WATER REQUIREMENTS OF MATURE PECAN TREES IN OKLAHOMA

By

SALIM BIN SAID

Bachelor of Science
University of Hawaii
Honolulu, Hawaii
1972

Master of Science
University of Hawaii
Honolulu, Hawaii
1975

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 1984

WATER REQUIREMENTS OF MATURE PECAN

TREES IN OKLAHOMA

Thesis Approved:

A. D. Barefoot

Thesis Adviser

Ronald L. Elliott

Michael Smith

James E. Gaston

Norman N. Durham

Dean of the Graduate College

ACKNOWLEDGMENTS

This study is concerned with the water requirements of mature pecan trees in Oklahoma. The main objectives are to determine the moisture use rate of the pecan trees and the effect of irrigation on pecan fruiting characteristics and nut yield.

The author wishes to express his gratitude to the Government of Malaysia and the authorities of the University of Agriculture Malaysia for granting him a scholarship and study leave which have enabled him to pursue the Doctor of Philosophy degree at the Oklahoma State University.

The author is full of appreciation to his major adviser, Professor A. Dudley Barefoot, for his wise guidance and assistance throughout this study. Appreciation is also expressed to the other committee members, Dr. James E. Garton, Dr. Ronald L. Elliott, and Dr. Michael W. Smith for their advice and suggestions and their invaluable assistance in the preparation of the final manuscript.

A note of thanks is given to Dr. Michael Smith for providing the author with the test plots and other research facilities at the Pecan Research Station at Sparks, Oklahoma. The staff at the Research Station whom the author knows only by their first names, Harold and Donny, have helped him a lot. The author is grateful for their help and much more for their friendship.

Thanks is also extended to Mr. Norvil Coel, his staff and student helpers at the Agricultural Engineering Laboratory for their assistance in the laboratory and field works; to Mr. Harold Gray and Mr. Joe Williams of the Soil Physics Department for their help in the construction and installation of tensiometers and in the operation and maintenance of the neutron probe meter; to Mrs. Pat Ager and Miss Brenda Cotten of the Horticulture Research Laboratory for their work on the leaf analysis; to Gayle Dowell for her work on the graphs; and to Mrs. Melanie Bayles for typing the final manuscript.

Finally, the author wishes to express his special gratitude to his two children, Leilani and Johan, for the joy they bring to him, and to his dear wife Leora, for typing the first two rough drafts of the thesis, and most of all for her love and sacrifices for him.

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CHAPTER I

INTRODUCTION

The Problem

Pecan is a nut tree native to this part of the world. It grows in wide areas of Oklahoma and Texas and over most of the southern states. As its commercial value increases many cultivars have been developed and distributed over a wider range of the region. Today Georgia is the principal state producer of pecans, followed by Texas, Alabama, Louisiana, Oklahoma, Mississippi, Arkansas and New Mexico, in that order.

Although pecan is a native tree of this area, its water requirements are unknown. Since mature pecan trees are large plants, it was believed that the trees could easily withstand short periods of drought via their ability to extract needed moisture from great depths. Now we realize that a majority of the highly active pecan feeder roots are in the upper 60 cm (24 in) of soil, even though some of the roots extend to 90 cm (36 in) and beyond (Smith and Hinrichs, 1975; White and Edwards, 1978).

The need for such a study has been realized for a long time. In 1964, the Oklahoma Agricultural Experiment Station and Extension Service published a report which, among other things, stressed the importance of undertaking some studies on the irrigation of pecan.[1]

The director of the Oklahoma Pecan Commission, addressing the factors responsible for better pecan nut production and good management of the crop, listed adequate moisture control as one of the factors. He stated that only 20 to 30 percent of the growers in Oklahoma are properly managing their trees.[2] He described good management in growing pecan trees as providing adequate spacing, pest control, fertilization and moisture control.

The annual production of pecan in Oklahoma is shown in Table I. It seems that alternate bearing in pecans in Oklahoma is very pronounced. Recent experiments and commercial practices have shown that alternate bearing can be virtually eliminated by good orchard management that includes optimum moisture by controlled irrigation and/or drainage (Woodroof, 1978; Jaynes, 1979).

Objectives

Knowledge of the water requirements of pecan trees is essential so that appropriate design criteria may be established for the irrigation and moisture management of

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[1]Pecans - A Program of Research and Education for Oklahoma. Oklahoma Agricultural Experiment Station and Extension Service. Oklahoma State University. 1964.

[2]Pecan Trees Respond to Good Management. Saturday Oklahoman and Times. p. 29. May 1, 1982.

TABLE I

OKLAHOMA PECAN PRODUCTION IN THOUSAND POUNDS

Year	Native Pecans	Variety Pecans	Total Production
1930	14,925	75	15,000
1931	13,365	135	13,500
1932	22,655	345	23,000
1933	10,240	260	10,500
1934	11,130	370	11,500
1935	26,880	1,120	28,000
1936	1,910	90	2,000
1937	17,480	920	18,400
1938	1,848	252	2,100
1939	18,240	760	19,000
1940	26,040	1,960	28,000
1941	29,376	1,224	30,600
1942	3,700	300	4,000
1943	24,450	1,550	26,000
1944	12,600	1,400	14,000
1945	24,500	1,500	26,000
1946	5,900	1,100	7,000
1947	40,900	3,100	44,000
1948	14,000	1,000	15,000
1949	21,960	2,040	24,000
1950	6,370	630	7,000
1951	24,500	1,500	25,000
1952	2,660	340	3,000
1953	26,000	1,600	27,600
1954	13,000	1,500	14,500
1955	29,700	3,300	33,000
1956	6,500	600	7,100
1957	28,800	2,200	31,000
1958	13,900	1,600	15,500
1959	8,500	500	9,000
1960	38,000	3,000	41,000
1961	10,900	700	11,600
1962	6,800	800	7,600
1963	15,000	1,000	16,000

TABLE I (Continued)

Year	Native Pecans	Variety Pecans	Total Production
1964	35,000	2,000	37,000
1965	40,000	3,000	43,000
1966	5,800	200	6,000
1967	49,000	4,000	53,000
1968	1,400	100	1,500
1969	13,800	700	14,500
1970	7,700	300	8,000
1971	17,500	1,500	19,000
1972	3,600	600	4,200
1973	26,000	2,000	28,000
1974	2,300	200	2,500
1975	18,500	1,500	20,000
1976	1,500	800	2,300
1977	12,000	1,500	13,500
1978	13,500	2,000	15,500
1979	9,000	1,000	10,000
1980	3,000	500	3,500

Source: USDA Crop Reporting Board (HORT 5) the crop. The specific objectives of this research were:

1. To determine any variations in moisture uptake by the tree from various distances and directions.

2. To determine the moisture use rate of mature pecan trees.

3. To monitor the presence of high water table and its effect on moisture distributions among the test plots.

4. To evaluate the effects of different irrigation treatment levels on:

(a) Concentrations of the minerals in the leaf;

(b) Percentage of fruit aborted;

(c) Fruit characteristics;

(d) Total nut yield.

Scope and Limitations

This research was conducted at the Oklahoma State University Pecan Research Station at Sparks, Oklahoma. Although the study covered a period of three years from 1981 to 1983, the bulk of the work was done during the last year of study. The first year was spent on Objective No. 1, while the second year was spent on the preparation of the plots and installation of access tubes on the plots for use with a neutron probe.

Information on the soils of the area was not determined by the author; rather it was taken from previous studies. A detailed soil survey of the research station was undertaken in 1963 and an excerpt of the report concerning the soil type of the test area is presented in Appendix A.[3]

Further information on the soil type and properties of the test area was obtained from a report on Soil Survey for Lincoln County, Oklahoma, published by the USDA in cooperation with the Oklahoma Agricultural Experiment Station.

During the course of work, it became obvious that the soil of the test area was not as homogeneous as previously believed. Measurements of the water table levels as well as the soil moisture tensions could be used to determine the variability of the soil.

The levels of the irrigation treatments were based on the cumulative moisture content over a root zone depth of 120 cm (4 ft). A common practice among many researchers was to take the root zone depth of pecan to be between 100 cm (3.3 ft) and 150 cm (5 ft) (Rothe and Madden, 1971; Miyamoto, 1982). It would have been desirable to establish a wide range of treatment levels. However, because of heavy spring rains, a high water table persisted in almost all the test plots till the middle of July. By then, half of the growing season had elapsed. Thus, the following irrigation treatment levels were chosen:

T_1 - No irrigation.

T_2 - Irrigate when the cumulative moisture content

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[3]Detailed Soil Survey: Pecan Research Station, Sparks, Oklahoma. Oklahoma State University. Processed Series P-451. April 1963.

reaches or falls below 27 cm (10.63 in). This represents a moisture content of 22.1%.

T_3 - Irrigate when the cumulative moisture content reaches or falls below 29 cm (11.42 in). This represents a moisture content of 23.8%.

T_4 - Irrigate when the cumulative moisture content reaches or falls below 31 cm (12.2 in). This represents a moisture content of 25.4%.

CHAPTER II

REVIEW OF LITERATURE

Pecan: An Overview

Distribution and Production

Pecan is a hickory and belongs in the Juglandaceae family. It has been classified as *Carya illinoensis*. It is indigenous to the North American continent where the native trees can be found in wide areas of Texas, Oklahoma, Arkansas, Louisiana, and Mississippi, and to a lesser extent in Kansas, Missouri, Tennessee, Kentucky, Indiana, Illinois, Iowa and Nebraska (Jaynes, 1979). Many cultivar pecans have been developed, and this cultural range extends well beyond the native range into Georgia, Alabama, Florida, Arizona, New Mexico and other fringe states.

Today, Georgia is the leading pecan producing state in the U.S., while Oklahoma ranks fifth. The annual production of pecans in Oklahoma in terms of thousand pounds is shown in Table I.

Growth Requirement of Pecan Trees

The growth and fruiting of pecan trees depends upon many climatic and environmental factors (Jaynes, 1979;

Westwood, 1978; Woodroof, 1978; Riotte, 1975). The pecan requires a long frost-free period from the time growth starts in the spring until the fruit matures in the fall. The number of days required varies with cultivars from 140 to 210. The classification of pecans into northern and southern cultivars is based largely upon the number of days of growth required for the normal maturity of the fruit.

Pecan can be considered as a warm-climate plant. It grows best where the average summer temperatures are within the 24°C (75°F) to 29°C (85°F) range, without too wide a variation between day and night. However, it definitely requires a certain chilling period for its buds to flower or grow properly in the spring. The approximate chilling requirements to break winter rest between low-chilling and high-chilling cultivars within the pecan species range from 600 to 1450 hours of temperature below 7°C (45°F) (Westwood, 1978).

New pecan growth is susceptible to injury by spring frosts and damage is reflected in reduced yield that year. Likewise, a hard frost or freeze in the fall will ruin immature pecans. Fall frosts also weaken trees and reduce fruitfulness the following year.

Pecan will grow on a wide range of soils, but it seems to do better on alluvial soil. In Texas, groves planted on deep, well-drained alluvial soils greatly outyield similar groves planted on shallow upland soil; in Georgia, trees planted on alluvial soils are strikingly larger and yield better than trees in the same grove on residual soils (Jaynes, 1979).

There are many other factors that can influence the growth and development of pecan. These include proper nutrients and an adequate amount of sunlight. Of course, as far as this author is concerned, the water requirement of pecan is of supreme importance and a separate section shall be devoted to it.

Water Requirements of Pecan

Like all living things, pecan requires an adequate supply of moisture for its healthy growth. The amount of soil moisture available affects the degree of nutrient absorptivity by the roots as well as the photosynthetic capability of the leaves (Kramer, 1969; Kramer and Kozlowski, 1960; Hewitt and Smith, 1974; Salisbury and Ross, 1969; Devlin and Barker, 1971; Poincelot, 1980).

Water Deficiency in Pecan

Mature pecan trees are large plants which are easily susceptible to drought. Alben (1955) observed that during the drought years of 1952-1954, many pecan trees suffered in varying degrees from drought injury. The nuts were not only small and poorly filled, but in some cases early defoliation of trees occurred and twigs, branches or even entire trees died. The severity of the drought injury was found to be related to the soil textures and profiles. Sandy soils and compact, poorly-drained clay soils were found to be detrimental to pecan trees under drought conditions.

Such maladies and other disorders in pecan due to an inadequate amount of moisture supply were also reported by other authors (Taylor, 1973; Madden, 1971; Smith and Hinrichs, 1975; Gammon et al., 1963).

Though pecan trees use water at all times, the critical periods at which adequate moisture must be available are during the rapid fruit sizing and shell hardening (mid-July to early August) and during fruit filling (early August to early September).

Irrigation Effects on Pecan

Studies on the effects of irrigation on pecan trees were conducted mainly in the states of Texas and Georgia. The only reported work on this topic in the state of Oklahoma was that by Smith and Hinrichs (1975). Twenty-three year old trees of 'Western', 'San Saba Improved', and 'Success' cultivars were used and the soil type was a Port silt loam. Trickle irrigation was applied. Some of their findings were that trunk growth was not affected by irrigation while shoot growth of some cultivars was, and that nuts were larger and heavier with irrigation but percent kernel remained the same in both irrigated and non-irrigated treatments.

Madden (1971) reported significant increases in yield (lb per acre) and nut size with irrigated trees as compared to non-irrigated trees. He too reported that irrigation had no effect on percent kernel. Madden used six cultivars of 35-year old pecan trees grown on Frio silty clay loam in Texas.

Daniell (1979) conducted a 4-year study on irrigation of pecan in Georgia. His data showed that irrigation up to the shell hardening stage, increased pecan size. After that time, irrigation improved quality and percent shellout of pecans. In addition, irrigation after shell hardening could improve next year's crop by supplying an adequate amount of water. With an adequate amount of water and a weed, disease and insect control program, he and his colleagues were able to get a good crop of pecans each year.

In addition to increased yield and nut size, Worley (1979) also found that irrigation improved the quality of nuts and reduced the percent stick-tights[1] on pecans tremendously. He reported that the percentage kernel and quality of the kernels were much greater for irrigated trees than for non-irrigated trees.

Aitken (1982), working with 8-year old Wichita pecan trees grown on Lakeland sandy soil type in South Carolina, compared the influence of different levels of soil moisture suction on pecan. In the experiment, soil moisture suction levels at the 60 cm (24 in) soil depth were maintained at 4

[1]A few weeks after the pecan fruit reaches maturity, its hull (the outer covering of the nut) dehiscences.

centibar and 14 centibar, respectively. He concluded that maintaining the soil moisture suction at the 4 centibar level gave a significantly greater mean trunk diameter when compared to the higher level. The lower treatment level also gave a greater yield of marketable nuts when compared to the 14 centibar level. He also reported a heavy fruit drop in the 14 centibar plots in late August.

Miyamoto (1982) conducted his experiment on 30-year old pecan trees grown on silt loam at the El Paso-Las Cruces area. He imposed three irrigation regimes: 25, 50 and 75% depletion of available water (which corresponded to soil moisture suctions of 0.6, 1.7 and 3.9 bar) in the root zone. He reported that tree growth in the driest treatment slowed, but the differences in trunk diameter among the treatments were not statistically significant at the 5% level. There were also no significant differences in the nut yields among the treatments, nor were there any differences in nut size, percent kernel and kernel color. He cautioned that during the year, a late spring freeze following a warm early spring had destroyed most of the emerging leaves and flower buds.

Irrigation Design Parameters

Pecan growers in the southeast and southwest U.S. rely heavily on rainfall for the water requirement of their trees. Irrigation is used to supplement the rainfall when needed during critical periods.

Many factors, such as the root zone depth, available soil moisture, consumptive use of the crop, etc., have to be considered when designing an irrigation system for pecan. These factors are in turn dependent upon the type of soil in which the trees are grown and also their locations. Many pecan groves or orchards are to be found on flood plains. In such cases, the presence or absence of high water tables needs to be studied.

Root Zone Depths

Although mature pecan trees are large plants, their roots are primarily distributed near the soil surface. Jaynes (1979) stated that pecan roots can grow laterally to a distance of 1 1/2 to 2 times the spread of the canopy and may reach a depth of at least 6 meters (20 ft). Romberg (1960) reported finding pecan roots as deep as 6 m (20 ft) in digging water wells; however, the greatest concentration of the roots was immediately below the tilled surface and the number decreased steadily with depth. Smith and Hinrichs (1975) stated that a majority of the active pecan feeder roots are in the upper 40 cm (15 in) of soil even though many roots extend to 90 cm (36 in) and beyond.

A rather comprehensive study on soil profile distribution and seasonal growth of pecan roots was conducted by White and Edwards (1978). Their study was conducted near Byron, Georgia, in an orchard of 'Moneymaker' pecan trees about 35 years old. Three sites of study were selected. The soils varied from grayish loamy topsoil to reddish sandy clay subsoil. At two of the sites some gray mottling appeared at the subsoil layer. They found that most of the roots larger than 1 mm were in the 15- to 75-cm profile area, with the largest (greater than 10 mm) in the 30- to 60-cm zone. The roots in this zone form the permanent framework of the tree root-systems. Their results also showed that most of the roots were smaller than 1 mm in diameter and that these roots were distributed fairly uniformly throughout the profile to depths of about 90 cm (35.4 in).

Their data on the seasonal growth of roots showed that root growth increased sharply during the spring, reached a maximum in late May and June, and then continued at a lower level to mid-September when it declined rapidly. A small amount of growth continued into January.

Based on field observations, Rothe and Madden (1971) set a root zone depth of 150 cm (5 ft) in their design of a flood irrigation system for pecan in Brownwood, Texas. Miyamoto set a depth of 100 cm (40 in) as a representative rooting depth in the El Paso-Las Cruces area. He cautioned that the figure had to be adjusted based on the given circumstances.

Daniell (1979), working with a drip irrigation system, obtained best nut yields from trees installed with 5 emitters and 8 emitters with a flow rate of 0.5 liter per second (2 gallons per hour). Thus, he recommended that drip irrigation systems should be designed to deliver 22,400 liters per hectare (2,400 gallons per acre) in 12 hours and that the system must be off for the other 12 hours for oxygen to return to the tree roots.

Privette (1979) defined the effective rooting depth as the depth from which most of the water was absorbed by the root systems. He stated that the effective rooting depth of pecan varied with soil textures, but normally the effective rooting depth of pecan was about 60 cm (24 in). Aitken (1982) installed tensiometers at the 60-cm (24-in) depth to monitor soil moisture tensions in his experiment. He followed Daniell's recommendation on the flow rate of the drip irrigation system.

Rothe and Madden (1971) estimated that pecan trees in the Brownwood area of Texas would use about 105-130 cm (42-50 in) of water per year with the average daily use to vary from 0.25 cm (0.1 in) in March and October to 0.7 cm (0.28 in) in May and June.

Woodroof (1978) proposed that the weekly water requirement (WWR), measured in hectare-cm, be calculated as follows:

$$\text{WWR} = \text{Total net evaporation for week (in cm)} \times 70\% \times 90\% \text{ canopy} \times 99927 \text{ liters of water} \qquad (2.1)$$

Available Soil Moisture

One of the factors that needs to be considered when setting up an irrigation program is the available soil water held by the soil. Traditionally, a soil's available water is defined as the amount of water held in the soil at field capacity less the amount of water held at the permanent wilting point (Arkin and Taylor, 1981; Privette, 1979). The water that is available between these two limits can be used or removed from the soil in the support of the life of higher plants (Black et al., 1965). The concepts of field capacity and permanent wilting point were introduced early in this century by Veihmeyer and Hendrickson (1949) and generated much discussion about their validity.

Field Capacity. Veihmeyer and Hendrickson (1949) defined field capacity as the amount of water held in the soil after the excess water drained away and the rate of downward movement of water has materially decreased, which usually takes place within 2 or 3 days after a rain or irrigation in pervious soils of uniform structure and texture.

They considered the field capacity as the starting point from which plants begin to use water from the soil in the normal functions of growth and fruiting, although some water might be used while the soil was being irrigated and before the field capacity was reached. They also asserted that the field capacity was not an equilibrium value, but one on a time-drainage curve. On the energy-soil-moisture-content curve, the position of the field capacity was in the region where the curve was almost horizontal, which further suggested that it was not a unique value.

Black et al. (1965) stated that the original intent in defining "field capacity" was to devise a procedure which would enable determination of the upper limit of available water. In ideal situations, such as deep permeable soils which are intitially dry, the values obtained do approximate the upper limit of the available water. However, there are many soil conditions which alter the upper limit from that prescribed by the field capacity definition. Any soil condition which would impede drainage would cause misleading results. Soil conditions which are effective in the formation of perched water tables should be carefully evaluated. He also noted that it was not possible in general to designate a time after which soil water movement is negligible.

Hillel (1971) argued that the criteria for the measurement of field capacity were subjective, depending as often as not upon the frequency and accuracy with which the soil water content was measured. The common working definition of field capacity took no account of such factors as the antecedent (pre-infiltration) wetness of the soil, the depth of wetting, or the amount of irrigation applied.

Permanent Wilting Point. The permanent wilting point has been defined as the water percentage of a soil when plants growing in that soil are first reduced to a wilted condition from which they cannot recover in an approximately saturated atmosphere (Black et al., 1965). It denotes the lower limit of available water.

Veihmeyer and Hendrickson (1949) concluded from work done by Briggs and Shantz in 1912 that the permanent wilting point should be characteristic of the soil and not of a plant. They observed that on a given soil all plants reduced the moisture content of the soil to about the same extent when permanent wilting was attained. However, later researchers gave ample evidence to indicate that the permanent wilting point was not a true constant or an intrinsic soil property.

Though the concepts of field capacity and permanent wilting are now regarded as imprecise, they are still quantitatively useful terms and appropriate for establishing general limits (Arkin and Taylor, 1981; Jensen, 1980).

Soil Water Characteristic

The concept of potential energy of water has formed the basis for the modern understanding of water availability to plants. The relation between soil water content and the water potential energy due to the pressure is termed the soil water characteristic (Jensen, 1980; Arkin and Taylor, 1981). A curve showing the functional relationship between the soil water content and the pressure potential is known as the soil moisture characteristic curve (Hillel, 1980; Jensen, 1980), or sometimes called the moisture release or desorption curve (Trout et al., 1982) or the moisture retention curve (Baver et al., 1972).

Soil Moisture Content. The fractional content of water in the soil can be expressed in terms of either mass or volume ratios. The mass ratio is often referred to as the gravimetric water content (Hillel, 1980), and it is the mass of water relative to the mass of dry soil particles.

$$w = M_w/M_s \tag{2.2}$$

where

w = gravimetric water content

M_w = mass of water

M_s = mass of dry soil

The volume ratio is often referred to as the volumetric water content (Hillel, 1980) and it is the volume fraction of soil water, generally computed as a percentage of the total volume of the soil.

$$\theta = V_w/V_t = V_w/(V_s + V_w + V_a) \tag{2.3}$$

where

θ = volumetric water content

V_w = volume of water fraction

V_t = total soil volume

V_s = solid fraction of soil

V_a = air fraction of soil

The two expressions can be related to each other by means of the bulk density ρ_b and the density of water ρ_w.

$$\theta = w\ (\rho_b/\rho_w) \tag{2.4}$$

<u>Measurement of Soil Moisture Content by Neutron Scattering Method</u>. Gardner (1965) discussed several methods of measuring the soil-moisture content of a soil. The traditional and accepted standard for soil water measurement is the gravimetric method which gives the ratio of mass of water loss by drying to mass of dry soil.

In recent years, the neutron scattering method which was first developed in the 1950's has gained widespread acceptance as an efficient and reliable technique for monitoring soil moisture in the field. Its principal advantages over the gravimetric method are that it allows the volumetric moisture content of a representative volume of soil to be determined with less laborious, more rapid, non-destructive, and periodically repeatable measurements in the same locations and depths. The method is practically independent of temperature and pressure. Its main disadvantages are the high initial cost of the instrument, difficulty of measuring moisture in the soil surface zone and the health hazard associated with exposure to neutron and gamma radiation (Hillel, 1980).

A neutron moisture meter is used to measure the soil moisture content by the neutron scattering method. The main components of the instrument are a probe which contains a source of fast neutrons and a detector of slow neutrons, and a scaler or rate meter (usually battery powered and portable) to monitor the flux of slow neutrons scattered by the soil.

A source of fast neutrons is generally obtained by mixing a radioactive emitter of alpha (α) particles with beryllium. A mixture of radium-beryllium has been used, but all current equipment uses an americium-beryllium source because it is less hazardous (Jensen, 1980).

The source commonly used is a mixture of americium ($^{241}_{95}Am$) with a half-life of 458 years, and beryllium ($^{9}_{4}Be$) and has an activity between 25-100 millicurie (mCi) (Goldberg et al., 1976).

The following equations describe the disintegration of the $^{241}_{95}Am$ source and the creation of the neutron source:

$$^{241}_{95}Am \xrightarrow[ev]{\alpha} {}^{237}_{91}Np \qquad \text{(Neptunium)} \tag{2.5}$$

$$^{4}_{2}He + {}^{9}_{4}Be \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n + 5.65ev \tag{2.6}$$

Note that the α-particle emitted is in fact the nucleus of the helium atom, with mass equal to 4 and containing 2 charged protons.

When the probe containing this radioactive source of fast neutrons is introduced into the soil, the neutrons will collide with the nuclei of the surrounding atoms and are scattered randomly in all directions. Every collision of a neutron causes it to lose part of its kinetic energy, which it passes on to the atomic nucleus with which it collided. This process of scattering and loss of energy continues until the kinetic energy of the neutron is reduced to the average energy of the atoms in the soil. At this low energy level, the neutron is called a slow or thermal neutron and its average energy is about 0.03 mev and has a speed of about 2.7 km/sec. The average energy of a fast neutron is about 4.5 mev (Goldberg et al., 1976; Troxler Instruction Manual, 1980).

Hillel (1980) described the effectiveness of various nuclei present in the soil in moderating or thermalizing fast neutrons. The average loss of energy was maximal for collisions between particles of approximately the same mass. Of all nuclei encountered in the soil, the ones most nearly equal in mass to neutrons were the nuclei of hydrogen, which were therefore the most effective fast neutron moderators of all soil constituents. The thermalized neutrons formed a swarm or cloud of constant density around the probe nearly proportional to the concentration of hydrogen in the soil and therefore proportional to the volume fraction of water present in the soil. As the thermalized neutrons repeatedly collided and bounced around randomly, a number of them would return to the probe, where they were counted by the detector of slow neutrons and then registered by the scaler or a ratemeter.

Soil Water Potential. Water in the soil is subjected to a number of force fields which cause its potential to differ from that of pure, free water. Factors that contribute to the total potential energy of soil water include the gravitational, osmotic and pressure potentials (Hille, 1980; Arkins and Taylor, 1981).

The pressure potential is often referred to as matric potential. Its relation with the soil water content gives rise to the characteristic curve which is important in determining water availability to plants. At saturation, all soils have a pressure potential of zero. Above their saturated zones, the soils will have negative pressure potentials. The negative pressure potential is termed soil moisture tension. If the negative sign is removed then the term becomes soil moisture suction.

<u>Measurement of Soil Moisture Tension with Tensiometers</u>. The soil moisture characteristic is usually determined in the laboratory by means of tension tables for suctions in the low range (<1 bar), and by means of pressure plates (membranes) for higher suctions (Hillel, 1980; Jensen, 1980). In the field, the soil moisture tension is usually determined by using tensiometers.

The essential parts of a tensiometer usually consist of a porous ceramic cup, connected through a tube to a mercury manometer, with all parts filled with water. When the cup is placed in the soil where the suction measurement is to be made, the bulk water inside the cup comes in to hydraulic contact and tends to equilibrate with soil water through the pores in the ceramic walls. Soil water, being generally at subatmospheric pressure, exercises a suction which draws out a certain amount of water from the rigid and airtight tensiometer, thus causing a drop in its hydrostatic pressure. This drop in pressure is indicated by the mercury manometer.

The pressure potential thus can be calculated as follows:

$$p = -\rho_m g h_m + \rho g h_w$$
$$\text{or } h_p = (p/\rho g) = -(\rho_m h_m/\rho) + h_w \qquad (2.8)$$

where

p = pressure potential

hp = pressure potential in terms of height of water column

h_m = height of mercury column

h_w = height of water column

ρ_m = density of mercury

ρ = density of water

g = acceleration due to gravity

Suction measurements by tensiometers are generally limited to matric suction values of below 1 atmosphere. This is due to the fact that the manometer measures a partial vacuum relative to the external atmospheric pressure, as well as to the general failure of water columns in macroscopic systems to withstand tensions exceeding 1 bar (Hillel, 1980).

So, in practice tensiometers are used to measure soil suction up to about 80 kPa (0.8 bar) only. However, they are still very useful since, with irrigation, soil moisture is usually maintained at low-suction conditions which are favorable for most plant growth.

Many attempts have been made to relate field gravity and permanent wilting point to the moisture release curve. Often, field capacity is correlated to the water content at -33 kilopascal (-1/3 bar) pressure, and the permanent wilting point is correlated to the soil water content at a pressure of -1500 kPa (-15 bar). Baver et al. (1972) contended that such attempts ignored the fact that water retention in a profile depended on transmission properties of the entire profile and the hydraulic gradients which existed rather than on only the energy state of water at a particular point in the profile. He cautioned that huge errors in water retention estimates might be expected from the arbitrary association of field capacity with a particular water potential such as -1/3 bar. Skaggs et al. (1980) also said that field capacity could not be determined on a single soil sample in the laboratory. However, such laboratory procedures could be taken as rough estimates and applied only to uniform soil. They concluded that field capacity, to be useful, should be determined in the field under conditions that will normally exist during the growing season, except for water removal by a growing crop.

Arkin (1981) stated that the matric potential indicates the energy by which water is retained in soil, but gave no indication of the amount of water retained at that energy.

He observed that the rate of change between water content and matric (pressure) potential is greatly different for different for different soils. For example, the water content of sandy soils, which retain less water than clay soils at -30 kPa (-0.3 bar) matric potential, decreases much more rapidly with decreases in potential than that of clay soil. As the potential decreases, plants must expend more energy to extract water from soil. So, he concluded that the field capacity of sandy soils would be at a potential of around -5 to -10 kPa rather than at -33 kPa as many had assumed. That is, water becomes available in sandy soils at a higher potential (smaller negative value) than in the clay soils.

High Water-table Phenomena

Many pecan groves or orchards are located on river flood plains where flooding occurs quite frequently. If heavy rains fall during the early stages of growth, high water-table conditions may persist until late into the growing season. This phenomenon may hamper the development of pecan roots and consequently the nut production. White and Edwards (1978) observed rooting differences at the lower depths of three soil profiles and suggested that rooting depth on those three sites was influenced by soil drainage. The site with the best drained soil had more root tips at the lower depths as compared to the site which had standing water continuously from December through April.

Freeze (1969) noted the dynamic behavior of a water-table and stated that water-table fluctuations resulted when the rate of ground-water recharge or discharge was not matched by the unsaturated flow rate created by infiltration or evaporation. Freeze and Witherspoon (1968) stated that both field evidence and theoretical research indicated that the rate of ground-water recharge or discharge was usually relatively constant with time at any given location, but varied areally throughout a basin.

A generalized statement about the water-table fluctuations can be made in that a water-table rise is indicative of an infiltration rate greater than the prevailing recharge rate or an evaporation rate less than the prevailing discharge rate (Freeze, 1969). He defined "recharge" as the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone. He defined "discharge" as the removal of water from the saturated zone across the water-table surface, together with the associated flow toward the water-table within the saturated zone.

The soil moisture profile above a water-table takes the form shown in Figure 1.

A zone of saturation is established right above the water-table up to the capillary fringe. If the soil can be regarded as analogous to a bundle of capillary tubes, an equation relating the equilibrium height of capillary rise

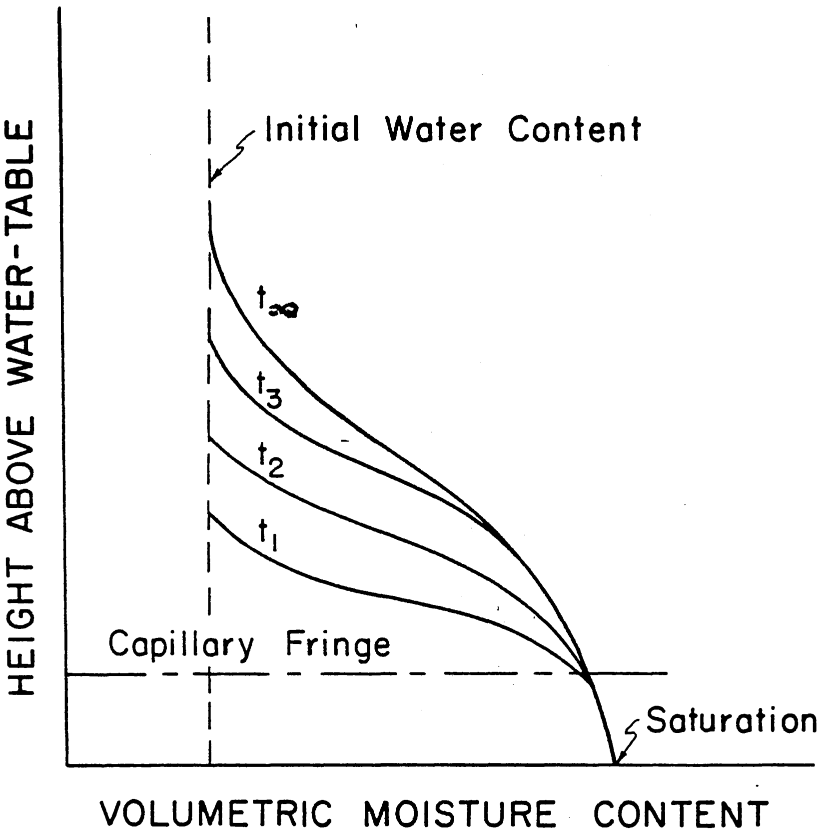

Figure 1. Soil Moisture Profile Above a Water-table for Various Times ($t_1 < t_2 < t_\infty$)

Source: Hillel, D. Soil and Water--Physical Principles and Processes

h_c to the radii of the pores can be stated as follows:

$$h_c = \frac{2\gamma \cos\alpha}{r \rho_w g} \quad (2.9)$$

where

γ = surface tension

r = capillary radius

ρ_w = density of water

g = gravitational acceleration

α = wetting angle (normally taken as zero)

This equation predicts that water will rise higher (though less rapidly) in a clay (smaller r) than in a sand. However, soil pores are not capillary tubes of uniform or constant radii, hence the height of capillary rise will differ in different pores.

Hillel (1971) noted that the evaporation rate from a shallow water-table was much higher than that from a deeper water-table. The evaporation rate approached a limiting value as the water-table lowered.

The presence of a shallow water-table can entail the hazard of salinization, especially when the groundwater is brackish and potential evaporativity is high. If the salinization process is irreversible, considerable destruction to agricultural crops may occur. Excessive irrigation tends to raise the water-table and thus aggravate the salinization problems.

CHAPTER III

MATERIALS AND EQUIPMENT

Research Location

This research on the water requirements of mature pecan trees was carried out at the Pecan Research Station at Sparks, Oklahoma. The research station was well-equipped for the proper maintenance and management of the pecan crop. Some weather recording instruments were installed at the station. The daily precipitation was recorded by a standard rain gauge. A recording thermograph was used to record the variations in temperature throughout the seasons. An evaporation pan equipped with an anemometer was also installed at the station to measure the evaporation rate.

The Test Trees (Plots)

Sixteen trees from a 10-year old pecan orchard were selected for the study on the irrigation treatment effects. Trees of this orchard were planted at 10.7 m x 10.7 m (35 ft x 35 ft) spacing and they were of the 'Mohawk' cultivar. The selected trees were equal or nearly equal in size and came either from row 12 or 13 of the orchard. Figure 2 is a schematic view of the orchard. A selected tree was marked with the symbol $\odot$. The rows ran in the north-south

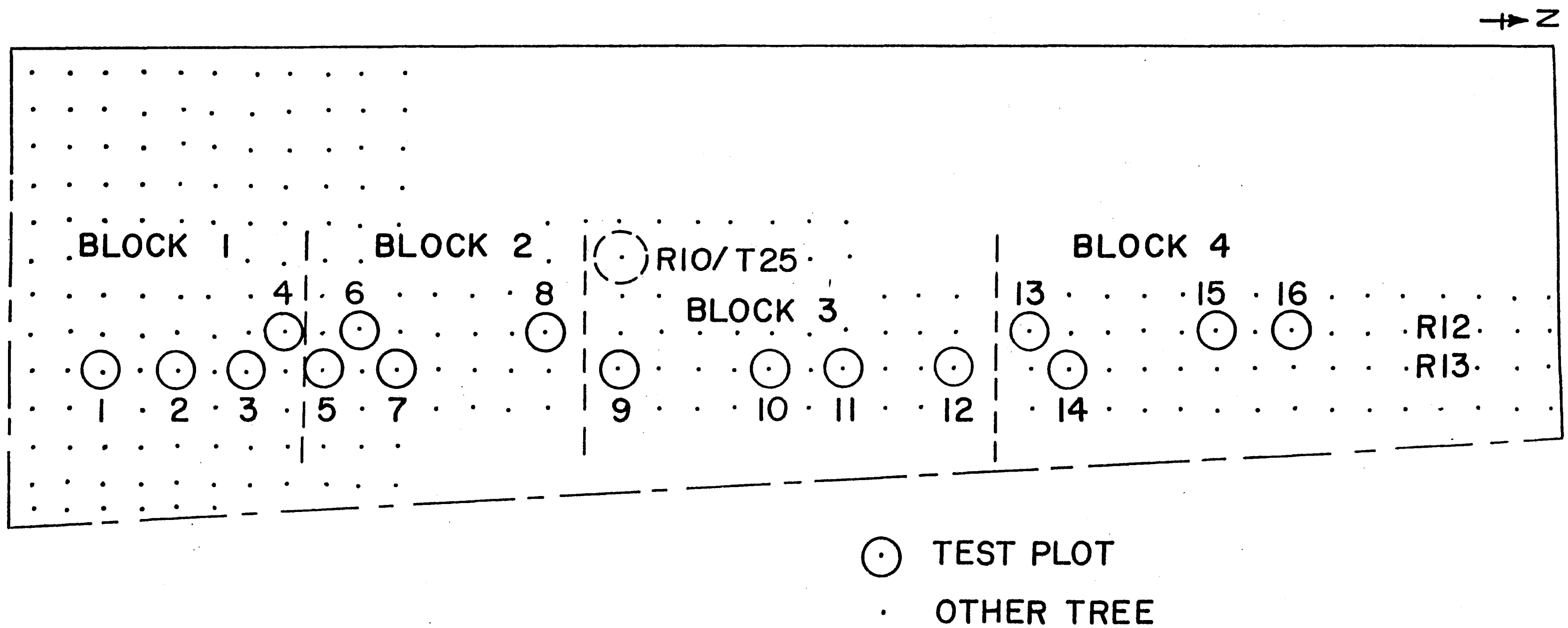

Figure 2. Schematic View of the Test Plots

direction and the land was sloping very gently towards the Quapaw Creek which bordered the orchard at its northern end. The elevation of each test plot (measured at ground level of the access tube) was taken and the ground slope was found to be about 0.25%.

The Soil of the Test Plots

The test plots were located in the flood plain of Quapaw Creek, a tributary to the Deep Fork River which is about 4 km (2 1/2 miles) to the north. The Quapaw Creek was reported to overflow on an average of once every five years. However, it had flooded the orchard for the last two consecutive years. In May of 1982, just when the flowers were forming, the whole orchard was flooded. Then in early October of 1983, just when all irrigation treatments were terminated, the orchard was flooded again.

A detailed soil survey of the research area was carried out in 1963 by the Department of Agronomy, Oklahoma State University, and was published as Processed Series P-451. The report stated that the soils of the research station were typical of those of many commercial pecan orchards operated throughout central Oklahoma. Thus, results of experiments at this location should be applicable to problems of the pecan industry on similar soils throughout the state of Oklahoma.

The soil of the test plots was established to be Port silty clay loam. An excerpt of the description of the soil and its profile is given in Appendix A.

The report on the Soil Survey of Lincoln County, Oklahoma described the Port Series as soils that occur on the bottom lands along the Deep Fork North Canadian River and along some of the smaller streams. The soils are occasionally to frequently flooded. The report also incorporated a few properties of the Port silty clay loam. The available water capacity for that soil was given as 0.17 cm per cm of soil.

The USDA Inter-Agency Ad Hoc Committee, in its report for guidelines for application of sprinkler irrigation systems in Oklahoma, suggested values for available water holding capacity of silty clay loams which range from 0.15 to 0.22 cm per cm (1.8 to 2.6 inches per foot).

Rawls et al. (1982) estimated the soil water properties for the various soil textures and classes. They used a comprehensive search of the literature and sources of hydraulic conductivity and related soil-water data obtained from all over the United States. Using 689 samples, the following soil-water properties for silty clay loam soils were estimated:

a) Water retained at -0.33 bar tension ranged from 0.304 to 0.428 cm^3/cm^3.

b) Water retained at -15 bar tension ranged from 0.138 to 0.278 cm^3/cm^3.

c) Effective porosity of soil ranged from 0.347 to 0.517 cm^3/cm^3.

These estimates should be helpful for comparing with the results of the soil moisture tension as measured by the tensiometers and the soil moisture content of the test plots.

The Neutron Moisture Gauge

The soil moisture contents of the test plots were measured with a Troxler neutron moisture gauge. The gauge was of the 3220 series and very portable.

The neutron probe, housed and shielded inside the gauge body when not in use, was connected to the gauge via a 5-conductor cable. Inside the probe was a pulse amplifier, a Helium-3 detector and a radioactive source. The source was located annularly at about the center of the detector. Since the effective center of the source corresponded to the center of the detector volume, the center of influence was the center of the probe.

The radioactive source was a compacted mixture of americium oxide and the beryllium metal target. The mixture nominally contains 10 mCi of americium-241. The mixture was fusion welded in two separate stainless steel capsules within the probe.

Since the neutron is not a charged particle, it is unaffected by electrical or magnetic fields. Accordingly, it cannot be detected directly by instruments used to detect charged particles such as protons or alpha particles. Detection of the thermal neutron is carried out indirectly with a gas counter filled with helium-3 (${}^{3}_{2}He$). Helium-3 is a gas having a high neutron capture cross-section (Goldberg et al., 1976). The detector is filled with the helium-3 gas to a pressure of 150 to 1010 kPa and the following reaction takes place:

$$ {}^{3}_{2}He + {}^{1}_{0}n \text{ ------> } {}^{3}_{1}He + {}^{1}_{1}p \qquad (3.1)$$

The reaction with the neutron causes the release of a proton with a mass four times smaller than that of the α-particle (helium atom).

The release of the proton results in a brief pulse of current flow. The transistorized preamplifier boosts the pulse signal and sends it through the cable to the gauge counter.

Calibration of the Moisture Gauge

Calibration of the moisture gauge can be accomplished directly in the field by making numerous measurements of soil moisture with the neutron probe and gravimetric methods concurrently. In most soils, a nearly linear relation between the volumetric soil moisture content and the count ratio (which is the ratio of the measured count made with the probe in the access tube in the soil to the standard count made with the probe secured within the gauge body) can be obtained. In the laboratory, calibration curves for a moisture gauge were determined by using barrels filled with materials of predetermined moisture contents.

Because of the anomalies and variability among different soils, it is best to calibrate the neutron moisture gauge specifically for each soil type. However, for Oklahoma soils, Stone and Nofziger (1983) have determined that there are no significant differences in their calibration curves. This fact is established over many years of data collection.

The neutron moisture gauge used for this study was calibrated in the Soil Physics Laboratory, Oklahoma State University. The calibration was determined in soil media containing (a) aluminum sulphate, $ALSO_4$ (b) urea and (c) pure water. For this gauge, its calibration curves are as follows:

For soil depths equal to 15 cm (6 in):

$$\theta = 0.0055 + (0.6207)\ (R) \tag{3.2}$$

For soil depths equal or greater than 30 cm (12 in):

$$\theta = -0.0215 + (0.6019)\ (R) \tag{3.3}$$

where

θ = volumetric moisture content

R = (measured count)/(standard).

The statistical stability and drift tests indicate that the instrument would be highly reliable in all of its measurements.

The Access Tubes

Electrical metallic thinwall (EMT) access tubes were used for the measurement of soil moisture content with the neutron probe. The 3.05-m (10-ft) tubes were cut into two equal halves before installation into the soil profile. The diameter of the tube was slightly larger than 3.8 cm (1 1/2 in) and its wall thickness was about 0.15 cm (1/16 in).

Proper installation of the access tubes was very important because the presence of air pockets could affect the readings of the soil moisture content (Black et al., 1965). Each of the tubes was installed by boring a hole with an auger of the same diameter as the tube, and then driving the tube into the hole with light tapping of a hammer. The tube was occasionally cleaned out with an internal auger and then with a wire brush. A portion of the tube, about 15 cm (6 in) in length, was left extended above the soil surface. The top of the tube was closed with a no. 9 rubber stopper.

The Tensiometers

The tensiometers were constructed in various lengths for the determination of soil moisture tension at different soil depths. Personnel of the Soil Physics Laboratory at Oklahoma State University assisted in this construction and installation.

Each tensiometer consists of a 1.3 cm (1/2 in) i.d. PVC tubing cut to the required lengths plus 3.2 cm (1 1/4 in) longer, a 5.1 cm (2 in) piece of clear 1.6 cm (5/8 in) plexiglass tube, a ceramic cup which is available commercially and a "Nylon 101" tubing. The plexiglass tube is fitted into the top of the PVC tube by drilling a 1.6 cm (5/8 in) hole to a depth of 1.3 cm (1/2 in). The ceramic cup is fitted into the bottom of the PVC tube. If fitting is not matched properly, the PVC bottom should be rasped for a good fit. To provide a good seal, a small amount of mixed epoxy cement is applied to the inside of the PVC tube and a more generous amount to the thin stem of the ceramic cup.

The nylon tubing is used to connect the tensiometer to a mercury manometer through a hole drilled 3 cm from the top of the PVC tube.

The tensiometers were tested for air leaks before their installation in the field.

The Irrigation Pump Sets

A submersible pump was used to deliver water from a well to the test plots. The electrically driven pump was capable of delivering about 1 liter/sec (15 gpm) of water. It was of continuous duty and had a rated power of 0.56 kW (3/4 Hp). Its maximum operating speed was rated at 3450 rpm.

Irrigation water was supplied to each test plot through a 5.1 cm (2 in) diameter pipeline. The pipeline was made of several 6.1 m (20 ft) PVC pipes which were coupled and glued together. The pipeline was branched to each plot and ended with a gate-valve which remained shut until irrigation was needed.

CHAPTER IV

EXPERIMENTATION

Preparation of Preliminary Test Plot

A preliminary test on the nature of soil moisture uptake by pecan was carried out in 1981. The aim of the test was particularly to determine whether sampling distance and direction from a pecan tree would show any significant differences in the moisture use rate. It was also desired to determine the moisture uptake at different depths in the soil profile.

A representative tree was chosen; it was tree no. 25 of row no. 10 (tree code: R10/T25) of the orchard. The ground surrounding the tree was levelled to within 0.03 of a meter (one-tenth of a foot). Then a circular bund was constructed at a distance of about 9.1 m (30 ft) from the tree. The bund was about 15 cm (6 in) high.

Access tubes were installed on the plot as shown in Figure 3. To determine the effect of sampling distance from the tree on moisture uptake, five access tubes were installed at the northern side of the tree. The tubes were 1 m apart with the first tube 1 m from the tree. To determine whether sampling direction from the tree has any effect on moisture use rate, an access tube was installed 3

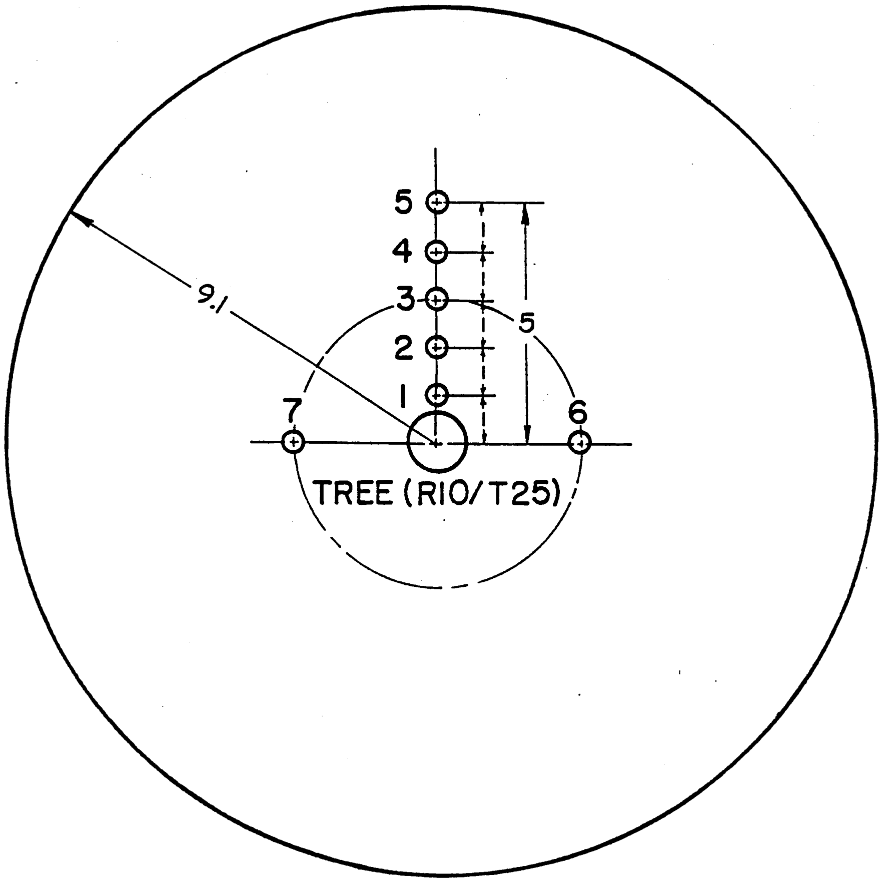

Figure 3. Installation of Access Tubes for Tree R10/T25

m to the east side, and another tube was installed 3 m to the west side. All the access tubes were 1.52 m (5 ft) in length except the one installed to the west side, which was 2.13 m (7 ft) in length.

Preparation of the Irrigation Plots

All the irrigation treatment plots (Figure 2) were prepared in the same manner as that of the preliminary test plot. However, the bunds were constructed closer to the trees and only one 1.52 m length access tube was installed 3 m to the west of each tree. The average radius of each plot was calculated by measuring the distance to the tree from six different locations on the bund and computing the area. Determination of the amount of water required per irrigation was based on the computed area and a predetermined irrigation depth.

Monitoring High Water-table Movement and Measurement of Soil Moisture Content at Saturation

During both years of study (1982 and 1983), a high water-table was present and persisted over most of the growing season. Table II shows the monthly rainfall distribution over the last six years at the Pecan Research Station at Sparks. During the early spring of 1982, the test plots were quite dry and measurements of soil moisture content could be taken to the 120-cm (48-in) depth which was

TABLE II

MM OF RAINFALL AT SPARKS RESEARCH STATION, OKLAHOMA

MONTH	YEAR					
	1978	1979	1980	1981	1982	1983
January	40	57	50	00	133	35
February	88	14	32	32	20	81
March	73	75	40	126	45	83
April	19	59	73	43	60	103
May	179	230	171	80	314	182
June	59	271	82	139	169	42
July	64	104	10	67	93	00
August	31	56	9	148	23	65
September	11	31	85	44	56	74
October	42	55	48	156	35	347
November	109	100	25	78	86	47
December	19	20	43	2	00	*

* denotes missing or incomplete data.

the lowest sampling depth. But in May of that year, the research station received a great deal of rain. The total rainfall for the month was 314 mm (12.35 in), which was one of the highest in history. This was followed with 169 mm (6.66 in) of rain in June, and 93 mm (3.68 in) in July. High water-table persisted in the field until late September of the year.

Standing water in the access tubes was again observed during March of 1983. It was then decided that the movement of the water-table in the soil profile be monitored. It was determined that the capillary pressure exerted by the access tube itself was negligible. This was done by comparing the water level in the access tube with the water level in a hole without any access tube, augered near to it. So, the water levels in the access tubes should represent the water-table line in the soil profile.

Figure 4 shows the decline of the water-table as the season progresses. The rate of decline was greatest during the summer months of June and July when very little rain was recorded and the evaporation rate started to increase rapidly. By early July, very little water was left in the first two tubes, and by the third week of July there was no water left in any of the tubes. It should be noted that debris had formed a blockage to the receding water in tube no. 5 (R13/T33) and later in tube no. 9 (R13/T25) and tube no. 15 (R12/T9), thus giving false readings on water levels in these tubes. When the debris was removed by forcing a

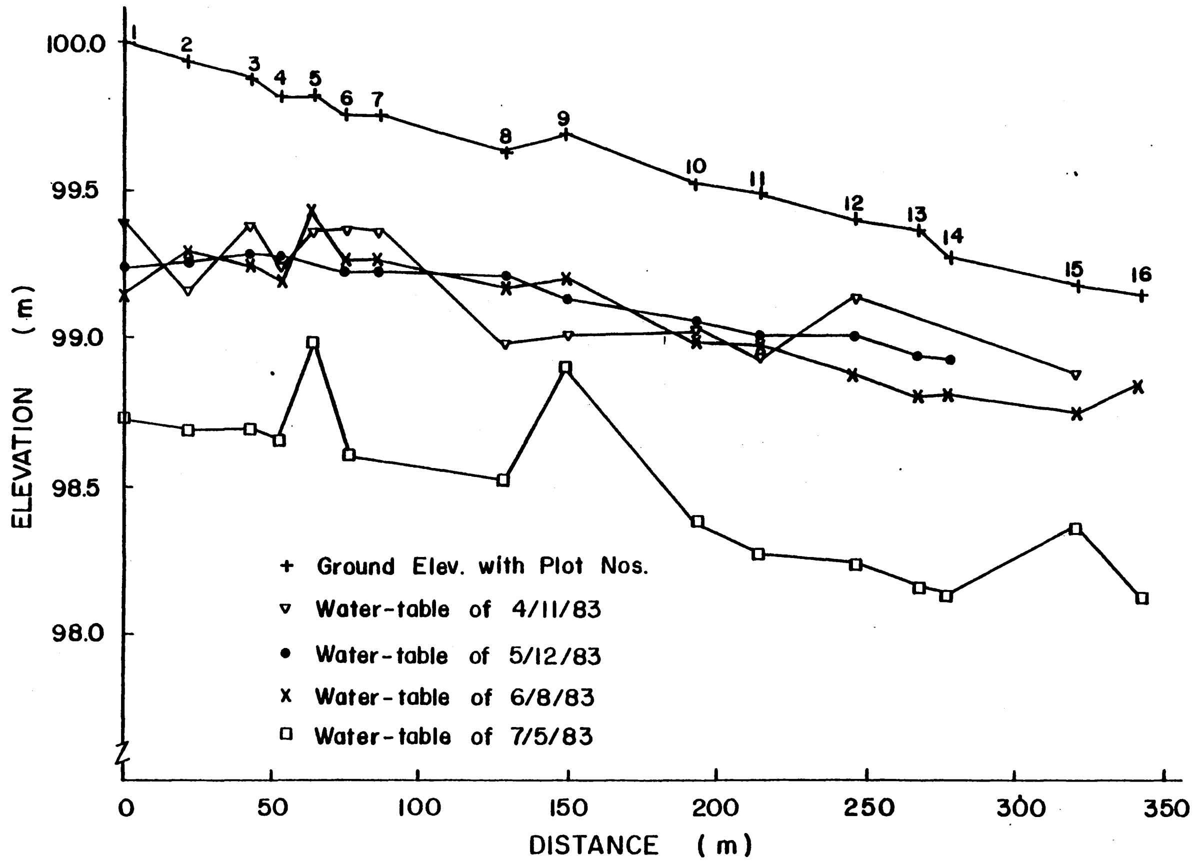

Figure 4. Water-table Elevations for Various Months

no. 9 stopper to the bottom of the tubes, the water disappeared.

The presence of the high water table could be used indirectly to measure the moisture content at saturation of the soil. This could be useful in estimating some of the soil's parameters, such as its effective porosity.

As seen in Figure 1, the region immediately above the water-table should be at saturation. The height of the capillary rise would vary with soil textures. However, it would be safe to assume that in a silty clay loam soil, a point 20.32 cm (8 in) above the water-table would be at saturation. Using equation (2.9) with h_c = 20.32 cm, γ = 73 dynes/cm, g = 980 cm/sec^2 and ρ_w = 1 g/cm^3, the capillary radius, r, was found to be 0.073 mm, which was larger than the mean particle size of the soil itself. Thus, taking the construction of the neutron probe into consideration, measurements of the soil moisture content from 8 cm (3 in) to 20 cm (8 in) above a measured water-table would represent the soil moisture content at saturation.

Measurement of Soil Moisture Tension

Soil moisture tensions were measured in the field by using tensiometers. In 1982, a set of tensiometers was installed at plot no. 4. The tensiometers consisted of a pair of 120-cm length tubes and a pair of 150-cm length tubes. The primary aim was to determine whether there was any hydraulic transition beyond the 120-cm depth. Later, more tensiometers were installed at plot no. 2, plot no. 5 and plot no. 8, as these plots were to receive different irrigation treatment levels. A set of four tensiometers, consisting of one 30-cm length tube, one 60-cm length tube, one 120-cm length tube and one 150-cm length tube was installed at each of the plots. These tensiometers were used to monitor the soil moisture tension at the different irrigation treatments. At the same time the volumetric content of the soil moisture could be measured by using the neutron probe; thus a relationship between the soil moisture tension and soil moisture content could be established.

Irrigation Treatments

A randomized block experiment was set up to determine the water requirements of mature pecan at the Sparks Research Station. Three levels of irrigation treatments plus a control treatment were used on the 16 selected trees. Since the land was sloping towards Quapaw Creek, the trees were assigned into four blocks based on their locations relative to the creek. Within each block one plot was assigned to each treatment at random by using the random digit table (Snedecor and Cochran, 1967). Table III shows the set-up of the randomized block experiment.

Some researchers have used the moisture content at the 60-cm (24-in) depth as the sampling depth in their irrigation treatments (Privette, 1979; Aitken, 1982). In order to minimize the effect of soil variability within the

TABLE III

A RANDOMIZED BLOCK EXPERIMENT ON WATER REQUIREMENTS OF MATURE PECAN TREES IN OKLAHOMA

Plot No.	Row No./ Tree No.	Block	Irrigation Treatment	Plot Area (m^2)	Liters of Water per Irrigation
1	R13/T39	1	T3	87.8	8930
2	R13/T37	1	T1	81.4	-
3	R13/T35	1	T4	81.8	8290
4	R12/T34	1	T2	79.1	8030
5	R13/T33	2	T4	81.6	8290
6	R12/T32	2	T2	84.7	8630
7	R13/T31	2	T1	85.3	-
8	R12/T27	2	T3	76.5	7760
9	R13/T25	3	T3	89.1	9050
10	R13/T21	3	T2	93.1	9460
11	R13/T19	3	T4	81.8	8290
12	R13/T14	3	T1	80.9	-
13	R12/T14	4	T2	71.0	7230
14	R13/T13	4	T1	87.7	-
15	R12/T9	4	T3	82.7	9050
16	R12/T7	4	T4	93.6	9500

soil profile, this author used the cumulative moisture content within the root zone (taken as 120 cm (4 ft)) to base his irrigation treatments. As mentioned previously, the irrigation treatment levels were as follows:

T1 - No irrigation

T2 - Irrigate when the cumulative moisture content reaches or falls below 27 cm (10.63 in)

T3 - Irrigate when the cumulative moisture content reaches or falls below 29 cm (11.42 in)

T4 - Irrigate when the cumulative moisture content reaches or falls below 31 cm (12.20 in).

Amount of Water Applied per Irrigation

The flow rate of the irrigation water to each plot was determined individually using a stop-watch and a bucket. The volume of the bucket was measured by weighing it in the laboratory.

Originally, the irrigation treatments were to be based on the average moisture content at the 60-cm (24-in) depth. For the high moisture level treatment (T4), the average should not fall below 0.25. Thus, when it fell below this level on July 25, irrigation was applied. At first, only 7.6 cm (3 in) of water was applied. This amount was found to be inadequate (Figure 5) to wet the whole root zone, so the irrigation depth was increased to 10.2 cm (4 in). The amounts of water needed per irrigation (Table III) were calculated based on this depth. It was observed that the

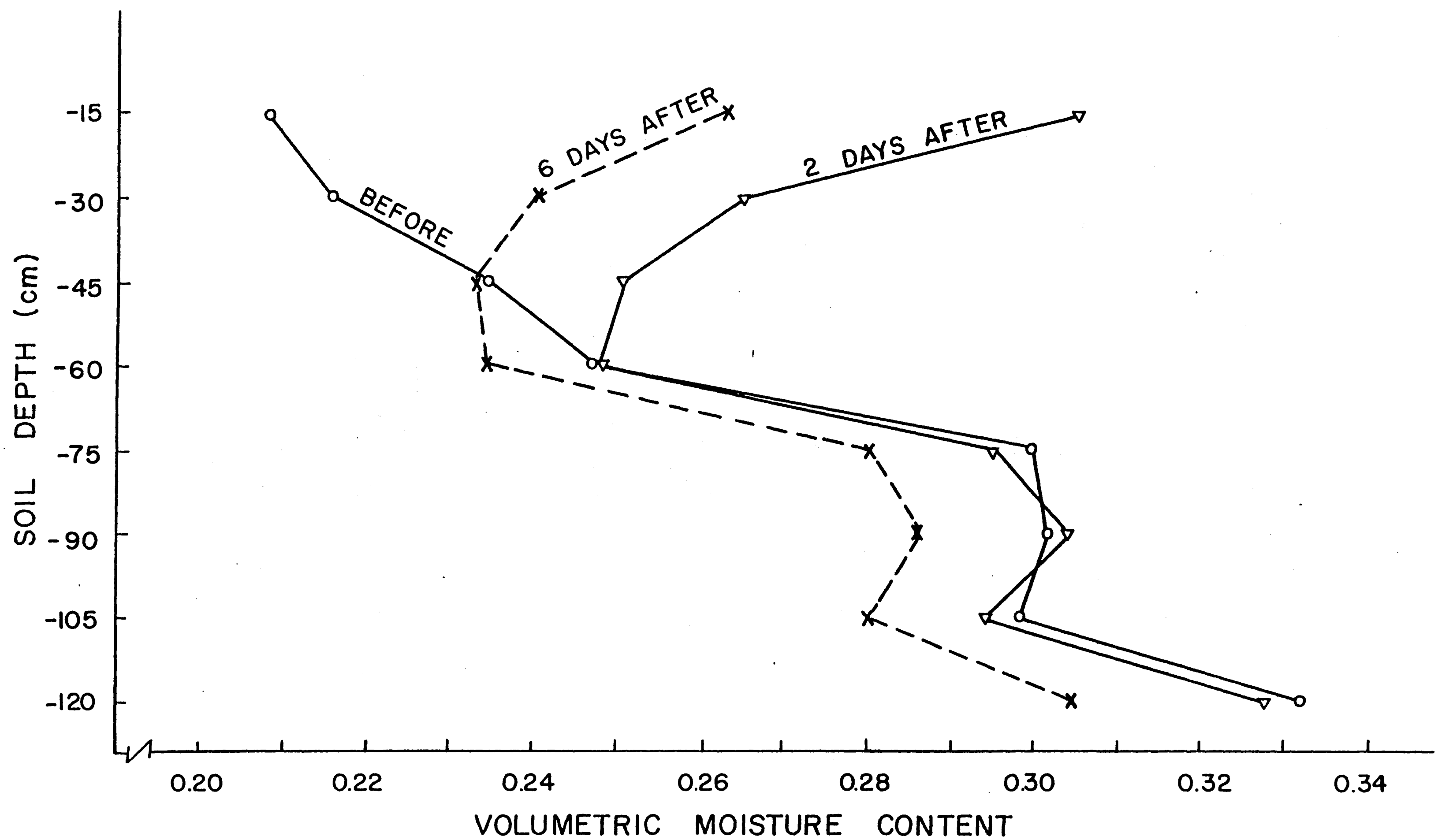

Figure 5. Soil Moisture Profiles of Treatment T4 Before and After Receiving 7.6-cm (3-in) Irrigation

soil texture varied from plot to plot within the same treatment and that the soil profile of many plots was not homogeneous. Thus an average cumulative moisture content value was used in the treatment. Irrigations were scheduled until the last day of September when nut-filling should be complete.

Table IV shows the cumulative moisture content of each plot within treatment T4 (wet treatment) and the average moisture content for the treatment during the period in which irrigations were scheduled. Similarly, Tables V, VI and VII show the cumulative moisture content of each plot within a treatment and the average moisture content for each treatment. Graphically, the scheduling of the irrigations treatments is shown in Figures 6, 7, 8 and 9.

Treatment T4 received one 7.6-cm (3-in) depth application plus seven 10.2-cm (4-in) depth applications of irrigation water during this period. The site also received 13.9 cm (5.46 in) of rainfall. Thus, each plot within treatment T4 received a total of 92.6 cm (36.46 in) of water. Each plot within treatment T3 received a total of 52 cm (20.46 in) of water and each plot within treatment T2 received a total of 24 cm (9.46 in) of water. Each plot within treatment T1 received only the rainfall of 13.9 cm (5.46 in) during this period.

Pecan Fruit Retention

Fruit drop is a serious problem in the pecan industry.

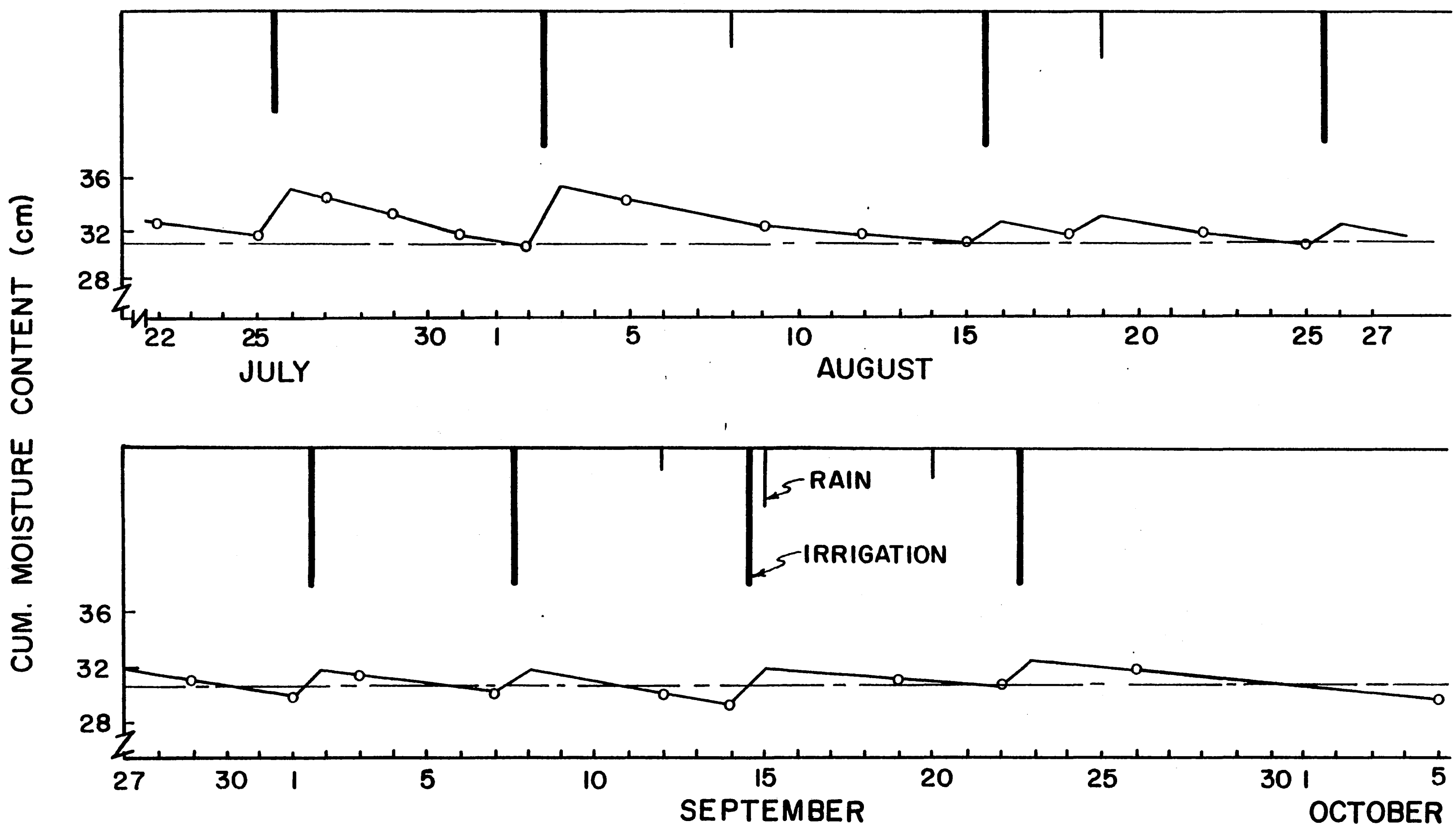

Figure 6. Irrigation Schedule for Treatment T4

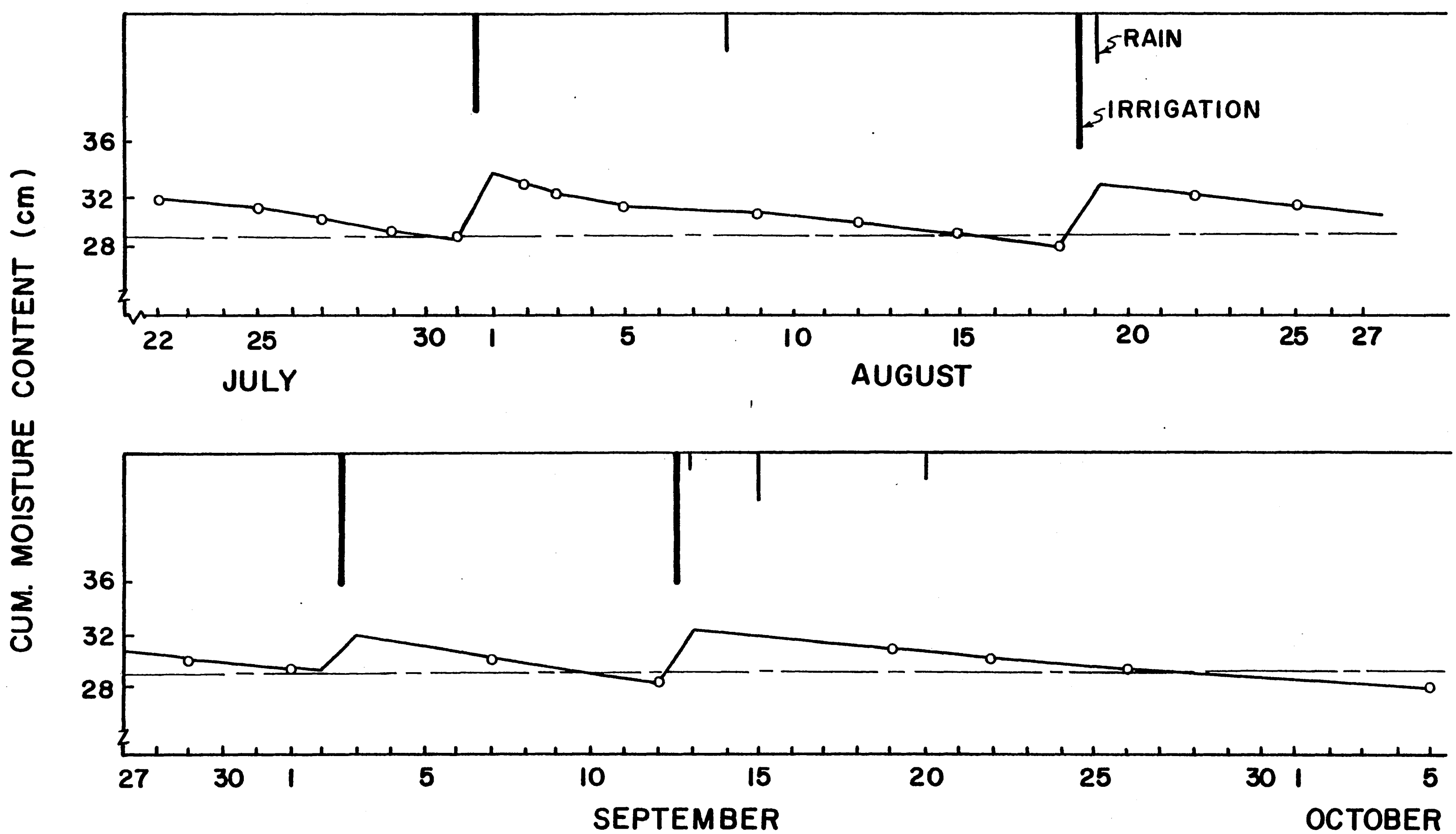

Figure 7. Irrigation Schedule for Treatment T3

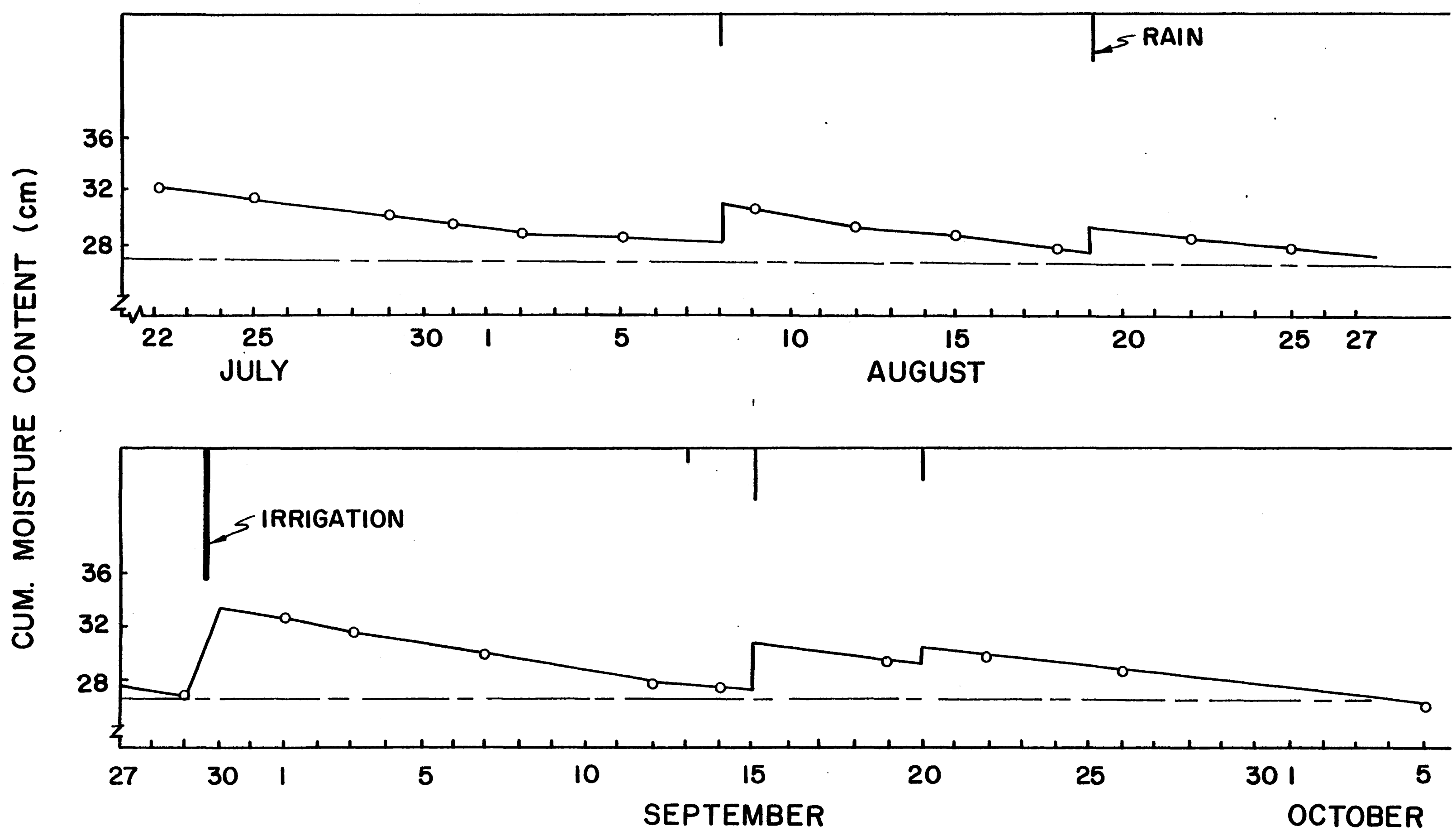

Figure 8. Irrigation Schedule for Treatment T2

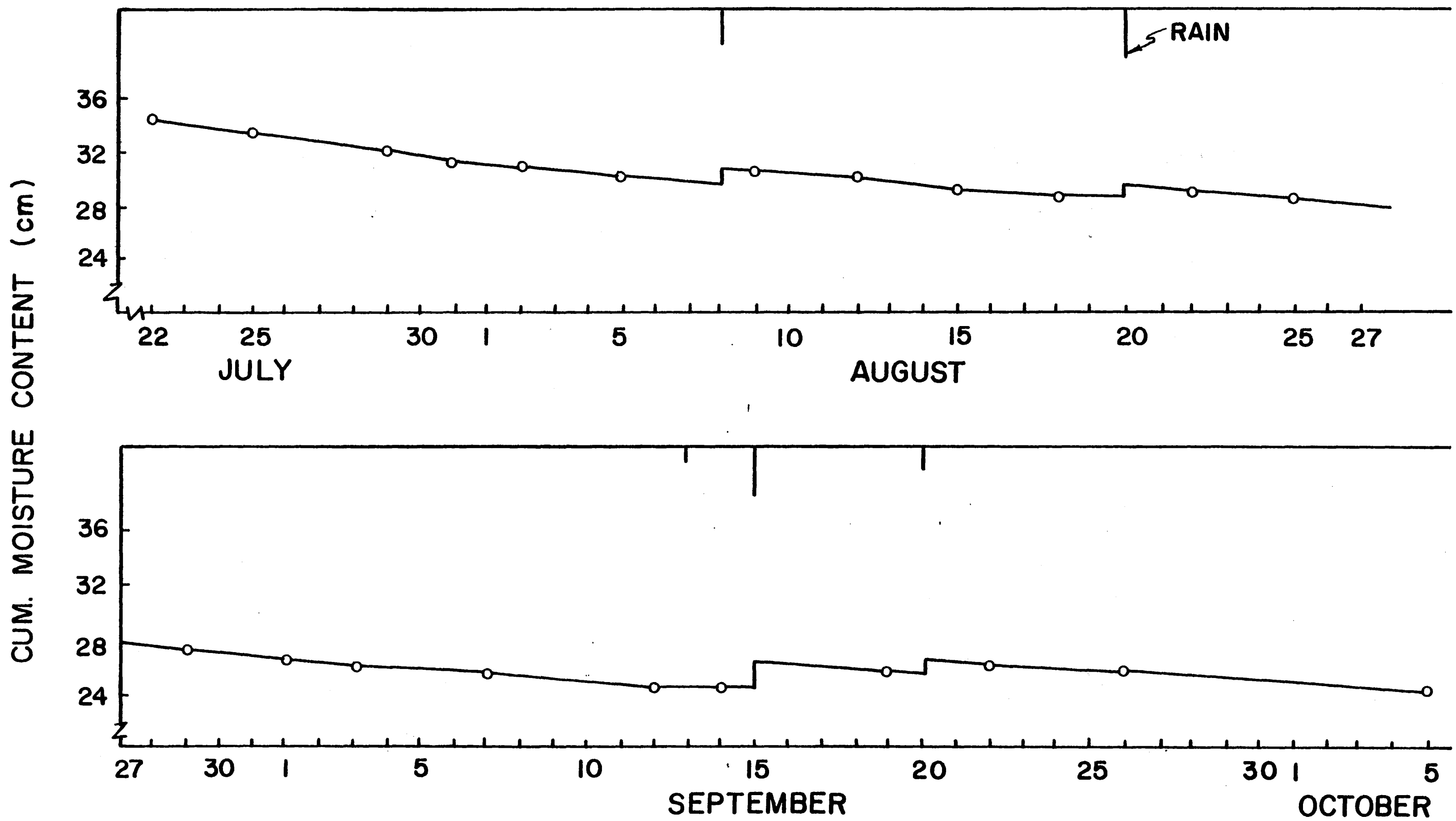

Figure 9. Cumulative Moisture Content of Treatment T1

TABLE IV

CUMULATIVE MOISTURE CONTENT OF TREATMENT T4
DURING IRRIGATION PERIOD

Date	Cumulative Moisture Content (cm)				Average
	Plot 3	Plot 5	Plot 11	Plot 16	
7/22	33.2	31.3	33.8	32.1	32.6
7/25	32.2	30.3	32.9	30.9	31.6
	Received 7.6 cm (3 in) of irrigation				
7/27	35.9	34.1	35.1	33.1	34.6
7/29	34.0	32.8	34.6	31.7	33.3
7/31	32.4	31.5	33.5	30.1	31.9
8/2	31.6	31.0	33.2	29.3	31.3
	Received 10.2 cm (4 in) of irrigation				
8/5	34.4	32.4	34.8	30.7	33.0
8/8	Received 2.8 cm (1.1 in) of rain				
8/9	33.4	31.7	34.3	30.1	32.4
8/12	32.3	30.6	33.8	29.3	31.5
8/15	31.6	29.7	33.2	28.2	30.7
	Received 10.2 cm (4 in) of irrigation				
8/18	33.6	30.7	34.4	28.1	31.7
8/20	Received 3.7 cm (1.45 in) of rain				
8/22	33.3	31.2	34.5	27.9	31.7
8/25	32.3	29.7	33.7	27.0	30.7
	Received 10.2 cm (4 in) of irrigation				
8/29	33.1	28.7	33.8	27.4	31.1

TABLE IV (Continued)

Date	Cumulative Moisture Content (cm)				Average
	Plot 3	Plot 5	Plot 11	Plot 16	
9/1	32.0	29.0	33.2	26.4	30.1
	Received 10.2 cm (4 in) of irrigation				
9/3	34.0	30.0	34.0	27.2	31.3
9/7	32.3	29.0	33.2	26.5	30.3
	Received 10.2 cm (4 in) of irrigation				
9/12	32.0	29.0	33.0	26.4	30.1
9/13	Received 1.0 cm (.41 in) of rain				
9/14	31.7	28.8	32.8	26.2	29.8
	Received 10.2 cm (4 in) of irrigation				
9/15	Received 4.0 cm (1.56 in) of rain				
9/19	33.9	29.5	33.6	27.3	31.1
9/20	Received 2.4 cm (0.94 in) of rain				
9/22	32.6	29.4	33.1	27.5	30.7
	Received 10.2 cm (4 in) of irrigation				
9/26	33.5	30.5	33.7	29.3	31.8
10/4	Received 0.4 cm (0.15 in) of rain				
10/5	29.3	27.9	32.1	26.7	29.0

TABLE V

CUMULATIVE MOISTURE CONTENT OF TREATMENT T3
DURING IRRIGATION PERIOD

Date	Cumulative Moisture Content (cm)				Average
	Plot 1	Plot 8	Plot 9	Plot 15	
7/22	30.7	34.0	25.7	36.9	31.8
7/25	30.1	33.2	24.3	36.4	31.0
7/27	29.5	32.8	23.3	35.6	30.3
7/29	29.1	31.8	22.3	34.7	29.5
7/31	28.4	31.6	21.7	33.9	28.9
	Received 7.6 cm (3 in) of irrigation				
8/2	34.0	35.4	26.0	37.0	33.1
8/3	32.9	34.9	25.4	36.3	32.4
8/5	31.9	33.1	24.3	35.7	31.2
8/8	Received 2.8 cm (1.1 in) of rain				
8/9	31.4	33.4	23.1	34.9	30.7
8/12	30.8	33.0	22.0	34.2	30.0
8/15	30.6	32.1	21.1	33.9	29.5
8/18	29.8	30.8	20.2	32.4	28.3
	Received 10.2 cm (4 in) of irrigation				
8/20	Received 3.7 cm (1.45 in) of rain				
8/22	34.6	33.9	24.6	36.4	32.4
8/25	33.3	33.8	23.1	35.3	31.4
8/29	32.2	31.8	21.0	34.3	29.8

TABLE V (Continued)

Date	Cumulative Moisture Content (cm)				Average
	Plot 1	Plot 8	Plot 9	Plot 15	
9/1	31.5	31.0	20.4	33.6	29.1
	Received 10.2 cm (4 in) of irrigation				
9/7	34.1	31.7	20.8	33.3	30.0
9/12	31.7	30.2	19.2	31.8	28.2
	Received 10.2 cm (4 in) of irrigation				
9/13	Received 1.0 cm (0.41 in) of rain				
9/15	Received 4.0 cm (1.56 in) of rain				
9/19	34.6	31.4	21.9	34.1	30.5
9/20	Received 2.4 cm (0.94 in) of rain				
9/22	33.5	31.2	21.6	33.7	30.0
9/26	33.3	30.9	21.0	33.6	29.7
10/4	Received 0.4 cm (0.15 in) of rain				
10/5	31.4	29.7	18.7	32.1	27.9

TABLE VI

CUMULATIVE MOISTURE CONTENT OF TREATMENT T2
DURING IRRIGATION PERIOD

Date	Cumulative Moisture Content (cm)				Average
	Plot 4	Plot 6	Plot 10	Plot 13	
7/22	31.2	33.4	30.6	34.9	32.5
7/25	30.1	32.7	29.6	34.5	31.7
7/29	28.0	31.5	28.8	33.5	30.5
7/31	27.0	31.3	28.0	33.2	29.8
8/2	26.6	30.7	27.8	33.1	29.6
8/5	25.5	30.4	27.4	32.5	29.0
8/8	Received 2.8 cm (1.1 in) of rain				
8/9	29.9	30.9	27.6	34.6	30.8
8/12	27.7	30.2	27.1	33.8	29.7
8/15	26.3	29.9	26.5	33.6	29.1
8/18	24.2	29.3	25.4	31.9	28.0
8/20	Received 3.7 cm (1.45 in) of rain				
8/22	26.6	29.9	26.1	32.9	28.9
8/25	25.6	29.4	25.3	32.1	28.1
8/29	24.3	28.6	24.5	31.0	27.1
	Received 10.2 cm (4 in) of irrigation				
9/1	33.9	31.4	31.8	34.5	32.9
9/3	32.8	30.8	30.7	33.9	32.1

TABLE VI (Continued)

Date	Cumulative Moisture Content (cm)				Average
	Plot 4	Plot 6	Plot 10	Plot 13	
9/7	29.9	30.0	28.9	32.2	30.3
9/12	26.5	28.4	27.1	30.3	28.1
9/13	Received 1.0 cm (0.41 in) of rain				
9/14	26.2	28.3	26.5	30.1	27.8
9/15	Received 4.0 cm (1.56 in) of rain				
9/19	30.3	29.0	29.1	31.8	30.0
9/20	Received 2.4 cm (0.94 in) of rain				
9/22	31.6	29.5	29.3	31.2	30.4
9/26	29.8	28.9	28.3	30.8	29.5
10/4	Received 0.4 cm (0.15 in) of rain				
10/5	25.6	27.6	25.2	28.9	26.8

TABLE VII

CUMULATIVE MOISTURE CONTENT OF TREATMENT T1
DURING IRRIGATION PERIOD

Date	Cumulative Moisture Content (cm)				Average
	Plot 2	Plot 7	Plot 12	Plot 14	
7/22	32.2	33.9	36.8	37.2	35.0
7/25	31.3	32.6	35.5	36.4	34.0
7/29	29.6	31.4	33.8	35.1	32.5
7/31	29.2	30.7	32.8	34.7	31.9
8/2	28.6	30.1	32.0	34.1	31.2
8/5	28.0	29.2	31.1	33.3	30.5
8/8	Received 2.8 cm (1.1 in) of rain				
8/9	28.0	29.7	31.9	34.2	30.9
8/12	27.5	29.2	31.7	33.8	30.6
8/15	27.1	28.4	30.1	33.4	29.7
8/18	26.7	27.5	29.1	32.5	28.9
8/20	Received 3.7 cm (1.45 in) of rain				
8/22	27.0	28.6	29.3	33.3	29.6
8/25	26.0	27.7	28.4	32.6	28.7
8/29	25.5	26.3	27.3	31.7	27.7
9/1	25.4	25.9	26.5	31.4	27.3
9/3	24.9	25.3	26.3	30.6	26.8
9/7	24.4	24.5	25.1	30.1	26.0

TABLE VII (Continued)

Date	Cumulative Moisture Content (cm)				Average
	Plot 2	Plot 7	Plot 12	Plot 14	
9/12	23.5	23.0	24.1	28.9	24.9
9/13	Received 1.0 cm (0.41 in) of rain				
9/14	23.4	22.9	23.7	29.0	24.8
9/15	Received 4.0 cm (1.56 in) of rain				
9/19	25.2	24.3	24.3	29.6	25.8
9/20	Received 2.4 cm (0.94 in) of rain				
9/22	25.7	24.7	25.4	29.2	26.3
9/26	24.6	24.2	25.1	28.9	25.8
10/4	Received 0.4 cm (0.15 in) of rain				
10/5	23.2	23.1	23.8	27.8	24.5

A higher percentage of fruit drop was reported to occur during the first 45 to 50 days after full bloom, followed by a gradual fruit loss for the remainder of the growing season (Smith and McNew, 1982). It was desired to see if there was correlation between the percentage of fruits retained and the irrigation treatment levels.

Bud break was first noticed on April 27, 1983, which was rather late. In 1976, bud break for 'Mohawk' cultivar occurred on March 26 (Burke and Hinrichs) and in 1981, bud break for 'Western' pecan grown at the same station occurred on April 6.

Tagging of the fruit clusters was initiated on June 7, 1983, when the fruits became more visible and grew to about 1 cm in length. Fifty fruit clusters were tagged per tree. The number of fruits per cluster was recorded.

Recounting of the number of fruits remaining per cluster was recorded one month later, and then again on September 7 and October 7, 1983. Percent of fruit drop was analyzed after each count.

Leaf Analysis

Leaf samples (the middle leaflet from the middle leaf of current season's growth) from each test plot were collected on September 14, 1983. The samples were analyzed for their mineral concentrations by a Laboratory Technician at the Horticulture Research Laboratory, Oklahoma State University.

Each sample was first washed in liquinox, then rinsed twice with deionized water. After drying the sample at 80°C, it was ground to 20 mesh. The sample was then ready to be analyzed using the standard methods: Nitrogen concentration was obtained by using the macro-kjeldahl method, while the concentration of phosphorus was obtained colorimetrically. The concentrations of the other elements were obtained by using the Perkin-Elmer Model 303 Atomic Absorption Unit.

Nut Yield and Nut Size

Harvesting of the nuts began during the middle of November. If the hull of the pecan was still attached to the shell, it was removed manually. Then the nut yield per tree was recorded.

Samples of nuts from each test tree were brought to the Horticulture Research Laboratory for the determination of the nut size. Two of the samples were missing (samples for R13/T21 and R12/T14). Thirty nuts per sample were weighed for the determination of the nut size. The weight of their kernels was also obtained. The weight of the kernels over the weight of the nuts would represent the percent kernels.

CHAPTER V

RESULTS AND DISCUSSION

Sampling Distance and Direction From the Tree

The location of the neutron access tube can be an important factor in the proper measurement of the water requirement of a mature pecan tree. The preliminary tests on plot R10/T25 were designed to examine this factor.

A computer program was developed to calculate the volumetric moisture content and the cumulative moisture content in the root zone (Appendix B). Analyses of the data were done by using the statistical analysis procedures in SAS (SAS User's Guide, 1979).

Results of the preliminary tests on plot R10/T25 are shown in Appendix C. There was a significant difference ($Pr>F = 0.0089$) in the moisture use rate among the tubes placed at different distances from the tree. However, from the Duncan's Multiple Range Test, it was observed that only measurements from tube no. 5, which was placed furthest from the tree, were significantly different from the readings of the other tubes. The cumulative moisture content at the distance of 3 m from the tree was the lowest, which might indicate that the moisture uptake of the tree was greatest at this distance.

The direction from the tree at which measurements were taken also showed a significant effect. The three directions were significantly different from one another, with the mean cumulative moisture content towards the west side of the tree being the least. The difference in the rates of evapotranspiration during the morning and the afternoon of a summer day might be responsible for this phenomenon.

So for the determination of the peak moisture use rate of a mature pecan tree, the placement of the access tube 3 m to the west of the tree was a logical choice.

Soil Moisture Content at Saturation

The soil moisture content at saturation was measured at a region 8 to 20 cm (3 to 8 in) above a water-table. After discarding some of the measurements from plot numbers 5, 9 and 15 due to blockage from the debris, the data were analyzed and are presented in Appendix D.

The overall mean of the moisture content at saturation, θ_s, of the plots was found to be 0.347 with a range of 0.306 to 0.413. The mean and range of each block is shown in Table VIII.

The table on the hydraulic soil properties classified by soil texture as prepared by Rawls et al. (1982) is included in the appendix so that comparisons between the values can be made. It is observed that the mean value fell

TABLE VIII

SOIL MOISTURE CONTENT AT SATURATION θ_s FOR EACH BLOCK

Block	n*	Mean θ_s	Mean θ_s	Mean θ_s
1	51	0.348	0.310	0.381
2	41	0.338	0.306	0.382
3	38	0.349	0.306	0.413
4	28	0.356	0.319	0.394

n* is the number of observations

within the lower range of that given by the authors. The mean for block no. 2 fell below their given range. Field observations indicated the presence of sandy loam strata within the profiles of the plots of this block.

Figure 10 shows the mean value of moisture content at saturation of various blocks at different depths. Due to the effect of the land slope, there was no measurement at the 15-cm (6-in) depths for block no. 1. Generally, the mean value increases with the soil depth, which may indicate changes in the soil textures along the profile. The soil tends to be sandier at the top and clayey at the bottom. Except for the 30-cm (12-in) depth, the moisture content at saturation for block no. 4 shows more uniformity throughout its profile than the other blocks. Statistical analyses on the values of the moisture content at saturation are shown in Appendix D.

The differences in the values of the moisture content at saturation between blocks were quite significant (Pr>F = 0.0450) and the differences between various soil depths were highly significant (Pr>F = 0.0001). If measurements at the 15-cm (6-in) depth were excluded so that the ANOVA procedure could be performed, the soil depth factor was still highly significant (P>F = 0.0824).

The Duncan's Multiple Range Test indicates that block no. 2 is significantly different from block no. 4, and that block no. 1 and block no. 3 can be grouped with either block no. 2 or block no. 4. The test also shows that the 30-cm

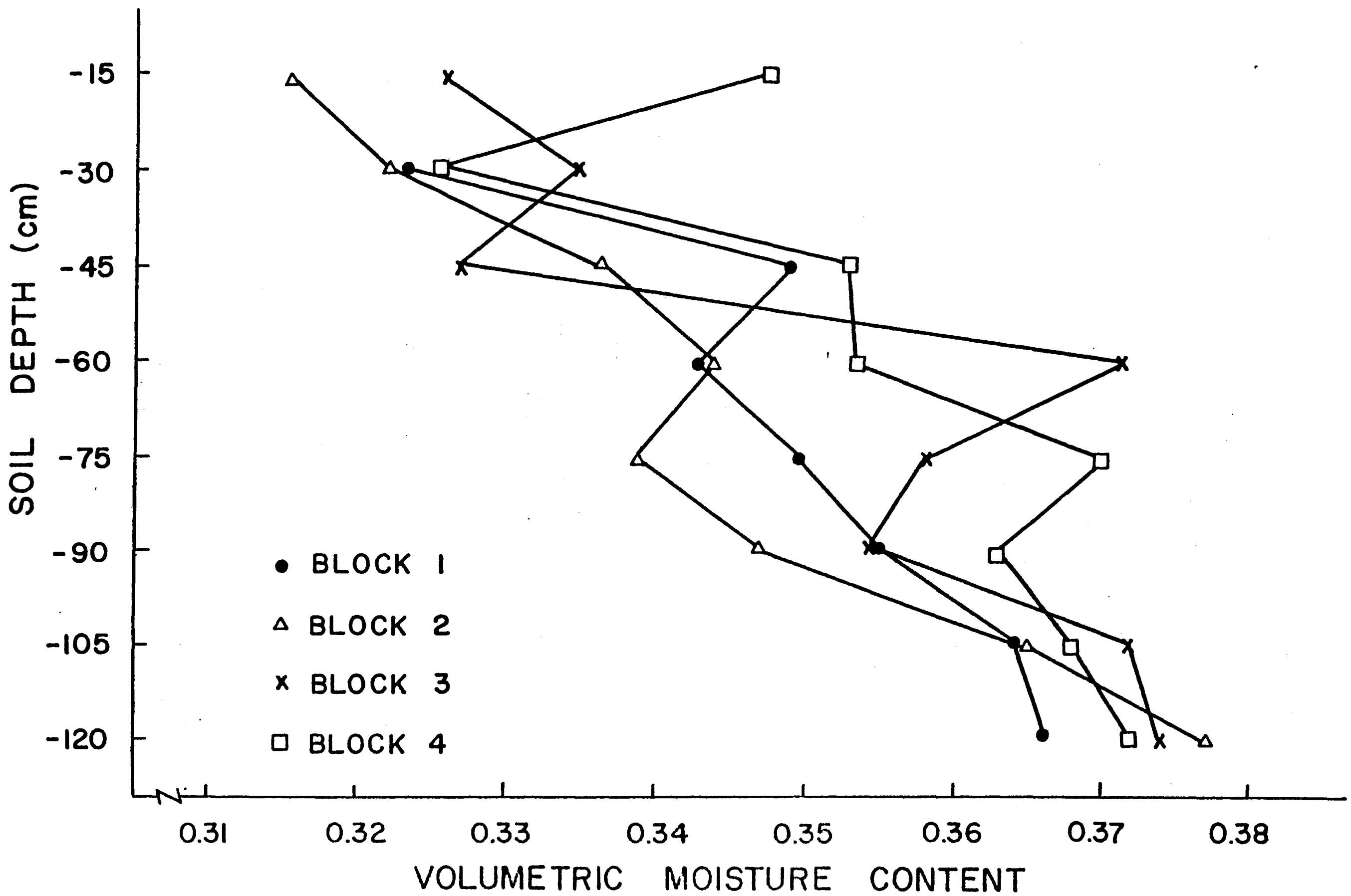

Figure 10. Moisture Content at Saturation Θ_s of the Experimental Blocks at Various Depths

(12-in) depth is significantly different from the other sampling depths. The 45-cm (18-in) depth is significantly different from the others except the 60-cm (24-in) depth. There are no significant differences between the 60-cm (24-in) depth, the 75-cm (30-in) depth and the 90-cm (36-in) depth. The same can be said between the 105-cm (42-in) depth and the 120-cm (48-in) depth.

This showed that the soil was not very homogeneous. Therefore, it would be more accurate to base an irrigation treatment level on the cumulative content over the whole root zone, rather than the moisture content at a representative depth of the root zone.

Soil Moisture Suction

The variations in soil moisture suction as the season progressed are shown in Figures 11 through 14. The figures were plotted for the period during which the trees received the irrigation treatment. The data on soil moisture suction over the season are given in Appendix E. It should be noted that the data represent only those four plots on which tensiometers were installed, and they are in experimental block 1 or 2.

Figure 11 shows the variations in soil moisture suction at four different depths of plot no. 2 during the irrigation period. This plot received no irrigation (Treatment T1). It can be seen that the soil moisture content was decreasing with depth as the season progressed.

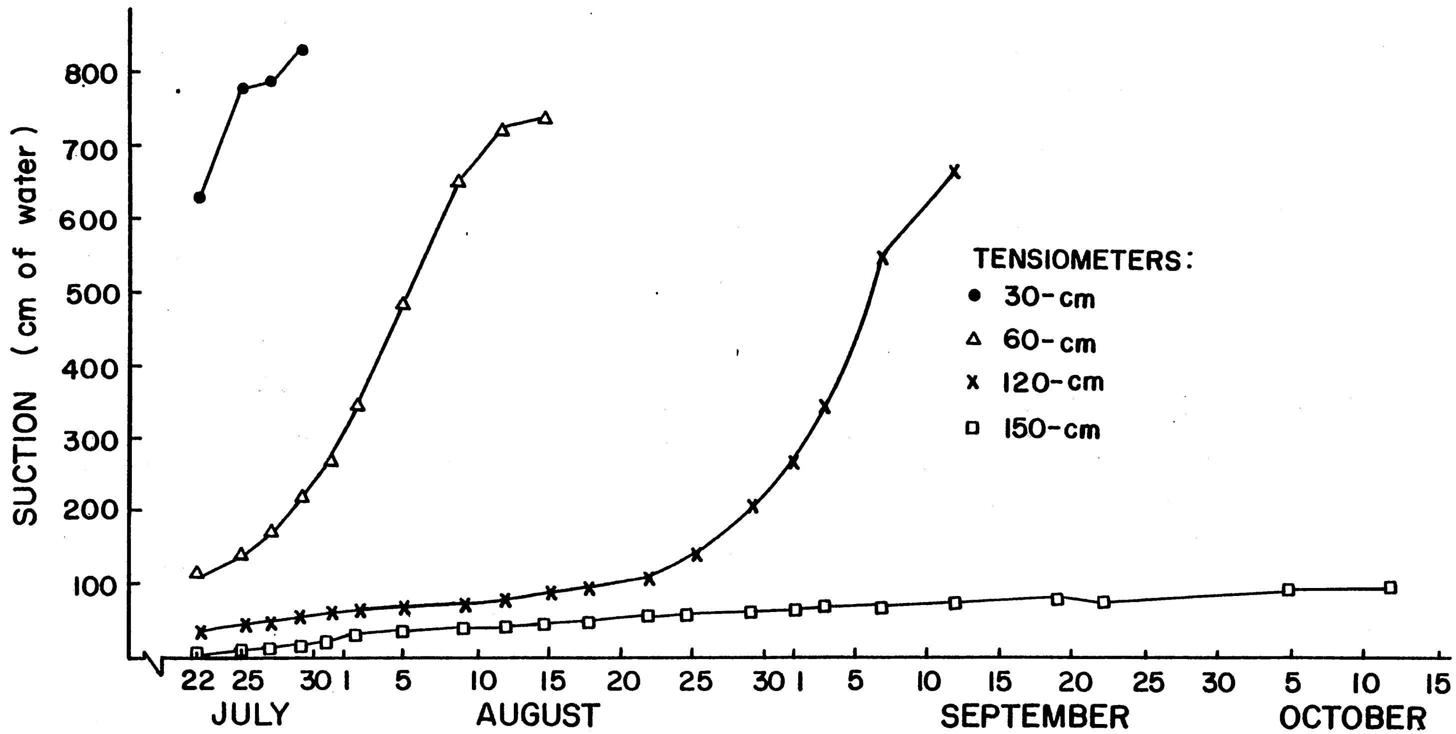

Figure 11. Soil Moisture Suction During the Irrigation Period for Plot No. 2 (Treatment T1)

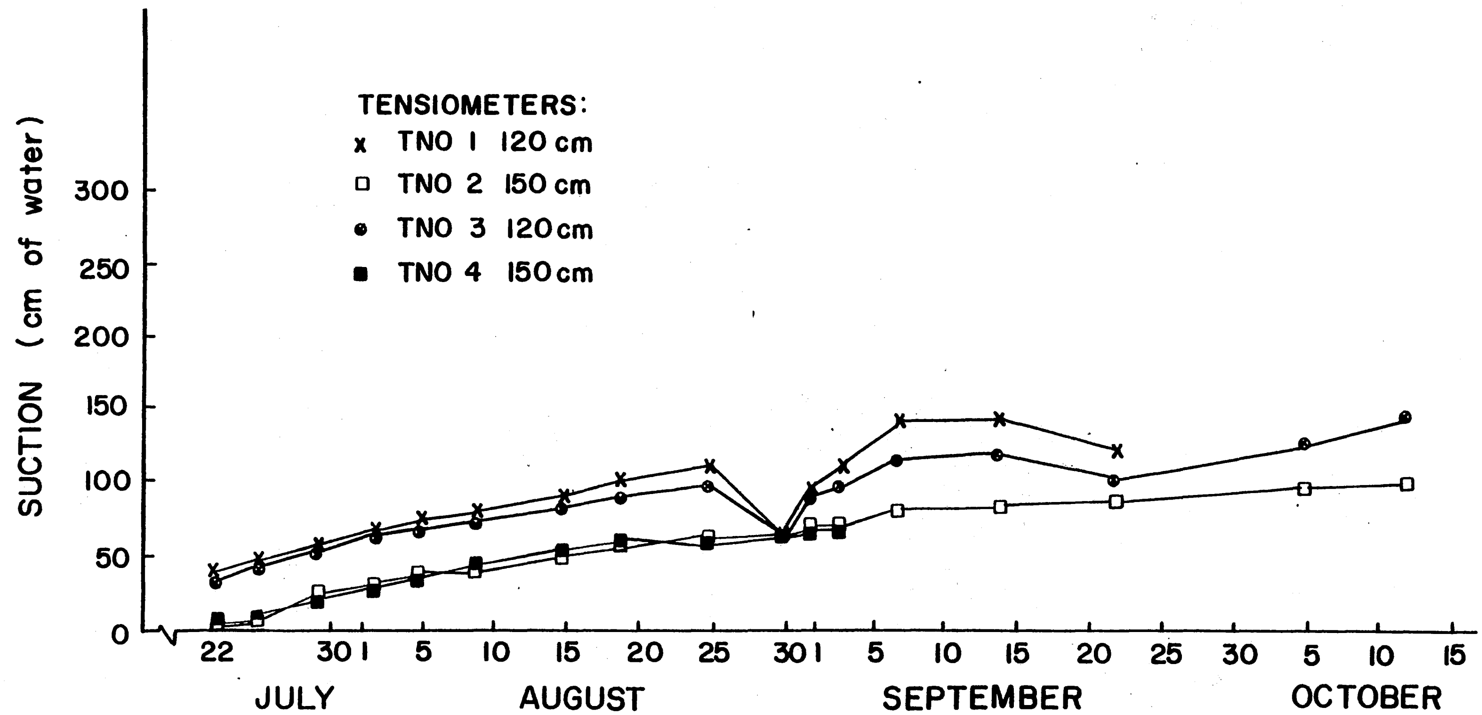

Figure 12. Soil Moisture Suction During the Irrigation Period for Plot No. 4 (Treatment T2)

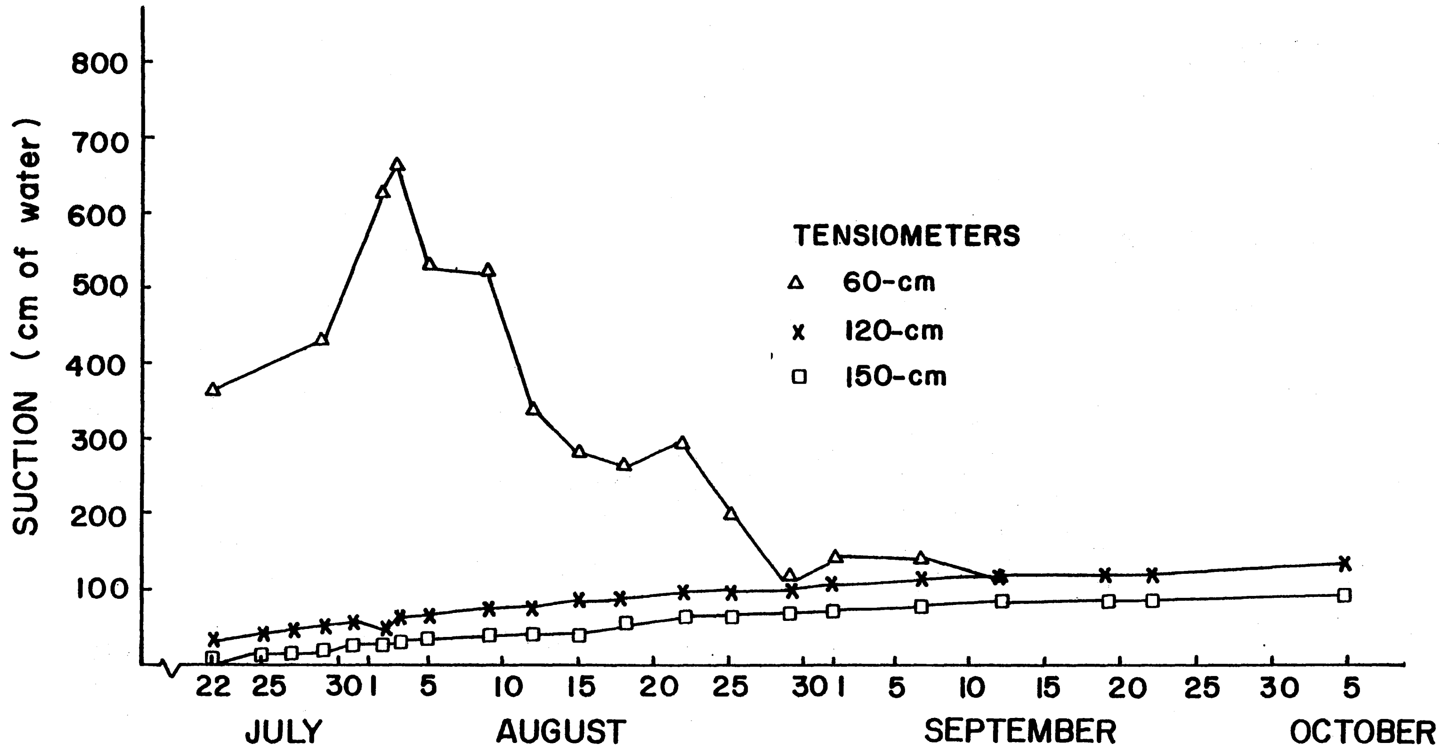

Figure 13. Soil Moisture Suction During the Irrigation Period for Plot No. 8 (Treatment T3)

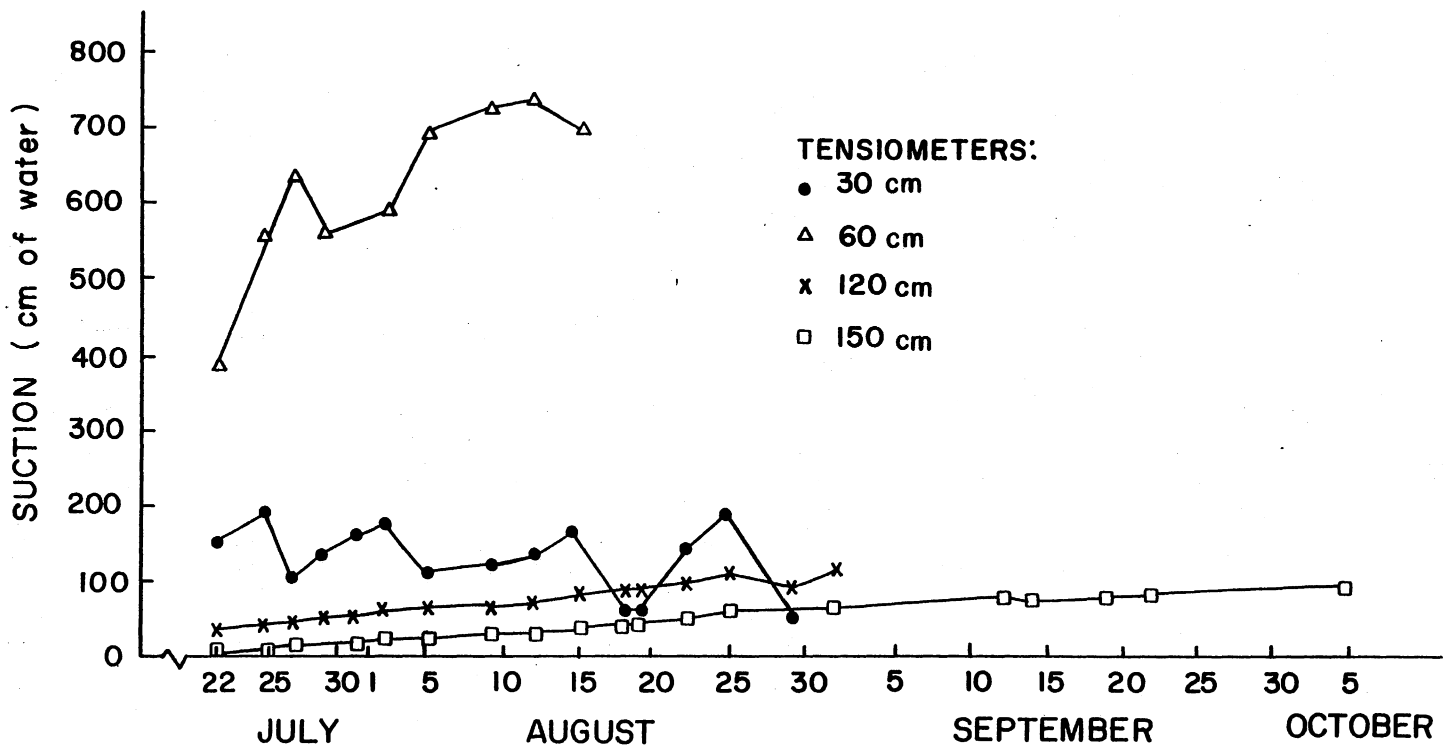

Figure 14. Soil Moisture Suction During the Irrigation Period for Plot No. 5 (Treatment T4)

The variations in soil moisture suction over the irrigation period for plot no. 4 are shown in Figure 12. The plot had a pair of the 120-cm tensiometers (TNO 1 and TNO 3) and a pair of the 150-cm tensiometers (TNO 2 and TNO 4). An irrigation application was made on August 29. Except on August 30, the total potentials (taken as the sum of the pressure potential and the gravitational potential) at the two depths were about the same over most of the period. Thus, there was practically no difference in hydraulic potential between the two depths.

Figure 13 shows the soil moisture suction over the irrigation treatment for plot no. 8 which received irrigation treatment T3. There was negligible water movement beyond the root zone. Even though the 30-cm tensiometer was working properly during the early season, it was incapable of sustaining the matric suction after July 25. Thus, its readings are not shown in the figure.

Figure 14 shows the soil moisture suction over the irrigation period for plot no. 5. Even though this plot received the heavy irrigation treatment (T4), there was negligible water movement beyond the root zone, as indicated by the potentials at the 120-cm (4-ft) and 150-cm (5-ft) depths. The soil moisture suction at the 30-cm (1-ft) depth was generally lower than the suction at the 60-cm (2-ft) depth. After August 20, the readings on the soil moisture suction at the 60-cm (2-ft) depth were not accurate, and are not included in the figure.

Relationship Between Soil Moisture Content and Suction

The data on the relationship between soil moisture content and tension (suction) are shown in appendix E.

Figure 15 shows the relationship between the two soil properties for all four plots taken together, and Figures 16 through 19 show the relationship between the two properties for each plot. It should be noted that plot numbers 2 and 4 are in block 1, and plot numbers 5 and 8 are in block 2.

The horizontal line in each figure represents soil moisture suction at 34 kPa (1/3-bar), which often has been related to suction at "field capacity". The range of the soil moisture content at this suction was from 0.16 to 0.31.

Figure 16 shows the characteristic curves for plot no. 2. This is the plot with no irrigation. There are three distinct curves formed by the three shorter tensiometers. At one time or another the mercury columns of these tensiometers broke as the suction reached 700 cm or more. The mercury column of the 120-cm length tensiometer broke on September 19, 1983, which was near the end of the growing season. The suction of the 150-cm tensiometer never reached above field capacity (see Figure 11). This should indicate that the soil was still fairly wet beyond the root zone.

Figure 18 shows the characteristic curve for plot no. 4. The readings of each pair of the tensiometers were consistent. Tube no. 4 was broken on September 7, 1983, so

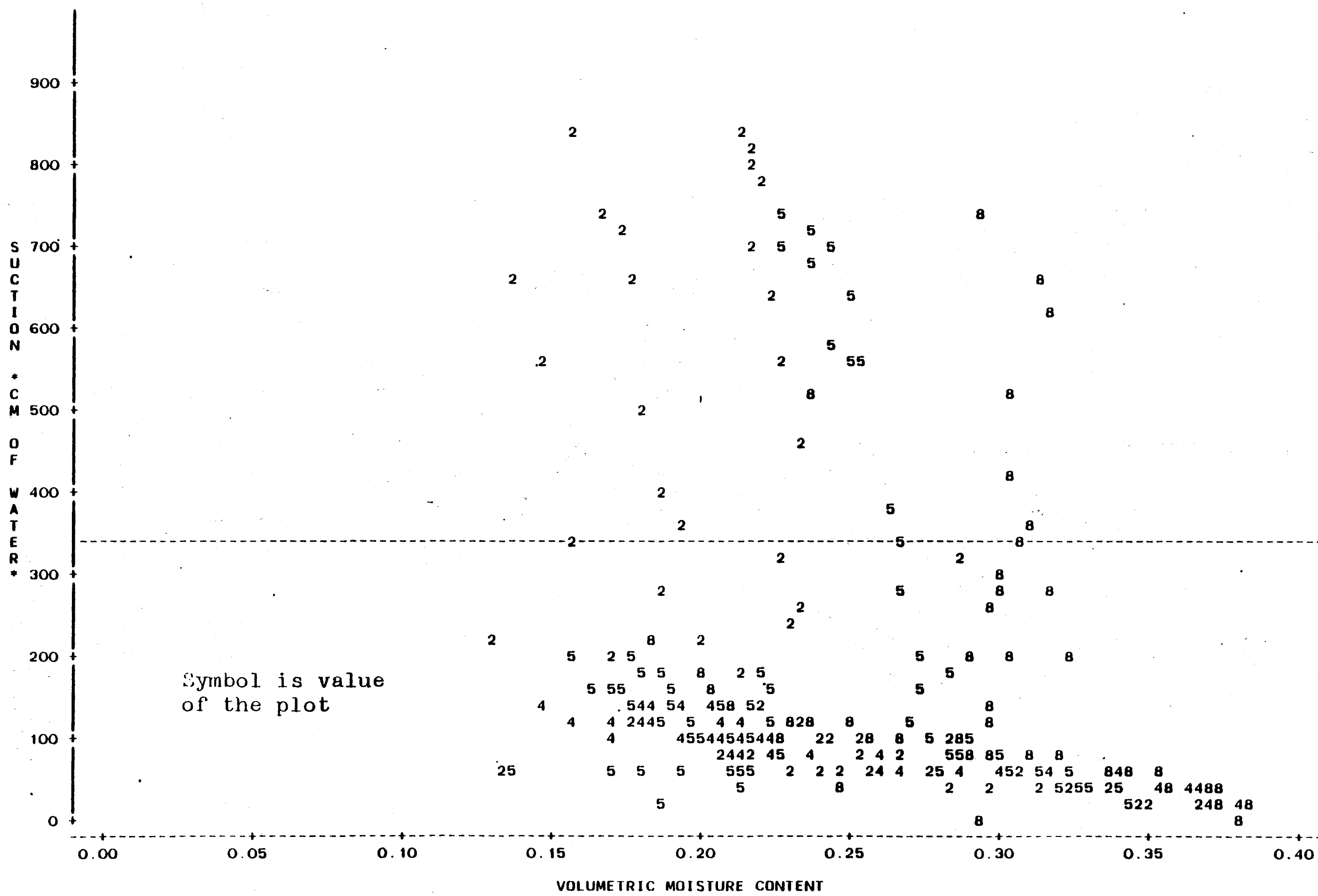

Figure 15. Volumetric Moisture Content Versus Soil Moisture Suction of the Four Plots

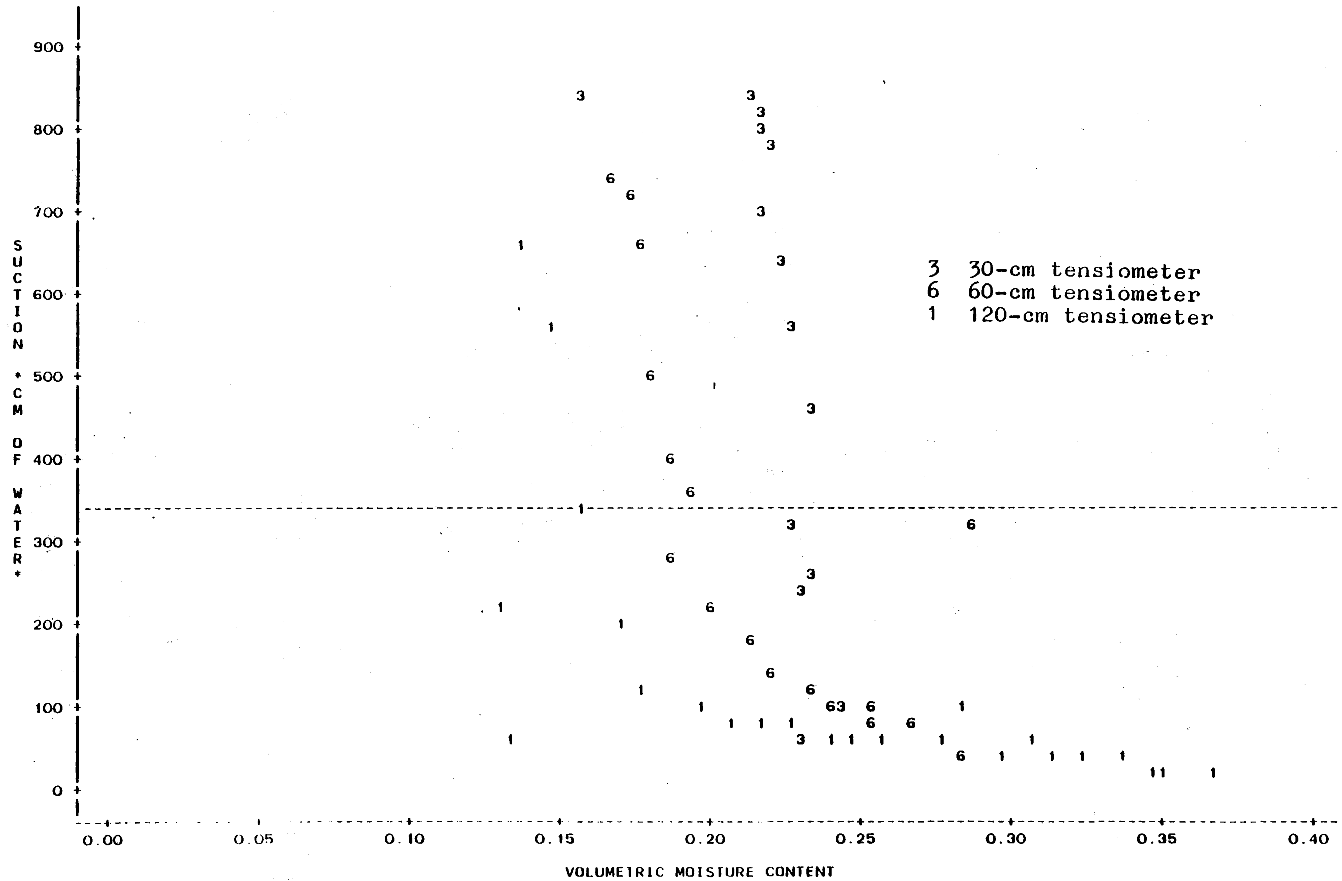

Figure 16. Volumetric Moisture Content Versus Soil Moisture Suction of Plot No. 2

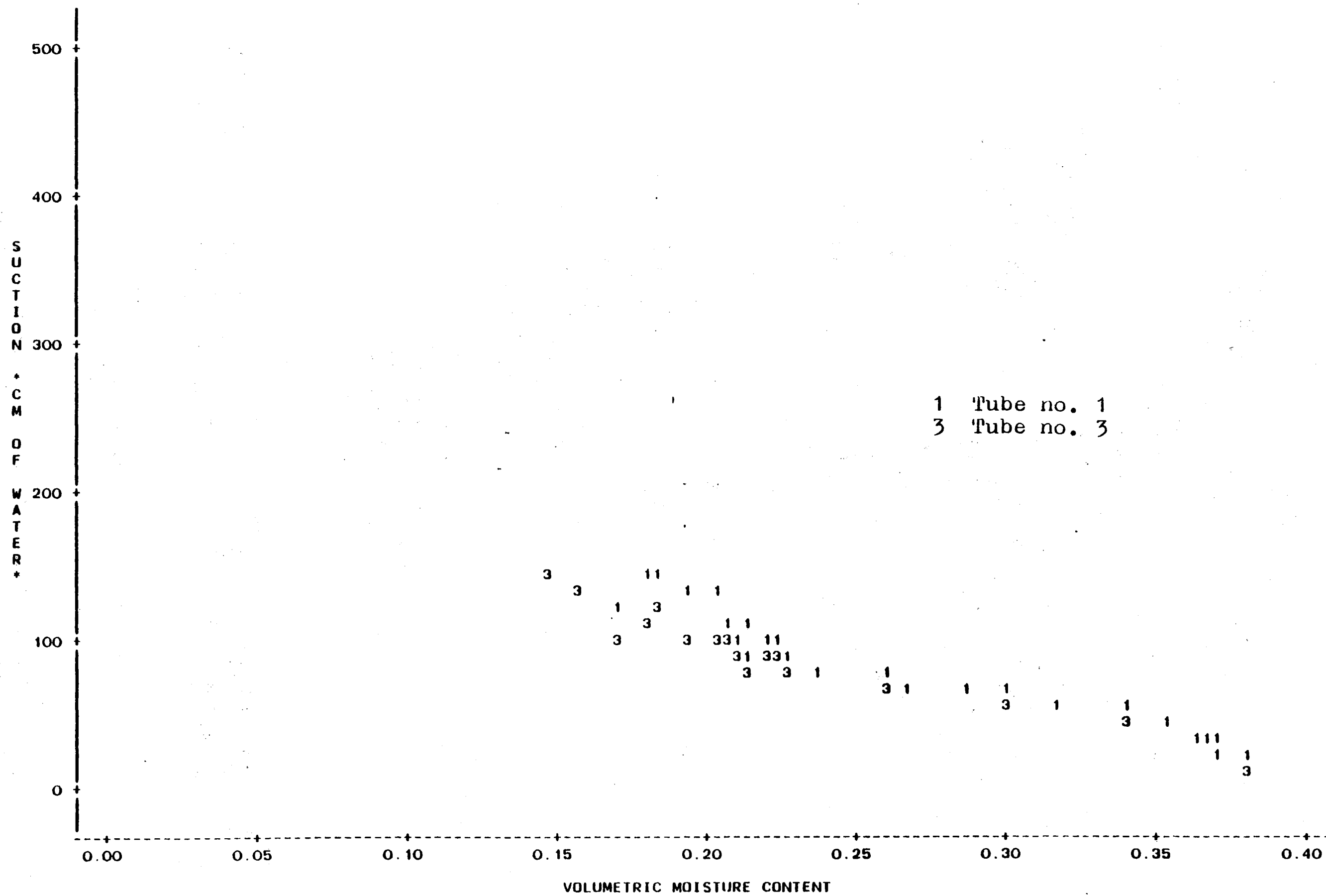

Figure 17. Volumetric Moisture Content Versus Soil Moisture Suction of Plot No. 4

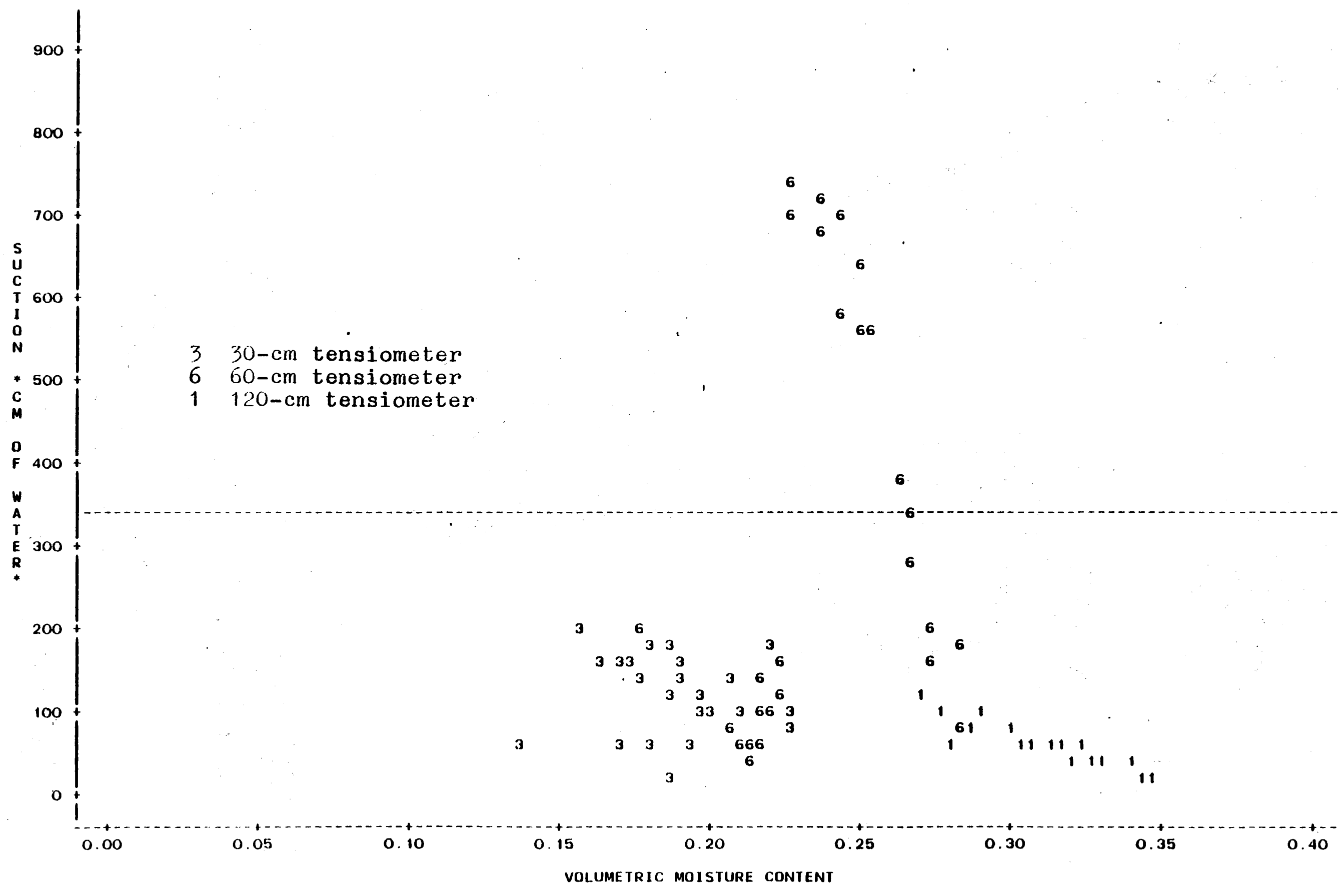

Figure 18. Volumetric Moisture Content Versus Soil Moisture Suction of Plot No. 5

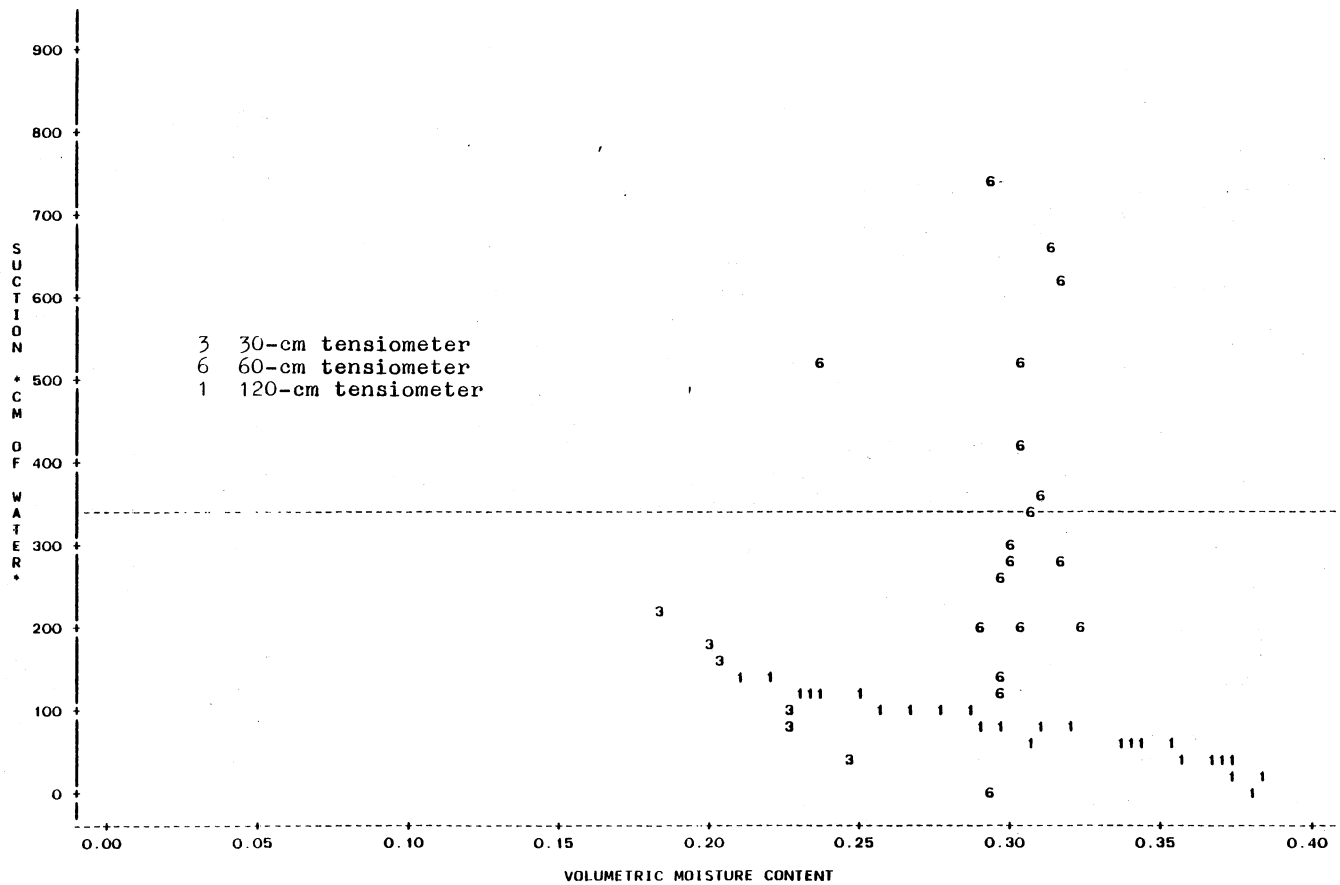

Figure 19. Volumetric Moisture Content Versus Soil Moisture Suction of Plot No. 8

no readings from the tube could be made thereafter. None of the tensiometers in this plot showed a suction above 15 kPa which was lower than the "field capacity".

Figure 19 shows the characteristic curve for plot no. 5. There was a distinct curve connecting measurements from the 60-cm tensiometer and the 120-cm tensiometer, and a separate group of points from the readings of the 30-cm tensiometer. From field observations, it was noted that the soil at the 30-cm depth tended to be sandier while the deeper depths tended to be silt loamy. The neutron probe readings at the 30-cm depth indicated that the soil was drier at this depth even though it was at a lower suction.

The characteristic curve for plot no. 8 is shown in Figure 19. Readings from the 30-cm tensiometer were not collected after July 25, 1983, as mentioned previously. The soil moisture content at "Field Capacity" at the 60-cm (2-ft) depth of the plot seemed to be higher than those of the other plots.

Water Use Rate of Pecan

The water use rates of a pecan tree for the various irrigation treatments can be calculated from Tables IV through VII. The difference in the averages of the cumulative moisture contents over the given interval should give the amount of water used during that interval. The water use rate is expressed in terms of cm per day or liters per day per tree.

Tables IX through XII give the water use rate of a pecan tree for the different irrigation treatment levels. The rate in cm per day was calculated based on the neutron probe readings of the soil moisture content at the access tube, while the rate in liters per day per tree was calculated by multiplying the rate in cm per day by the average area of the basins (plots) within an irrigation treatment. The variations in the water use rate during the season for the different treatment levels can be seen in Figures 20 and 21.

The period from July 22 to September 12 of 1983 can be considered as the period during which moisture used by the pecan trees was the highest. There was a direct correlation between the average moisture use rate during this period and the levels of the irrigation treatment. The average moisture use rate of the high moisture levels treatment (T4) was found to be 0.36 cm per day or 308 liters per day per tree. The rate for treatment T3 was found to be 0.34 cm per day or 284 liters per day per tree, and the rate for treatment T2 was 0.32 cm per day or 259 liters per day per tree. The average moisture use rate of the control treatment (T1) was 0.26 cm per day or 214 liters per day per tree.

Irrigation Effects on Percent Fruit Drop

As reported earlier, the first fruit count was

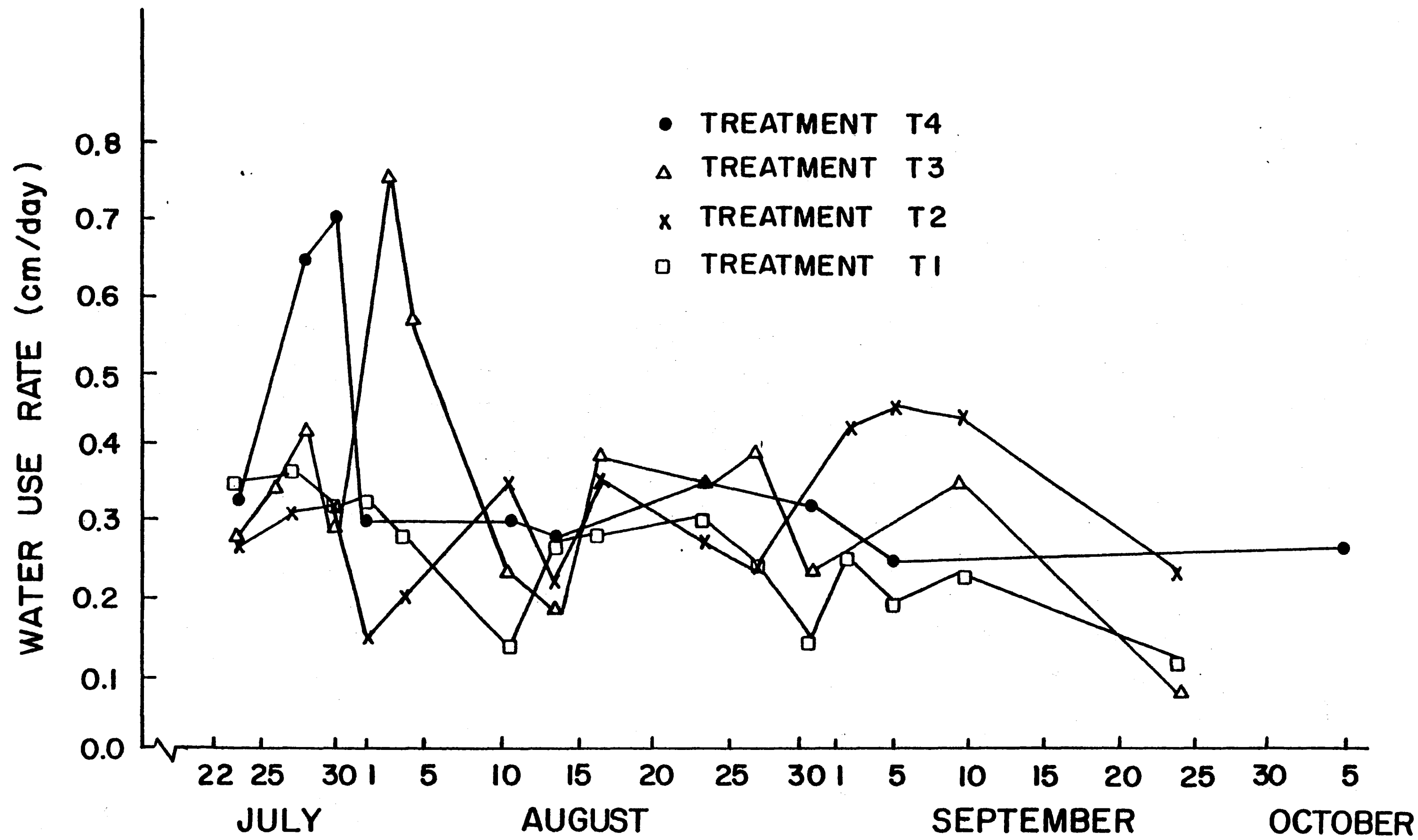

Figure 20. Water Use Rate of a Pecan Tree in Centimeters per Day

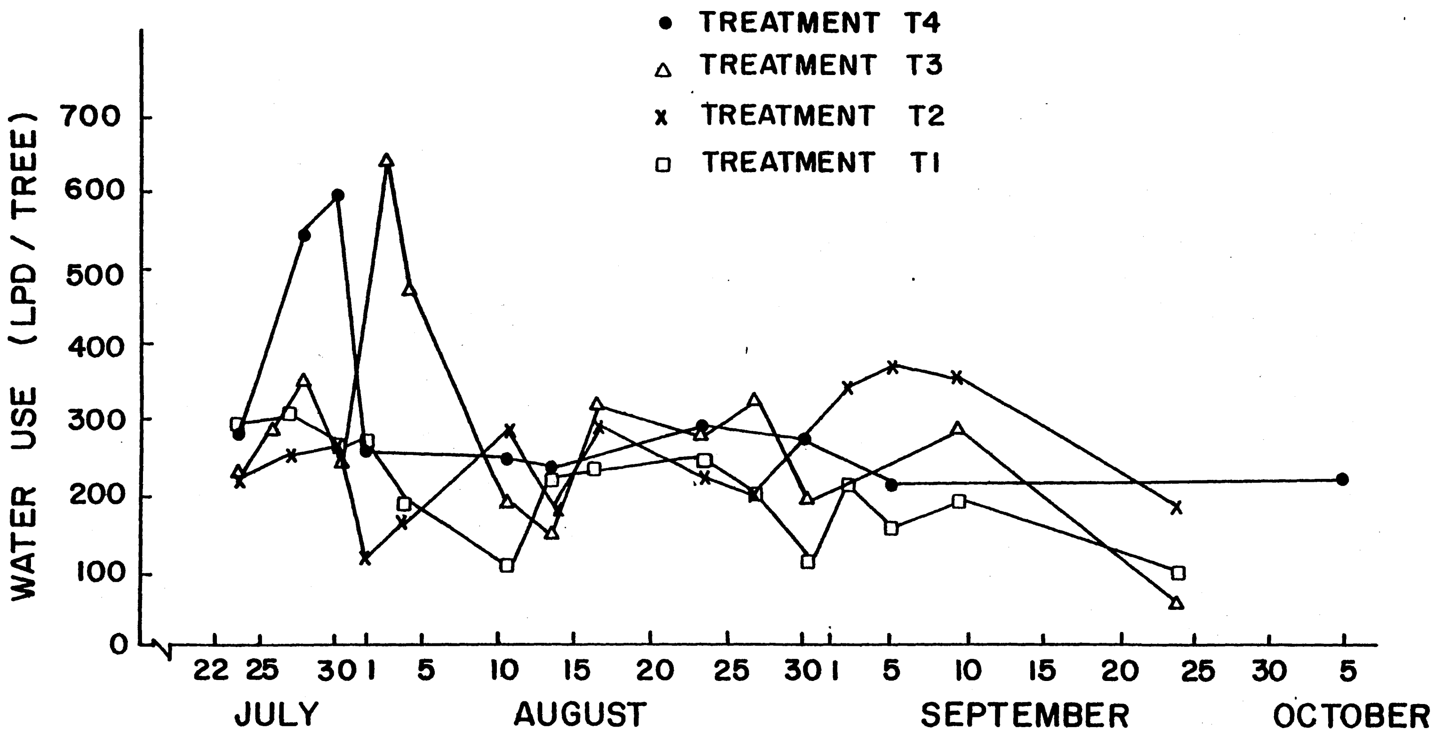

Figure 21. Water Use Rate of a Pecan Tree in Liters per Day per Tree

TABLE IX

AVERAGE WATER USE RATE FOR TREATMENT T4

Time Interval	No. of Days	Cm of Water Used	Water Use Rate cm/day	Water Use Rate liters/day/tree**
7/22 - 7/25	3	0.99	0.33	280
7/27 - 7/29	2	1.30	0.65	543
7/29 - 7/31	2	1.42	0.71	602
7/31 - 8/2	2	0.61	0.30	258
8/9 - 8/12	3	0.89	0.30	251
8/12 - 8/15	3	0.84	0.28	237
8/22 - 8/25	3	1.04	0.35	294
8/29 - 9/1	3	0.97	0.32	272
9/3 - 9/7	4	1.02	0.25	215
9/26 - 10/5	9	2.34*	0.26	220

*This value was calculated on the assumption that the 0.4 cm (0.15 in) rain of September 4 was 100% effective.

**Average basin area = 84.7m^2

Note: The weighted mean of the water use rate (calculated through the September 7 reading) is 0.36 cm/day or 308 liters/day/tree.

TABLE X

AVERAGE WATER USE RATE FOR TREATMENT T3

Time Interval	No. of Days	Cm of Water Used	Water Use Rate cm/day	Water Use Rate liters/day/tree*
7/22 - 7/25	3	0.84	0.28	235
7/25 - 7/27	2	0.69	0.34	288
7/27 - 7/29	2	0.84	0.42	352
7/29 - 7/31	2	0.58	0.29	245
8/2 - 8/3	1	0.76	0.76	640
8/3 - 8/5	2	1.12	0.56	469
8/9 - 8/12	3	0.69	0.23	192
8/12 - 8/15	3	0.53	0.18	149
8/15 - 8/18	3	1.14	0.38	320
8/22 - 8/25	3	1.02	0.34	285
8/25 - 8/29	4	1.53	0.39	325
8/29 - 9/1	3	0.69	0.23	192
9/7 - 9/12	5	1.73	0.35	290
9/22 - 9/26	4	0.28	0.07	59

*Average basin area = 84.0 m^2.

Note: The weighted mean of the water use rate (calculated through the September 12 reading) is 0.34 cm/day or 284 liters/day/tree.

TABLE XI

AVERAGE WATER USE RATE FOR TREATMENT T2

Time Interval	No. of Days	Cm of Water Used	Water Use Rate cm/day	liters/day/tree*
7/22 - 7/25	3	0.81	0.27	222
7/25 - 7/29	4	1.24	0.31	255
7/29 - 7/31	2	0.64	0.32	260
7/31 - 8/2	2	0.28	0.14	114
8/2 - 8/5	3	0.61	0.20	167
8/9 - 8/12	3	1.04	0.35	285
8/12 - 8/15	3	0.66	0.22	180
8/15 - 8/18	3	1.09	0.36	298
8/22 - 8/25	3	0.81	0.27	222
8/25 - 8/29	4	0.97	0.24	198
9/1 - 9/3	2	0.84	0.42	343
9/3 - 9/7	4	1.80	0.45	370
9/7 - 9/12	5	2.18	0.44	358
9/22 - 9/26	4	0.91	0.23	187

*Average basin area = 82.0 m^2.

Note: The weighted mean of the water use rate (calculated through the September 12 reading) is 0.32 cm/day or 259 liters/day/tree.

TABLE XII

AVERAGE WATER USE RATE FOR TREATMENT T1

Time Interval	No. of Days	Cm of Water Used	Water Use Rate cm/day	Water Use Rate liters/day/tree*
7/22 - 7/25	3	1.04	0.35	291
7/25 - 7/29	4	1.47	0.37	309
7/29 - 7/31	2	0.64	0.32	266
7/31 - 8/2	2	0.66	0.33	277
8/2 - 8/5	3	0.71	0.28	199
8/9 - 8/12	3	0.38	0.13	106
8/12 - 8/15	3	0.81	0.27	227
8/15 - 8/18	3	0.84	0.28	234
8/22 - 8/25	3	0.89	0.30	248
8/25 - 8/29	4	0.97	0.24	202
8/29 - 9/1	3	0.41	0.14	114
9/1 - 9/3	2	0.51	0.25	213
9/3 - 9/7	4	0.76	0.19	160
9/7 - 9/12	5	1.14	0.23	192
9/22 - 9/26	4	0.46	0.11	96

*Average basin area = 83.8 m^2.

Note: The weighted mean of the water use rate (calculated through the September 12 reading) is 0.26 cm/day or 214 liters/day/tree.

initiated on June 7, 1983, followed by a second fruit count one month later on July 7, a third fruit count on September 7, and the final fruit count on October 7.

It would be necessary to start the irrigation treatments as soon as the bud breaks in order to comprehend fully the effect of irrigation on the percent fruit drop. However, it was not until July 25 that irrigation became necessary for the wet treatment (T4) and not until July 31 for treatment T3. By then, the second fruit count had already been concluded. Treatment T2 received its only irrigation on August 29. Thus, the percent of fruit loss between the first and second fruit count would not reflect any irrigation effects; however, it was carried out anyway, because a higher percentage of the fruit tends to drop during this period.

Table XIII shows the number of fruits during a fruit count, the percentage of fruit drop after successive counts, and also the cumulative percentage of fruit drop.

Statistical analyses were performed to determine the randomized block experiment effects on percent fruit drop (Appendix F). There were no significant differences in the treatment effects as well as in the blocking effects on the percent fruit drop.

Results of Leaf Analysis

Table XIV shows the results of the leaf analysis performed on the samples taken from the experimental plots.

TABLE XIII

NUMBER OF FRUITS AND % FRUIT DROP AFTER SUCCESSIVE COUNT

Trt.	Block	Number Fruits 1st Ct.	Number Fruits 2nd Ct.	% Fruit Drop	Number Fruits 3rd Ct.	% Fruit Drop	Number Fruits 4th Ct.	% Fruit Drop	Cumul. Fruit Drop
1	1	189	151	20.12	119	21.19	114	4.20	39.68
1	2	193	163	15.54	122	25.15	105	13.93	45.60
1	3	206	167	18.93	119	28.74	102	14.29	50.49
1	4	184	155	15.76	137	11.61	131	4.38	28.80
2	1	206	153	25.73	106	30.72	94	11.32	54.37
2	2	210	142	32.38	90	36.62	84	6.67	60.00
2	3	198	140	29.29	109	22.14	104	4.59	47.47
2	4	197	169	14.21	136	19.53	118	13.24	40.10
3	1	174	125	28.16	65	48.00	52	20.00	70.11
3	2	188	164	12.77	132	19.51	123	6.82	34.57
3	3	211	181	14.22	148	18.23	141	4.73	33.18
3	4	188	152	19.15	120	21.05	110	8.33	41.49
4	1	196	134	31.63	95	29.10	89	6.32	54.59
4	2	193	148	23.32	118	20.27	112	5.08	41.97
4	3	199	163	18.09	124	23.93	115	7.26	42.21
4	4	185	144	22.16	113	21.53	103	8.85	44.32

TABLE XIV

MINERAL CONCENTRATIONS OF THE LEAF SAMPLES

OBS	TRT	BLOCK	N	P	K	CA	MG	ZN	FE	MN
1	1	1	2.29	0.106	0.55	1.94	0.54	27.84	48.34	1405
2	1	2	2.31	0.104	0.57	1.72	0.57	45.61	45.17	973
3	1	3	2.45	0.118	0.51	1.32	0.59	51.95	43.30	534
4	1	4	2.31	0.117	0.76	1.44	0.52	62.78	49.50	838
5	2	1	2.36	0.108	0.66	1.76	0.57	21.06	57.86	1334
6	2	2	2.59	0.120	0.71	1.59	0.44	20.03	52.36	1327
7	2	3	2.36	0.110	0.51	1.58	0.50	82.37	47.60	655
8	2	4	2.36	0.115	0.72	1.22	0.46	39.79	45.70	585
9	3	1	2.38	0.099	0.60	1.78	0.50	13.16	44.47	1442
10	3	2	2.57	0.103	0.48	1.50	0.57	31.21	50.93	970
11	3	3	2.48	0.122	0.61	1.96	0.57	68.46	49.18	1571
12	3	4	2.40	0.148	0.57	1.38	0.57	36.69	48.60	532
13	4	1	2.40	0.112	0.71	1.88	0.54	33.58	52.36	1655
14	4	2	2.40	0.111	0.66	1.71	0.49	55.73	47.04	948
15	4	3	2.37	0.112	0.82	1.54	0.49	37.57	48.00	1107
16	4	4	2.46	0.131	0.64	1.22	0.49	44.86	49.50	990

The nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents are expressed in percentages, while zinc (Zn), iron (Fe) and manganese (Mn) contents are expressed in ppm.

There were no significant differences in the irrigation treatments effect on the uptake of the elements; however, there were some differences in the uptake of some of the elements between the blocks.

The leaf phosphorus concentration of block no. 4 was significantly different from blocks no.1 and 2. Generally, the leaf phosphorus concentration increased with the block numbers toward the creek.

The leaf calcium concentration of block no. 4 was significantly different from the other blocks. Generally, the leaf calcium concentration decreased as the block number increased toward the creek.

The leaf zinc concentration of block no. 1 was significantly different from that of block no. 3. Within block no. 1, the leaf zinc concentration of plot no. 1 was considerably less than those of the other plots.

The manganese concentration of the leaves of block no. 1 was significantly different from that of block no. 4. A complete statistical analysis of the mineral concentrations of the pecan leaves is given in Appendix G.

Irrigation Effects on Nut Yield

Table XV shows the nut yield per tree of the randomized

TABLE XV

NUT YIELD IN KG (AND LBS) PER TREE

Treatment	Block	Yield	
		Kg	Lbs
T1	1	16.2	35.7
	2	12.1	26.6
	3	23.2	51.2
	4	16.0	35.2
T2	1	16.5	36.3
	2	16.1	35.6
	3	28.3	62.4
	4	17.3	38.2
T3	1	1.8	4.0
	2	21.6	47.6
	3	27.6	60.8
	4	14.7	32.3
T4	1	15.4	33.9
	2	11.2	24.8
	3	19.6	43.3
	4	2.2	4.8

block experiment. The yields of tree no. 1 (in block 1 and receiving treatment T3) and tree no. 16 (in block 4 and receiving treatment T4) were extremely low. So, statistical analyses were performed in two ways: first, with the yields from the two trees included and second, with the yields from the two trees excluded (Appendix H).

When the yields of the two trees were included in the analysis, the irrigation treatment effect was found to be insignificant. However, the blocking effect was significant (Pr>F = 0.0458). From the Duncan's Multiple Range Test it was found that the average yield of block no. 3 was significantly different from the average yields of the other blocks.

When the yields of the two trees were excluded from the analysis, the irrigation treatment effect became quite significant (Pr>F = 0.0885), while the blocking effect became more significant (Pr>F = 0.0039).

The average yield of each treatment with and without the yields of the two trees is shown in Table XVI, and the average yield of each block with and without the yields of the two trees is shown in Table XVII.

It would be more appropriate to accept the results of analyses which exclude the yields of trees no. 1 and 16, since their yields differ extremely from the yields of the other trees. In the case of tree no. 1 (in block 1), the irrigation treatment level (T3) should not be a factor for its low yield, because the average yield of the other trees

TABLE XVI

AVERAGE NUT YIELD IN KG (AND LBS) OF EACH TREATMENT

Treatment	Average Yield (All yields included) Kg	(Lbs)	(Two yields excluded) Kg	(Lbs)
T1	16.86	(37.18)	16.86	(37.18)
T2	19.56	(43.13)	19.56	(43.18)
T3	16.41	(36.18)	21.27	(46.90)
T4	12.11	(26.70)	15.42	(34.00)

TABLE XVII

AVERAGE NUT YIELD IN KG (AND LBS) OF EACH BLOCK

Block	Average Yield (All yields included) Kg	(Lbs)	(Two yields excluded) Kg	(Lbs)
1	12.46	(27.48)	16.01	(35.30)
2	15.26	(33.65)	15.26	(33.65)
3	24.69	(54.43)	24.69	(54.43)
4	12.53	(27.63)	15.98	(35.23)

receiving the same level was the highest among all the treatments. This tree was affected probably more from zinc deficiency and possibly from phosphorus deficiency as well (Table XIV). The percentage fruit drop from this tree was 70.11%, which was the highest among all the test trees.

The low yield of tree no. 16, which was in block no. 4 and received treatment T4, should not be attributed to any mineral deficiency. The tree simply bore less fruit since the percentage nut drop was only 44.32%, which was slightly less than the overall average (45.56%).

Irrigation Effects on Nut Characteristics

The percent kernel was determined by taking the weight of the kernel over the weight of the unshelled nut. Thirty nuts were used per sample. Table XVIII shows the weight of 30 nuts per sample (WTNUTS), the weight of their kernels (WTKERNEL) and the percent kernel weight (PERKER).

Appendix H shows the results of the analyses of the experimental effects on pecan nut characteristics. There were no significant effects on the nut size, kernel size and percent kernel.

TABLE XVIII

WEIGHT OF 30 NUTS, THEIR KERNELS AND PERCENT KERNEL WEIGHT PER SAMPLE

Treatment	Block	WTNUTS (gm)	WTKERNEL (gm)	PERKER (%)
1	1	331.48	183.02	55.21
	2	347.05	183.82	52.97
	3	329.42	171.58	52.09
	4	359.09	191.00	53.19
2	1	356.79	194.35	54.47
	2	337.79	178.74	52.91
	3	*	*	*
	4	*	*	*
3	1	337.42	180.51	53.50
	2	350.00	185.28	52.94
	3	328.76	174.62	53.11
	4	375.19	204.03	54.38
4	1	332.39	179.45	53.99
	2	365.43	200.66	54.91
	3	373.01	199.10	53.38
	4	350.43	183.54	52.38

* denotes missing data

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

This research was conducted primarily to define the water requirements of mature (10-year old) pecan trees under Oklahoma climatic conditions. A 4 x 4 randomized block experiment was used, assigning four trees to each block based on their relative locations. The trees within a block were selected at random to receive different levels of irrigation treatment. The treatment levels were based on the average cumulative moisture contents within the root zone, taken as 120 cm (4 ft) deep. The presence of a high water-table at the test sites from late March to late July of 1983 had kept the soil relatively wet. The following irrigation treatment levels were used:

T1 - No irrigation

T2 - Irrigate when the cumulative moisture content reaches or falls below 27 cm (10.6 in)

T3 - Irrigate when the cumulative moisture content reaches or falls below 29 cm (11.4 in)

T4 - Irrigate when the cumulative moisture content reaches or falls below 31 cm (12.2 in).

A neutron moisture gauge was used to measure the soil moisture content of each plot at a point 3 meters to the west side of the tree. The daily moisture use rate of the tree was computed based on the measurements of the soil moisture content at this location.

The soil moisture content at saturation was determined by making use of the presence of the high water-table. A region 8 to 20 cm (3 to 8 in) above the water-table was used in the determination of soil moisture content at saturation. The values obtained were related to soil textures.

A relationship between the soil moisture content and soil moisture suction was determined in four of the test plots. Sets of tensiometers of various lengths were used to measure the soil moisture suctions. The relationship between the two soil properties was used to estimate the "field capacity" of the soil.

Determinations were also made of the blocking and irrigation level effects on:

1. percent pecan fruit drop
2. mineral concentrations in pecan leaves
3. nut size, kernel size and percent kernel
4. nut yield

Conclusions

One of the characteristics of pecan is that its fruiting and nut production is related to its vegetative growth of the previous year. Thus, the effects of irrigation may have not been shown in this year's crop;

rather they will be evident in the crop of the following year. However, based on the prevailing field and tree conditions under which the research was conducted, the following conclusions were made:

1. There was a direct correlation between the average moisture use rate by a pecan tree and the levels of the irrigation treatment. The average moisture use rate was 0.26 cm per day (214 liters per day per tree) for the trees receiving irrigation treatment T1, 0.32 cm per day (259 liters per day per tree) for the trees receiving irrigation treatment T3, and 0.36 cm per day (308 liters per day per tree) for the trees receiving irrigation treatment T4.

2. The experimental blocks exhibited significant differences in the values of the average moisture content at saturation, suggesting differences in soil textures between some of the blocks. This has to be proven by analyzing the soils using the conventional method of soil analysis. The differences in saturation moisture content between depths were highly significant, with the higher values occurring at the lower depths.

3. The mean value of the soil moisture retained at -34 kPa (-1/3 bar) tension for the experimental blocks 1 and 2 was about 0.25. This mean value would have possibly increased if the soil moisture tensions had been measured in all blocks.

4. There were no significant differences in the leaf mineral concentrations between the irrigation treatments;

however, there were significant differences in some of the leaf mineral concentrations between the blocks.

5. The differences in yield due to the various irrigation treatment levels were not very great (Pr>F = 0.0885). Treatment T3 gave the best mean yield, followed by treatment T2, then the control treatment (T1) and lastly treatment T4. Obviously, there was not a great deal of water stress experienced by the trees throughout their growing season, as evidenced from the average moisture content of the control experiment, T1 (Table VII). So, the irrigation effects were not significant. In fact, the higher water treatment (T4) may have been harmful to the trees since their average nut yield was the lowest.

6. The differences in nut yields between the experimental blocks were highly significant (Pr>F = 0.0039). The average yield of block no. 3 was significantly higher than the yields of the other blocks. The variability of the soils between the blocks may have been responsible for these effects. The significant differences in some of the leaf mineral concentrations may suggest further reasons for the yield differences.

7. Under the prevailing conditions, irrigation had no significant effect on percent fruit drop, nut size, kernel size, percent kernel or nut yield.

Recommendations for Future Research

Based on the experience from the work which constituted this dissertation, the following recommendations are made for future considerations:

1. Perform the conventional method of soil mechanical and chemical analysis on the soils of the test plots, since there seem to be some variabilities between the soils of the experimental blocks. The soil profiles also seem to be non-homogeneous.

2. Investigate the effects of the presence of a high water-table on the growth and development of pecan roots. Also perform a feasibility study on the drainage requirements of the area.

3. Perform statistical analyses on next year's (1984) crop to determine the significance of this year's irrigation treatments on fruit characteristics and nut yield.

4. Carry out the randomized block experiment again, but this time with the irrigation treatment levels set at lower cumulative soil moisture contents. It will also be helpful to get a complete moisture characteristic curve for each soil type in the test area.

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APPENDIXES

APPENDIX A

EXCERPT OF A DETAILED SOIL SURVEY OF THE PECAN RESEARCH STATION, SPARKS, OKLAHOMA

A-1 Port Silty Clay Loam (0-1% slopes) occupies slightly depressed areas through which flow the small side drainageways. Here water has a tendency to pond or run very slowly during overflow periods, allowing very fine sediments to settle out so that textures are generally finer throughout the profile than in Port silt loam. These areas lie from 1 to 2 feet below adjacent areas.

The forest on these areas included a higher proportion of pecan than were on Port silt loam. Many pecans were left and now occur in groves or as single trees on this land. Thinning and spacing studies are being conducted on the thick stand of pecans in the southeast corner of this area.

This soil was described at a point 1300 feet north and 1000 feet west of the southeast corner Section 13, T 13 N, R 4 E west of Quapaw Creek. It is from a level area where the surface is weak, concave and has a gradient of about 1/2 percent. A scattering of native pecan trees and a thick stand of vetch was on the land at the time of sampling.

Profile:

A_{1p} 0-6" Reddish brown (5 YR 4/3; 3/3, when moist) heavy silty clay loam; moderate subangular blocky to coarse granular; firm; crumbly when moist; hard when dry and sticky when wet; permeable; pH 6.5; peds contain many pores and worm holes; grades shortly to the layer below.

A_1	6-12"	Dark reddish-brown (3.5 YR 4/3; 3/3, when moist) heavy silty clay loam; weak fine blocky; very firm; hard dry; slowly permeable; pH 6.5; sides of peds are slightly darker than above and have faintly shiny films; grades to the layer below.
C_1	12-22"	Reddish-brown (2.5 YR 5/4; 4/4, when moist) heavy silty clay loam or light silty clay; weak blocky; very firm; slowly permeable; pH 7.0 at 22 inches; very fine pores numerous; fine roots penetrate the peds; grades to the layer below.
C_2	22-50"	Red (1 YR 4/4; 3/4, when moist) heavy silty clay loam weakly stratified with silty clay seams; weakly irregular blocky; very firm; slowly permeable; sides of peds faintly shiny when moist; pH 7.5 at 36 and 52 inches.

Variations: Variations are chiefly in the nature and stratification of soil materials. Profiles with fine sandy loam strata occur from 10 to 20 inches over clay loam to light clay. Silty clay layers commonly occur below 18 inches. In some profiles the surface 10 to 14 inches is a heavy silt loam weakly stratified with clay loams, and the subsurface material is of clay loam stratified with silty clays. Reactions range from neutral to weak alkaline below 24 inches.

If desired the surface drainage could be speeded by the use of shallow ditches.

APPENDIX B

A COMPUTER PROGRAM TO CALCULATE THE VOLUMETRIC MOISTURE CONTENT OF SOIL

```
$JOB              ,TIME=(,3)
C
C
C   THIS PROGRAM IS USED IN THE MEASUREMENT OF SOIL MOISTURE CONTENT
C  BY USING NEUTRON PROBE NO. 310.   MEASUREMENTS ARE OF THE TEST PLOTS
C   TAKEN AT  PECAN RESEARCH STATION AT SPARKS, OKLAHOMA.
C     IF OTHER PROBES WERE USED THEN THE APPROPRIATE VALUES WILL BE
C  USED IN THE DATA STATEMENT.
C
C
      DIMENSION NPLOT(20),NDATE(80) ,STD(100),DEPTH(10),CMEA(10)
      DIMENSION    RATIO(10),SMC(10),CUMMC(10)
      DIMENSION THETA(10)
      DATA IN,LP,A,B,AA,BB/5,6,.0043,.6207,-0.0215,.6019/
C    NOTE:   RENUMBERING OF THE PLOTS.  PLOT NO. 8  IS DISCARDED.
C    SO,  PLOT NO  9  BECOMES NO. 8  AND SO FORTH.
C
C   READ DATE AND STD. COUNT
      N=20
      M=10
      J=1
   11 CONTINUE
      READ(IN,1) NDATE
    1 FORMAT(80A1)
      WRITE(LP,2) NDATE
    2 FORMAT('1'////14X,'DATE: ',80A1)
      READ(IN,100) STD(J)
  100 FORMAT(F10.4)
      WRITE(LP,200) STD(J)
  200 FORMAT(/14X,'STANDARD COUNT = ',F10.0)
      IF(STD(J).EQ.0.) GO TO 22
C
C   READ THE PLOT NOS.  AND DEPTHS AND MEASURED COUNTS
      DO 3 K=1,N
      READ(IN,4) NPLOT(K)
    4 FORMAT(I5)
      WRITE(LP,5) NPLOT(K)
    5 FORMAT(//14X,'PLOT NO. = ',I5)
      IF(NPLOT(K) .EQ. 0) GO TO 9
C   IF CMEA = 0. , IT MEANS THAT NO READING WAS TAKEN AT THAT DEPTH
      WRITE(LP,80)
   80 FORMAT(/10X,'STD COUNT',5X,'DEPTH',5X, 'MEA. COUNT',5X,
     1   'RATIO',3X,'THETA',3X,'S/MOISTURE',3X,'CUM. S/MOISTURE')
      DO 6 L=1,M
      READ(IN,7) DEPTH(L),CMEA(L)
    7 FORMAT(2F10.4)
      IF(DEPTH(L).EQ.0.) GO TO 30
C
C
C   USE SUBROUTINE SOILMC TO CALCULATE SOIL MOISTURE
      CALL SOILMC(N,M,J,K,L,NPLOT,STD,DEPTH,CMEA,RATIO,SMC,THETA
     1      ,CUMMC)
    6 CONTINUE
   30 CONTINUE
      WRITE(LP,300) CUMMC(L)
  300 FORMAT(/14X,'CUM. SMC = ',F10.4)
    3 CONTINUE
    9 CONTINUE
      J=J+1
      GO TO 11
```

```
   22   CONTINUE
        STOP
        END
C
C
C
C
        SUBROUTINE SOILMC(N,M,J,K,L,NPLOT,STD,DEPTH,CMEA,RATIO,SMC
       1      ,THETA,CUMMC)
C
C   THIS SUBROUTINE IS USED TO CALCULATE THE SOIL MOISTURE CONTENT, SMC,
C   ON VOLUMETRIC BASIS.     SMC = A + B*R   WHERE
C        A   AND   B   ARE DETERMINED IN THE LAB AND   R   IS THE RATIO OF
C        MEASURED COUNT TO THE STANDARD COUNT.
C   THE CALIBRATION CURVE FOR SOIL DEPTH = 6 INCHES IS DIFFERENT FROM THE
C   CALIBRATION CURVE FOR SOIL DEPTHS GREATER THAN 6 INCHES.  THUS THE
C   DIFFERENT VALUES FOR A AND AA,  AND B AND BB.
C
        DIMENSION NPLOT(N),STD(J),DEPTH(M),RATIO(M),SMC(M),CUMMC(M)
        DIMENSION CMEA(M)
        DIMENSION THETA(M)
        DATA LP/6/
        DATA A,B,AA,BB/0.0039,0.6200,-0.0219,0.6012/
        DATA DTOP,DINT,DLAST/9.,6.,3./
C
C
        DTOT=48.
        CUMMC(1)=0.
        IF(STD(J) .EQ. 0.) GO TO 64
        IF(NPLOT(K) .EQ. 0) GO TO 64
        RATIO(L)= CMEA(L)/STD(J)
        IF(CMEA(L) .EQ. 0.)GO TO 51
        IF(DEPTH(L).EQ.  6.) GO TO 60
        IF(DEPTH(L) .EQ.0.) GO TO 64
        THETA(L)=AA+BB*RATIO(L)
        IF(DEPTH(L).EQ.DTOT) GO TO 49
        SMC(L)=THETA(L)*DINT
        GO TO 50
   49   SMC(L)=THETA(L)*DLAST
        GO TO 50
   51   CONTINUE
        SMC(L)=0.
   50   CONTINUE
        CUMMC(L)=CUMMC(L)+SMC(L)
        GO TO 61
   60   CONTINUE
        THETA(L)=A+B*RATIO(L)
        SMC(L)=THETA(L)*DTOP
        CUMMC(L)=CUMMC(1)+SMC(L)
   61   CONTINUE
        WRITE(LP,63) STD(J),DEPTH(L),CMEA(L),RATIO(L),THETA(L),SMC(L)
       1      ,CUMMC(L)
   63   FORMAT(/10X,F8.0,3X,F8.0,3X,F10.0,3X,4F10.4)
        CUMMC(L+1)=CUMMC(L)
   64   CONTINUE
        RETURN
        END

$ENTRY
```

APPENDIX C

PRELIMINARY TESTS ON SAMPLING DISTANCE AND DIRECTION FROM A TREE

CUM. MOISTURE CONTENT IN MM (AND IN.) IN ROOTZONE

OBS	TUBE	REP	MMCMC	CUMMC	THETA
1	1	1	257.556	10.14	0.211250
2	1	2	286.766	11.29	0.235208
3	1	3	280.416	11.04	0.230000
4	1	4	272.796	10.74	0.223750
5	2	1	267.208	10.52	0.219167
6	2	2	279.400	11.00	0.229167
7	2	3	272.542	10.73	0.223542
8	2	4	259.334	10.21	0.212708
9	3	1	249.428	9.82	0.204583
10	3	2	281.940	11.10	0.231250
11	3	3	273.304	10.76	0.224167
12	3	4	268.478	10.57	0.220208
13	4	1	260.350	10.25	0.213542
14	4	2	280.670	11.05	0.230208
15	4	3	289.052	11.38	0.237083
16	4	4	275.336	10.84	0.225833
17	5	1	295.656	11.64	0.242500
18	5	2	292.100	11.50	0.239583
19	5	3	293.624	11.56	0.240833
20	5	4	282.702	11.13	0.231875
21	6	1	321.818	12.67	0.263958
22	6	2	338.328	13.32	0.277500
23	6	3	337.058	13.27	0.276458
24	6	4	332.232	13.08	0.272500
25	7	1	233.172	9.18	0.191250
26	7	2	251.968	9.92	0.206667
27	7	3	263.144	10.36	0.215833
28	7	4	268.732	10.58	0.220417

APPENDIX D

SOIL MOISTURE CONTENT AT SATURATION

HYDROLOGIC SOIL PROPERTIES CLASSIFIED BY SOIL TEXTURE

Texture class	Sample size	Total porosity (θ), cm^3/cm^3	Residual saturation (θ_r) cm^3/cm^3	Effective porosity (θ_e), cm^3/cm^3	Bubbling pressure (ψb) Arithmetic, cm	Bubbling pressure (ψb) Geometric,† cm	Pore size distribution (λ) Arithmetic	Pore size distribution (λ) Geometric†	Water retained at -0.33 bar tension, cm^3/cm^3	Water retained at -15 bar tension, cm^3/cm^3	Saturated Hydraulic Conductivity‡ (K_s) cm/h
Sand	762	0.437** (0.374-0.500)	0.020 (0.001-0.039)	0.417 (0.354-0.480)	15.98 (0.24-31.72)	7.26 (1.36-38.74)	0.694 (0.298-1.090)	0.592 (0.334-1.051)	0.091 (0.018-0.164)	0.033 (0.007-0.059)	21.00
Loamy sand	338	0.437 (0.368-0.506)	0.035 (0.003-0.067)	0.401 (0.329-0.473)	20.58 (0.0-45.20)	8.69 (1.80-41.85)	0.553 (0.234-0.872)	0.474 (0.271-0.827)	0.125 (0.060-0.190)	0.055 (0.019-0.091)	6.11
Sandy loam	666	0.453 (0.351-0.555)	0.041 (0.0-0.106)	0.412 (0.283-0.541)	30.20 (0.0-64.01)	14.66 (3.45-62.24)	0.378 (0.140-0.616)	0.322 (0.186-0.558)	0.207 (0.126-0.288)	0.095 (0.031-0.159)	2.59
Loam	383	0.463 (0.375-0.551)	0.027 (0.0-0.074)	0.434 (0.334-0.534)	40.12 (0.0-100.3)	11.15 (1.63-76.40)	0.252 (0.086-0.418)	0.220 (0.137-0.355)	0.270 (0.195-0.345)	0.117 (0.069-0.165)	1.32
Silt loam	1206	0.501 (0.420-0.582)	0.015 (0.0-0.058)	0.486 (0.394-0.578)	50.87 (0.0-109.4)	20.76 (3.58-120.4)	0.234 (0.105-0.363)	0.211 (0.136-0.326)	0.330 (0.258-0.402)	0.133 (0.078-0.188)	0.68
Sandy clay loam	498	0.398 (0.332-0.464)	0.068 (0.0-0.137)	0.330 (0.235-0.425)	59.41 (0.0-123.4)	28.08 (5.57-141.5)	0.319 (0.079-0.559)	0.250 (0.125-0.502)	0.255 (0.186-0.324)	0.148 (0.085-0.211)	0.43
Clay loam	366	0.464 (0.409-0.519)	0.075 (0.0-0.174)	0.390 (0.279-0.501)	56.43 (0.0-124.3)	25.89 (5.80-115.7)	0.242 (0.070-0.414)	0.194 (0.100-0.377)	0.318 (0.250-0.386)	0.197 (0.115-0.279)	0.23
Silty clay loam	689	0.471 (0.418-0.524)	0.040 (0.0-0.118)	0.432 (0.347-0.517)	70.33 (0.0-143.9)	32.56 (6.68-158.7)	0.177 (0.039-0.315)	0.151 (0.090-0.253)	0.366 (0.304-0.428)	0.208 (0.138-0.278)	0.15
Sandy clay	45	0.430 (0.370-0.490)	0.109 (0.0-0.205)	0.321 (0.207-0.435)	79.48 (0.0-179.1)	29.17 (4.96-171.6)	0.223 (0.048-0.398)	0.168 (0.078-0.364)	0.339 (0.245-0.433)	0.239 (0.162-0.316)	0.12
Silty clay	127	0.479 (0.425-0.533)	0.056 (0.0-0.136)	0.423 (0.334-0.512)	76.54 (0.0-159.6)	34.19 (7.04-166.2)	0.150 (0.040-0.260)	0.127 (0.074-0.219)	0.387 (0.332-0.442)	0.250 (0.193-0.307)	0.09
Clay	291	0.475 (0.427-0.523)	0.090 (0.0-0.195)	0.385 (0.269-0.501)	85.60 (0.0-176.1)	37.30 (7.43-187.2)	0.165 (0.037-0.293)	0.131 (0.068-0.253)	0.396 (0.326-0.466)	0.272 (0.208-0.336)	0.06

* First line is the mean value
Second line is ± one standard deviation about the mean
† Antilog of the log mean
‡ Obtained from Fig. 2

Source: Rawls, W. J., D. L. Brakensiek and K. E. Saxton. Estimation of Soil Water Properties. Trans. Am. Soc. of Agric. Engineers. 25:1316-1328. 1982.

SAT. MOISTURE CONTENT OF EXP. BLOCKS

OBS	BLOCK	MDEPTH	MC
1	1	-30	0.3223
2	1	-45	0.3484
3	1	-60	0.3424
4	1	-75	0.3496
5	1	-90	0.3552
6	1	-105	0.3645
7	1	-120	0.3659
8	2	-15	0.3155
9	2	-30	0.3219
10	2	-45	0.3358
11	2	-60	0.3437
12	2	-75	0.3389
13	2	-90	0.3470
14	2	-105	0.3650
15	2	-120	0.3766
16	3	-15	0.3257
17	3	-30	0.3343
18	3	-45	0.3281
19	3	-60	0.3709
20	3	-75	0.3586
21	3	-90	0.3546
22	3	-105	0.3714
23	3	-120	0.3738
24	4	-15	0.3478
25	4	-30	0.3251
26	4	-45	0.3524
27	4	-60	0.3532
28	4	-75	0.3694
29	4	-90	0.3623
30	4	-105	0.3680
31	4	-120	0.3717

MOISTURE CONTENT AT SATURATION (BLOCKING EFFECTS)

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: MC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	2	0.00726729	0.00363365	46.89	0.0001	0.770092	2.5127
ERROR	28	0.00216962	0.00007749		ROOT MSE		MC MEAN
CORRECTED TOTAL	30	0.00943691			0.00880264		0.35032258

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
BLOCK	1	0.00034140	4.41	0.0450	1	0.00059174	7.64	0.0100
MDEPTH	1	0.00692589	89.38	0.0001	1	0.00692589	89.38	0.0001

PARAMETER	ESTIMATE	T FOR H0: PARAMETER=0	PR > |T|	STD ERROR OF ESTIMATE
INTERCEPT	0.30932039	58.16	0.0001	0.00531836
BLOCK	0.00397298	2.76	0.0100	0.00143769
MDEPTH	-0.00044625	-9.45	0.0001	0.00004720

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: MC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	9	0.00628297	0.00069811	10.55	0.0001	0.840584	2.3079
ERROR	18	0.00119156	0.00006620		ROOT MSE		MC MEAN
CORRECTED TOTAL	27	0.00747452			0.00813619		0.35253571

SOURCE	DF	ANOVA SS	F VALUE	PR > F
BLOCK	3	0.00052016	2.62	0.0824
MDEPTH	6	0.00576280	14.51	0.0001

DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: MC
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DF=18 MSE=6.6E-05

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN	GROUPING	MEAN	N	BLOCK
	A	0.35744	7	4
	A			
B	A	0.35596	7	3
B	A			
B	A	0.34976	7	1
B				
B		0.34699	7	2

DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: MC
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DF=18 MSE=6.6E-05

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN	GROUPING	MEAN	N	MDEPTH
	A	0.37200	4	-120
	A			
	A	0.36722	4	-105
	B	0.35477	4	-90
	B			
	B	0.35412	4	-75
	B			
C	B	0.35255	4	-60
C				
C		0.34117	4	-45
	D	0.32590	4	-30

APPENDIX E

DATA ON SOIL MOISTURE TENSION AND VOLUMETRIC MOISTURE CONTENT

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
1	7/5	2	.	120	2.94	.
2	7/5	2	.	60	-49.20	0.284
3	7/5	2	.	30	-103.70	0.244
4	7/5	4	1	120	2.00	.
5	7/5	4	2	150	34.46	.
6	7/5	4	3	120	7.04	.
7	7/5	4	4	150	33.92	.
8	7/5	5	.	150	38.63	.
9	7/5	5	.	120	8.06	.
10	7/5	5	.	60	-74.92	0.282
11	7/5	5	.	30	-70.94	0.227
12	7/5	8	.	150	35.20	.
13	7/5	8	.	120	7.07	.
14	7/5	8	.	30	-97.06	0.225
15	7/7	2	.	150	27.90	.
16	7/7	2	.	120	-3.99	.
17	7/7	2	.	60	-58.02	.
18	7/7	2	.	30	-135.83	.
19	7/7	4	1	120	-4.30	.
20	7/7	4	2	150	30.81	.
21	7/7	5	.	150	29.81	.
22	7/7	5	.	120	1.76	.
23	7/7	5	.	60	-96.43	.
24	7/7	5	.	30	-76.76	.
25	7/7	8	.	150	30.16	.
26	7/7	8	.	120	0.77	.
27	7/7	8	.	30	-114.70	.
28	7/12	2	.	150	12.78	.
29	7/12	2	.	120	-15.96	0.367
30	7/12	2	.	60	-70.62	0.268
31	7/12	2	.	30	-233.48	0.230
32	7/12	4	1	120	-18.16	0.380
33	7/12	4	2	150	14.30	.
34	7/12	4	3	120	-15.64	0.380
35	7/12	4	4	150	13.76	.
36	7/12	5	.	150	22.25	.
37	7/12	5	.	120	-12.10	.
38	7/12	5	.	60	-160.60	0.274
39	7/12	5	.	30	-98.66	0.200
40	7/12	8	.	150	18.82	.
41	7/12	8	.	120	-9.31	0.381
42	7/13	2	.	150	6.48	.
43	7/13	2	.	120	-21.00	0.366
44	7/13	2	.	60	-73.14	0.265
45	7/13	2	.	30	-259.94	0.233
46	7/13	4	1	120	-19.42	0.380
47	7/13	4	2	150	13.04	.
48	7/13	4	3	120	-16.90	0.380
49	7/13	4	4	150	13.76	.
50	7/13	5	.	150	17.84	.
51	7/13	5	.	120	-14.62	.
52	7/13	5	.	60	-176.98	0.284
53	7/13	5	.	30	-105.59	0.198
54	7/13	8	.	150	18.82	.
55	7/13	8	.	120	-13.72	0.382
56	7/13	8	.	60	-193.06	0.322

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
57	7/13	8	.	30	-154.76	0.204
58	7/15	2	.	150	-8.64	.
59	7/15	2	.	120	-22.26	0.351
60	7/15	2	.	60	-79.44	0.252
61	7/15	2	.	30	-317.90	0.227
62	7/15	4	1	120	-21.94	0.369
63	7/15	4	2	150	10.52	.
64	7/15	4	3	120	-19.42	0.369
65	7/15	4	4	150	8.72	.
66	7/15	5	.	150	12.17	.
67	7/15	5	.	120	-18.40	.
68	7/15	5	.	60	-209.74	0.273
69	7/15	5	.	30	-117.56	0.187
70	7/15	8	.	150	16.30	.
71	7/15	8	.	120	-18.13	.
72	7/15	8	.	60	-272.44	0.315
73	7/15	8	.	30	-182.74	0.200
74	7/19	2	.	150	2.70	.
75	7/19	2	.	120	-29.82	0.346
76	7/19	2	.	60	-92.04	0.252
77	7/19	2	.	30	-459.02	0.232
78	7/19	4	1	120	-29.50	0.370
79	7/19	4	2	150	2.96	.
80	7/19	4	3	120	-26.98	0.370
81	7/19	4	4	150	1.16	.
82	7/19	5	.	150	7.13	.
83	7/19	5	.	120	-23.44	0.348
84	7/19	5	.	60	-279.04	0.267
85	7/19	5	.	30	-137.72	0.177
86	7/19	8	.	150	4.96	.
87	7/19	8	.	120	-26.95	0.374
88	7/21	2	.	150	-3.60	.
89	7/21	2	.	120	-33.60	0.335
90	7/21	2	.	60	-104.64	0.239
91	7/21	2	.	30	-564.86	0.226
92	7/21	4	1	120	-35.80	0.365
93	7/21	4	2	150	-2.08	.
94	7/21	4	3	120	-32.02	0.365
95	7/21	4	4	150	-2.62	.
96	7/21	5	.	150	0.83	.
97	7/21	5	.	120	-29.74	0.343
98	7/21	5	.	60	-344.56	0.267
99	7/21	5	.	30	-160.40	0.169
100	7/21	8	.	150	-15.20	.
101	7/21	8	.	120	-31.99	0.372
102	7/21	8	.	60	-346.78	0.308
103	7/22	2	.	150	-6.12	.
104	7/22	2	.	120	-36.12	0.324
105	7/22	2	.	60	-112.20	0.232
106	7/22	2	.	30	-634.16	0.223
107	7/22	4	1	120	-38.32	0.364
108	7/22	4	2	150	-4.60	.
109	7/22	4	3	120	-35.80	0.364
110	7/22	4	4	150	-6.40	.
111	7/22	5	.	150	-1.69	.
112	7/22	5	.	120	-32.36	0.339

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
113	7/22	5	.	60	-381.10	0.264
114	7/22	5	.	30	-151.58	0.162
115	7/22	8	.	150	-3.86	.
116	7/22	8	.	120	-31.99	0.370
117	7/22	8	.	60	-360.64	0.311
118	7/22	8	.	30	-226.84	0.182
119	7/25	2	.	150	-13.68	.
120	7/25	2	.	120	-46.20	0.312
121	7/25	2	.	60	-146.22	0.219
122	7/25	2	.	30	-782.84	0.221
123	7/25	4	1	120	-47.14	0.354
124	7/25	4	2	150	-14.62	.
125	7/25	4	3	120	-44.62	0.354
126	7/25	4	4	150	-13.96	.
127	7/25	5	.	150	-6.73	.
128	7/25	5	.	120	-39.82	0.328
129	7/25	5	.	60	-554.98	0.253
130	7/25	5	.	30	-194.42	0.155
131	7/25	8	.	150	-11.42	.
132	7/25	8	.	120	-42.07	0.368
133	7/27	2	.	150	-17.46	.
134	7/27	2	.	120	-49.98	0.296
135	7/27	2	.	60	-177.72	0.214
136	7/27	2	.	30	-796.70	0.218
137	7/27	4	1	120	-52.18	0.341
138	7/27	4	2	150	-19.09	.
139	7/27	4	3	120	-49.66	0.341
140	7/27	4	4	150	-19.00	.
141	7/27	5	.	150	-14.29	.
142	7/27	5	.	120	-44.86	0.329
143	7/27	5	.	60	-635.62	0.251
144	7/27	5	.	30	-101.18	0.226
145	7/27	8	.	150	-17.72	.
146	7/27	8	.	120	-48.37	0.356
147	7/29	2	.	150	-21.24	.
148	7/29	2	.	120	-55.02	0.278
149	7/29	2	.	60	-220.56	0.199
150	7/29	2	.	30	-840.80	0.214
151	7/29	4	1	120	-58.48	0.318
152	7/29	4	2	150	-24.76	.
153	7/29	4	3	120	-53.44	0.318
154	7/29	4	4	150	-24.04	.
155	7/29	5	.	120	-48.64	0.321
156	7/29	5	.	60	-554.98	0.249
157	7/29	5	.	30	-131.42	0.207
158	7/29	8	.	150	-18.98	.
159	7/29	8	.	120	-50.89	0.354
160	7/29	8	.	60	-428.68	0.303
161	7/31	2	.	150	-22.50	.
162	7/31	2	.	120	-57.54	0.305
163	7/31	2	.	60	-276.00	0.186
164	7/31	2	.	30	-838.28	0.157
165	7/31	4	1	120	-62.26	0.300
166	7/31	4	2	150	-27.28	.
167	7/31	4	3	120	-58.48	0.300
168	7/31	4	4	150	-27.82	.

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
169	7/31	5	.	150	-19.33	.
170	7/31	5	.	120	-53.68	0.322
171	7/31	5	.	30	-156.62	0.189
172	7/31	8	.	150	-26.54	.
173	7/31	8	.	120	-58.45	0.344
174	8/2	2	.	150	-32.58	.
175	8/2	2	.	120	-65.73	0.258
176	8/2	2	.	60	-350.34	0.192
177	8/2	4	1	120	-68.56	0.286
178	8/2	4	2	150	-32.32	.
179	8/2	4	3	120	-62.26	0.286
180	8/2	4	4	150	-32.23	.
181	8/2	5	.	150	-20.59	.
182	8/2	5	.	120	-54.94	0.315
183	8/2	5	.	60	-586.48	0.244
184	8/2	5	.	30	-171.74	0.179
185	8/2	8	.	150	-27.80	.
186	8/2	8	.	120	-58.45	0.336
187	8/2	8	.	60	-623.98	0.315
188	8/3	2	.	150	-33.84	.
189	8/3	2	.	120	-65.10	0.245
190	8/3	2	.	60	-390.66	0.187
191	8/3	2	.	30	-697.16	0.217
192	8/3	4	1	120	-69.82	0.268
193	8/3	4	2	150	-33.58	.
194	8/3	4	3	120	-63.52	0.268
195	8/3	4	4	150	-34.12	.
196	8/3	5	.	150	-21.85	.
197	8/3	5	.	120	-54.94	0.312
198	8/3	5	.	60	-683.50	0.238
199	8/3	5	.	30	-170.48	0.220
200	8/3	8	.	150	-30.32	.
201	8/3	8	.	120	-66.01	0.341
202	8/3	8	.	60	-664.30	0.312
203	8/5	2	.	150	-33.84	.
204	8/5	2	.	120	-66.36	0.240
205	8/5	2	.	60	-490.83	0.179
206	8/5	2	.	30	-813.08	0.216
207	8/5	4	1	120	-73.60	0.261
208	8/5	4	2	150	-38.62	.
209	8/5	4	3	120	-67.30	0.261
210	8/5	4	4	150	-37.90	.
211	8/5	5	.	150	-20.59	.
212	8/5	5	.	120	-58.72	0.308
213	8/5	5	.	60	-692.32	0.242
214	8/5	5	.	30	-108.74	0.209
215	8/5	8	.	150	-32.84	.
216	8/5	8	.	120	-67.27	0.308
217	8/5	8	.	60	-524.44	0.238
218	8/9	2	.	150	-40.14	.
219	8/9	2	.	120	-72.66	0.226
220	8/9	2	.	60	-651.48	0.178
221	8/9	4	1	120	-77.38	0.238
222	8/9	4	2	150	-43.66	.
223	8/9	4	3	120	-74.86	0.238
224	8/9	4	4	150	-45.46	.

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
225	8/9	5	.	150	-28.15	.
226	8/9	5	.	120	-63.76	0.302
227	8/9	5	.	60	-727.60	0.238
228	8/9	5	.	30	-116.30	0.197
229	8/9	8	.	150	-37.88	.
230	8/9	8	.	120	-71.05	0.319
231	8/9	8	.	60	-515.62	0.304
232	8/12	2	.	150	-43.92	.
233	8/12	2	.	120	-80.22	0.217
234	8/12	2	.	60	-727.08	0.172
235	8/12	4	1	120	-83.68	0.226
236	8/12	4	2	150	-48.70	.
237	8/12	4	3	120	-78.64	0.226
238	8/12	4	4	150	-47.98	.
239	8/12	5	.	150	-31.93	.
240	8/12	5	.	120	-70.06	0.300
241	8/12	5	.	60	-733.90	0.228
242	8/12	5	.	30	-131.42	0.189
243	8/12	8	.	150	-41.66	.
244	8/12	8	.	120	-74.83	0.309
245	8/12	8	.	60	-336.70	0.306
246	8/15	2	.	150	-46.44	.
247	8/15	2	.	120	-81.48	0.206
248	8/15	2	.	60	-747.24	0.168
249	8/15	2	.	30	-792.92	0.216
250	8/15	4	1	120	-89.98	0.214
251	8/15	4	2	150	-52.48	.
252	8/15	4	3	120	-82.42	0.214
253	8/15	4	4	150	-53.02	.
254	8/15	5	.	150	-36.97	.
255	8/15	5	.	120	-81.40	0.287
256	8/15	5	.	60	-696.10	0.227
257	8/15	5	.	30	-165.44	0.174
258	8/15	8	.	150	-45.44	.
259	8/15	8	.	120	-82.39	0.298
260	8/15	8	.	60	-278.74	0.299
261	8/18	2	.	150	-54.00	.
262	8/18	2	.	120	-97.86	0.195
263	8/18	4	1	120	-97.54	0.223
264	8/18	4	2	150	-56.26	.
265	8/18	4	3	120	-87.46	0.223
266	8/18	4	4	150	-55.54	.
267	8/18	5	.	150	-44.53	.
268	8/18	5	.	120	-87.70	0.286
269	8/18	5	.	60	-116.50	0.224
270	8/18	5	.	30	-53.30	0.136
271	8/18	8	.	150	-54.26	.
272	8/18	8	.	120	-88.69	0.291
273	8/18	8	.	60	-264.88	0.298
274	8/19	2	.	150	-59.04	.
275	8/19	2	.	120	-104.16	.
276	8/19	4	1	120	-101.32	.
277	8/19	4	2	150	-58.78	.
278	8/19	4	3	120	-89.98	.
279	8/19	4	4	150	-59.32	.
280	8/19	5	.	150	-47.05	.

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
281	8/19	5	.	120	-90.22	.
282	8/19	5	.	60	-129.10	.
283	8/19	5	.	30	-59.60	.
284	8/22	2	.	150	-60.30	.
285	8/22	2	.	120	-109.20	0.283
286	8/22	2	.	60	-322.62	0.285
287	8/22	4	1	120	-105.10	0.219
288	8/22	4	2	150	-61.30	.
289	8/22	4	3	120	-92.50	0.219
290	8/22	4	4	150	-60.58	.
291	8/22	5	.	150	-50.83	.
292	8/22	5	.	120	-91.48	0.289
293	8/22	5	.	60	-121.54	0.224
294	8/22	5	.	30	-145.28	0.207
295	8/22	8	.	150	-63.08	.
296	8/22	8	.	120	-93.73	0.286
297	8/22	8	.	60	-293.86	0.301
298	8/22	8	.	30	-41.62	0.245
299	8/25	2	.	150	-57.78	.
300	8/25	2	.	120	-124.32	0.178
301	8/25	2	.	30	-804.26	0.218
302	8/25	4	1	120	-113.92	0.206
303	8/25	4	2	150	-63.82	.
304	8/25	4	3	120	-97.54	0.206
305	8/25	4	4	150	-63.10	.
306	8/25	5	.	150	-60.91	.
307	8/25	5	.	120	-104.08	0.277
308	8/25	5	.	60	-166.90	0.223
309	8/25	5	.	30	-186.86	0.187
310	8/25	8	.	150	-63.08	.
311	8/25	8	.	120	-94.99	0.275
312	8/25	8	.	60	-200.62	0.303
313	8/25	8	.	30	-80.68	0.227
314	8/26	2	.	150	-57.78	.
315	8/26	2	.	120	-143.22	.
316	8/26	4	1	120	-118.96	.
317	8/26	4	2	150	-65.08	.
318	8/26	4	3	120	-97.54	.
319	8/26	4	4	150	-63.10	.
320	8/26	8	.	150	-64.34	.
321	8/26	8	.	120	-94.99	.
322	8/26	8	.	60	-164.08	.
323	8/29	2	.	150	-62.82	.
324	8/29	2	.	120	-203.70	0.169
325	8/29	4	1	120	-131.56	0.202
326	8/29	4	2	150	-67.60	.
327	8/29	4	3	120	-101.32	0.202
328	8/29	4	4	150	-66.88	.
329	8/29	5	.	150	-58.39	.
330	8/29	5	.	120	-87.70	0.284
331	8/29	5	.	60	-56.02	0.217
332	8/29	5	.	30	-53.30	0.193
333	8/29	8	.	150	-66.86	.
334	8/29	8	.	120	-98.77	0.266
335	8/29	8	.	60	-112.42	0.298
336	8/30	2	.	150	-60.30	.

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
337	8/30	2	.	120	-217.56	.
338	8/30	4	1	120	-64.78	.
339	8/30	4	2	150	-61.30	.
340	8/30	4	3	120	-61.00	.
341	8/30	4	4	150	-61.84	.
342	8/30	5	.	150	-59.65	.
343	8/30	5	.	120	-95.26	.
344	8/30	5	.	60	-45.94	.
345	8/30	5	.	30	-55.82	.
346	8/30	8	.	150	-66.86	.
347	8/30	8	.	120	-100.03	.
348	8/30	8	.	60	-102.34	.
349	9/1	2	.	150	-62.82	.
350	9/1	2	.	120	-269.22	.
351	9/1	4	1	120	-98.80	0.209
352	9/1	4	2	150	-70.12	.
353	9/1	4	3	120	-84.94	0.209
354	9/1	4	4	150	-69.40	.
355	9/1	5	.	150	-60.91	.
356	9/1	5	.	120	-106.60	0.276
357	9/1	5	.	60	-91.30	0.221
358	9/1	5	.	30	-62.12	0.180
359	9/1	8	.	150	-74.42	.
360	9/1	8	.	120	-106.33	0.257
361	9/1	8	.	60	-143.92	0.296
362	9/3	2	.	150	-66.60	.
363	9/3	2	.	120	-347.34	0.156
364	9/3	4	1	120	-113.92	0.212
365	9/3	4	2	150	-71.38	.
366	9/3	4	3	120	-93.76	0.212
367	9/3	4	4	150	-71.92	.
368	9/3	5	.	150	-58.39	.
369	9/3	5	.	120	-65.02	0.280
370	9/3	5	.	60	-34.60	0.214
371	9/3	5	.	30	-29.36	0.186
372	9/7	2	.	150	-72.90	.
373	9/7	2	.	120	-551.46	0.148
374	9/7	4	1	120	-137.86	0.194
375	9/7	4	2	150	-77.68	.
376	9/7	4	3	120	-102.58	0.194
377	9/7	5	.	150	-70.99	.
378	9/7	5	.	120	-119.20	0.271
379	9/7	5	.	60	-95.08	0.217
380	9/7	5	.	30	-62.12	0.171
381	9/7	8	.	150	-79.46	.
382	9/7	8	.	120	-110.11	0.249
383	9/7	8	.	60	-130.06	0.298
384	9/12	2	.	150	-76.68	.
385	9/12	2	.	120	-669.90	0.138
386	9/12	4	1	120	-146.68	0.181
387	9/12	4	2	150	-83.98	.
388	9/12	4	3	120	-113.92	0.181
389	9/12	5	.	150	-77.29	.
390	9/12	5	.	60	-59.80	0.211
391	9/12	8	.	150	-83.24	.
392	9/12	8	.	120	-113.89	0.237

SOIL MOISTURE SUCTION

OBS	DATE	PLOT	TNO	L	HP	MC
393	9/12	8	.	60	-113.68	0.296
394	9/14	2	.	150	-80.46	.
395	9/14	2	.	120	-56.28	0.133
396	9/14	4	1	120	-146.68	0.184
397	9/14	4	2	150	-85.24	.
398	9/14	4	3	120	-118.96	0.184
399	9/14	5	.	150	-77.29	.
400	9/14	5	.	60	-87.52	0.207
401	9/19	2	.	150	-85.50	.
402	9/19	4	2	150	-87.76	.
403	9/19	5	.	150	-78.55	.
404	9/19	5	.	60	-53.50	0.215
405	9/19	8	.	150	-87.02	.
406	9/19	8	.	120	-118.93	0.232
407	9/19	8	.	60	-4.06	0.293
408	9/22	2	.	150	-79.20	.
409	9/22	2	.	120	-228.90	0.130
410	9/22	2	.	30	-69.68	0.230
411	9/22	4	1	120	-121.48	0.170
412	9/22	4	2	150	-89.02	.
413	9/22	4	3	120	-102.58	0.170
414	9/22	5	.	150	-79.81	.
415	9/22	5	.	60	-58.54	0.213
416	9/22	8	.	150	-83.24	.
417	9/22	8	.	120	-115.15	0.229
418	9/22	8	.	60	-731.08	0.294
419	10/5	2	.	150	-96.21	.
420	10/5	4	2	150	-97.84	.
421	10/5	4	3	120	-127.78	0.158
422	10/5	5	.	150	-93.67	.
423	10/5	5	.	60	-144.22	0.215
424	10/5	8	.	150	-94.58	.
425	10/5	8	.	120	-130.27	0.219
426	10/5	8	.	60	-205.66	0.290
427	10/12	2	.	150	-98.10	.
428	10/12	4	2	150	-100.36	.
429	10/12	4	3	120	-146.68	0.148
430	10/12	5	.	150	-96.19	.
431	10/12	5	.	60	-202.18	0.177
432	10/12	8	.	150	-94.58	.
433	10/12	8	.	120	-132.79	0.211
434	10/12	8	.	60	-314.02	.

APPENDIX F

EXPERIMENTAL EFFECTS ON

PERCENT FRUIT DROP

RB EXPT. IRRIGATION AND BLOCKING EFFECTS ON NUT ABORTION

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: PL1

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	335.76797610	55.96132935	1.75	0.2166	0.538190	26.5125
ERROR	9	288.11543980	32.01282664		ROOT MSE		PL1 MEAN
CORRECTED TOTAL	15	623.88341589			5.65798786		21.34083125

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	177.26748446	1.85	0.2092
BLOCK	3	158.50049164	1.65	0.2461

RB EXPT. IRRIGATION AND BLOCKING EFFECTS ON NUT ABORTION

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: PL2

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	477.68884736	79.61480789	1.18	0.3960	0.439830	33.1079
ERROR	9	608.38664569	67.59851619		ROOT MSE		PL2 MEAN
CORRECTED TOTAL	15	1086.07549305			8.22183168		24.83343125

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	82.29344245	0.41	0.7526
BLOCK	3	395.39540492	1.95	0.1922

RB EXPT. IRRIGATION AND BLOCKING EFFECTS ON NUT ABORTION

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: PL3

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	38.50534363	6.41755727	0.21	0.9646	0.122655	63.2224
ERROR	9	275.42627641	30.60291960		ROOT MSE		PL3 MEAN
CORRECTED TOTAL	15	313.93162004			5.53199056		8.75005000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	20.96358062	0.23	0.8744
BLOCK	3	17.54176301	0.19	0.8998

APPENDIX G

STATISTICAL ANALYSIS ON THE LEAF MINERAL CONCENTRATIONS

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: N

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	0.05563750	0.00927292	1.50	0.2813	0.499467	3.2719
ERROR	9	0.05575625	0.00619514		ROOT MSE		N MEAN
CORRECTED TOTAL	15	0.11139375			0.07870920		2.40562500

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	0.02856875	1.54	0.2709
BLOCK	3	0.02706875	1.46	0.2904

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: P

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	0.00119000	0.00019833	1.88	0.1900	0.555815	8.9581
ERROR	9	0.00095100	0.00010567		ROOT MSE		P MEAN
CORRECTED TOTAL	15	0.00214100			0.01027943		0.11475000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	0.00011250	0.35	0.7869
BLOCK	3	0.00107750	3.40	0.0671

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: K

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	0.05770000	0.00961667	1.03	0.4662	0.406338	15.3621
ERROR	9	0.08430000	0.00936667		ROOT MSE		K MEAN
CORRECTED TOTAL	15	0.14200000			0.09678154		0.63000000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	0.04675000	1.66	0.2433
BLOCK	3	0.01095000	0.39	0.7634

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: CA

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	0.58690000	0.09781667	3.19	0.0581	0.679932	10.9761
ERROR	9	0.27627500	0.03069722		ROOT MSE		CA MEAN
CORRECTED TOTAL	15	0.86317500			0.17520623		1.59625000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	0.02822500	0.31	0.8202
BLOCK	3	0.55867500	6.07	0.0152

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: MG

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	0.01523750	0.00253958	1.43	0.3012	0.488479	8.0107
ERROR	9	0.01595625	0.00177292		ROOT MSE		MG MEAN
CORRECTED TOTAL	15	0.03119375			0.04210602		0.52562500

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	0.01286875	2.42	0.1333
BLOCK	3	0.00236875	0.45	0.7265

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: ZN

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	2938.29443750	489.71573958	1.90	0.1866	0.558206	38.2335
ERROR	9	2325.52110625	258.39123403		ROOT MSE		ZN MEAN
CORRECTED TOTAL	15	5263.81554375			16.07455237		42.04312500

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	196.29346875	0.25	0.8572
BLOCK	3	2742.00096875	3.54	0.0613

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: FE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	67.63303750	11.27217292	0.83	0.5768	0.355481	7.5726
ERROR	9	122.62455625	13.62495069		ROOT MSE		FE MEAN
CORRECTED TOTAL	15	190.25759375			3.69119909		48.74437500

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	38.75671875	0.95	0.4575
BLOCK	3	28.87631875	0.71	0.5719

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: MN

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	1250420.50000000	208403.41666667	2.33	0.1225	0.608292	28.3752
ERROR	9	805203.25000000	89467.02777778		ROOT MSE		MN MEAN
CORRECTED TOTAL	15	2055623.75000000			299.11039396		1054.12500000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	160009.25000000	0.60	0.6333
BLOCK	3	1090411.25000000	4.06	0.0443

```
DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: P
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,
      NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05  DF=9  MSE=1.1E-04

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN    GROUPING          MEAN       N  BLOCK

                A           0.12775    4  4
                A
        B       A           0.11550    4  3
        B
        B                   0.10950    4  2
        B
        B                   0.10625    4  1
```

```
DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: CA
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,
      NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05  DF=9  MSE=.0306972

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN    GROUPING          MEAN       N  BLOCK

                A           1.8400     4  1
                A
                A           1.6300     4  2
                A
                A           1.6000     4  3

                B           1.3150     4  4
```

```
DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: ZN
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,
      NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05   DF=9   MSE=258.391

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN    GROUPING                MEAN       N  BLOCK

                 A              60.087       4  3
                 A
          B      A              46.030       4  4
          B      A
          B      A              38.145       4  2
          B
          B                     23.910       4  1
```

```
DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: MN
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,
      NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05   DF=9   MSE=89467

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN    GROUPING                MEAN       N  BLOCK

                 A              1459.0       4  1
                 A
          B      A              1054.5       4  2
          B      A
          B      A               966.8       4  3
          B
          B                      736.3       4  4
```

APPENDIX H

STATISTICAL ANALYSIS ON NUT CHARACTERISTICS AND YIELD

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: YIELD

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	2504.58375000	417.43062500	2.57	0.0981	0.631614	35.5930
ERROR	9	1460.78562500	162.30951389		ROOT MSE		YIELD MEAN
CORRECTED TOTAL	15	3965.36937500			12.74007511		35.79375000

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TRT	3	553.98687500	1.14	0.3850
BLOCK	3	1950.59687500	4.01	0.0458

DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: YIELD
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DF=9 MSE=162.31

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN GROUPING	MEAN	N	TRT
A	43.125	4	2
A			
A	37.175	4	1
A			
A	36.175	4	3
A			
A	26.700	4	4

DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: YIELD
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DF=9 MSE=162.31

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

DUNCAN GROUPING	MEAN	N	BLOCK
A	54.425	4	3
B	33.650	4	2
B			
B	27.625	4	4
B			
B	27.475	4	1

ADJUSTED NUT YIELDS OF THE RB EXPERIMENT

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: YIELD

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	1484.30969643	247.38494940	7.59	0.0086	0.866839	14.1696
ERROR	7	228.01387500	32.57341071		ROOT MSE		YIELD MEAN
CORRECTED TOTAL	13	1712.32357143			5.70731204		40.27857143

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
TRT	3	320.72857143	3.28	0.0885	3	357.35029167	3.66	0.0716
BLOCK	3	1163.58112500	11.91	0.0039	3	1163.58112500	11.91	0.0039

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: WTNUTS

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	1296.89243869	216.14873978	0.75	0.6321	0.389755	4.8919
ERROR	7	2030.56365417	290.08052202		ROOT MSE		WTNUTS MEAN
CORRECTED TOTAL	13	3327.45609286			17.03175041		348.16071429

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
TRT	3	370.53311786	0.43	0.7407	3	385.38082083	0.44	0.7298
BLOCK	3	926.35932083	1.06	0.4231	3	926.35932083	1.06	0.4231

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: WTKERNEL

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	349.75779821	58.29296637	0.44	0.8349	0.271677	6.2088
ERROR	7	937.64428750	133.94918393		ROOT MSE		WTKERNEL MEAN
CORRECTED TOTAL	13	1287.40208571			11.57364177		186.40714286

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
TRT	3	139.35646071	0.35	0.7929	3	141.08882083	0.35	0.7900
BLOCK	3	210.40133750	0.52	0.6797	3	210.40133750	0.52	0.6797

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: PERKER

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	6	4.11019280	0.68503213	0.66	0.6834	0.362509	1.8983
ERROR	7	7.22798713	1.03256959		ROOT MSE		PERKER MEAN
CORRECTED TOTAL	13	11.33817993			1.01615431		53.53009886

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
TRT	3	0.24332117	0.08	0.9696	3	0.25755182	0.08	0.9671
BLOCK	3	3.86687163	1.25	0.3626	3	3.86687163	1.25	0.3626

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VITA

Salim Bin Said

Candidate for the Degree of

Doctor of Philosophy

Thesis: WATER REQUIREMENTS OF MATURE PECAN TREES IN OKLAHOMA

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Kedah, Malaysia, May 20, 1946, son of Mr. and Mrs. Hj. Said Hj. Ali; married to Leora Shiroma in 1976; daughter, Leilani Binti Salim, born on June 28, 1977; son, Johan Ariff Salim, born on October 6, 1979.

Education: Graduated from Ibrahim Secondary School, Sg. Patani, Kedah, Malaysia in 1967; received Bachelor of Science in Agricultural Engineering from University of Hawaii in 1972; received Master of Science in Agricultural Engineering from University of Hawaii in 1975; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in May, 1984.

Professional Experience: Employed as a Lecturer in Agricultural Engineering at University of Agriculture Malaysia, Serdang, Selangor, Malaysia, 1975-1980.

Professional Organizations: Student member of the American Society of Agricultural Engineers; student member of Oklahoma Society of Professional Engineers; member of Alpha Epsilon - the Honor Society of Agricultural Engineering.