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9. ABSTRACT Summarizes a field experiment to study the feasibility and operational techniques of drip irrigation and fertilization in tropical acid soils. Laboratory studies of profile water movement from line source were conducted using one clayey Oxisol and one sandy Oxisol. Functional relationships between water application rates and vertical/horizontal advances were established. P distribution was also examined. High P concentration was observed in the vicinity of the water source in both soils under various water application rates. A drip irrigation system was designed based on the laboratory results. For the field experiment, a randomized complete block design was chosen to compare there different fertilization techniques. All treatments but the control plot received the same total amount of fertilizer and the whole experimental area was uniformly drip irrigated. The three fertilization techniques included: fertigation (drip application of N and K, banded P); banded N, P, and K; and broadcast N, P, and K. The fertigation treatment and the banded fertilizer treatment produced the highest yield. The drip method of irrigation is feasible and may be profitable for certain crops in the tropics. However, detailed studies on drip discharge rates and irrigation and fertilizer schedules are needed in order to modify and standardize the drip system operations.

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Water and Nutrient Management With Drip Irrigation

in

Highly Weathered Soils of the Tropics.

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment for the Degree of

Doctor of Philosophy

by

John Ching-Win Keng

January, 1978

ABSTRACT

Water and Nutrient Management With Drip Irrigation

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John Ching-Win Keng, Ph.D.

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Laboratory studies of profile water movement from line source were conducted using one clayey Oxisol and one sandy Oxisol. Functional relationships between water application rates and vertical/horizontal advances were established. In both finer and coarser textured soils, the horizontal advance tended to approach to a limit with prolonged time, while a linear relationship was found between the vertical advance and the square root of time. Higher application rates resulted in further lateral water movement and shallower downward movement.

P distribution, together with water movement, was also examined in the laboratory in both sandy and clayey soils. High P concentration tion was observed in the vicinity of the water source in both soils under various water application rates. P moved as far as 30 cm from the application point in the sandy soil profile, but no significant P movement was noticed in the clayey Oxisol.

Based on the laboratory results, a drip irrigation system was designed for the field experiment to study the feasibility and operational techniques of drip irrigation and fertilization in a tropical acid soils (Coto Clay) area. Sweet pepper (Blanco de Pais variety)

was the test crop. A randomized complete block field experimental design was chosen to compare three different fertilization techniques. In addition to the check plot, the three other treatments were: fertigation (drip application of N and K, banded P); banded N, P, and K; and broadcast N, P, and K. All treatments but the control plot received the same total amount of fertilizer and the whole experimental area was uniformly drip irrigated. The fertigation treatment and the banded fertilizer treatment resulted in the highest yield, and therefore, are considered more desirable.

The drip method recommended in the this thesis is a technique developed under a genuine tropical environment. Generally speaking, the drip method is feasible and may be profitable for certain crops in the tropics. However, results of the root system development, and fertilizer distribution under field conditions suggested that detailed studies on drip discharge rates and irrigation and fertilizer schedules are needed in order to modify and standardize the drip system operations.

BIOGRAPHICAL SKETCH

John Ching-Win Keng was born on November 29, 1946 in Shantung Province, China. He and his family migrated to Taiwan in May, 1950 and lived there until June, 1971. From 1965 to 1969, he was enrolled in National Chung-Hsing University, Taichung, Taiwan and received the B. S. degree in Soil and Water Conservation. He served in the Army Engineering Corps of R.O.C. during July, 1969 to June, 1970 as a Second Lieutenant.

In June, 1971 he was granted an East-West Center scholarship to study soil science at the University of Hawaii, Honolulu, Hawaii, U.S.A. He completed his M.S. degree at the University of Hawaii in May, 1974 with a thesis on surface chemistry of soil colloids.

In the autumn and winter of 1973, he conducted a field study at the University of California, Davis campus and Cornell University. During the four month travel and study period, his interests in soil physical properties and water management developed. In January, 1974 he was accepted into the Graduate School at Cornell University to pursue the Ph.D. degree with a major in Soil Science and minors in Soil and Water Engineering and Geotechnical Engineering. The purpose was to utilize soil physical knowledge as it relates to engineering problems. He conducted his Ph.D. thesis research in Puerto Rico during March, 1976 to July, 1977 in the area of soil-water-nutrient management with drip irrigation.

The author was a member of α-β-γ Honor Society of Agriculture, Hawaii Chapter, in 1972-1973. He has been a member of the American Society of Agronomy and the Soil Science Society of American since 1972.

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CHAPTER ONE: INTRODUCTION

I-1 The Progress of Drip Irrigation

Drip (Trickle) irrigation is a relatively recent technique in which water and/or fertilizers are directly applied to the plant's root zone at a high frequency. It is based on the concept that optimum plant performance may be realized through preventing moisture stress by maintaining favorable soil moisture conditions in the root zone. Because of the low operational pressure (usually 30 psi or less) and slow discharge rate, drip irrigation does not need high energy inputs and losses from surface runoff is negligible and surface evaporation is reduced.

Therefore, irrigation efficiency could be as high as 90% or above. A recent world wide drip irrigation survey shows that, at the present time, about 71,000 acres are irrigated by this method outside the U.S. It is estimated that by 1980 the total area under drip irrigation will be expanded to 9[illegible],000 acres. In the United States, approximately 72,000 acres are now under drip irrigation and it is estimated that by 1980 the total will expand to 217,000 acres (Gustafson, 1974). There are two dozen or more systems that are commercially available in the U.S. today (Davis, 1970).

Previous research indicated that drip irrigation has a number of potential advantages in addition to more efficiency water use. Depending on the crop, soil conditions and type of system, there should be a reduction in labor, less erosion on sloping lands, higher yields with saline water, dry soil surface between rows, easing of field operations, reduction of weed growth, more efficient application of plant nutrients through irrigation water and elimination of ground water pollution.

The accumulation of knowledge and experience with the drip irrigation techniques has led scientists and growers to some more exciting thinking. With appropriate understanding of the soil properties and soil moisture movement pattern, the exact amount of chemicals, such as herbicides and nematocides, may be added through a drip system at a desired time to modify the ecology of the root zone. This implies that drip techniques may not only be used as an irrigation and fertilization process but also be used for plant protection, weed control and other soil disinfection purposes Uzard, (1974). It is safe to assume that the dawn of a new epic of agricultural technology is in sight by using drip irrigation techniques.

I-2 Potential of Drip Irrigation in Agricultural Development in the Tropics

To a large extent, Ultisols and Oxisols and closely related soils predominate in the potentially arable areas of the tropics not yet under cultivation. These are high in sesquioxides and kaolinite and related clay minerals. Characteristically, Oxisols have low cation exchange capacities, and low nutrient holding powers. The usually high rainfall intensities prevailing during the wet season in most tropical areas demand special management of plant nutrients for intensive production of most food crops.

With repsect to the hydraulic properties of Oxisols of Puerto Rico, Wolf and Drosdoff, (1974) reported relatively high permeability and low available water holding capacities. Wolf, (1975) and Fruntel, (1975) reported similar findings for several Oxisols in Central Brazil. Periodic drought can occur even during the rainy season requiring supplemental

irrigation in most areas of the tropics for stable crop production.

The water-nutrient management problem may be studied jointly by using drip irrigation. Woudt, (1968) pointed to the potential importance of drip irrigation techniques in food production in the tropics. However, work on the application of drip irrigation in tropical areas, especially on Oxisols, has been scant. There is no information in the literature with respect to combined water and nutrient management on Oxisols using drip techniques.

The following are considered to be advantages of drip irrigation, particularly in Oxisols:

1. With drip irrigation, it is no longer required for the soil to serve as a "reservoir" for water and/or plant nutrients. The depleted water or fertilizer could be recharged in the root zone almost continuously. In other words, the soil has been reduced in importance as a factor in holding the water or nutrients between irrigations or fertilizations. Thus, soil with poor available water holding ability and low cation exchange capacity have a potential for being highly productive, if the factors are conducive to crop growth. Since drip irrigation encourages root development in the surface soil, (Goldberg, 1971) it may also be advantageous on many Oxisols where crop rooting in the subsoil is restricted by Al toxicity.

2. In the wet-dry tropics, such as tropical America, where dry season water supplies are usually limited, drip irrigation may permit the largest expansion of the acreage under irrigation.

3. Drip irrigation shortens the growing season of many crops. Thus, this type of system may be particularly advantageous in the tropics increasing the potential for two or three crops per year.

4. Keeping a concentrated fertilizer band continuously moist with drip irrigation or applying soluble fertilizer in very small amounts with each irrigation may minimize leaching losses and maximize efficiency of applied nutrients. During the wet season, the drip system could be utilized as a fertilization device. All fertilizers can be applied to the soil as a mixed solution. This conveys an improved method of nutrient management for both dry and wet seasons achieved by installing a single drip system.

5. With respect to socio-economic factors, drip irrigation systems fit better in intensively cultivated farms and/or plantations which are free from freezing throughout the year. The system is rather simple and can be fully automated. Therefore, only low energy and low labor inputs are required. Since most of the drip irrigation components can be made from plastics, no major difficulties are expected in the manufacturing of such materials with the present level of technology in most tropical countries. This implies that the cost of drip irrigation materials could be reduced by locally manufactured components.

Despite these promising features of drip irrigation, problems will undoubtedly need to be solved when introducing this technique into the tropics. Much of the research information and experience with drip irrigation have been developed in temperate regions. Directly transferable information is not available. Application of current knowledge and technology should be preceeded by careful study, testing and perhaps modification before it can be successfully employed in a tropical environment.

I-3 Special Knowledge Needed in Oxisol Under Drip Irrigation

The basic idea of drip irrigation is to manage the soil water regime in the root zone for the most economical use of water and fertilizers. Therefore, the moisture pattern under emitter or drip tubing becomes the most critical factor that affects irrigation efficiency, oxygen deficiency and possible salt accumulations.

Climatological conditions and soil properties are factors which dominate water movement through the soil profile. These factors are very difficult, if not impossible, to modify. The discharging rate and irrigation frequency are adjustable factors which could affect the moisture movement pattern. Therefore, one of the basic needs for drip irrigation design and management in each particular soil type is to obtain the functional relation of the moisture pattern versus the water discharge rate.

When considering the chemical properties of Oxisols, many of the phenomenon between the reversible charged mineral surface and the various ions in the bulk solution have remained unknown. For intensive production of most crops on Oxisols, special management of certain plant nutrients may be required. Together with the fact that root systems develop only in the moisture zone under drip irrigation, fertilizers should be placed or applied to take advantage of soil water movement and root distribution in this zone.

Woudt, (1968) has pointed out the potential importance of drip irrigation techniques to food production in the tropics. Sanchez et al (1975) concluded that phosphorus fixation is the foremost soil fertility problem in Oxisols. The water-phosphorus problem may be studied jointly by using drip irrigation. However, very little work has been done toward this direction.

There is no information in the literature with respect to combined water and phosphorus management on Oxisols using drip techniques.

I-4 Objectives

This thesis presents the research and results of laboratory and field studies across the subject matter areas of soil hydraulic properties, moisture and nutrient movement patterns, drip irrigation design and field agronomic practices. All field and laboratory research was conducted during an eighteen-month period in Puerto Rico.

The first objective of this thesis was to determine the P distribution patterns in Oxisols and the functional relationships of moisture movement patterns under different water discharge rates. The results from this study would then be applied to drip irrigation design and management. It is expected that the information obtained could be extended to other Oxisols with similar soil hydraulic properties and natural conditons. The second objective was to develop a combined fertilization and irrigation field technique which would meet the requirements of simple operation, low energy input, low pollution hazard and economic feasibility for the emerging societies of tropical countries.

CHAPTER TWO: LITERATURE REVIEW

II-1 Soil-Water Movement from Line Source

Water enters into the soil from natural rainfall and/or sprinkler or flood irrigation in one dimension. Under drip irrigation, however, it enters either from a point source and then spreads in all directions or from line source and then moves both laterally and downwardly. This special feature of drip irrigation, i.e., a partially wetted soil volume, restricts root development to given boundaries and, therefore, limits total nutrient uptake. If liquid fertilizer should be injected into the drip system, the complexity of the problem increases and questions of fertilizer efficiency and/or dangers of chemical accumulation may arise.

Theoretical considerations and mathematical approaches to describe and predict drip infiltration are based on Darcy's flow equation and on an assumption of a homogeneous soil medium with uniform moisture distribution. A non-linear partial differential equation, the Fokker-Planck equation is usually used to describe the unsaturated, isothermal moisture flow in a porous medium.

Finite different solutions, aided with high speed computer, to this non-linear partial differential equation have been presented by Rubin (1968), Brandt et al (1971), Selim and Kirkham, (1973) and Amerman, (1976). Good agreement between laboratory and field experiment's data and Brandt's theoretical model have been reported by Bresler et al (1971). Van Der Ploeg and Benecke (1974) published a simplified computer solution which, according to them, provided acceptable accuracy when tested with existing analytical solutions. This solution is programmed with the computer program

System/360 Continuous System Program (CSMP). For one- and two-dimensional flow problems, with simple initial and boundary conditions, linearized analytical or quasi-analytical solutions have been investigated by Phillip, (1969, 1971); Raats (1970) and Lomen and Warrick, (1974).

The continuous infiltration model (Brandt et al, 1971 and Bresler et al, 1971) is the only theoretical model that has been tested so far using field data. The basic concept of the continuous infiltration model is briefly explained here with particular consideration of line source water application. The analytical solution will be used to check against water movement data obtained in the work reported in this thesis.

Let us assume that Darcy's law applied in both saturated and unsaturated zones, and that the soil is a stable, isotropic and homogeneous, semi-infinite body. Since infiltration involves only wetting, soil water content at any point in the system always will be increasing with time, and therefore, both water suction and the hydraulic conductivity of the soil are continuous fuctions of soil water content.

As observed under field conditions, a strip of ponded water develops in the vicinity of the porous tubing shortly after drip irrigation starts. The width of the strip increased with time but the rate of increasing (dX/dt) decreases as time continues. Water is able to infiltrate into the soil (ponded water infiltration) or evaporate into the air (evaporation from free water surface) only from the ponded water strip. Evaporation could become an important factor when the saturated hydraulic conductivity of the soil is very low and/or the evaporation rate is high. Clearly, the rate of water intake into the soil is equal to the tubing discharge rate minus the evaporation rate.

In an X-Y-Z rectangular Cartesian coordinate system, the porous tubing is placed at the origin (0,0) along the Y-axis, water flows both horizontally along the Z-axis and vertically downward in the Z-axis. The flow is assumed planar with respect to the Y-axis.

The flow equation in two dimensional forms is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[\kappa(\theta)\frac{\partial P}{\partial x}\right] + \frac{\partial}{\partial z}\left[\kappa(\theta)\frac{\partial H}{\partial z}\right] \quad \text{----------} \quad (1),$$

Where, θ is the volumetric moisture content, t is time, z is the vertical depth pointing downward, x is the horizontal distance normal to the tubing, P is the matric suction of the soil, H is the hydraulic head (the sum of gravitational and matric suction heads), and κ is the hydraulic conductivity which is a function of the soil wetness.

The water content (θ) at a specified time (t) and position (x,z) is governed by Eq. 1. The initial and boundary conditions for (x,z,t) are as follows:

1. $\theta(x,z,0) = \theta_{\cdot}(x,z)$ in W, when $t = 0$.

   $\theta_{\cdot}$ is the initial soil moisture content; W in the unit volume within the boundaries specified here.

2. $\frac{\partial \theta}{\partial z} = 0$ at $z = Z$, $0 \leq x \leq X$, $0 \leq t \leq T$.

   $\frac{\partial \theta}{\partial x} = 0$, at $x = 0$, $x = X$, $0 \leq z \leq Z$, $0 \leq t \leq T$

   where Z, X, are arbitrary horizontal distance and depth beyond the wetting front. T is the end time of infiltration.

3. $\theta = \theta_s$ in $0 \leq x \leq \phi(t)$, $z = 0$, $0 \leq t \leq T$

   $\phi(t)$ is the width of the ponded strip.

   $$\int_0^{\phi(t)} \left[\kappa_s \frac{\partial H}{\partial z}\right] dx = 1/2\, q(t) \quad \text{----------} \quad (2)$$

4. at $z = 0$, $0 \leq t \leq T$.

   Ks is saturated conductivity. q (t) is the water discharged per unit length of porous tubing.

By integrating Eq. 2 becomes

$$\kappa_s \sigma \phi(t) = 1/2\, q(t) \qquad \text{----------} \quad (3)$$

where $\sigma = (\overline{H\frac{\partial P}{\partial z}})_{Z=0}$ is the average surface pressure head across the ponded zone.

Rearranging eq. 3 $\phi(t) = (\frac{1}{2\sigma})(\frac{q}{\kappa s})$ ---------- (4)

From Eq. 4 it is clear that $\phi(t)$ is proportional to the discharging rate q, and inversely proportional to the saturated hydraulic conductivity K_s. $(\frac{\partial H}{\partial z})_{Z=0}$ is not a constant; however, the average of $(\overline{\frac{\partial H}{\partial Z}})_{Z=0}$ can be treated as a constant if the surface flux approaches constant.

II-2 Fertilizer Management

II-2-1 Fertigation

Fertilizer applied through the drip irrigation system has been used to some extent. It is generally considered as a much simpler and more efficient method than any other conventional fertilization practice. As mentioned before, by increasing the application frequency and reducing the amount of fertilizer, the nutrient can be applied to the soil with controlled quantities directly to the root zone at the proper time. Goldberg et al (1976) state: ".....scientists have adopted a policy of adhering to the existing practices with only minor change such as application of nitrogen through the system and studies on some fertilizers and their properties not to clog drippers. Their aim has been limited to finding means to adjust existing practices to Drip Irrigation concepts. This conservation attitude is totally wrong." As a mtter of fact, research on fertigation with drip systems has indicated that a complete range of fertilizer application with drip irrigation could be possible in both arid and humid regions' agriculture.

The Hawaiian Sugar Planters' Association investigated the fertilizer efficiency and the safe level of using aqua ammonia with drip irrigation (Isobe, 1974). Solutions of urea, phosphoric acid and potash were injected into the irrigation system to compare with traditional fertilization methods. Data from nutrient uptake and cane growth indicated that the slow method of feeding N and K was advantageous over conventional methods. However, monthly phosphoric acid injections did not improve P uptake nor the fresh cane weight. A simple equation was suggested for calculation of the safe level of aqua ammonia that may be used in the drip system without causing chemical precipitates. Grobbelaar and Lourens (1974), in their studies of fertilizer application with drip irrigation in South Africa, reported that application of urea, monoammonium phosphate and potassium nitrate in the drip system caused a high degree of emitter blockage. They explained that the high content of calcium and magnesium in the irrigation water could have reacted with the phosphate fertilizer and formed non-soluble calcium and magnesium phosphates. They suspected that organic matter in the irrigation water floculated by the potassium and settled in the emitter could also cause blockage. After lowering the pH of the fertilizer mixture to 2.0, sedimentation of solids in the drip system was eliminated. In a subsequent field experiment on fruit trees and vegetables using low pH fertilizer mixtures, they concluded that the drip fertigation method is not only feasible, but beneficial. The most interesting part of this study is that there was very little effect of this low pH nutrient solution on soil pH itself. After the application of 2,200 kg per hectare of 3:1:5 (41) on an uncropped area, the soil pH in the top 0-30 cm

layer hardly changed (from 3.98 to 3.96) and in the 30-60 cm layer (from 3.93 to 3.82).

Lindsey and New, (1974) studied the distribution of Zn and N in the field when applied together with drip irrigation. "Extremely variable distribution" was noticed when the fertilizer materials were added to the system by diverting part of the water flow through a fertilizer tank (see next section: the differential pressure system). However, an acceptable distribution pattern was obtained when injecting the fertilizer solution with a positive pressure pump.

II-2-2 Methods of Applying Fertilizer Through a Drip System

Various fertilizer application devices to be used in connection with drip irrigation are available in the market. Basically, they can be classified into three categories: 1) the differential pressure system; 2) the positive pressure system and 3) the negative pressure (or suction) system.

The differential pressure system is usually constructed by connecting a closed fertilizer tank parallel to the main water supply line. A pressure regulator is installed on the mainline between the inlet and outlet of the fertilizer tank. Part of the irrigation water is forced to pass through the fertilizer tank when a pressure differential is induced between the inlet and outlet of the tank by properly adjusting the pressure regulator. A diluted fertilizer solution is then carried into the system as outflow from the tank.

A positive pressure system is most commonly seen as a fertilizer metering pump. Nutrient solution is injected into the irrigation system under pressure. Outside power, such as gasoline engine or electricity, is necessary to operate the injecting pumps. Pressure tank and gravity force

(as used in the work herein reported) can also be used to inject chemical solutions by a positive pressure.

A negative pressure, or suction, system is based on the theory that a solution can be withdrawn into the irrigation system when a suction force is generated by the water flow in the main line. Both an open container and a closed container may be used in this kind of system.

II-1-4 Fertilizer Movement

Studies of soil fertility have been made often designed to determine available nutrient elements in the soil when predicting optimal fertilizer for plant growth. In soil irrigation, however, the irrigated area is always under a specified water and fertilizer application. The dynamic aspect, i.e., rate and direction of nutrient movement becomes very important. Olsen and Demmer (1963) reviewed the then accumulated knowledge of nutrient movement in soils including both diffusive and convective (bulk-mass) flow conditions. Nielsen and Biggar (1961) first presented the theory of miscible displacement which discussed the ion movement in a porous medium in terms of molecular diffusion and variations of water flow velocity within and between pores. Bruce et al (1974) have tried to combine elements of mobile layer theory with the miscible displacement equation and quantitatively described the salt concentration and flow velocity considering the exchange and adsorption processes between charged particles and ions.

Warrick (1974) discussed in mathematical terms the movement of water and solutes under conditions of trickle irrigation. Bresler et al (1971) studied salt accumulation under sprinkle infiltration under field conditions and concluded that salt distribution in the soil is related to the irrigation discharge

rate and the hydraulic characteristics of soil. In general, salt concentration rises when approaching the wetting front boundary. It should be noted that in Bresler's study, the interactions between solute and soil particles were ignored.

P distribution in the soil is another problem that needs further attention. Usually, there is little or no movement of P in most soils. There is also danger of precipitation of P compounds in pipe and emitters. P applications through drip irrigation systems are not commonly recommended. However, Goldberg et al (1971) reported that P can be applied with a drip irrigation system and they noticed that P moved [illegible] cm, both vertically and horizontally from the trickle emitter in a clay soil. Robins et al (1976) compared the movement of inorganic and organic orthophosphate compounds in soils and P and that organic orthophosphate is [illegible] than inorganic orthophosphate. In a subsequent study of the organic orthophosphate movement, Ramsek Ibrahim et al (1976) pointed out that since Hydroxyethylphosphate is definitely water-soluble and does not undergo chemical hydrolysis, it might be suitable to be applied through a drip irrigation system with no fear of precipitation in the system and achieve placement of P in the root zone.

II-4 Crop Response

With point or line application of water and/or fertilizer, drip irrigation provides a unique soil environment and drastically affects plant performance. Goldberg et al (1970 ; 1970b; 1971b), in a study of the physiological response of plants under drip irrigation, indicated that higher yields were achieved through maintaining a low and uniform matric and osmotic tension. Goldberg et al (1970) also emphasized that drip irrigation is preferable to sprinkle irrigation when brackish water is used. This is because plants

tolerate more salt water when applied in the root zone than when sprayed on the foliage. Phene (1974) compared drip, sprinkler and furrow irrigation in the humid North Carolina coastal plains and reported that the highest yield of corn was obtained by using drip irrigation. Phene explained that in the sandy soils, moisture stress does occur periodically due to erratic rainfall patterns. By the same token, the unreliable rainfall would also preclude irrigation with surface applied water, such as furrow or sprinkler system, since a subsequent rainfall would saturate the soil and decrease the aeration status. Aiyer and Dixit (1970) reported from India, that in continuously moistened soil under drip irrigation, cotton yields increased significantly because of the reduced soil strength. Ikeda (1970) measured the ratio between water used by transpiration and pan evaporation. The ratio is lower in a drip irrigated area than in a sprinkler irrigated area. Higher yields of various vegetable and fruit crops under drip irrigation have also been reported by Batchelor et al (1972); Jamieli and Duthers (1971); Smart et al (1974) and many others.

The plant root system is probably the most affected part under drip irrigation. Black and Mitchell (1974) observed massive development of fine and fibrous roots of pear trees within the wetted diameter created by a trickle emitter, and noticed the absence of fine and fibrous root outside the wetted diameter in the older root system which was established before the trickle system was used. Soliberg et al (1971a) examined the root development of drip-irrigated greenhouse carnations and reported that 68.7% of total dry weight of the root system is developed within a 5-10 cm layer of soil. Hudson (1962) studied tomato root development in relation to the location of a dripper. He noticed that the roots tend to concentrate at the periphery of the saturated soil cone created by the dripper. In other

[illegible] water in the saturated center, but outside in the [illegible] zone is [illegible], [illegible] studies and [illegible]tions have shown that most [illegible] is [illegible] under drip irrigation are much smaller, while [illegible] yields are higher. [illegible] may suggest that under drip irrigation [illegible] system is required to maintain a [illegible] (1/5). [illegible] normal crops, such as vegetable and fruit trees, [illegible] systems are affected by the wetted soil volume and water [illegible].

CHAPTER THREE:

INFILTRATION AND [illegible] MOVEMENT FROM A [illegible] IN TROPICAL SOILS

III-1 Materials and Methods

During January to April, 1977, laboratory studies of soil hydraulic properties and three-dimensional infiltration and associated solute movement from a simulated line source water application were conducted at the Soil Physics Laboratory of the Agricultural Experiment Station, Río Piedras, Puerto Rico. Physical information of the soils, such as bulk density, soil texture, pH, and soil-water characteristics (soil-water content v.s. soil water tension) were measured in the laboratories of the Tropical Agronomy and of the Agronomy Department of the University of Puerto Rico.

III-1-1 Soils

A clayey soil of the Coto Series and a sandy loam soil of the Bayamón Series in Puerto Rico were selected as representative of two differently structured, highly weathered tropical soils. The Coto soil was collected from the Lajas Experimental Farm near the field experiment site. The Bayamón soil was obtained from the Fortuna Farm, east of Manatí, Puerto Rico. Figure 4 shows the geographical location of the sampling sites. Subsoil samples (10 cm to 25 cm) were used for laboratory studies. The surface 10 cm of soil was discarded to eliminate the effect of disturbances of soil properties by tool as cultural activities.

Soil Series:

Location: Lajas Substation

Classification: Typic Hydrothox, clayey, kaolinitic, isohyperthermic

Depth: 10 cm to 25 cm

Texture: Clayey ([illegible]% sand; 11.3% silt; and [illegible]% clay)

Bulk density: 1.33 at field conditions

Slope: 2%

Vegetation: Native grasses

Bayamon Series:

Location: Fundador Farm, east of Manati

Classification: Tropeptic Eutrotrox, Sandy, Mixed, Isohyperthermic

Depth: 10 cm to 35 cm

Texture: Sandy ([illegible]% sand; [illegible]% silt; and [illegible]% clay)

Bulk density: 1.[illegible] at field moisture

Slope: Flat

Vegetation: Pineapple

The soil samples collected from the field were air dried, crushed with a soil grinder, passed through a No. [illegible] ([illegible] mm) screen sieve, thoroughly mixed and then kept in [illegible]" x [illegible]" heavy-duty polyethylene bags. The moisture content of both soils, air dried, was 1.[illegible]% by dry weight.

III-1-2 The Soil Bin

A soil bin, [illegible] cm thick, [illegible] cm wide and [illegible] cm deep was built with 1/4" (0.64 cm) perspex glass. One face of the bin was removable and was held together by three large metal clamps. The weak perspex glass container was re-enforced by a metal frame made of angle steel (Fig. 1). Forty-eight tensiometer holes, 1.2 cm in diameter, 10 cm apart both vertically and horizontally from each other (Fig. 3) were drilled on the detachable face of the container. The advancing wetting front during water application could be observed and followed on the face opposite to where the tensiometers were installed.

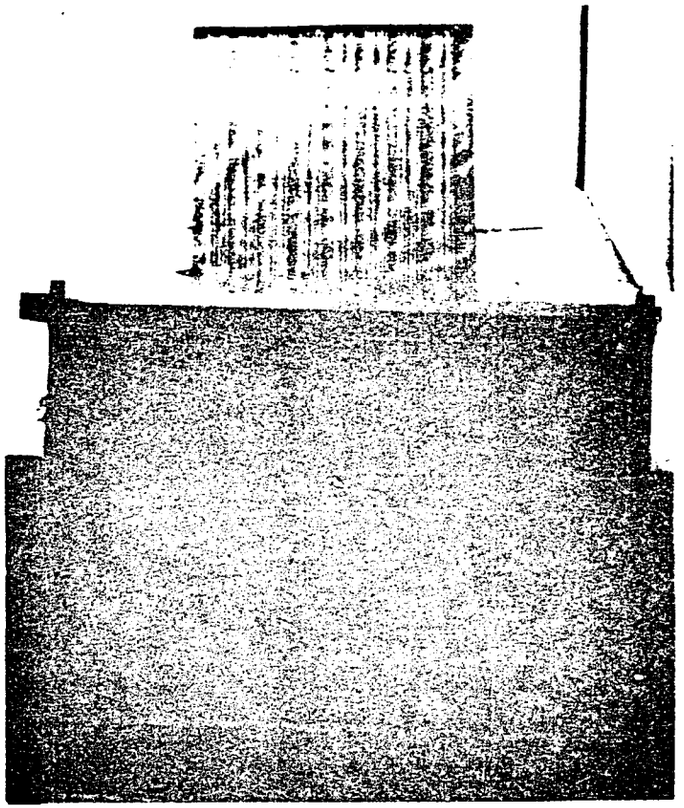


Fig. 1 The soil bin

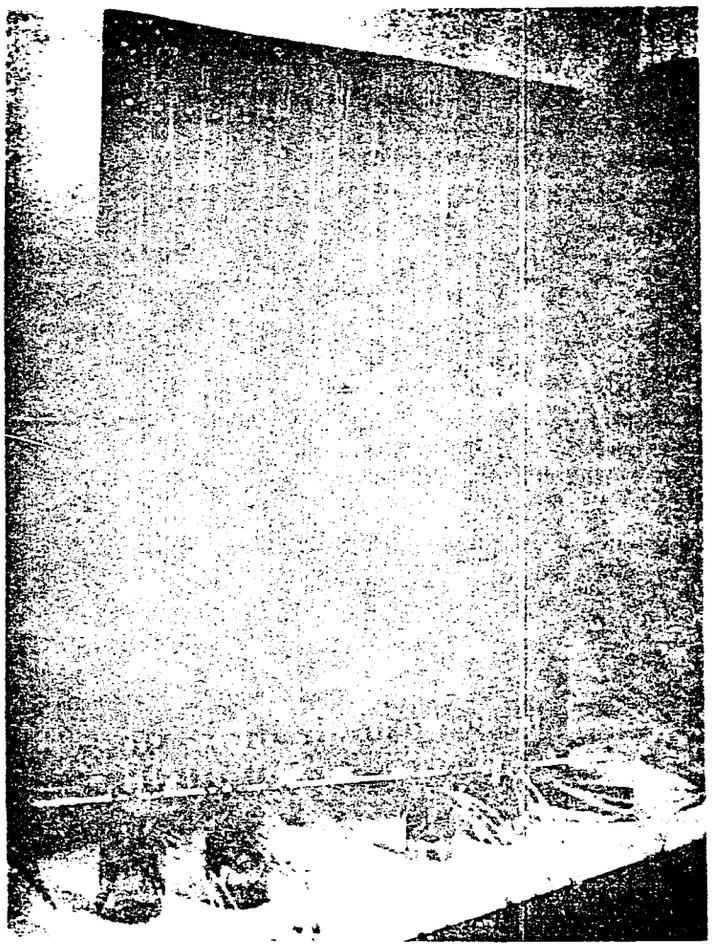


Fig. 2 Tensiometers and associated Mercury Monometers

III-1-3 Water Application Device

The water application apparatus consisted of three major components: 1) the emitters, 2) the flow regulator and 3) the water supply reservoir. Three glass capillary tubes , spaced 1.5 cm in a straight line on a wooden holder, were used as emitters to simulate irrigation from a line source of water supply. The tips of the emitters were so adjusted that they barely touched the soil surface thus minimizing the impact or disturbance of the soil. The flow rate was regulated by using a roller drop controller, the kind commonly used in hospitals for controlling the injection rate of glucose or biosal' water. The advantage of the drop controller is that the desired flow rate can be quickly obtained by adjusting the number of drops per unit time. The drop contoller also provided accurate and uniform water application at various discharge rates. Two ten liter glass bottles with a constant head siphon device were used as the water supply reservoir. Water was delivered from the reservoir to the emitters through a 1/8"(0.31 cm) flexible tubing.

III-1-4 The Tensiometers

Forty-eight laboratory built tensiometers each one consisting of a water filled manometer and a sensitive, thin wall ceramic cup, were installed in the soil profile to monitor the change and distribution of the soil matrix potential.

The ceramic cups were 2.5 cm long, 1 mm thick and 9 mm in diameter. The material had an approximate flow rate of 160 ml/hr/cm^2 (compared to about 5 ml/hr/cm^2 in conventional tensiometer cups) and a bubbling pressure of 20 to 25 psi (1034 mm to 1293 mm of mercury). Each ceramic cup was fitted into a 10 cm long 1 cm diameter copper tube. The other end of the copper tube was cemented with a section of clear tygon tube, which

can be plugged with a glass roll stopper. The whole unit was then connected to a mercury well through a 3 meter long Nylaflow pressure tubing. (Fig. 4 shows a diagram of the tensiometers used in the experiment). Fig. 2 shows the set-up of the tensiometers before being installed into the soil profile during the experiment.

III-1-5 Preparation of the Soil Profile

An air-dried, sieved soil was packed into the soil bin using a big funnel with a flexible tube. Based on the field bulk density, pre-weighed soil samples were added as uniform as possible and then compacted into 5 cm layers. An electric tapper was also used on both sides of the soil bin to provide a homogeneous medium. It was hoped that the bulk density of the finished profile should not exceed $\pm$ 5% of the natural bulk density of the same soil.

III-1-6 Obtaining Soil Moisture Patterns and Matric Potential Distribution

A 0.02 N Diamoniaphosporate solution ($(NH_4)_2HPO_4$) was used for irrigation in studying the advance of the wetting front and the P movement in the soil profile. Four discharge rates of 0.24 ml/min/cm and 1.02 ml/min/cm for Manati sandy loam and 0.20 ml/min/cm and 1.30 ml/min/cm for Coto clay were studied. The solution was applied through the emitters placed at the center of the soil bin (X = 0; Y = 0; Z = 0) and a constant and continuous flow was maintained throughout each experiment. The room temperature during all the experiments was kept at 25 $\pm$ 1°C. Each experimental run was continued until at least 5,000 ml of the solution was applied.

A transparent plastic sheet attached on one side of the soil bin was used to observe and mark the displacement of the wetting fronts. The

advance of the wetting front was recorded at various time intervals as well as when every 1,000 ml of solution was applied. The soil surface was covered with a plastic sheet to prevent evaporation. Tensiometer readings were recorded when 5,000 ml of water were applied in each experiment.

III-1-7 Measurement of P Movement in the Profile

Immediately after turning off the water application, the tensiometers were removed and the soil profile turned by 90 degrees from a vertical to a horizontal position. The detachable face of the soil bin was then opened for sampling. The whole wetted volume of soil was divided into 25 cm^2 sections. Soil samples were taken from each section and placed into plastic bags for laboratory analysis of P. Another set of soil samples from each section was used for soil moisture determination.

III-1-8 Estimation of Soil Hydraulic Properties

A perfect and reproducible method for measuring soil hydraulic conductivity is still an open question. The hydraulic conductivity functions used in this experiment were estimated from the measured soil water diffusivity functions and corresponding soil-water characteristic curves.

The diffusivity function within the interval of saturated and air-dried soil water content was measured by employing the method first proposed by Bruce and Klute(1956) and the modfied by Reichardt et al (1972) and Miller and Bresler (1977). The apparatus used for soil water diffusivity studies contains a horizontal lucite plastic column, 3.5 cm inner diameter and 30 cm long, sectioned into 1 cm and 2 cm rings. A pre-treated soil sample was packed into this column to its natural field bulk density.

Water was applied from a constant head at a pressure of 5 cm below the atmospheric pressure. The measurements were: 1) the air-dried soil water content d, 2) the water content θs of saturated soil adjacent to the infiltration surface, and 3) the visually observed distance of the wetting front, X, as a function of time, t. Through plotting X v.s. $\sqrt{t}$, a slope, m, of the X- $\sqrt{t}$ curve was obtained. The empirical expression for the desired soil water diffusivity function, $D(\theta)$, is given by $D(\theta) = \alpha m^2 \exp[\beta(\theta-\theta\alpha)/(\theta_s-\theta\alpha)]$. ---------- (5)

where according to Reichardt et al (1972), $\alpha = 1.05 \times 10^{-3}$ and $\beta = 8.06$. The hydraulic conductivity function is then estimated from $D(\theta)$ and the soil water characteristic curves using the relationship

$$D(\theta) = -\frac{1}{\rho g}\frac{K(\theta)}{\partial\theta/\partial\rho} = \frac{K(\theta)}{\partial\theta/\theta h} \quad \text{---------- (6)}$$

where ρ is the density of water , g is the acceleration due to gravity, and $\partial\theta/\partial\rho$ or $\frac{\partial\theta}{\partial h}$ is the slope of the soil-water characteristic curve at a certain appropriate water content.

III-1-9 Other Soil Parameters

Soil water characteristic curves for the range of 0 to 100 cm H_2O were determined through measuring the capillary rise in a soil column packed to each soil's field bulk density. For the range larger than 100 cm H_2O, traditional pressure plate apparatus was used. Soil textures were determined by the standard pipet method. Bulk densities were determined using the saran coating method. Total N was determined by Kjeldahl method, K was measured by flame photometer method and available P was determined using the Olsen method extracted by NH_4HCO_3.

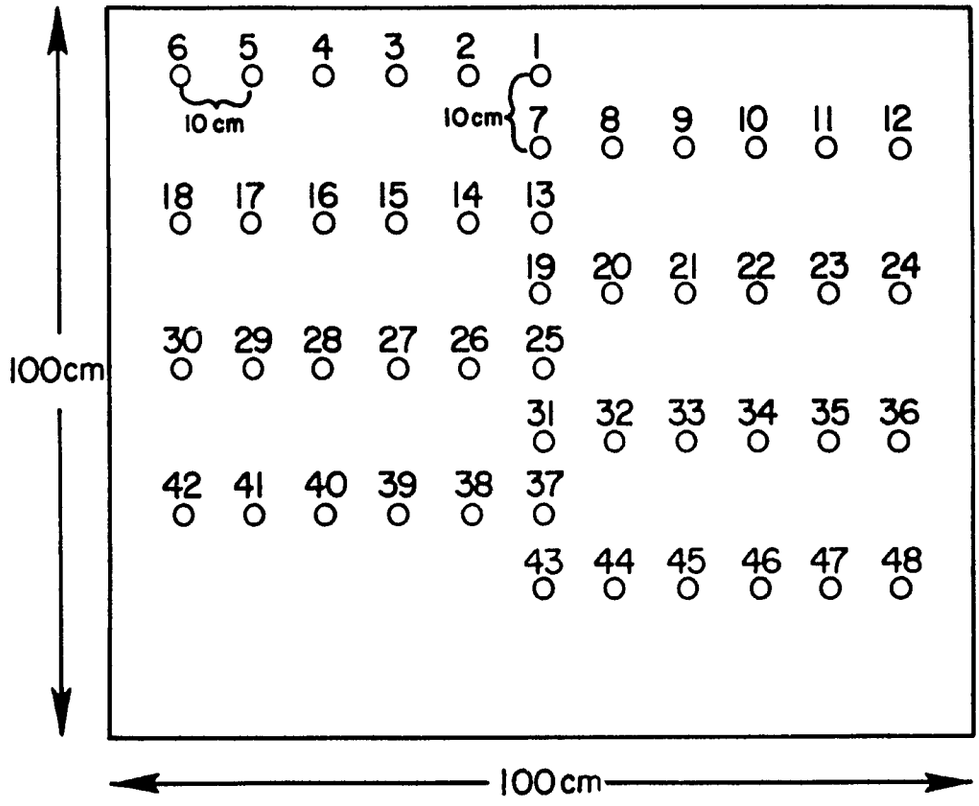


Fig. 3 Arrangement of tensiometers in the soil profile.

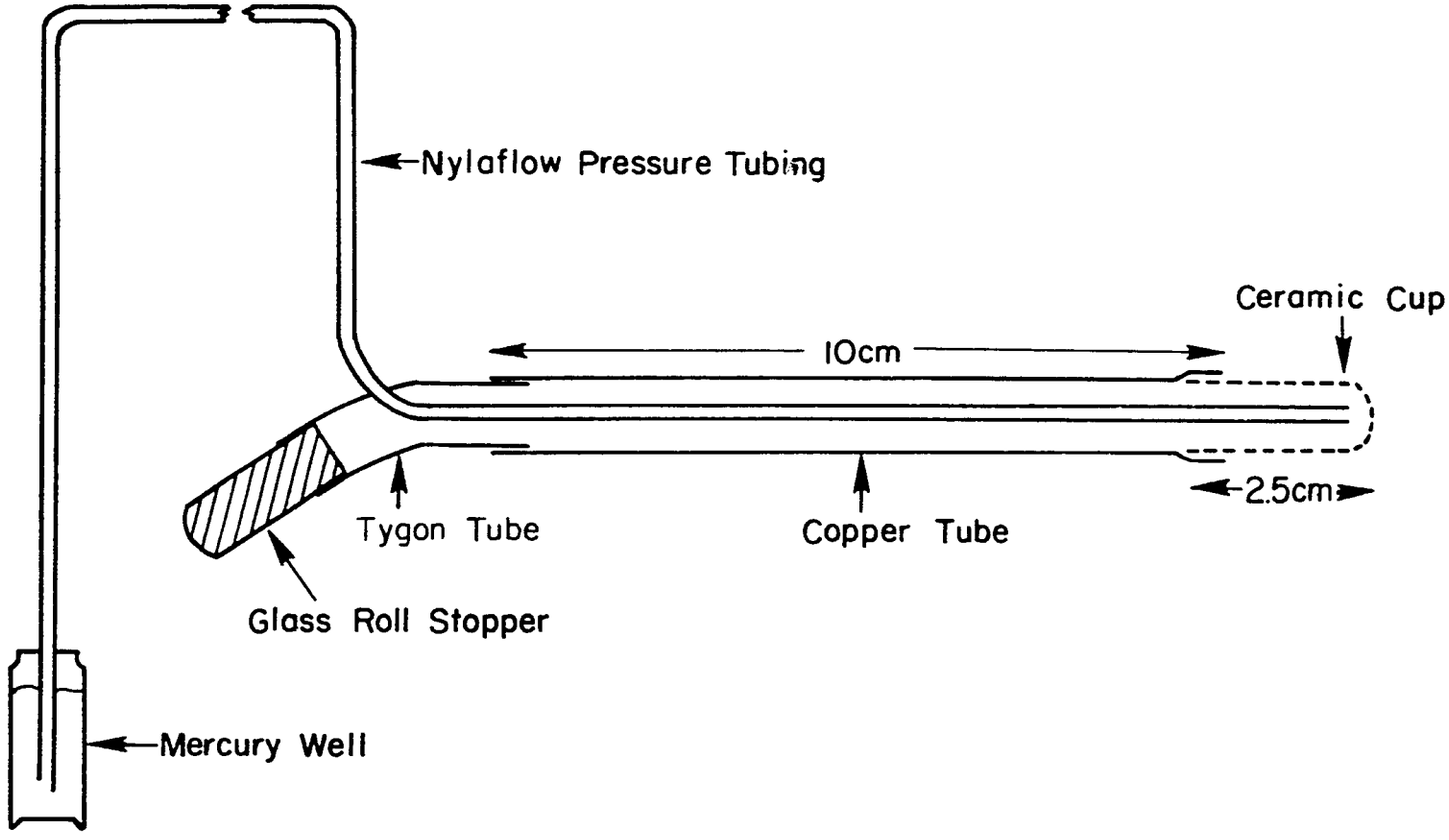


Fig. 4 Diagram of tensiometer.

III-2 RESULTS

III-2-1 Wetting Front Advance

Figures 5 and 6 show the wetting front advance with time in the profiles of Bayamon sandy loam. The amount of water applied was 7.00 liters and 7.04 liters with discharge rates of 0.24 ml/min/cm and 1.02 ml/min/cm, respectively. As shown in Figures 5 and 6, laterial movement of infiltration water near the soil surface is faster if the water application rate is higher. The vertical advance of the wetting front reveals no difference between the two discharge rates at the early stage of infiltration. When the accumulated infiltration water exceeded 3,000 ml, the vertical advance of the wetting front at the low discharge rate experiment showed faster downward movement.

Figures 7 and 8 show the wetting front advance with time in Coto clay profiles. Equal amounts of water, 5,000 ml, were applied in two experimental runs with discharge rates of 0.2 ml/min/cm and 1.30 ml/min/cm. Ponded water on the soil surface and pronounced horizontal water movement was observed with the 1.30 ml/min/cm discharge rate. Although the vertical advance of the wetting front was faster with higher discharge rates, no difference in the vertical advance was noticed when the accumulated infiltration water reached 4,000 ml and 5,000 ml level.

The two dimensional soil profile may be described by X and Z axes with the water source as the point origin of (0.0). The X axis has a direction toward the gravity center and increasing with the depth of the profile. The Z axis is the horizontal axis which is perpendicular to the X axis. The expanding rate of wetted area on the soil surface, in both Coto and Bayamon soils, decreased with increasing irrigation time. In other words, $\left.\frac{\partial z}{\partial t}\right|_{x=0} \rightarrow 0$ when $t \rightarrow \infty$, where t is irrigation time.

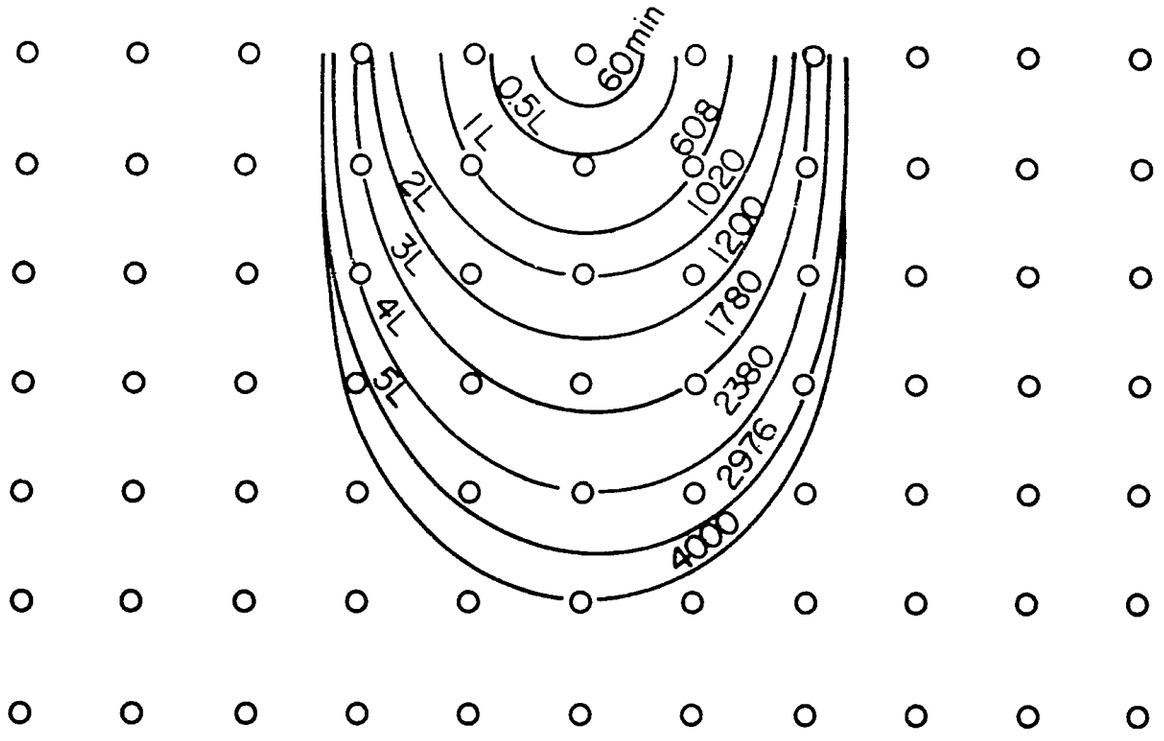


Fig. 5 Wetting front advance versus time for sandy loam. Discharge rate was 0.24 ml/min/cm. Total water applied was 7.00 liters.

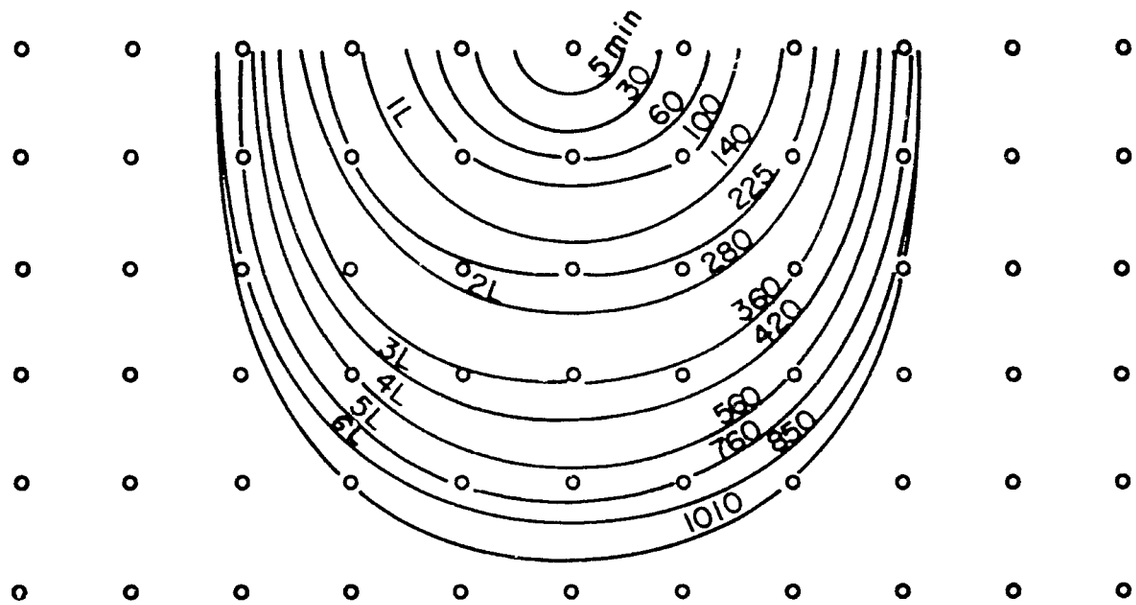


Fig. 6 Wetting front advance versus time for Bayamon sandy loam. (Discharge rate is 1.02 ml/min/cm, total water added is 7.04 liters.)

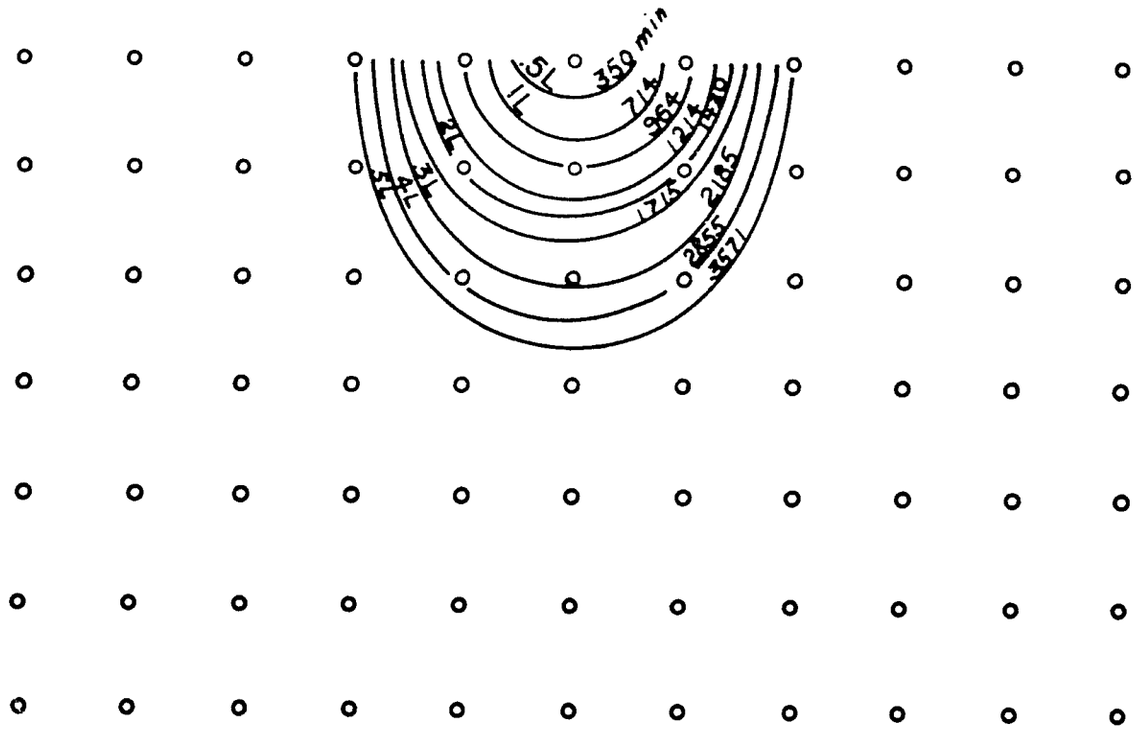


Fig. 7 Wetting front advance versus time for Coto clay. (Discharge rate is 0.20 ml/min/cm, total water added is 5.0 liters.)

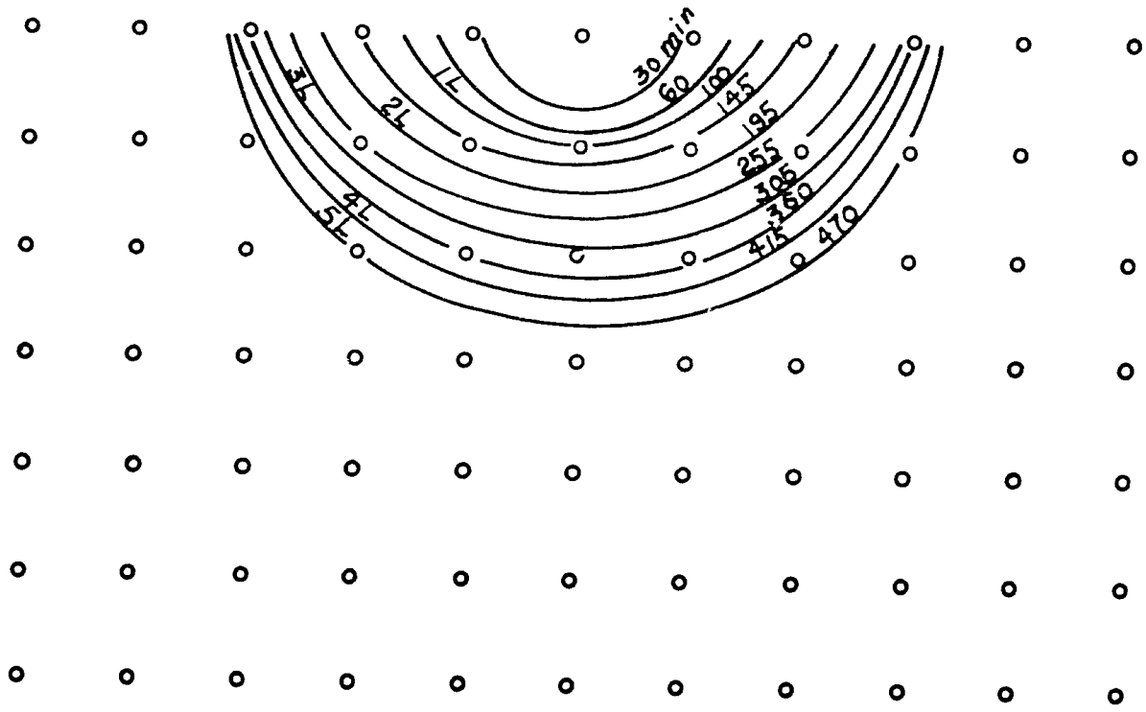


Fig. 8 Wetting front advance versus time for Coto clay. (Discharge rate is 1.30 ml/min/cm, total water added is 5.0 liters.)

III-2-2 Matric Potential Distribution

Table 1 shows the values of matric potential distribution when 5,000 ml of water were applied to each soil profile. The numerical data were plotted in Figures 9 and 10 as flow-nets. The equi-potential lines were interpolated using the adjacent tensiometer readings. Because of the fact that soil matric potential increases sharply across the wetting front, it is often impossible to obtain detailed data about potential changes across the wetting front with pre-spaced tensiometers. Under such circumstances, estimated equi-potential lines were drawn. The dotted sections of the equi-potential lines on Figures 9 and 10 are only estimates.

From Figure 9-a, the major part of water flow tended to move downward when the accumulated infiltration water reached 5,000 ml under the discharge rate of 0.24 ml/min/cm in the sandy soil profile. More sideward water flow was observed in the same soil medium with a higher discharging rate (Figure 9-b).

Figure 10-a suggests that, in a semi-infinite Coto clay profile and under a discharging rate of 0.2 ml/min/cm, a relatively equal amount of water flows in all directions in the wetted zone. Ponded water on the soil surface was only observed in the Coto clay with a discharge rate of 1.30 ml/min/cm. Under the ponded water situation, free water no longer infiltrates into the soil from a point or line, but from an area. Flow-net as shown on Figure 10-b, indicates that a distinguishable amount of infiltrated water contributes to lateral movement in the profile.

Table 1.--Matric potential distribution in the profiles when 5 liters of water were applied.

Location of tensiometers[1/]	Tensiometer Readings (cm of Hg)			
	Manati sandy loam		Coto clay	
	Q=0.24 ml/min/cm	Q=1.02 ml/min/cm	Q=0.2 ml/min/cm	Q=1.30 ml/min/cm
1	5	5	5	4
2	10	5	21	4
3	20	10	58	13
4	68	41	68	47
5	68	68	68	68
6	68	68	68	68
7	10	5	23	17
8	10	5	33	15
9	22	17	64	30
10	68	40	68	66
11	68	68	68	68
12	68	68	68	68
13	15	7	40	44
14	15	10	49	46
15	21	19	68	54
16	68	42		68
17	69	68		
18	68	68		
19	16	17		
20	17	25		
21	25	33		
22	46	59		
23	68	68		
24	68	68		
25	37	45		
26	40	51		
27	55	66		
28 - 48	68	68		

1/ Tensiometer numbers refer to locations on Fig. (3).

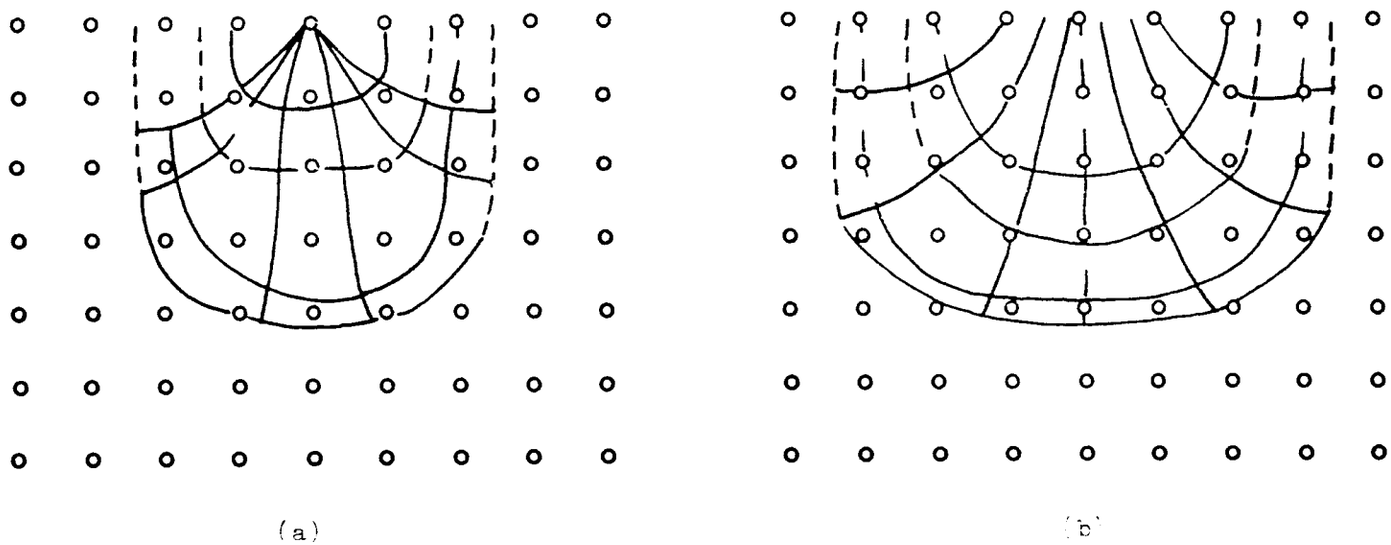


Fig. 9 Equi-matric potential and flow direction of Bayram Sandy loam under two discharge rates when five liters were applied, (a) Q = 0.24 ml/min/cm and (b) Q = 1.00 ml/min/cm.

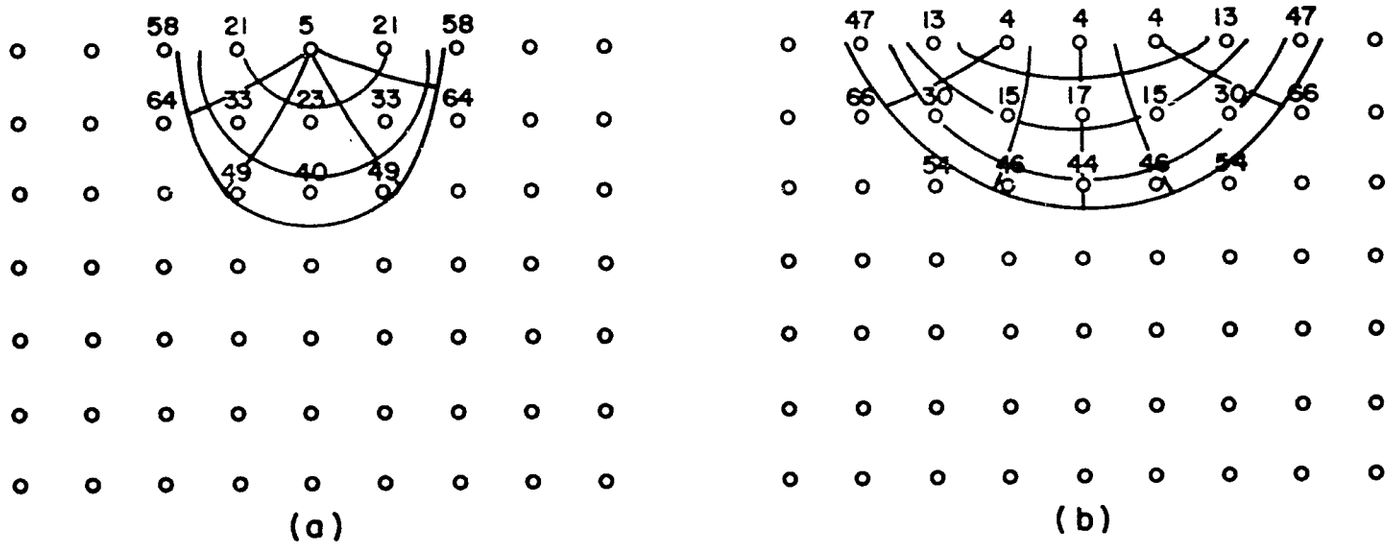


Fig. 10 Equi-Matric potential and flow direction of Coto clay under two discharge rate when 5 liters of water was applied. (a) Q = 0.20 ml/min/cm, (b) Q = 1.30 ml/min/cm.

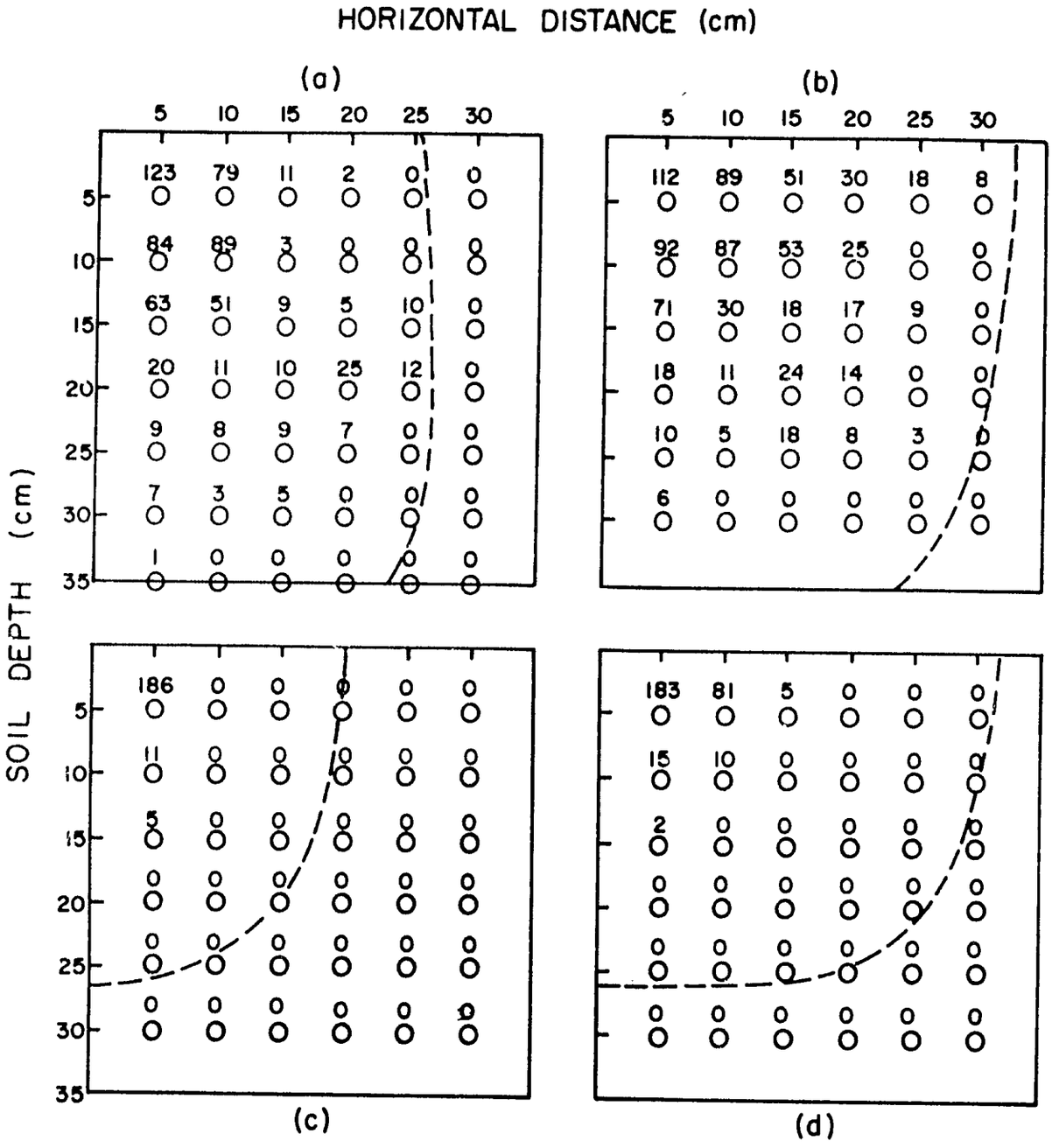


Fig. 11 P distribution in soil profiles. Numbers above points are ppm of P. Dotted lines are the final wetted fronts. (a) Bayamon soil Q = 0.24 ml/min/cm, (b) Bayamon soil Q = 1.02 ml/min/cm, (c) Coto soil Q = 0.2 ml/min/cm, (d) Coto clay Q = 1.3 ml/min/cm.

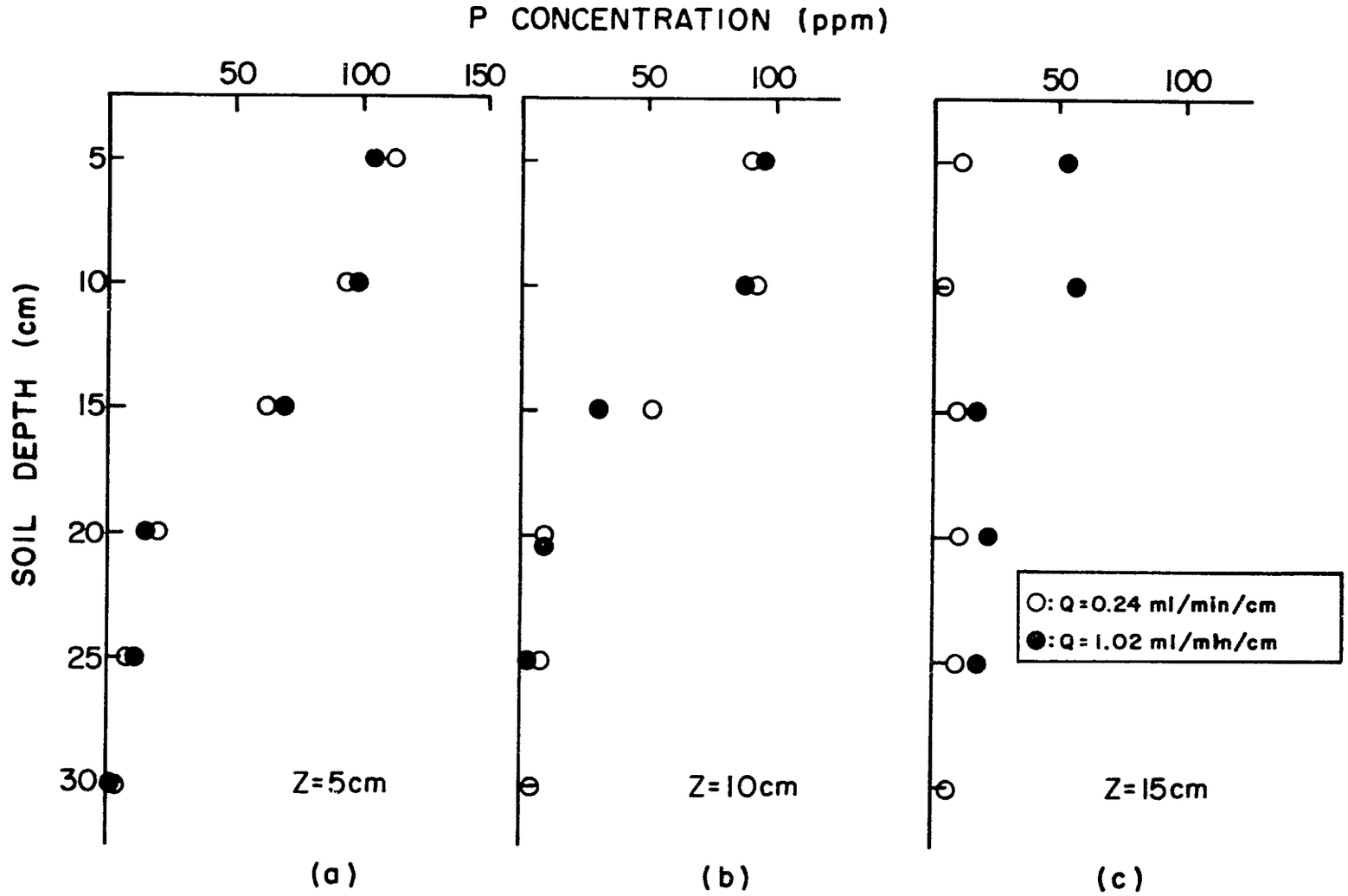


Fig. 12 Vertical concentration of P at (a) Z= 5cm; (b) Z= 10cm and (c) Z= 15cm from drip emitter of Bayamon sandy loam.

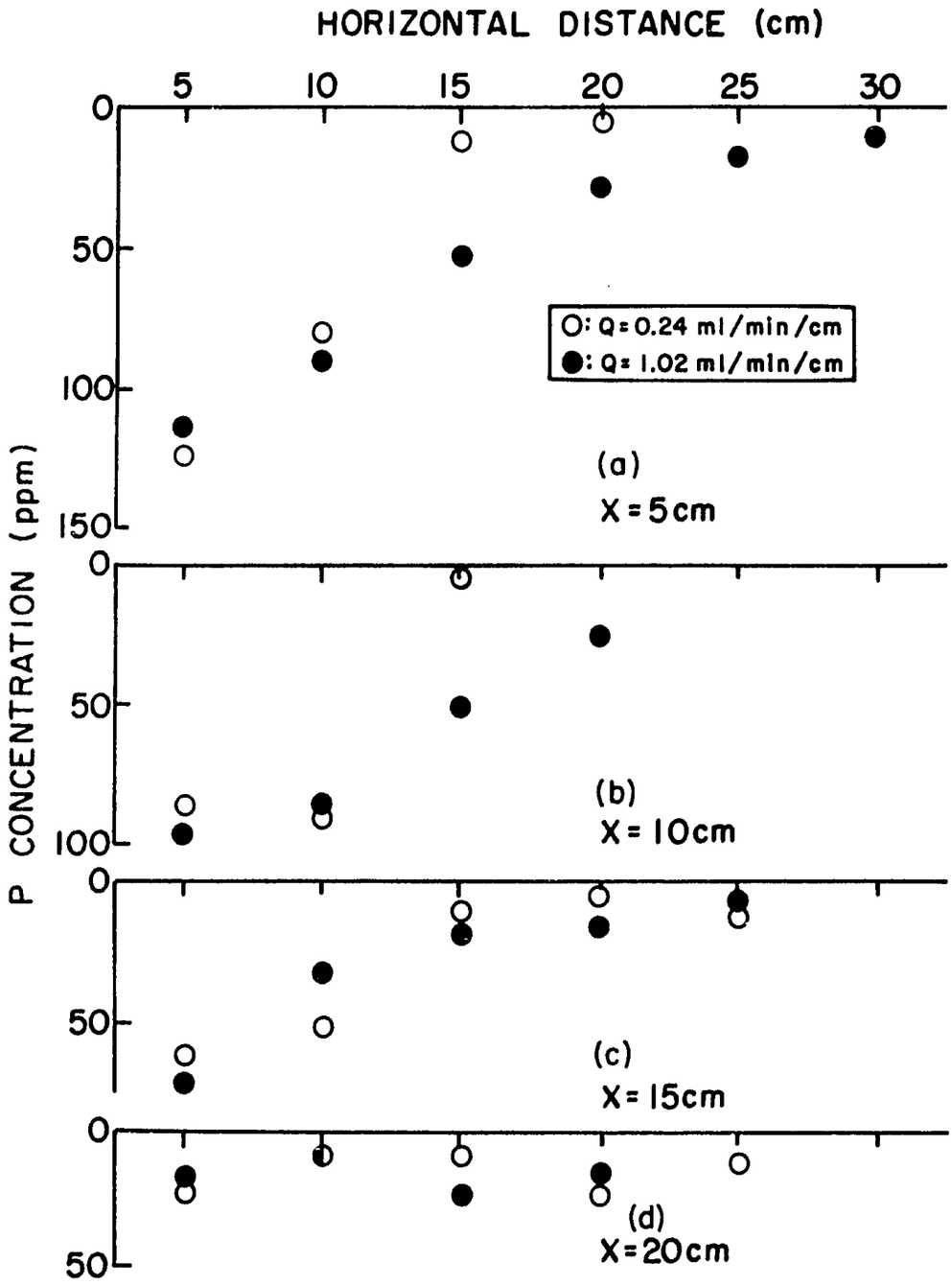


Fig. 13 Horizontal concentration of P of Bayamon soil at four depths.

III-2-3 P Movement in the Soil Profile

P movement in Coto clay and Bayamon sandy loam with respect to water application rate is presented in Figure 11. Dotted lines on each profile mean the wetting front at the termination of irrigation. The numbers are the values of bicarbonate extractable P in each sampling site. It is apparent that the P applied in ammonium-phosphorate form concentrated beneath the emitter shows little downward movement and no laterial movement in the Coto clay under a water discharging rate of 0.2 ml/min/cm. There was a 15 cm horizontal movement at the surface 5 cm layer under discharging rate of 1.30 ml/min/cm in the same soil. P movement in the Bayamon sandy loam was surprisingly close to the wetting front, although high P concentration in the vicinity under the emitters was also observed. Figures 12 and 13 present the vertical and horizontal soil P content at various distances and depths in the Bayamon soil profiles. From Figure 12, at the horizontal distance Z - 15 cm, higher P content is noticed down to a depth of 25 cm when the discharge rate is higher. At Z = 15 cm and Z = 10 cm, there are no differences in downward P movement between the two water application rates. Figure 18 also indicates more P movement in the top 10 cm layer with higher discharge rates.

III-2-4 Calculation of Hydraulic Conductivity

Figure 14 shows the relationship of the advance of water front versus time measured with the apparatus described in section III-1-8. The correlation coefficients of the data are calculated as γ=0.98 and γ=0.99, and the slopes of the regression functions are 0.555 and 0.202 for Bayamon sandy loam and Coto clay respectively. Based on Figure 14 and equation 5, the functional relationships between D (θ) and θ of the two soils are calculated and presented as Figure 15. The hydraulic conductivity function

$K(\theta)$ is calculated from Figure 17 and equation 6. The soil-water characteristic curve, shown on Figure 16, is used to estimate the values of $d\theta/d\psi$. Soil water hysteresis in the lower suction range of Oxisols has been found small (Sharma 1966 and Santo 1974). Hence, hysteresis effect is considered to be negligible. Calculated conductivity functions $K(\theta)$ are presented on Figure 17.

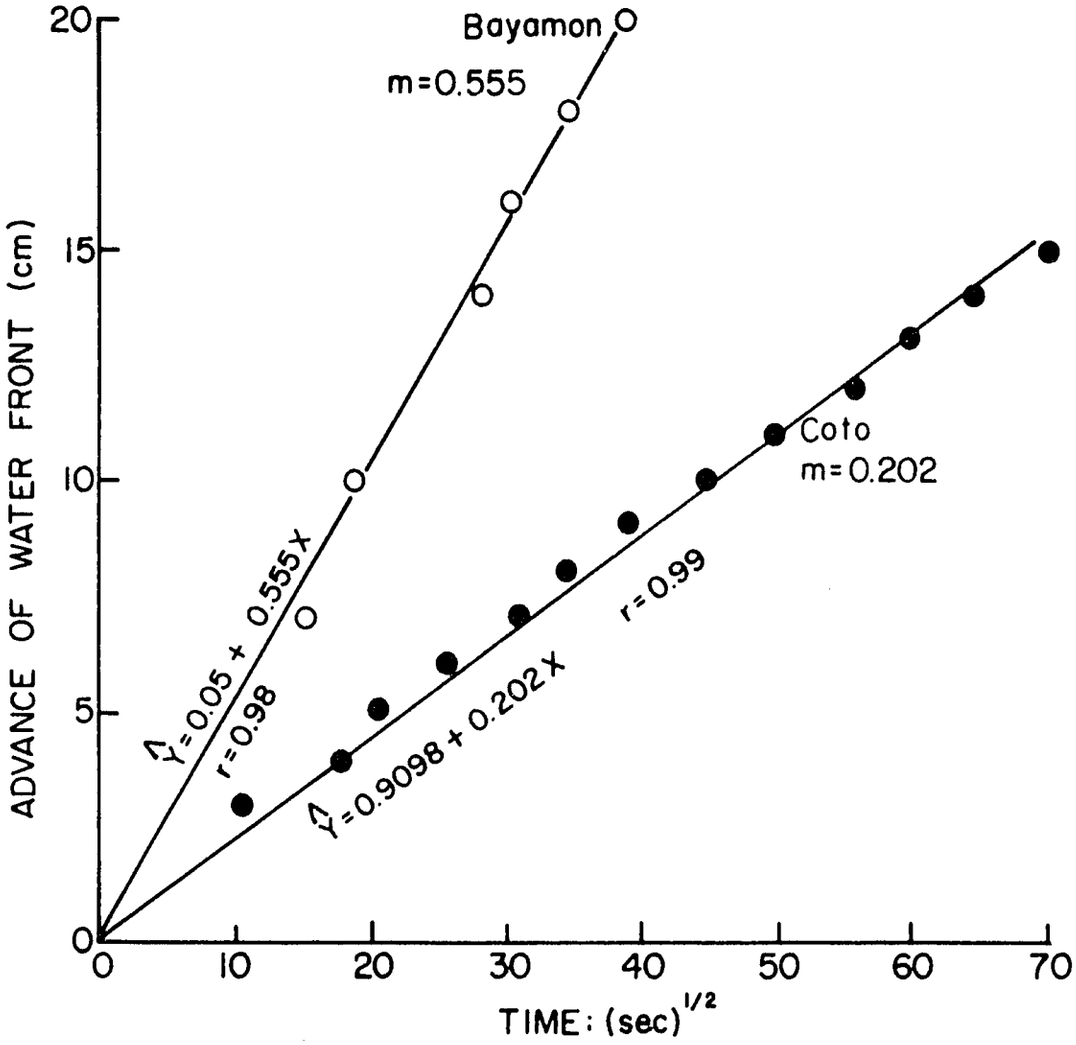


Fig. 14 Distance from water source to the wetting front versus square root of time for horizontal infiltration into air-dry Coto clay and Bayamon sandy loam.

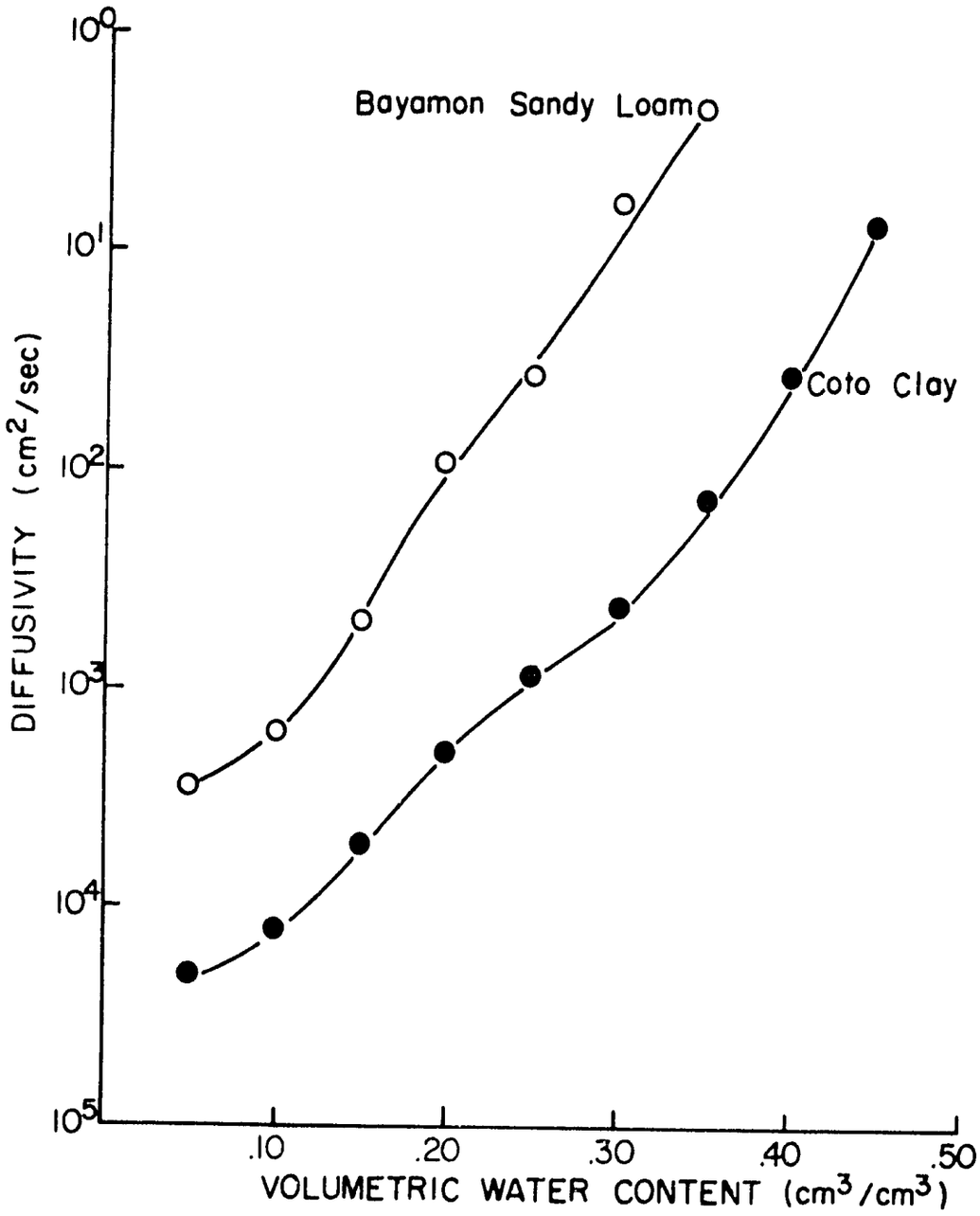


Fig. 15 The soil water diffusivity (D) as a function of water content (θ).

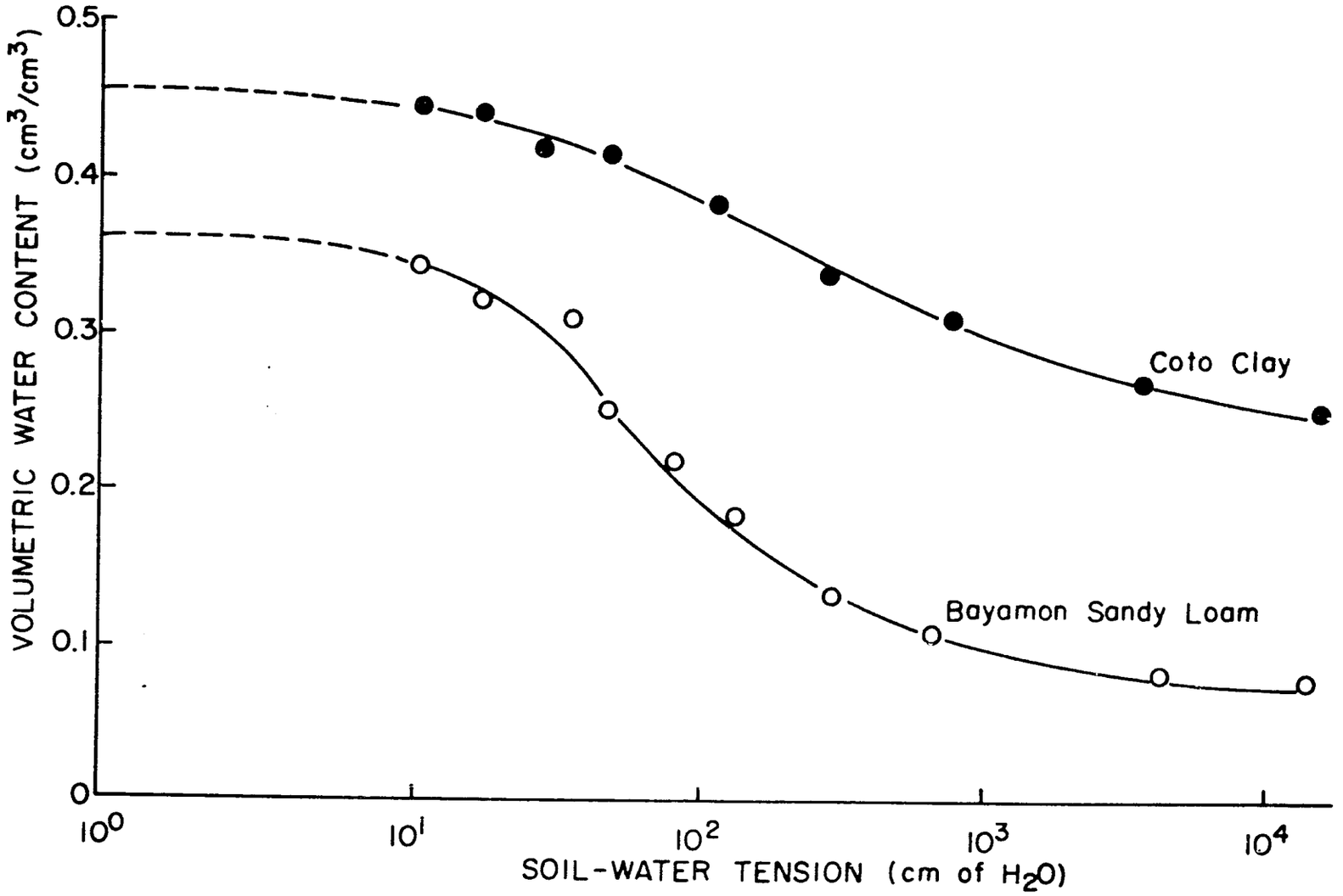


Fig. 16 Soil-water tension as a function of water content for Coto clay and Bayamon sandy loam.

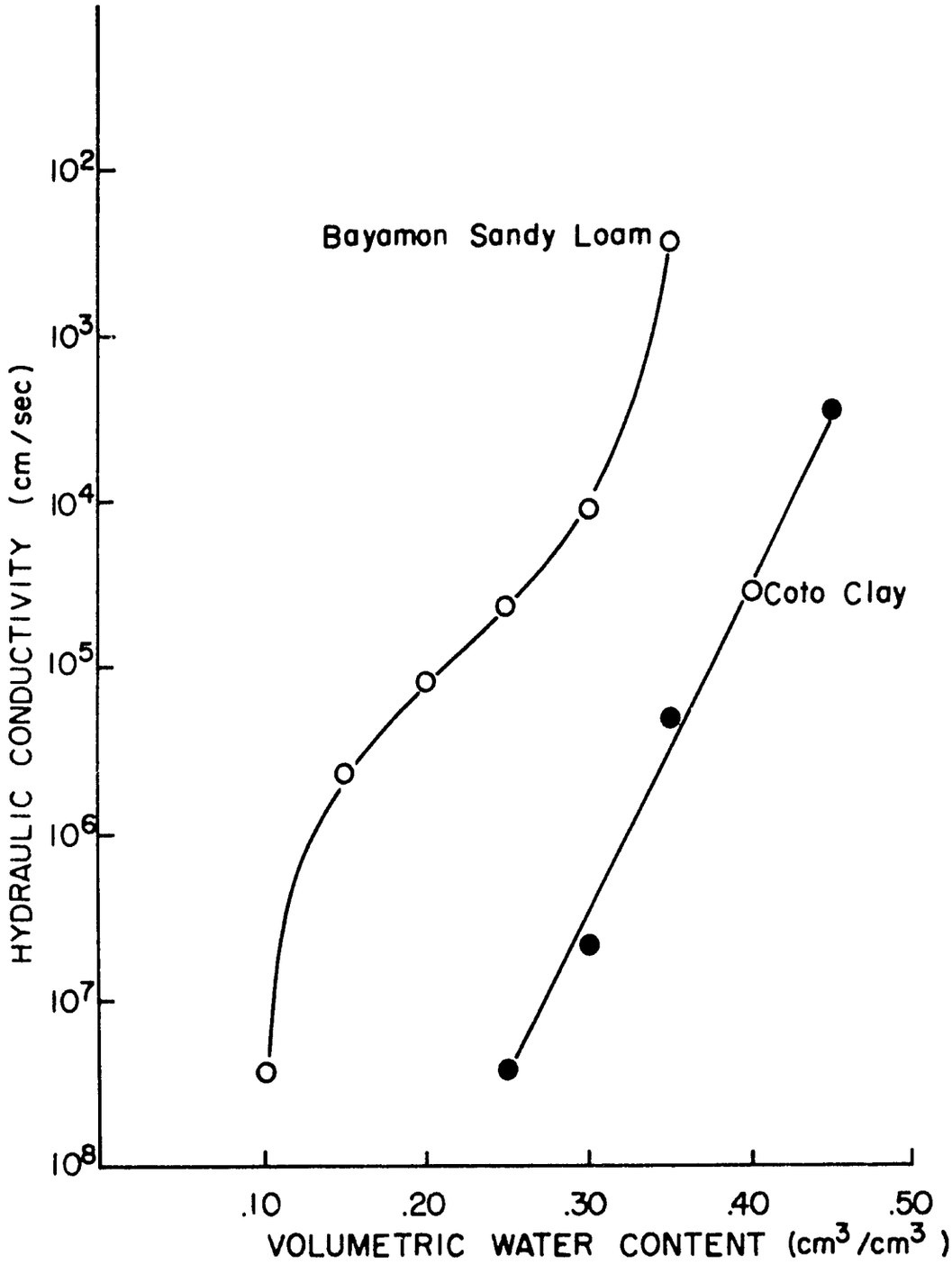


Fig. 17 Hydraulic conductivity (K) as a function of water content (θ).

III-3 DISCUSSION AND PRACTICAL IMPLICATIONS

III-3-1 Vertical and Horizontal Advances

The semi-ellipse shaped wetting fronts as shown in figures 5, 6, 7 and 8, may be considered as boundaries of the irrigated soil volume at various times. Lateral spreading of the wetted zone would provide essential information for the design of space between irrigation tubing, and also suggests the optimum distance between plant seedlings and irrigation water source. The depth of downward soil water movement, as function of discharge rate and time, can help to estimate the depth where the leaching process stops and/or where applied fertilizer materials can reach. The matric potential distribution indicates the difference in wetness of soil at varied locations related to the irrigation tubing and divides the wetted soil volume into 1) a region under prolonged water saturation where, due to the oxygen deficiency problems, may not be suitable for root development, and 2) a region of partial saturation and slower water movement, where the soil moisture is within the field capacity range and soluble plant nutrients may accumulate and, therefore, is ideal for plant growth. Understanding the vertical and horizontal movement of irrigation water as well as the matric potential distribution in the wetted area is important in engineering design and crop management.

A comparison of vertical and horizontal advance in the two soils under different discharge rates as a function of cumulative infiltration rate is shown in figure 18. In the sandy Bayamón soil profile with a lower discharge rate, Q = 0.24 ml/min/cm, the vertical and horizontal advances were similar

to each other at the very beginning and then the vertical advance surpassed the horizontal advance by a large distance. As the discharge rate increased to Q = 1.02 ml/min/cm, the horizontal advance was greater than the vertical advance at the beginning of irrigation, when the cumulative infiltration water reached 2,000 ml, the vertical advance surpassed the horizontal advance. It is apparent that, in a sandy soil profile, the capillary forces are the dominating forces when the soil is not saturated. Water added from the soil surface has an equal chance to move vertically as well as horizontally. If the rate of water addition is greater than the unsaturated hydraulic conductivity of the air-dried soil, a layer of free water might be ponded on top of the soil surface and cause a greater lateral movement. This may be the reason why, at the beginning of irrigation, the horizontal advance under high discharge rate in Bayamon sandy loam was greater than the vertical advance. As the water content in the profile increases, the major water movement will take place in larger soil pores and water flow will be domianted by gravity forces. The gravity flow is much greater in quantity and speed than capillary flow in soil media. This is the reason that the shape of the vertical advance curves in the sandy soil profile increase steadily as cumulative infiltration water increase. Figure 18 also suggests larger horizontal movement with higher discharge rate. The distance of horizontal advance depends on the gradient of suction force across the wetting front and with higher discharge rate the water content near the drip emitters increases, enhancing the horizontal advance of water.

In the Coto clay profiles, with low discharge rate, Q=0.2. ml/min/cm, the horizontal advance and vertical advance are almost identical with the first 2000 ml of irrigation water. This indicates that capillary forces

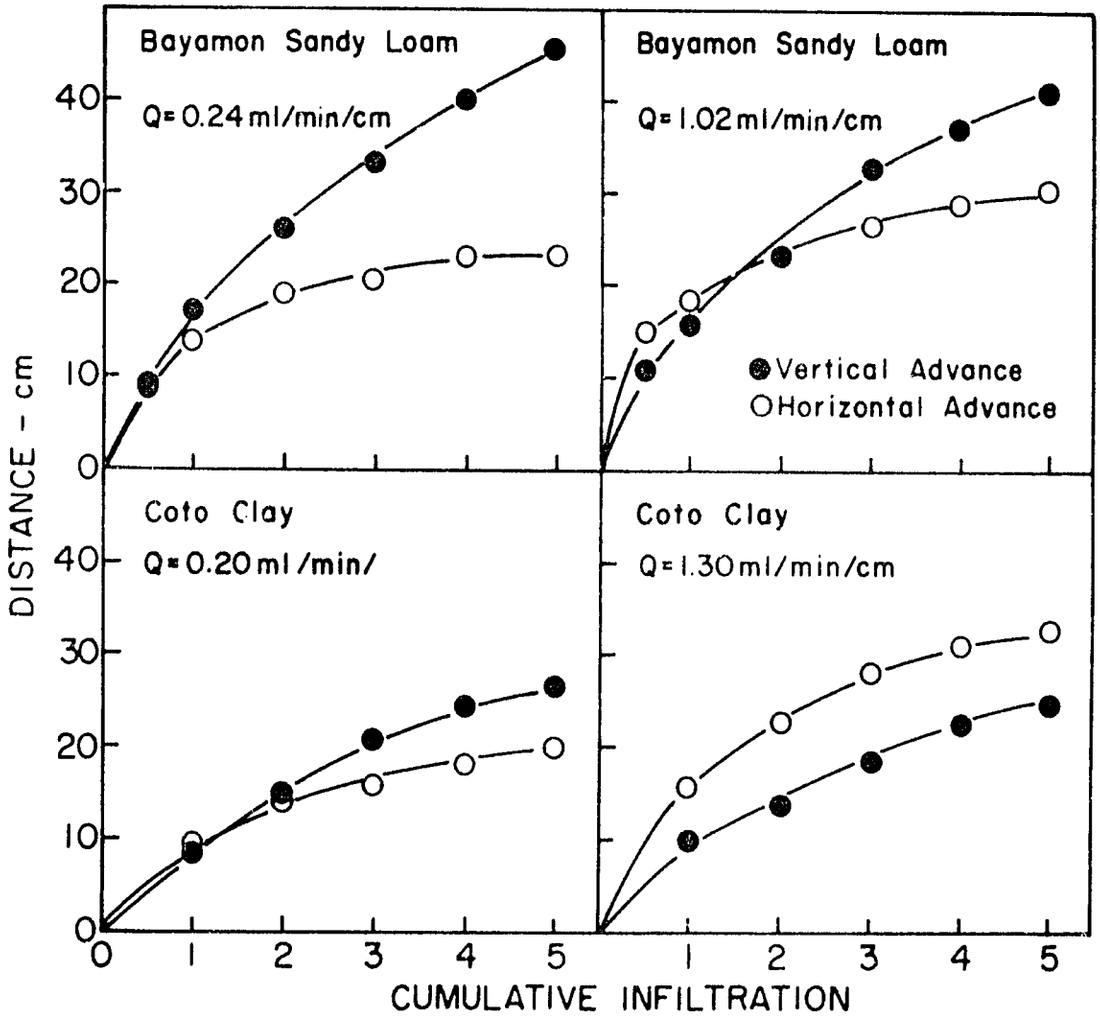


Fig. 18 The distance of the wetting front from the center of the trickle source as a function of the amount of infiltration water.

dominate the water movement in finer textured soils. Oxisols, however, have a unique structure in that there are two groups of pore size: the intra aggregate porosity carries only capillary flow, while a large portion of the inter aggregate pores are beyond the capillary limit and permit certain degree of gravity flow. The effect of this kind of bi-model pore size distribution causes greater vertical advance in the two dimensional water movement experiment. Curves with the greater discharge rate, Q = 1.30 ml/min/cm, in Coto clay profile show a different pattern: the horizontal advance is greater than the vertical advance throughout the irrigation period; the distances of vertical advance at various amounts of cumulative irrigation water are very close to the corresponding values under the lower discharge rate. This suggests that the effect of gravity forces in water movement in a clayey textured soil is limited. When the rate of surface applied water increases, the excess water will pond on the soil surface and flow laterally as free surface water. The free surface water flow extends the infiltration area of water which enters across the soil surface and the infiltration rate will keep increasing until the infiltration rate and the discharge rate reached equilibrium. The subsequent horizontal advance will, follow the same mechanism as capillary flow. In the Coto clay profile, ponded water was seen near the emitters under the high discharge rate tests. The matric-potential profile presented in Figure 10-b indicates that water enters the soil from a strip of ponded water instead of from a intermittent line source formed by the emitters. As a conclusion: the difference of ratio between the vertical and horizontal advance is a function of both water discharge rate and the soil porosity.

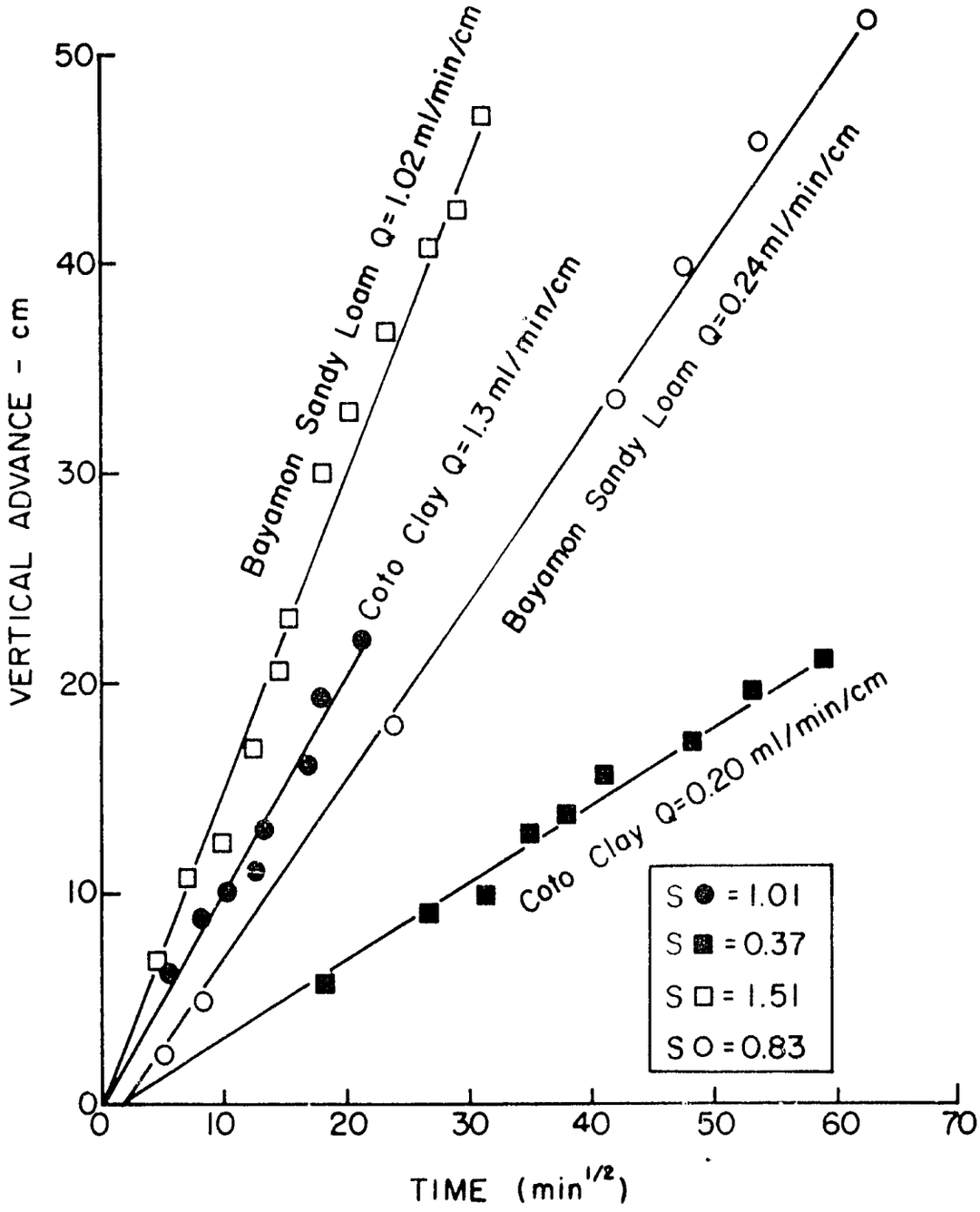


Fig. 19 The vertical advance of wetting front versus square root of application time.

To further examine quantitatively the downward water movement, the vertical advance, at Z = 0, the data from Figures 6, 7, 8, and 9 are plotted against the square root of irrigation time, in Figure 19. For the two water discharge rates in both Coto and Bayamon soils, a linear relationship between vertical advance and square root of application time is observed. Recalling Darcy's equation for one-dimensional downward infiltration into an isotropic, homogeneous soil profile:

$$F = -\kappa \frac{dh}{dz} = -\kappa \frac{d}{dz} (H_p - Z) \text{----------} (7)$$

where F is the flux, at the soil surface and Q is equal to the infiltration or drip discharge rate. H is the total hydraulic head, H_p is the pressure head, κ is the hydraulic conductivity and Z is the distance of vertical advance downward.

In unsaturated water flow conditions, H_p is negative, and can be expressed as a suction head ψ , and

$$F = Z \frac{d\psi}{dz} + \kappa \text{----------} (8)$$

the equation of continuity is combined with equation 8:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} (\kappa \frac{\partial\psi}{\partial z}) - \frac{\partial\kappa}{\partial z} = \frac{\partial\kappa}{\partial z}(D \frac{\partial\theta}{\partial z}) - \frac{\partial\kappa}{\partial z} \text{----------} (9)$$

where D is diffusivity.

To solve equation 9, Philip (1957) developed a method of power series:

$$Z(\theta,t) = \sum_{n=1}^{\infty} f_n (\theta)\, t^{n/2} = f_1(\theta)t^{1/2} + f_2(\theta)t + f_3(\theta)t^{3/2} + \text{------} (10)$$

under the conditions:

$t = 0,\ Z > 0,\ \theta = \theta;$

$t > 0,\ Z = 0,\ \theta = \theta,$

where θ , is the initial moisture content of the profile, and θ is the saturated moisture content.

Since the power series converges rapidly, only the first few terms are significant in practical calculations. Figure 24 indicates linear relationship between Z and $t^{1/2}$, which coincides with the Philip's power series when using only the first term. This suggests that in a two dimensional plane flow model, the vertical water advance may be expressed by one-dimensional vertical infiltration equation. Its simplified solution is

$$Z = St^{1/2} \qquad (11)$$

In the Coto clay profile, S values are found as 1.01 and 0.37 with repect to discharge rates of Q = 1.3 ml/min/cm and Q = 0.2. ml/min/cm respectively. In Bayamón Sandy Loam, S values are 1.51 and 0.83 under the discharge rate of Q = 1.02 ml/min/cm and Q = 0.24 ml/min/cm repectively. The S value which has the dimensions of $L/T^{1/2}$, is an arithmetic parameter reflecting both soil properties and water application rate. In the same soil media, Hachum (1976) in his study of two dimensional water flow found that S is a linear function of water application rate. This means, in soils with similar structures, the vertical water advance can be calculated by equation 8 with estimated S values based on information of water movement under two different discharge rates.

In contrast to the vertical advance, the horizontal advance cannot be expressed with the simple diffusivity equation which has been discussed by many soil-water researchers. (Bruce & Klute 1956; Gardner & Mayhugh, 1958; Ashcroft et al 1962; and Nielson et al, 1962). When the horizontal advance plotted from figures 5, 6, 7 and 8 is plotted against the square root of time, as shown in figure 19a, the linear relationship is not pronounced. The

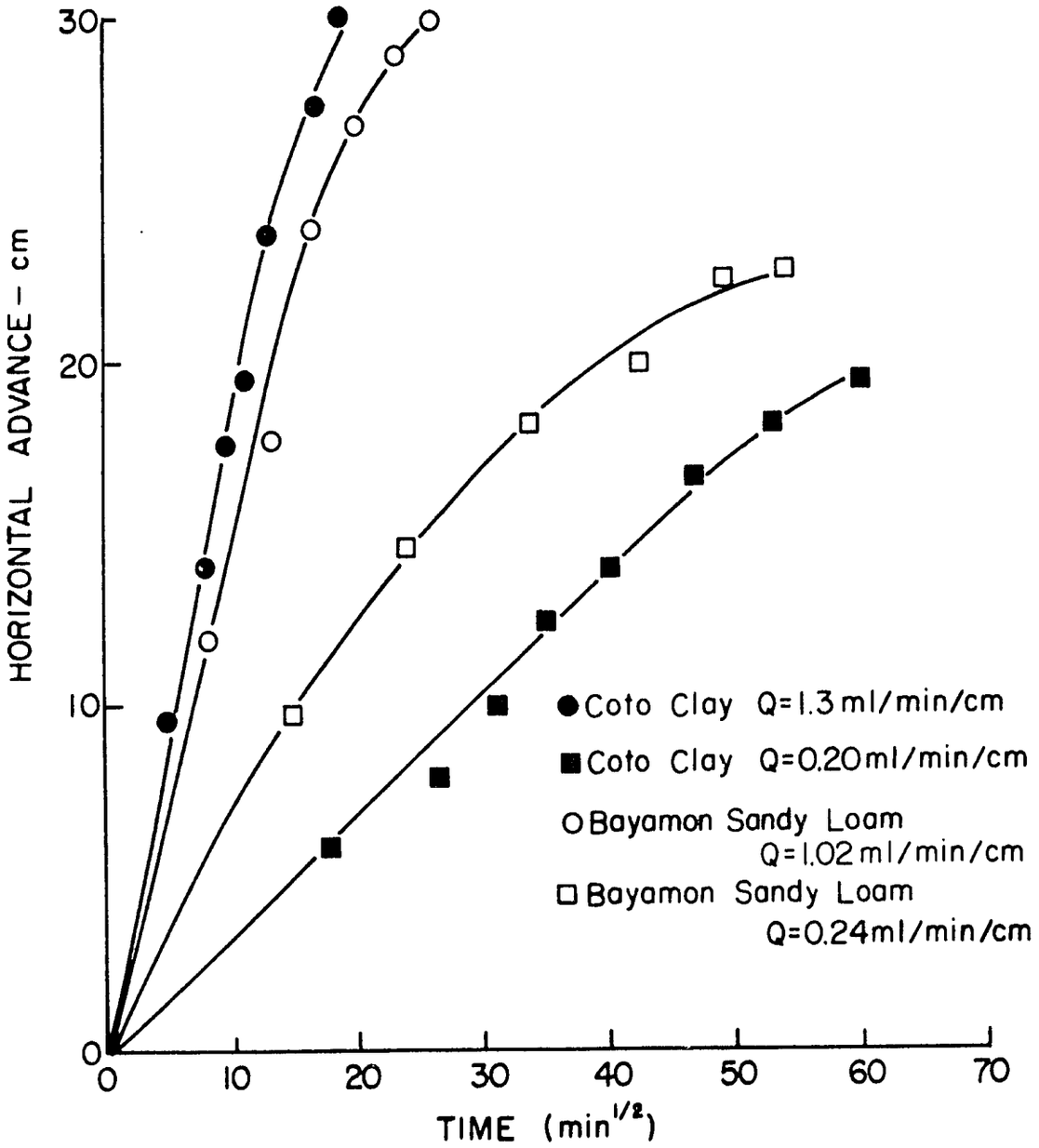


Fig. 19a The horizontal advance of wetting front versus square root of application time.

distance of lateral movement tends to approach a limit with increased infiltration time. This phenomena has been observed and reported by Bresler et al (1971) and its quantitative treatment has been presented in Chapter II, Section 1 of this dissertation.

The matric potential distribution in figure 9 and 10 can be used to estimate the width of saturated strips discussed in Bresler's equation. Recall equation (4).

$$\Phi(t) = \frac{1}{2\sigma}\left(\frac{q}{K_s}\right)$$

From figure 17, the saturated hydraulic conductivity, K_s, of Coto Clay is 3.187×10^{-4} cm/sec or 1.9068×10^{-2} cm/min. The K_s of Bayamón Sandy Loam is 3.89×10^{-3} cm/sec/ or 0.2334 cm/min. From figure 10, the estimated half widths of saturated strips in Coto Clay are 14 cm and 2.5 cm with discharge rate of Q = 1.30 ml/min/cm and Q = 0.20 mi/min/cm respectively. From figure 9, under discharge rate of Q = 1.02 ml/min/cm and Q = 0.24 ml/min/cm the saturated strips (half width) in Bayamón Sandy Loam are 12.5 cm and 4.0 cm.

Using $\Phi(t)$ = 17 cm; q = 1.3 ml/min/cm; and $K_s = 1.907 \times 10^{-2}$ cm/min in equation 4, the calculated value of σ in Coto soil is 1.9 cm^{-1}. Letting σ = 1.9 cm^{-1}, to check the experiment data under low discharge rate, Q = 0.20 ml/min/cm and the calculated half width of saturated strip is 2.6 cm, which is practically identical to the 2.5 cm estimated from figure 10. Using the same procedure, in the case of the Bayamón soil, σ is calculated to be 0.1748 cm^{-1}. Which again fits both discharge rates.

It has to be pointed out that during the four infiltration experiments

a ponded water strip was seen only in Coto Clay under the discharge rate $Q = 1.30$ ml/min/cm. However, from the tensionmeter readings, it is clear that a saturated zone near the drip emitters did occur. Water in the saturated zone is under zero tension and can be considered as free water. The saturated strip may be thought of as an invisible thin film of ponded water. Therefore, there is no physical difference between the two phrases "saturated strip" used in this thesis and "ponded water strip" which was used in the original report of Bresler et al (1971).

Based on the previous discussion, Equation 9 can be used to calculate the time needed per each irrigation. For example: let R be the desired depth of the root zone, substitute V by R in equation 9, then $R = St^{\frac{1}{2}}$ or the irrigation time t in minutes is equal to $(R/S)^{\frac{1}{2}}$.

Equation 7 is used to estimate the adequate distance between plant and drip tubing. In both direct planting and transplanting, the seeds or seedlings should not be planted within the saturated strip, particularly, in soils of poor drainage. Space for root system development should also be considered when choosing water application rates and frequency. Previous reports on drip irrigation design have stressed the distance between drip tubings by using the lateral water movement information, however, for all practical purpose, the distance between tubings, or the row space, is more subject to the nature of the crop and/or other cultivation factors such as machinery, micro-topograph, etc., than soil-water properties alone. Discussion of row space design based on the horizontal advance of irrigation water means very little to practical agriculture management. Calculated values of the width of saturated strip is useful information to help determine the distance and density of crop along both sides of the irrigation

tubing.

III-3-2 Distribution of Phosphorous

Inorganic P fertilizer tends to react with soil minerals, expecially with iron and aluminum Oxides of Oxisols, and become immobile in the soil. The larger the contacting surface between P fertilizer and soil particles, the more rapidly precipitation and/or adsorption reactions will take place. This is the reason banded P applications with minimum contacting surface is commonly recommended in soils with high oxide contents. When P is applied in solution form through a drip system, the soil structure or the nature of the pore tortuosity become important factors. Larger or less tortuous pore paths allow not only faster percolation, (less reacting time) but also reduce the total contacting surface. Consequently, dissolved P fertilizer may be carried deeper and farther in a medium. This is exactly what has been observed in the laboratory: Figure 11-a and 11-b show that P movement almost coincides with the wetting front in the sandy Bayamón soil. In Coto Clay, (figure 11-c and 11-d), however, very little mobilization of P is observed.

To further examine the P movement in sandy soil with relation to water application rate, figures 12 and 13 present the vertical and horizontal P distribution at various distances and depths from the simulated drip emitters. At horizontal distances of 5 cm and 10 cm from the emitters, the vertical distribution of P concentrations at the two discharge rates are almost identical to each other. However, high P concentrations along the vertical line 15 cm from the emitters is found at higher drip discharge rates. The P concentration differences between two discharge rates are more pronounced in the top 10 cm layer. This is because of the higher discharge

rate, Q = 1.02 ml/min/cm, the saturated zone around the emitters is larger than with the lower discharge rate. (figure 9). When there is solution flow in saturated pores, the solute which is in the central stream would have much less chance to be absorbed by or reacted with the soil surface and therefore, can be carried farther. From figure 9, the matric potential distribution in Bayamón Sandy Loam profile indicates that there tends to be less difference between the two discharge rates with increasing soil depth, and P concentrations decrease sharply between fully saturated and partially saturated soils. This explanation is further supported by data from the horizontal P distribution shown in figure 18. At the depths of 5 cm and 10 cm from the soil surface, the large amount of laterally moving saturated water flow at a discharge rate of Q = 1.02 ml/min/cm pushed P as far as 40 cm from the emitters at 5 cm depth and 20 cm from the emitters at 10 cm depth. At Q = 0.24 ml/min/cm, the P concentrations(at the depth and distance of 5 cm and 10 cm) are close to the concentrations when Q = 1.02 ml/min/cm. Beyond the 10 cm radius saturated zone, P concentrations drop rapidly. At the depth of 15 cm and 20 cm, the distribution of P concentration shows no relation with discharge rate.

In conclusion: P moves more freely with saturated soil-water flow in the soil. The distance of P migration is reflected by the matric tension or degree of saturation of the soil. High P concentrations are also noticed near the emitters. Because the saturated conditions near the emitter prevent root development, the efficiency of P utilization in this zone as applied through a drip system would probably be low. Other methods of P fertilizer placement should be considered together with P solution applied through a drip system.

CHAPTER FOUR:

A DRIP IRRIGATION EXPERIMENT AT ISABELA, PUERTO RICO

IV-1 The Physical Environment

The Isabela Experimental Substation is located in northwestern Puerto Rico on an area dominated by Coto series soil, an Oxisol, about five miles south of the coast (Fig. 20). The general topography of this area is flat to gently rolling. Major vegetation consists of sugarcane and pasture, with small areas in plantains, citrus and vegetable crops. Average annual rainfall is around 170 cm (66 inches). However, much of the rainfall may not be utilized by crops because of the erratic distribution pattern and the low available water holding capacity of the soil.

Figure 19 shows the soil-water retention curve and corresponding unsaturated hydraulic conductivities of the Coto soil. The narrow range of adequate soil moisture content for optimal plant growth, usually occurs in the field for only a half day after a heavy rainstorm. With the rapid loss [illegible] assuming an average evapotranspiration rate of [illegible] cm/day under the tropical sun, in four or five days without subsequent precipitation, most of the shallow rooted crops suffer from moisture stress.

Figures 21 and 22 show the annual rainfall distribution during the years of 1966 to 1975 and the average, highest, and lowest monthly rainfall distribution in the same ten-year period. Figure 23 is the monthly rainfall distribution and pan evaporation rate during June, 1976 to May, 1977, the period of this field experiment. In spite of the high rainfall in August and September of 1976, drought periods did occur in those two months. Supplemental irrigation is necessary in this area to assure a stable crop yield.

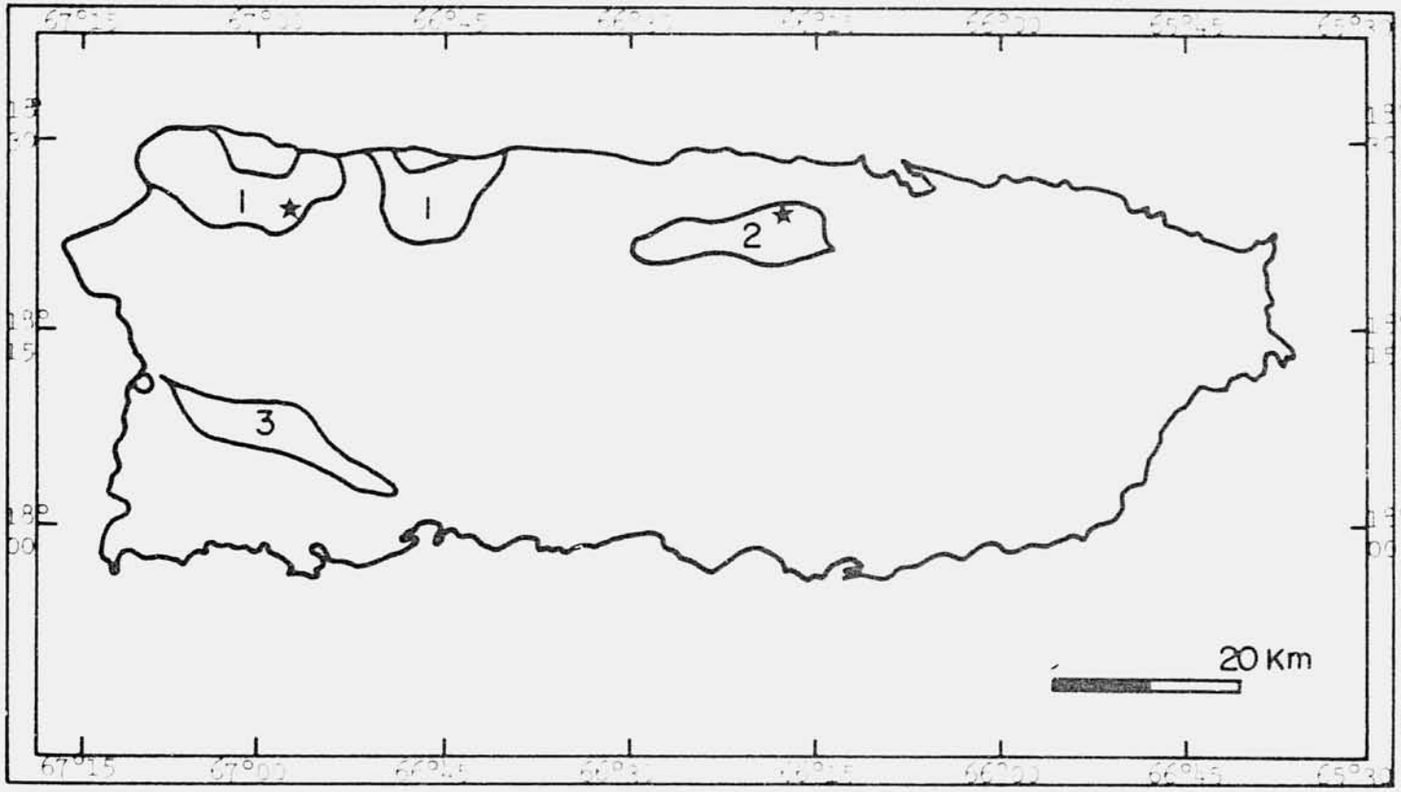


Fig. 20 Distribution of xinolite in Baffin Island: 1. [illegible] series, 2. Paquet series and 3. Tire series. Star marks indicate the [illegible] sites of Clay Lake and Mansel Lake [illegible].

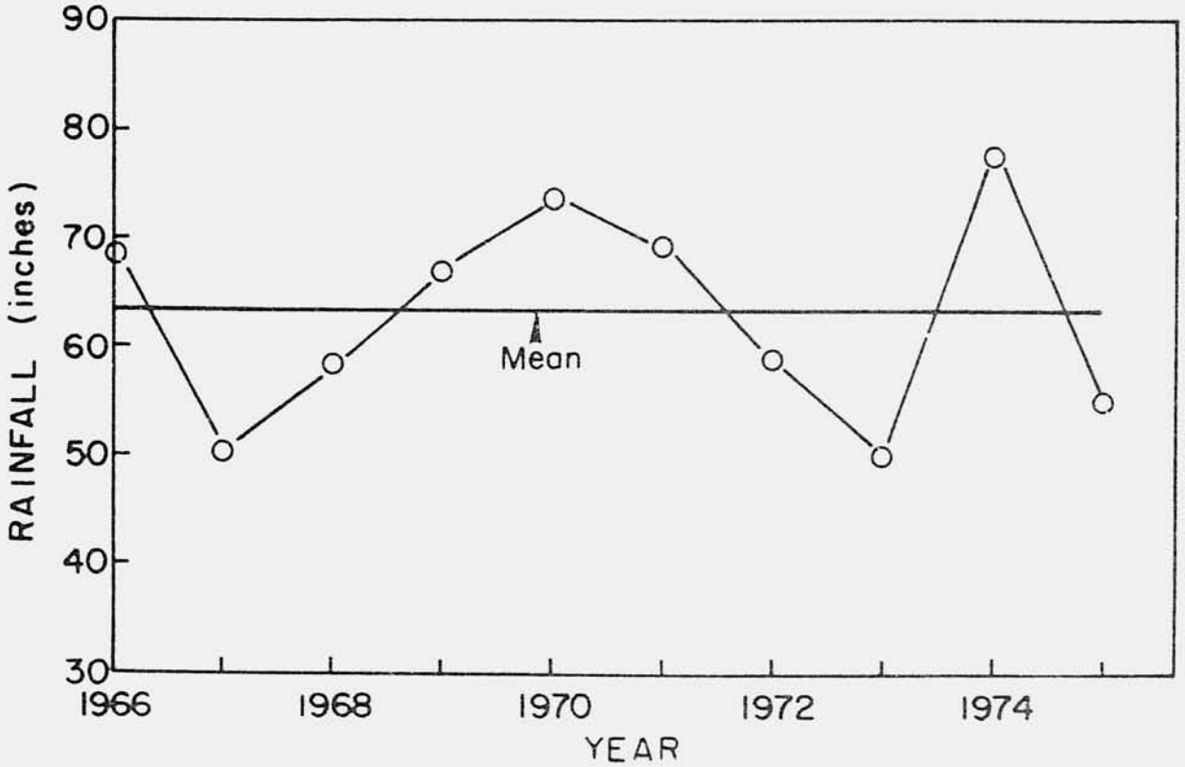
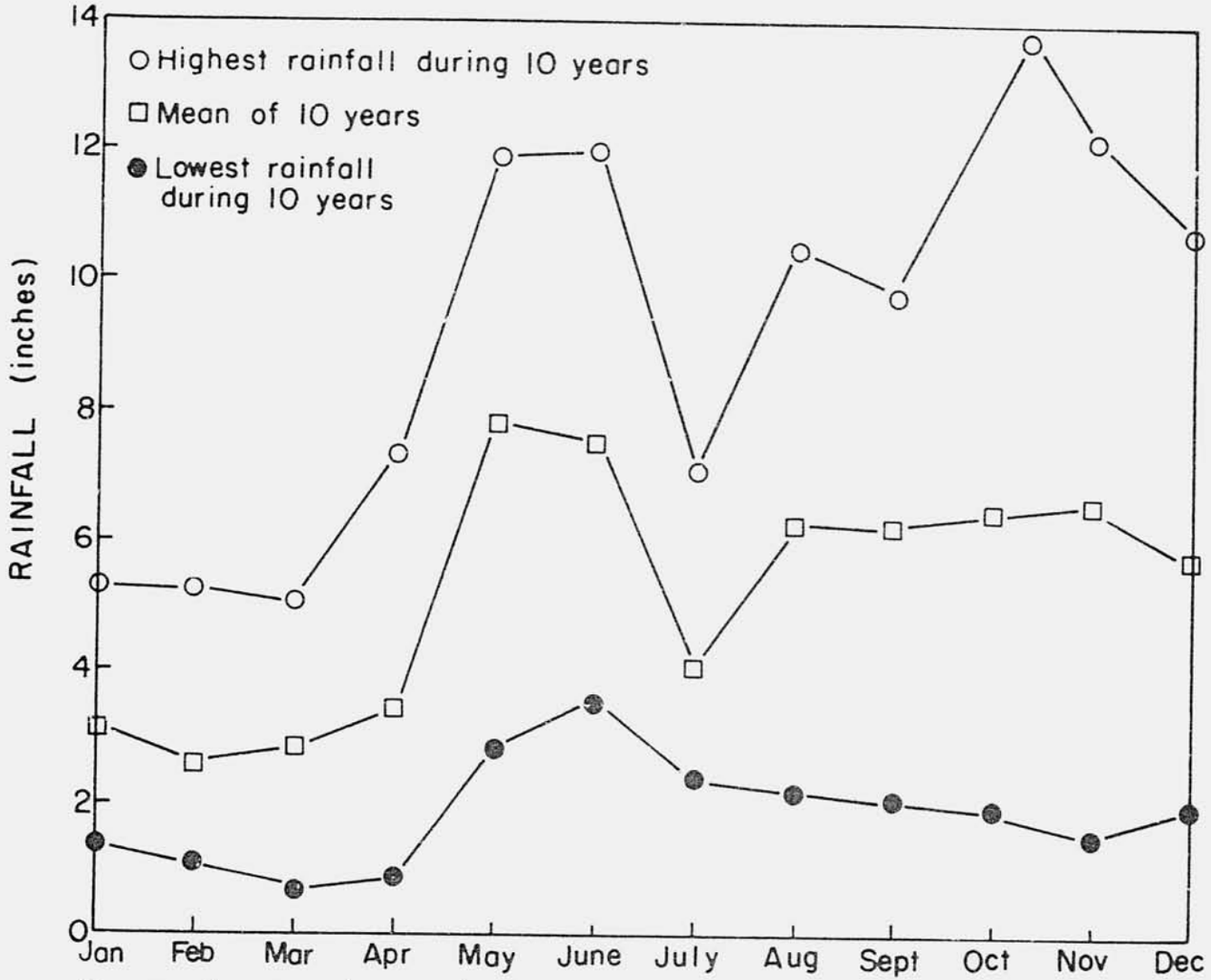


Fig. [illegible] Annual rainfall [illegible] Experiments, Farm Plant [illegible]


Highest rainfall during 10 years
Mean of 10 years
Lowest rainfall during 10 years
RAINFALL (inches)
0
2
4
6
8
10
12
14
Jan
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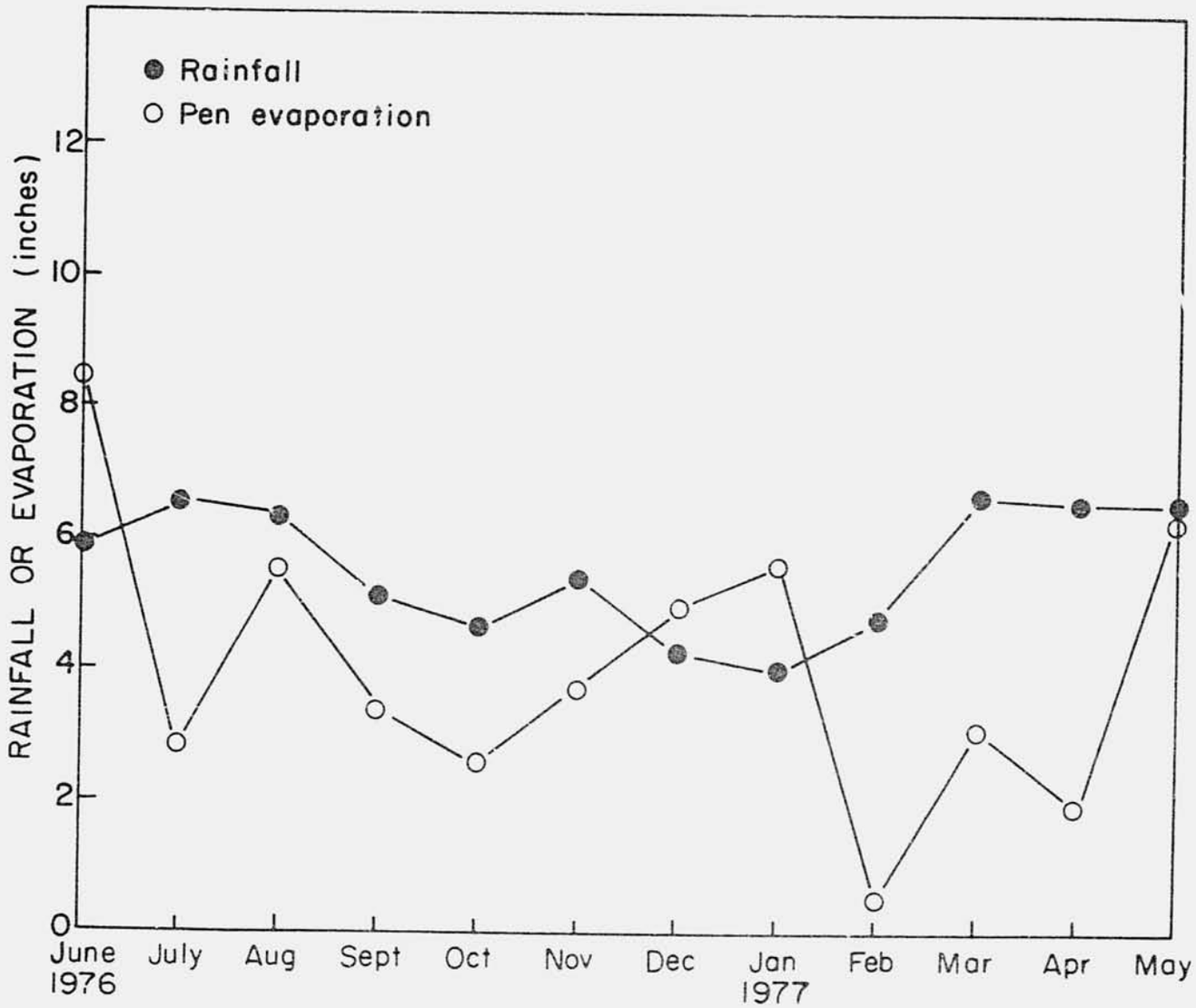
July
Aug
Sept
Oct
Nov
Dec


Rainfall
Pen evaporation
RAINFALL OR EVAPORATION (inches)
0
2
4
6
8
10
12
June 1976
July
Aug
Sept
Oct
Nov
Dec
Jan 1977
Feb
Mar
Apr
May

IV-3 Materials and Methods

IV-3-1 Experimental Design

The field experiments were designed to determine the feasibility of drip irrigation under both wet and dry seasons and to compare different fertilization techniques that may be employed together with a drip irrigation system.

An area, 40 meters by 50 meters with a slope of less than 2% from south to north, was selected as the experimental site. There were windbreaks along the east and north edges of the selected area and a farm road with a line of Australian Pine trees form the west border. To the south across a 5 meter wide border zone, were some other experimental plots. Surface soil pH is 5.4 in H_2O and 4.8 in 1N KCl, and the subsoil (10 to 21 cm) pH is 5.0 in H_2O and 4.7 in 1N KCl. This data soil is classified as Typerolic Eutrorthox, clayey, kaolinitic, isohyperthermic. Exact history of land use of the experimental area was difficult to obtain, however, this area has been fallow for at least five years. Laboratory tests suggested rather uniform soil fertility over the entire area.

Three different methods were used to apply the same total amount of fertilizer throughout each growing season. Including the check plots, the total four treatments were arranged into a completely randomized block design with six replicates (Fig. 24). Each block had two 2m x 10m beds. Irrigation tubings were laid along the center line of each bed. Thirty sweet pepper plants, Blanco del Pais variety, were planted triangularly in two rows on each bed, 15 cm to each side of the irrigation tubing. Pepper was chosen as the indicator crop for its long growing season and also for its sensitive response to soil moisture and nutrient supply.

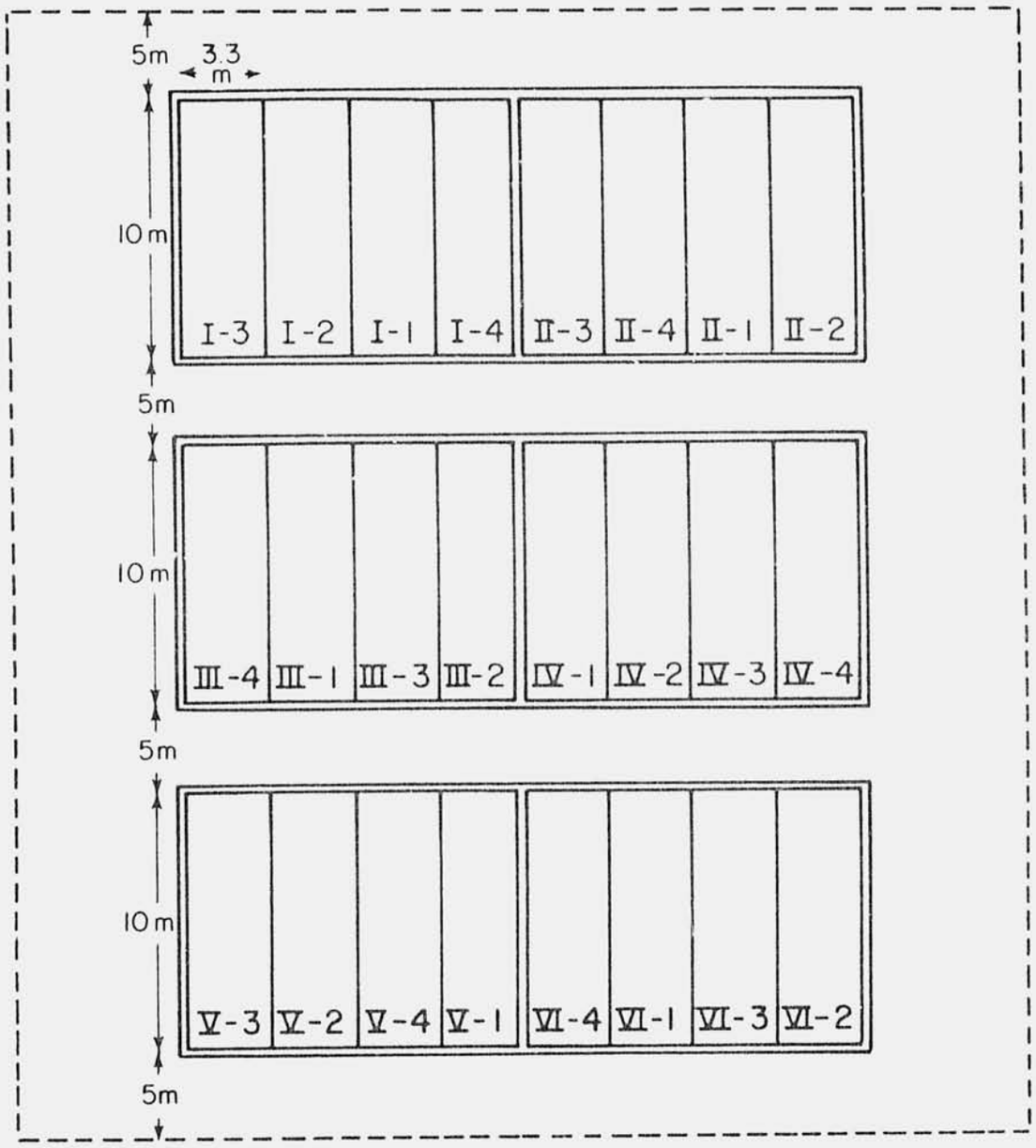


Fig. 4. Field Experimental Design = Randomized Complete Blocks.

Treatments = No. 1. Soluble N, P, through tubing, banded P.

No. 2. Banded N, P, P.

No. 3. Broadcast N, P, P.

No. 4. Check

Since the experimental site had been fallow for at least five years, a small amount of complete fertilizer, 12 kg of 10-10-10, was broadcast over the entire area, including check plots, to guarantee at least minimum crop growth especially during the initial stage. Pre-emergence herbicide and soil and leaf sanitizers were applied regularly at recommended dosages (in consultation with local agronomists). Detailed cultural practices are described in section 12-3-3.

The recommended fertilizer rate for pepper in Puerto Rico are two grams (2.7 oz) of a 10-10-10 fertilizer per plant, or 1000 pounds/acre (1120 kg/ha) as base fertilizer, and a sidedress of an equal amount after the third pickings. Based on this fertilizer rate, the four treatments used in the experiment were as follows:

Treatment I: Fertigation

Urea (46% N) and potash (60% K_2O) were dissolved in water and injected into the drip system with positive pressure. In total, 9 kg of urea and 4.5 kg of potash were applied per plot through each growing season. The injections were carried out weekly and the dosage of each injection was adjusted so as to meet the plant's need during the various growth periods. Detailed field operations are discussed in section 12-3-3.

Triple superphosphate (TSP), 46% P_2O_5) was applied to the inner side of each row within 7 cm of the plants. 4.5 kg of TSP were banded before transplanting and an additional 4.5 kg were sidedressed after the third picking.

Treatment II: Banded Application of Fertilizer

Twenty kg of a 10-10-10 fertilizer were banded along both sides of the irrigation tubing, 7-10 cm deep and 7 cm to the side of the plants be-

Tape transplanting included band fertilizer for this treatment with an additional 10 kg fertilizer of the same kind were distributed after the first picking.

Treatment III: Broadcast fertilizer application

A 10-10-10 fertilizer was broadcast in the center 1 m wide strip of each bed. The amount of fertilizer and time of application were identical to Treatment II.

Treatment IV: Check plots

Additional fertilizer was applied in the check plots, after the 1[illegible] kg initial application of 1[illegible]-1[illegible]-1[illegible] fertilizer broadcast over the entire experimental area.

IV-2-[illegible] Drip System Design and Operation

The drip system was designed for row crops using porous plastic tubing (Jiaflo tube, [illegible]. I. Dupont De Nemours, Wilmington, Delaware)* to apply water to the soil. Other parts of the system were constructed by using materials which were available in most hardware stores.

The system includes three major components: 1) the head unit, 2) the chemical injection apparatus and 3) water delivery system. Both the head unit and the chemical injection device were designed to avoid the use of electricity and other types of fossil fuel energy input.

Head Unit: In order to independently manage the fertigation and other water application treatments, a "double head" head unit (Fig. [illegible]) was designed for this experiment. All the components and pipes of the

*/ Trade names are used for identification purposes only and do not imply preference for this material by the researcher.

head unit were of 3/4 inches (1.9 cm) inner diameter. Durable metallic components were used in the up-stream side of each filter, but only plastic materials were used in the down-stream side of the filters to avoid the appearance of fragments of metal rust in the tites. The function of each component is described as follows: (numbers refer to numbers in Figure 25).

1. On-off valve: to control water flow into the irrigation system, usually opened.
2. Pressure regulator; to reduce the inlet water pressure to and maintain at a favorable operational pressure. In this particular system it was about 4 psi.
3. Standpipe with clear tygon tube: this 2 inch (5.08 cm) diameter 2.7 m high standpipe was used as a safety device to vent excess water and reduce the system pressure when the pressure regulator failed to function. 3/8 inch (0.6 cm) diameter tygon tube is attached to the standpipe for pressure measurement.
4. Section on-off valves: used to control the water flow in different treatments.
5. Pressure gauges: to indicate pressure in the two separate pipe lines.
6. Water meters: to record the amount of water used in each irrigation.
7. Check valve: to prevent back flow of irrigation water and fertilizer contamination of the non-fertigation treatments.
8. Chemicals or fertilizer inlets: inlets to inject predetermined chemicals.

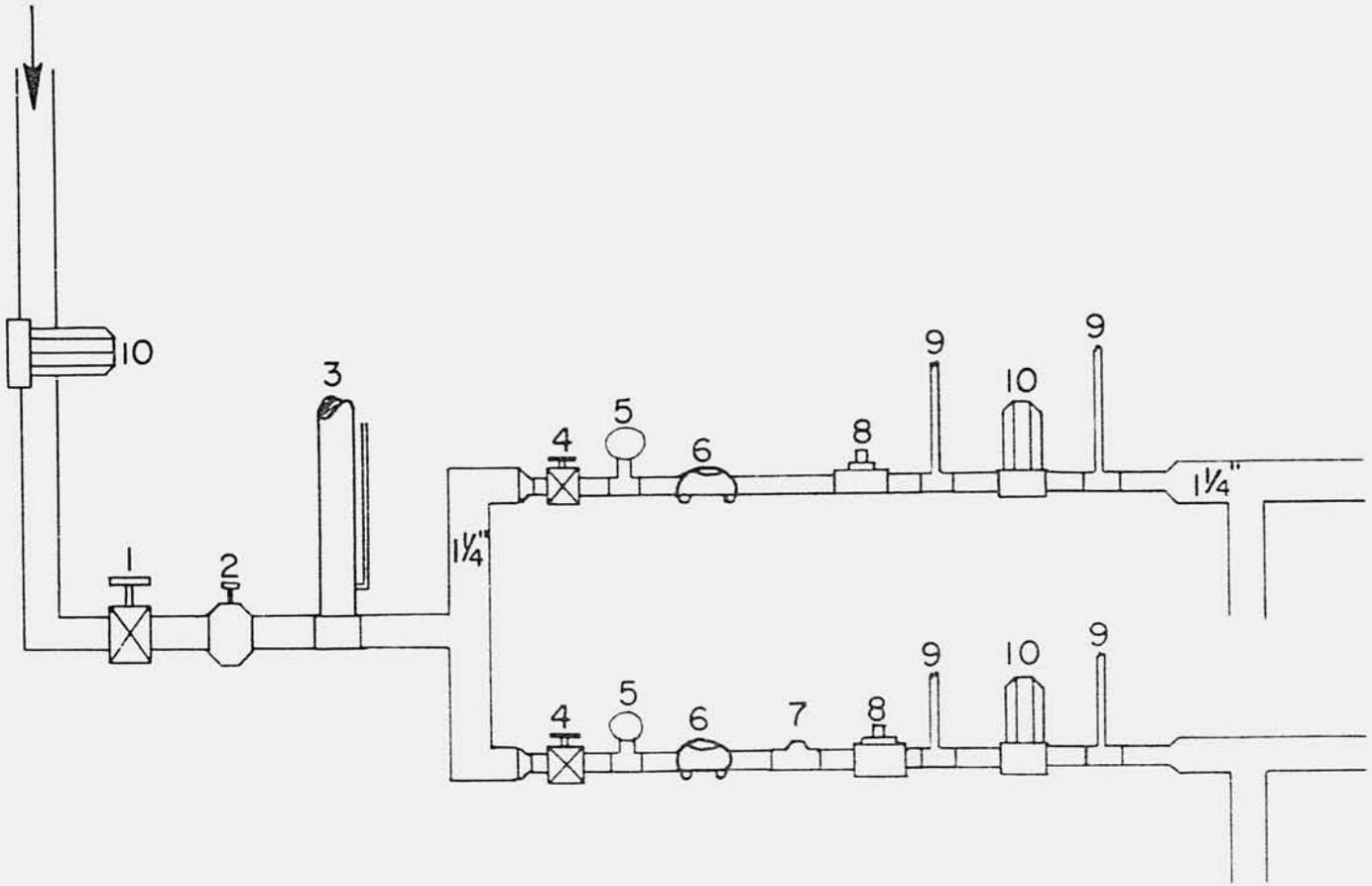


Fig. 35 "Heat Unit" of the Irradiation System.

9. Clear standtubes: to indicate the pipe pressure before and after the filters. When the difference in height of each pair of tubes exceeds 0.5 m the cartridge of the filter should be changed.

10. Filters: to remove suspended solids from irrigation water and nutrient solutions and to protect the porous plastic tubing from clogging.

<u>The Chemical Injection Apparatus</u>: The chemical injection methods employed in this experiment were designed: (1) to avoid the use of electrical or fossil fuel energy, and (2) to obtain reliable operational accuracy.

A simply gravity method was used to inject chemicals such as pesticides or system cleaner (HCl or other detergent), which are usually used in small quantities. As shown in Fig. 29, the set-up consists of a 5m pole, a 5 cm pulley and a 2000 ml polyethylene bottle tied on with No. 5 nylon string.

Secondly, the concentrated chemical solution in the hanging bottle falls by gravity through a tygon tubing and a 17 gauge syringe needle and is injected into the irrigation system. The injecting pressure can be controlled by raising the bottle to the desired height. In this experiment, the bottle was always hung at the top of the pole; 4.5 m or 6 psi. The operational pressure of the drip system was 3 psi., therefore, the chemicals were injected into the system with a 3 psi positive pressure. Time needed to inject 2000 ml of concentrated HCl into the system was about 28 minutes, and to inject 2000 ml of soil insecticide (Lannate 90%) was about half an hour.

The concentration (ppm) of chemicals in irrigation water can be calculated by the following equation:

$$ppm = N \times 2000\ ml \times 1/VT \quad \text{----------} (12)$$

where:

N = concentration of the solution in the hanging bottle,

V = Volume in ml of irrigation water discharged within time T, and

T = Time needed to inject the 2,000 ml solution. T varies with height of the bottle. The values of T vs. different heights are shown in Appendix (Fig. 41).

A pressure system was designed to apply fertilizers. The system (Fig. 27) contains a 30 gallon steel fertilizer container which can withstand at least 100 psi internal pressure. The interior of the container was painted to prevent corrosion. A compressed air tank was connected to the fertilizer container to provide the essential pressure through an air valve. The fertilizer solution was injected into the system through a 1/8 (0.31 cm) inch tube which was built in the inlet of the heat unit. Some glass-wool material was stuffed in the connecting tube for preliminary filtration.

Desired injecting rates may be obtained by adjusting the container pressure. The injected quantities of fertilizer solution vs. container pressure are presented in Appendix (Fig. 4). A 20 psi container pressure was used all through the experiment.

Equation (13) is used to determine the concentration of the fertilizer solution:

$$C = F/a \times A \times 1/ft \quad \text{----------} (13)$$

where

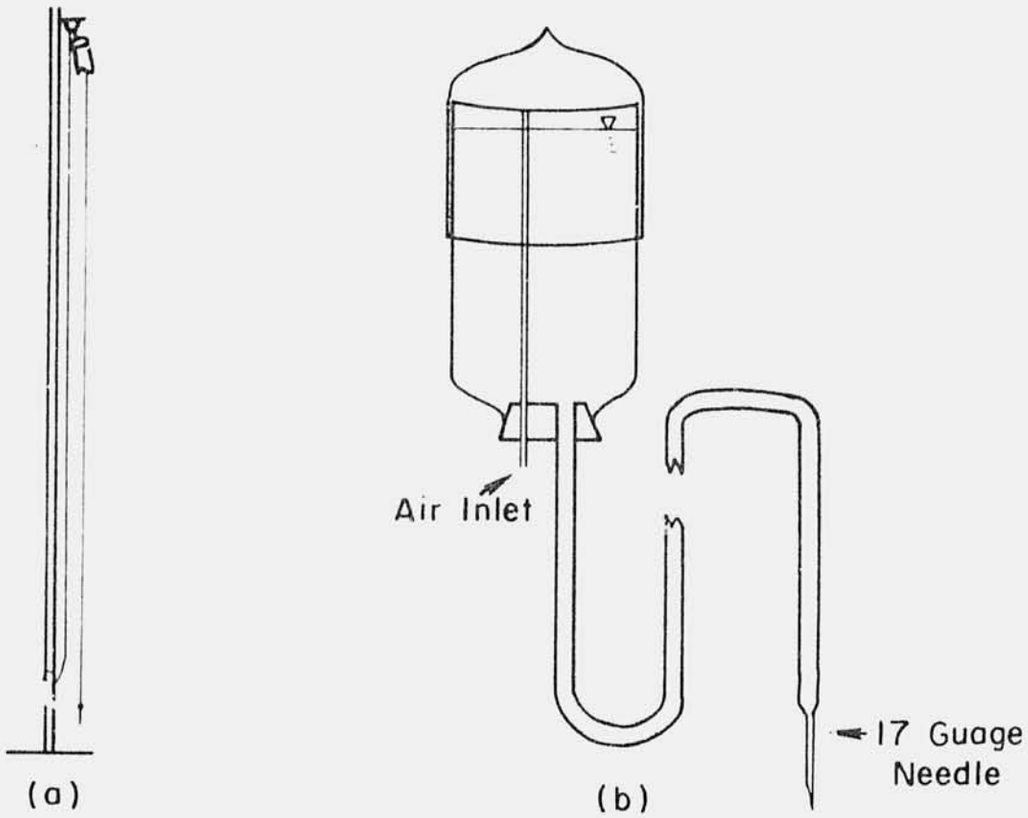


Fig. 4. The principle design of the gravity method.

a. The bottle hung on a standing pole.

b. The structure of the bottle.

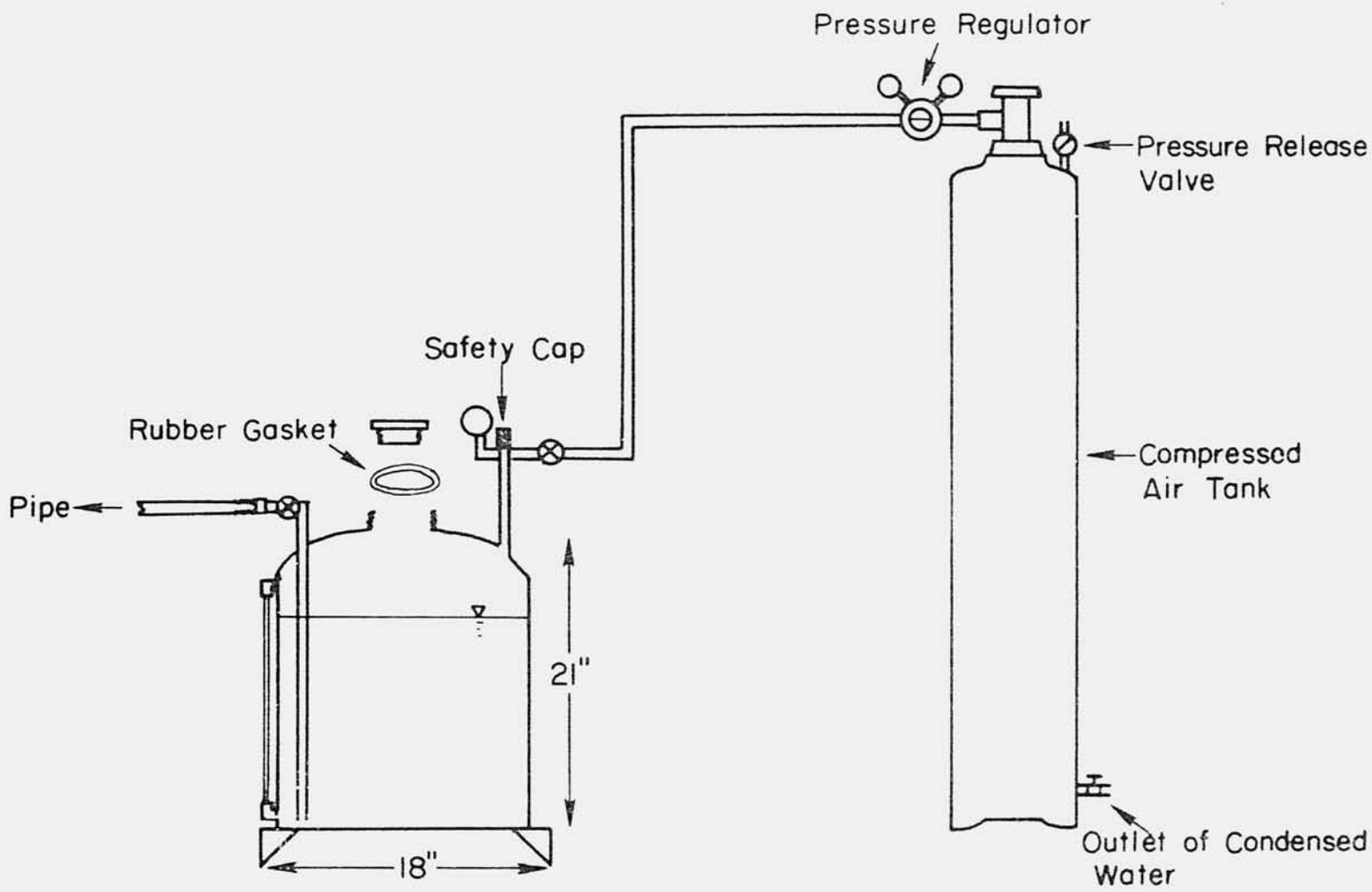


Fig. [illegible] The Condition Interior [illegible].

C = the concentration of fertilizer solution (kg/ml),

Q = the rate of injection (ml/min) (see Fig. b., Appendix),

F = the quantity of fertilizer being applied (kg/ha),

A = irrigated area (ha.),

t = the duration of each irrigation time (min.) and

f = the ratio between fertilization time and irrigation time.

A shorter fertilization period is necessary to allow time to flush the system. An f value equal to 0.25 was chosen in this experiment. The injection of fertilizer was usually started 10 to 15 minutes after the irrigation started and lasted 30 minutes, or 1/4 of each irrigation time.

Water Delivery System and Filtration:

Plastic pipes (PVC) 1-1/4" (3.17 cm) diameter, polyvinyl, non-corrosive plastic accessories were used for the main water distribution lines. The larger pipe diameter was chosen in consideration of friction head losses in this low-pressure, low-flow system.

Viaflo porous plastic tubings were used to deliver water and/or fertilizer solution to the plants. The porous plastic tubings were placed along the central line of each bed, 2 m apart from each other. In order to protect the tubings from the tropical sun as well as to make field operations easier, all the delivery tubings were buried about 5 cm below the soil surface.

A 30 cm long, 0.9 cm outer diameter plastic feeder tube was used to connect each porous delivery tubing and the main water conducting line. One end of the feeder tube was pushed into a 21/64" (0.83 cm) hole drilled on the main line and the other end was coupled to the porous tubing using

an O-ring and a connector cone. To close off the ends of the porous tubing, the tubing was folded back about 3 to 4 cm, pinching the fold together and inserting into a connector cone. The folded ends could be opened to clean the porous tubing by flushing if a build up of solids occurred inside the tube. In this experiment, it was not necessary to flush the tubes.

House water filters, 3/4" (1.9 cm) with 5μ cartridges were used to protect the system from clogging. With the high content of solid suspensions, the filter cartridges had to be replaced every 4 or 5 weeks. HCl was injected into the system once in the middle of every growing season to dissolve the possible chemical precipitates on the inner wall of the porous tubing. However, there was no significant increase in water discharge rate immediately after the cleaning. This might suggest that the mineral ion concentration in the water source was not very high.

Reasonably constant water delivery rate was observed throughout the experimental period. As shown in Fig. (5), Appendix, after a 2-week breakthrough period, the discharge rate of the system was maintained at about 1,500 ml/hour/meter length of tubing.

IV-2-3 Cropping

Two crops of sweet pepper were grown to cover a complete dry season and a complete wet season experiment. The sweet pepper, Blanco del Pais variety, is a local, high-yielding, disease resistant variety. Recommended growth period/crop of this variety is 6 to 7 months. Previous data showed that under traditional cultivation, with proper moisture and nutrient

management 10 to 12 tons of pepper may be harvested/crop/acre (about 10,000 kg/ha).

The pepper was planted from seeds in peat pots under greenhouse conditions. Thirty-five days later, when the plants were about 20 cm tall, they were transplanted, after hardening, into the field experimental plots. The plant population in the field was established as equivalent to 5,400 plants/acre.

The experimental area was machine-plowed to a 25 cm depth before the first crop and hand plowed to 15 cm before the second crop. Base fertilizer was applied four days before each transplanting. Side-dressed fertilizer was applied after the third picking, or 13 weeks after transplanting. The fertigation treatment received liquid N and K fertilizer weekly. The total 9 kg of urea and 6.8 kg of potash used in the fertigation treatment/each crop was divided into 30 subunits. In the 2nd crop, in the first and last five weeks of the 20 week growth period, one unit of fertilizer was applied each week. During the middle 10 weeks of the growing season, two units of fertilizer were applied in each fertilizer application to meet the plants' need. However, due to a delay in the construction of the fertilizer tank, fertigation was not used in the wet season crop until the 3rd week after transplanting. Two and half units of fertilizer were injected in the first two fertigation treatment of the wet season crop.

Diphenamid (Enile 50W), a pre-emergent herbicide, was sprayed over all the plots three days after transplanting. Insecticide (Lannate 90S)

and fungicide (Dithane M-45) were applied biweekly or whenever necessary. Insecticide (Lannate 90%), which injected into the drip system, was applied every two to three months to control damage by soil insects (ants, earwigs, etc.). Monthly weeding was necessary during the wet season crop, while during the dry season crop, only two weedings were needed. All weedings were performed by using garden hoes.

Twelve tensiometers were randomly installed in the experimental area at depths of 15 cm and 30 cm. Irrigation frequency and duration were manually controlled on the basis of the soil matric potential and/or previous day's pan evaporation. Tensiometer readings indicated a uniform distribution of irrigation water through the drip system and the soil moisture content in the root zone was maintained within field capacity throughout the growing season.

Small holes in the porous tubing punched by soil insects (ants?) or other animals (rats?) were observed quite frequently during both the wet and dry season crops. In most instances, these holes could be sealed by applying a small quantity of plastic cement to the damaged point. Injection of soil insecticide through the system reduced the number of holes observed the following week.

Plant diseases appeared in the dry season crop 12 weeks after transplanting. The leaves of affected plants first curled and turned yellow in color. Although only a few of the affected plants eventually wilted and died, in most of them flowers and fruits were less than in non-affected plants and suffered a setback in growth. Pathological analysis of leaf samples revealed the presence of Puerto Rican mosaic virus, a major disease

of pepper and tomato plants in Puerto Rico, usually spread by aphids. After increasing the number of insecticide sprays, the aphid population was controlled and the spreading of virus slowed down. However, the total yield of the dry season crop was decreased by almost 20% as compared to the first crop.

Leaf samples were taken at the 8th and 16th week after transplanting for nutrient up-take analysis. At the end of the first crop, soil samples were taken for fertilizer residue studies from each treatment with 50 centimeter increments both vertically and horizontally from the irrigation tubing. Soil samples were also taken on August 18, 31, 1976 and February 28, 1977 for moisture distribution studies (Fig. 28). Mature fruits were selected and hand-harvested by experienced farm laborers biweekly to obtain yield data.

Table 7 is a farm calendar for all the cultural practices during the two cropping seasons.

IV-2-4 A Study of the Development of Root Systems

Just before the removal of the first crop, the root system development of plants from each treatment was examined and measured both visually and quantitatively. Plants with well-developed crowns and reasonable yield history were chosen for root pattern studies. Weeds, if any, on the selected spots were removed carefully with their own roots.

Table 2. Major activities of cropping and dates performed in both wet and dry season crops

Activities	Dates performed	
	Wet season crop	Dry season crop
Preparation of soil mix for seedlings	May 25 - June 1, 1976	Oct. 2[illegible] to Oct. 25, 197[illegible]
Plant seeds in rent pots	June 7, 1976	Nov. 1, 1977
Apply bacteriacide to seedlings	June 2[illegible], 1976	--
Land preparation	July 5 & 6, 1976	Dec. [illegible] & 5, 1977
Install irrigation system and apply base fertilizer	July 10, 11 & 12, 1976	Dec. 4, 5 & 6, 1977
Transplanting	July 14 & 15, 1976	Dec. 7 & 8, 1977
Apply pre-emergence herbicide	July 1[illegible], 1976	Dec. 1[illegible], 1977
Install tensiometers	July 1[illegible], 1976	Dec. 1[illegible], 1977
Sidedress fertilizer	Sept. 7, 1976	Feb. [illegible], 1977
1st. weeding	Sept. 7, 1976	March 2, 1977
2nd. weeding	Oct. 1[illegible], 1976	--
Clean irrigation system	Sept. 2[illegible], 1976	Feb. [illegible], 1977

Table 2 (Cont.)

Activities	Dates performed	
	Wet season crop	Dry season crop
Inject soil insecticide	August 19, 1976 & Sept. 29, 1976	--
Take soil moisture samples	August 14 & 31, 1976	Feb. 28, 1977
Take leaf samples	Nov. 4, 1976	April 20, 1977
Take soil samples for nutrient distribution studies	Nov. 22, 1976	--
Measure root system development	Nov. 24 & Nov. 26, 1976	--
Harvests	Sept. 10, 24, Oct. 8, 22, Nov. 5, 19 and Dec. 3, 1976	Jan. 28, Feb. 11, 25, March 11, 25, April 7, 22, May 6 and May 20, 1977
Routine sprays of pesticide	Same day after each harvest	Same day after each harvest
Extra sprays of pesticide	--	March 4, 18, April 1 & April 15, 1977
Apply N & K to Treatment I through irrigation system	Aug. 6, 13, 20, 27, Sept. 3, 10, 17, 24, Oct. 1, 8, 15, 22, 29, Nov. 5, 12, 19, 26, 1976	Dec. 10, 17, 24, 31, 1976 Jan. 7, 14, 21, 28 Feb. 4, 11, 18, 25 March 4, 11, 18, 25 April 1, 8, 15, 22, 1977
Irrigation	Every one or two days depending on pan evaporation data	Same as wet season

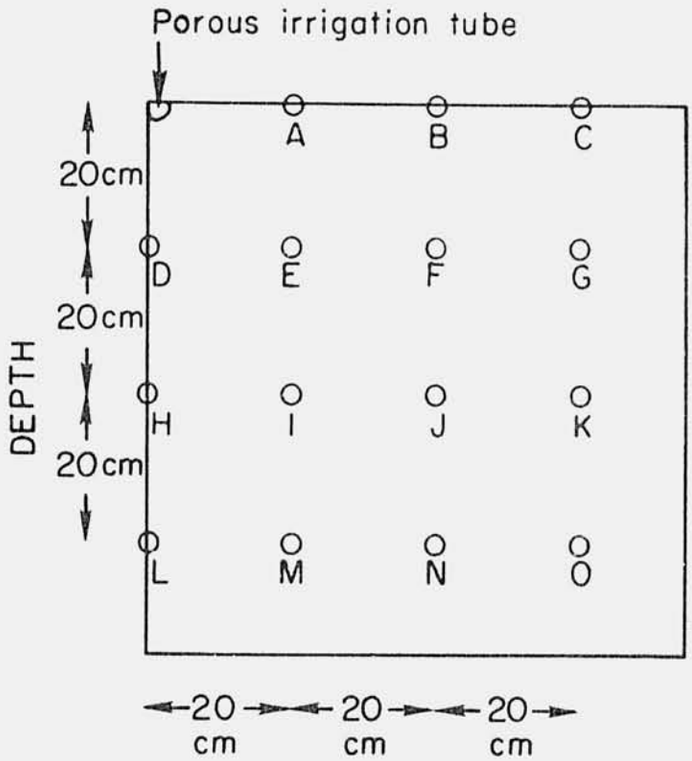


Fig. 3 Positions of soil samples taken from the profile for soil moisture content and nutrient distribution study.

Visual examination of root system distribution: After preliminary determination of the maximum vertical and horizontal extension of the root system in each treatment, a complete root sytem was washed out with water by using a hose. The hose was connected to the irrigation head unit and the water pressure was controlled within 4 to 5 psi. The entire root systems, then, were air-dried, and photographed.

Root Weight: In each treatment, a soil block of 90 cm wide, 100 cm long (along the irrigation tube) and 35 cm deep, containing two pepper plants, was divided into 4 layers lengthwise and 5 sections in width. (Fig. 29). The whole block was then divided into 1[illegible] units. Each unit was excavated with a square edged shovel. The roots and soil were separated by washing through a large home-made sieve. Roots were then oven-dried at 80°C for 24 hours and weighed. Because the extended root sytems of two adjacent plants usually mixed to various degrees in the central zone of soil, average root weight in each section of two adjacent plants were used for analysis.

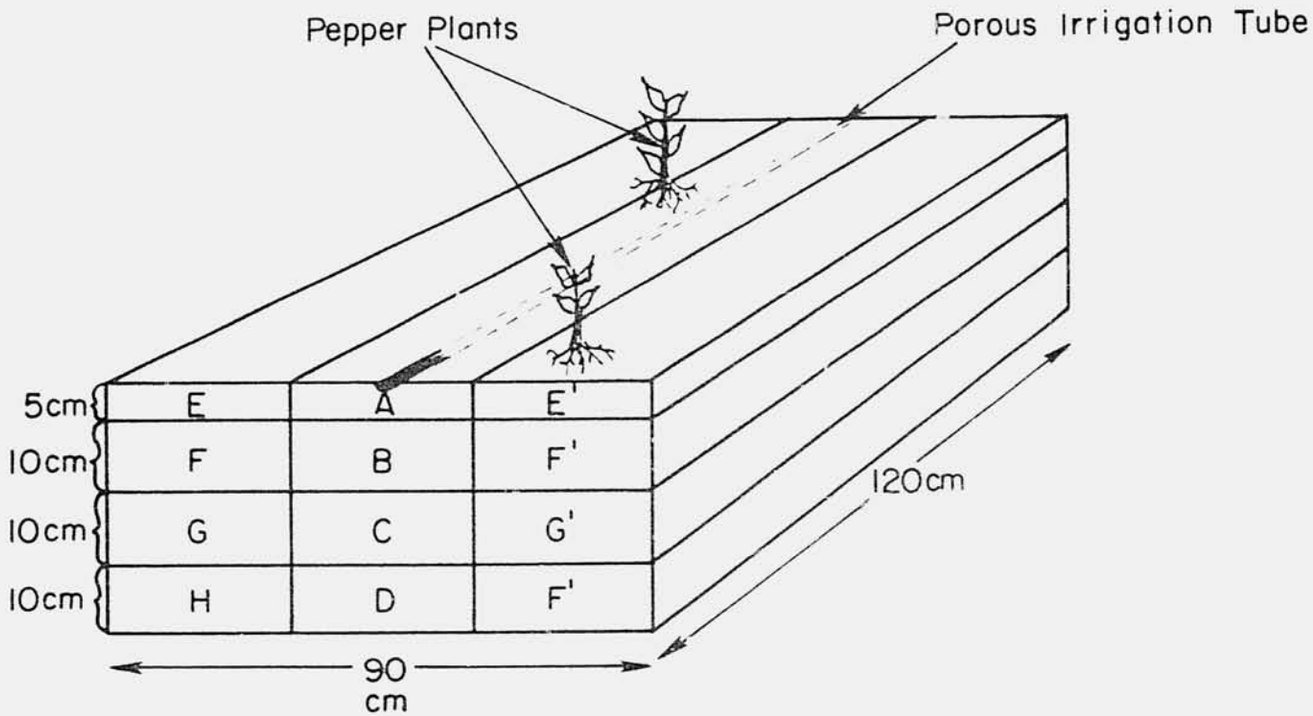


Fig. [illegible] Dimensions of [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

IV-3 RESULTS

IV-3-1 Soil Moisture Profiles

Table 3 presents data on soil moisture content. Figure 30-a presents average values of soil moisture content in the profile (wet season). Figure 30-b is the dry season soil moisture profile. The wet season moisture profile suggests a steady soil moisture increase with depth under the irrigation tubing. The increase follows a line at an angle of 45° more or less to the soil surface and extends down to about 50 cm deep. Above this line, the soil moisture content is on the higher tension side of field capacity. Below this line, soil moisture content is on the lower tension side of field capacity. The relatively drier soil surface started at a horizontal distance of 30 cm from the drip tubing and extended to a depth of less than 20 cm.

The dry season moisture profile showed an interesting bulb shaped wetted soil mass immediately below the drip tubing extending to a depth of 40 cm. Below 40 cm, the soil moisture content increased steadily with depth. The dry soil surface followed a similar pattern as the wet season soil moisture profile, at 30 cm horizontal distance from the drip tubing, but the top 20 cm layer of soil was much drier than it was in the wet season. The soil moisture content of the dry strips between two drip tubings practically reached the permanent wilting point.

IV-3-2 N, P, K and Conductivity Distribution Patterns

Figures 31, 32, 33 and 34 show the N, P, K and conductivity distribution patterns under the four treatments. Selected soil chemical characteristics of Cato clay are listed on Table 4. The N, P and K values on Figures 31, 32, 33, and 34 have been adjusted to the depth effect. These adjusted values reflect the true movement of the fertilizer added.

Table 3. Soil moisture distribution in the profile under drip irrigation

Wet season crop

Sample location 1/	Moisture content on % dry weight basis		
	1st sampling (Aug. 18, 1976)	2nd sampling (Aug. [illegible], 1976)	Average
A	25.4	27.0	26.19
B	23.8	24.1	23.96
C	[illegible]	[illegible]	[illegible]
D	26.4	29.[illegible]	29.56
E	[illegible]	28.4	27.11
F	4.8	25.3	25.02
G	4.5	28.0	25.13
H	25.[illegible]	29.1	28.86
I	28.9	29.[illegible]	29.11
J	25.0	26.6	25.9[illegible]
K	27.1	25.[illegible]	25.39
L	29.1	28.[illegible]	28.68
M	29.6	28.[illegible]	29.29
N	27.7	27.[illegible]	27.44
O	28.3	27.9	28.10

Dry season crop

Sample location 1/	Moisture content on % dry weight basis
	Sampling date: February 29, 1977
A	24.5
B	18.8
C	19.4
D	27.[illegible]
E	24.8
F	20.[illegible]
G	21.2
H	29.2
I	26.7
J	24.7
K	23.1
L	29.0
M	27.7
N	24.0
O	24.0

1/ Alphabetical letters refer to sampling location on Figure

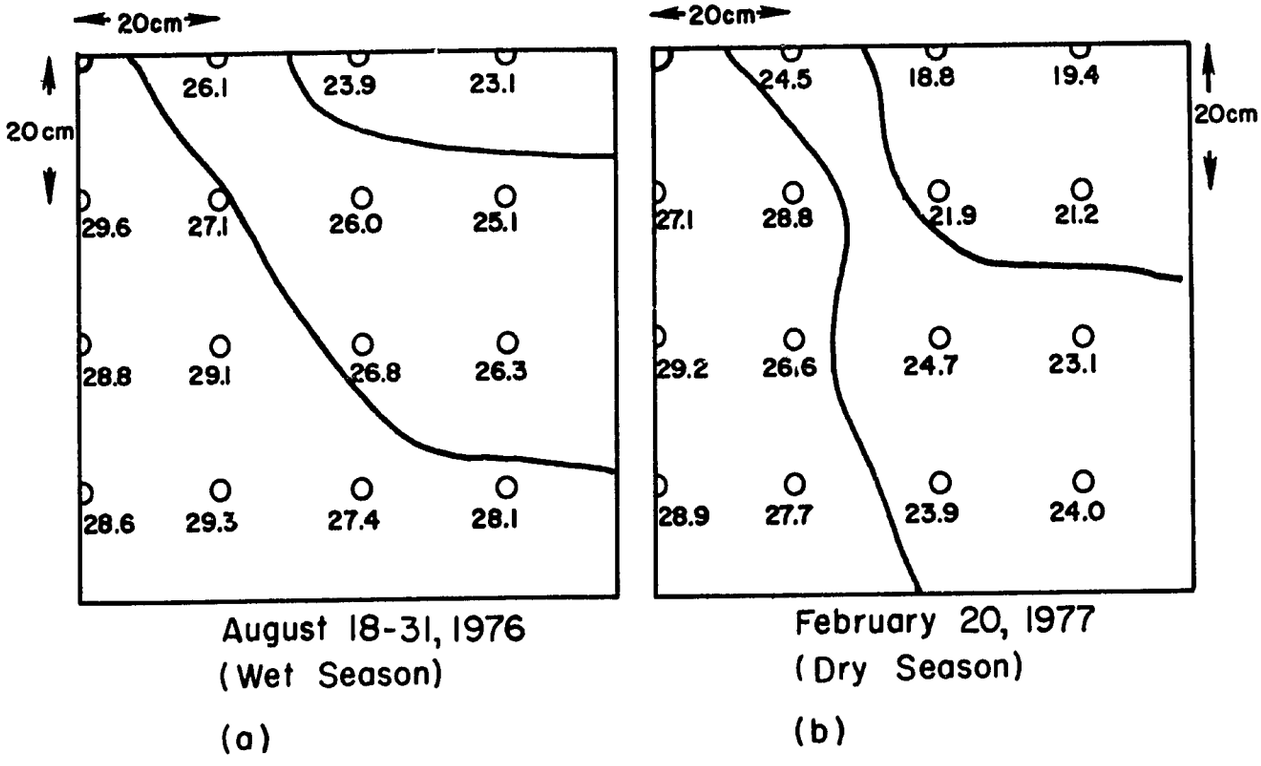


Fig. 30 Soil moisture distribution pattern under drip tubing 24 hours after last irrigation. (Numbers refer to percent moisture of dry soil.)

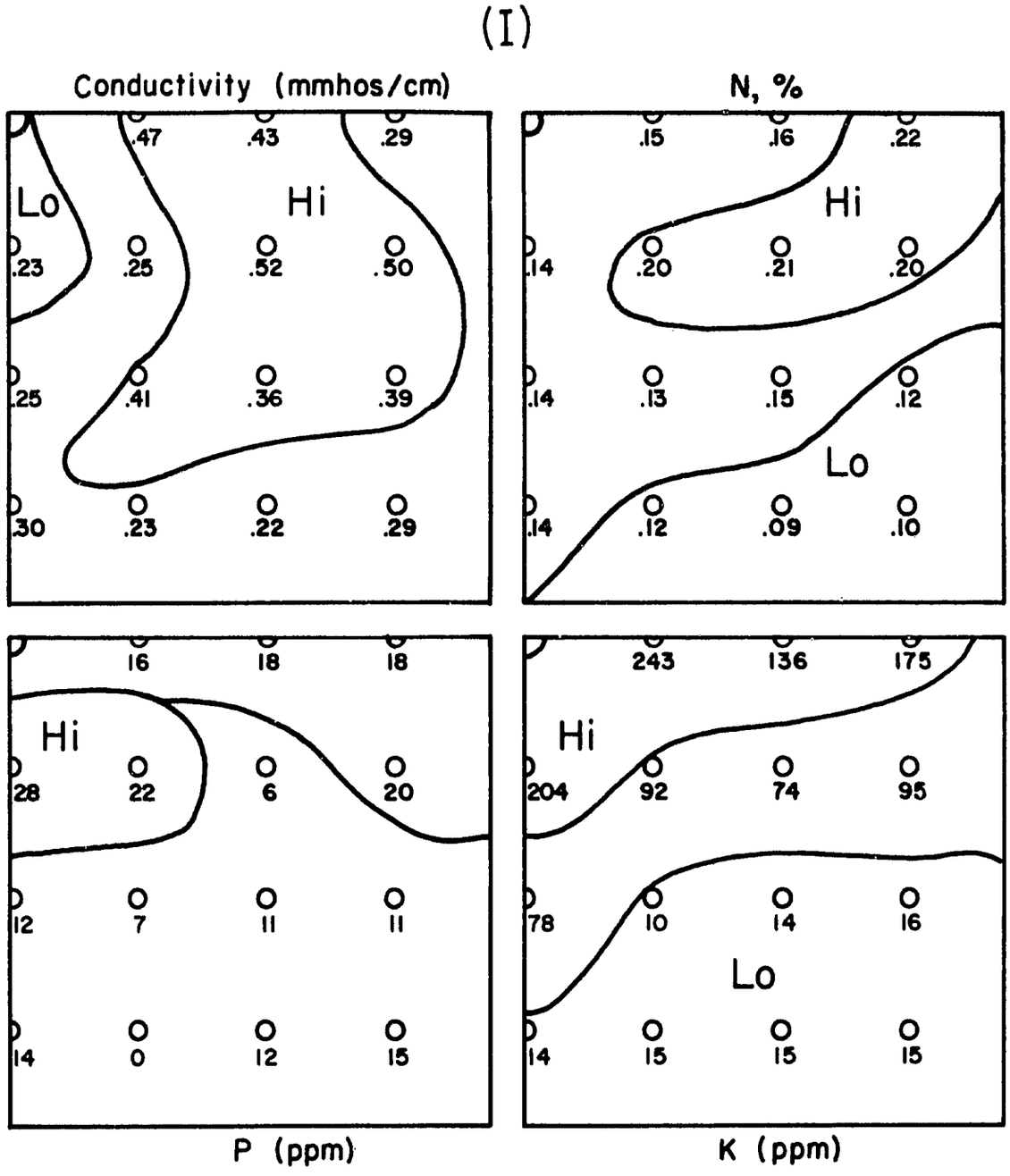


Fig. 31 N, P, K, and conductivity distribution patterns after five months of cultivation under drip fertigation.

II

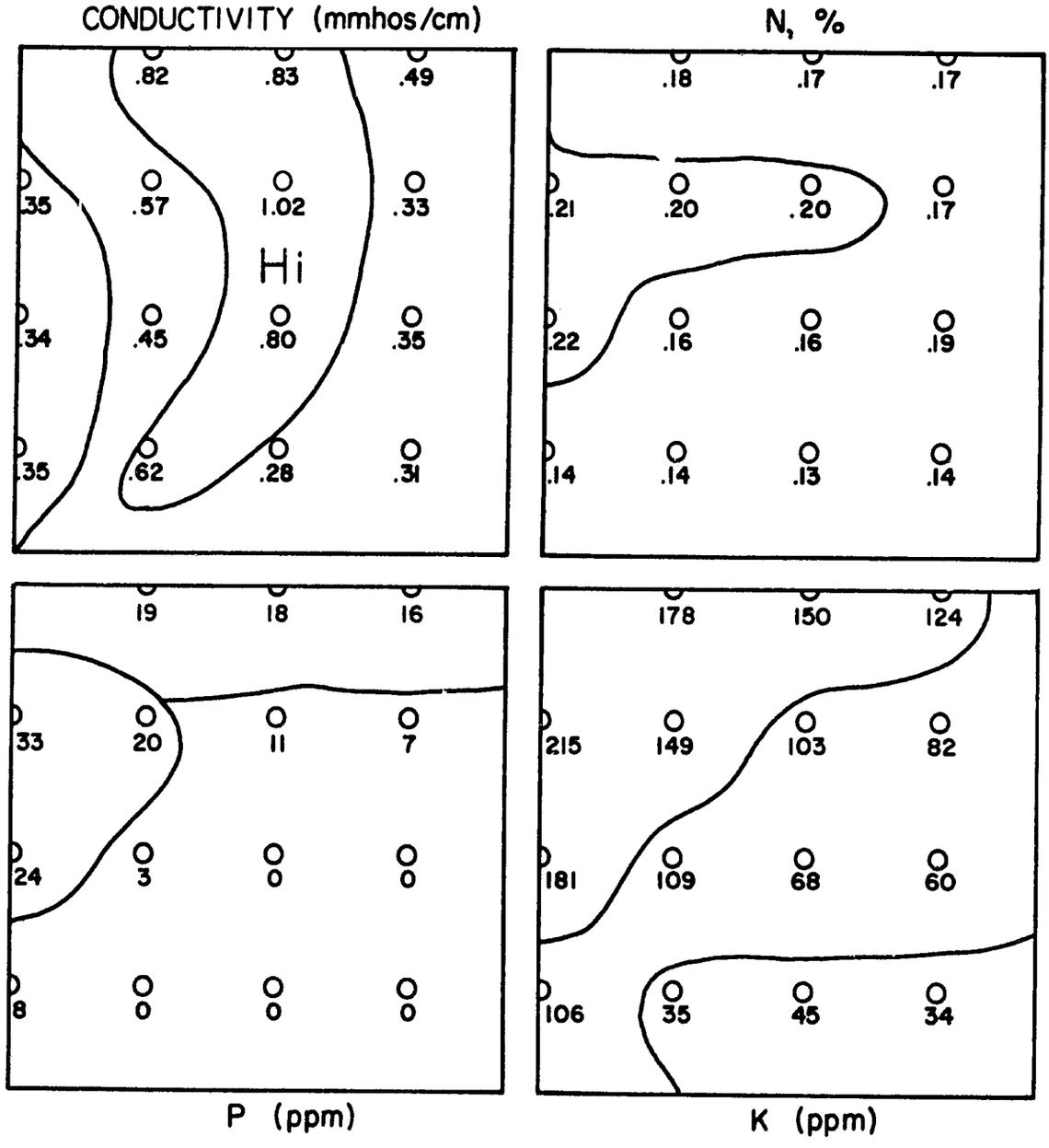


Fig. 32 N, P, K and conductivity distribute--patterns of the check plot often five months of cultivation under drip irrigation and banded fertilizer treatment.

III

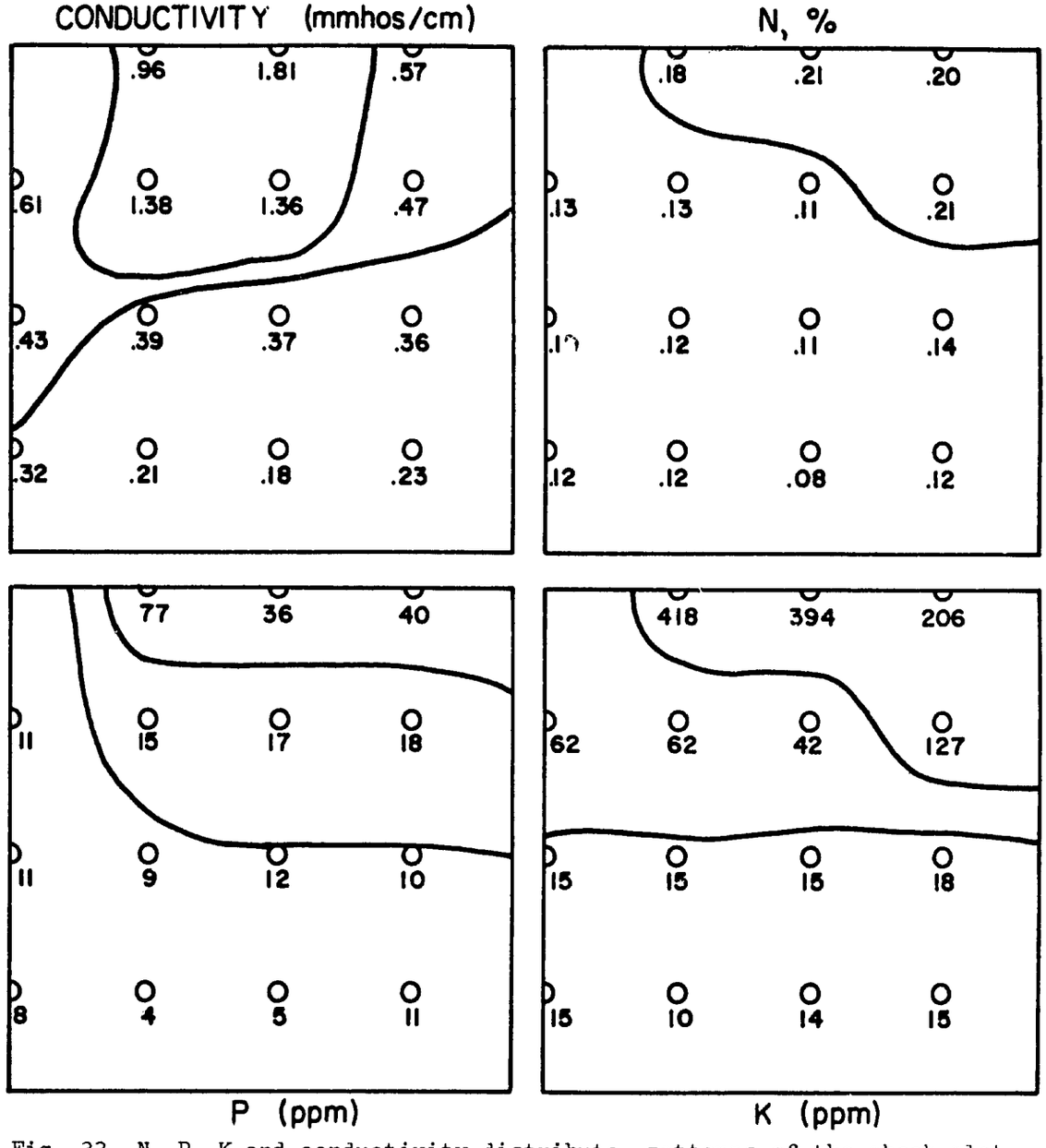


Fig. 33 N, P, K and conductivity distribute--patterns of the check plot often five months of cultivation under drip irrigation and broadcast fertilizer treatment.

IV

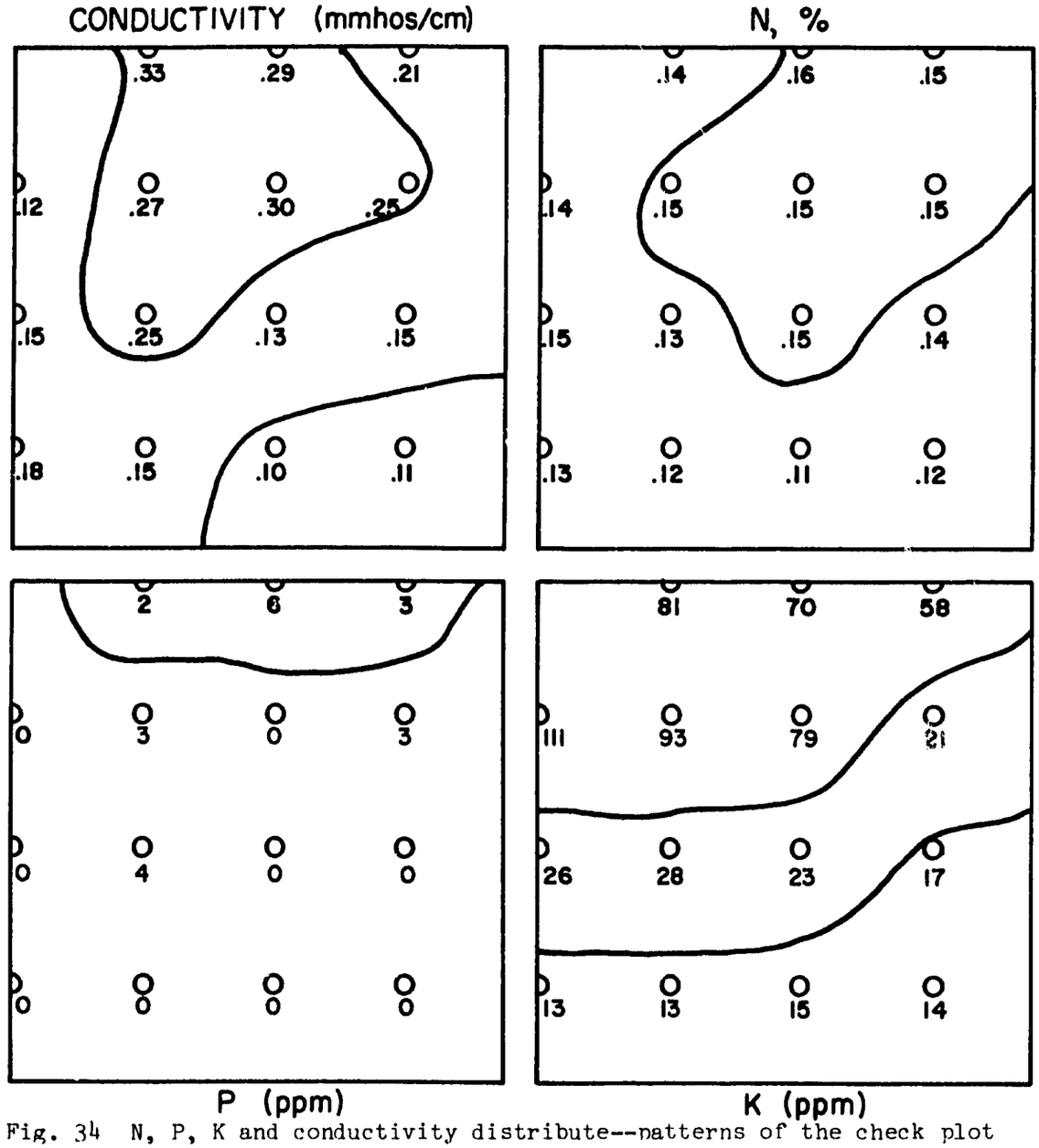


Fig. 34 N, P, K and conductivity distribute--patterns of the check plot often five months of cultivation under drip irrigation.

Table 4. Selected chemical characteristics of Coto clay in different depths prior to initiation of treatment differentials.

Depth cm	N %	P 2/ P/M	K P/M	Ca P/M	Mg P/M	Mn P/M
0-10	0.17	0	43	690	138	4
10-30	0.14 0.05 0.02 1/	0 0 0 1/	19 30 6 1/	323	84	2
30-50	0.12	0	13	325	73	3
50-70	0.12	0	13	430	74	0

1/ Adjusting factor for depth effect.

2/ Extracted with $NaHCO_3$.

In the fertigation treatment, a bulk-shaped low conductivity area was observed immediately below the drip tubing. The high conductivity region started at the soil surface, 20 cm from the tubing, continued as a strip 30 cm to 40 cm wide down to a depth of 50 cm (Fig. 31). The two skew vertical boundaries of this high conductivity region are roughly parallel to the low conductivity bulb. In Treatments III and IV, the broadcast fertilizer and check plots, were of similar shape, but much shallower high-conductivity regions were observed. Unlike Treatment I, the low conductivity areas in Treatments III and IV, are located at the lower layer and lower corner in the profiles. Treatment II, banded fertilizer, showed a relatively narrower (15 to 30 cm), very high conductivity strip extending down to more than 60cm. A lower conductivity region formed by a bulb shaped soil mass was noticed directly under the drip tubing.

High nitrogen regions were noticed in Treatment I and II. Soil nitrogen accumulated along the wetting front in the fertigation treatment, and concentrated around the fertilizer band in Treatment II. In Treatments III and IV, the surface broadcast nitrogen showed a tendency to move both downward and sideward.

Phosphorus fertilizer, in TSP form, did not show too much movement in the profiles under all four treatments. P either stayed at the surface of the soil, as originally broadcast, or in the vicinity, where first banded in Treatments I and II. A relatively higher phosphorus concentration was observed at a depth of 20 cm in Treatment III.

K movement in the profiles, with respect to the irrigation water's leaching effect was not very pronounced either. However, K was more moveable than phosphorus. In Treatment I, K concentration decreased along the radii from the

irrigation tubing. Treatment II showed high potassium concentrations on the surface layer of soil as well as around the fertilizer band. The movement of K in Treatment III followed a similar pattern as the movement of N under the same treatment; the concentration decreasing with increasing soil depth and distance from the irrigation tubing. A consistent-downward movement of K fertilizer was observed in the check treatment.

Table 5 gives data on N, P and K content and electrical conductivity at each sampling point of the soil profile.

IV-3-3 Root System Development

Table 6 presents quantitative data of oven-dried root weight in each layer and different sections of the soil root zones. Root development in the upper 15 cm layer were of the order 67.44%, 64.89%, 54.63% and 67.06% of total root weight in Treatments I, II, III and IV, respectively. In general, a major part of the root system was developed within the 5 cm to 15 cm layer.

Figures 35, 36, 37 and 38 illustrate the proportional weight distribution of root systems under each treatment. Symmetrical root weight distributions with respect to the direction of moisture gradient were observed in Treatments I, III and IV. In other words, the root systems developed relatively equal weights in the inner and outer sections of the three treatments. However, root development in Treatment II (Fig. 36) was heavier (50% more dry weight) in the inner sections than in the outer sections within the upper 15 cm layer.

In spite of the fact that symmetrical distributions of root weight were obtained in three out of the four treatments, more fibrous roots were developed toward the direction of water and/or nutrient sources. Figure 39 gives four photographs of the root systems of ten-week old pepper plants.

Table 5. N, P, K content and conductivity values of soil samples taken from a 60 cm x 60 cm profile in each treatment.

Treatment and location[1]	N% sample	N% adjusted[2]	P (p/m) sample	P (p/m) adjusted[2]	K (p/m) sample	K (p/m) adjusted[2]	Conductvity Mmhos/cm
I-A	0.20	0.15	16	16	273	243	0.47
I-B	.21	.16	18	18	166	136	.43
I-C	.27	.22	18	18	205	175	.29
I-D	.16	.14	28	28	210	204	.23
I-E	.22	.20	22	22	98	92	.25
I-F	.23	.21	6	6	80	74	.52
I-G	.22	.20	20	20	101	95	.50
I-H	.14	.14	12	12	78	78	.25
I-I	.13	.13	7	7	10	10	.41
I-J	.15	.15	11	11	14	14	.36
I-K	.12	.12	11	11	16	16	.39
I-L	.12	.12	14	14	14	14	.30
I-M	.12	.12	0	0	15	15	.23
I-N	.09	.09	12	12	15	15	.22
I-O	.10	.10	15	15	15	15	.29
II-A	0.23	0.18	19	19	218	178	0.82
II-B	.22	.17	18	18	180	150	.83
II-C	.22	.17	16	16	154	124	.49
II-D	.23	.21	33	32	221	215	.35
II-E	.22	.20	20	20	155	149	.57
II-F	.22	.20	11	11	109	103	1.02
II-G	.19	.17	7	7	88	32	.33
II-H	.22	.22	24	24	181	181	.34

Table 5 (Cont.)

Treatment and location[1]	N% sample	N% adjusted[2]	P (p/m) sample	P (p/m) adjusted[2]	K (p/m) sample	K (p/m) adjusted[2]	Conductivity Mmhos/cm
II-I	.16	.16	3	3	109	109	.45
II-J	.16	.16	0	0	68	68	.80
II-K	.19	.19	0	0	60	60	.35
II-L	.14	.14	8	8	106	106	.35
II-M	.14	.14	0	0	35	35	.62
II-N	.13	.13	0	0	45	45	.28
II-O	14	.14	0	0	34	34	.31
III-A	0.23	0.18	77	77	448	418	0.96
III-B	.26	.21	36	36	424	394	1.81
III-C	.25	.20	40	40	436	206	.57
III-D	.15	.13	11	11	68	62	.61
III-E	.15	.13	15	15	68	62	1.38
III-F	.13	.11	17	17	48	42	1.36
III-G	.23	.21	18	18	133	127	.47
III-H	.10	.10	11	11	15	15	.43
III-I	.12	.12	9	9	15	15	.39
III-J	.11	.11	12	12	15	15	.37
III-K	.14	.14	10	10	18	18	.36
III-L	.12	.12	8	8	15	15	.32
III-M	.12	.12	4	4	10	10	.21
III-N	.08	.08	5	5	14	14	.18
III-O	.12	.12	11	11	15	15	.23

Table 5 (Cont.)

Treatment and location 1/	N% sample	N% adjusted 2/	P (p/m) sample	P (p/m) adjusted 2/	K (p/m) sample	K (p/m) adjusted 2/	Conductivity Mmhos/cm
IV-A	.19	.14	2	2	111	81	0.33
IV-B	.21	.16	6	6	100	70	.29
IV-C	.20	.15	3	3	88	58	.21
IV-D	.16	.14	0	0	117	111	.12
IV-E	.17	.15	3	3	99	93	.27
IV-F	.17	.15	0	0	85	79	.30
IV-G	.17	.15	3	3	21	21	.25
IV-H	.17	.15	0	0	26	26	.15
IV-I	.13	.13	4	4	28	28	.25
IV-J	.15	.15	0	0	23	23	.13
IV-K	.14	.14	0	0	17	17	.15
IV-L	.13	.13	0	0	13	13	.18
IV-M	.12	.12	0	0	13	13	.15
IV-N	.11	.11	0	0	15	15	.10
IV-O	.12	.12	0	0	14	14	.11

1/ Alphabetical letters refer to the sampling locations on Figure

2/ Adjusted value means value after corrected for depth effect.

Table 6. Root system development in soil profile with different moisture and nutrient gradients

Treatments	Root Development								
	Inner Sections			Outer Sections			Each Layer		
	Section		Wt.	Section		Wt.	Depth (cm)		Wt.
I	A	0.4496	5.7	E	0.4210	5.3	0-5	0.8706	11.0
	B	2.2326	28.4	F	2.2016	28.04	5-15	4.4342	56.44
	C	0.8956	11.4	G	0.9011	11.48	15-25	1.7967	22.88
	D	0.3736	4.76	H	0.3740	4.76	25-35	0.7476	9.52
	Subtotal	3.9514	50.26	Subtotal	3.8977	49.58	Total	7.8491	100.00
II	A	0.8649	9.45	E	0.4279	4.67	0-5	1.2928	14.12
	B	2.6969	29.47	F	1.9519	21.3	5-15	4.6488	50.77
	C	0.9039	9.88	G	1.0599	11.58	15-25	1.9638	21.46
	D	0.3629	3.96	H	0.8809	9.62	25-35	1.2438	13.58
	Subtotal	4.8286	52.76	Subtotal	4.3206	47.17	Total	9.1492	100.00
III	A	0.5657	5.85	E	0.4992	5.16	0-5	1.0651	11.01
	B	2.1861	22.61	F	2.0311	21.01	5-15	4.2170	43.62
	C	1.4549	15.05	G	1.3219	13.67	15.25	2.7768	28.72
	D	0.9479	9.80	H	0.6577	6.80	25.35	1.6056	16.60
	Subtotal	5.1546	53.31	Subtotal	4.5099	46.64	Total	0.6645	100.00
IV	A	0.3414	5.14	E	0.2991	4.50	0.5	0.6407	9.64
	B	1.9296	29.07	F	1.8821	28.35	5-15	3.8117	47.42
	C	0.5818	8.76	G	0.5903	8.89	15-25	1.1719	17.65
	D	0.5126	7.72	H	0.5000	7.53	25-35	1.0126	15.25
	Subtotal	3.3654	50.69	Subtotal	3.2715	49.27	Total	6.6369	100.00

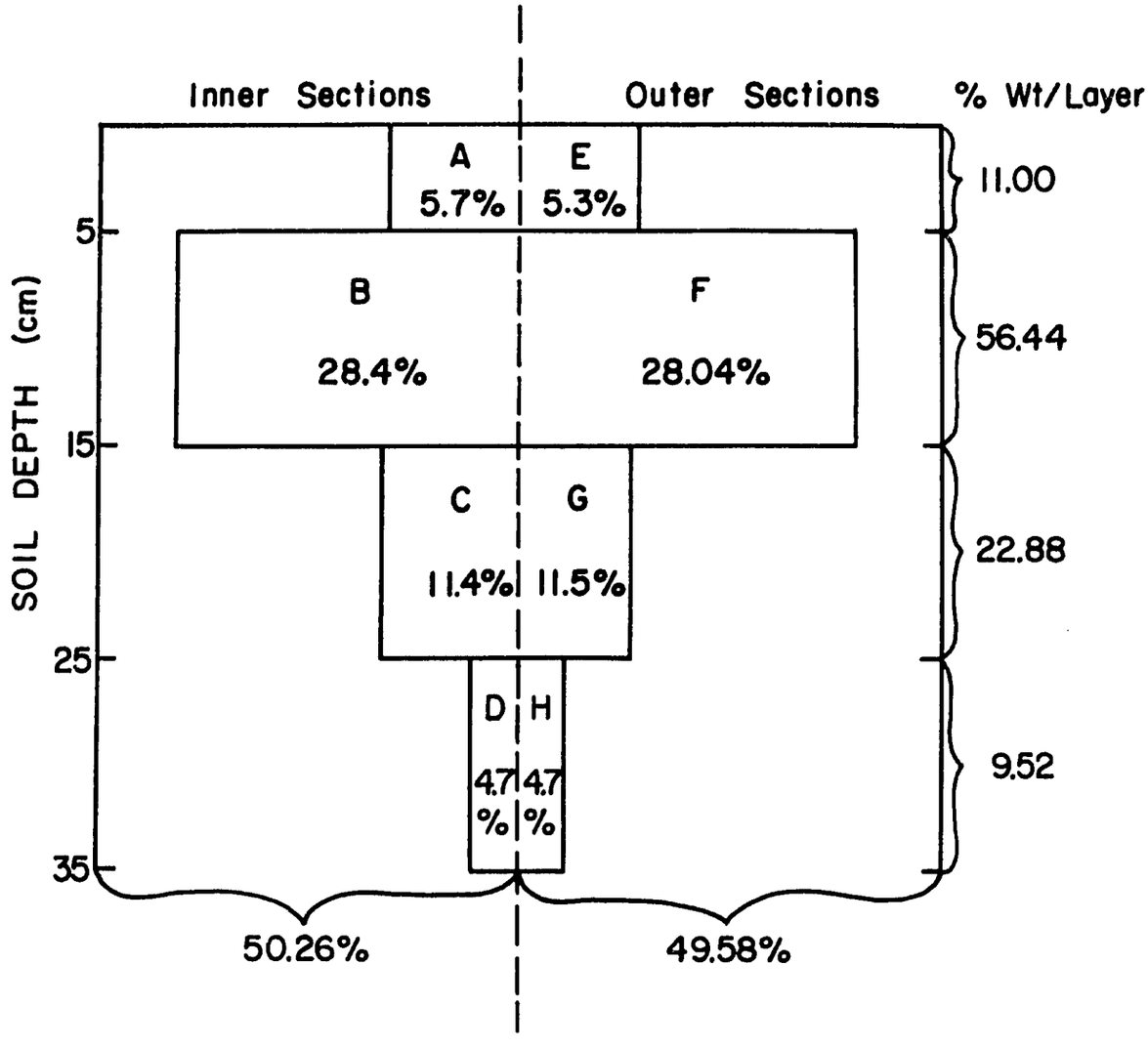


Fig. 35 Root system development of sweet pepper in various soil sections, treatment No. 1 fertigation.

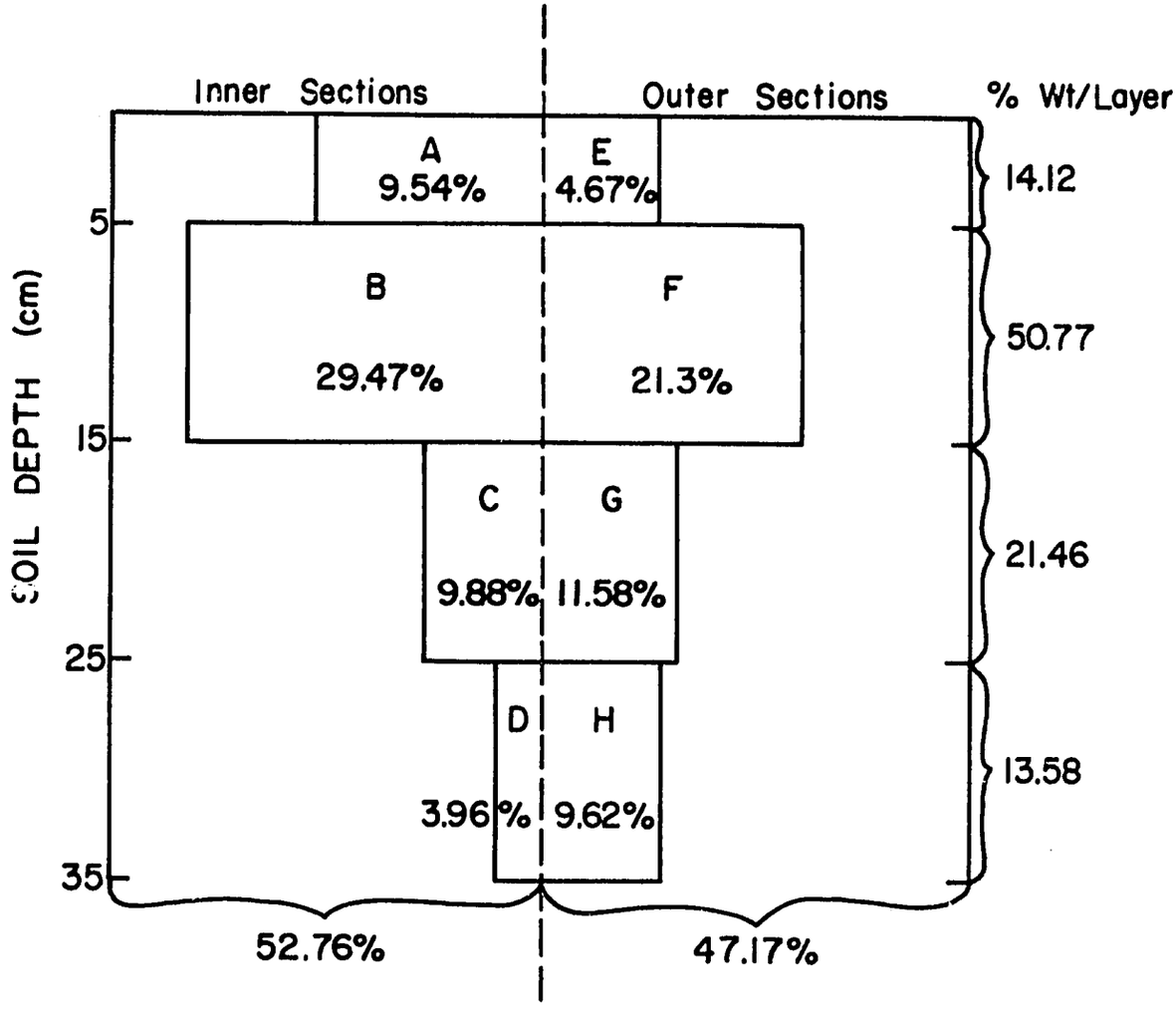


Fig. 36 Root system development of sweet pepper in various soil sections, treatment No. 2 banded fertilizer.

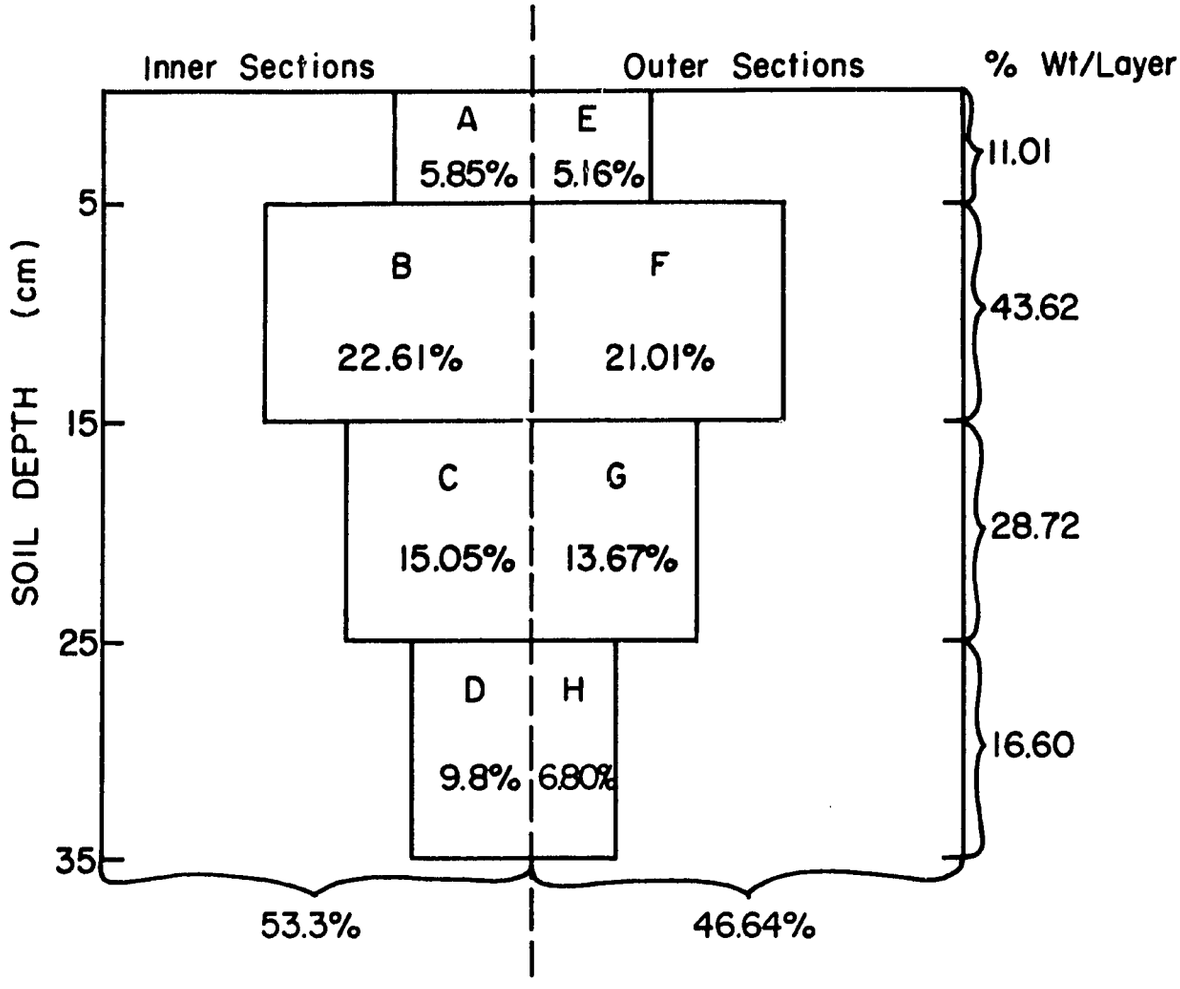


Fig. 37 Root system development of sweet peppers in various soil sections, treatment No. 3, broadcast fertilizer.

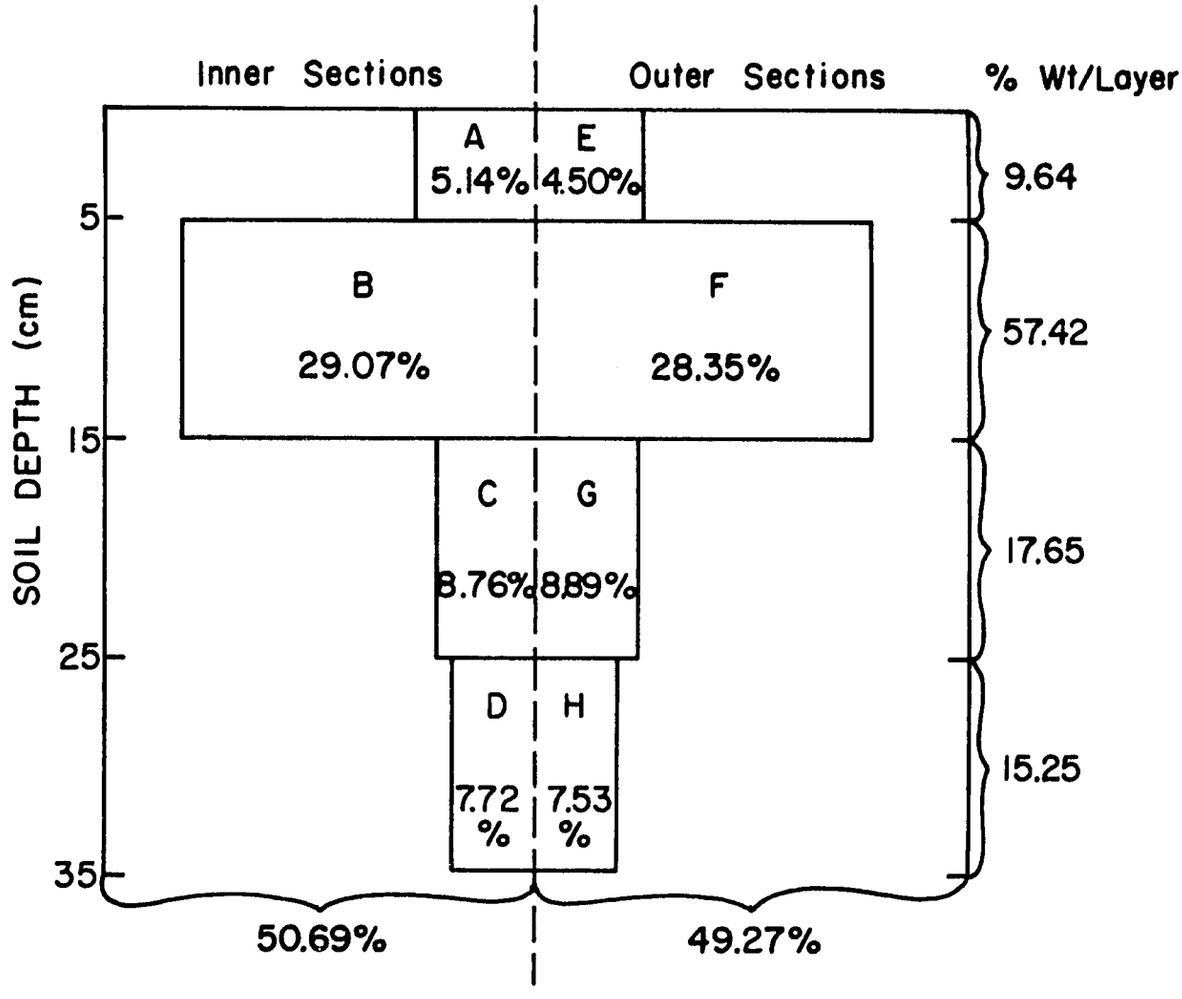


Fig. 38 Root system development of sweet peppers in various soil sections, treatment No. 4, check.

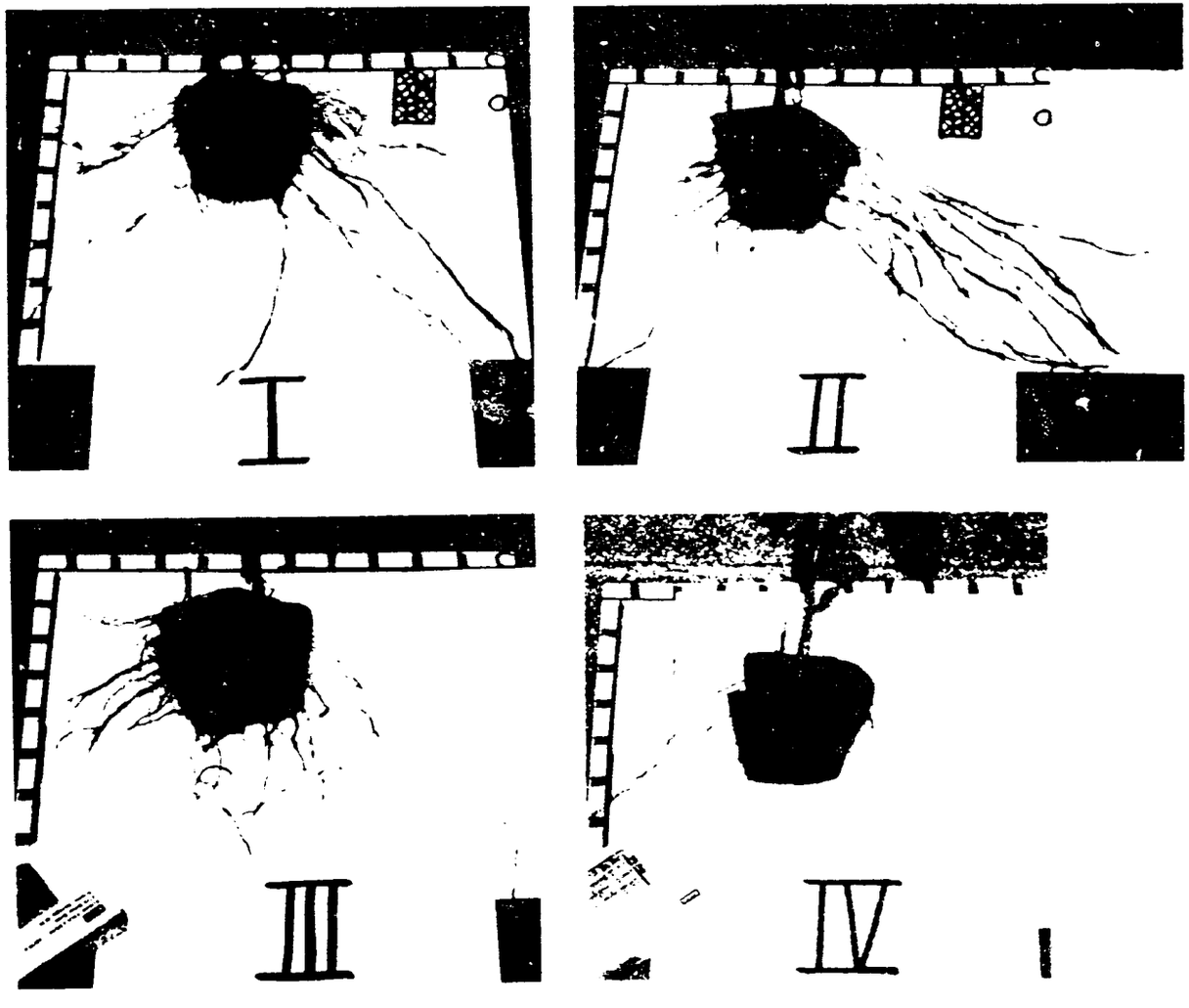


Fig. 39 Root system development of 10 week old pepper plants.
(I,II,III,IV refer to treatments)

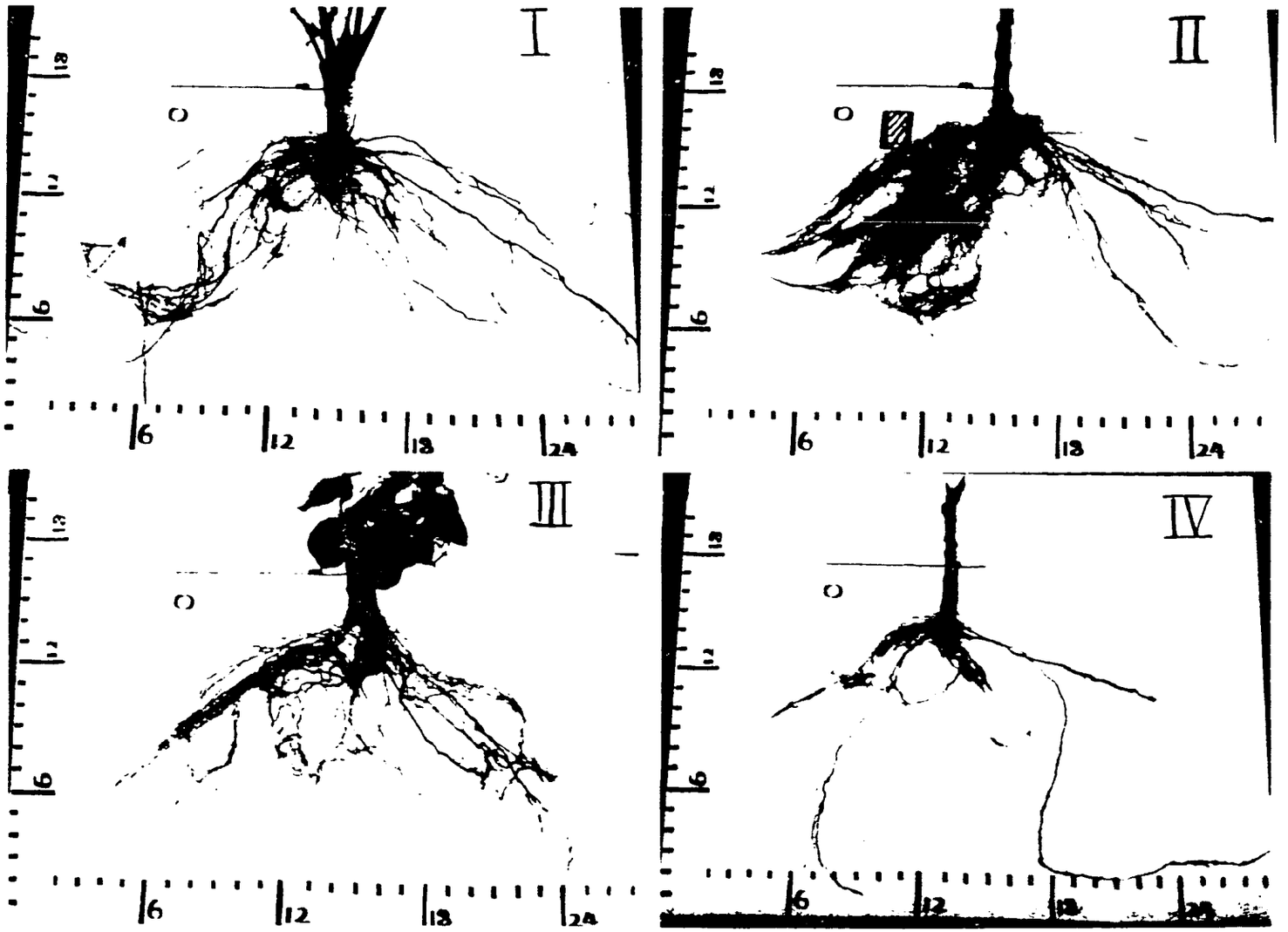


Fig. 40 **Root system development of mature pepper plants. (5 month old, I,II,III,IV refer to treatments)**

Figure 40 present a view of the mature plants' root systems. From both figures 39 and 40, it is quite clear that, under all four treatments, there was much more specific surface area of roots in the inner parts than in the corresponding outer parts.

IV-3-4 Yield

Analysis of variance of total yield data indicates a highly significant difference between Treatments I, III and IV and also beween Treatments II, III and IV. Total yield of Treatment I, the fertigation treatment and Treatment II, the banded fertilizer treatment, are significantly higher than the total yields of Treatment III, the broadcast fertilizer and Treatment IV, the check plot. For the wet season crop and the combined yield analysis no statistically significant difference (95% level) between Treatments I and II are found. The difference in yield between these two treatments in the dry season crop is highly significant, (Table 7).

Figure 41 shows that the banded fertilizer treatment was conducive to the highest yield at the first three harvests. Increasing of yield with maturity leveled off in Treatments II, III and IV after the third pickingand increased again after the fourth picking. Yields in Treatment I were continuously increasing between the third and fourth pickings (when plants were four months old) and topped the other three treatments in yield at the last two pickings. A drop in yield was first noticed in the check plots when plants were five months old. The other three treatments also showed decreasing yield two weeks later.

Figure 42 shows the yield distribution of the dry season crop. Favorable winter temperature caused a faster growth rate in the early stage after transplanting. The dry season crop later suffered from aphid attacks and a spreading of the Puerto Rican mosaic virus which affected yields adversely. The fertigation treatment maintained the highest yield throughout the growing season, and plants apparently were less affected by the virus. The fertigation treatment had the highest yield in each picking followed in order by decreasing yield the banded fertilizer treatment, broadcast fertilizer treatment and the check plots.

The combined wet season and dry season yield distribution, as shown in Figure 43, indicates that yield increased with maturity until the plants were five months old. Treatment I had the steepest and smoothest increasing rate and also the highest total yield. Treatment II followed, a close second in terms of total yield. The increase in yield of Treatment III was slowed down after the fourth month of growth. The check plots did not show much improvement with maturity.

IV-4 DISCUSSIONS:

IV-4-1 Moisture Distribution

The moisture distribution under field conditions is always a process of dynamic continuity. The water content at a particular point varies with time and is a function of the external conditions, such as the evapotranspiration rate, soil and air temperature, precipitation and irrigation, etc. However, for a prolonged time period during similar weather conditons, e.g. within the wet season or dry season only, and

Table 7. Test of statistical significance between treatments.

	Treatments	Average yield	t value
Wet season crop:	I v.s. II	190.65 v.s. 197.51	-1.92 none
	I v.s. III	190.65 v.s. 175.55	4.22**
	I v.s. IV	190.65 v.s. 81.65	30.48**
	II v.s. III	197.51 v.s. 175.55	6.14**
	II v.s. IV	197.51 v.s. 81.65	32.40**
	III v.s. IV	175.55 v.s. 81.65	26.26**
Dry season crop	I v.s. II	182.15 v.s. 160.90	4.10**
	I v.s. III	182.15 v.s. 138.66	8.40**
	I v.s. IV	182.15 v.s. 69.52	21.76**
	II v.s. III	160.90 v.s. 138.66	4.29**
	II v.s. IV	160.90 v.s. 69.52	17.65**
	III v.s. IV	138.66 v.s. 69.52	13.36**
Combined crop:	I v.s. II	373.30 v.s. 358.41	2.10 none
	I v.s. III	373.30 v.s. 314.21	8.37**
	I v.s. IV	373.30 v.s. 151.17	31.48**
	II v.s. III	358.41 v.s. 314.21	6.26**
	II v.s. IV	358.41 v.s. 151.17	29.37**
	III v.s. IV	314.21 v.s. 151.17	23.10**

Remarks: t^{*}_{95}: 2.131

t^{**}_{99}: 2.947

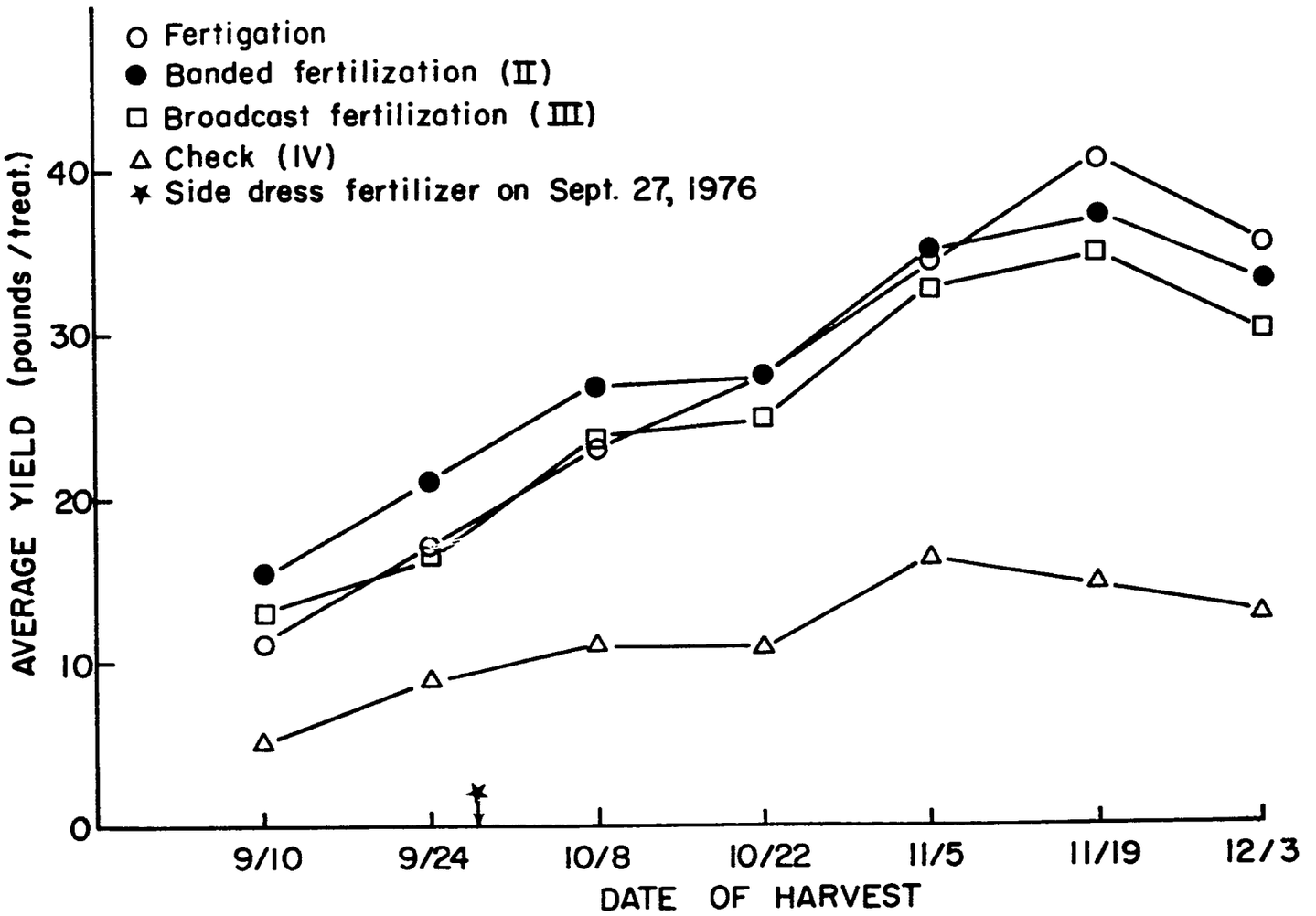


Fig. 41 Yield curves of the wet season pepper crop.

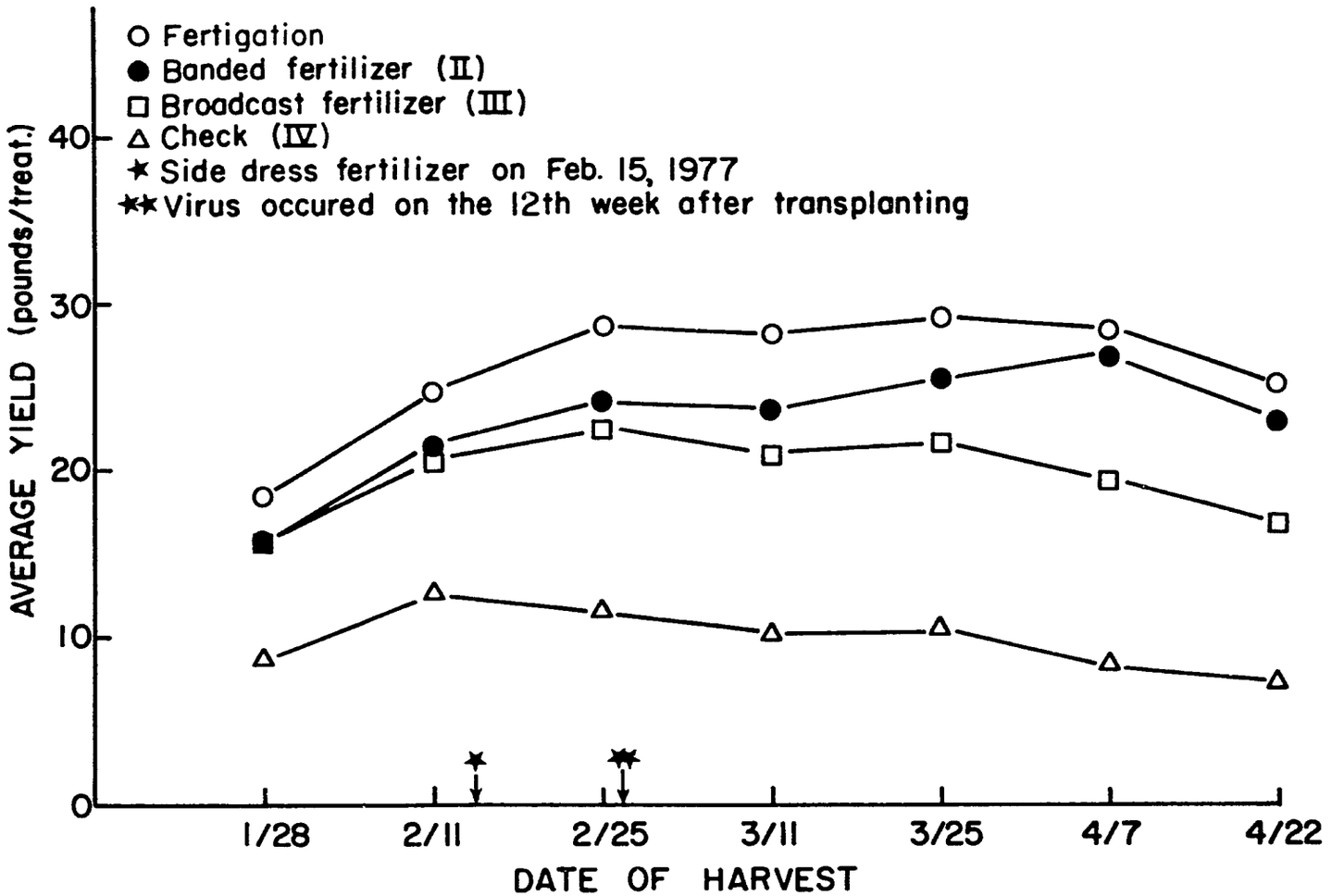


Fig. 42 Yield curves of the dry season pepper crop.

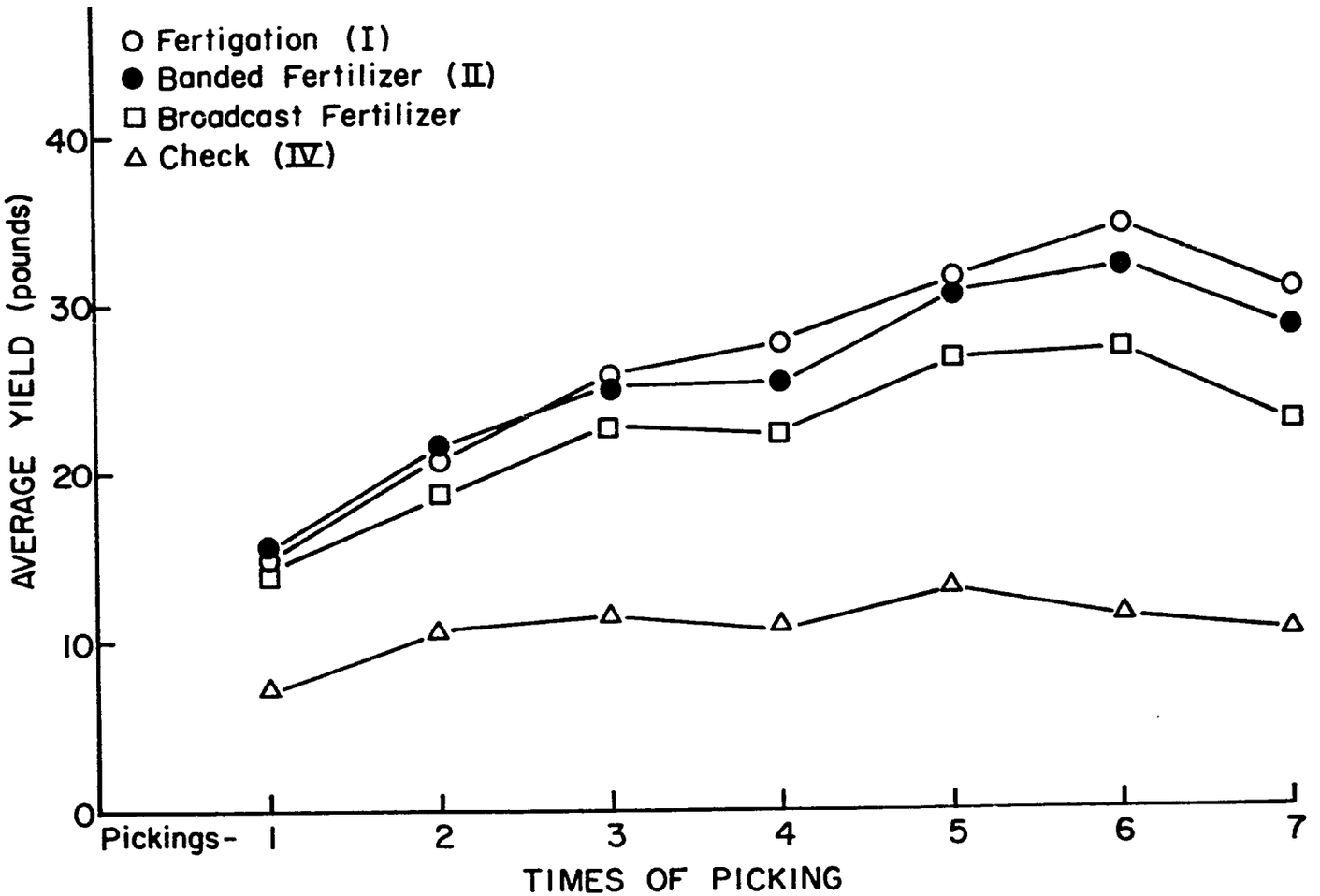


Fig. 43 Average yield of wet and dry season pepper crops.

Table 8. Yield of pepper fruit at each harvest in the wet season crop

	Yield							
	Sept. 10	Sept. 24	Oct. 8	Oct. 22	Nov. 5	Nov. 19	Dec. 3	Total
Treatment I								
Replication								
1	12.2	19.2	25.5	28.9	34.1	44.0	38.8	202.7
2	12.0	21.3	26.2	28.6	34.5	42.0	37.2	201.8
3	21.0	18.4	24.2	28.4	32.5	43.1	38.2	196.8
4	11.5	15.5	23.1	29.0	40.1	39.6	36.9	195.6
5	11.0	14.2	20.3	25.5	32.5	36.2	34.2	173.9
6	11.4	15.0	21.1	26.4	33.2	38.0	30.0	176.1
Total	70.1	103.6	140.4	166.8	206.8	242.5	215.3	1143.90
Average	11.68	17.26	23.4	27.8	34.46	40.41	35.88	190.65
Treatment II								
Replication								
1	18.0	26.5	30.3	33.4	34.5	42.0	35.5	222.9
2	15.1	23.2	27.1	28.4	34.0	36.2	32.6	196.6
3	16.0	22.7	26.6	29.2	40.0	35.0	35.1	204.6
4	13.5	18.2	27.0	25.5	36.2	36.2	36.0	192.6
5	14.0	19.1	23.3	24.2	30.2	36.2	33.1	180.1
6	16.0	19.0	26.9	22.2	33.6	40.6	30.0	188.3
Total	92.6	128.7	161.2	162.9	208.5	226.2	202.3	1185.09
Average	15.4	21.45	26.86	27.15	34.75	37.7	33.7	197.51

Table 8 (Cont.)

	Yield							
	Sept. 10	Sept. 24	Oct. 8	Oct. 22	Nov. 5	Nov. 19	Dec. 3	Total
Treatment III								
Replication								
1	14.6	22.4	27.5	28.4	28.0	34.5	30.0	185.4
2	13.5	23.0	23.5	24.6	29.5	41.3	33.2	188.7
3	13.0	16.1	25.0	22.2	34.0	36.2	34.2	180.7
4	13.8	16.2	28.2	26.9	34.5	32.5	28.0	180.1
5	12.5	13.2	19.2	22.6	31.0	33.2	29.0	160.7
6	12.2	12.0	19.6	24.2	31.1	32.2	26.4	157.7
Total	79.7	102.9	143.0	148.9	188.1	209.9	180.8	1053.30
Average	13.28	17.15	23.83	24.81	31.35	34.98	30.13	175.55
Treatment IV								
Replication								
1	6.6	8.5	9.5	11.4	18.5	18.1	18.2	90.8
2	6.0	9.4	10.2	11.6	14.2	14.2	13.3	79.4
3	5.9	11.8	14.7	13.3	16.9	19.6	13.2	95.4
4	7.0	10.7	16.2	12.9	70.2	11.3	11.4	89.7
5	4.5	6.9	8.7	9.9	14.0	14.0	11.0	69.0
6	3.4	5.9	9.0	9.2	14.2	13.9	10.0	65.6
Total	33.4	53.2	68.3	68.3	98.0	91.1	77.1	489.89
Average	5.56	8.86	11.38	11.38	16.33	15.18	12.85	81.65

Table 9. Yield of pepper fruit at each harvest in the dry season crop.

	Yield							
	Jan. 28	Feb. 11	Feb. 25	March 11	March 25	April 7	April 22	Total
Treatment I								
Replication								
1	19.50	25.75	28.40	27.75	29.50	29.00	24.05	183.95
2	14.25	26.50	31.20	32.50	33.75	30.65	25.75	194.60
3	12.75	19.25	23.50	22.75	24.65	24.50	20.50	147.90
4	22.50	28.50	33.25	31.95	34.95	32.00	29.75	212.90
5	18.75	22.50	25.20	25.50	25.00	26.25	24.35	167.55
6	21.0	25.00	29.00	28.00	27.25	27.75	28.00	186.00
Total	108.75	147.50	170.55	168.45	175.30	170.90	152.4	1092.90
Average	18.12	24.58	28.42	28.07	29.21	28.48	25.14	182.15
Treatment II								
Replication								
1	12.50	18.00	20.50	22.50	24.00	28.45	20.85	146.80
2	20.00	20.00	26.25	26.75	28.25	28.00	25.35	174.60
3	14.40	21.50	23.50	20.20	23.00	23.65	21.00	147.25
4	16.20	24.75	26.25	25.00	27.25	27.00	24.75	171.20
5	11.50	21.25	23.50	23.00	25.75	25.50	20.25	150.75
6	20.50	25.00	24.50	25.55	27.00	28.00	24.45	175.00
Total	95.10	130.50	144.50	143.00	155.25	160.60	136.45	965.40
Average	15.85	21.75	24.08	23.83	25.87	26.76	22.74	160.90

Table 9. (Cont.)

	Yield							
	Jan. 28	Feb. 11	Feb. 25	March 11	March 25	April 7	April 22	Total
Treatment III								
Replication								
1	12.25	16.50	18.75	18.75	19.55	17.65	13.35	116.80
2	16.00	21.00	22.25	20.00	24.00	23.00	17.50	143.75
3	14.50	18.50	19.75	19.50	19.00	16.40	13.20	120.85
4	19.75	25.00	26.75	24.25	26.00	24.75	20.00	166.50
5	12.50	21.50	24.50	22.75	21.35	19.05	16.25	137.90
6	20.00	21.75	23.50	21.00	22.00	19.00	18.95	146.20
Total	95.00	124.25	132.50	126.25	131.90	119.85	99.25	831.99
Average	15.83	20.70	22.58	21.04	21.98	19.97	16.54	138.66
Treatment IV								
Replication								
1	9.50	11.00	7.20	8.50	8.75	7.50	7.50	59.95
2	7.75	8.50	12.00	9.25	12.25	8.00	9.00	66.75
3	5.50	12.75	9.75	7.00	8.25	8.00	6.55	57.80
4	11.50	15.25	16.00	12.70	13.50	10.50	9.00	88.45
5	8.75	12.00	10.75	8.75	8.75	6.00	7.75	62.75
6	9.00	14.50	15.00	13.95	12.00	9.75	7.25	81.45
Total	52.00	7.400	70.70	60.15	63.50	69.75	47.05	417.14
Average	8.66	12.33	11.78	10.02	10.58	8.29	7.84	69.52

Table 10. Average yield of pepper fruit of the wet and dry season crops.

	Yield of each harvest							
	1st harvest	2nd harvest	3rd harvest	4th harvest	5th harvest	6th harvest	7th harvest	Total
Treatment I								
Wet season crop	11.68	17.26	23.40	27.80	34.46	40.41	35.88	190.65
Dry season crop	18.12	24.58	28.42	28.07	29.21	28.48	25.40	182.15
Average	14.90	20.92	25.91	27.93	31.83	34.44	30.64	186.40
Treatment II								
Wet season crop	15.40	21.45	26.86	27.14	34.75	37.70	33.70	197.51
Dry season crop	15.85	21.75	24.08	23.83	25.87	26.76	22.74	160.90
Average	15.62	21.60	25.47	25.49	39.31	32.23	28.22	179.20
Treatment III								
Wet season crop	13.28	17.15	23.83	24.81	31.35	34.98	30.13	175.55
Dry season crop	15.83	20.70	22.58	21.04	21.98	19.97	26.54	138.66
Average	14.55	18.92	23.20	22.92	26.66	27.47	23.33	157.10
Treatemnt IV								
Wet season crop	5.56	8.86	11.38	16.33	15.18	12.84	81.85	
Dry season crop	8.66	12.33	11.78	10.02	10.58	8.29	7.84	69.52
Average	7.11	10.59	11.58	10.70	13.45	11.73	10.34	75.58

under routine farming operations, the soil moisture regime may be considered to be in a state of dynamic equilibrium. In other words, the irrigation additions are offset by evapotranspiration and deep percolation thus, the average value of the volume of water in the plant occupied soil profile may be considered a constant. This constant soil-moisture state should coincide with root development and the distribution of water soluble chemicals in the soil profile.

Figure 30 presents the dynamic equilibrium field moisture profiles in the wet season and the dry season. Owing to the higher initial soil-moisutre content in the wet season and the increasing moisutre content with depth, the ellipse shaped wetting pattern does not appear under field conditions. As shown in Figure 30-a, the moist soil mass is more or less in a fan shape. While in the dry season, because of the higher suction force created by the dry surface soil, the wetted soil mass is in a bulb shape in the surface 30 cm layer and a fan shaped moist zone develops in the subsoil (Figure 30-b). The dry strip between the irrigation tubes is dryer and deeper in the dry season than it is in the wet season. This is because of less rainfall and higher evaporation rate from the soil surface in the dry season. It should be pointed out that the moisture patterns under field contitions, in both wet and dry seasons, are not identical to the wetting patterns developed in the laboratory soil bin (Fig. 7 & 8). In a laboratory profile, with uniform initial moisture content, the total suction force across the wetting front is uniform and independent of depth. But in a field profile the moisture content increases with depth, the suction forces decrease with depth and in the process of water movement in subsoils gravity force will prevail. Figure 44-a

illustrates the water movement in a wet season profile, the higher hydraulic conductivity in the subsoil accelerates the major water flow move downward by gravity force. Figure 44-b simulates the dry season moisture pattern, more lateral movement of the added water is due to the higher matric-suction in the dry surface layer.

In conclusion: the field soil-water movement under fixed rate drip irrigation is a function of the various moisture contents in the whole profile. Application of the laboratory soil water movement model should be limited only to soils with a deep dry layer of relatively uniform initial moisture content. Water movement patterns obtained under over simplified laboratory conditions sometimes are misleading in practical field irrigation operations. This simple fact has been ignored too frequently in previous discussions about drip irrigaton design and managment.

IV-4-2 Solute Distribution

Profile of Conductivity

The result of total solute movement in the soil may be represented by the distribution of the conductivity of soil solutions. From Figures 31, 32, 33 and 34 the conductivity distribution in all the four treatments are quite similar to each other. There is a low conductivity bulb immediately under the drip tubing and a pocket of accumulated solutes surrounding the bulb shaped low conductivity zone. This may be explained by Figure 44 using the "transmission zone" concept. The moisture content in the transmission zone is close to saturation, and irrigation water supplied from the porous tubing continuously flows through

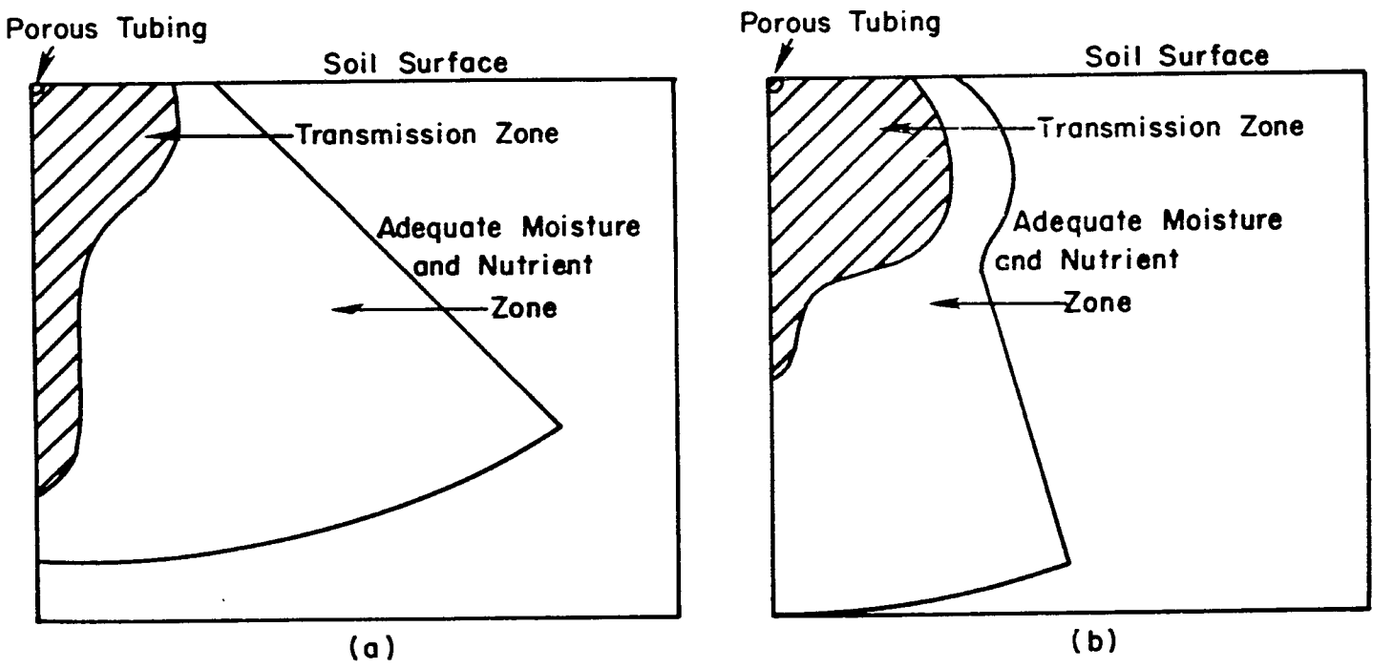


Fig. 44 Illustration of the "Transmission Zone Concept". (a). The wet season soil profile. (b). The dry season soil profile.

the transmission zone toward the root zone or into deeper soil profile. This kind of "no return" flow pattern causes a leaching effect in the transmission zone. Outside the transmission zone is an area defined as the adequate moisture and nutrient zone. In the adequate moisture and nutrient zone a balance between soil-water flux and moisture depletion through root suction is reached. The irrigation water flow, together with dissolved salts from the transmission zone, stopped at various locations in the adquate moisture and nutrient zone. The excess fertilizer materials and other soluble soil components accumulated in this zone and created the high conductivity region.

N, P, & K, Distributions

Distinguishable differences are noticed in the N, P, and K distribution patterns with different treatments. Because of differences in solubility and reactivity, N, P, and K move separately in soil media. They might, however, affect each other.

Most of the nitrogen salts are very soluble in water and tend to stay in the soil solution. Therefore, the nitrogen fertilizer is highly susceptible to leaching loss. Under drip irrigation, it can be drifted in whichever direction the soil water moves. When applying N solution through drip tubings, the N accumulated along the periphery of the wetting front (Figure 31). It is also noticed that the concentrated N zone is within the 30 cm layer of the surface soil. This is because in the surface soil layer, the higher pH creates more exchange sites in the soil for cations, and the NH_4 ions from hydrolized urea undergoes the cation exchange process with the soil particles and are retained in the surface soil. While in the subsoil, with a lower pH value, most of the exchangable sites are occupied by Al^{+++}, which has a higher affinity to the soil surface

than either NH_4^+ or K^+. Once NH_4^+, NO_3^- and K^+ in the soil solution reach the lower soil layers, their chances of being retained in the soil as exchangable ions is very slight, and most possibly, they are lost by deep percolation.

Figure 31 also shows a high concentrated potassium zone around the drip irrigation tubing within the surface layer. As just mentioned there are more negative surface charges in surface soil and K^+ applied with the irrigation water can be adsorbed by the negative surface charges as soon as they contact the soil particles. An interesting and important phenomenon was noticed when comparing the N and K distribution patterns in Figure 31: at those locations of high N concentration, the K concentration are low. This is because the urea does not participate in the ion exchange process in the zone, where K^+ is high however, once urea is hydrolized into NH_4^+, the NH_4^+ will compete for exchange sites. This is why K^+ is concentrated immediately around the drip tubing and NH_4^+ is located at some distance away.

The N and K distribution patterns shown on Figure 32 strongly reflect the location of the fertilizer band. This suggests that banded application of fertilizer does create a region of high nutrient concentration. The irrigation water flows through this region and continuously carries nutrients to the root zone. A major part of the dissolved nutrients from the fertilizer band is removed from the soil by root suction. High concentrations of both N and K are noticed directly under the drip tubing down to about 50 cm. This is because there was less root activity in the transmission zone.

N and K patterns presented in Figures 33 and 34 are a direct result of the topical application method, irrigation leaching and root suction. It shows that topical application of fertilizer may lead to a concentrated fertilizer strip between rows and hardly useable by crop root systems.

Phosphorus fertilizer has been realized as a non-mobile material in most soil media. The P distribution patterns for all treatments show on Figures 31, 32, 33, and 34 are not surprising. Although Treble superphosphate (TSP) is classified as moderately water soluble, monocalcium phosphate, the main constituent of TSP; changes rapidly to dicalcium phosphate which is very insoluble in water. In Coto clay and other Oxisols, the phosphate ions also undergo reactions with the large amount of iron and aluminum oxides and are "fixed" in the soil.

IV-4-3 Root System Development

With the four different treatments employed in this research, two general types of root environments are created. In treatments I and II, fertigation and banded fertilizer treatments, moisture moves outward from the transmission zone flow through the fertilizer band and toward the plant zone. Both moisture and nutrient gradients are established in the same side of the plants and theoretically, the root system should develop in the direction opposite to the moisture and/or nutrient gradients. Treatments III and IV create the same moisture gradient but the broadcast fertilizer plus the rainfall effect develops a downward nutrient gradient. Figure 39 shows a dense fibrous root growth toward the

nutrient and moisture sources in treatment I and II. The fertilizer band in Treatment II also causes a 13% more (dry matter) growth toward the fertilizer band than away from the band. Treatments III and IV have a relatively symmetrical root system development in terms of both dry weight and fibrous root growth. This may be because of the frequent rainfall and high soil moisutre content in the soil offset the effect of moisture gradient created by irrigation water. The above phonomena can be checked by the N, P and K distribution patterns in Figures 31, 32, 33 and 34.

Drip irrigation provides an adequate moisture and fertilizer condition in the surface soil and, therefore, encourages the development of a shallow root system (see sec. III-3-4). This is important evidence to support the use of the drip method in Oxisol areas. Subsoil acidity or Al^{+++} toxicity would not be a limiting factor in crop production in acid soils if the crop does not need the subsoil.

IV-4-4 Yield

The understanding of the nutrient distribution and root system development make it apparent that the fertigation and banded fertilizer methods are superior to the broadcasting method in Oxisols. With the analysis of the distribution of yield data with time, some interesting points are found: 1) The increasing yields of treatments II, III, and IV slow down after the third harvest reflecting the decreasing nutrient supplying power of the soil. The side-dressed fertilizer pushes the yield up again in the fifth harvest. 2) In the fertigation treatment, because of the continuous nutrient supply, the yield increases smoothly without interruption. 3) In the wet season crop, the yield in the first three harvests of the fertigation treatment were lower than the banded fertilizer

treatment. This may be due to the insufficient lateral movement of irrigation water with the result that the nutrient solution applied with the drip system cannot reach the pre-developed root system.

4) In the dry season experiment, the residual effect of the previous season's fertilization activities provide the initial nutrients for early crop growth, and, therefore, the yield of the fertigation treatments are higher than the others all through the season.

CHAPTER FIVE: FUTURE RESEARCH NEEDS AND CONCLUSIONS

V-1 Future Research Needs

Results from the field experiment have shown that the drip technique is a promising method to increase agriculture production and profit. However, the research has also exposed some new questions. The following theoretical and technical problems have to be studied before a standardized operational procedure can be realized:

1. Instead of a constant discharge rate throughout the whole growing season, a variable discharge rate irrigation program should be considered as an alternative to assure that the crop receives enough water and nutrients during emergence, early growth and maturation periods.
2. Since only the top soil layer is used in crop growth with the drip method, the chemistry of the fertilizer solution and their effects on soil acidity should be carefully studied.
3. A fertilizer rate and economical feasibility studies of both fertigation and banded fertilizer techniques can provide further information on the method and quantity of fertilization which would yield the most profitable returns.
4. New types of phosphate compounds, such as glycerophosphate, and their behavior in irrigation water and in the soil should be studied. They may be used as alternatives for the non-mobil inorganic P fertilizer.

V-2 Conclusions

To summarize the results of this thesis, the following conclusions have been drawn:

Two-dimensional water movement in the soil profile

1. In vertical water movement, a linear relationship exists between the wetting front advance and the square root of time.

2. In horizontal movement, the equation proposed by Brandt et al (1971) serves as a good estimation of surface wetting distance. This wetting distance tends to approach a limiting value.

3. In both sandy and clayey soils, for the same amount of water, the horizontal advance increases with increasing discharge rate. With similar water discharge rates, downward movement of irrigation water is greater in sandy soil than in clayey soil.

4. With defined lateral and vertical movement distances, the two-dimensional wetting pattern may be approximated by a semi-ellipse. This semi-ellipse may exist in natural soil profiles under relatively uniform soil moisture contents, but may not exist when the profile water contents increase with depth. The surface wetting distance would be useful information to predict water movement under most field conditions.

5. Because of the subsoil acidity and Al^{+++} toxicity, most vegetable crops in acid soils tend to develop shallow root systems in the less acid surface soil layers. In this case, higher drip discharge rates (less irrigation time) with the resulting further lateral movement are recommended for drip irrigated row crops.

Fertilization techniques

1. In the sandy Oxisol, inorganic P moves with the water flow and reached as far as the wetting front. However, a major amount of drip supplied P was located in the vicinity of the drip

emitters. In a clayey Oxisol, almost all of the applied P was concentrated in the vicinity of the drip emitters. For all practical purposes there was no P movement in clayey Oxisols.

2. Soluble P fertilizer applied through a drip system is recommended in a sandy soil area only if other fertilization methods, banding and/or broadcasting, can not be profitably justified. Those situations may occur when there is a seasonal shortage of farm labor or the land is too steep to use farm machinery. When applying P through drip systems, special care should be given to emitter cleaning and soil water management. The commercially available P fertilizer is not recommended to be used in drip irrigation in clayey Oxisols.

3. N and K fertilizer can be applied with irrigation water and the yield result under this technique is as good as the banded fertilizer treatment.

4. The fertigation technique has the advantages of simple operation and minimizing field activities, such as applying fertilizer, which might cause man-made damage to crops. However, banded fertilizer has the advantage that only filtered irrigation appears in the drip system, and eliminates the risks of fertilizer clogging of emitters or chemical damage of drip components.

The drip irrigation technique opens a new direction for overcoming the fertility and soil-water management problems in the highly weathered acid soils. It is particularly advantageous for smaller sized farms and relatively steep agricultural land. Although memory of the early failures of some drip systems still exist among many farmers and technical advisors, and lack of enthusiam for drip irrigation has also resulted from criticism that drip systems are too sophisticated to be accepted by

the general public, with the advanced manufacture of drip irrigation materials and improved system design, drip irrigation operation can be as easy and simple as any other irrigation method. Since only low operational pressure is required, the use of electrical and fuel energy can be easily eliminated through proper system design. With further studies on economical and operational aspects, the drip technique may be developed as an alternative to the management of water and fertilizer and increase land capability in the tropics.

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APPENDIX

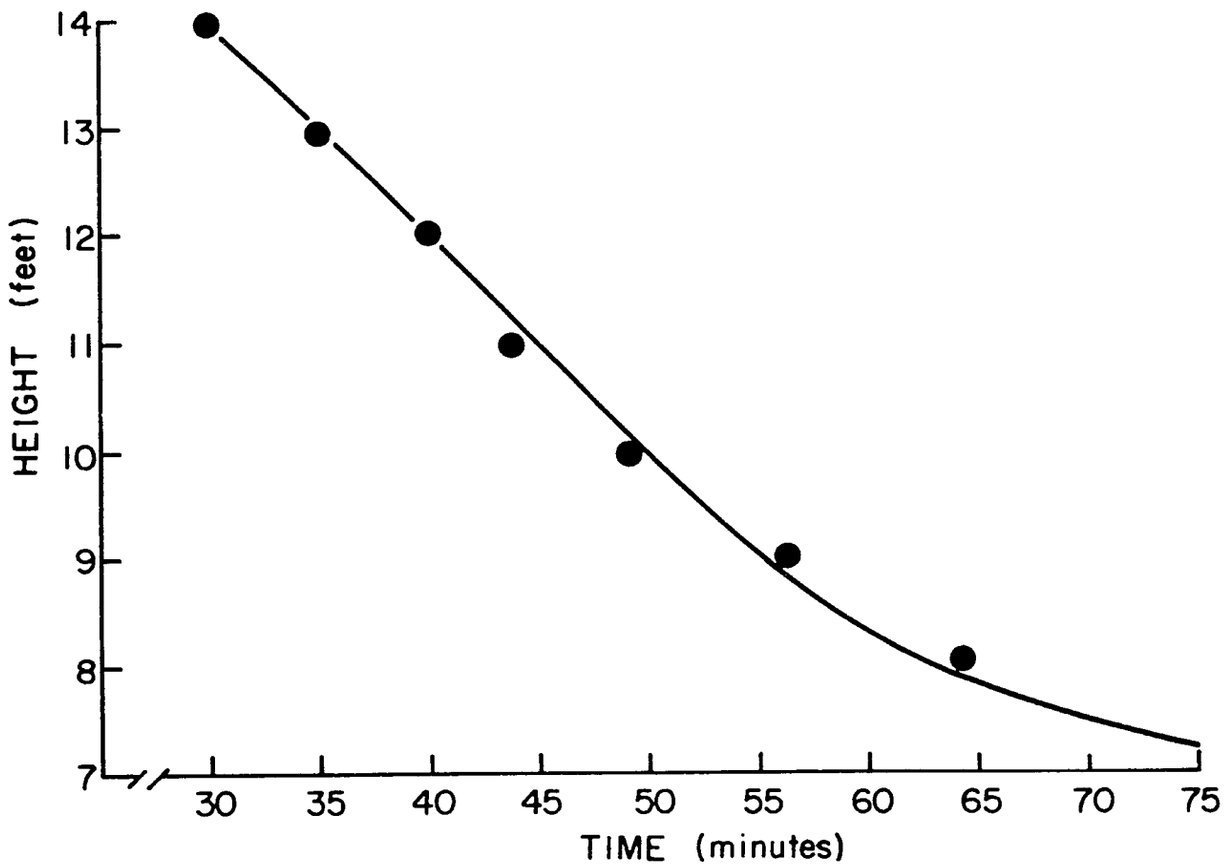

Fig. a The curve of injecting time versus height of the solution bottle.

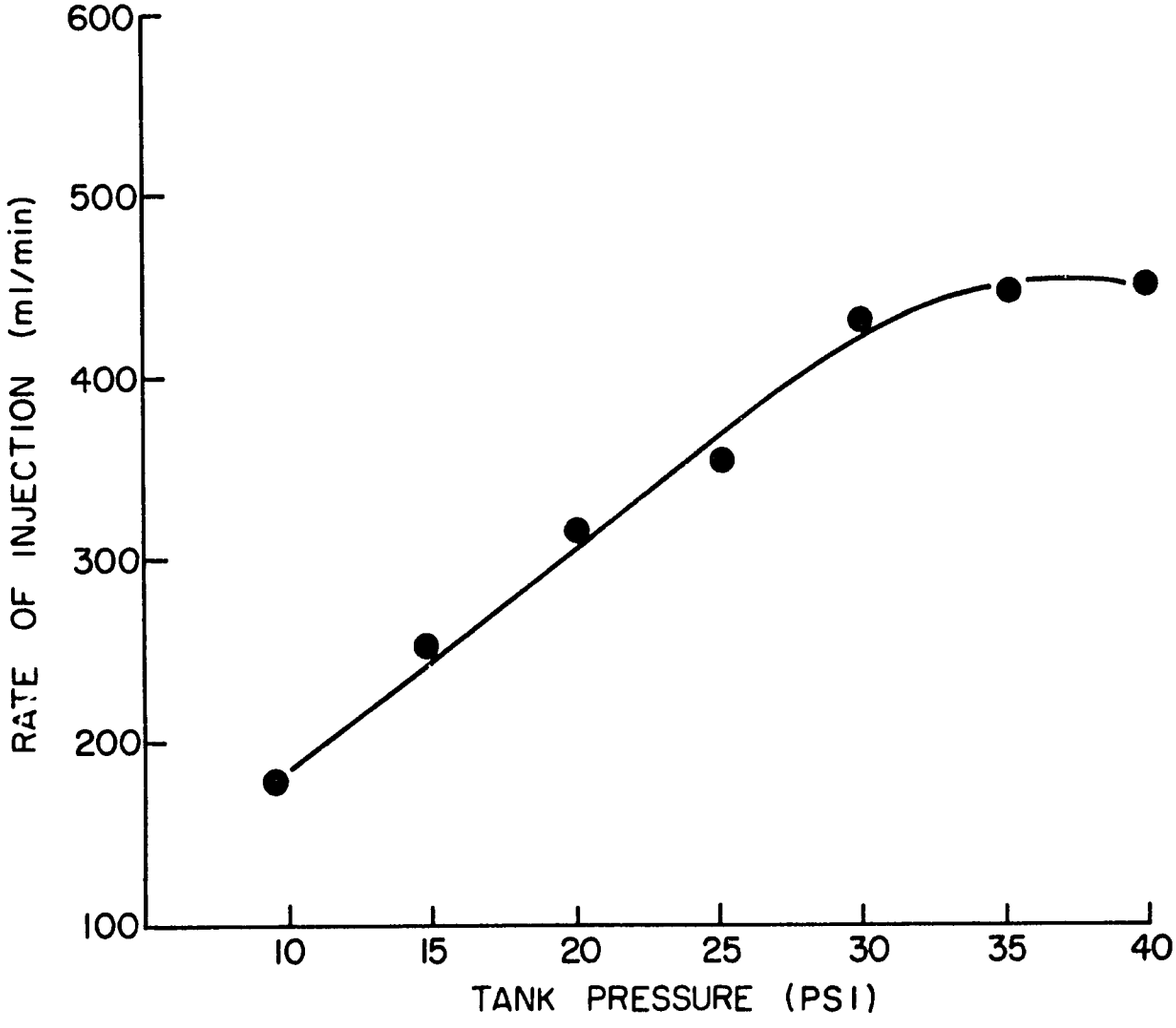

Fig. b Injection rate versus pressure of the fertilizer tank.

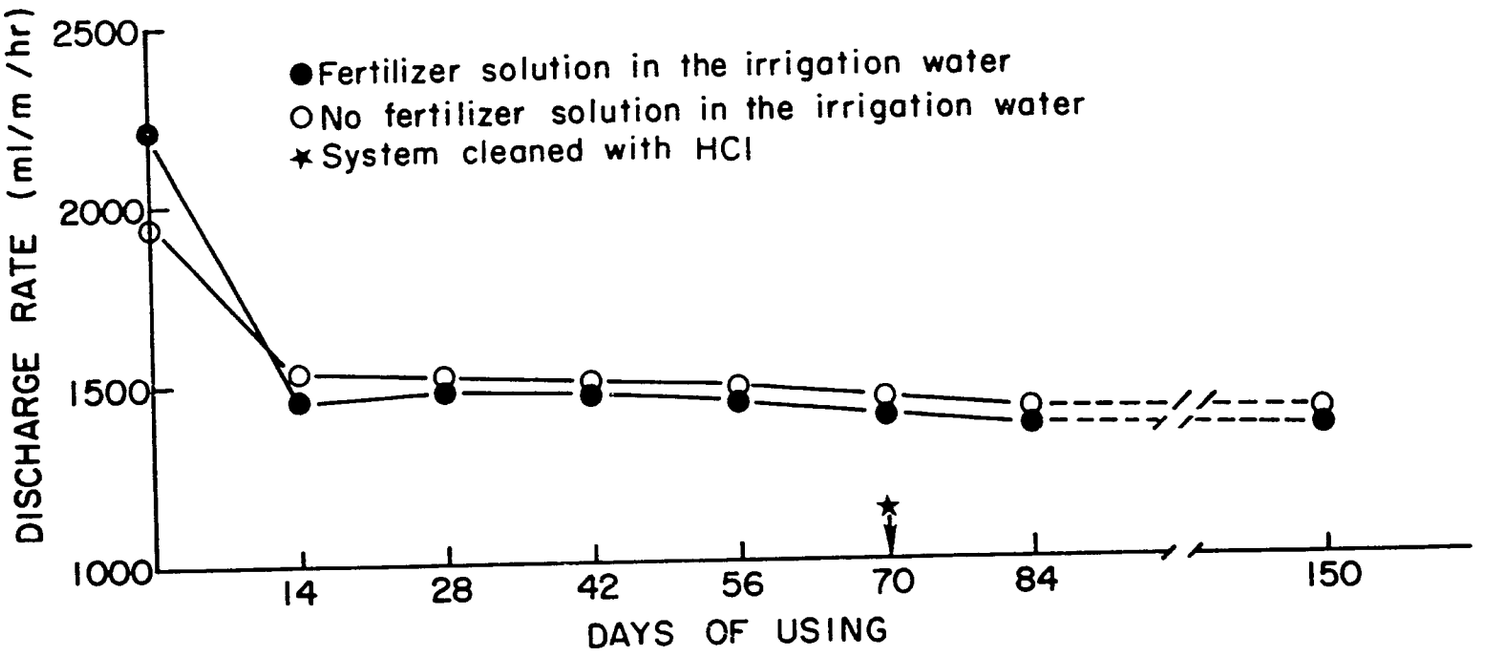

Fig. c Discharge rate of porous irrigation tube versus its age. System was cleaned by HCl on the 70th day.