these soils. Reactions such as adsorption-desorption, chemical precipitation and immobilization (fixed) greatly influenced the movement and thus potential leaching of these solutes through the soil.

# CHAPTER 1: INTRODUCTION

Fertilizers, herbicides, and irrigation water are commonly applied to Florida's sandy soils for the purpose of maintaining high levels of food production from soil-water-plant systems. These soils generally have limited capacities to temporarily store applied water and solutes, and thus proper management of agrichemical and water applications is needed to minimize leaching losses of nutrients and herbicides from the "rooting zone" of the soil profile. Excessive leaching, which may occur during periods of intense rainfall greatly increases the potential for contamination of the underlying groundwater with agrichemicals. Efficient usage of fertilizers, herbicides, and water therefore provides two very important beneficial results: (1) optimum plant growth and yields, and (2) minimal pollution of groundwater resources.

Management of crops growing in these sands to produce optimum crop yields requires irrigation during periods of drought and frequent applications of fertilizer during the growing season. Although the average annual rainfall for the state "... ranges from near 52 inches on the central and northern peninsula to nearly 65 inches in the panhandle west of Tallahassee ..." (Butson and Prine, 1968), severe drought commonly occurs during the spring growing season followed by heavy rains during the summer when the state receives approximately 60% (Jones, 1967) of its rainfall. The uneven rainfall distribution coupled with low retention capacities of the surface soil of the sands for water and solutes result in relatively high leaching losses of applied agricultural chemicals. Also crop yields may be decreased by periods of drought as a result from soil-water deficiency or high osmotic pressures of the soil solution due to improper timing of fertilization.

Water, fertilizers, and herbicides are applied to the sands to create a favorable plant root environment with optimum supplies of available water and nutrients. The herbicides are used to destroy weeds and undesirable grasses which compete with the crop plants for water, nutrients, and light. Failure to maintain minimum threshold levels of water and fertilizer nutrients in the root zone during critical periods of plant growth can result in decreased yields. However, levels of water and nutrients in the root zone in excess of plant requirements may result in waste of resources, possible detrimental effects on crop growth, and potential contamination of ground water with herbicide or fertilizer solutes.

To insure optimum crop growth on sands, irrigation during periods of low rainfall is needed to maintain low soil-water suction (0 to -200 cm of water). Consequently, the profile will of necessity be high in soil-water content and undergo some drainage or redistribution of water at all times. Since the hydraulic conductivity of the deep sands increases greatly with soil-water content, heavy irrigation or rainfall imposed upon relatively moist soil will result in much of the infiltrating water being lost from the root zone by drainage.

The simultaneous transport of water and soluble chemicals through soil has important implications with regards to the efficient management of fertilizer, herbicide, and irrigation water applied to agricultural crops growing in sandy soils. Transport of water and nutrients through sandy soils is particularly important to phenomena such as plant uptake of nutrients and water which tends to increase fertilizer and water use efficiencies. Thus, improper water management combined with inefficient application of herbicides and fertilizer nutrients to sands may result in leaching loss of some of the chemicals from the "rooting zone" of the soil profile. Thus potential contamination of groundwater may result as leached herbicides and nutrients move deeper into the soil. Fortunately, processes such as adsorption-desorption, ionic exchange, microbiological transformations, chemical interactions, and uptake by plant roots tend to decrease the leaching loss of herbicides and nutrients from soils.

Therefore, detailed knowledge of simultaneous movement of water and solutes in Florida's sandy soils is critically needed to insure efficient use of water, fertilizer, and herbicide resources for crop production without undesirable contamination of the underlying groundwater.

## CHAPTER 2: OBJECTIVES

Specific objectives for this project were as follows:

(1) To determine rates of movement of soil-applied herbicide and fertilizer (nutrients) solutes in irrigated agricultural sands and to determine leaching losses of these chemicals from the "rooting zone" of the soil profile;

(2) To determine the influence of limestone application to acid, sandy soils upon movement and leaching losses of soil-applied fertilizer solutes from the "rooting zone;"

(3) To determine the influence of adsorption and desorption processes upon rates of movement of 2,4-D herbicide, potassium fertilizer and orthophosphate fertilizer with water through irrigated sandy soils; and

(4) To utilize existing mathematical models to describe the simultaneous movement of water, selected herbicides, and fertilizer nutrients in sandy soils during periods of water infiltration and redistribution.

## CHAPTER 3: FIELD EXPERIMENTS

### A. Description of Soils

Most Florida soils can be classified into either of four orders (Fig. 1): Spodosols, Ultisols, Entisols, and Histosols. Representatives of two of these soil orders were selected for the location of field experiments to determine the simultaneous movement of water and agricultural chemicals in the "rooting zone" of irrigated and fertilized corn. One experiment was located at the University of Florida Beef Research Unit near Gainesville on a Wauchula sand which is a Spodosol (family: sandy-over-loamy, siliceous and hyperthermic; subgroup: Ultic Haplaquods). Although the Wauchula soil is a Spodosol it appears in an area which is broadly characterized by the presence of Ultisols. Another experiment was located at the Agricultural Research and Education Center of the University of Florida near Quincy on a Troup sand which is an Ultisol (family: loamy, siliceous, and thermic; subgroup: Grossarenic Paleudults).

Spodosols and associated flatwood soils represent the most extensive order (Fig. 1) of Florida soils (Zelazny and Carlisle, 1971) and account for one fourth of the total land area. Most of these soils occur on nearly level to gently sloping landscapes with a generally shallow ground water table which fluctuates near the soil surface during periods of high rainfall (Brasfield et al. 1973). Spodosols are characterized by the presence of a subsurface spodic horizon which is an accumulation of organic matter with varying amounts of aluminum and iron. Brasfield et al. (1973) state that the spodic horizon has a high ionic exchange capacity, large specific surface area, high water retention, and high exchangeable acidity. The spodic horizon commonly occurs less than 75 cm beneath the soil surface and is overlain by sandy $A_2$ eluvial and $A_1$ surface horizons. These soils may be classed as strongly acid sands with low fertility and base saturation. Although the spodic horizon is generally slowly permeable, the overlying $A_1$ and $A_2$ transmit water rapidly.

Ultisols are the most extensive soils (Fig. 1) of northwest Florida (Carlisle and Zelazny, 1973). These soils are also located in northcentral Florida. Perkins et al. (1973) describe these soils as having B horizons that contain an appreciable amount of translocated silicate clay but few bases. Sandy or loamy surface horizons generally are underlain by horizons with loamy or clayey texture. Ultisols are typically acid, relatively infertile, and have a low base saturation ($\leq$ 35%) within about 2 meters of the soil surface.

### B. Experiments on WAUCHULA SAND, a Spodosol

Nutrients applied as fertilizers to crops growing on acid, sandy soils in Florida's humid climate are susceptable to partial leaching loss from the "rooting zone" of the soil. Fertilizers are typically applied to the soil surface as dry solid materials which eventually undergo dissolution in infiltrating rainwater (or irrigation water). Thus with time a portion of the nutrients become solutes in the soil solution. As the soil solution moves downward in the soil profile, nutrient solutes may be removed from solution by uptake through plant roots, sorption onto soil particles, chemical precipitation, and biological degradation (denitrification). As the solution moves further from the soil surface, nutrient solutes are subject to loss by drainage in tile-drained soil and by deep seepage to the groundwater in well-drained soil. Highly mobile nutrients such as $NO_3$ (Thomas, 1970) are particularly susceptible to leaching from the soil; whereas the amount of a reactive solute such as P moving in the soil solution is usually very low relative to the total quantity of P in the soil. The mobility of potassium in soil is usually intermediate to that for $NO_3$-N and orthophosphate-P.

During the spring of 1974 a field experiment was established on a subsurface-drained Wauchula sand (a Spodosol) to determine in situ distributions of $NH_4$-N, $NO_3$-N, $PO_4$-P, and K in the solution phase of the soil profile during the growth of corn. A subsurface system of parallel (10-cm clay tile) drains 75 cm deep and spaced 6 m apart provided drainage for the soil profile. Nutrient distributions with soil depth were determined in soil receiving two levels of dolomite limestone application: a low level, 567 kg/ha and a high level, 9,070 kg/ha. The experiment was located at the University of Florida Beef Research Unit, approximately 10 miles northeast of Gainesville. A randomized block design with four blocks and two limestone application levels was used. Each block contained six replications to give an overall replication of 24 for each lime treatment. Each plot, 3.6 m wide and 9 m long, contained four rows of corn.

A commercial fertilizer 4-7-16 (N-$P_2O_5$-$K_2O$) with micronutrients was applied broadcast to the soil surface on March 26 at the rate of 2841 kg/ha which contained 113.6, 99.2 and 377.3 kg/ha each of N, P, and K, respectively. McNair 73011 hybrid seed corn was planted on April 1 (day 0) in rows 90 cm apart and at 15-cm intervals within each row. On May 14 (day 43) 250 kg/ha of N as $NH_4NO_3$ was applied in a narrow (5 cm) band near each corn row. The actual amount of N applied in the band and adjusted for the band width was 4,570 kg/ha.

Soil solution samplers and soil water tensiometers were installed in the middle of six plots for each of the two limestone applications within one block. Solution samplers composed of 6-cm diameter porous ceramic cups (bubbling pressure of 1 bar) and attached to the bottom of plastic pipes were installed in a corn row adjacent to the tensiometer installations.

The porous cups were located at 30, 60, 90, 120, and 150-cm depths, and samples of soil solution were removed periodically. Approximately 10 to 50 ml of soil solution were collected from each sampler, and samples were analyzed for K, $NH_4$-N, $NO_3$-N, and $PO_4$-P. Methods of analyses were flame photometry for K, specific ion electrodes for $NH_4$-N and $NO_3$-N, and the ascorbic acid technique as described by Watanabe and Olsen (1965) for P. Tensiometers with 2.3-cm diameter porous ceramic cups (1 bar bubbling pressure) and mercury manometers were installed adjacent to corn rows at depths of 15, 30, 60, 90, 120, and 150 cm. Manometer readings provided distributions of soil water suction, h, and total hydraulic head, H. Soil water content-suction characteristic curves for undisturbed soil cores were determined in the laboratory by the method of Hammond, Carlisle, and Rogers (1971). By use of these drainage characteristic curves, values of h for a given depth were converted to volumetric water contents, θ. This conversion is normally adequate for conditions of soil water desorption, but at best provides an approximation for water sorption due to possible error caused by soil water hysteresis.

Soil water content-suction and hydraulic conductivity-water content curves (Mansell, et al. 1975) for soil materials taken from several depths showed that the hydrologic properties among the Ap (0-25 cm), $A_2$ (25-75 cm), $B_{2h}$ (45-75 cm), $B_{2t}$ (75-145 cm, and C ( > 145 cm) horizons were greatly different. For practical purposes water movement through the soil profile was considered to be that for a soil having a pervious zone overlying a slowly pervious zone. Soil above 45 cm ($A_p$ and $A_2$) had saturated conductivities at least 10-fold greater than that for soil between 45 and 150 cm depths ($B_{2h}$, $B_{2t}$ and C).

Emergence of corn seedlings occurred on April 7 (day 8), tasseling began on June 14 (day 74), and development of ears began on June 24 (day 84). Growth curves showing relative heights of corn plants versus time for 567 and 9,070 kg/ha of dolomite limestone applied to the soil are presented in Fig. 2. Maximum plant heights ($L_f$) for both low and high lime treatments were 275 cm. Growth curves were sigmoid in shape and differences between the treatments were not appreciable. Plant heights reached 95% of the maximum after 80 days.

Grain and stover were harvested September 5 (day 157) and their oven-dry weights were determined. Even though appreciable differences of corn growth curves did not occur between limestone treatments, average grain yields for high limestone application were 25% greater than for the low limestone application. Average yields were 6,346 and 7,907 kg/ha for low and high limestone treatments.

During the 157 days between planting and harvest of the corn crop, the experimental site received a total of 76.5 cm of rainfall. Since only 3.4 cm of rainfall was received during the first 30 days after planting, 3.5 cm of water was applied to the experimental site on day 29 by sprinkler irrigation. During the first 30 days, depths to the water table exceeded 100 cm, but for the remainder of the growing season the water table fluctuated about the 75 cm depth. Thus, one month following planting of the corn, conditions of water saturation and poor aeration occurred in the soil beneath 90 cm depth. For soil depths above 60 cm, water pressure heads were always negative indicating water unsaturation and favorable aeration conditions. Negative pressure heads at 15 cm depth fluctuated widely with time relative to that for the subsoil. Extremes in soil water suction head of 30 and 200 cm of water were observed in the soil at 15 cm depth and these heads correspond to volumetric water contents of 28 and 8%, respectively. Relative to underlying soil horizons, water contents in the top 15 cm of soil increased rapidly during rainfall events and then subsequently decreased during the first 3 to 5 days of the post-infiltration period.

Distributions of K, $NH_4$-N, $NO_3$-N, and $PO_4$-P nutrients in the soil solution as a function of depth and time are presented in Figs. 3-6 for both lime treatments. Each data point represents the mass of a specific nutrient in the solution phase per unit volume of the bulk soil, as determined from the nutrient concentrations ($\mu g/cm^3$ of soil solution) in the soil solution and volumetric water contents ($cm^3$ of soil solution per $cm^3$ of bulk soil). Furthermore, each data point represents an average from six replicate plots. Distributions of nutrients in the solution phase of Wauchula soil provide a means for describing movement of the various solutes downward through the profile. Although 80 cm of irrigation and rain water occurred during the first 150 days after fertilization, nutrients did not move appreciably to depths below approximately 70 cm. Nutrient contents in the soil solution for profile depths greater than 70 cm showed only small changes with time throughout the entire growing season of the corn crop.

Initially, downward movement of the zone of maximum concentration occurred from the soil surface with time to day 43. Following day 43, this zone showed slow penetration of these solutes beyond 50-70 cm depths. This apparent slow transport of solutes was due to the presence of a slowly-permeable layer ($B_{2t}$ horizon) at a relatively shallow depth (75 cm). Under such conditions, flow of water as well as nutrients in the $B_{2h}$ horizon above the impermeable $B_{2t}$ layer occurred predominantly in the lateral direction rather than vertically downward. Obviously much deeper penetration of the solutes would be expected in deep, uniform, well-drained soil profiles, resulting in more rapid leaching loss of nutrients than observed for the Spodosol reported here. Such nutrient losses are minimized when a shallow water table is present; however, the solute concentrations become more dilute depending upon depth to an impermeable layer. Also, one would expect nutrient losses in Spodosols to be closely related to the frequency of high intensity rainfall. Such rainfall patterns would cause appreciable lateral flow of water and solutes to drain tiles. Therefore, we conclude that the presence of a shallow, slowly permeable layer such as the $B_{2t}$ horizon in Wauchula sand is beneficial in minimizing rapid leaching losses of nutrients from a tile-drained soil.

During 1975 a second corn experiment was performed at the Beef Research Unit, but three irrigation treatments--no irrigation, daily irrigation (0.64 cm/day), and controlled irrigation-were imposed. Controlled irrigation was maintained by irrigating with 1.3 cm of water when the soil water suction at 15 cm depth exceeded 100 cm of water. A total of 2.6 cm of water was applied during the entire season. Line sources (plastic tubing) with discrete emitter holes were placed adjacent to corn rows to provide irrigation by the trickle method. For the daily irrigated plots, irrigation was provided between April 2 (day 8) and May 30 (day 70). Water was pumped at a constant hydraulic head through the emitters in the plastic tubing to provide a constant volume discharge of water with time for unit length of the irrigation tube. The trickle concept offers advantages of increased water conservation and improved control of soil water matric potential in the root zone. Approximately 2000 to 3000 acres in Florida are currently irrigated (private communication with Dalton Harrison, Extension Irrigation Specialist, Department of Agricultural Engineering, University of Florida) by trickle irrigation. A disadvantage of the concept from a technological standpoint is that the irrigation water must undergo intensive filtering of Fe, S, particulate matter, and algae to prevent premature clogging of trickle nozzles. Theoretical and experimental analysis of transient infiltration from a trickle source irrigation system have been presented by Brandt et al (1971) and Bresler et al. (1971).

Two fertilizer application treatments--conventional and programmed application--were also established in the 1975 experiment. Prior to planting of corn, 4,235 kg/ha of a 5-10-15 (percentages for $N$-$P_2O_5$-$K_2O$) fertilizer was applied broadcast to the soil surface for the conventional application. The corn was planted on March 26 (day 0), and 672 kg/ha of $NH_4NO_3$ fertilizer was applied to the soil on May 28 (day 68). The programmed fertilizer treatment was established by applying 5% of the total N, P and K fertilizer (4,235 kg/ha of 5-10-15 fertilizer plus 622 kg/ha of $NH_4NO_3$) in a band near each corn row at the time of seedling emergence, another 10% two weeks later, 10% at 4 weeks, 15% at 6 weeks, and 20% each at eight, ten, and 12 weeks. The tasseling stage for the corn began on May 30 (day 70) and the corn was harvested on August 11 (day 152).

The effect of daily irrigation upon the soil water suction head at 15 cm beneath the soil surface can be seen in Fig. 7 for the programmed fertilization. During the period when irrigation was applied daily (day 8 to 70) the soil water suction head in the irrigated plot was maintained between 40 (15% water content) and 60 (10% water content) cm of water; whereas the suction head in the plot that received no irrigation fluctuated from as low as 45 (14% water content) to as high as 380 (less than 6% water content) cm of water. During days when rainfall occurred (Table 1) soil water suction for the unirrigated plot was greatly decreased but increased sharply during periods of minimal rainfall. After day 70 soil water suction in both plots tended to decrease during periods of rainfall and to increase during the days after a rainfall. The increases in soil water suction in both plots resulted from soil water being removed by evaporation at the soil surface, water uptake by plant roots (transpiration) and downward water movement by soil water redistribution (gravitational drainage).

As expected, the effect of trickle irrigation upon soil water suction was less evident for soil depths of 30 (Fig. 8) and 60 (Fig. 9) cm than at the shallower 15 cm (Fig. 7) depth. This effect can also be seen in Figs. 10 and 11 where distributions of soil water pressure head with soil depth are presented for the unirrigated and irrigated plots during a 26-day period of minimal rainfall. In the plot receiving no irrigation, soil at the 15 cm depth underwent the greatest drying in the soil profile. Soil at the 30 cm depth also exhibited drying but to a lesser extent than at the 15 cm depth.

At day 20 the distributions of soil water pressure head with soil depth were similar for both the irrigated and unirrigated plots. Water tables (pressure head = 0) were located at 70 and 65 cm depths, respectively, for the irrigated and unirrigated soil profiles, indicating conditions for water saturation for soil depths greater than these depths and unsaturation at shallower depths. Vertical gradients for hydraulic head, H, with depth were approximately -0.011 in both irrigated and unirrigated soil for all depths greater than 60 cm. This small negative gradient of hydraulic head indicates that water is slowly draining from the soil profile. As time passed from day 20 to day 46 the gradients of H in the top 30 cm of the unirrigated soil reflected a net upward water movement due to evaporation and water uptake by plant roots. For example at day 30 the gradient of H between 15 and 30 cm depths was +0.933; whereas for the irrigated soil that value was -1.067 indicating a net downward flow of water due to the daily addition of 0.64 cm of water. Thus the distributions of soil water pressure head shown in Figs. 10 and 11 show that the daily application of 0.64 cm of water by trickle irrigation was more than sufficient to compensate for water loss in the top 60 cm of soil due to evaporation, transpiration, and drainage. The amount of 0.64 cm of water per day was selected because it represents the maximum potential removal of water from the soil by evapotranspiration for the summer months.

Average grain yields for corn grown on Wauchula sand during 1975 under three irrigation and two fertilizer management programs are presented in Table 2. For either the conventional or programmed fertilization, daily irrigation resulted in higher yields of grain, but the percentage yield increases due to daily irrigation were relatively small (21.7% for conventional fertilization and 20.5% for programmed fertilization). For conventional fertilization, grain yields for controlled irrigation were only slightly higher than for corn irrigated daily. The grain yield reported for corn receiving programmed fertilization and controlled irrigation was unexplainably lower than other treatments.

Irrigation use efficiencies (calculated by subtracting grain yields for unirrigated corn from yields for corn receiving daily irrigation and controlled irrigation and dividing the results by 39.7 cm of water for the daily irrigation treatment and 2.6 cm for the controlled irrigation) were 31.1 and 510.4 kg/ha/cm for conventionally fertilized corn receiving daily and controlled irrigation. These values in conjunction with soil water suction and grain yield data indicate that the controlled irrigation provided much more efficient use of the water applied and that the daily irrigation resulted in water application to the soil in excess of that actually needed to produce economically profitable grain yields in Wauchula sand. Even the grain yields for unirrigated corn could be considered to be economically profitable for the Wauchula sand. The relatively large yields for unirrigated corn was partially attributable to the presence of a water-saturated zone in the lower portion of the soil profile during the growing season for the corn. For the daily irrigated corn, irrigation use efficiencies were not greatly influenced by the method of fertilizer application (31.1 and 33.0 kg/ha/cm for conventional and programmed fertilization, respectively). That result is also supported by the observation from the 1974 experiment which showed that leaching fertilizer nutrients in Wauchula sand was primarily limited to the top 50-70 cm of soil.

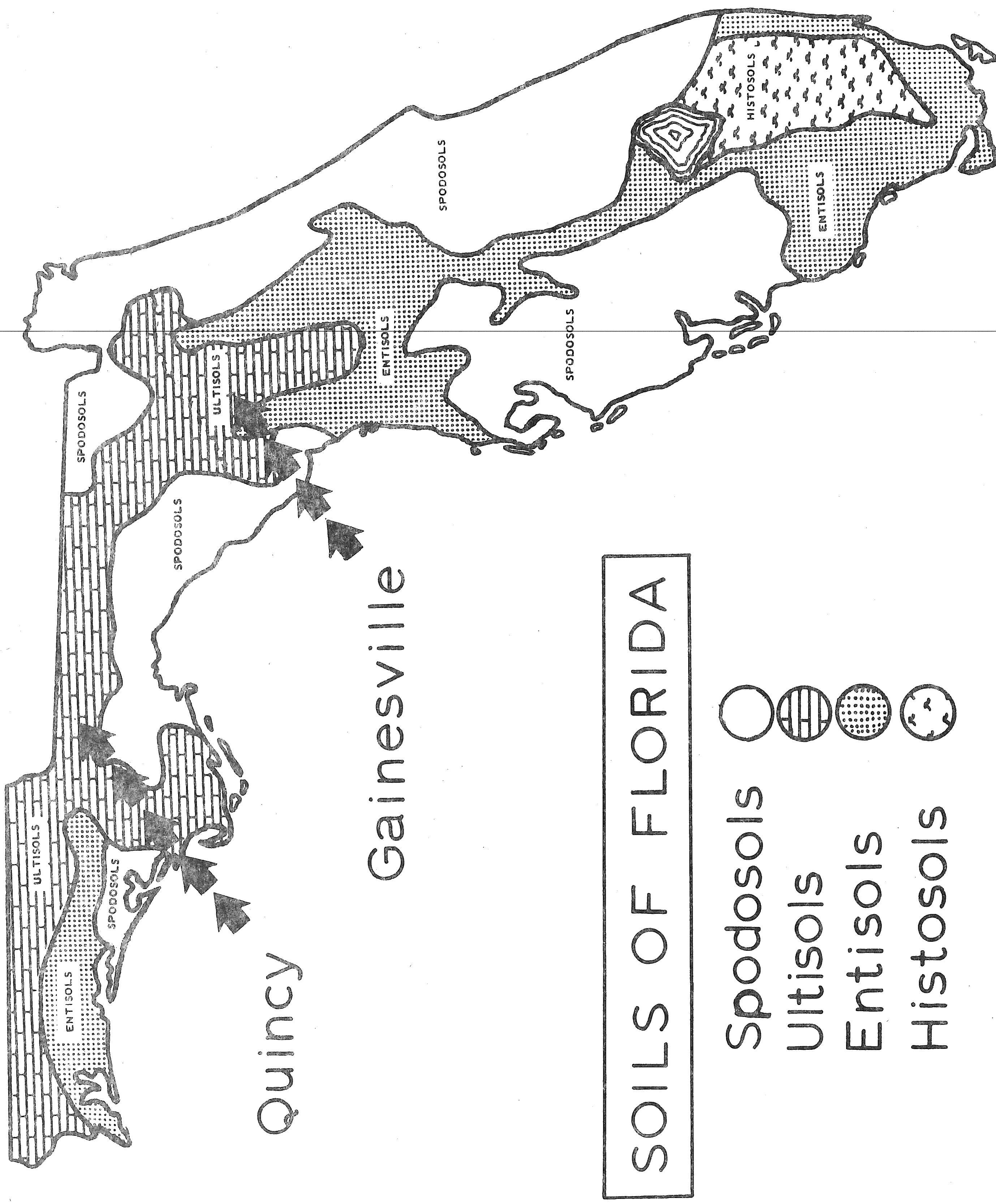


Figure 1: Map showing location of major soils of Florida

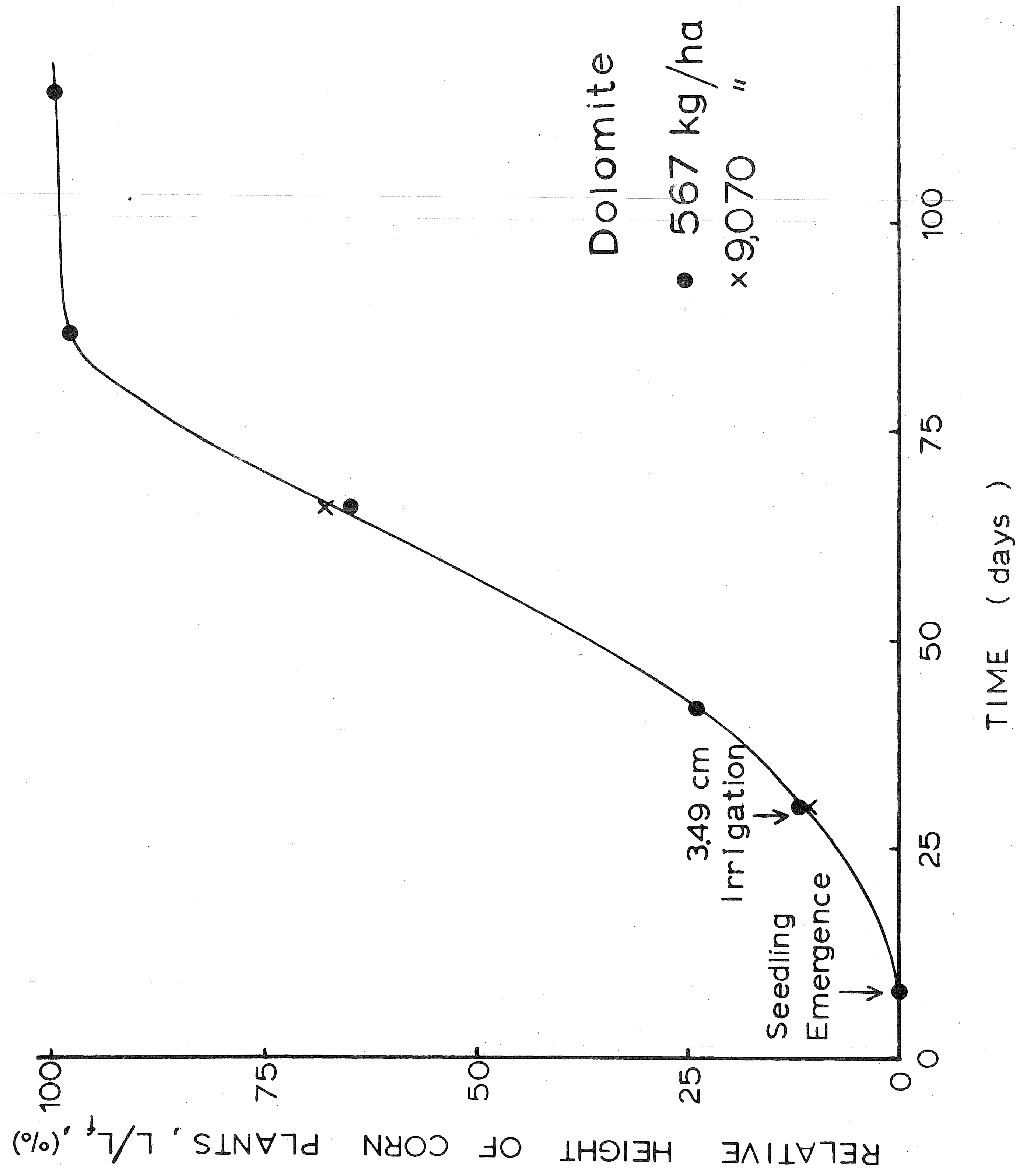


Figure 2: Average relative height of corn grown during 1974 on Wauchula sand treated with 567 and 9,070 kg/ha of dolomite limestone.

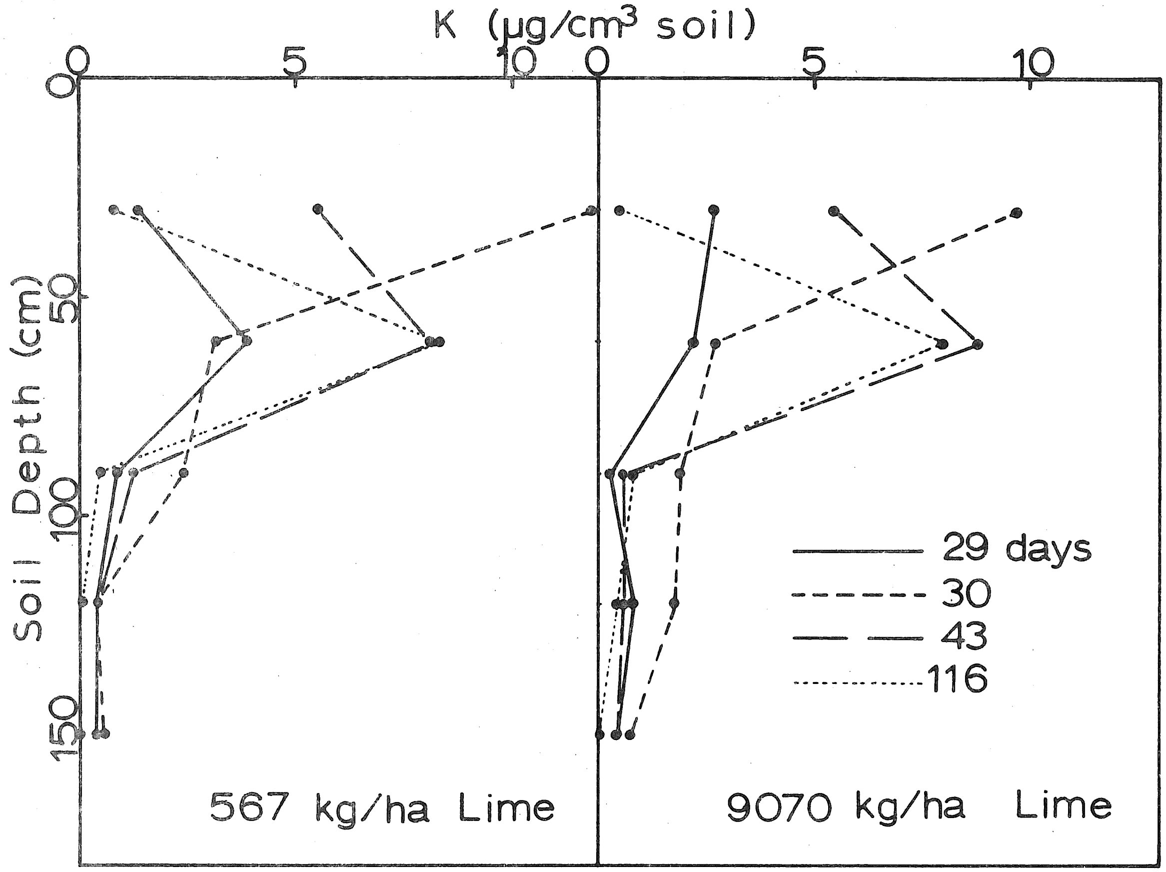


Figure 3: Distributions of potassium with depth in Wauchula sand treated with 567 and 9,070 kg/ha of limestone during 1974.

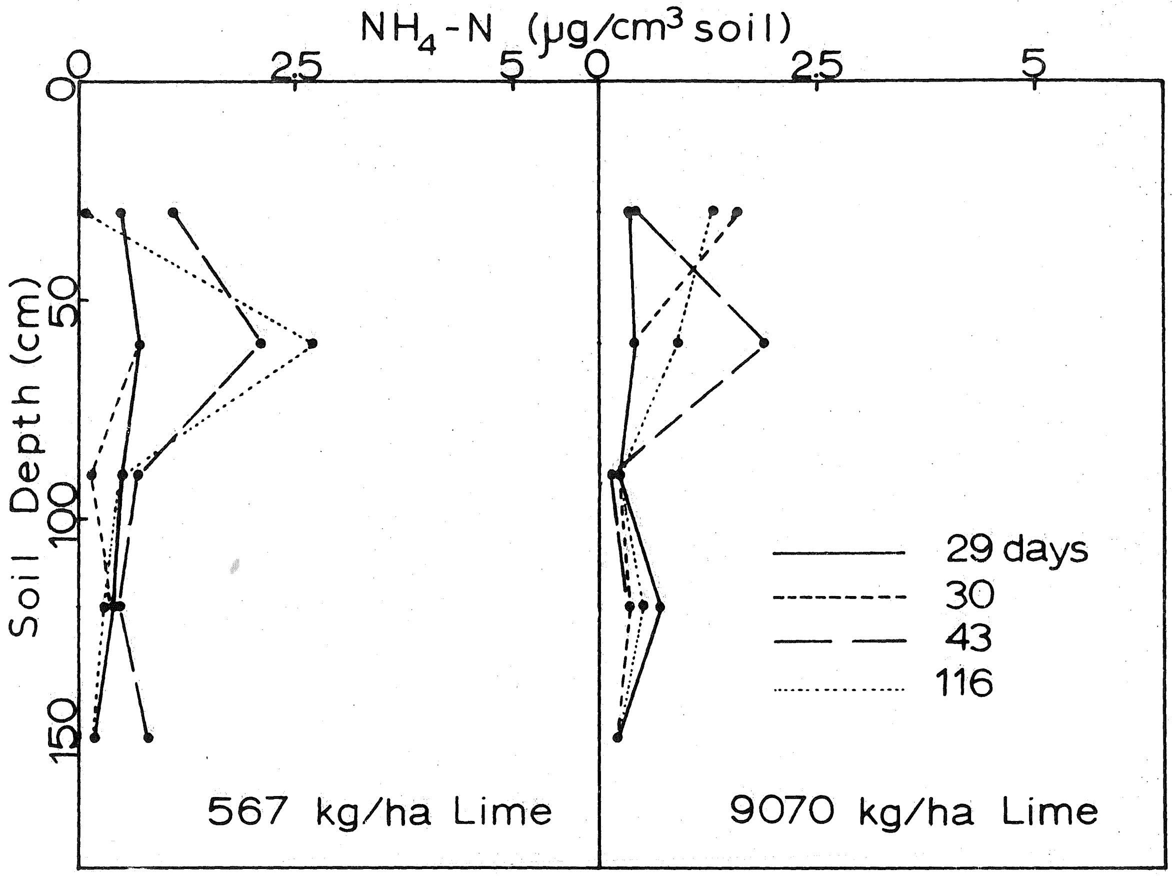


Figure 4: Distributions of $NH_4$-N with depth in Wauchula sand treated with 567 and 9,070 kg/ha of limestone during 1974.

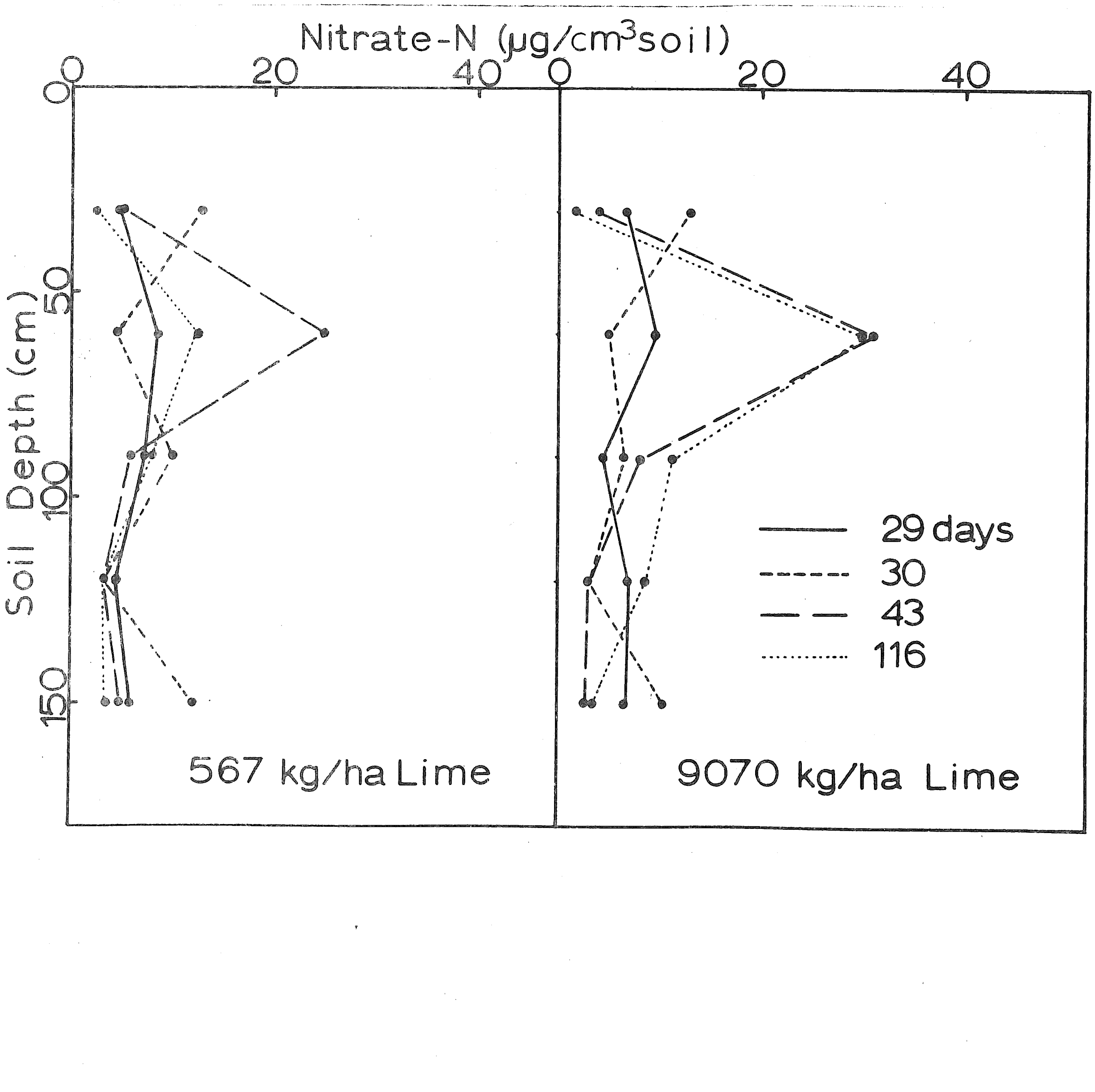


Figure 5: Distributions of $NO_3$-N with depth in Wauchula sand treated with 567 and 9,070 kg/ha of limestone during 1974.

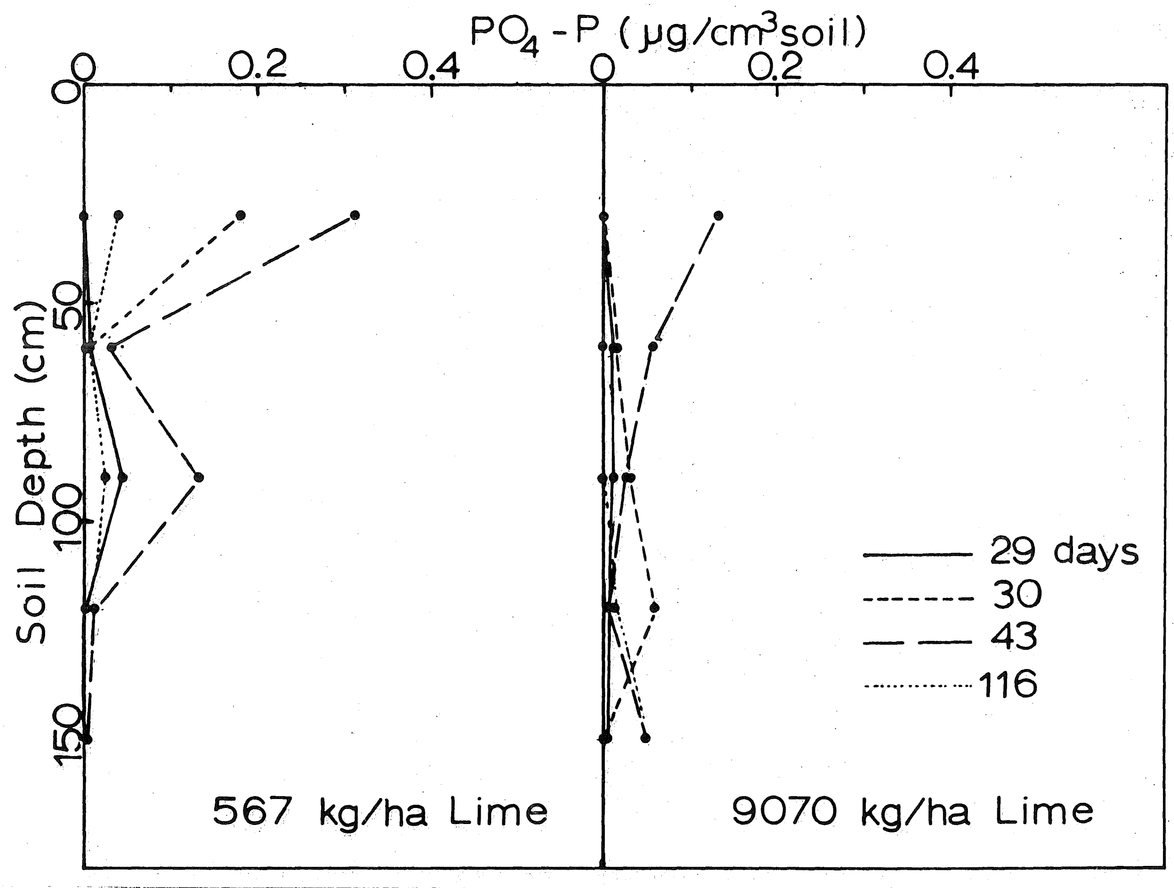


Figure 6: Distributions of $PO_4$-P with depth in Wauchula sand treated with 567 and 9,070 kg/ha of limestone during 1974.

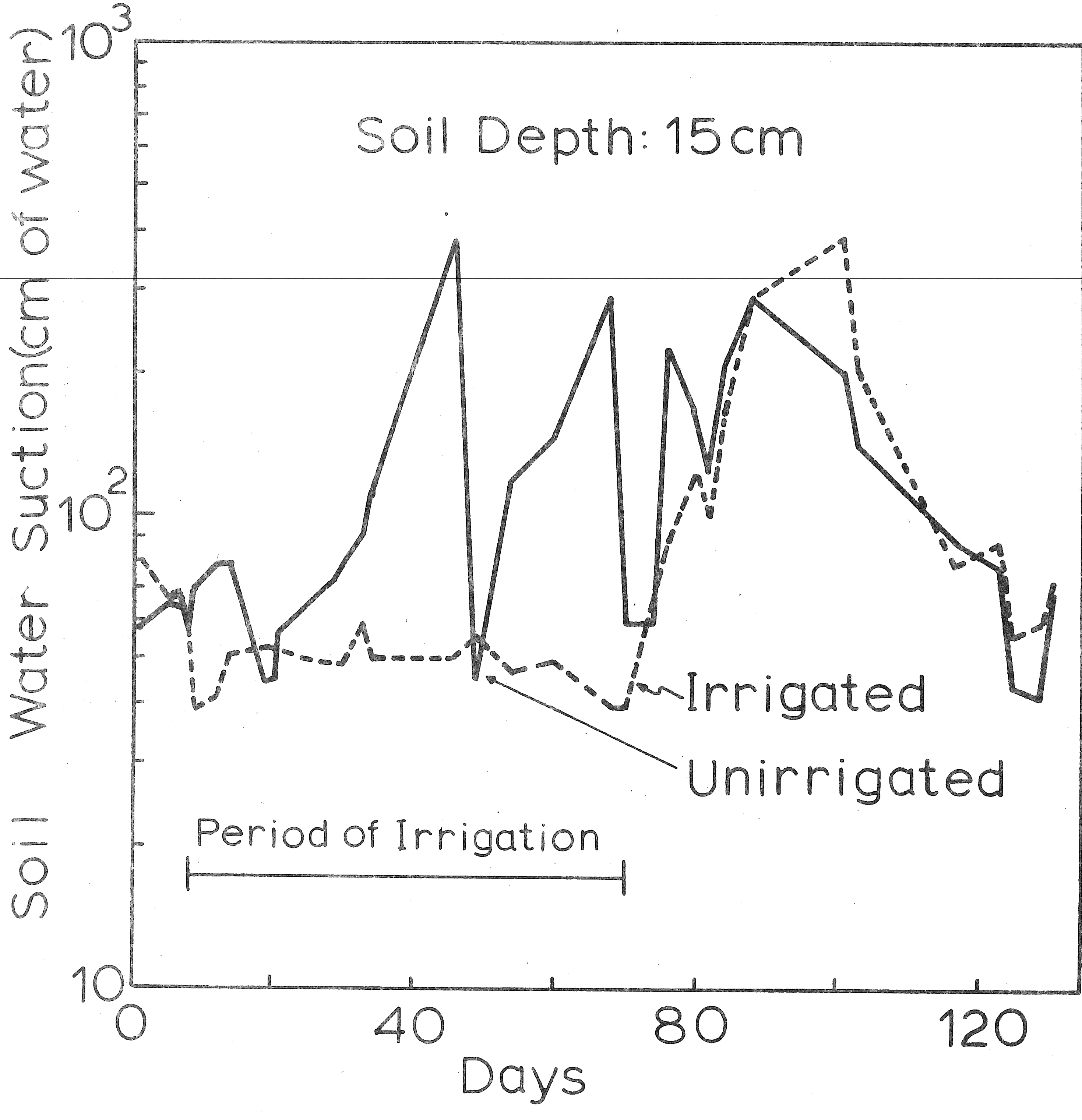


Figure 7: Soil water suction head at 15 cm soil depth in Wauchula sand during the 1975 growing season for daily irrigated and unirrigated corn.

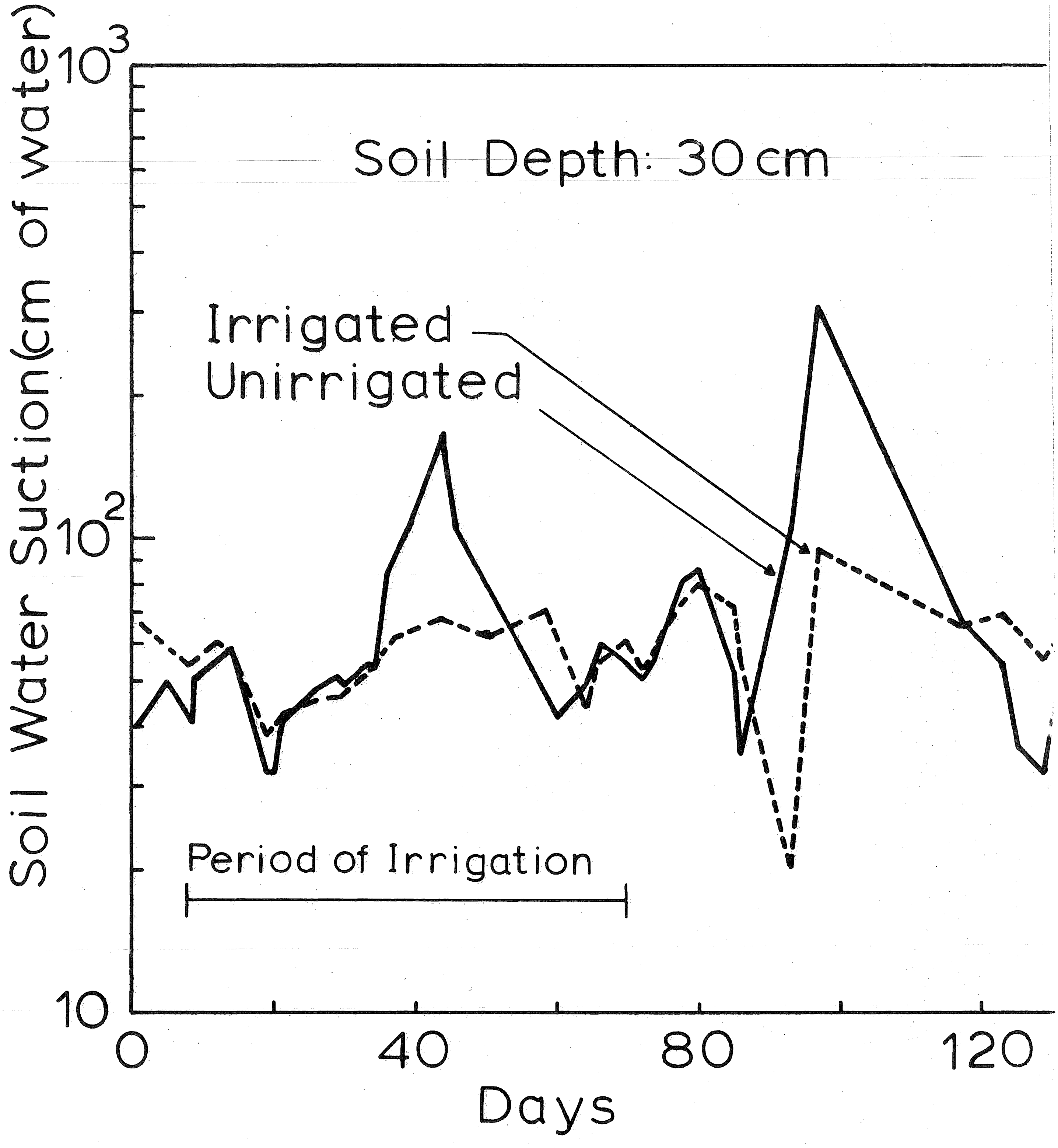


Figure 8: Soil water suction head at 30 cm soil depth in Wauchula sand during the 1975 growing season for daily irrigated and unirrigated corn.

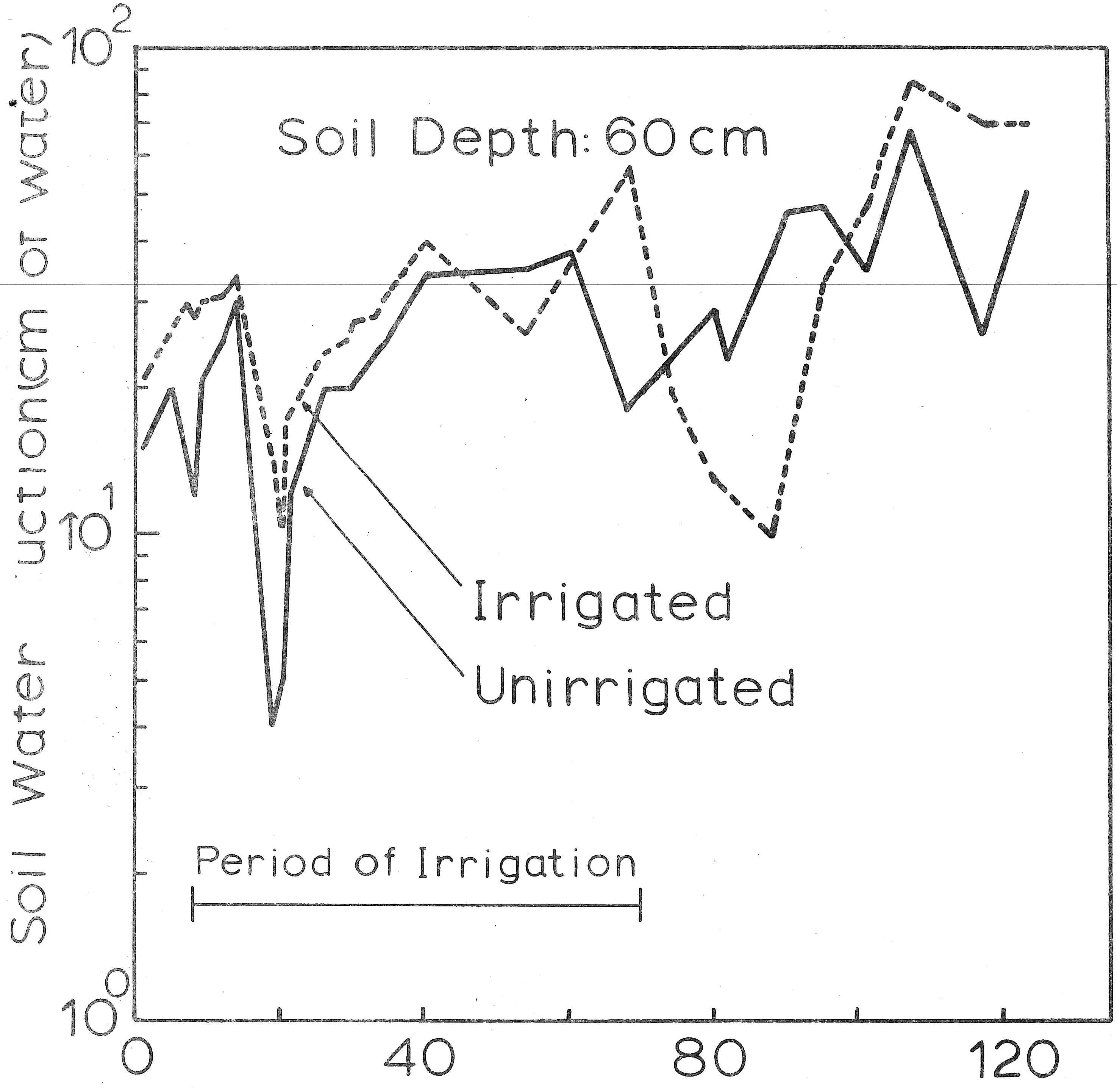


Figure 9: Soil water suction head at 60 cm soil depth in Wauchula sand during the 1975 growing season for daily irrigated and unirrigated corn.

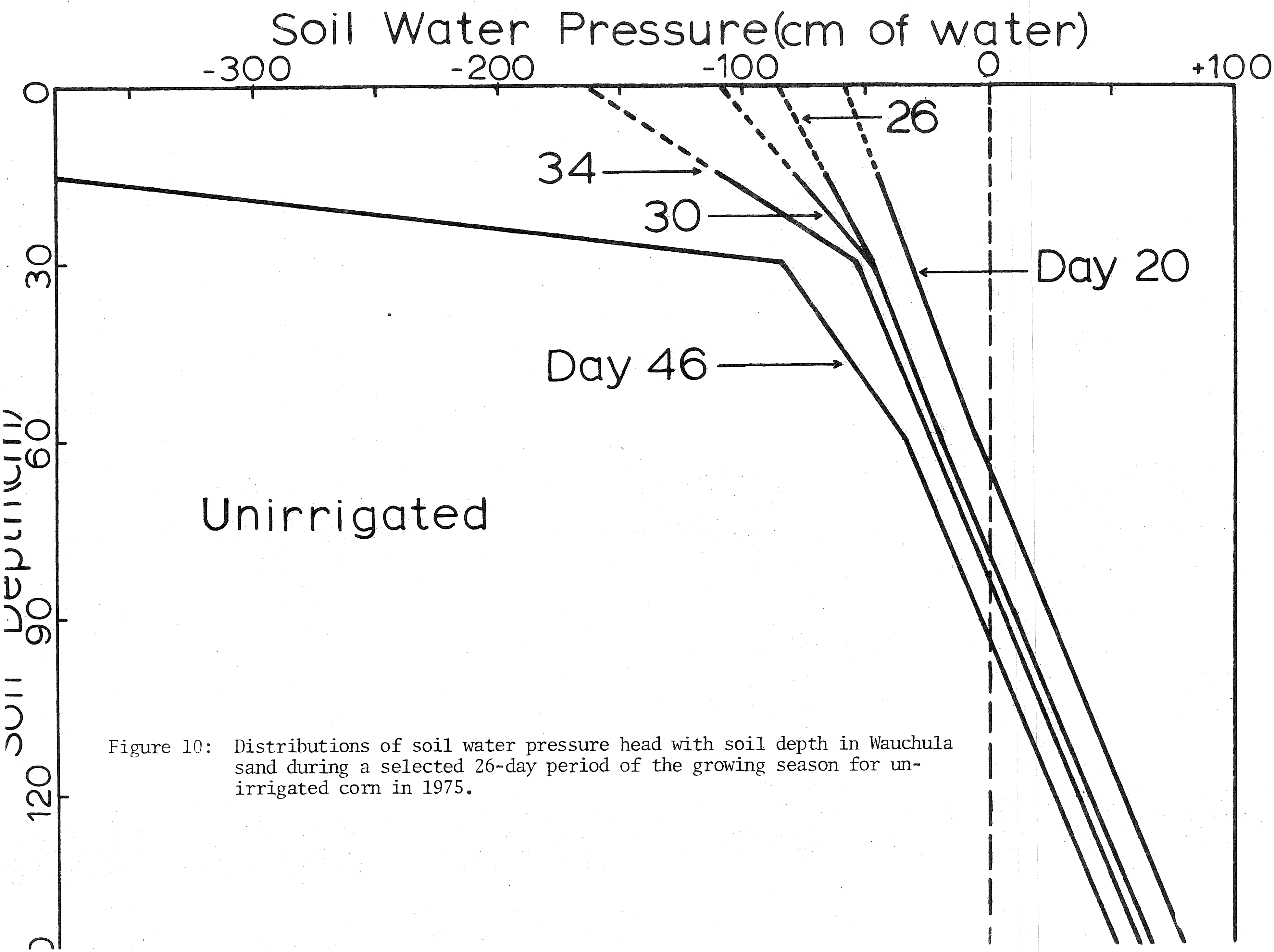


Figure 10: Distributions of soil water pressure head with soil depth in Wauchula sand during a selected 26-day period of the growing season for unirrigated corn in 1975.

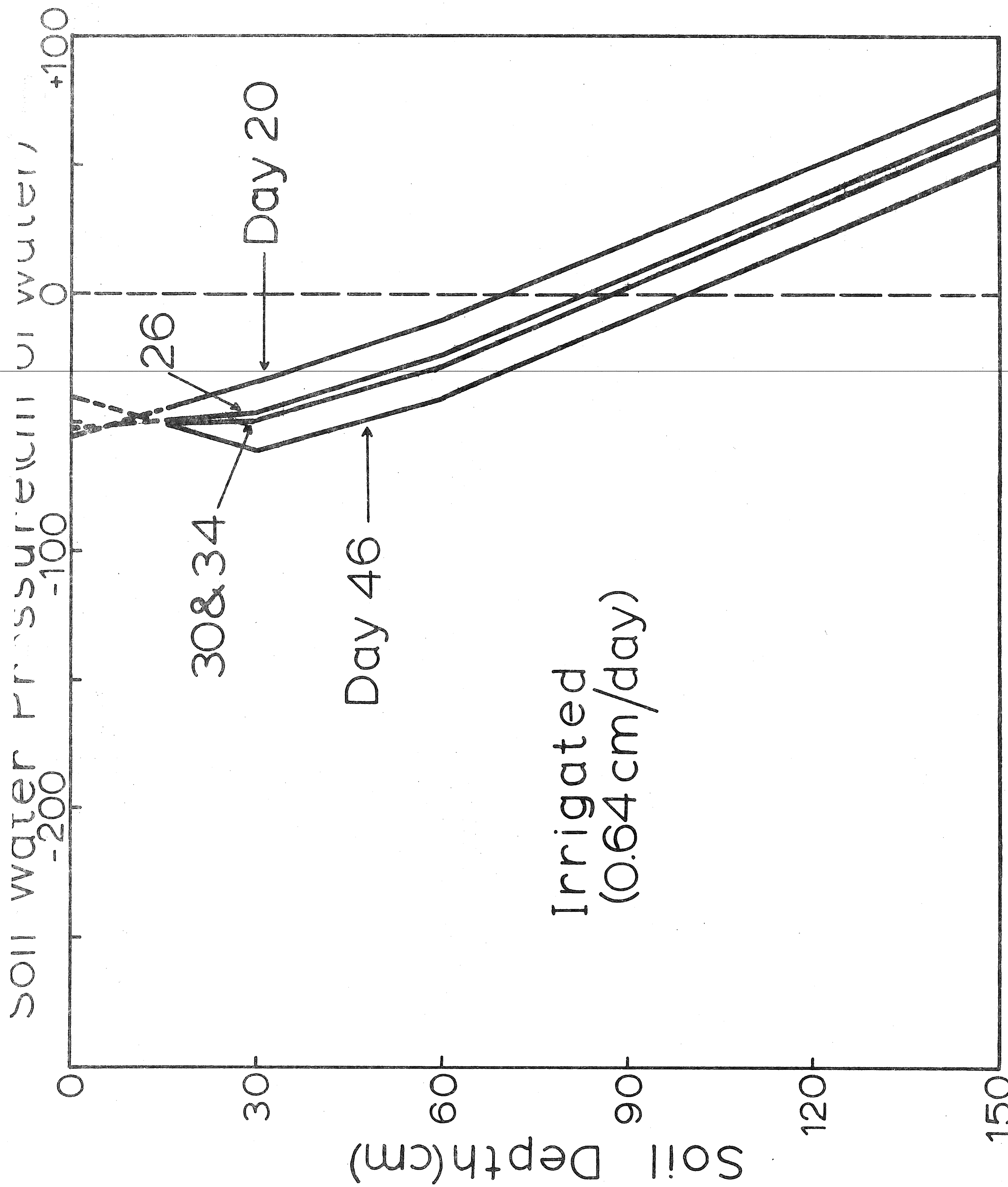


Figure 11: Distributions of soil water pressure head with soil depth in Wauchula sand during a selected 26-day period of the growing season for daily irrigated corn in 1975.

Table 1: Rainfall at the Beef Research Unit near Gainesville during the spring and summer of 1975.

| Day | Rainfall (cm) | Day | Rainfall (cm) | Day | Rainfall (cm) |
|---|---|---|---|---|---|
| *0-8 | 0.0 | 72 | 1.8 | 96 | 1.0 |
| 9 | 0.3 | 73 | 0.1 | 97-99 | 0.0 |
| 10-14 | 0.0 | 74-77 | 0.0 | 100 | 0.3 |
| 15-26 | 10.7 | 78 | 0.4 | 101-105 | 0.0 |
| 27-40 | 0.0 | 79 | 0.1 | 106-108 | 0.8 |
| 41 | 0.1 | 80 | 1.4 | 109 | 0.6 |
| 42-43 | 0.0 | 81 | 0.0 | 110 | 0.2 |
| 44 | 0.2 | 82 | 0.2 | 111 | 0.0 |
| 45-49 | 0.0 | 83 | 0.1 | 112 | 2.4 |
| 50 | 0.8 | 84 | 0.0 | 113 | 2.0 |
| 51-53 | 0.0 | 85 | 0.2 | 114 | 0.6 |
| 54-60 | 2.7 | 86 | 0.0 | 115 | 0.2 |
| 61-64 | 0.0 | 87 | 0.3 | 116-118 | 0.0 |
| 65 | 0.4 | 88-91 | 0.0 | 119 | 2.7 |
| 66 | 1.3 | 92 | 0.9 | 120 | 0.2 |
| 67 | 0.0 | 93 | 0.1 | 121-123 | 0.0 |
| 68 | 6.1 | 94 | 1.1 | 124-131 | 3.6 |
| 69 | 0.7 | 95 | 0.0 | 132 | 0.6 |
| 70-71 | 0.0 | | | 133 | 2.4 |
| | | | | Total | 47.6 |

* Day 0 was March 26

Table 2: Corn grain yields on Wauchula sand under three irrigation and two fertilizer management programs, Gainesville, 1975.

| Fertilizer management | Grain Yield, kg/ha[1] | | |
|---|---|---|---|
| | No irrigation | Daily irrigation[2] | Controlled irrigation[3] |
| Conventional | 5708 ac | 6949 ab | 7035 ab |
| Programmed | 6366 abc | 7672 b | 5206 c |

[1] $LSD_{0.05}$ = 1612 kg/ha. Grain yields followed by the same alphabetical letter (a,b or c) or combination of letters did not differ from each other. $LSD_{0.05}$ is the least significant difference at a 5% probability level (Steel and Torrie 1960).

[2] Application of 0.64 cm/day from day 8 to day 70; total application, 39.7 cm.

[3] Irrigation with 1.3 cm of water when soil water suction at 15 cm depth exceeded 120 cm of water; total application, 2.6 cm.

## C. EXPERIMENTS ON TROUP SAND, AN ULTISOL

During 1975 a field experiment of irrigated corn was established on Troup sand (an Ultisol) at the University of Florida Agricultural Research and Education Center near Quincy. The purpose of the experiment was to determine distributions of soil water pressure head with depth during the growth of irrigated and unirrigated corn and to determine grain yields for corn grown under 3 irrigation and 2 fertilizer management programs. The soil profile had a compacted plow layer in the top 15 cm but was essentially a uniform sand between 15 to 150 cm depths with a sandy clay material located at 150 cm. This soil was originally classified as Lakeland sand, but the profile characteristics more closely resemble Troup sand. The names Lakeland sand and Troup sand are used to represent the same soil in this report. Graphs of hydraulic conductivity versus soil water content for selected horizons of this soil are presented elsewhere (Elzeftawy and Mansell, 1975).

Coker 77 hybrid corn was planted on March 24 (day 0) in rows 90 cm apart and with 15 cm spacing between seed in each row. Three soil-water management treatments were maintained: (a) no irrigation, (b) daily irrigation of 0.64 cm of water applied through plastic trickle irrigation tubing placed near each corn row, and (c) 1.30 cm of water applied with trickle tubing when the soil water suction head at 15 cm depth exceeded 100 cm of water. Two fertilizer treatments were also used: (a) conventional fertilization where 2240 kg/ha of a 5-4.4-12.4 (percentages of N-P-K) fertilizer was applied prior to planting of the corn and 670 kg/ha of $NH_4NO_3$ was later applied in two equal applications (May 14 and 17) and (b) programmed fertilization of 2240 kg/ha of 5-4.4-12.4 fertilizer and 670 kg/ha $NH_4NO_3$ applied in several split applications. In the programmed fertilization treatment 5% of the N, P and K was applied at the time of seedling emergence, 5% two weeks later, 10% at four weeks, and 20% applications at 6, 8, 10 and 12 weeks.

Tensiometers were installed at 15, 30, 60, 90, 120, and 150 cm depths beneath the soil surface and adjacent to the corn rows. Soil water pressure head measurements were obtained from the tensiometers at selected times during the growth of the corn. The grain was harvested on August 8 (day 141).

Major fluctuations in soil-water suction head with time at the 15 and 30 cm soil depths were observed in the unirrigated plots (Fig. 12). At the 15 cm depth suction heads ranged from as low as 100 cm of water immediately following a rain to as high as 800 cm of water several days following rain. Major periods during which the surface soil underwent extensive drying were observed during 30-40, 55-59, 70-80, and 86-100 days after planting of the corn. Only minor fluctuations in suction head were observed deeper in the soil profile. For example, at the 90 cm soil depth the suction head ranged from near 0 to slightly above 100 cm of water between 25 and 100 days after planting of the corn. Between days 25 and 37, positive soil water pressure heads were temporarily observed above the slowly permeable sandy clay layer at 150 cm depth. Heavy rains in the early part of the season were responsible for the positive soil water pressure at 150 cm depth.

Daily irrigation of 0.64 cm of water resulted in soil water suction heads less than 100 cm at all depths (Fig. 13) in the profile during the growing season for the corn. A total of 56 cm of water was applied as irrigation during the growing season for the corn. Major fluctuations in suction head as seen in the unirrigated plot were not observed at the 15 cm depth in the daily irrigated treatment. Thus, daily irrigation of 0.64 cm of water was apparently more than sufficient to compensate for water uptake by plant roots. At the 60 cm soil depth the suction head ranged from 55 to 80 cm of water.

Soil water pressure head for 15, 60 and 150 cm soil depths are shown in Fig. 14 for the treatment which was irrigated with 1.30 cm of water when the suction head at 15 cm depth exceeded 100 cm of water. A total of 31 cm of water was applied by irrigation during the growth season for the corn. The irrigation minimized the magnitude of major fluctuations in the soil suction head at the 15 cm depth. The suction head ranged from a low of 40 cm of water to a high of 300 cm of water in the surface soil.

Yields of corn grain harvested from plots receiving the three soil-water management and the two fertilizer management treatments are presented in Table 3. The highest yields and the highest use efficiency for the irrigation water (Table 4) were obtained for corn grown with programmed fertilization and controlled irrigation (1.30 cm of water applied when the soil water suction head at 15 cm depth exceeded 100 cm of water). In unirrigated plots the fertilizer treatment did not affect the grain yields; however, in irrigated plots programmed fertilization resulted in higher grain yields than when the fertilizer was applied in a conventional manner. Programmed fertilization resulted in more efficient use of irrigation water in the irrigated corn plots. In plots receiving daily irrigation, water use efficiency for programmed fertilization was approximately 4 times larger than for conventional fertilization, and in plots receiving controlled irrigation, water use efficiency for programmed fertilization was approximately twice that for conventional fertilization. For plots receiving either conventional or programmed fertilization, grain yields as well as irrigation use efficiencies were higher for controlled irrigation where tensiometers were used to schedule water applications than for daily applications of irrigation water.

One of the major conclusions that can be obtained from this experiment is that fertilizer and water management for corn growing in sandy soil should be treated as mutually dependent phenomena. For example, excessive and indescriminate use of irrigation may decrease use efficiency of fertilizer and irrigation water by excessive leaching from the "rooting zone" of the soil profile and can result in nutrient contamination of ground-water. Also programmed fertilization tended to improve the use efficiency of irrigation water applied to corn.

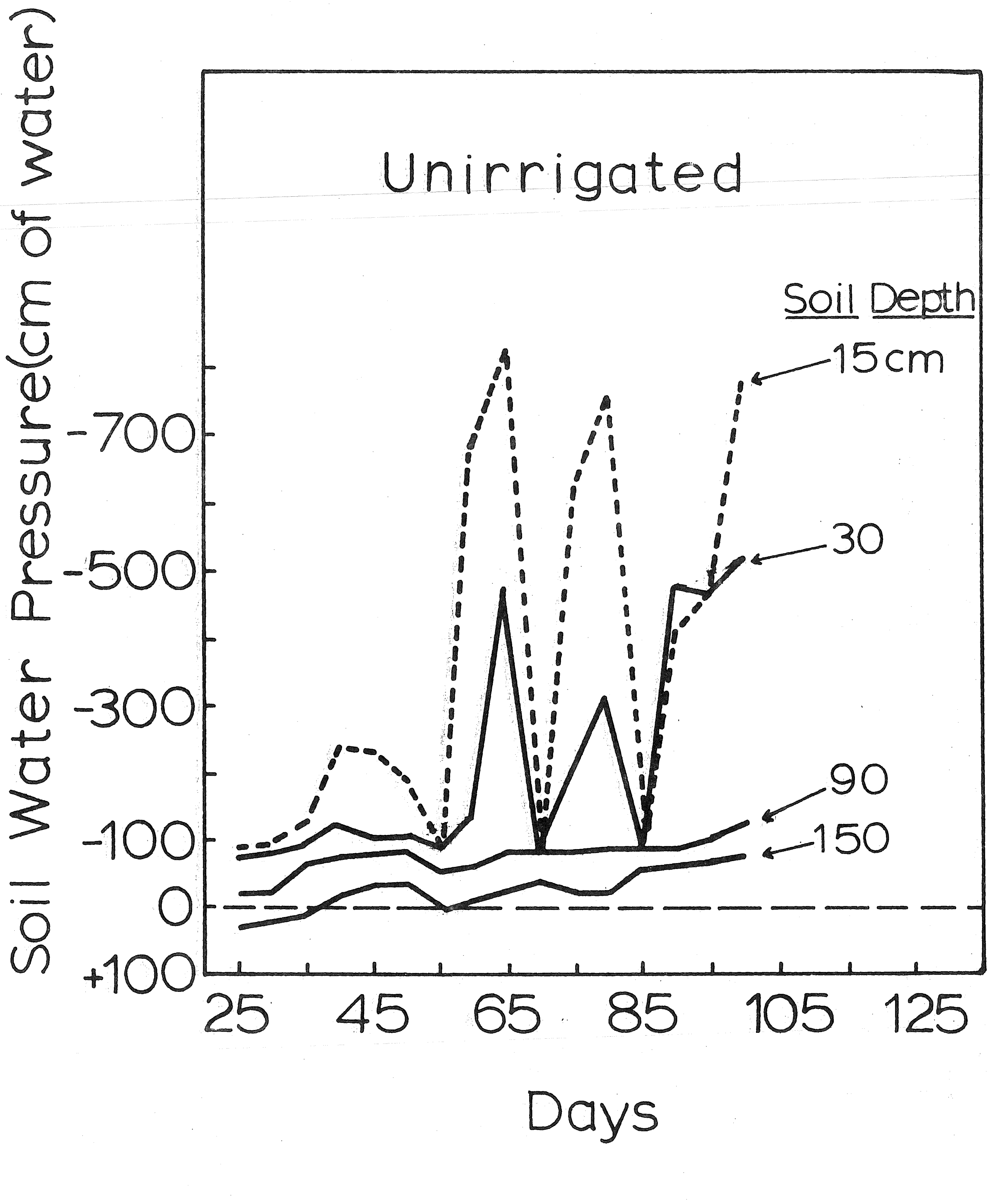


Figure 12: Soil water pressure head at 15, 30, 90, and 150 cm soil depths in Troup sand during the 1975 growing season for unirrigated corn.

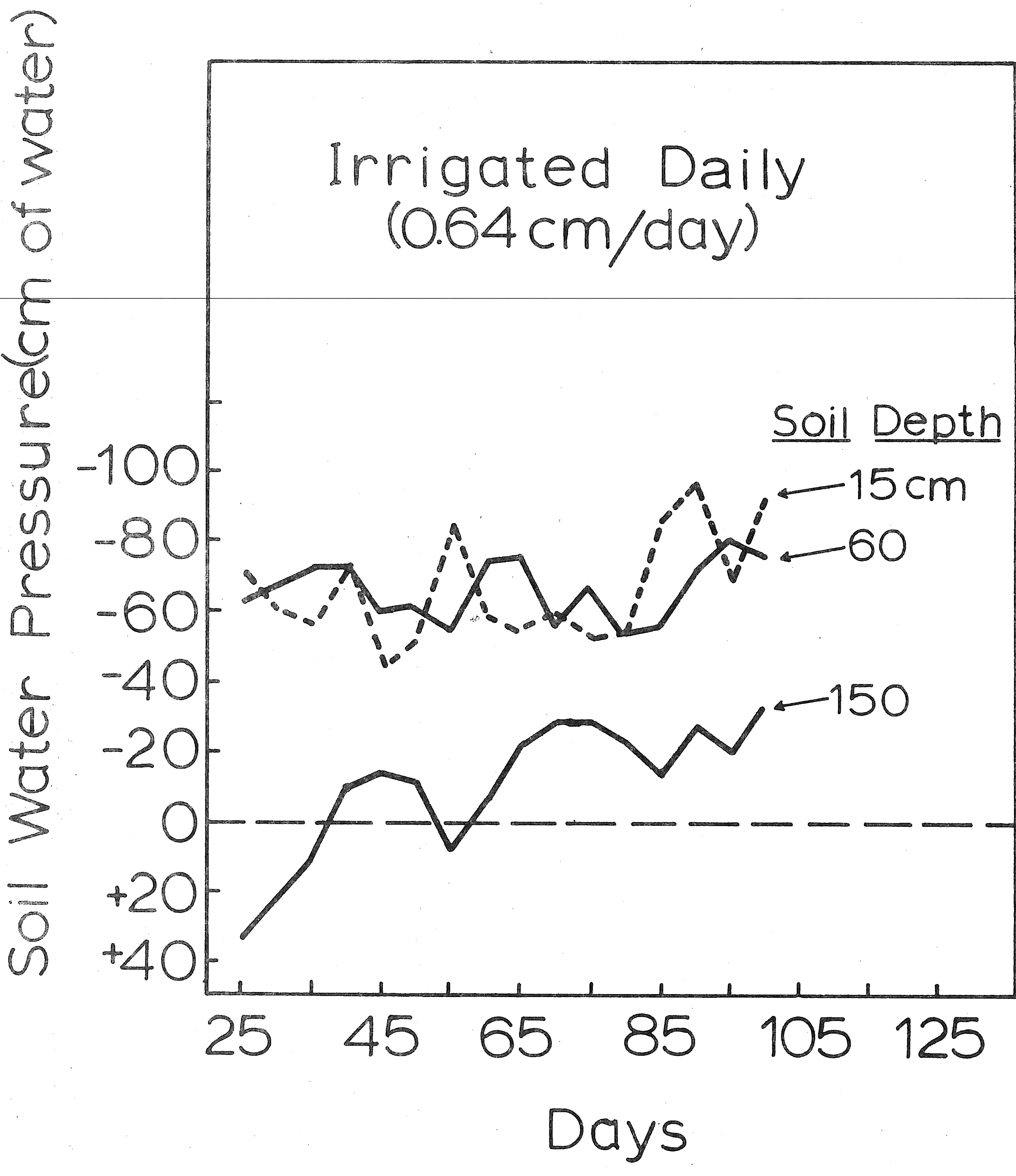


Figure 13: Soil water pressure head at 15, 60, and 150 cm soil depths in Troup sand during the 1975 growing season for daily irrigated corn.

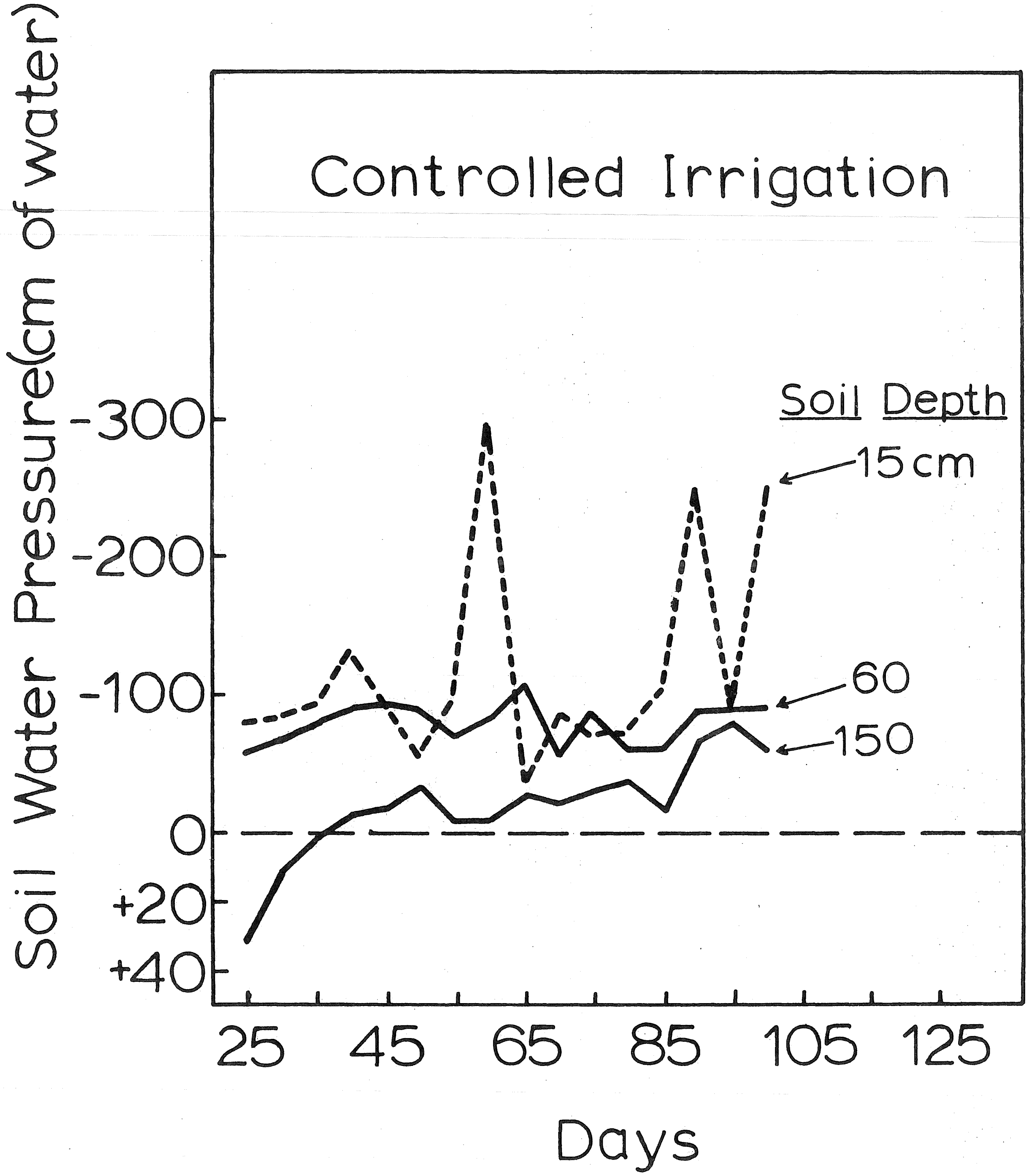


Figure 14: Soil water pressure head at 15, 60, and 150 cm soil depths in Troup sand during the 1975 growing season for corn irrigated when the pr sure head became less than -100 cm of water at 15 cm depth.

Table 3: Grain yields for corn grown under three irrigation and two fertilizer management programs on Troup sand, Quincy, 1975.

| Fertilizer Treatment | Grain Yield, kg/ha[1] No Irrigation | Daily Irrigation (0.64 cm/day) | Controlled Irrigation[2] |
|---|---|---|---|
| Conventional | 2,860 a | 3,380 a | 4,760 b |
| Programmed | 2,710 a | 4,950 b | 6,600 c |

$LSD_{0.05}$ (a,b,c) = 1190

[1] $LSD_{0.05}$ is the least significant difference at a 5% probability level (Steel and Torrie 1960).

Grain yields followed by the same alphabetical letters (a,b or c) or combination of letters did not differ from each other.

[2] 1.30 cm of irrigation water applied when the soil water suction head at 15 cm depth exceeded 100 cm of water.

Table 4: Irrigation use efficiency* for corn grown under two irrigation and two fertilizer management programs.

| Fertilizer Program | Irrigation Treatments | |
|---|---|---|
| | Daily Irrigation | Controlled Irrigation |
| | (kg of grain/ha/cm of irrigation water) | |
| Conventional | 9.3 | 61.3 |
| Programmed | 37.3 | 120.6 |

* Irrigation use efficiency was calculated by subtracting grain yield for the unirrigated plots from those for the irrigated plots and dividing the result by 56 cm for the daily irrigated treatment and by 31 cm for the controlled irrigation treatment.

## CHAPTER 4: MATHEMATICAL MODELS

During the course of this study several mathematical models have been developed for the purpose of describing soil water movement during infiltration and redistribution and the transport and interactions of applied 2,4-D, orthophosphate, and potassium in soils. Initially, existing models were utilized to describe the fate of these solutes in soils. However, it was found that new models were needed in order to account for the various mechanisms governing solute interactions which influence the movement of these solutes in the soil-water system. The capability of such models to predict the simultaneous movement of water and applied solutes is clearly dependent upon their validity under controlled laboratory conditions and more crucially under field conditions. In this study, the water movement model as well as the 2,4-D and orthophosphate models have been tested against field and laboratory results.

### A. Water and 2,4-D Models:

The water and 2,4-D models are based on the numerical solution of the water flow equation and the solute transport equation for transient and unsaturated water flow conditions. The transient one-dimensional water flow equation for unsaturated soils is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} D(\theta) \frac{\partial \theta}{\partial z} - \frac{\partial K(\theta)}{\partial z} \qquad (1)$$

where t denotes the time (hr); z the vertical distance in the soil (cm) positive downward; $\theta$ the volumetric soil water content ($cm^3/cm^3$); $D(\theta)$ the soil water diffusivity ($cm^3/hr$); and $K(\theta)$ the hydraulic conductivity (cm/hr). The corresponding equation governing transient one-dimensional solute transport through soils may be written as

$$\frac{\partial (S + \theta C)}{\partial t} = \frac{\partial}{\partial z} (\theta D_S(\bar{v}) \frac{\partial C}{\partial z}) - \frac{\partial (vC)}{\partial z} \qquad (2)$$

where C is the solute concentration in soil solution ($mg/cm^3$); S the amount of solute sorbed by the soil matrix per unit volume of soil ($mg/cm^3$); v the Darcy water flux (cm/hr); $D_S(\bar{v})$ the solute dispersion coefficient ($cm^2/hr$); and $\bar{v}$ (= $v/\theta$) the pore water velocity (cm/hr). The dispersion coefficient $D_S(\bar{v})$ of equation (2) is assumed to be a function of pore water velocity, $\bar{v}$. Adsorption isotherms which express relationships between quantities of solute adsorbed by the soil, S, and corresponding concentration in soil solution, C, were used to evaluate the rate-of-sorption term $\partial S/\partial t$. Equations (1) and (2) subject to appropriate boundary and initial conditions were solved numerically using explicit-implicit finite difference approximation techniques (see Selim and Mansell, 1974; Selim, Mansell, and Elzeftawy, 1976). Simulated results from the water and 2,4-D models were compared with field measurements during continuous water infiltration in a Lakeland sandy soil (Ultisol) near Quincy, Florida. It was found that increasing the water flux from 2.08 to 4.10 cm/hr during irrigation caused the maximum soil water content, $\theta$, at the surface to increase (Fig. 15 and 16) from 0.26 to 0.29 $cm^3/cm^3$. The higher flux resulted in more rapid penetration of the wetting front. Predicted profiles of soil water as obtained using the numerical solution of the water flow equation (1) agreed well with water contents measured in the field; differences were within 0.02 to 0.05 $cm^3/cm^3$. Thus predicted water content profiles enabled evaluation of water penetration with time into the soil for the infiltration period studied.

Figures 17 and 18 show measured and calculated 2,4-D distributions during water infiltration with flux of 2.08 and 4.10 cm/hr. These field measurements indicate that the calculated 2,4-D distributions lagged behind the measured ones for all times during the infiltration process. The lag between calculated and measured distributions were between 2 and 5 cm. Retardation of calculated distributions with respect to measured values did not appear extensive; thus adequate agreement may be concluded. However, such retardation of calculated solute distributions could be attributed to overestimation of 2,4-D adsorption as determined by equilibrium isotherms.

Results of 2,4-D and water movement in laboratory soil columns of Lakeland fine sand (Elzeftawy, Mansell, and Selim, 1976) showed essentially the same trends as that from the field studies. Moreover, from the field and laboratory results it was clear that following water application of 14.3 cm, penetration of 2,4-D did not exceed 30 cm below the soil surface. Therefore, we may conclude that 2,4-D movement in the soil is extremely slow which minimizes potential contamination of groundwater resources when small applications of 2,4-D herbicide are used.

B. Phosphorus Models:

It was necessary to develop several models in order to describe the fate of phosphorus in a Spodosol. These models (see Mansell et al., 1976), are based upon solving the solute transport equation with several phosphorus interaction mechanisms.

The transport equation governing one-dimensional phosphorus movement through soils may be written as

$$\rho\frac{\partial S}{\partial t} + \theta \frac{\partial C}{\partial t} = \theta D_s \frac{\partial^2 C}{\partial z^2} - q \frac{\partial C}{\partial z} - Q, \tag{3}$$

where C is the concentration of the solute in soil water ($\mu g/cm^3$), $\rho$ the soil bulk density ($g/cm^3$), $\theta$ the soil water content ($cm^3/cm^3$), $D_S$ the hydrodynamic dispersion coefficient ($cm^2/hr$), q is the soil water flux (cm/hr), S the amount of solute sorbed by the soil particles ($\mu g/gm$), Q the rate of solute removal per unit volume of soil ($\mu g/cm^3/hr$), t is time (hr), and z is distance in the soil (cm). The term $\partial S/\partial t$ represents the rate for reversible adsorption (or exchange) of solute by soil particle surfaces, and the sink term, Q, is the rate for irreversible removal (i.e., precipitation and immobilization) of solute from the soil.

In this study, three phosphorus sorption processes were considered for the reversible term, $\partial S/\partial t$, in equation (3). First, adsorption was assumed to be linear and instantaneous

$$S = KC \tag{4}$$

where K is the solute distribution coefficient ($cm^3/g$) as determined from adsorption isotherms. Secondly, a nonlinear instantaneous adsorption mechanism was considered,

$$S = K\,C^N \tag{5}$$

where $N < 1$. Thirdly, a kinetic reaction between S and C such that

$$\frac{\partial S}{\partial t} = \frac{\theta}{\rho} k_a C^N - k_d (KC^N - S) \tag{6}$$

was used. This equation describes a finite adsorption rate proportional to the difference between the equilibrium adsorption and the amount which is already adsorbed. The parameter $k_a$ is the forward (adsorption) and $k_d$ is the backward (desorption) reaction rate coefficients ($hr^{-1}$), respectively. When the value of N equals unity, equation (6) describes a reversible, first-order kinetic reaction. For many reactive solutes such as herbicides and phosphorus, the value of N has been found to be less than unity.

Irreversible sorption processes assigned to the Q term of equation (1) were considered in two ways. First, the sink term was given the form

$$Q = k_c(\theta C) \tag{7}$$

where $k_c$ is the rate coefficient ($hr^{-1}$) for precipitation and/or chemisorption of solute from the soil solution. Secondly, the sink term Q is expressed as,

$$Q = k_s(\rho S) \tag{8}$$

where $k_s$ is considered the rate coefficient ($hr^{-1}$) for chemical immobilization of physically adsorbed phosphorus.

The phosphorus models were used to describe experimental data for miscible displacement of phosphorus solution in Oldsmar fine sand (Spodosol) columns. The soil was obtained from an uncultivated and unfertilized area at the University of Florida Agricultural Research Center located near Fort Pierce, Florida. Duplicate samples from undisturbed soil cores (5.4 cm inside diameter and 10 cm in length) were collected from surface $A_1$, and subsurface, $A_2$, horizons.

Phosphorus breakthrough curve from the $A_2$ subsurface soil is shown in Fig. 19 where the relative concentration in the effluent ($C/C_o$) is plotted against the number of pore volumes ($V/V_o$). Calculated concentration distributions in the effluent using equilibrium adsorption isotherm ($S = 0.23\ C$) overestimated the measured retardation of phosphorus transport in the $A_2$ soil. Only when the distribution coefficient, K, was arbitrarily decreased tenfold ($S = 0.023\ C$) did the simulated curve fit experimental results. This tenfold decrease in K assumes that only 10% of the adsorption sites were active in phosphorus removal. Therefore, we conclude that the equilibrium adsorption isotherm did not adequately describe phosphorus transport for the relatively high soil water pore velocities used in the subsurface $A_2$ soil. However, using the kinetic equation (6) to represent phosphorus adsorption, calculated breakthrough curves provided an adequate description of phosphorus transport in the $A_2$ soil. Therefore, we conclude that phosphorus transport in the $A_2$ soil appeared to occur under fully reversible conditions. In addition, the adsorption-desorption mechanism is of the first order kinetic type.

The phosphorus breakthrough curve from surface $A_1$ soil core (Fig. 20) is distinctly different from that for the $A_2$ soil (Fig. 19). The breakthrough curve shows a large retardation, assymmetry, and extensive tailing during desorption (right-hand side). Calculated results from the equilibrium adsorption model (curve not shown) did not describe the shape or position of the experimental data. However, the calculated phosphorus breakthrough curve based upon the kinetic adsorption model (the NO SINK curve in Fig. 20) adequately described the left-hand side of the experimental data. Deviation between calculated and experimental results as well as incomplete recovery of applied phosphorus (80% recovery after 32 pore volumes) suggests that phosphorus retention in the $A_1$ soil may involve irreversible as well as reversible processes.

Since complete recovery of phosphorus in the effluent was not attained in the $A_1$ soil, an irreversible sink term Q was included in the kinetic transport model for the purpose of providing better description of the experimental data. Equation (7) was first used to represent irreversible precipitation or chemisorption, and equation (8) to describe chemical immobilization of physically adsorbed solute. Calculated breakthrough curves (Fig. 20 and 21) clearly depend upon the magnitude of these rate coefficients; however, optimum values for $k_c$ and $k_s$ were 0.1 $hr^{-1}$. Thus, phosphorus sorption during transport through the $A_1$ soil apparently occurred under conditions greatly removed from equilibrium with sorption-desorption mechanisms occurring primarily as reversible processes but also accompanied by irreversible processes such as chemical immobilization or precipitation.

Although the sink models for irreversible chemical immobilization and precipitation of phosphorus improved the agreement with experimental data, such agreements were not considered satisfactory. Furthermore, the exact mechanisms of irreversible adsorption were not identified. Therefore, a new phosphorus model (see Mansell, Selim, and Fiskell, 1976) was developed to describe various transformations which might occur for different soil and under different conditions. The model is a multistep one where phosphorus is considered to be present in four phases: A) solution, B) adsorbed, C) immobilized, and D) precipitated. The four phases of phosphorus are interrelated to each other by the rates of individual transformations which are determined by both the rate coefficients and the amounts of phosphorus in each phase. Under steady flow conditions, the transport and transformations of these four phases of phosphorus may be expressed as

$$\frac{\partial A}{\partial t} = D_s \frac{\partial^2 A}{\partial z^2} - v \frac{\partial A}{\partial z} - [k_1 A^N + k_5 A] + \frac{\rho}{\theta} [k_2 B + k_6 D] \tag{9}$$

$$\frac{\partial (\rho B)}{\partial t} = k_1 \theta A^N - [k_2 + k_3] \rho B + k_4 \rho C \tag{10}$$

$$\frac{\partial (\rho C)}{\partial t} = k_3 \rho B - k_4 \rho C \tag{11}$$

$$\frac{\partial (\rho D)}{\partial t} = k_5 \theta A^N - k_6 \rho D \tag{12}$$

where $\theta$ = volumetric soil water content ($cm^3/cm^3$),

$\rho$ = soil bulk density ($g/cm^3$),

$t$ = time (hr),

$z$ = transport distance in soil (cm)

$v$ = average pore water velocity (cm/hr),

$D_s$ = dispersion coefficient ($cm^2/hr$).

B, C and D = amounts of phosphorus per gram of soil for adsorbed, immobilized, and precipitated phases, respectively ($\mu g/g$),

A = phosphorus concentration in soil solution phase ($\mu g/cm^3$)

N = constant representing the order of the adsorption process,

and $k_1$, $k_2$, $k_3$, $k_4$, $k_5$, $k_6$ = rate coefficients for adsorption, desorption, immobilization, mobilization, precipitation, and dissolution, respectively ($hr^{-1}$).

At any given time, the sum of the amounts of phosphorus per gram of soil in the adsorbed (B), immobilized (C), and precipitated (D) phases will be referred to collectively as the total amount of phosphorus sorbed per gram of soil, S. The rate coefficients are assumed to depend upon characteristics of the soil environment such as level of acidity (pH), concentrations of reactive Fe and Al present, and the redox potential of the soil. Adsorption was assumed to be $N^{th}$ order where N = 0.35 (Mansell et al. 1976), whereas desorption, immobilization, mobilization, precipitation, and dissolution reactions were assumed to follow first order kinetic reactions. The model, however, is versatile and other transformation processes can be included as deemed necessary. Furthermore, validation of this model is needed in order to fully predict the fate of applied phosphorus in soils.

C. Potassium Model:

A mathematical model was developed (Selim, Mansell, and Zelazny, 1976) for the purpose of describing potassium transport and transformations in a soil profile. Potassium was considered to be present in the soil in four phases; solution, exchangeable, nonexchangeable (complex secondary minerals), and primary mineral. Simulated results were presented for assumed conditions of first-order kinetic reactions between the exchangeable, nonexchangeable, and primary mineral phases. However, the model is flexible and can be adapted to incorporate other transformation processes as well as variable rate coefficients with soil depth and time.

Potassium distribution results (see Selim, Mansell, and Zelazny, 1976) illustrate the dependence of the leaching loss and transformation among the various potassium phases upon the rate coefficients governing the transformation mechanism. Since water flow through the soil was maintained constant at all times, i.e., continuous water infiltration, the results presented here provide optimum conditions for transport and leaching losses of potassium. Transformations and transport of potassium under the more realistic conditions of water infiltration and redistribution should result in less movement of applied potassium. Such infiltration and redistribution conditions have been considered previously and can be adapted for the transport and transformations of potassium.

Verification of the model presented here is needed in order to fully describe the chemical fate of applied potassium in soil. Experimental evaluation of our model for various potassium transformation mechanisms is currently being investigated for several soils.

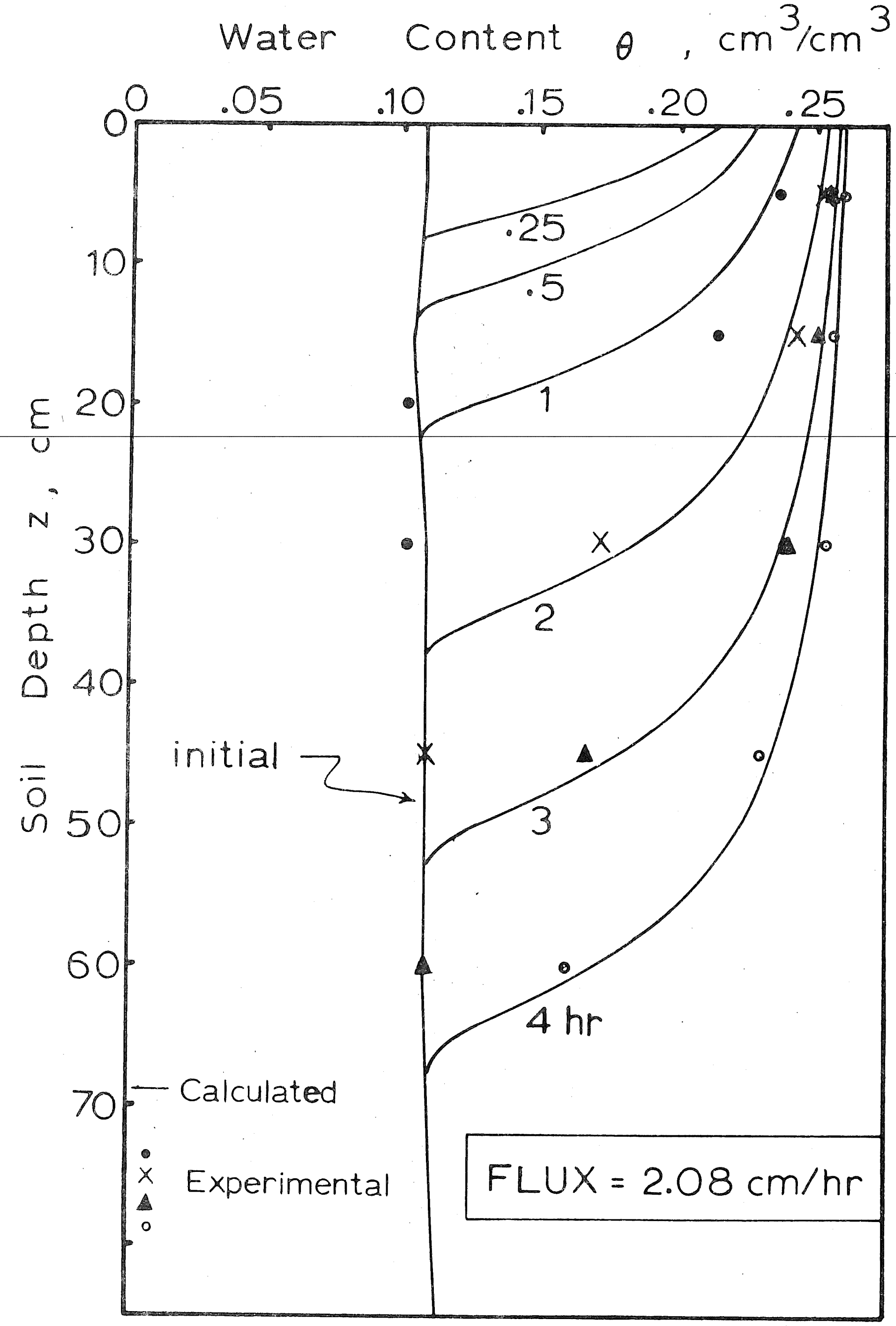


Figure 15. Experimental and calculated soil water profiles in Lakeland fine sand near Quincy, Florida during water infiltration with 2.08 cm/hr flux.

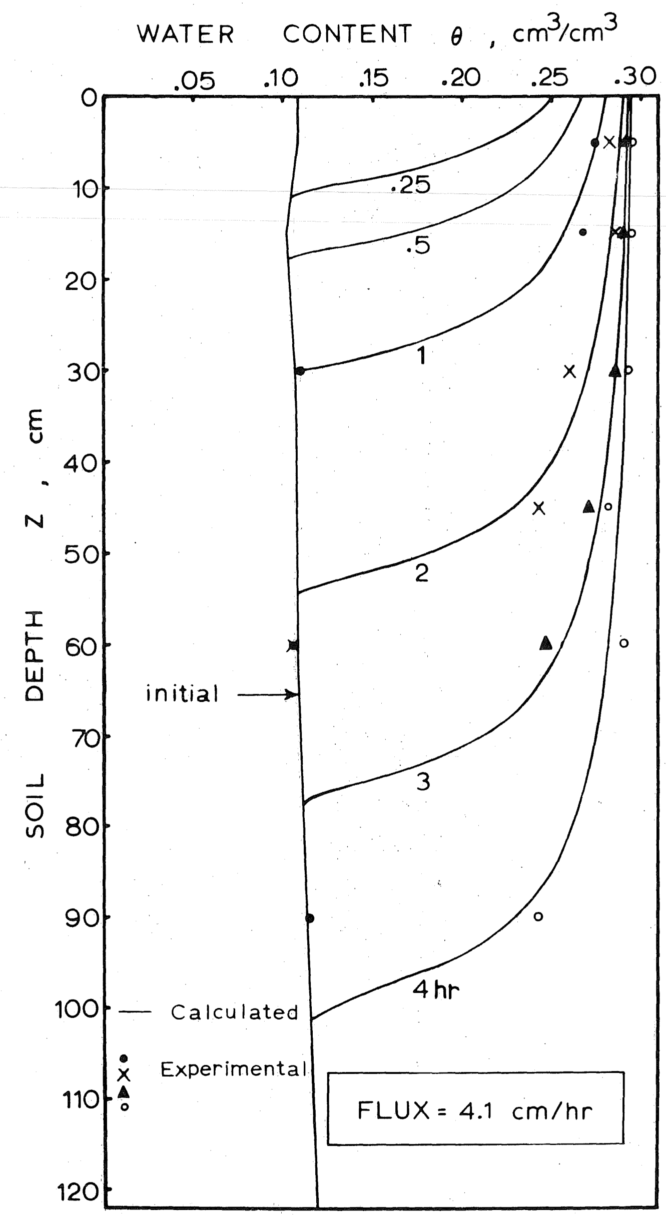


Figure 16. Experimental and calculated soil water profiles in Lakeland fine sand near Quincy, Florida during water infiltration with 4.10 cm/hr flux.

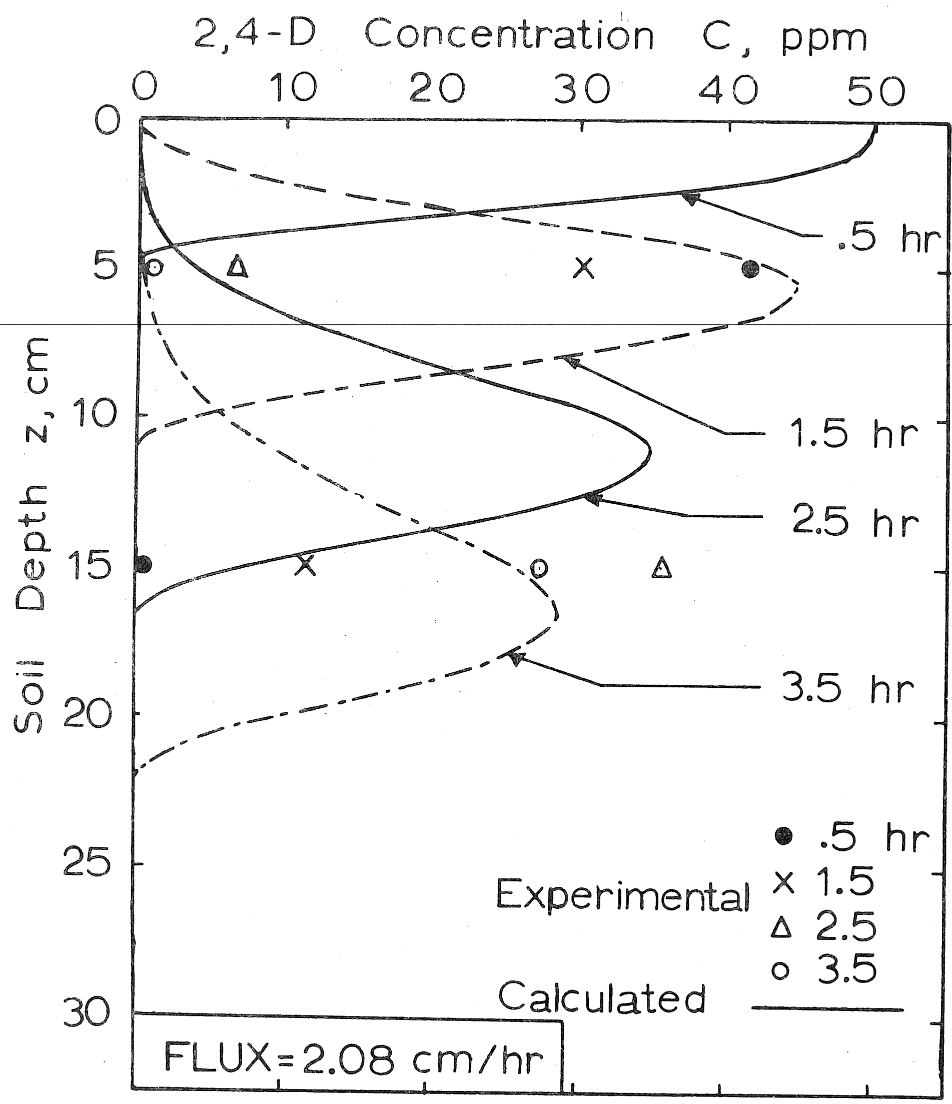


Figure 17. Distributions of 2,4-D in the solution phase of the soil profile of Lakeland fine sand near Quincy, Florida during water infiltration with 2.08 cm/hr flux.

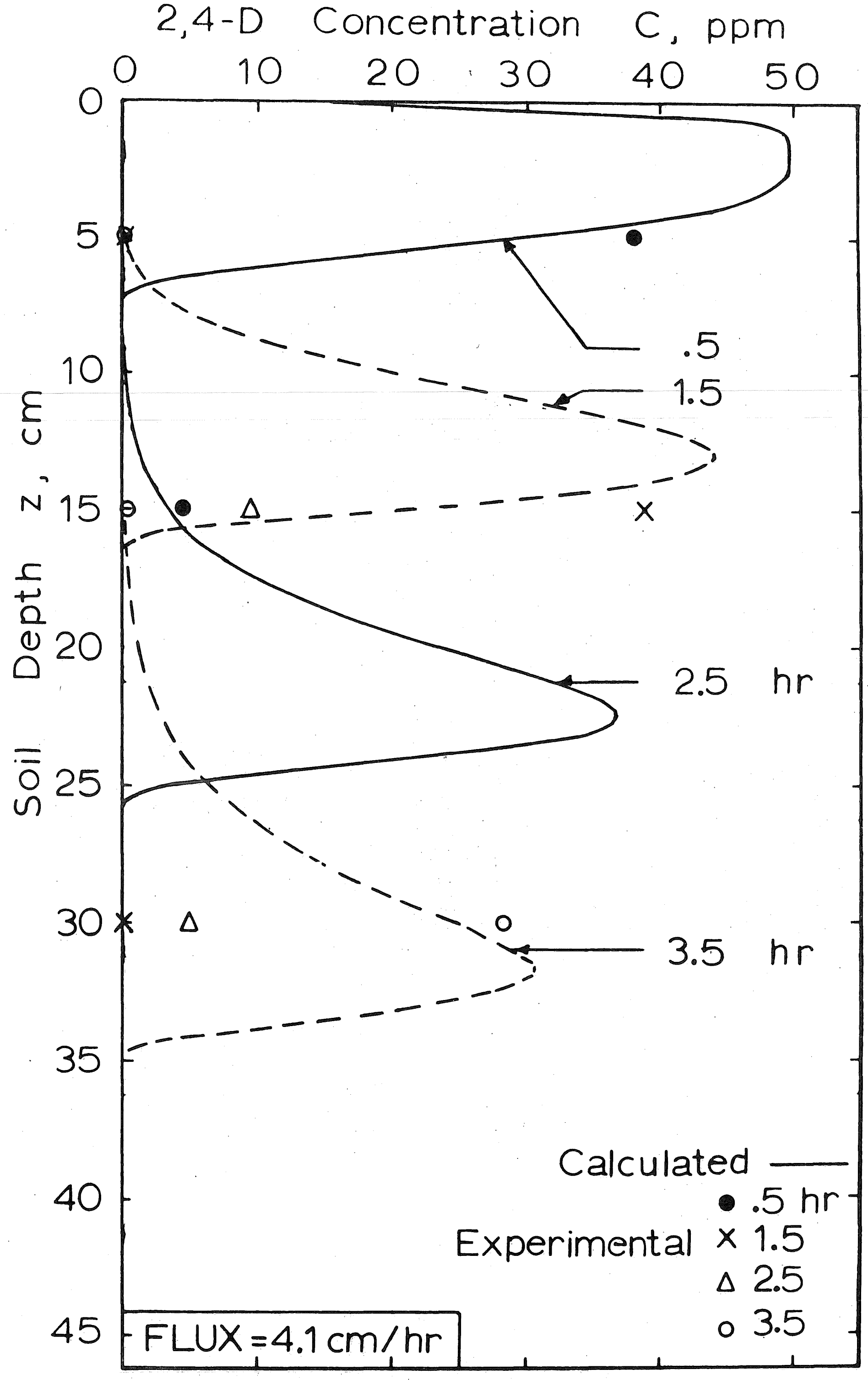


Figure 18. Distributions of 2,4-D in the solution phase of the soil profile of Lakeland fine sand near Quincy, Florida during water infiltration with 4.10 cm/hr flux.

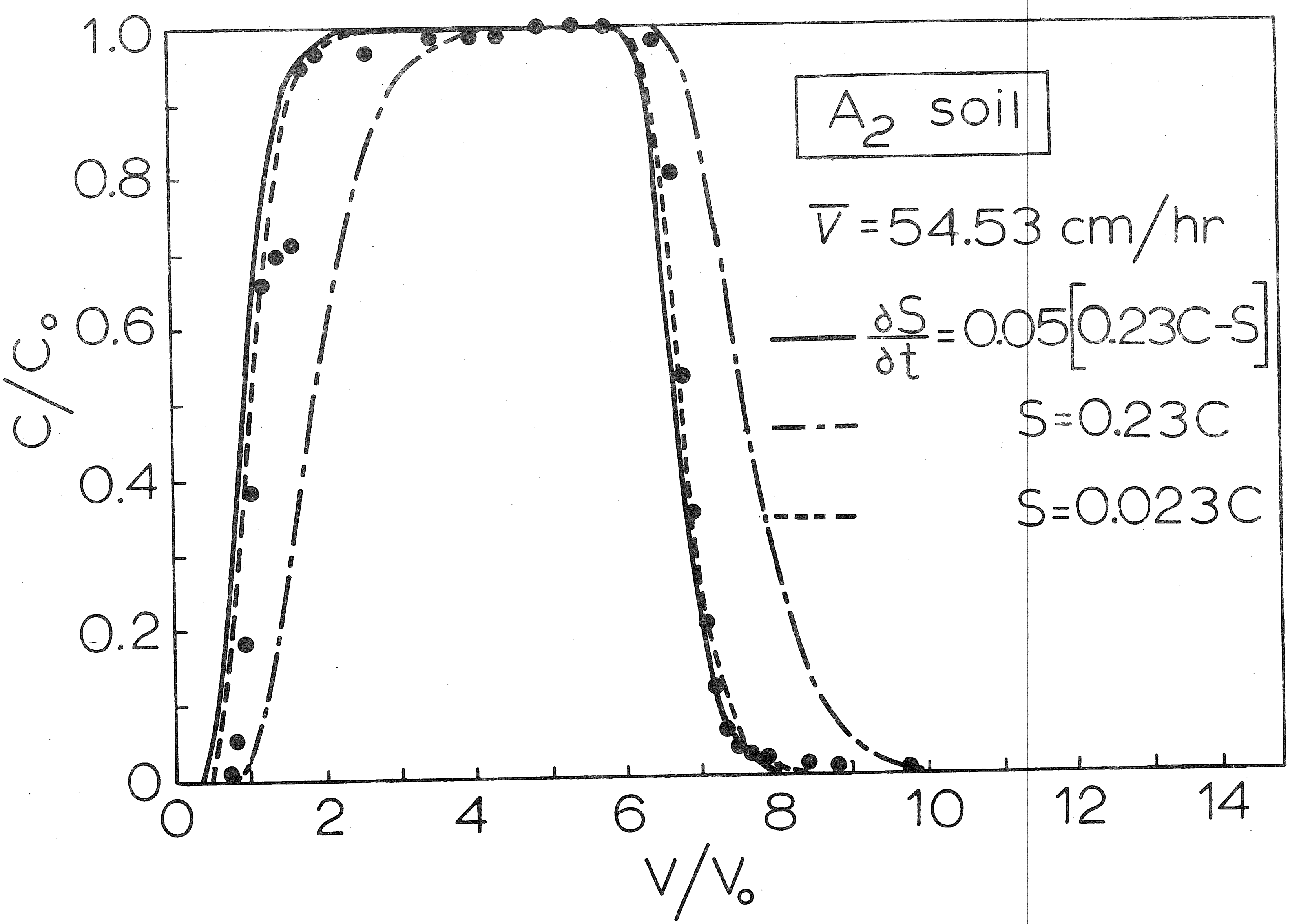


Figure 19. Experimental and predicted phosphorus breakthrough curves for a water-unsaturated core of subsurface ($A_2$) Oldsmar soil.

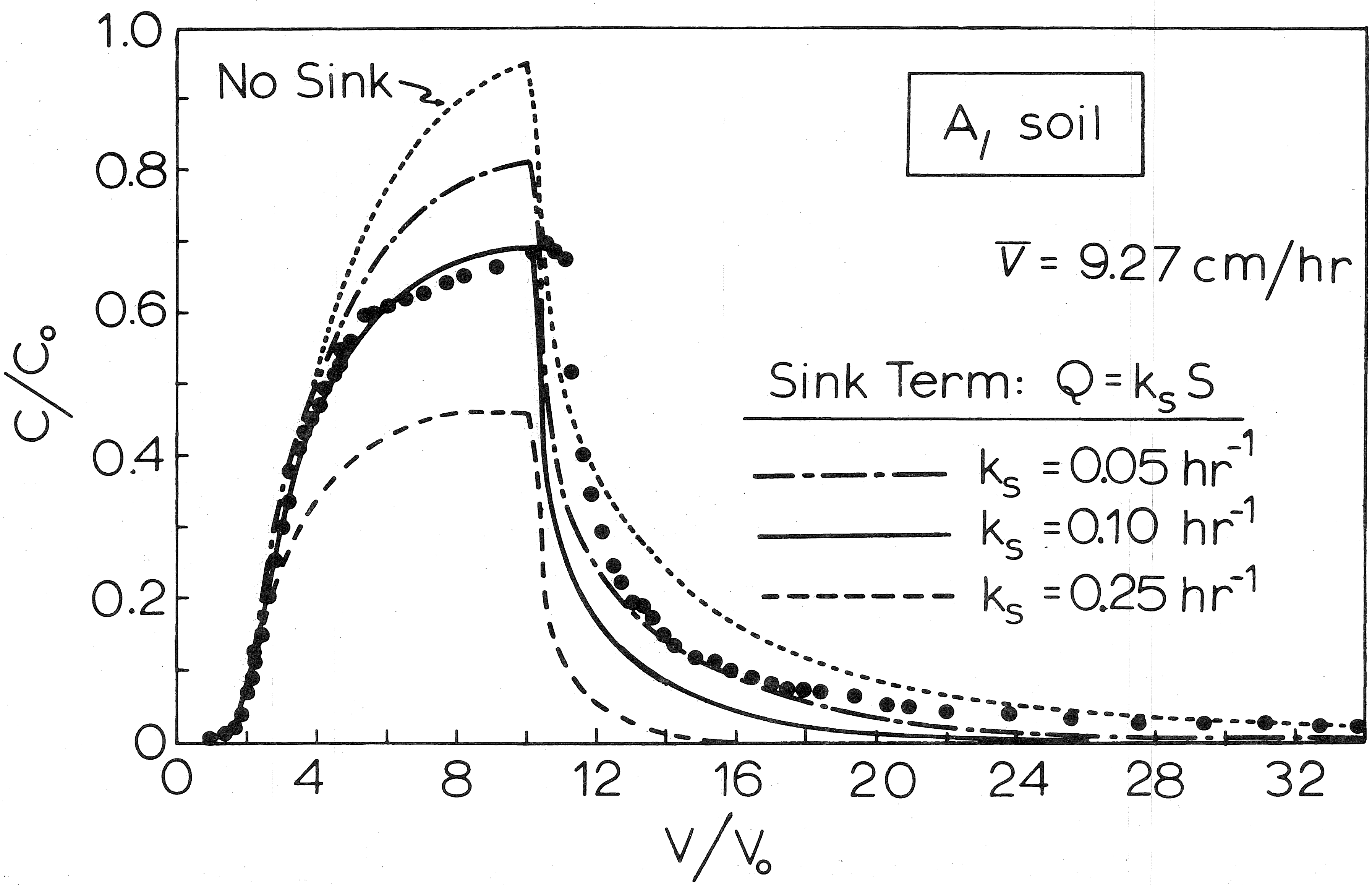


Figure 20. Predicted phosphorus breakthrough curves with and without a sink term for irreversible immobilization of adsorbed P during transport through a wa -unsaturated core of surface ($A_1$) Oldsmar soil.

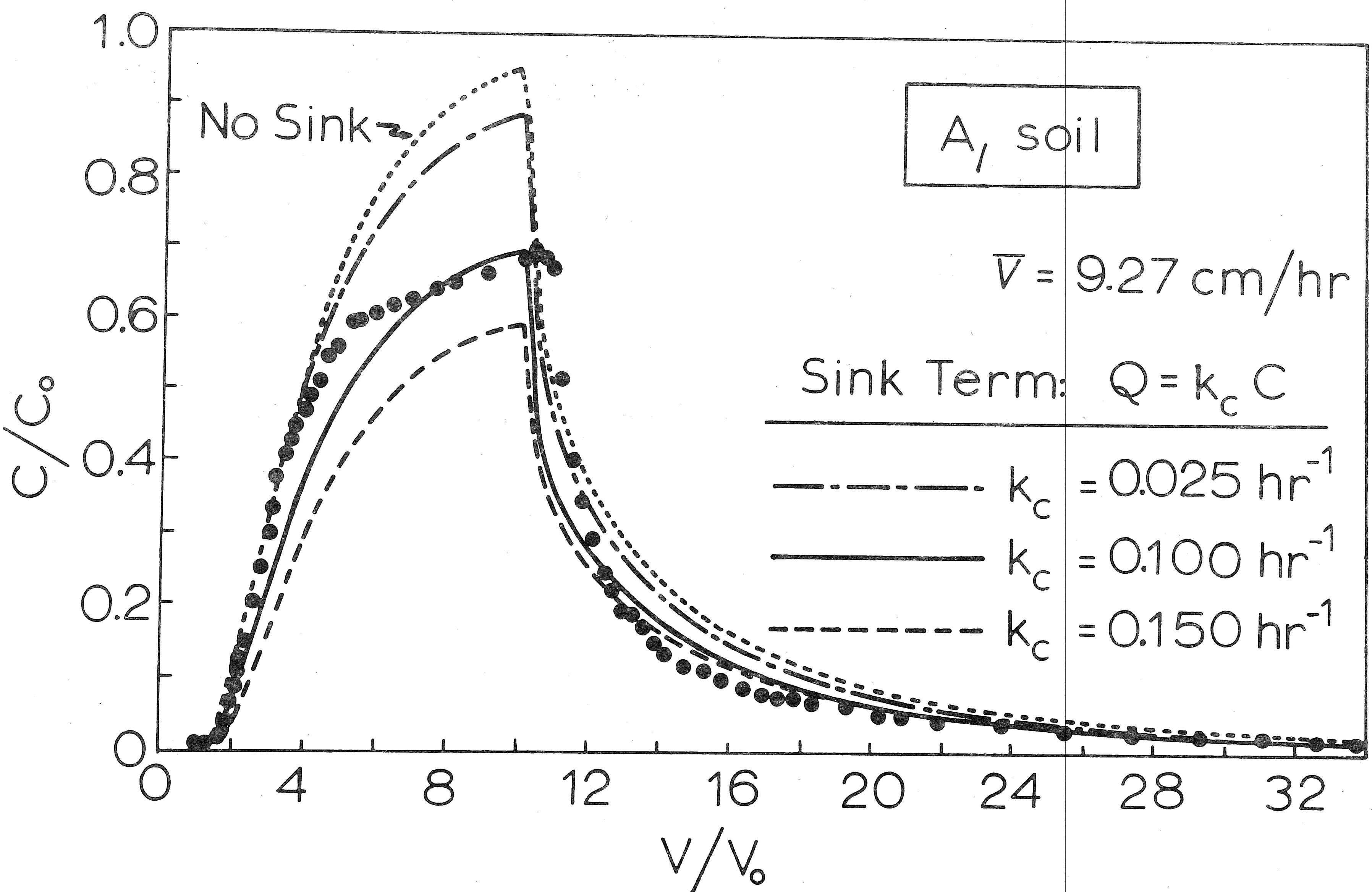


Figure 21. Predicted phosphorus breakthrough curves with and without a sink term for irreversible precipitation of soluble P during transport through a water-unsaturated core of surface ($A_1$) Oldsmar soil.

## CHAPTER 5: Summary and Conclusions

Sandy agricultural soils of Florida are typically limited in their capacities to retain irrigation water and applied chemicals such as fertilizers and herbicides. Therefore in order to economically grow optimum yields of crops on these soils under the humid climate of Florida, frequent applications of fertilizer is often required to compensate for leaching losses of nutrients from the "rooting zone" of the soil profile. Since these soils also have limited capacity to store infiltrated water during periods of redistribution, irrigation is also required during extended periods of infrequent rainfall. The simultaneous transport of nutrients and water through these sandy soils is therefore of utmost importance to the efficient use of both fertilizers and irrigation water for agricultural production of food. For example, leaching of nutrients from the soil tends to decrease the efficient use of fertilizers, whereas uptake of nutrients by plant roots tends to increase the use efficiency. Not only is the leaching of nutrients detrimental to food production but leached nutrients that move with the soil solution into underlying groundwater also pose a potential problem for environmental pollution. Results from this research indicate that irrigation and fertilizer management of corn growing on sandy soils in a humid climate mutually effect the individual use efficiencies for applied water and nutrients.

Field experiments of irrigated and fertilized corn were established on two representative Florida soils: Wauchula sand, a Spodosol, and Troup sand, an Ultisol. The Wauchula sand was characterized by relatively slow rates of natural internal drainage due to the presence of subsurface horizons of slowly-permeable material in the soil profile and due to relatively flat terrain. By contrast, the Troup sand was characterized by a relatively uniform profile of sand which transmits soil water rapidly downward. Beneath 150 cm depth, however, the Troup sand was underlain by a slowly-permeable sandy clay material. Water tables were commonly observed in the Wauchula soil profile between depths ranging from 60 to 100 cm during the growing season for corn; whereas, water tables rarely existed in the Troup soil profile. Although the Troup soil profile was primarily composed of sand material to a 150 cm depth, a compacted plow layer occurred in the top 30 cm of soil which was observed to limit much of the plant root growth to the top 15 cm of the entire 150 cm profile. Soil water movement was not observed to be decreased by the presence of the plow layer.

Corn was grown under three irrigation treatments--no irrigation, daily irrigation (0.64 cm/day), and controlled irrigation (1.3 cm of water was applied when the soil water suction at 15 cm soil depth exceeded 100 cm of water) and two fertilizer application treatments--conventional (bulk of fertilizer applied prior to planting of corn and nitrogen fertilizer applied later as a sidedressing) and programmed (fertilizer applied in several split applications). Without irrigation, grain yields of corn were approximately twice as great for either fertilizer treatment in the Wauchula sand as compared to those in the Troup sand. The larger yields were attributed to the larger water contents and less leaching of fertilizer nutrients that occurred in the Wauchula soil profile as compared to the Troup soil during the growing season. For both soils with corn grown at either irrigation treatment, grain yields for corn fertilized in a programmed manner were higher than yields where fertilizer was applied conventionally. Water use efficiency (net grain yield divided by amount of irrigation water applied) was only slightly altered by changing the method of fertilization for corn growing in the Wauchula soil; however, for corn growing in Troup sand irrigation water was used much more efficiently by applying the fertilizer in a programmed manner. The differences in water use efficiencies for corn on the two soils were attributed to the greater magnitude of nutrient leaching observed in the Wauchula sand relative to that in the Troup sand. Water use efficiency for corn growing in both soils was greater for controlled irrigation than for daily irrigation. In the Troup soil highest grain yields and water use efficiencies were observed for corn fertilized in a programmed manner and irrigated in a controlled fashion. Daily irrigation apparently resulted in excessive leaching of both nutrients and irrigation water in the Troup sand. Thus corn growing in both soils used irrigation water and fertilizer nutrients more efficiently for programmed versus conventional fertilization and more efficiently for controlled versus daily irrigation.

Several mathematical models were developed and used to describe the simultaneous transport of water and applied agrichemicals (fertilizer nutrients and herbicides) to sandy soils. A transport model for water alone was successfully verified with experimental results from laboratory and field experiments for periods of infiltration and redistribution. This model is flexible and can be adjusted to incorporate a variety of initial and boundary conditions for a range of soil types. Nutrient (phosphorus and potassium) and herbicide (2,4-D) models were also developed and used to describe chemical-physical interactions and movement of these reactive solutes through soil. Simulated and limited experimental results associated with these models indicate that mechanisms such as physical adsorption-desorption, chemical precipitation, and immobilization or fixation have a large influence upon the transport of potassium and phosphorus, even in sandy soils. Further experimental validation of possible interactions of these agricultural chemicals during movement with water through soil is needed in order to precisely predict the leaching loss of agrichemicals applied to sandy soils of humid climates.

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APPENDIX: Titles and abstracts of published papers resulting from this research.

1. Saxena, G. K., R. S. Mansell, and C. C. Hortenstine. 1975. Drainage of vertical columns of Lakeland sand. Soil Sci. 120:1-12.

   A drainage experiment was conducted to determine the time-dependence of soil-water retention during drainage of a quasi-uniform column of Lakeland sand and similar columns to which phosphatic clay was added as an amendment or a layer. Phosphatic clay was observed to increase and prolong water retention in the soil. Saturated hydraulic conductivity of the column with soil amended with 5 percent phosphatic clay in the surface 30 cm was 13 cm/hr as compared to 25 cm/hr for the quasi-uniform column of Lakeland sand. Drainage from the column with a 1-cm-thick layer of phosphatic clay and the column with a 2-cm-thick layer of phosphatic clay aggregates was greatly restricted. The non-aggregated phosphatic clay layer provided nearly constant impedence to flow across the layer, whereas successive water desaturation of the larger pores in the layer aggregates resulted in a time-dependent impedence to water flow. At saturation the hydraulic conductivities of the aggregated and nonaggregated clay layers were calculated to be 5.0 and 0.8 cm/hr, respectively. Maximum hydraulic head gradients across the aggregated and nonaggregated clay layers were 4 and 13, respectively. Values of unsaturated hydraulic conductivity calculated from soil-water characteristic curves for the Lakeland sand and measured water-saturated hydraulic conductivity were in good agreement with values measured experimentally from the soil columns.

2. Elzeftawy, Atef and R. S. Mansell. 1975. Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand. Soil Sci. Soc. Amer. Proc. 39:599-603.

   Using a method employed by Green and Corey (1971), hydraulic conductivity was calculated as a function of water content for Lakeland fine sand. A gamma ray transmission method for measuring soil water content and a tensiometer-pressure transducer arrangement for measuring soil water suction were also used to experimentally determine values of hydraulic conductivity for a similar range of soil water contents in undisturbed soil cores and hand-packed soil columns. Measured and calculated values were in good agreement for steady flow.

   During transient flow soil water content was observed to be a non-unique function of suction for water desorption, but depended upon the state of flow. Higher water contents were found at a given pressure head during unsteady flow than during steady flow or static equilibrium (zero flow). Graphs of water content versus soil water suction were similar for cases of steady and no-flow conditions. For transient flow, the soil water pressure depended upon the soil-water content and rate of change of pressure head with time.

3. Mansell, R. S., L. W. Zelazny, L. C. Hammond, and H. M. Selim. 1975. Nutrient distributions in a Spodosol during corn growth. Soil and Crop Sci. Soc. Florida Proc. 34:24-29.

   Distributions of K, P, $NH_4$-N, and $NO_3$-N in a tile-drained Wauchula sand (Spodosol) were determined under corn cultivation in the spring of 1974. Grain yields of 6,346 and 7,907 kg/ha were obtained from plots receiving 567 and 9,070 kg/ha of limestone, respectively. Nutrient distributions in the soil solution phase were used to describe nutrient movement with time in the soil profile. Movement of $NO_3$-N, $NH_4$-N, K, and Cl proceeded downward in the profile during the first 43 days. However, for times greater than 43 days downward movement of these nutrients did not exceed 50-70 cm depth. Restricted downward transport of nutrients was attributed to the presence of a slowly-permeable $B_{2t}$ horizon located 75 cm from the soil surface.

4. Selim, H. M. 1975. Water flow through a multilayer stratified hillside. Water Resources Research 11:949-957.

The objective of this study is to present a mathematical analysis for steady state saturated flow through multilayer stratified hillsides of semi-infinite depth. Two soil surface shapes were considered: a constant soil surface slope and a surface of arbitrary shape. Potential and stream functions were obtained for one-, two-, and three-layered hillsides. The method of solution was based on the Gram-Schmidt orthonormalization method. For two-layered hillsides the hydraulic conductivities were $K_1:K_2 = 1:10$ and 10:1. For three-layered hillsides the hydraulic conductivities were $K_1:K_2:K_3 = 1:10:1$ and 10:1:10. Flow nets, seepage velocities, and flow rates are presented. These results are useful particularly with regard to subsurface flow, runoff, erosion, and solute movement through sloping soils.

5. Selim, H. M. and R. S. Mansell. 1976. Analytical solution of the equation for transport of reactive solutes through soils. Water Resources Research 12:528-532.

Mathematical solutions of the differential equation governing reactive solute transport in a finite soil column were developed for two specific cases: continuous solute input and pulse-type solute input at the soil surface. These solutions incorporate reversible linear adsorption as well as irreversible solute adsorption. The irreversible adsorption was expressed by a sink/source term which either may be a constant or may have a concentration-dependent form. The boundary condition used across the surface (X = 0) was that of the third type, which accounts for advection as well as dispersion. To illustrate the significance of using the proper boundary conditions, comparisons were made with two other mathematical solutions, one by Cleary and Adrian (1973) and another by Lindstrom et al. (1967). We conclude that the solution presented here is highly recommended for low flow velocities or specifically for $\nu_0 L/D_s$ values less than 20. For large pore velocities, or specifically for $\nu_0 L/D_s > 20$, all three solutions are in agreement.

6. Selim, H. M., R. S. Mansell, and Atef Elzeftawy. 1976. Distributions of 2,4-D and water in soil during infiltration and redistribution. Soil Sci. 121:176-183.

A numerical model was developed to predict transient water and reactive solute transport in water-unsaturated soil. An implicit-explicit method of finite difference approximation was used to simultaneously solve the water and solute flow equations. The model was used to calculate transport of water and 2,4-D (2,4-Dichlorophenoxyacetic acid) in a field profile of Lakeland fine sand during infiltration at constant intensities (2.08 and 4.10 cm/hr). Calculated values of the soil-water distributions compared well to experimental determinations, but agreement obtained between 2,4-D distributions was only adequate. Simulated results were also obtained to study the effect of irrigation intensity on water and herbicide transport during redistribution following irrigation. It was found that for advanced stages of redistribution solute movement became negligible and the maximum herbicide concentration was located at the same depth in the soil profile regardless of irrigation intensity.

7. Selim, H. M., R. S. Mansell, and L. W. Zelazny. 1976. Modeling reactions and transport of potassium in soils. Soil Sci. 22:77-84.

A mathematical model was developed to describe potassium reactions and transport in soils. Kinetic reactions were assumed to govern the transformation between solution, exchangeable, nonexchangeable (secondary minerals), and primary mineral phases of potassium. Simulated results were presented for two soils, a weakly sorbing soil and a strongly sorbing soil. The effect of kinetic rate coefficients upon transport and transformation of applied potassium was also investigated. The model is flexible and can be adapted to incorporate various transformation mechanisms between the different phases of potassium. Model validation with the aid of experimental data is needed to further describe the fate of potassium in soil.

8. Elzeftawy, Atef, R. S. Mansell, and H. M. Selim. 1976. Distributions of water and herbicide in Lakeland sand during initial stages of infiltration. Soil Sci. (accepted for publication).

Penetration depths and concentration distributions were determined in columns of Lakeland sand for surface-applied 2,4-D herbicide during initial stages of steady water infiltration. Water was applied with application rates, R, of 2 and 4 cm/hr to soil with initial water contents, $\theta_i$, of 0.20, 0.11 and 0.01 $cm^3/cm^3$. Increasing R resulted in faster rates of advance for both the water wetting fronts and the depths of 2,4-D peaks. Larger values of $\theta_i$, however, increased the rate of advance for the wetting front but did not affect the location for 2,4-D peaks. Penetration of 2,4-D peaks per unit of water applied to the soil was observed to be independent of both R and $\theta_i$ during initial stages of water infiltration. Distributions of 2,4-D concentration as calculated from water and solute transport equations were observed to lag slightly behind experimentally measured distributions.

9. Mansell, R. S., H. M. Selim, and J. G. A. Fiskell. 1976. Simulated transformations and transport of phosphorus in soil. Soil Sci. (accepted for publication).

A mechanistic, multistep model was developed using chemical kinetics and mass transport theory to describe transformations and movement of orthophosphate in soil. Soil phosphorus was assumed to occur simultaneously in any of four primary phases: water-soluble, physically adsorbed, immobilized, and precipitated. Kinetic reactions which control the transformation of phosphorus between any two of the four phases were considered to be reversible and of $N^{th}$ order. A range of values for the reaction rate coefficients were used in the model to describe the transport of applied phosphorus in the solution phase of the soil profile.

10. Mansell, R. S., H. M. Selim, P. Kanchanasut, J. M. Davidson, and J. G. ~~A. Fiskell. 1976. Experimental and simulated transport of phosphorus~~ through sandy soils. Water Resources Research (accepted for publication).

Reversible equilibrium adsorption-desorption relationships were inadequate for describing the transport of orthophosphate through water-saturated and unsaturated cores from surface ($A_1$) and subsurface ($A_2$) horizons of Oldsmar fine sand (a Spodosol). Using a kinetic model with nonlinear reversible adsorption-desorption improved descriptions of phosphorus transport through these soils. Phosphorus effluent concentrations were described best using an irreversible sink for chemical immobilization or precipitation with a nonlinear reversible, kinetic adsorption-desorption equation.

11. Selim, H. M. and R. S. Mansell. 1974. Transient one-dimensional and simultaneous solute and water flow in soils. Program No. 360 D-17.4.003, SHARE Program Library Agency, Triangle Universities Computation Center, Research Triangle Park, North Carolina.

A computer program has been developed for the problem of solute and water movement in unsaturated soils or porous media under transient flow conditions. The two nonlinear partial differential equations governing the solute and water flow are solved simultaneously for the water content and solute concentration at any specified time and location as desired. The initial conditions used are uniform salt and water content distributions at time t=0. The boundary conditions at the soil surface are water flux and constant salt concentration conditions. The method of solution is a numerical one which utilizes the explicit-implicit finite difference technique.

The computer program is written in FORTRAN language and consists of a source program, eleven subprograms, and an input data section. An important feature of the program is that incremental distance and time steps are adjusted automatically to satisfy stability and convergence criteria for the water and solute finite difference criteria. A second feature is that the number of nodal points are automatically calculated from the length of the flow region. A third feature of the program is that output data of water content, water flux, solute concentration, and solute flux in the flow region are provided at specified times as desired.

12. Elzeftawy, Atef A. 1974. Water and solute transport in Lakeland fine sand. Ph.D. Dissertation, Soil Science Department, University of Florida, Gainesville.

The objective of this study was to investigate effects of three water supply rates--2, 4, and 8 cm/hr -- and three initial soil water contents -- 1.2, 10.9, and 20.2% by volume -- upon the simultaneous transport of water and solutes -- 2,4-D herbicide and chloride -- in vertical columns of Lakeland fine sand. Columns were prepared by packing air-dry soil into cylinders 7.6 cm diameter and 107 cm long. A specific volume of aqueous solution containing 57.9 ppm chloride and 5 ppm 2,4-D was introduced and displaced through each column. Gamma-ray attenuation and pressure-transducer-tensiometers were used to precisely monitor soil-water content and pressure distributions with time. Soil solution was extracted at selected depth intervals along the soil columns and extracted samples were then analyzed for 2,4-D and chloride content.

Depths to which chloride and 2,4-D moved for a given quantity of water infiltrated into the surface of the soil was found to depend upon the surface water flux. Increasing water application rates resulted in an increased water content in surface soil and in shallower displacement of chloride and 2,4-D for equal quantities of accumulative infiltration. For a given quantity of water infiltrated, initial soil-water content did not influence depths of chloride or 2,4-D transport. Adsorption, caused 2,4-D distributions to lag behind those for chloride for all experiments.