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EFFECTS OF COMPRESSION OF SOME SUBTROPICAL SOILS ON THE SOIL PROPERTIES AND UPON ROOT DEVELOPMENT

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ABSTRACT

EFFECTS OF COMPRESSION OF SOME SUBTROPICAL SOILS ON THE SOIL PROPERTIES AND UPON ROOT DEVELOPMENT

Representative soils of four Great Soil Groups from Hawaii were compressed artificially to develop a study on the effects of compaction in subtropical soils. Although this study was primarily concerned with the Low Humic Latosols which are of great importance agriculturally in Hawaii, representatives of the Hydrol Humic Latosol, Gray Hydromorphic Clay and Alluvial Soils were also included. The dominant criterion investigated was the effect of increasing soil bulk density on sugarcane roots. A method was devised to produce the conditions under which roots could be grown in soils which were compressed to various bulk densities. The relationship of the effects of variations in bulk density and aeration porosity on root morphology and proliferation was examined and is discussed.

With increasing soil bulk density, roots of sugarcane develop quite normally until a density is reached at which proliferation is reduced and then roots and rootlets gradually become more distorted. Roots are incapable of penetrating a soil compressed above a critical bulk density. Seven stages of degradation to root proliferation and development are described for this continuous trend between these extremes. Each of these stages has been correlated with bulk density and aeration porosity values for each soil studied. Even though the particle density values, determined by standard means, for soil

material are similar (2.86 to 2.87 gm/cc), a Grey Hydromorphic Clay allowed cane roots to enter soil at 1.89 gm/cc while a Hydrol Humic Latosol did not allow roots to enter soil compressed to 0.96 gm/cc. Bulk density, per se, plays an even less significant role when variations in particle density are considered: a soil horizon of a Humic Ferruginous Latosol with a particle density of 4.01 gm/cc allowed good root distribution and proliferation at bulk densities as high as 2.71 gm/cc. Despite this great variation in the soil bulk density associated with a particular stage of degradation to root proliferation and development for widely different soils, when one particular horizon of a particular soil series is compared, the seven stages of degradation described occur at remarkably similar bulk densities.

Aeration porosity values correlate much more closely with each of the seven stages of root degradation than do bulk density values. However, variations in aeration porosity are quite wide for a particular soil material which has been compressed at different moisture contents. Some preliminary investigations, not developed further in this study, indicate that there is a still closer correlation of each stage of root degradation with air permeability.

Detailed investigations of other factors establish the actual weight and volume of roots within representative soils which had been compressed to various bulk densities. Distortion to the cells of roots was not established, but morphological distortions are related to increases in soil bulk density. Rates of root elongation decrease with increasing soil bulk density. Despite reduced proliferation and distortions, radio rubidium investigations indicate that roots may function when they are able to penetrate compressed soil.

A system for estimating root development in an unknown soil is proposed from particle density and moisture retention characteristics.

EFFECTS OF COMPRESSION OF SOME SUBTROPICAL SOILS ON THE SOIL PROPERTIES AND UPON ROOT DEVELOPMENT

ALBERT CHARLES TROUSE, JR.

INTRODUCTION

1. GENERAL

With the increase of mechanized operations in agricultural endeavors there has been an associated increase in interest in physical aspects of soils. In Hawaii, farming of many thousands of agricultural acres has shifted recently from hand operations to highly mechanized cultural systems. Many of the mechanized operations are practiced on a year-round basis: the shortage of suitable land, the value of the land, and the labor situation induce the operators to exploit the year-round mild climate. However, agricultural mechanization in Hawaii has introduced several new problems and emphasized several older ones. One of the newer problems now receiving much attention is the increased destruction of the physical condition of the soil. Often the designs of new implements were not in accord with the maintenance of good soil tilth, and frequently the actual system of operations abets the destruction of the soil structure. The need to know the conditions under which the soil could adequately withstand the forces of the new implements has become more acute: the need to know how to reduce damaging forces, or to eliminate them, requires attention while the principles involved in the detrimental effects to the physical condition of the soil and the subsequent effects on the agricultural crop need to be established.

Much information has been published on soil compaction, using soils of the temperate climatic belts of the world (6, 8, 18, 31, 35). Although many details of the complicated mechanism causing detriment to agricultural soils and how this detriment directly affects the crop are known, much is still to be determined. Much less is known of compaction of subtropical soils upon which much less research has been done. Soil compaction has been defined as "the increase of the soil bulk density by reduction of pore space." (5) Although this definition is widely accepted, it more precisely defines compressed soil: soil compaction is commonly thought of as that phase of soil compression in which detrimental results can be expected. The complete acceptance of this definition of soil compaction would infer that firming of soils, for better contact with seeds and roots during the planting and transplanting operations, is a detrimental operation although most agriculturists often accept firming as a beneficial, if not a required, operation.

To be compressed, a soil must be strained when a force is applied to it. Whether a soil will rebound completely to its former status or will remain compressed after removal of the force depends on whether or not soil particles have been forced into a tighter arrangement that fills former voids. Reduction in volume or an increase in unit weight of a sand or a soil can be accomplished by a more compact alignment of the grains or of the structural units, or by the development of forces great enough to shatter grains or cause plastic deformation (6) to some structural units. An increase in bulk density of any object can be explained by the following expression:

$$D = (P, M, T)$$

D = Increase in bulk density

P = Applied pressure

M = Bulk Modulus

T = Time

The term "bulk modulus" includes many factors with respect to soils and is meaningless except for a particular soil in a specific situation. Soils with various physical properties and moisture contents can range from rigid, elastic solids through the plastic range to viscous fluids. Until such time when all factors which comprise bulk modulus are completely understood and the interrelation between these factors is established, this expression can be used to indicate which factors are involved.

An understanding of what pressure acting over a period of time is required to accomplish an increase in soil bulk density and how this pressure must be increased to increase the bulk density therefore depends on knowledge of: 1. the strength of the individual structural units, 2. the pressure pattern, 3. distribution of pressure to the contact points of structural units, and 4. the resistance to movement developed between the moving particles. The strength of the structural unit is related to soil-moisture content (10), size, shape, bulk density, clay type, clay content, and clay arrangement or cementation within or around structural units. These factors are difficult to evaluate and, since structural units that make up "normal" soils are not similar, the required information becomes more difficult to acquire. Individual contact pressures are also difficult to determine (28) and are continually being altered with deformation (6).

Friction is reduced by increases in soil-moisture content but it also depends upon pressure and increased contact area caused by deformation of structural units with pressure. Increases in moisture content can also alter the cohesive and adhesive forces of soil particles. Van den Berg (28) has stated that "with respect to plant growth, the magnitude of deformations is more important than the magnitude of forces which cause the deformation." What are the characteristics of soil deformation which make it so important to plant growth? It is generally assumed that root development of a healthy plant is regulated predominantly by nutrient, moisture, and oxygen availability. Unpublished studies by the author, using sugarcane, substantiate the conclusions of Hendrickson and Veihmeyer (11, 30) that roots will not develop in soil which is at a moisture content below the permanent wilting percentage. Rate of oxygen movement through soil to the roots is important to plant growth (3) and roots will not develop into an oxygen-deficient soil atmosphere. These unpublished studies do not confirm the supposition that plant nutrients must be available to each root: as long as other roots of the same stalk of sugarcane are adequately supplied with all of the required nutrients, a root can proliferate in a moist, oxygenated soil in an apparently normal manner. Naturally, adequate pore space must be present or made available so that roots may proliferate. Also, toxic concentrations of substances must be absent so that the roots can survive and develop. Deformation, because of increased unit weight or puddling, can reduce the moisture and oxygen permeability rates, but increased unit weight alone is not the cause of reduction in either moisture or oxygen permeability. It is believed that pore size and pore geometry are more directly related to inflow of oxygen and moisture as well as to outflow of carbon dioxide from the immediate surroundings of the root.

In a non-rigid system, the relationship of the size of the pores to the diameter of the roots is not as important as reported for artificial rigid pore systems (33). Roots have the ability to compress the soil adjacent to the channels created as they force their way through a soil (1). How great a pressure a root is capable of generating has been the object of much speculation. It has been generally conceded that a soil may be compressed until roots are incapable of physical entry, but this has not been proven. Since it has been demonstrated that the pressure developed by a root is related to the oxygen content (9), the importance of oxygen and moisture relationships to physical impedance are now a subject of greater speculation.

The present research was conducted to investigate some of the factors involved with some subtropical soils following an increase in unit weight and how various increases affect the roots of an important subtropical crop. Although bulk density is a common measure of soil deformation and is often correlated with yield suppression, it is doubtful that bulk density is solely responsible for the detriment to agricultural crops as is generally believed. Its basic importance has been investigated and discussed herein: use of other criteria is presented also in order to express the effects of soil deformation, both to the soil media and to the roots attempting to develop in the soil media.

2. ACKNOWLEDGMENTS

The author wishes to express his gratitude to the Hawaiian sugar industry for its generosity in supplying most of the soils used, for the equipment, laboratory and greenhouse facilities, and for the financial assistance in conducting these studies. From the Experiment Station, Hawaiian Sugar Planters' Association, the able assistance of Mr. George Yamamoto and his staff, the statistical assistance of Mr. George Darroch and his staff, and the radio rubidium assistance of Mr. Tyrus Tanimoto are most gratefully acknowledged.

MATERIALS AND METHODS

The effects of increased soil bulk density of some subtropical soils were examined from several approaches. Although field experiences guided the study, most of the results reported are from carefully controlled laboratory studies. From a practical aspect, important correlations of physical properties of the soil must be made with plant growth. These correlations were made with growing plants under greenhouse conditions. Since basic agronomic effects of soil bulk density are upon roots developing in the soil, it is the roots of plants that received the initial attention.

1. ROOT STUDIES: A technique was developed whereby roots growing in soil compressed to various bulk densities could be observed. Degradation of root development could then be determined for soil bulk density. Seven stages of root degradation could be recognized.

a. Stages of Root Degradation: In the primary investigation the effects of increasing the bulk density of subtropical soils on the root system of sugarcane were studied predominantly by low-power optical magnification and with the unaided eye. Observations were made on the roots grown in 1, 781 soil samples artifically compressed specifically for this phase of the study. A minimum of 21 samples was prepared at different bulk densities for each soil material tested and usually the material was collected from three locations in each soil delineation. When large delineations of one soil existed, multiple samples were collected from each island delineation. The root observations are reported mainly through descriptive ranking of the ability of roots and rootlets to proliferate and develop within compressed soils.

To assure adequate opportunity for root development and proliferation within the compressed soil, it was decided that a small pot containing a relatively large sample of compressed soil must be utilized. This pot must be of adequate size, however, that sufficient available nutrients and moisture could be supplied to the plant so that the plant would be healthy and the root development active. It soon became evident that the 20-cm. Mitscherlich pots would serve this purpose if the soils were fertilized with adequate phosphate for a crop and refertilized, at approximately monthly intervals, with other nutrients. The pots required two waterings per day and, on warmer days, were given three waterings.

The soils collected were from several representative sites for each series studied: care was exercised that each collected sample should contain material from only one horizon. A sample from each horizon weighed approximately 250 kg.; this sample was taken to the laboratory, dried, ground with a hammermill, and screened through a 2-mm. sieve, after which it underwent chemical and physical analyses. The required nutrients were added, then enough moisture was added to assure achieving the predetermined bulk densities desired with adequate moisture still available for plant root development. A series of cylinders of soil was manufactured from this moistened, fertilized soil and placed in the pots. Each soil cylinder was about half the volume of the Mitscherlich pot. Figure 1 illustrates the arrangement of a compressed cylinder of soil in a Mitscherlich pot prior to surrounding it with loose fertilized soil of the same type. A germinated one-eye seedpiece of sugarcane was planted over the compressed cylinder of soil. Seedpieces of multi-specie hybrids of sugarcane were used which had been selected for field production due to their adaptation to the ecological conditions in the area from which the soils were collected: the hybrids used had a wide range in ecological adaptability. They were Hawaiian varieties 37-1933, 38-2915, 44-3098, 49-5, and 50-7209.

The compressed cylinders of soil were 11.2 cm. in height and 10.7 cm. in diameter. The moist weight of the soil cylinder varied from approximately 1,200 to 2,400 gm., depending on the soil bulk density, the moisture content and particle density of the soil used. To achieve a fairly uniform bulk density, each cylinder of soil was compressed in three equal layers. The bulk density of the compressed cylinders of each soil material ranged from below that known to affect root proliferation to above that suspected of allowing root penetration. During the growing period the roots, confined in these small pots, were allowed every possible opportunity to develop and proliferate in the compressed soil cylinders. After one year, the cane was harvested and the root-bound soil was removed from the pots. Root-bound soil from each pot was sawed in half and then the compressed soil was broken out and carefully examined. Notes were made on the abundance of roots, their mode of proliferation, and the severity of

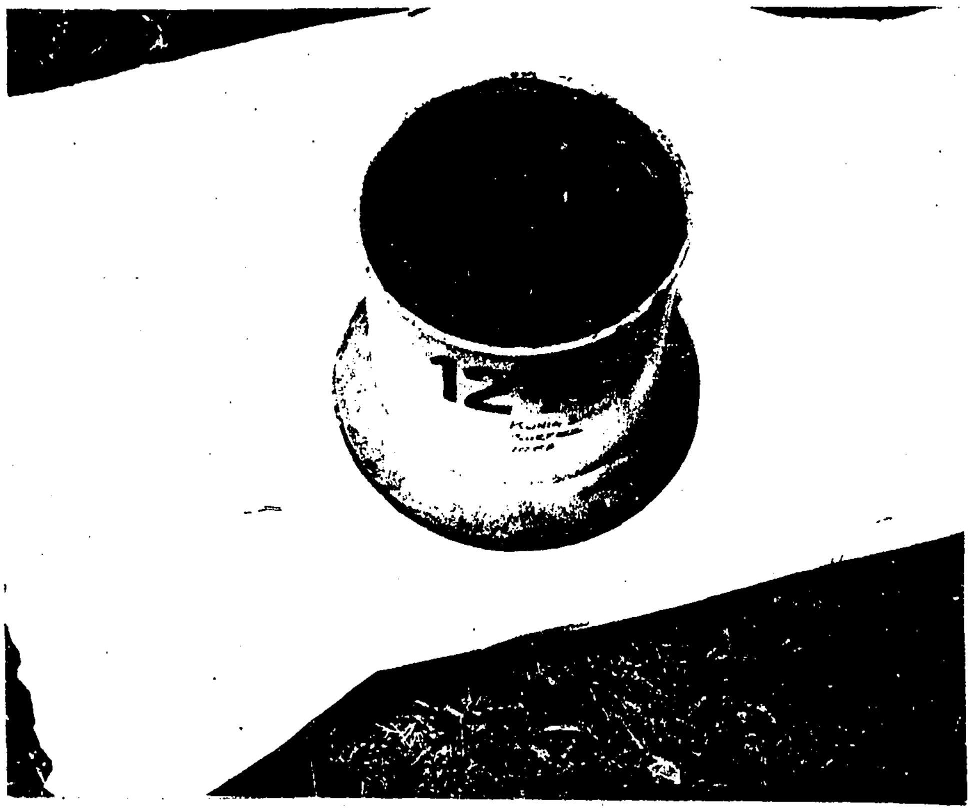


Figure 1. A Mitscherlich pot with a compressed soil cylinder in place. A layer of loose soil is on the bottom and a compressed soil cylinder has been placed on it prior to completely surrounding the cylinder with loose fertilized soil and planting the cane seedling.

distortion to the roots grown in each pot. Later, these data were arranged into seven groupings, or stages of root degradation, for each soil.

b. Root Weight and Volume Determinations: In order to supplement descriptive and photographic evidence of reduced proliferation of roots which developed in compressed soil, actual volume and weight determinations were made on a unit volume of representative soils from three soil Groups. Following harvest of the cane, lumps of compressed soil were removed from each pot and the volume of each lump was determined by the paraffin-immersion method. All roots and rootlets within each lump of compressed soil were carefully removed from the lump, washed, and then subjected to a volume determination by the water-pycnometer technique. Later, 60° C. oven-dried weight of the roots from each compressed lump of soil was determined. Seventy-three sets of such determinations were made to correlate the observation ratings with actual root weight and root volume data. Weights of roots in milligrams of root material per cubic centimeter of soil will be reported. To circumvent the possibility of distortion of such data by changes in the volume-weight of root material which develops in denser soils, the actual volume of space occupied by root material was determined as a percentage of the soil volume. A correlation of the volume relationship and the weight relationship of root material developed in a soil at different bulk densities could then be made as a crude means of investigation of suspected cellular changes within the root.

c. Cellular Examination of Root Tissue: Microscopy was employed to give a more direct examination of cellular construction of the root with changes in soil bulk density. After experimenting with quicker and easier techniques of preparing root tissue, it was decided that paraffin embedding had to be employed. Detailed techniques used in preparation of the slides were suggested by Johansen (13). The sections were microtoned 25 to 35 microns in thickness, mounted on glass slides, and stained prior to a careful microscopic examination. Four hundred slides were prepared, each with longitudinal and cross-sectional segments of a rootlet, a young root, and an older root. At least one slide was prepared of roots grown in each soil at each bulk density manufactured during the 1961 test period. Detailed notes and photographs were made of the cellular distortions to each root.

d. Estimates of Root Functioning Capabilities: From a practical aspect, the agriculturist is interestednot so much in the degree of distortion to the morphological or anatomical make-up of a root as he is in the effectiveness of the root to absorb nutrients and moisture. In order to investigate the functioning ability of sugarcane roots, as related to bulk density, 153 special cylinders of compressed soil were manufactured to bulk densities ranging from 1.12 to 1.56 gm/cc. The compressed soil cylinders were of the same external measurements as the soil cylinders used in the primary investigation, but contained a centrally located hole approximately 2 cm. in diameter; a 5 cc. solution of rubidium chloride containing approximately one millicurie of radioactivity was pipetted into the central hole. The hole was then plugged with a rubber stopper and sealed. Sugarcane was planted in the standard manner and, after three and one-half to four months of growth, the cane was harvested, chopped, dried at 60° C., weighed, and counts per gram per minute determined. The counts could then be expressed as total counts per plant to determine the effectiveness of root functioning in each bulk density tested.

e. Rate of Root Elongation: Although the rate of root elongation may be closely related to the pressure required by the root to penetrate through the soil, widely different techniques were employed to study each phase. The rate of elongation for sugarcane roots in relation to soil bulk density was estimated by a crude window-box technique. Each box was especially constructed so that the back could be removed, the sides could be braced, and a steel form could be inserted and braced to form a mold with the special glass of the window-box container as the bottom. The proper amount of moistened, fertilized soil was added so that a 20-ton press could compress a band of soil to the desired bulk density directly against the window: the forms could then be removed, soil poured in and gently firmed on either side of the compressed horizon to fill the container, and the back replaced. The window-box container could then be placed upright and a one-eye seedpiece of sugarcane planted. A light-tight wooden cover was placed over this vertical window except during periods of examination. Each root was marked on the observation window and daily measurements were made as the roots developed along the window in the compressed soil band so that mean rates of elongation in centimeters per day could be determined for each predetermined soil bulk density. Figure 2 shows the apparatus during determination of root elongation.

f. Physical Impedance: If a root is capable of developing a specific pressure and is impeded by a physical resistance in dense soils, then the soil bulk density which impedes a root should be related to the ability of the soil to resist the pressure exerted by a root. Since the moisture content of a soil has a very effective influence on the ability of a soil to resist pressure, then root penetration would be related directly with the soil-moisture content. In order to establish whether or not the lack of roots in dense soil is involved with the pressure a root is capable of developing and with the resistance to penetration presented by the soil, the following investigation was carried out.

Two hundred and sixteen standard compressed soil cylinders were manufactured at the approximate bulk density determined to inhibit root penetration. Each representative soil was compressed to its specific threshold bulk density at a wide range of moisture contents. When possible, the compressed cylinders of soil were manufactured at soil-moisture contents which varied, by 5 percent increments, from 15 to 40 percent soil moisture. Frequently, the predetermined bulk density could not be obtained at the extreme moisture contents. Cane was planted in the standard manner and grown for one year. Root proliferation and development were then examined and described in the standard manner.

2. SOIL STUDIES: The mechanisms which affected the root system

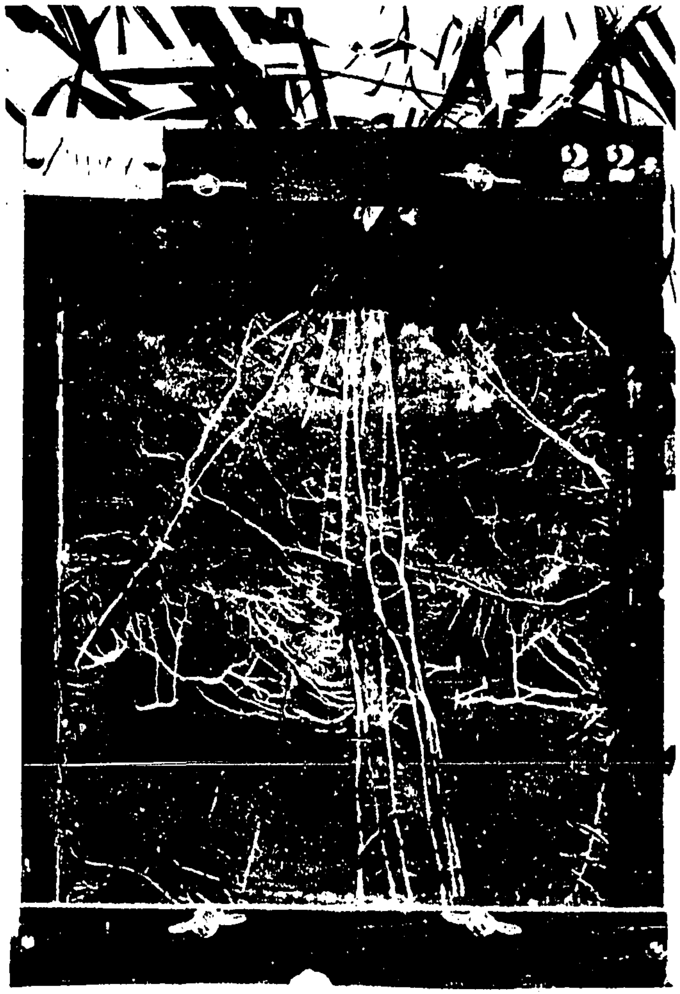


Figure 2. Window-box used to determine root elongation rates in compressed soil. A Kunia silty clay subsoil with the compressed soil band at a bulk density of 1.28 gm/cc.

of sugarcane became apparent with an increase in bulk density of a soil. In order to investigate the mechanisms involved with root development that are related to compression of soil, one may examine the physical properties of the compressed soil. Although van Bavel et al. (27) have defined the measurement and terms used in such research, throughout this report the following procedures and terms were employed.

a. Particle Density: The real, or particle, density of soil is basic and must be determined in order to calculate a predetermined bulk density, porosity or zero void situation. Particle densities were determined for all of the soils used by the water-pycnometer technique. Fifteen determinations, using twelve 50-ml. pycnometers and three 100-ml. thermometer-pycnometer bottles, distilled water, and vacuum pumping, gave a mean value which represents each soil. One thermometer-pycnometer was included with each set of four 50-ml. pycnometers to allow for temperature corrections. Each of the three sets of five pycnometer determinations was made on a different day.

b. Moisture Retention: Another basic aspect of the soil is its capacity to retain moisture. A complete moisture-retention curve was developed for each soil investigated from samples of soil which had been screened through a 2-mm. sieve. The soils were saturated overnight and were under treatment until an equilibrium condition was attained at "tensions" of 1/3, 2/3, 1, 2, 4, 8, and 15 atm. in a pressure-membrane apparatus. The soil-moisture content retained at equilibrium was calculated from the standard oven-dry weight of the soil and from the water loss. These data assure that the compressed soil cylinders contain moisture available for root proliferation.

To determine moisture retention in the range of the macro-pore, a tension table was employed. The soils were prepared in the manner described above and were under treatment for 24 hours before the moisture content was determined.

b. Standard Compaction: Soil moisture must also be considered from the compression standpoint in order to ascertain that: 1. the desired soil bulk density can be obtained with the force available, and 2. plastic flow under pressure will not occur due to excessive moisture. In order to determine the moisture content at which to compress the soils, the information from standard compaction curves and the moisture-retention curves were consulted. The former curves were prepared from data obtained for each soil using the standard Proctor mold and compacting sequence (18) but using a modified 254-gm. hammer dropped 45 cm.

d. Bulk Density: The volume weight, or bulk density, for soils was determined in three manners within this study. In each case, the bulk density is an expression of the oven-dry weight (in grams) of the soil after treatment for 72 hours in an oven set to operate between 105° and 110° C. The volume is determined for the moist, or actual, field condition of the soil and expressed in terms of cubic centimeters.

1. The bulk density of each compressed soil cylinder was determined from the calculated volume of the mold and the measured moist weight of the soil cylinder corrected to the dry weight by application of a moisture correction.

2. Periodically, checks were made by a paraffin-immersion

determination of the volume and an actual oven-dry weight measurement: sample portions from compressed soil cylinders affirmed relative uniformity of bulk density throughout the test cylinders by this method.

The paraffin-immersion technique was used also for volume determinations of all odd shaped field and laboratory samples.

3. Field data were usually determined by use of the Cornelison hammer-driven soil sampler: rings of known volume containing 150 cc. of undisturbed soil, 4.45 cm. high, were collected in the field and then taken to the laboratory for field and oven-dried weight determinations.

e. Porosity: Total porosity and aeration porosity values were calculated for each soil bulk density at the moisture content at which each compressed soil cylinder was manufactured. Total porosity was calculated from the simple relationship:

$$\text{Total porosity} = \frac{\text{1-dry bulk density}}{\text{particle density}}$$

The particle density was determined by using pycnometer bottles and the dry bulk density was calculated for the compressed soil cylinders from calculated volume determinations and actual weight values to which moisture corrections had been applied. The aeration porosity was determined by subtraction of the moisture content, on a volume basis, from the total porosity value. It is an expression of the percent of the total space filled with air, expressed on a volume basis within the soil. As any particular soil is compressed, the percent filled with solid material will increase; the percent filled with water will increase until finally a two-phase system is obtained.

f. Water Permeability: As the percent of pore space decreases, size of the macro-pores usually decreases and it can be theorized that the soil then becomes less permeable. Field permeability was determined by use of water in a "falling head permeameter". A steel drum with the top and bottom removed usually served as a "container" for water: each barrel was approximately 45 cm. in diameter and had a modified "double ring" feature. An earthen dam ringed each barrel; this moat, surrounding the drum, was maintained with water after it was firmly established that the barrel did not leak (7). The measurements were taken on an hourly basis until a constant rate of water loss from the barrel was obtained. These crude field in-flow rate determinations are referred to as infiltration-permeabilities and are reported as a mean, usually of 20 replicates. Since the least permeable horizon within the profile determines the constant rate of flow, usually the surface infiltration is the limiting factor and sets the rate of flow in compressed fields, but subsurface horizons, in some cases, could be equally responsible. Care was exercised that a shallow bedrock should not be the determining factor which set the constant flow rate.

Since flow rates are dependent on the moisture content of the soil, all measurements were made after "saturation" was reached and the clays had swelled and reduced the size of the pores.

g. Air Permeability: Water addition causes a decrease in air pore percentages by: 1. a replacement of air space by water, and 2. a swelling of the clays which also causes a replacement of air space. To circumvent these factors, air permeability determinations can be made of conditions existing as the plant roots find them in compressed soil. Air permeability was calculated from the reduction in air pressure with time, due to air loss through a ring of known area (35 sq. cm.) containing the soil sample (14). The flow rate was held essentially constant by maintaining a head loss of several centimeters on a water manometer. A large-volume system of 225 liters was employed so that the time of testing would approach one hour for most samples. The soil, water, and air volume contents of each sample were determined and associated with each air permeability rate. Figure 3 shows the apparatus used for air permeability measurements. Air permeability was calculated in terms of cubic centimeters per hour per square centimeter of soil sample surface area.

h. Soil Structure: Changes in arrangement of structural units within a soil and contact between structural units were optically investigated with increases in soil bulk density. A few thin-section, plastic impregnated soil slides were prepared and ground down to a thickness of about 25 microns: these slides were prepared from oven-dried lumps of compressed soil. Slides at low-power magnification offer good observation of pore space relationships between structural units; at high-power magnification the pore space within structural units can be observed to good advantage.

Low-power magnification of fresh surfaces of compressed soil was used to describe and photograph the plastic deformation of the structural units with increasing soil bulk density. These observations were not subjected to distortion by prior oven drying. Photomicrographs are

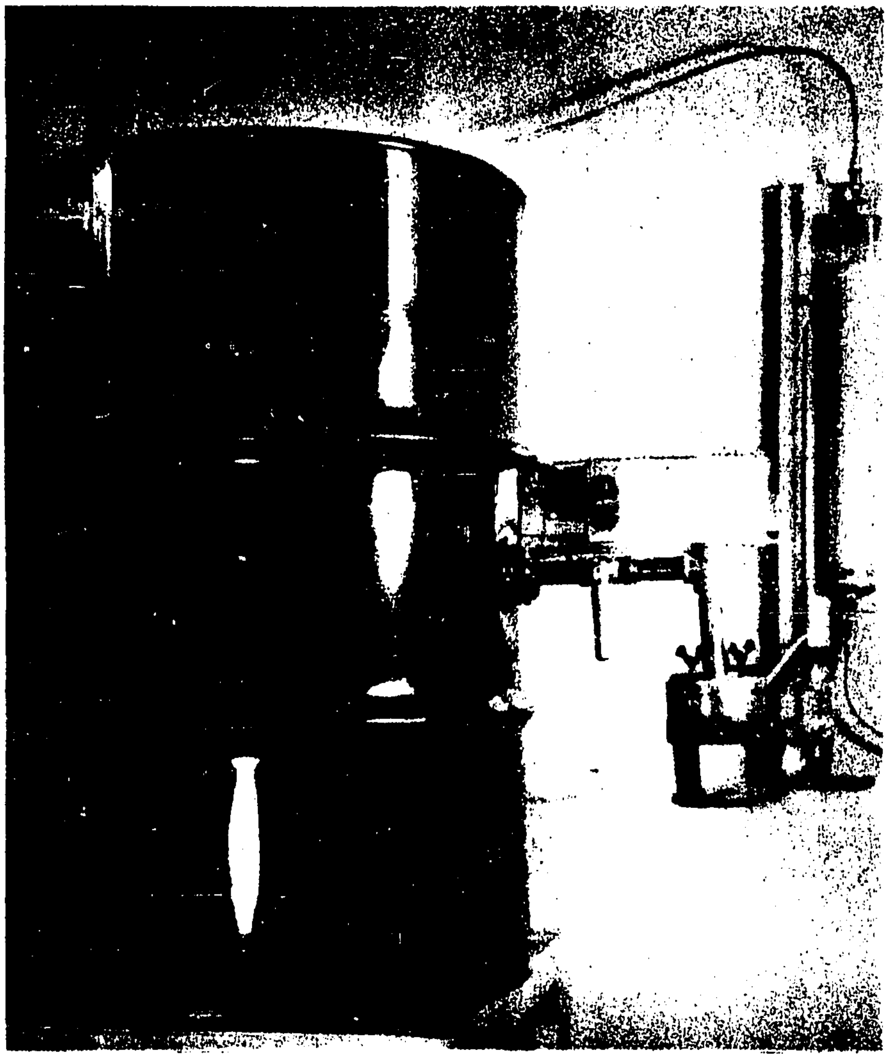


Figure 3. The apparatus used to measure air permeability.

presented of two soils compressed through a range of bulk densities. The photomicrographs were prepared from samples taken from compressed soil cylinders used in the primary investigation after harvest.

RESULTS AND DISCUSSION

The primary objective of this study is to delineate some of the effects of increased bulk density upon soil properties and upon the root system of agricultural crops grown in compressed soil. Comparison of yields of the aerial portion of plants has been a common method of assessing the effects of increased soil bulk density. All too frequently, however, other factors influenced by an increase in soil bulk density are more effective than the increase, per se, in affecting crop yields. The use of plant roots to ascertain the effect of soil bulk density is more direct, but previous applications of this technique have been restricted to determination of the "critical" or the "threshold" bulk density (31, 32, 35) which prevented root proliferation. The correlation of stages of root degradation to soil bulk density is not believed to have been investigated previously. A simple method has been devised to produce the conditions under which roots can develop in soils at various bulk densities which can then be described and photographed. This method is described in the "MATERIALS AND METHODS" section on page 10. A correlation of changes in certain physical properties of compressed soil can also be made with particular stages of root degradation.

Throughout most of this study, the roots of the sugarcane plant are used to assess the gradual destruction of the physical condition of a soil. The roots of sugarcane proved to be a much better indicator of effects of increased soil bulk density than the aerial portion of the plant. Under the cultural system utilized in this study, the total yield of the aerial portion of the plant gave absolutely no indication as to whether roots were, or were not, able to proliferate in the compressed portion of the pot. Figures 4, 5, 6, and 7 show that aerial growth can be maintained by roots in the half of the small Mitscherlich pot in which the root system could function when the pots were fertilized lightly and frequently and irrigated twice daily. Every effort was made to keep all of the plants healthy throughout this entire study. The effects of increased soil bulk density on roots should be confined, either directly or indirectly, to soil bulk density and not include factors which cause a weakened condition of the roots due to other factors. As recognized by Wiersum (33), it is difficult to separate physical impedance, poor aeration, and excessive moisture when studying roots and soil bulk density. All efforts were made, however, to eliminate any other limiting factors from affecting the results of this study.

1. STUDY WITH ROOTS:

a. General: Since the studies have been conducted using subtropical soils, the roots of a dominant agricultural crop grown in these soils were selected as an indicator. Not only were roots of several of the commercial sugarcane varieties utilized, but the roots of the smooth cayene pineapple, *Anans comosus*, and Sudan grass, *Sorghum sudanénse*, were occasionally investigated. Although these roots are different in appearance, the distortions recorded for sugarcane could describe those found on the roots of these other plants.

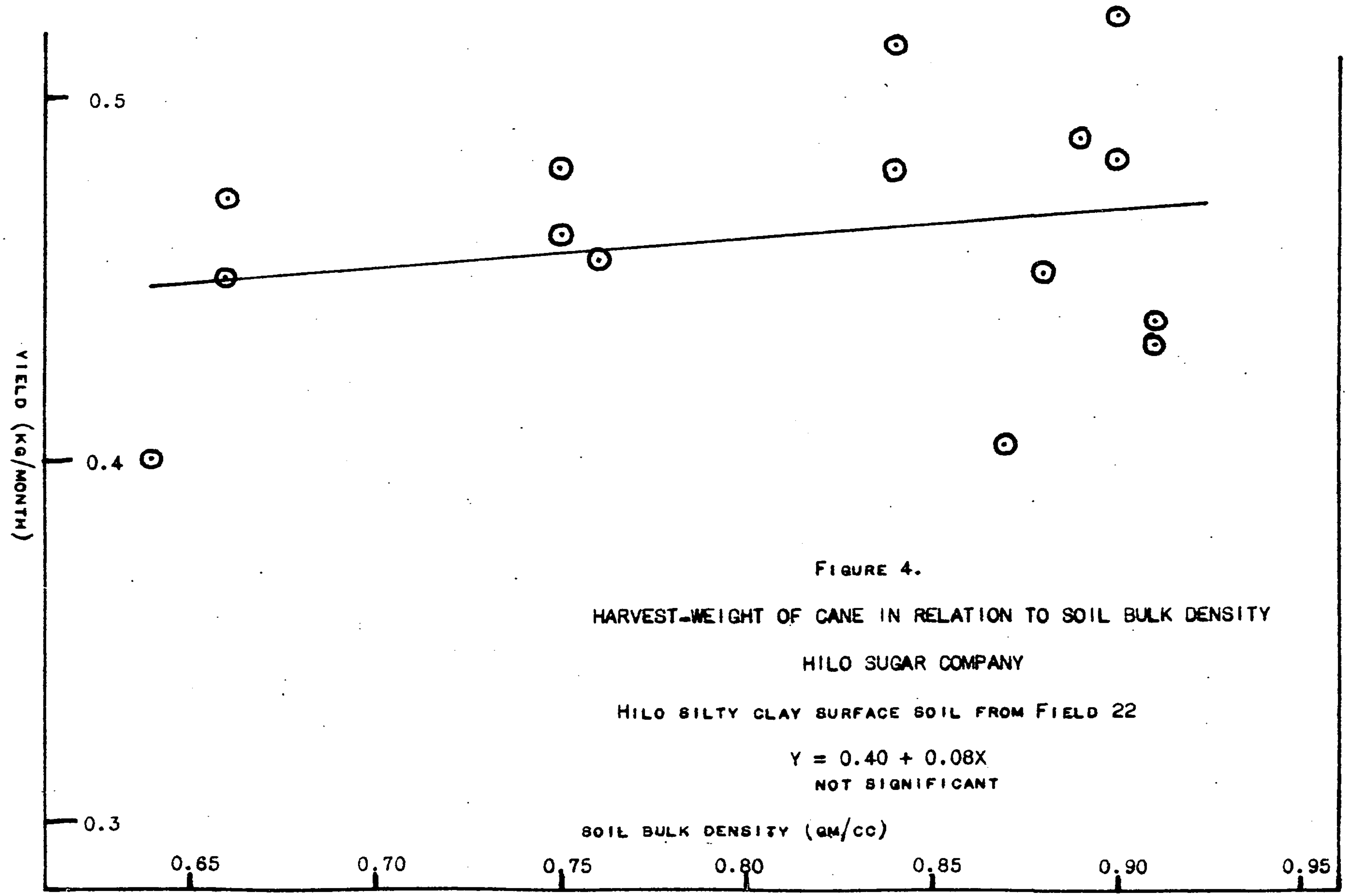


FIGURE 4.

HARVEST-WEIGHT OF CANE IN RELATION TO SOIL BULK DENSITY

HILO SUGAR COMPANY

HILO SILTY CLAY SURFACE SOIL FROM FIELD 22

$Y = 0.40 + 0.08X$

NOT SIGNIFICANT

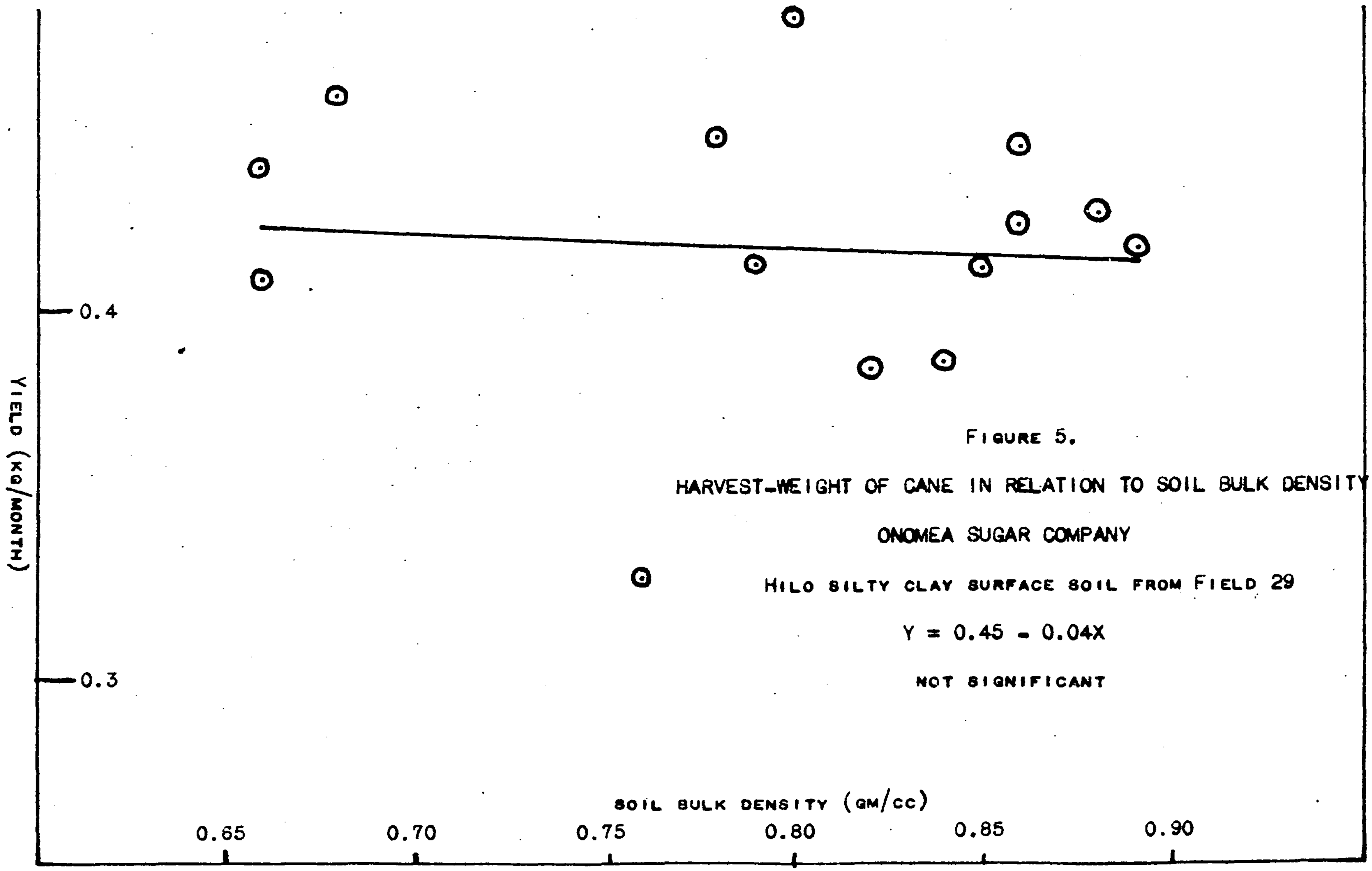


FIGURE 5.

HARVEST-WEIGHT OF CANE IN RELATION TO SOIL BULK DENSITY

ONOMEA SUGAR COMPANY

HILO SILTY CLAY SURFACE SOIL FROM FIELD 29

$Y = 0.45 - 0.04X$

NOT SIGNIFICANT

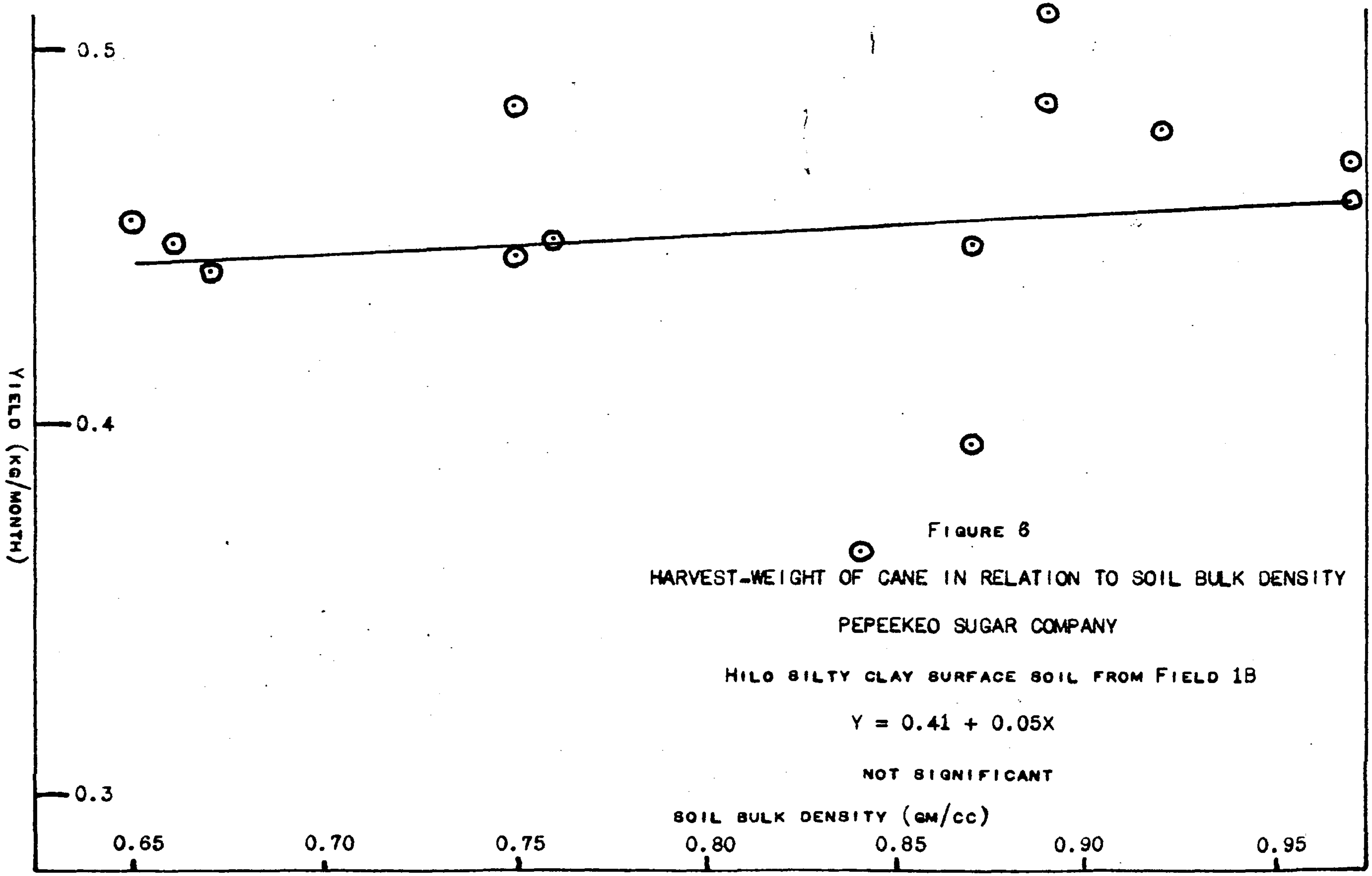


FIGURE 6

HARVEST-WEIGHT OF CANE IN RELATION TO SOIL BULK DENSITY

PEPEEKEO SUGAR COMPANY

HILO SILTY CLAY SURFACE SOIL FROM FIELD 1B

$Y = 0.41 + 0.05X$

NOT SIGNIFICANT

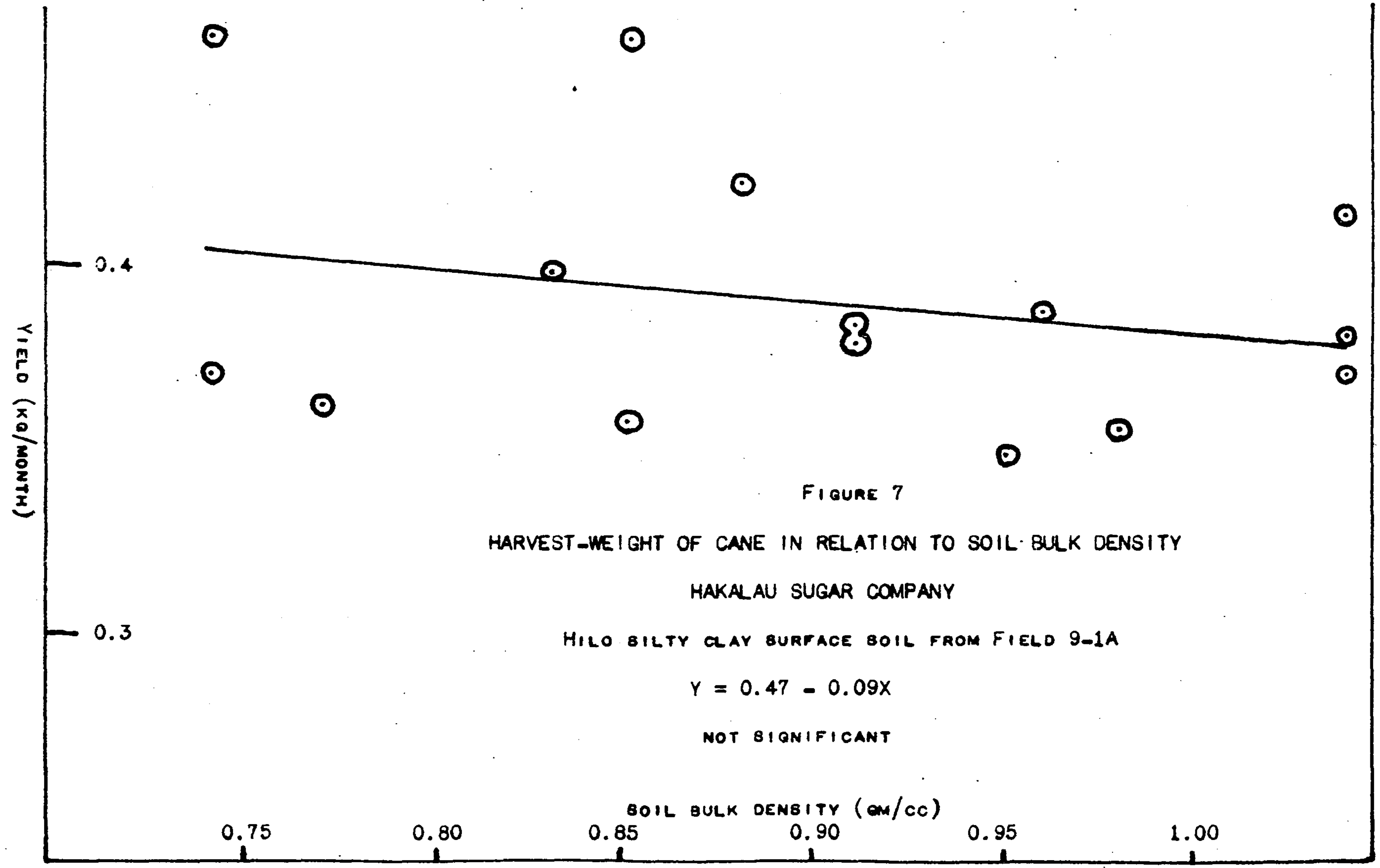


FIGURE 7

HARVEST-WEIGHT OF CANE IN RELATION TO SOIL BULK DENSITY

HAKALAU SUGAR COMPANY

HILO SILTY CLAY SURFACE SOIL FROM FIELD 9-1A

$Y = 0.47 - 0.09X$

NOT SIGNIFICANT

Several leguminous plants were used in earlier studies on soils compressed to the "threshold bulk density" as determined by sugarcane roots. Although this group of plants included sweet clover, Melilotus sp., none of the roots appeared capable of proliferating in the cylinders of compressed soil which were at a critical bulk density for sugarcane. These observations appear contrary to the opinions of many agriculturists although Taylor and Gardner (24) confirmed results of this study when they determined that the root-penetrating ability of legumes was not greater than nonlegumes in proliferating into waxes of various resistances.

Sugarcane produces a fibrous root system which, under normal conditions, can maintain a mean elongation rate of 5 cm/day. Elongation stops or slows down during periods of heavy lateral branching, while, at other times, elongation rates of 13 cm/day have been measured. Under unhampered conditions, sugarcane roots can proliferate and develop to depths in excess of 4 meters in four months. In this particular phase of this study we are interested in the morphology of the roots and rootlets and not in the extent of the root system. From all appearances, roots go from an "ideal" stage to the total inability-to-penetrate stage in an uninterrupted, gradual process. For ease of correlations and comparisons, root distortions were arranged into seven groups. It is not intended to infer that there are seven separate stages in this process.

b. Stages of Root Degradation:

(1) Stage A - Ideal Roots: Figure 8 represents ideal root proliferation while Figure 9 is a drawing to aid the untrained eye in

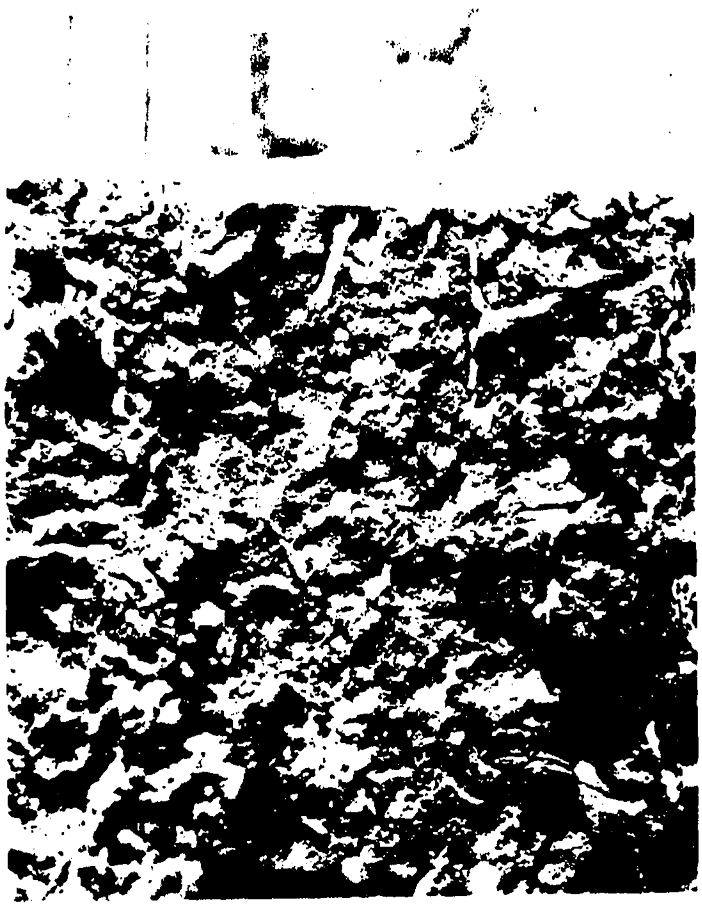


Figure 8. Ideal root proliferation: Stage A root degradation. Root development in a Lahaina silty clay surface soil. The scale is in millimeters.

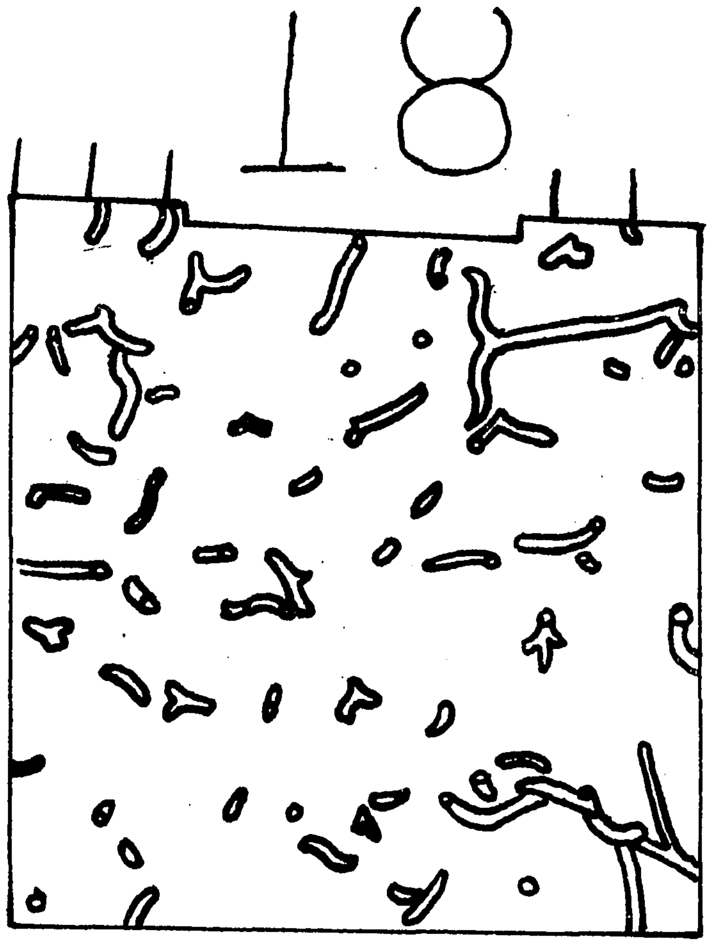


Figure 9. Drawing of root proliferation evident in Figure 8.

determining root proliferation in Figure 8. During the examination of root proliferation in the compressed soil cylinders, comparisons could be made with the roots in the loose soil surrounding the compressed cylinders. These comparisons are particularly helpful in separating Stage A from Stage B root degradation. The large primary roots are cylindrical and spiral through the soil in a relatively tight spiral. Rootlets and secondary branch roots have a smooth curving, or spiral, appearance and they also have the circular cross section of the large primary root. Figure 10 shows "ideal" stage roots washed free of most of the surrounding soil. Branching is evident in all planes and, usually, the spacing between rootlets on a finer root is approximately 1.5 mm. The associated physical constants in Table I (page 50) and Table III (page 61) are presented for the last values at which root growth appears in the "ideal" stage.

(2) Stage B - Reduced Proliferation: The first evidence of degradation to the root system is a slight reduction in root mass in a given volume of soil. Usually no other distortions are noted. The morphological development appears ideal, so Stage B includes the range of reduced root proliferation from Stage A until a slight bit of flattening of some portion of some rootlets is evident.

(3) Stage C - Good Distribution: The roots in Stage C are very similar to those found under better field conditions. The distribution and proliferation of roots and rootlets are good. Figure 11 shows root proliferation which, although reduced, is still considered quite good. Some of the rootlets exhibit a slight flattening and there

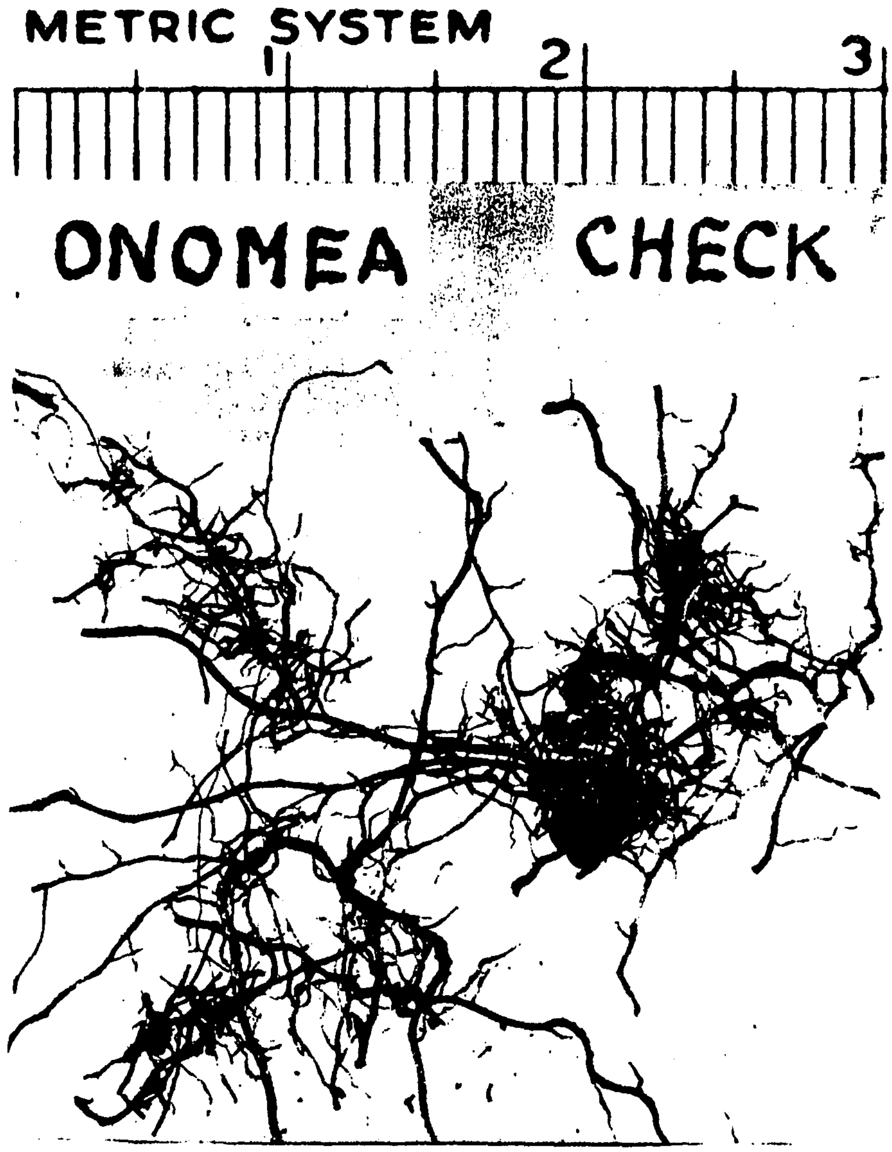


Figure 10. Roots and rootlets in Stage A root degradation. Scale is in tenths of centimeters.

Figure 11. Good root proliferation with slight rootlet flattening and some angularity in branching: Stage C root degradation. Rootlets can be seen confined in a larger root channel. Lahaina silty clay. Scale is in millimeters.

is a slight tendency for angularity instead of the normal curved nature exhibited by rootlets which developed under the "ideal situation". There is also a tendency for secondary roots to become confined within the channels created by the larger primary roots. Figure 12 shows Stage C roots washed free of excessive soil.

(4) Stage D - Fair Distribution: The roots in the range of Stage D are common in field situations and, under the present cultural system of farming, roots in this stage do not appear to seriously reduce crop yields. It is possible to perceive that, if the entire root mass were in this stage of degradation and, say, irrigation were withheld to near drought conditions, some loss in growth could result. Figure 13 represents root development and proliferation under Stage D conditions. Figure 14 is a drawing to aid the untrained eye in determining root proliferation in Figure 13. In Stage D, flattening of rootlets becomes more common and the degree of flattening is more severe. Width to thickness of roots and rootlets is commonly in the ratio of 1.50:1.00. The roots tend to lose more of their curved characteristics and adopt a more angular appearance. There is also a tendency for rootlets and branch roots to develop in planes of weakness or fracture zones. Figure 15 shows Stage D roots washed free of excessive soil.

(5) Stage E - Poor Distribution: Root proliferation in Stage E root degradation is inadequate. It is in this stage that more roots and rootlets become confined to fracture planes and that the proliferation of roots between the planes is thereby seriously

Figure 12. Roots and rootlets in Stage C root degradation. Scale is in tenths of centimeters.

Figure 13. Fair root proliferation. The flattening is more common and more severe: Stage D root degradation. Mokuleia silty clay loam. Scale is in millimeters.

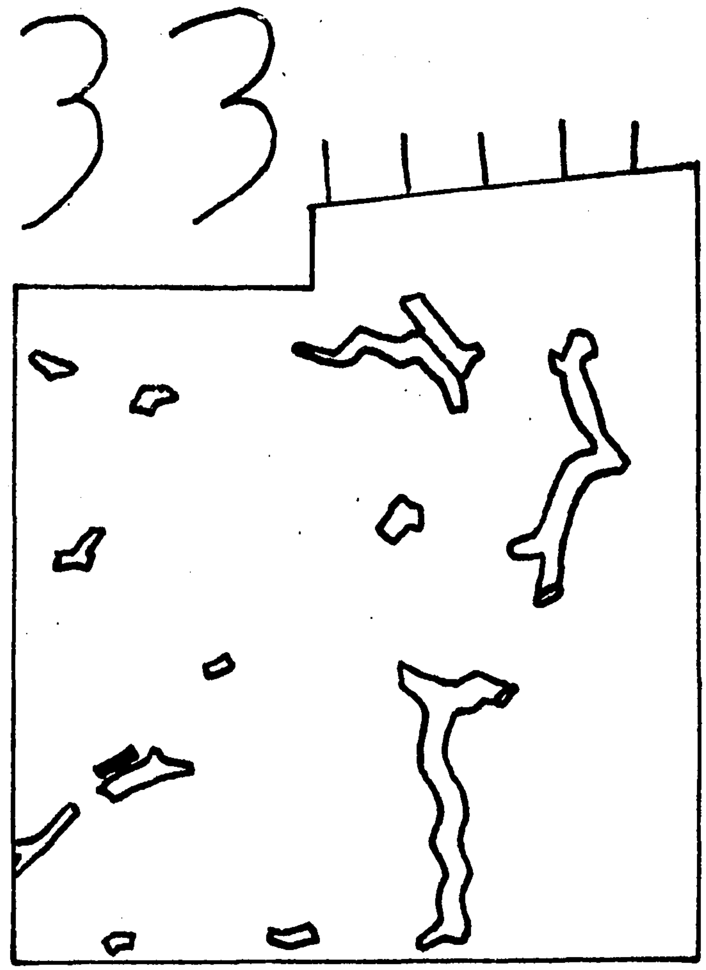


Figure 14. Drawing of root proliferation evident in Figure 13.

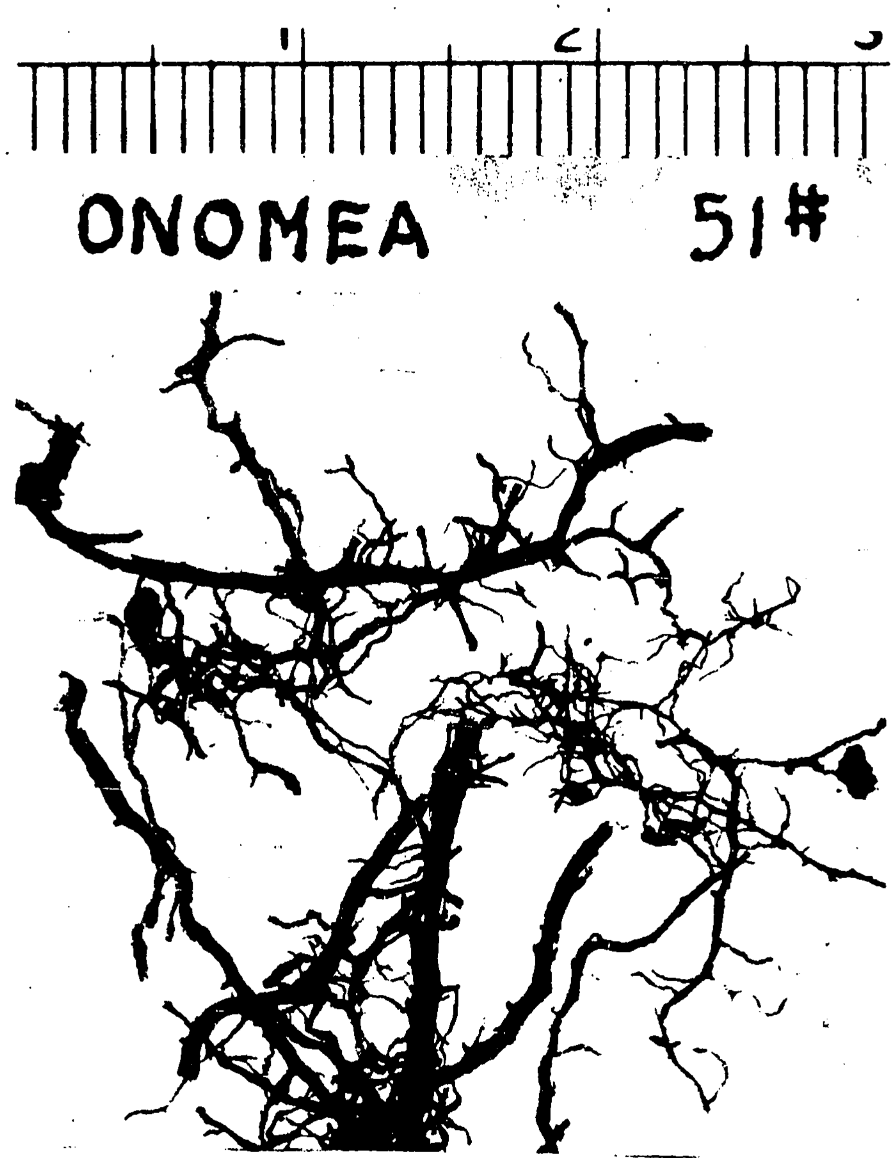


Figure 15. Roots and rootlets in Stage D root degradation. Scale is in tenths of centimeters.

reduced. Figure 16 is typical of root proliferation in Stage E root degradation. Flattening of roots and rootlets, especially in the fracture planes, is extended to all portions of all roots: all branching occurs with angularity and there is a strong tendency for rootlets and branch roots to develop in a single plane. The rootlet spacing appears closer, with rootlets on a finer root approximately 0. 75 mm. apart. Figure 17 shows the development of roots from a fracture plane which is typical of Stage E root degradation.

(6) Stage F - Very Few Roots: A few straggler roots or rootlets are capable of finding an environment within the more compressed soils which will allow penetration. Figure 18 illustrates root development in the better portion of the Stage F range from a field soil. Most of the roots are confined to fracture planes; they are flattened to the extent that the width to thickness ratio is usually between 2:1 to 4:1. Although the roots appear to develop branches and rootlets in one plane. they initiate from normal locations within the stele, but are turned within the cortex and then confined to the fracture plane so that they appear to develop in only one plane: this is illustraged in Figure 19. The straggler roots which penetrate the soil, and are not within fractures, are few and are usually flattened only slightly (1.25:1).

(7) Stage G - No Roots: With additional compression, the few remaining zones in which a root could survive are closed off and no roots are capable of penetration. In Table I (page 50) and Table III (page 61) Stage G root degradation is initiated at the terminus of the Stage F range. Sometimes it was difficult to delineate the exact division between Stage F and Stage G. Establishing the precise division

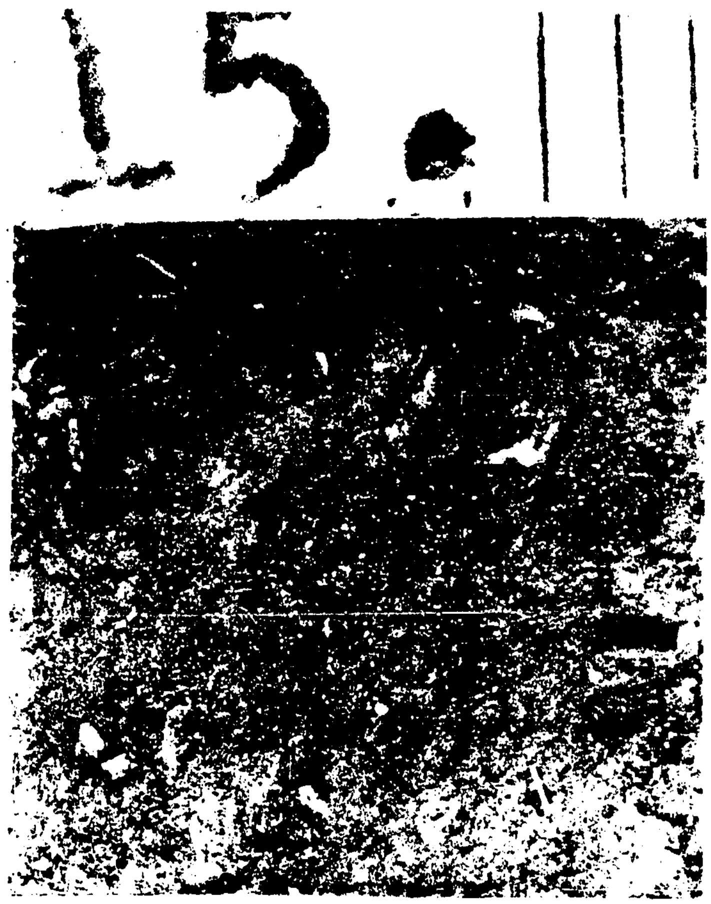


Figure 16. Poor root proliferation with many roots restricted to fracture planes: Stage E root degradation. Lahaina silty clay. Scale is in millimeters.

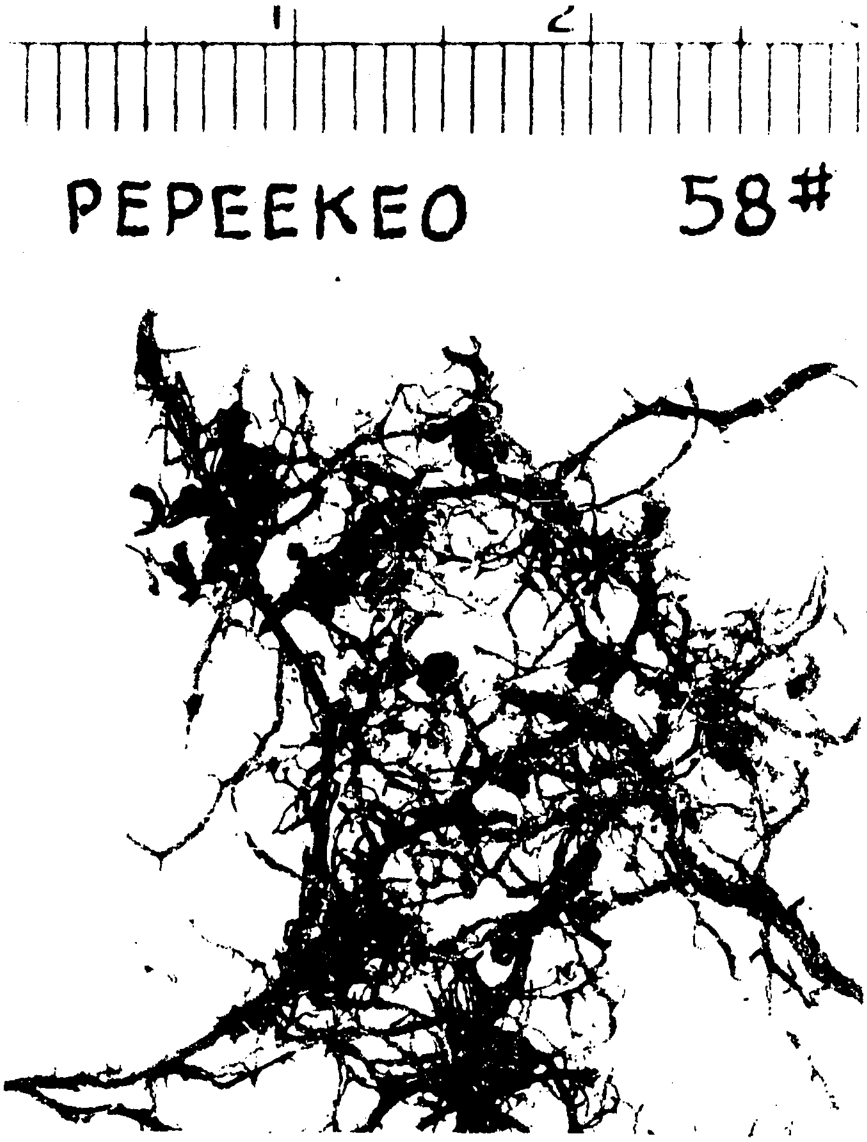


Figure 17. Roots and rootlets from a fracture in State E root degradation. Scale is in tenths of centimeters.

Figure 18. Very few roots proliferate the soil while most roots are confined to fracture planes. This photograph illustrates the better portion of the range of Stage F root degradation. Lahaina silty clay.

Figure 19. Branch rootlet developing from the stele but diverted within the cortex of a root.

has little practical importance, but locating a single straggler-root in compacted soil may appeal to the critic.

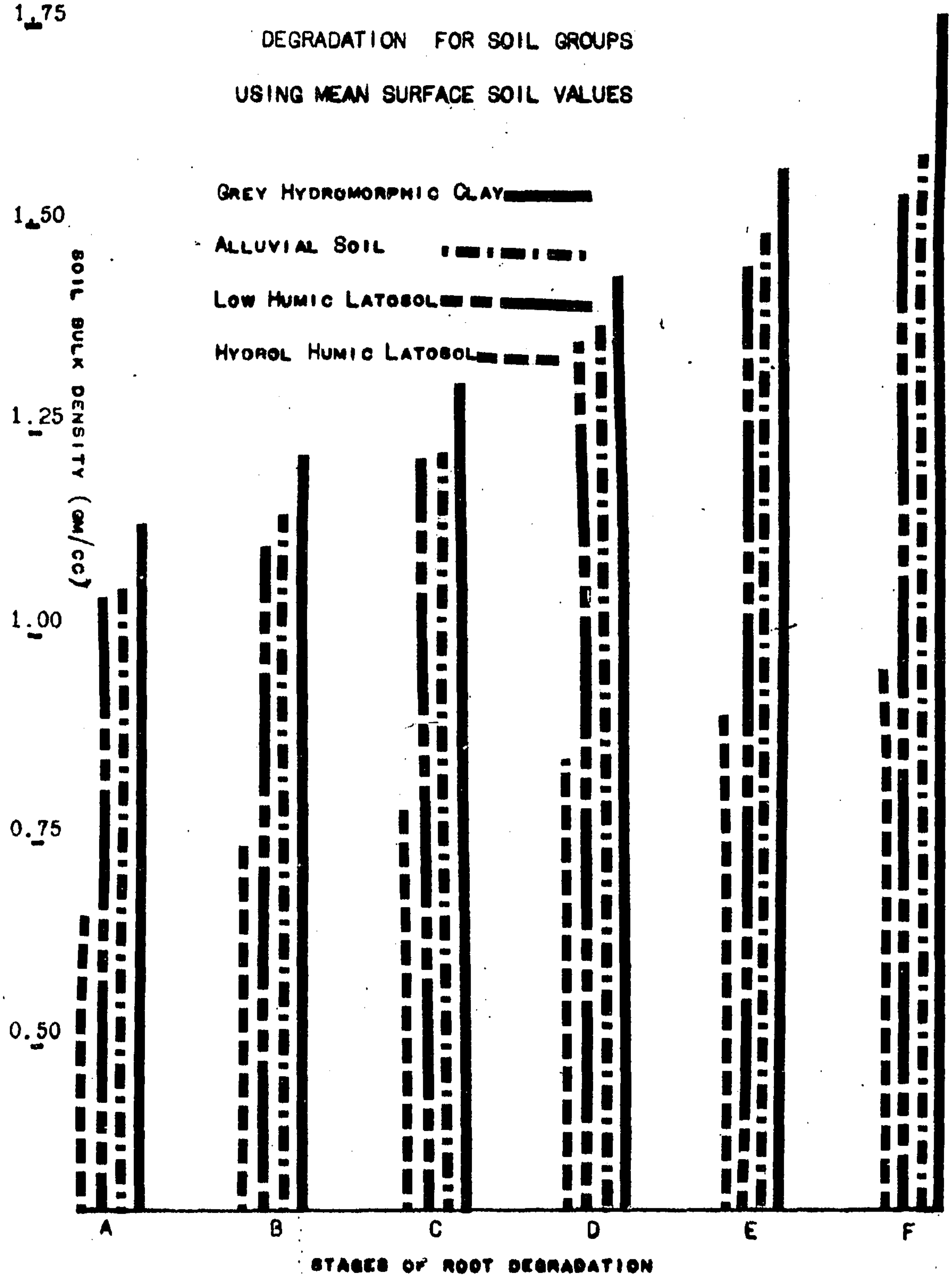
c. Relationship of Soil Bulk Density:

(1) With the Soil Groups: Figure 20 sums up the results by soil Groups. In this figure it can be seen that the Hydrol Humic Latosol surface soil (4) reaches each stage of root degradation at a much lower bulk density than do soils in the other Groups listed. A moisture content of about 100 percent is normal in the field for the surface soils of this Group. This high soil-moisture content indicates that a large percentage of the soil volume is composed of water. Although the soil bulk density value is low, many of the pores containing water seem to be effective in reducing root proliferation and increasing root distortions. The effects to the root system appear identical to those produced with the other soils at each stage of root degradation. Although material from subsurface horizons of the Hydrol Humic Latosol Group was not included in the primary investigation, field samples were found in which bulk densities as low as 0.40 gm/cc prevented root penetration (Stage G). Other stages could be identified at still lower bulk densities and, again, these appear identical to those produced in other soils at much higher densities. Subsurface horizons characteristically contain 200 to 400 percent moisture under field conditions and samples have been collected with over 600 percent moisture, calculated on a dry-weight basis.

At the other extreme, Figure 20 shows that the Grey Hydromorphic Clay (4) surface soils reach each stage of root degradation at higher

FIGURE 20

RELATIONSHIP OF SOIL BULK DENSITY TO ROOT DEGRADATION FOR SOIL GROUPS USING MEAN SURFACE SOIL VALUES



bulk density values than do soils in the other Groups listed. This situation exists even though particle densities are almost equal for the two extreme soil Groups. The mean particle density values, as determined by standard means, vary from 2.85 gm/cc, for the Hydrol Humic Latosols,[1] to 2.88 gm/cc for the Grey Hydromorphic Clays. An individual Hilo silty clay (a Hydrol Humic Latosol) with a particle density of 2.86 gm/cc and a Honouliuli clay (a Grey Hydromorphic Clay) with a particle density of 2.87 gm/cc can be selected which show the same relationship as does the mean determination for each Group. Thus, with almost identical particle densities, the Hilo silty clay has a bulk density which is 55 percent of the bulk density of the Honouliuli clay at the Stage G root degradation.

The mean values for the Low Humic Latosolic surface soil (4) (Figure 20) are intermediate, but much closer to those of the Grey Hydromorphic Clay. The bulk density values reported in Table I fall above the general alignment in Stage D and Stage E. Just why this happens is not definite: the general alignment of these points is not based on a direct association with bulk density. Later discussions on effects of compression to structural units, including alteration of macro-pores between structural units, may be more enlightening. It is believed that a relationship with the pores, and not with the bulk density, is more realistic. Although Taylor found that diffusion is related to bulk density, he concurs when he also found that the nature of the particle has a pronounced effect which invalidates bulk density measurements, per se, as criteria of air movement in the soil (25).

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[1]See Appendix

Table I

RELATIONSHIP OF SOIL BULK DENSITY OF HAWAIIAN SOILS TO SUGARCANE ROOT DEGRADATION

	STAGES OF ROOT DEGRADATION*					
	A	B	C	D	E	F
Soil Type	Soil Bulk Density (gm/cc)					
LOW HUMIC LATOSOLS						
MOLOKAI FAMILY						
Makaweli si. cl. surf.	1.01	1.06	1.17	1.35	1.47	1.55
Molokai si. cl. surf.	1.03	1.15	1.23	1.38	1.47	1.57
Mean (surf.)	1.03	1.11	1.20	1.36	1.47	1.57
Makaweli si. cl. sub.	1.04	1.20	1.28	1.38	1.44	
Molokai si. cl. sub.	1.01	1.12	1.23	1.41	1.47	
Mean (sub.)	1.03	1.17	1.27	1.39	1.46	
LAHAINA FAMILY						
Keahua si. cl. surf.	1.06	1.15	1.25	1.38	1.51	1.51
Lahaina si. cl. surf.	1.04	1.12	1.23	1.38	1.46	1.55
Paia si. cl. l. surf.	1.07	1.17	1.23	1.38	1.47	1.57
Waikapu si. cl. l. surf.	1.04	1.17	1.27	1.41	1.51	1.62
Mean (surf.)	1.06	1.15	1.25	1.39	1.49	1.51
WAHIAWA FAMILY						
Kunia si. cl. surf.	1.04	1.11	1.19	1.33	1.46	1.54
Wahiawa si. cl. surf.	1.03	1.07	1.20	1.31	1.39	1.52
Mean (surf.)	1.04	1.09	1.20	1.33	1.43	1.54
Kunia si. cl. sub.	1.04	1.14	1.20	1.30	1.39	1.52
Wahiawa si. cl. sub.	1.04	1.15	1.23	1.36	1.39	1.47
Mean (sub.)	1.04	1.15	1.22	1.33	1.39	1.51
KAHANA FAMILY						
Haliimaili si. cl. surf.	1.09	1.14	1.22	1.41	1.47	1.55
Kahana si. cl. Kilauea-type (surf.)	1.04	1.12	1.20	1.30	1.36	1.46
Kahana si. cl. Pioneer-type (surf.)	1.09	1.15	1.25	1.41	1.49	1.55
Koloa si. cl. surf.	1.06	1.12	1.22	1.35	1.44	1.57
Lihue si. cl. surf.	1.07	1.15	1.28	1.36	1.46	1.54
Mean (surf.)	1.07	1.14	1.23	1.36	1.44	1.54
Haliimaili si. cl. sub.	1.09	1.19	1.31	1.36	1.43	1.52
Kahana si. cl. Kilauea-type (sub.)	1.11	1.19	1.25	1.33	1.36	1.47
Kahana si. cl. Pioneer-type (sub.)	1.07	1.22	1.31	1.41	1.46	1.52
Koloa si. cl. sub.	1.06	1.15	1.22	1.31	1.43	1.54
Lihue si. cl. sub.	1.07	1.12	1.22	1.35	1.44	1.52
Mean (sub.)	1.07	1.17	1.27	1.35	1.43	1.52

Table I (Continued)

Soil Type	STAGES OF ROOT DEGRADATION* A	B	C	D	E	F
	Soil Bulk Density (gm/cc)					
GREY HYDROMORPHIC CLAYS						
Honouliuli cl. surf.	1.14	1.22	1.31	1.44	1.55	1.76
Honouliuli cl. sub.	1.04	1.11	1.22	1.28	1.57	1.76
HYDROL HUMIC LATOSOL						
Hilo si. cl. surf.	0.66	0.74	0.79	0.85	0.91	0.96
ALLUVIAL SOILS						
Mokuleia si. cl. l. surf.	1.06	1.15	1.25	1.38	1.52	1.62
Pulehu cl. l. surf.	1.04	1.14	1.22	1.36	1.44	1.55
Mean (surf.)	1.06	1.15	1.23	1.38	1.49	1.59

*STAGES OF ROOT DEGRADATION

A. Roots and rootlets appear normal.

B. Proliferation is reduced slightly, but no distortions are noted to root or rootlet behavior.

C. Root proliferation is definitely reduced, but still good. Some rootlets show a slight flattening (1.25 width:1.00 height) and a tendency toward angular development.

D. Root proliferation is only fair. Most rootlets and some roots are flattened (1.50:1.00) and there is a tendency for rootlets to develop along zones of weakness or fractures within the soil.

E. Root proliferation is poor: unsuited for agricultural production. Badly flattened rootlets form weak mats in fractures.

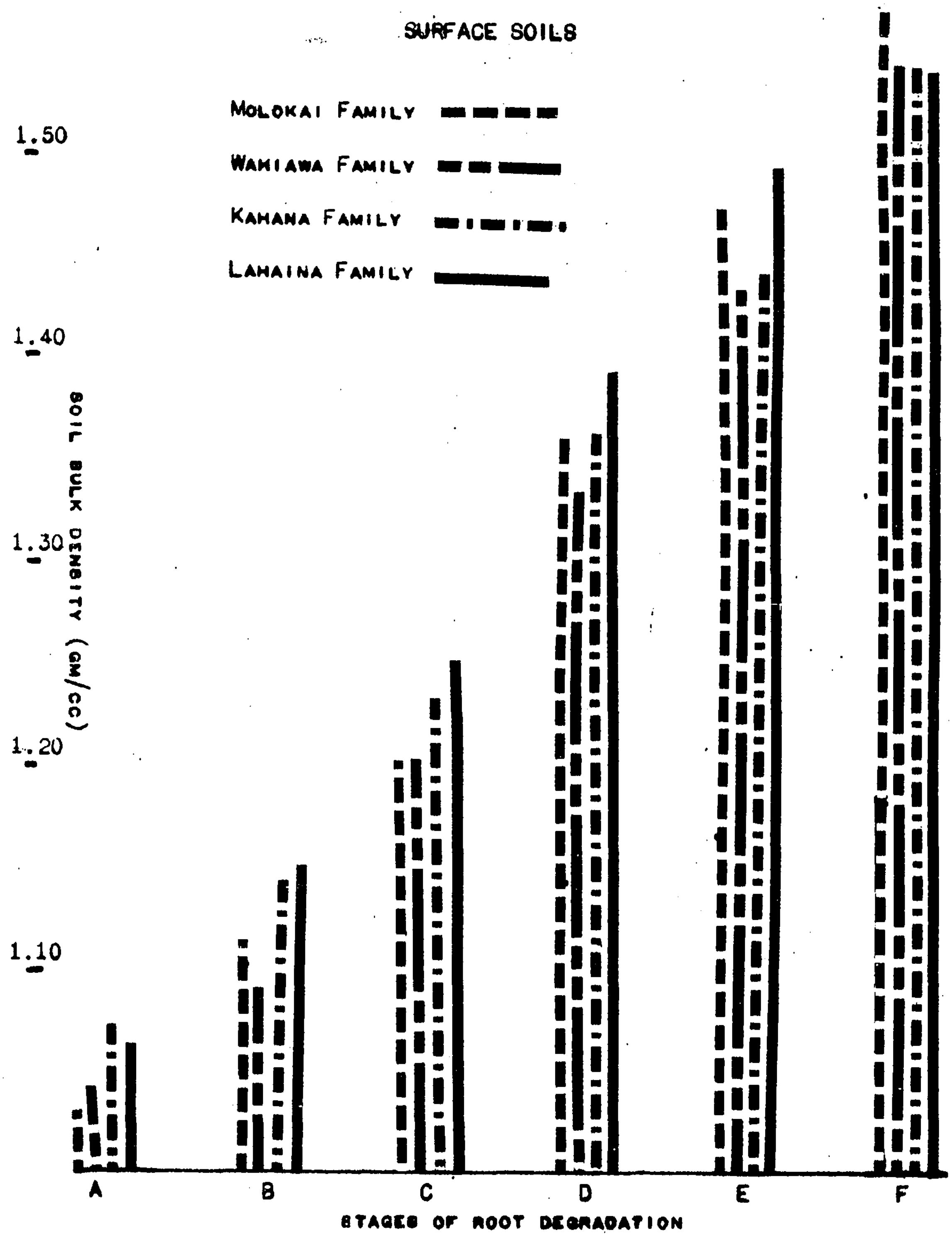
F. Few roots or rootlets are able to penetrate unfractured soil. Roots are badly flattened (2:1) and essentially confined to fractures.

The recent Alluvial Soils (4) of the Kawaihapai Family are formed from deposition of material eroded from upstream soils transported by small intermittent streams. Since the Kawaihapai soils are formed in the Low Humic Latosolic belt, it can be suspected that they would be composed predominantly of material from the higher rainfall types of Low Humic Latosols. Therefore, it might be assumed that the Alluvial Soils, which are the members of the Kawaihapai Family, reported in Table I, would resemble the surface soil material reported for the Low Humic Latosols. Figure 20 shows that the Alluvial Soil curve closely follows that of the Low Humic Latosol: even the bulk density values at Stage D and Stage E fall above the general alignment curve. A possible explanation for the slightly higher bulk density value at each stage of root degradation may be due to the higher particle density of the Alluvial Soils: the higher particle density of Alluvial Soils might be attributed to inclusion of some surface material eroded from nearby Humic Ferruginous Latosols (4) which do have higher particle densities.

(2) Within the Low Humic Latosol Group: Figure 21 presents the relationship of bulk density for several families of the Low Humic Latosol Group to six stages of root degradation. In this figure the range of bulk densities for each family mean in any particular stage of root degradation is separate from the range in any other stage. The stages of root degradation delineate points on a continual and gradual deformation pattern: there is no reason to assume that the constant-space plotting of the stages of root degradation in Figures

FIGURE 21.

RELATIONSHIP OF SOIL BULK DENSITY TO ROOT DEGRADATION FOR LOW HUMIC LATOSOLIC SURFACE SOILS



20 and 21 exists. In fact, there is reason to believe that a sigmoid-type curve is more realistic; that Stage B should be plotted closer to Stage A; and that Stage E should be plotted closer to Stage F.

(3) Within a Soil Series: As Table I indicates, soil bulk density, *per se*, is not the factor which limits root proliferation. For any particular horizon of any particular series, however, remarkably close similarity of root degradation is obtained at each bulk density. Presumedly, this close similarity is related to the fact that the soil material from one particular soil horizon has the same type of structural unit with essentially the same characteristics for a particular soil series. Consequently, a similar breakdown of the structural units is obtained at any particular bulk density and a similar pore size relationship and pore geometry will result. Therefore, it appears that the bulk density value is a useful tool for understanding a particular soil material and the behavior of crop roots.

Table II was prepared to indicate how the values reported in Table I were obtained. Twenty-one soil cylinders, compressed to various bulk densities, were examined in an attempt to determine the limits for each stage of root degradation for soil from each of six locations. Even though the limits were not established for each stage of root degradation with soil from each location, the values for each stage are remarkably close for all samples of the soil series. By referring back to the original notes on actual bulk density values and root deformation conditions that were recorded, it is possible to set the limits for the soil series with reasonable confidence. This is possible only because

Table II

EFFECT OF ROOT DEGRADATION BY SOIL BULK DENSITY
USING SIX LIHUE SILTY CLAY SURFACE SOILS

Location	Particle Density	STAGES OF ROOT DEGRADATION* A	B	C	D	E	F
		Soil Bulk Density (gm/cc)					
McBryde Fd. 8A	2.92 g/cc	< 1.10	< 1.16	1.30	> 1.33	1.45	1.55
McBryde Fd. 13E	2.92 g/cc	< 1.11	> 1.11	> 1.22	1.36	> 1.41	1.54
McBryde Fd. 21A	2.92 g/cc	< 1.09	> 1.11	> 1.20	> 1.33	< 1.47	< 1.60
Lihue H-15	2.94 g/cc	> 1.04	1.15	> 1.27	< 1.38	< 1.47	1.55
Lihue L-34A	2.96 g/cc	> 1.01	> 1.11	> 1.25	1.35	1.46	1.54
Lihue M-3	2.94 g/cc	> 1.01	> 1.11	> 1.20	> 1.35	> 1.44	1.54

*STAGES OF ROOT DEGRADATION

A. Roots and rootlets appear normal.
B. Proliferation is reduced slightly, but no distortions are noted to root or rootlet behavior.
C. Root proliferation is definitely reduced, but still good. Some rootlets show a slight flattening (1.25 width:1.00 height) and a tendency toward angular development.
D. Root proliferation is only fair. Most rootlets and some roots are flattened (1.50:1.00) and there is a tendency for rootlets to develop along zones of weakness or fractures within the soil.
E. Root proliferation is poor: unsuited for agricultural production. Badly flattened rootlets form weak mats in fractures.
F. Few roots or rootlets are able to penetrate unfractured soil. Roots are badly flattened (2:1) and essentially confined to fractures.

of the similarity of root deformation with bulk density for soils of the same series.

(4) Within a Soil Profile: An indication of poor correlation of root degradation to bulk density within a soil profile was presented with the discussion of the Hilo silty clay surface and subsurface horizons. The Stage G root degradation was reported at 0.40 gm/cc for a subsurface horizon while the same stage was obtained at a bulk density of 0.96 gm/cc for the surface material. Field evidence indicates that the greatest differences may exist within the profile of the Humic Ferruginous Latosol Group where not only extreme variations in moisture characteristics occur but also great differences in particle density.

Table I shows a difference in the surface and subsurface horizons of the Honouliuli clay. The Honouliuli subsoil appears to distort roots more gradually over a wider range in bulk density than do the other soils studied.

Although no subsurface horizon is listed in Table I for the Alluvial Soil Group, the few sample tests conducted did not indicate that complete testing was warranted: surface and subsurface material appeared equally effective in producing root distortions. The Mokuleia silty clay loam, however, is underlain with coral sand which was not tested; it is suspected that, should the sand have been compressed, differences in effectiveness would have been evident.

Bulk densities of surface and subsurface materials from Low Humic Latosols characteristically differ in effectiveness in producing root deformation. In the Molokai Family, the B_1 horizon material has a narrower range for Stage E and Stage F than does the surface material; in fact, Stage F is so narrow it is questionable as to whether or not it exists. The few samples of Waipahu and Mamala series soil material tested appeared similar to those reported for the Molokai Family, but, due to insufficient testing, it was impossible to assign reliable boundary values between the stages of root degradation. Soil material from the B_2 horizon of this family was not tested.

Insufficient tests were conducted using the B_2 horizon of soils of the Lahaina Family to make a conclusive report, but the material that was tested did seem to follow that reported for the B_1 horizon of the Molokai Family quite well.

In the Wahiawa Family, the Wahiawa silty clay B_2 horizon material differs from the surface material in having a narrower Stage F root-degradation range. The strength of the structural units of the B_2 horizon is greater than those of the subsurface materials from the Lahaina and Molokai Families. It may be that the strength of the structural unit, in resisting complete plastic deformation until a bulk density of about 1.45 gm/cc is reached, is, at least, partially responsible for the reaction reported for the B_2 horizon of the Wahiawa series. Very little difference is noted between the surface and B_2 horizon materials for the Kunia series. The subsurface structural units of the Kunia series have more strength than those of the Wahiawa series and resist plastic deformation almost as well as the Kunia surface material.

Table I shows that the subsurface material of most soils of the Kahana Family approaches the values reported for the surface material quite closely, although there are some differences. The structural units of the B_2 horizon resemble those of the surface material in size, shape and strength much more closely than they do in the other Low Humic Latosols reported. In most physical properties Kahana silty clay from the Kilauea area of Kauai does not resemble soil of the Kahana series from the other islands, nor does it resemble soil of the Lihue series from Kauai. In fact, with respect to stages of root degradation, this soil does not match the other members of the Kahana Family reported in Table I either.

(5) To Particle Density: With Hawaiian soils there exists a unique opportunity to investigate variations in a single property over a wide range of conditions using actual soil instead of artificial media. With respect to particle density, the A_2 horizon of some Humic Ferruginous Latosolic soils offers an excellent example of this statement. Although soils of the Humic Ferruginous Latosol Group were not included in the primary investigation, some field studies were conducted. Roots were found to proliferate in the purplish (A_2 horizon) material of one series in Stage C to Stage D condition when the bulk density was as high as 2.71 gm/cc: the particle density of this material was determined as 4.01 gm/cc. Although this bulk density exceeds any value reported in Table I, even at Stage G root degradation, heavier particle densities do not assure a higher bulk density value at each stage of root degradation.

In the Makaweli series the mean particle density for the surface materials used was 3.10 gm/cc, while the subsurface material had a mean particle density of 3.16 gm/cc. In the Molokai series the surface material had a mean particle density of 2.88 gm/cc while the subsurface material had a mean particle density of 2.93 gm/cc. It is normal for particle density to increase with depth in Low Humic Latosols, yet the values reported in Table I indicate that, with many soils, the stages of more severe root degradation occur at lower bulk densities with the subsurface materials. Many threshold densities reported for soils of the Continental United States are approximately 1.8 gm/cc, yet the only soil which approaches this value in Table I is the Grey Hydromorphic Clay. The particle density for most soils of the Continental United States is close to 2.65 gm/cc while the Hawaiian soils reported in Table I have particle densities varying from 2.85 gm/cc to 3.21 gm/cc.

Although particle density influences bulk density, there are other factors which affect the bulk density of a soil at which any particular stage of root degradation occurs. Except for extreme variations in particle density, the other factors appear more influential. One factor, worthy of consideration, concerns aeration for physiological development of plant roots.

d. Relationship of Aeration Porosity: That portion of the bulk volume of a soil which is neither solid material nor water is often referred to as the aeration porosity. It is the air-filled pore space of the soil. Such values have been computed for the 1,781 compacted soil cylinders used in the primary investigation. Table III presents the mean aeration porosity values calculated using the moisture content at which the soils were compressed. No claim is intended that these values persisted throughout the study, although they are good estimates of the aeration porosities which did exist through some of the study.

In Hawaiian soils the available range of moisture is quite narrow: a range of 10 percent is common and, in compressed soils, the available range is reduced (31). Since each soil was compressed at moisture contents within the available moisture range, the moisture content is expected to fluctuate somewhat from the moisture content at the time of compression. Therefore, the aeration porosity value would be subject to a small fluctuation from the reported value. Two other factors favoring a close approximation of the reported aeration porosity values are: 1. the low bulk density values which cause smaller changes in aeration porosity for each change in soil-moisture content and 2. the higher aeration porosity values which cause a smaller percentage of change for a given aeration porosity alteration.

Other investigations indicated that the aeration porosity values reported in Table III were maintained close to the calculated value throughout the early portion of the study because of the limited amount of wetting and drying of the compressed soil cylinders. Wetting the compressed soil cylinders will decrease the aeration porosity. Tests were conducted using compressed soil cylinders placed in unplanted pots which were watered twice a day for a period of one month. Except

Table III

RELATIONSHIP OF AERATION POROSITY OF HAWAIIAN SOILS TO SUGARCANE ROOT DEGRADATION

Soil Type	STAGES OF ROOT DEGRADATION* A	B	C	D	E	F
	Aeration Porosity (Per Cent)					
LOW HUMIC LATOSOLS						
MOLOKAI FAMILY						
Makaweli si. cl. surf.	40	36	30	22	14	6
Molokai si. cl. surf.	40	33	27	20	14	7
Mean (surf.)	40	35	29	21	14	7
Makaweli si. cl. sub.	40	33	29	21	16	12
Molokai si. cl. sub.	39	34	28	21	15	8
Mean (sub.)	40	34	29	21	16	10
LAHAINA FAMILY						
Keahua si. cl. surf.	40	34	29	22	12	12
Lahaina si. cl. surf.	36	32	23	16	10	4
Paia si. cl. l. surf.	38	32	28	20	15	10
Waikapu si. cl. l. surf.	36	29	22	15	8	2
Mean (surf.)	38	32	26	18	11	3
WAHIAWA FAMILY						
Kunia si. cl. surf.	37	32	27	18	12	5
Wahiawa si. cl. surf.	37	32	24	16	13	4
Mean (surf.)	37	32	26	17	13	5
Kunia si. cl. sub.	36	31	27	18	12	4
Wahiawa si. cl. sub.	33	29	24	17	10	4
Mean (sub.)	35	30	26	18	11	4
KAHANA FAMILY						
Haliimaili si. cl. surf.	35	31	25	14	8	4
Kahana si. cl. Kilauea-type (surf.)	35	30	26	20	14	6
Kahana si. cl. (other) surf.	36	30	23	14	10	4
Koloa si. cl. surf.	38	32	26	17	8	5
Lihue si. cl. surf.	33	28	24	15	8	4
Mean (surf.)	35	30	25	16	10	5
Haliimaili si. cl. sub.	34	28	23	18	8	5
Kahana si. cl. Kilauea-type (sub.)	31	25	20	15	9	3
Kahana si. cl. Pioneer-type (sub.)	33	27	24	14	8	4
Koloa si. cl. sub.	38	33	28	21	12	3
Lihue si. cl. sub.	35	30	23	16	11	4
Mean (sub.)	34	29	24	17	10	4

Table III (Continued)

Soil Type	STAGES OF ROOT DEGRADATION* A	B	C	D	E	F
	Aeration Porosity (Per Cent)					
GREY HYDROMORPHIC CLAYS						
Honouliuli cl. surf.	35	29	24	18	11	3
Honouliuli cl. sub.	45	39	35	30	15	4
HYDROL HUMIC LATOSOL						
Hilo si. cl. surf.	35	25	18	8	4	1
ALLUVIAL SOILS						
Pulehu cl. l. surf.	41	35	31	20	15	8
Mokuleia si. cl. l. surf.	40	33	27	20	13	3
Mean (surf.)	41	34	29	20	14	6

*STAGES OF ROOT DEGRADATION

A. Roots and rootlets appear normal.

B. Proliferation is reduced slightly, but no distortions are noted to root or rootlet behavior.

C. Root proliferation is definitely reduced, but still good. Some rootlets show a slight flattening (1.25 width:1.00 height) and a tendency toward angular development.

D. Root proliferation is only fair. Most rootlets and some roots are flattened (1.50:1.00) and there is a tendency for rootlets to develop along zones of weakness or fractures within the soil.

E. Root proliferation is poor: unsuited for agricultural production. Badly flattened rootlets form weak mats in fractures.

F. Few roots or rootlets are able to penetrate unfractured soil. Roots are badly flattened (2:1) and essentially confined to fractures.

for the least compressed soil cylinders, the moisture content of the soil cylinders changed very little. The ease of water movement around the cylinders and the decreased infiltration into the compressed soil are largely responsible for this response.

Removal of water by roots proliferating in compressed soil will increase the aeration porosity. It has already been established that the limited reduction in moisture by root sorption would increase the aeration porosity slightly in most Hawaiian soils. Another point is worthy of consideration: water sorption is apparently performed behind the root cap, behind the region of cell formation, and even behind the region of elongation. It is in the region of cell functional differentiation that water is sorbed and translocated. With a large primary root of sugarcane, this may well be in excess of 10 cm. back of the root tip, i.e., a root can penetrate into 10 cm. of soil without removing appreciable water from the soil, or without changing the aeration porosity appreciably. A similar situation would exist with the smaller roots and rootlets, but the distance would be less.

In the region of cell formation and in the region of elongation much energy is being expended and much oxygen is required. Since these regions are acropetal of the zones in which appreciable water is removed, the oxygen would be withdrawn from the aeration porosity value reported in Table III. Water movement at moisture contents below a 1/3 atm. tension is slow and roots will develop to the water. This process is continued until a soil is fairly well permeated with roots so the reported aeration porosity value may hold for an even longer period of root development than is indicated above.

Meeting respirational requirements farther to the rear of the region of functional differentiation, or in areas already permeated by another root, presents another condition. In this condition, which persists throughout the rest of the study, the aeration porosity values are altered and the reported aeration porosities no longer exist.

(1) With the Soil Groups: The relationship of the mean aeration porosity for four soil Groups to stages of root degradation is shown in Figure 22. It can be noted that, except for the Hydrol Humic Latosol Group, the variations in aeration porosity are within 6 percent of each other at each stage of root degradation. These variations are extended to as much as 12 percent of each other in two stages of root degradation with the inclusion of the Hydrol Humic Latosols. This relationship is much closer than the relationship of bulk density to root degradation presented in Figure 20.

In Figure 22, the Hydrol Humic Latosol Group has a lower aeration porosity value at each stage of root degradation than do the other soil Groups reported. Speculations as to possible causes for such a relationship will be withheld until other factors have been discussed.

Figure 22 shows the mean aeration porosity determinations for the two series presented in Table III, which represent the Alluvial Soil Group. Although the mean aeration porosity value, at each stage of root degradation for the Alluvial Soil Group, is higher than the mean values for the other soil Groups listed, the mean value for the Mokuleia series is similar to that of most Low Humic Latosols. The

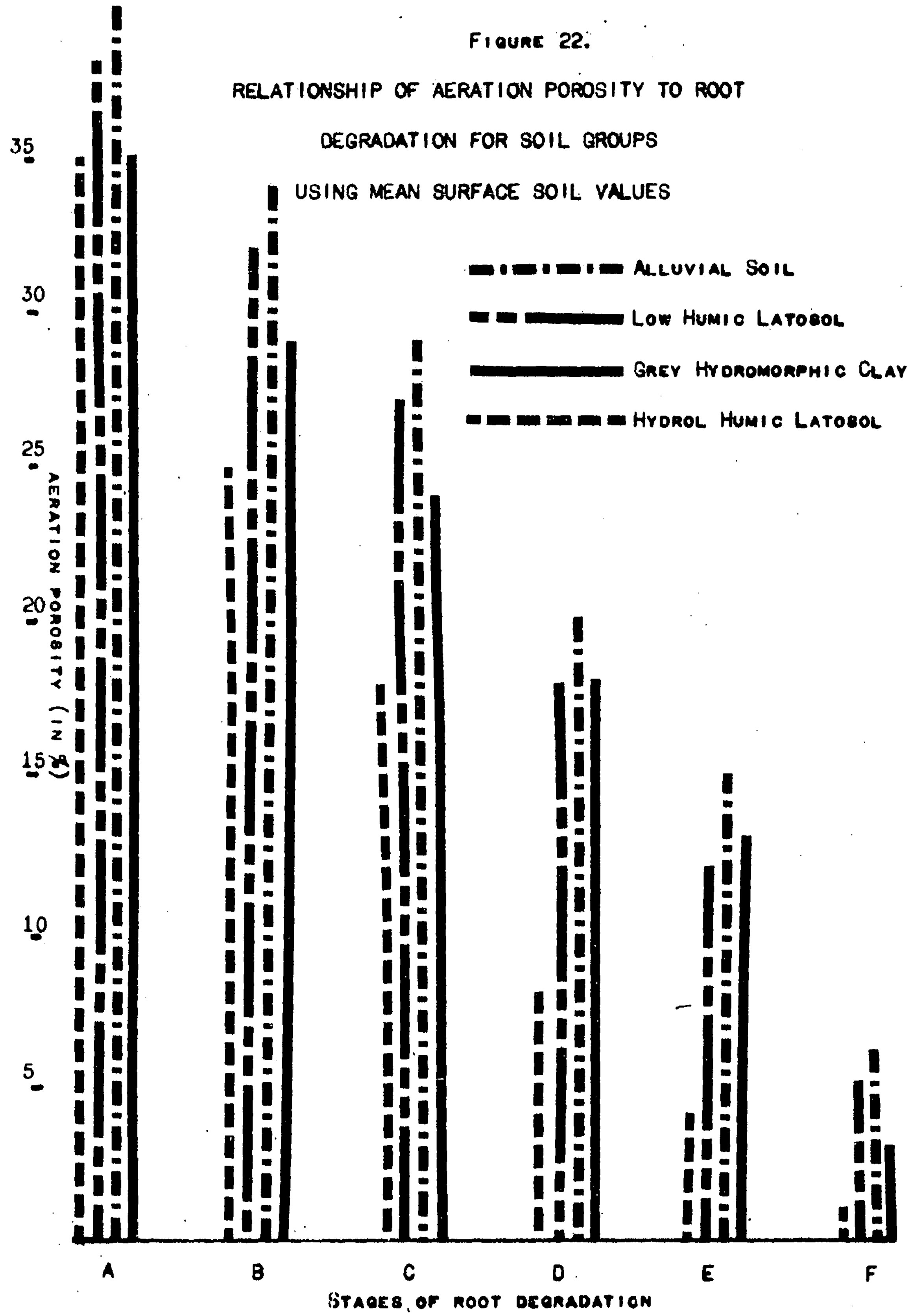


FIGURE 22.
RELATIONSHIP OF AERATION POROSITY TO ROOT
DEGRADATION FOR SOIL GROUPS
USING MEAN SURFACE SOIL VALUES
ALLUVIAL SOIL
LOW HUMIC LATOSOL
GREY HYDROMORPHIC CLAY
HYDROL HUMIC LATOSOL
AERATION POROSITY (IN %)
35
30
25
20
15
10
5
A
B
C
D
E
F
STAGES OF ROOT DEGRADATION

range in variations of aeration porosity at each stage of root degradation for the Low Humic Latosol, the Alluvial Soil, and the Grey Hydromorphic Clay is narrow and may be the result of the moisture content at which each soil was compressed rather than a relationship with a particular soil. In order to confirm the existence of this situation, the following calculation is referred to: at a bulk density of 1.5 gm/cc, each change in moisture content of one percent changes the aeration porosity by 1.5 percent; therefore, if compression occurs at moisture contents differing by 4 percent, a 6 percent range in aeration porosity would be produced. These differences in aeration porosity may well be due to the selected soil-moisture content at time of compression.

(2) With Similar Bulk Densities: Figure 23 shows the relationship of a Molokai silty clay after it has been compressed to a predetermined bulk density at a wide range of moisture contents. This figure is typical of the results obtained with many other soils. In this study the cylinders of soils were compressed to a bulk density close to the division between Stage F and Stage G root degradation. For a variation of approximately 15 percent in moisture, a 24 percent aeration porosity variation was obtained. This relationship clearly indicates that root development does not appear different in soil at a bulk density of 1.56 gm/cc when the aeration porosity is maintained at any value within a range as wide as 24 percent. Aeration porosity, *per se*, does not regulate root development.

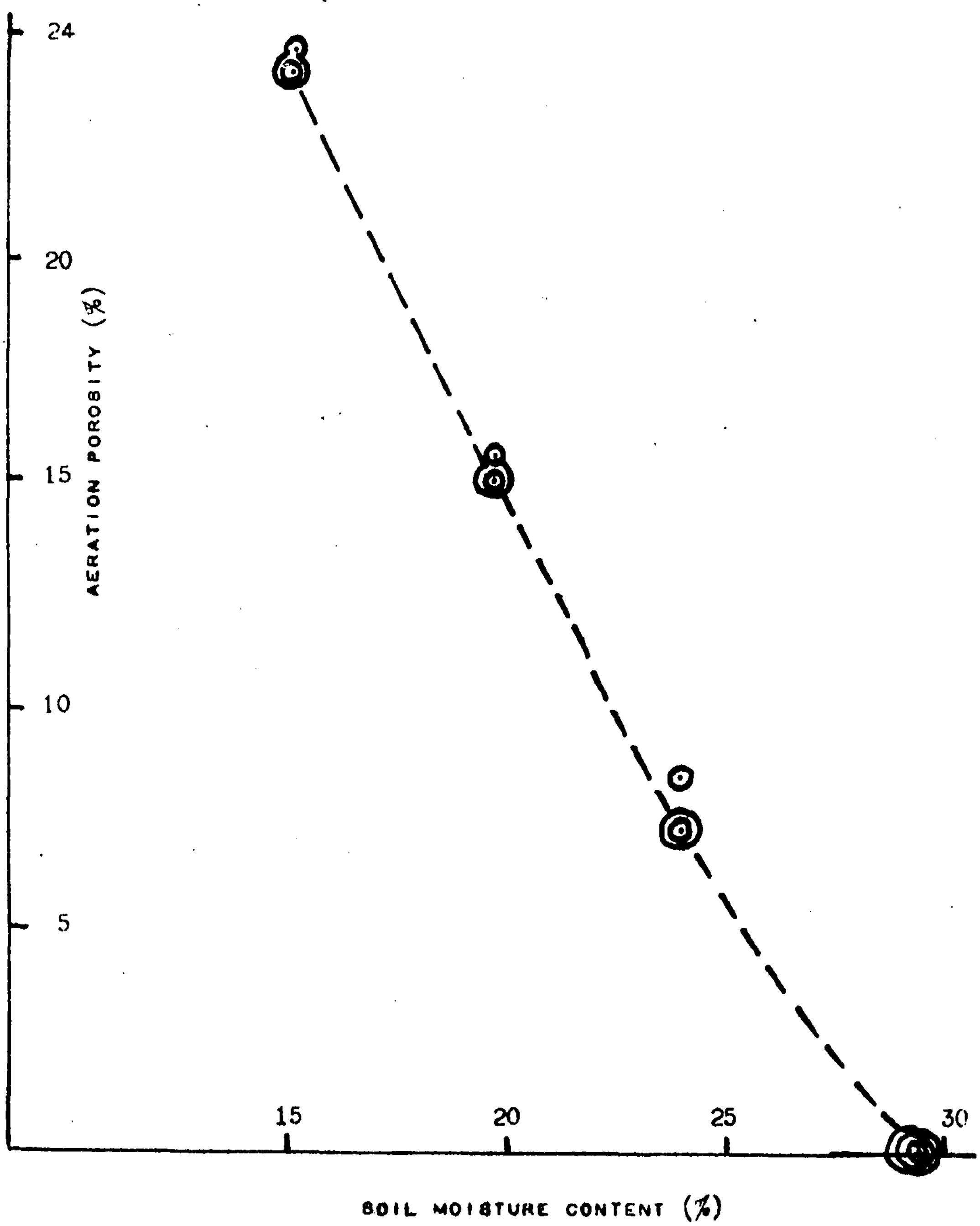
It should, in all honesty, be pointed out that there are some

FIGURE 23.

RELATIONSHIP OF SOIL-MOISTURE CONTENT TO AERATION POROSITY WITH SIMILAR SOIL BULK DENSITIES

MOLOKAI SILTY CLAY (SURFACE SOIL) FROM FD. 33

OAHU SUGAR COMPANY



additional limitations to this type of study. Dry soil is difficult to compress and, at a moisture content of 14.7 percent, the predetermined bulk density could not be reached with the equipment used by about 0.03 gm/cc. Root proliferation can be restricted also because of dry soil conditions. At 33.3 percent soil moisture, the bulk density of the soil cylinders was about 0.1 gm/cc short of the predetermined target density. At higher moisture contents free water was released with compression so moisture was lost and aeration porosity was altered. These values are not reported. In wet soil, lack of movement of air is important since the aeration porosity exists only because some air is trapped during compression.

This study indicates that our research must extend beyond the static situation and enter into a dynamic system. All life is involved with a dynamic situation; roots appear to be no exception. The calculated aeration porosity is significant during the entry stage of a root into a soil. Many roots do enter into soil at an existing aeration porosity, but as soon as they do so, a dynamic situation is initiated. Oxygen is utilized and carbon dioxide is liberated. The carbon dioxide must diffuse away and more oxygen must diffuse to the root surface. As water is sorbed by the roots, air must replace it. This situation suggests the importance of movement of the gaseous atmosphere of the soil.

e. Relationship of Air Movement: In the gas-filled pores of a soil, diffusion and mass-flow gaseous movement are possible. Penman (16, 17) has stated that diffusion can account for the requirements of plants, but in nature both mechanisms are operating. At the root interface, diffusion through the moisture film in contact with the root is considered dominant. Cannon (3) relates all gaseous movement to only diffusion in the water-film -- cell-wall -- cell portion of the gaseous chain. Plant roots are believed to require the range between a certain least and a certain upper critical oxygen partial pressure for growth. For "normal" plant growth the oxygen partial pressure must be related to definite temperatures for specific plant species (3).

In the present studies it was found that very permeable Hydrol Humic Latosols maintained a very desirable oxygen supply at depths in excess of 1 meter throughout the cycle of a sugar crop. However, when in a compressed state, these same soils accumulated nitrite, sulfide and ferrous compounds, and methane and hydrogen sulphide gas accumulated about organic residues within a few weeks. In such areas roots did not develop and the aerial portion of the crop was stunted. In another study sugarcane roots were found to enter a nitrogen atmosphere (deficient in oxygen), but only for a short distance, while they would not enter an atmosphere of carbon dioxide.

Maintaining control of mixtures of various gases, temperature, moisture, complete circulation, etc., was difficult with the apparatus available. The complex nature of this situation and the elaborate equipment required discouraged an application of a laboratory-greenhouse technique to investigate air movement on stages of root degradation any further.

f. Relationship of Root Proliferation: Reduced proliferation of roots is described in Tables I and III in soil at increasing bulk density and decreasing aeration porosity. It is difficult to define proliferation for each stage of root degradation in terms which are other than relative. Although photographic evidence is submitted to convey some estimate of proliferation, this technique is not entirely satisfactory. A study was therefore initiated to determine the root proliferation in representative soils in terms which could be conveyed more easily.

The system devised to determine root proliferation is described in the "MATERIALS AND METHODS" section on page 14. Technical aspects caused the study to fall short of the desired goals. The fractures frequently occurring in the manufactured compressed soil cylinders were developed from planes of weakness caused by swelling of the compressed soil immediately following the manufacture of the cylinders. As the molds were being disassembled, radial weaknesses developed from the region of joints between mold sections and proceeded toward the center of the soil cylinders. This was due to moist soil tenaciously adhering to the mold sections and, in Hawaiian soils where adhesive forces often exceed cohesive forces, the weaknesses would develop where adhesion was not a factor. When a sample lump contained a fracture it was questionable whether or not the roots which had developed within the fracture should be part of the measurement. In Stage D, a few roots and rootlets tend to locate in fractures, or to develop in planes of weakness. As the bulk density of the soil increases, the tendency for roots to develop in fractures increases until all root proliferation is confined to a dense root mat either within a few fracture planes or around the compressed soil cylinders.

Many compressed soils in the field contain fractures similar to those in the manufactured soil cylinders, but the percentage of fractures is not necessarily similar. There is no known way of differentiating roots which normally develop in planes of weakness from those confined in fractures except for the stages of more severe root degradation. None the less, the decision was made to include all roots from all lumps, realizing that this would present a larger root population than the stages of root degradation descriptions indicate when an excessive amount of roots from fractures occurred in the sample.

An entire root system of a plant, confined in a small pot, does not duplicate a field situation which has many times the volume for root expansion. It may be suspected that pots would therefore contain more roots per unit volume than do field soils. Oddly enough, when the borders and bottom of the pot were ignored, the root mass within the pot appeared similar to the mass determined in the field for corresponding soil depths, ages of plants and soil bulk densities. Root mass and root volume normally show an inverse relation with soil depth or, more correctly, with distance from the plant. Plants with a fibrous root system, except for an inverted truncated cone about 20 cm. deep under each plant, show a lessened relationship of roots with distance. If primary roots and larger branch roots are removed from the sample, the effect of distance appears to become negligible, even directly under the plant.

Assuming that small roots and rootlets accomplish most of the active sorption of nutrients and moisture while larger roots serve predominantly as conducting tissue, the removal of larger roots would not have been amiss. Due to conducting tissue and to roots that were confined within fractures being included in these determinations, the stages of root degradation, as previously delineated, could not be applied. Although many fairly large lumps of compressed soil were used and many man-hours were invested in washing and collecting all roots and rootlets, the variability of distribution of roots within the lumps of soil, both in size and location, still proved that there had been insufficient sampling. Therefore, the decision was made to compare the results of this study directly with soil bulk density.

(1) To Root Mass: Table A-XIV, located in the Appendix, presents the 60° C. oven-dried weights, expressed in milligrams of root material per cubic centimeter of soil, for roots that developed in each of four soil materials at various soil bulk densities. The four soil materials all indicate an inverse relationship between root weight and soil bulk density. By linear regression, three materials could be related by an expression showing a 99 percent confidence, statistically, while the relation with the fourth material shows better than a 95 percent confidence. Zimmerman and Kardos (35) also obtained inverse relationships with root weight and soil bulk density although about half of the correlations were not statistically significant because of root variations as discussed above.

The representative of the Grey Hydromorphic Clay Group shows a sixfold reduction in root weight when the soil bulk density was increased from 1.02 gm/cc to 1.72 gm/cc (Figure 24). The expression

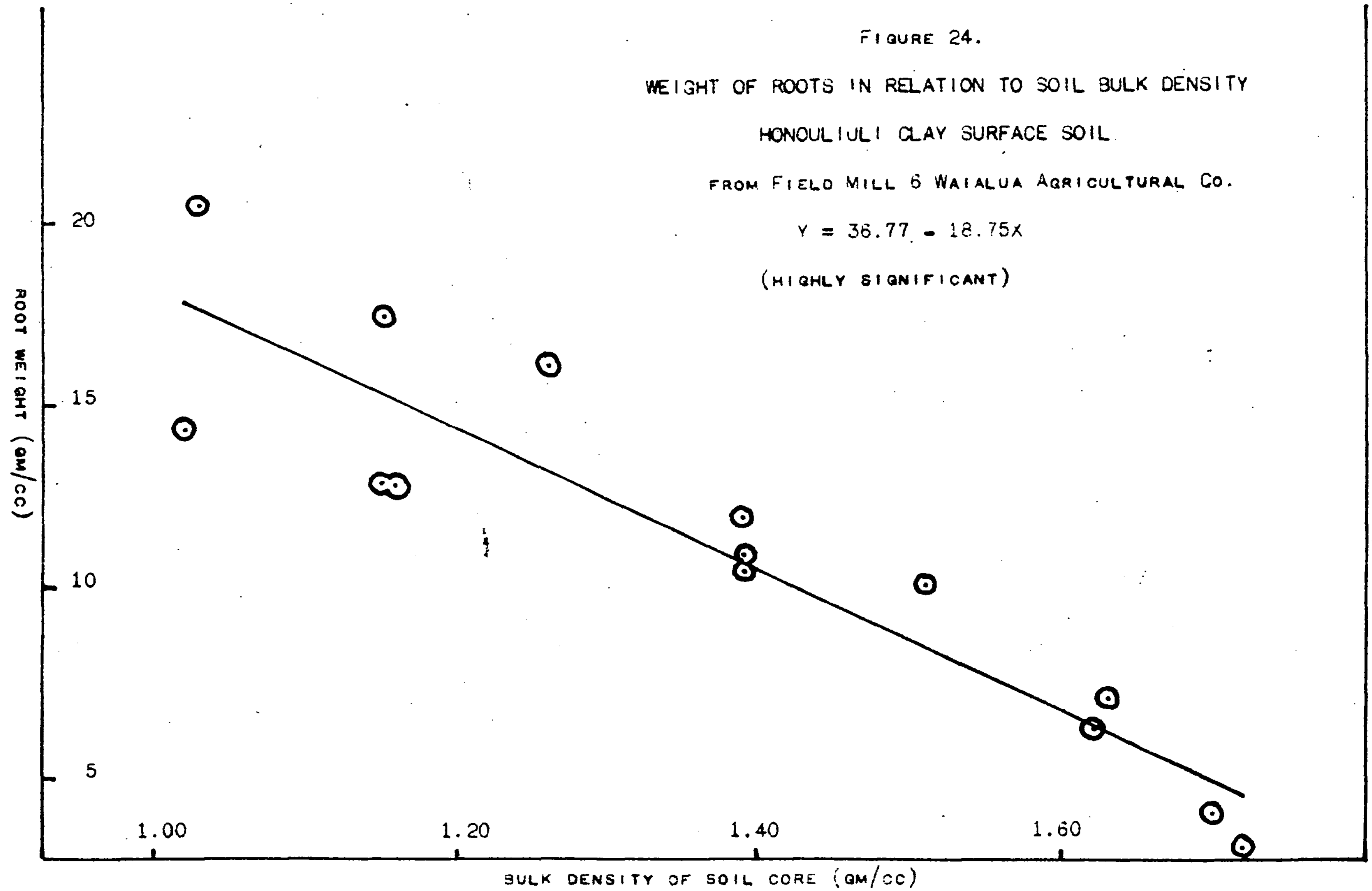


FIGURE 24.

WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

HONOULIULI CLAY SURFACE SOIL

FROM FIELD MILL 6 WAIALUA AGRICULTURAL CO.

$Y = 36.77 - 18.75X$

(HIGHLY SIGNIFICANT)

Y = 36. 77 - 18. 75X is statistically highly significant. The variability in sample data in the low density region is due to the inclusion of large primary roots which are responsible for most of the mass and volume reported.

The representative of the Alluvial Soil Group shows a twofold reduction in root mass when the soil bulk density was increased from 1. 03 gm/cc to 1. 57 gm/cc (Figure 25). Despite the inclusion of many roots located in fractures at the higher soil bulk densities, the expression Y = 39. 03 - 17. 32X is statistically highly significant.

The representative of the surface soil for the Low Humic Latosol Group shows more than a tenfold reduction in root mass when the soil bulk density was increased from 1. 03 gm/cc to 1. 57 gm/cc (Figure 26). The expression Y = 86. 95 - 53. 45X is significant despite the inclusion of many large primary roots in some samples at lower bulk densities and of much root material from fracture planes in soils at higher bulk densities.

The representative of subsoil material of the Low Humic Latosol Group shows a reduction in root mass more similar to the other soil Groups than to the surface material from the same soil Group (Figure 27). The expression Y = 35. 37 - 19. 98X is statistically highly significant.

Despite the weaknesses of this technique, it was determined that the mass of roots would decrease as soil bulk density was increased. Through the usual range of bulk densities encountered in the field, the decrease in mass can be estimated by the expression Y = 37 - 19X.

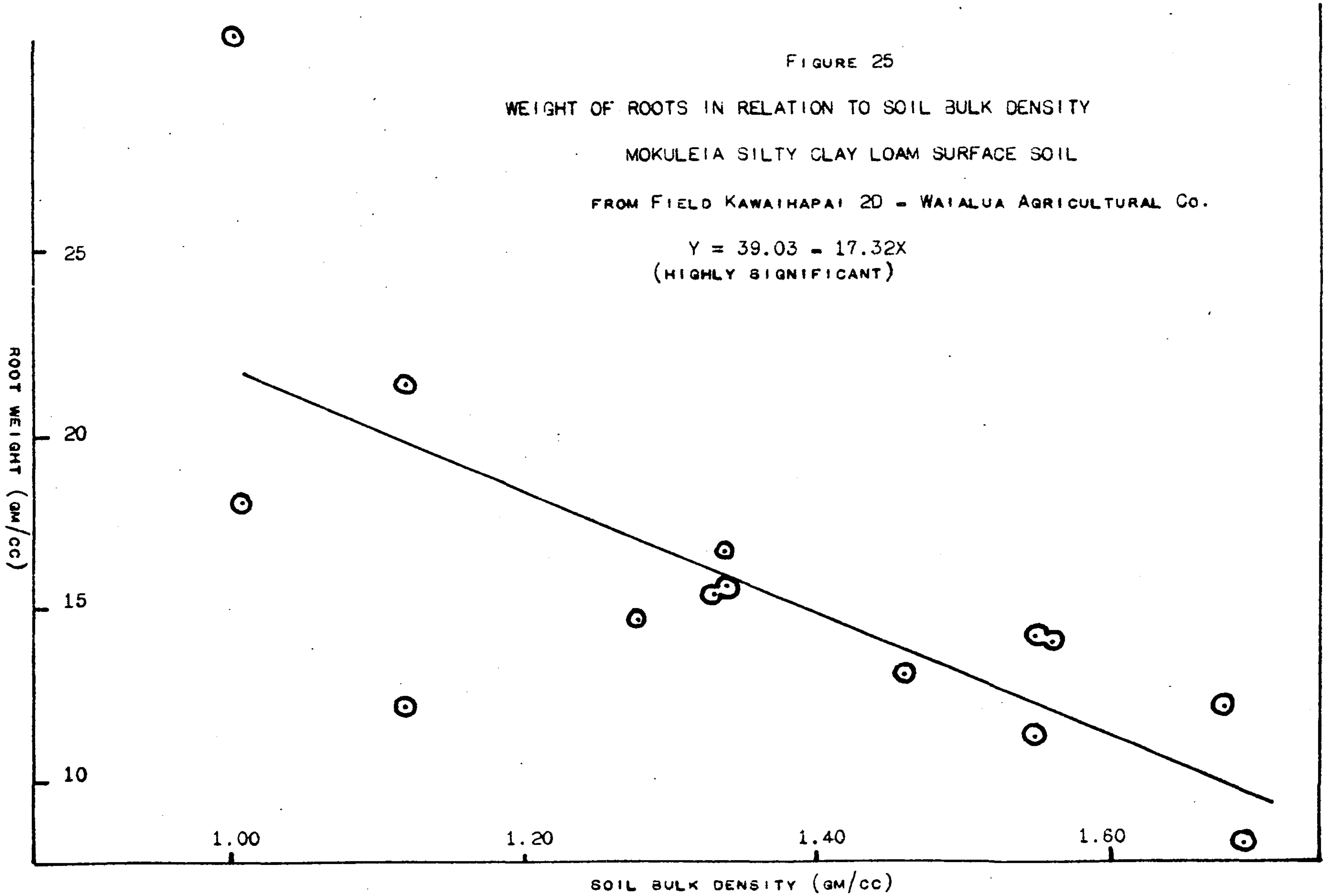


FIGURE 25

WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

MOKULEIA SILTY CLAY LOAM SURFACE SOIL

FROM FIELD KAWAIHAPAI 2D - WAIALUA AGRICULTURAL CO.

FIGURE 26

WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

WAHIAWA SILTY CLAY SURFACE SOIL

FROM FD. HELEMANO 6 WAIALUA AGRICULTURAL CO.

Y = 86.95 - 53.45X

(SIGNIFICANT)

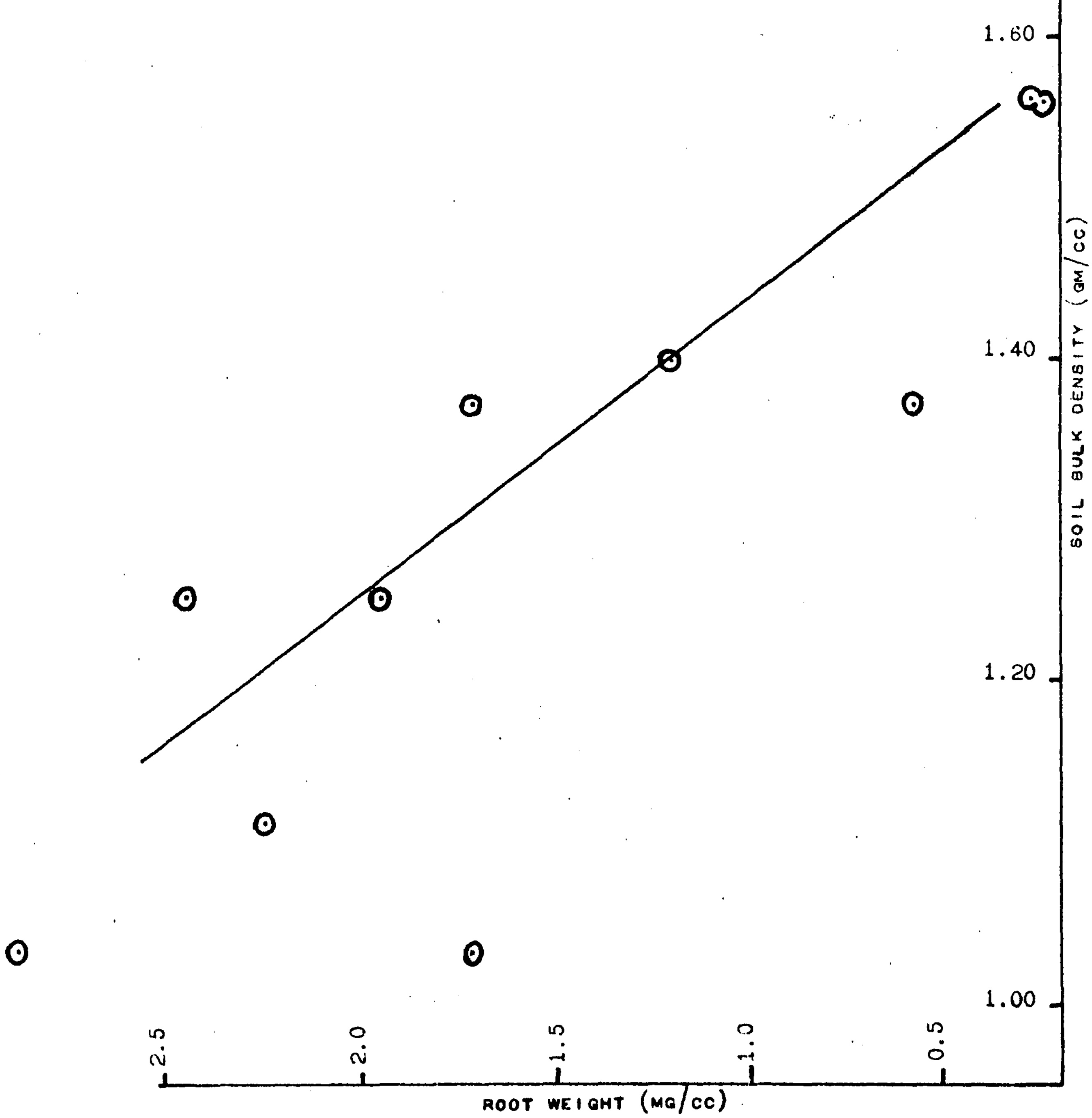


FIGURE 27

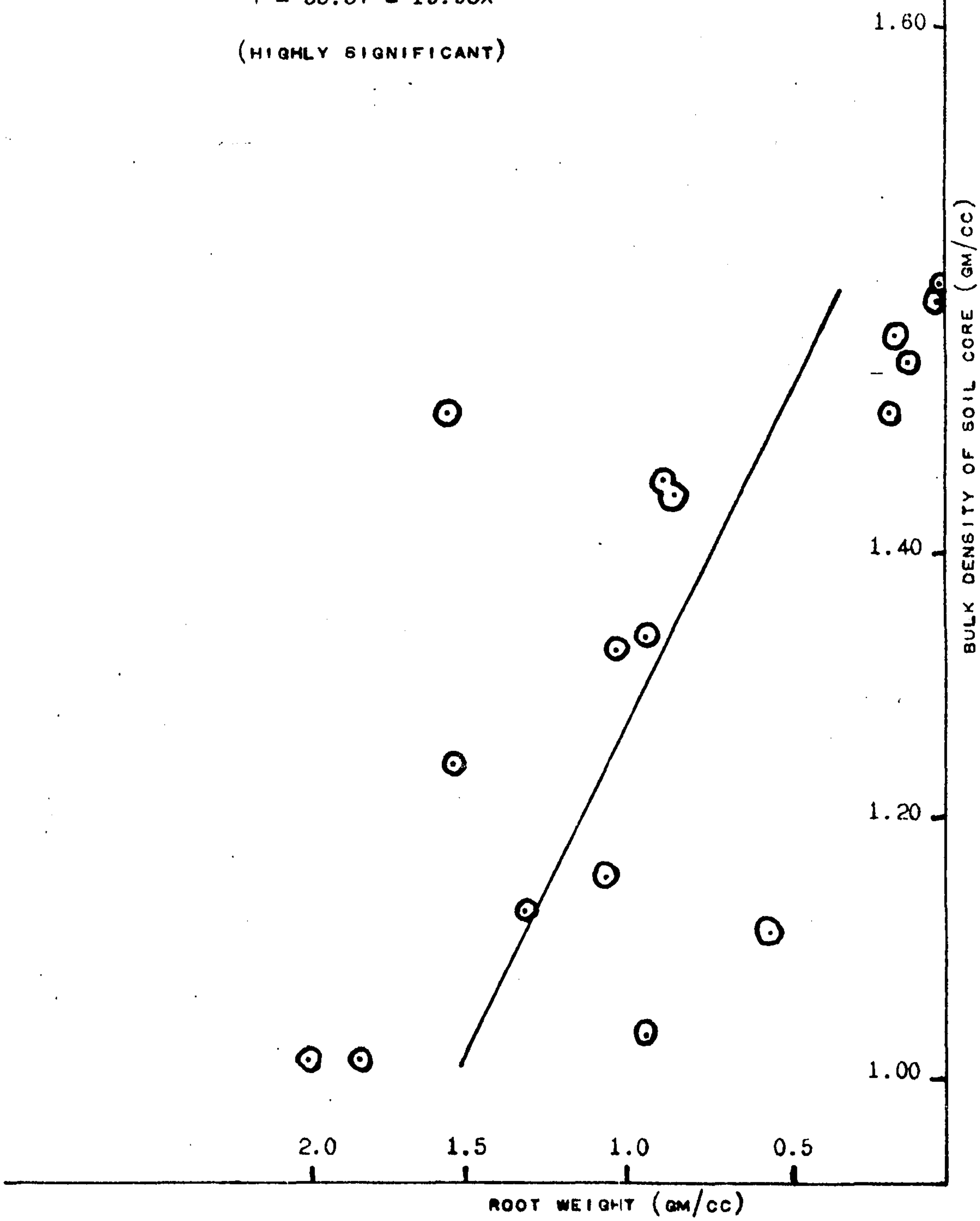
WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

WAHIAWA SILTY CLAY SUBSOIL

FROM PRI WAIPIO SUBSTATION

$Y = 35.37 - 19.98X$

(HIGHLY SIGNIFICANT)



This approximate expression is too generalized to separate the soils from which it was derived, and its application cannot be extrapolated to include the Hydrol Humic Latosols.

(2) To Root Volume: Table A-XV, located in the Appendix, presents the volume of roots, expressed as a percentage of the soil volume, which developed in various soil bulk densities for the four soil materials just discussed. Each soil gave an inverse relationship between root volume and soil bulk density. By linear regression, expressions were obtained which fit two materials with less than a one percent chance of error while expressions were obtained for the other two soil materials which gave less than a 5 percent chance of error.

The representative of the Grey Hydromorphic Clay Group showed a threefold reduction in volume of roots when the soil bulk density was increased from 1.02 gm/cc to 1.72 gm/cc (Figure 28). The expression Y = 2.68 - 1.36X is statistically highly significant.

The representative of the Alluvial Soil Group showed a twofold reduction in volume of roots when the soil bulk density was increased from 1.03 gm/cc to 1.57 gm/cc (Figure 29). The expression Y = 2.99 - 1.30X is statistically highly significant.

The representative of the surface soil of the Low Humic Latosol Group showed a tenfold reduction in volume of roots when the soil bulk density was increased from 1.03 gm/cc to 1.57 gm/cc (Figure 30). The expression Y 6.58 - 4.04X is statistically significant.

The representative of subsoil material of the Low Humic Latosol

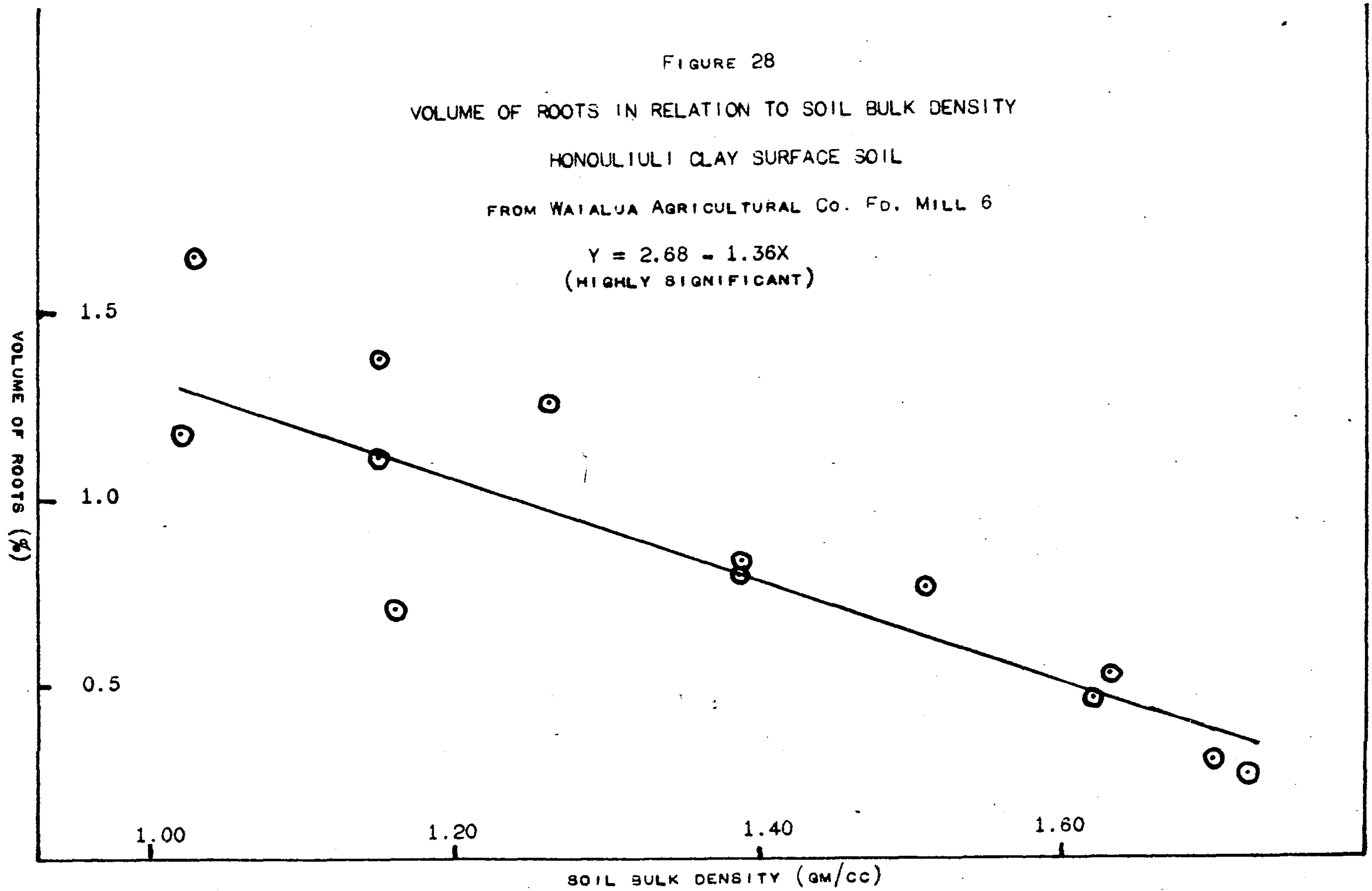


FIGURE 28

VOLUME OF ROOTS IN RELATION TO SOIL BULK DENSITY

HONOULIULI CLAY SURFACE SOIL

FROM WAIALUA AGRICULTURAL CO. FD. MILL 6

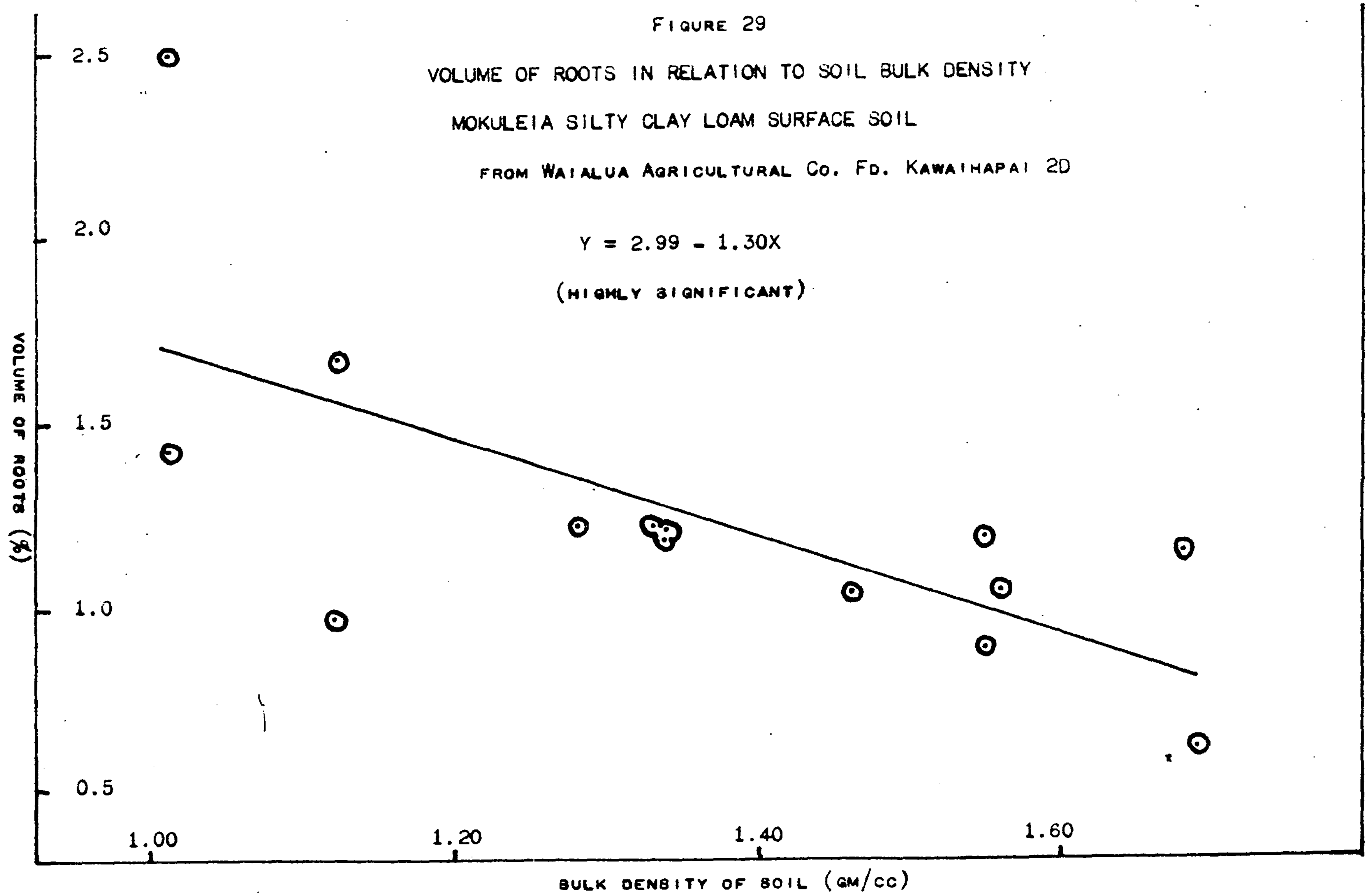


FIGURE 29

VOLUME OF ROOTS IN RELATION TO SOIL BULK DENSITY

MOKULEIA SILTY CLAY LOAM SURFACE SOIL

FROM WAIALUA AGRICULTURAL CO. FD. KAWAIHAPAI 2D

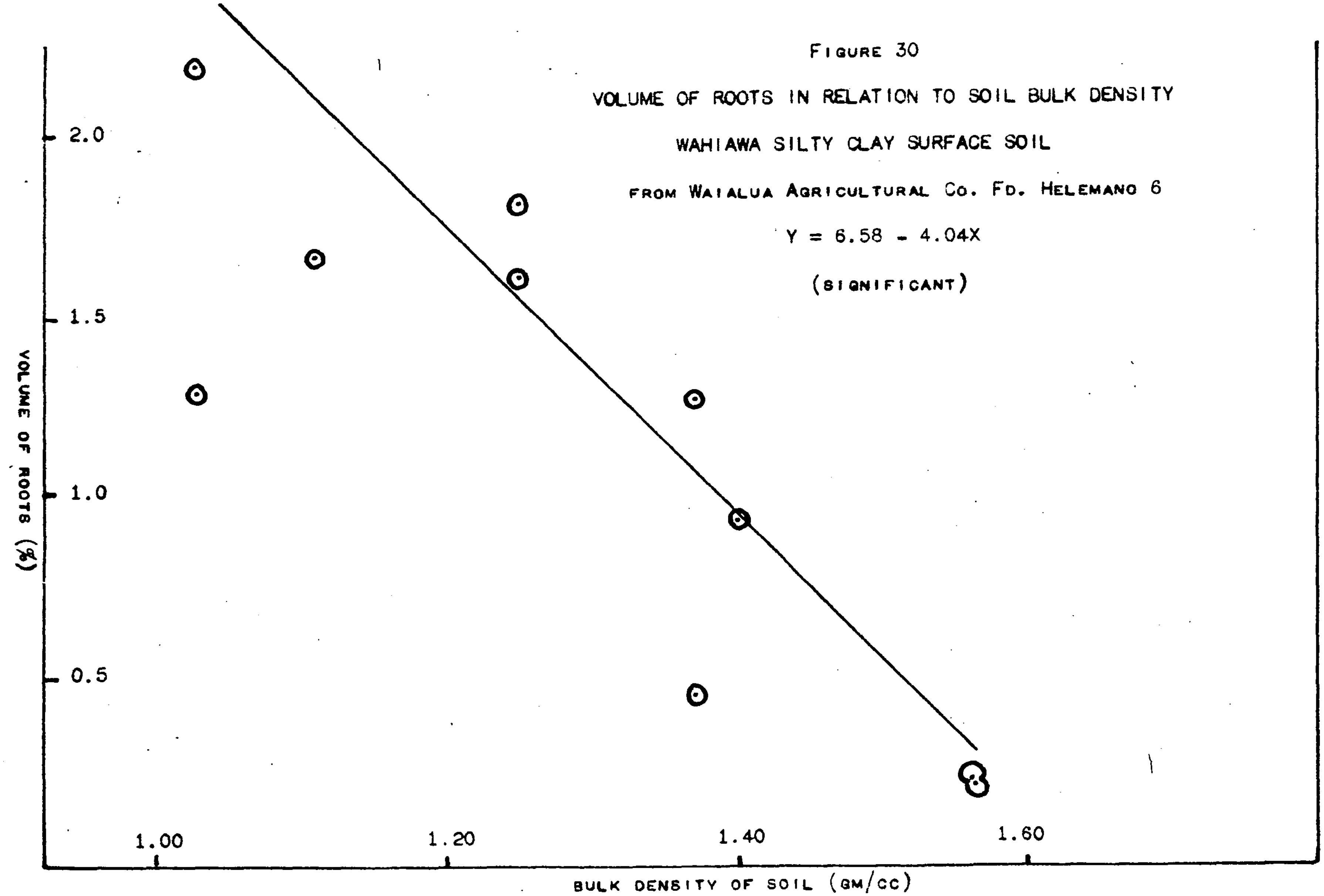


FIGURE 30
VOLUME OF ROOTS IN RELATION TO SOIL BULK DENSITY
WAHIAWA SILTY CLAY SURFACE SOIL
FROM WAIALUA AGRICULTURAL CO. FD. HELEMANO 6
Y = 6.58 - 4.04X
(SIGNIFICANT)
2.0
1.5
1.0
0.5
VOLUME OF ROOTS (%)
1.00
1.20
1.40
1.60
BULK DENSITY OF SOIL (GM/CC)

Group showed a threefold reduction in volume of roots when the soil bulk density was increased from 1.01 gm/cc to 1.60 gm/cc (Figure 31). The expression Y = 2.65 - 1.43X is also statisticially significant.

In a newly tilled field, the volume of roots is approximately one percent of the soil volume. As the bulk density is increased the expression Y = 2.8 - 1.4X will present a close approximation of the percentage of roots located in soil at each bulk density. The use of this approximate expression cannot be extrapolated for use with Hydrol Humic Latosols.

g. Functioning Capability: The presence of distorted roots developing in compressed soil does not assure that such roots function normally. In fact, the question may be asked as to whether or not badly flattened and distorted roots function at all. The soil atmosphere in compressed soil contains less oxygen and has a slower diffusion rate (24) than does soil at lower bulk densities. Cannon (3) states that oxygen enters root cells predominantly by a diffusion process. With the oxygen content reduced below optimum, a slower than normal nutrient movement may be obtained within the root cells due to cell functioning being less efficient under poorer oxygen relationships.

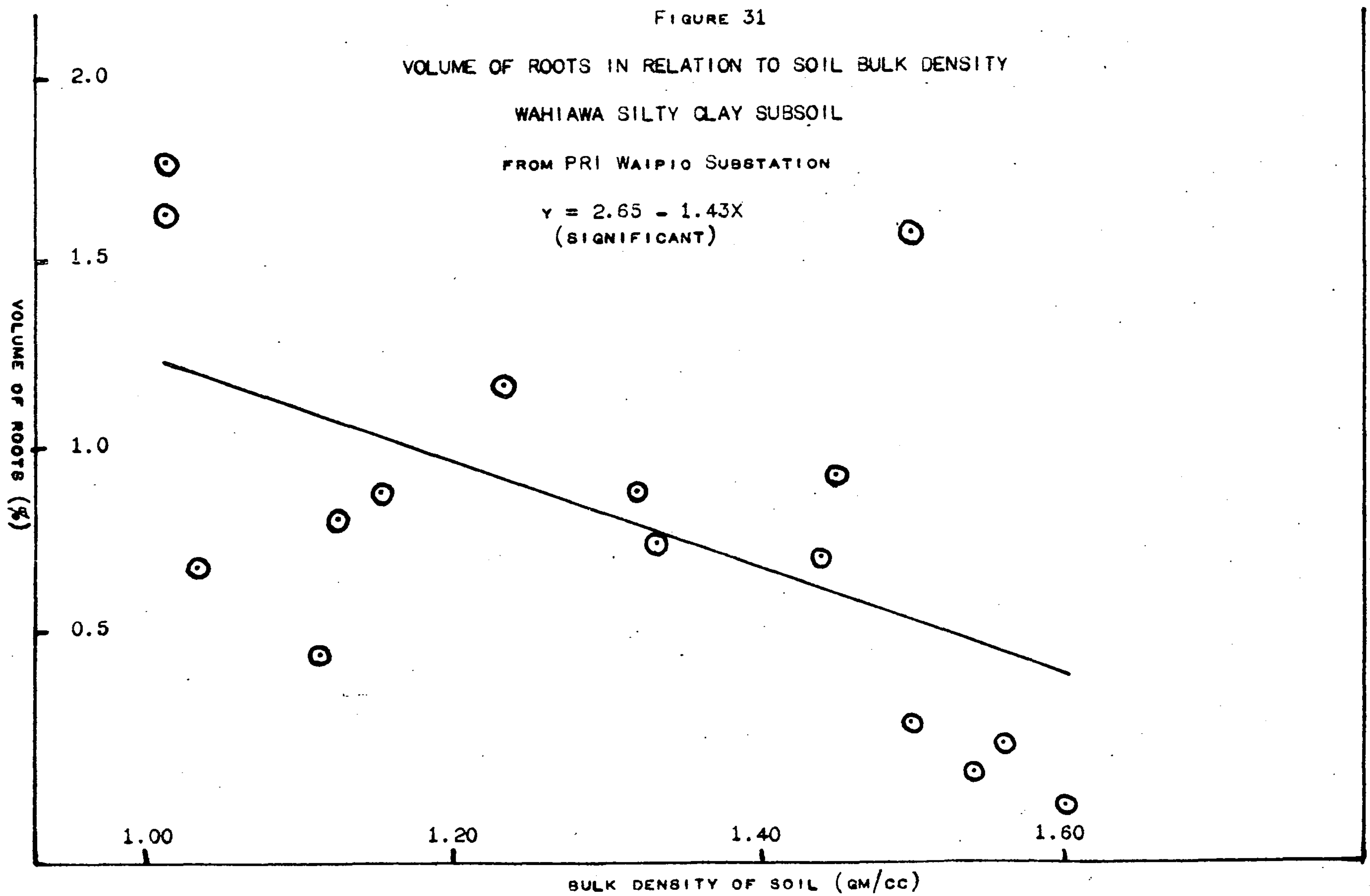
A simple technique, described in the "MATERIALS AND METHODS" section on page 15, was devised to determine the uptake of radio-rubidium in compressed soils. Although studies were not conducted on the diffusion rates of radio-rubidium in Hawaiian soils, it is

Figure 31

VOLUME OF ROOTS IN RELATION TO SOIL BULK DENSITY

WAHIAWA SILTY CLAY SUBSOIL

FROM PRI Waipio Substation



assumed that, since phosphate ions are easily fixed in Hawaiian soils, radio-rubidium would follow the general pattern established for Continental United States soils. From the apparent diffusion coefficient for Rb^{86} established by Vasey and Barber (29) for two Continental United States soils, radio-rubidium diffusion would calculate to about 0.01 sq. cm/year. If this is true, roots must enter the compressed soil cylinders to absorb rubidium. Unfortunately, the fractures, discussed under "Relationship of Root Proliferation" on page 69, formed a passageway for roots to the rubidium supply in many of the compressed soil cylinders. In general, there was a reduction in uptake of radio-rubidium as the soil bulk density was increased (26). Variations in uptake in different soils made much of the data of little statistical value. Since it has already been established that root proliferation is reduced in soils at increased bulk densities, then, with fewer roots present to absorb radio-rubidium, these few roots must be capable of functioning quite well. The implication is that badly distorted roots and rootlets cannot be said to be any less proficient than normal roots in absorption.

h. Physical Impedance: Gill and Miller (9), using a concise technique in a well-designed study, were unable to prove physical impedance, *per se*. They were able to distort and flatten seedling roots and reduce rates of growth with applied pressures which extended to as much as 5 kg/sq cm, but elongation continued at much reduced rates. They reported oxygen levels (without associated temperatures) and did show that, by fluctuating the oxygen content, the apparent physical impedance obtained at lower oxygen contents was not real. Wiersum (33) did produce evidence of physical impedance in a rigid system, but Barley (1) shows that soil is not a rigid system.

Under normal conditions, physical impedance is difficult to separate from poor aeration: to determine whether soil bulk densities at which roots fail to penetrate may be classified as physical impedance, soils were compacted at a range of soil-moisture contents. The bulk modulus developed by soil when compressed to the threshold bulk density is related to the soil-moisture content. As soil moisture greatly influences soil strength, relatively small changes in moisture content might be thought to affect the ability of roots to develop in dense soil. If physical impedance were a factor, a drier soil would then have a lower threshold bulk density than the same soil compressed to a threshold bulk density in a more moist state.

Hydrol Humic Latosols are more moist, and have a lower soil strength, than material from other soil Groups. Yet, in Hydrol Humic Latosols, cane roots reach each stage of root degradation at much lower bulk density values than in soils with greater strength. Table IV shows one soil material compressed to nearly identical bulk densities at various moisture contents. Although the strength factor changed severalfold within the range of moisture variations, the stage of root degradation is identical.

One major limitation to this technique is the decreased aeration porosity that is associated with increased moisture content. However, adequate aeration has been allowed in some compressed soil

Table IV

RELATIONSHIP OF SOIL MOISTURE CONTENT TO AERATION POROSITY WITH SIMILAR SOIL BULK DENSITIES

Molokai Silty Clay (Surface Soil)

From Fd. 33   Oahu Sugar Company, Ltd.

Replicate No.	Soil Moisture (%)	Bulk Density (gm/cc)	Aeration Porosity (%)	Remarks
1203	14.7	1.54	24.07	Very few roots, most in fractures. Badly distorted.
1204	14.7	1.53	24.57	Very few roots and rootlets, most in fractures. Both badly distorted.
1205	14.7	1.53	24.57	Very few roots and rootlets, most in fractures. Both badly distorted.
1206	19.5	1.57	15.05	No roots.
1207	19.5	1.56	15.60	One primary root in compressed soil cylinder.
1209	19.5	1.57	15.05	No roots.
1189	23.7	1.59	7.30	No roots.
1192	23.7	1.59	7.30	No roots.
1193	23.7	1.57	8.46	No roots.
1200	29.5	1.57	0	No roots.
1201	29.5	1.57	0	No roots.
1202	29.5	1.57	0	No roots.
1210	33.3	1.48	0	Few primary roots and rootlets. Both flattened, angular close branching--mostly in fractures.
1212	33.3	1.47	0.18	Few primary roots and rootlets. Both flattened, angular close branching--mostly in fractures.
1213	33.3	1.48	0	Few primary roots and rootlets. Both flattened, angular close branching--mostly in fractures.

cylinders which were manufactured at several drier moisture contents, but yet with available water. Roots appeared identical, regardless of soil-moisture content, in soils compressed to similar bulk densities. Those roots which developed in the same soil, compressed to identical bulk densities with a very small aeration porosity value, appeared identical to those developed under much better aeration porosity conditions.

This study does not prove the existence of physical impedance. It is true that roots are incapable of physical entry into soil material under some conditions, e. g., toxic concentrations of certain compounds and gases, moisture contents below the permanent wilting percentage, etc., but such situations are not intended to describe physical impedance. Careful examination of soil compressed above the threshold bulk density indicates that the roots were often able to dent the soil or to "etch" a groove in compressed soil material, but were incapable of further entry. Could not a toxic concentration of carbon dioxide surround a young root, which is tightly sealed in this atmosphere, prevent the further entry?

i. Rate of Elongation: In the previous considerations, the time factor was ignored with respect to root activity. Just as the rate of diffusion, or rate of mass flow, of gases may apply to a static situation with roots, the application of the time factor to a dynamic root situation may be equally important. We have identified roots in soils at various bulk densities and under various aeration porosity conditions. The fact that a single root, or a dense proliferation of roots, is noticed after the lapse of one year does not indicate the rate of activity of the root, or roots. The rate of root growth may possibly assist in understanding the effect on roots with respect to increased soil bulk density.

A technique which allows observation of elongation was devised and described in the "MATERIALS AND METHODS" section on page 16. Rates of root elongation in soils at various bulk densities were obtained from daily measurements of root elongation along plate glass windows. Figure 32 is typical of the data obtained and establishes a definite reduction in elongation rate with relation to increased soil bulk density. For two reasons, no attempt was made to establish the rate of deceleration of root elongation with increasing soil bulk density: 1. root elongation is sporatic; a root may elongate for a short period of time at one rate, then continue at a new rate or stop elongation completely for several days before continuing on. With such varying activity many hundreds of measurements would be required to establish a reliable mean elongation rate for each soil bulk density. 2. The presence of the compressed soil horizon destroyed the normal moisture drainage pattern, causing reduced aeration conditions. Roots elongated at a slower than normal rate in the loose soil above the compressed soil horizon due to the poorer moisture drainage. Bubbling air through porous aeration applicators allowed roots better aeration in the loose soil. Under applied aeration the roots elongated at about a 5 cm/day rate, which is normal for cane roots in loose soil. The effect of applied aeration on root elongation in compressed

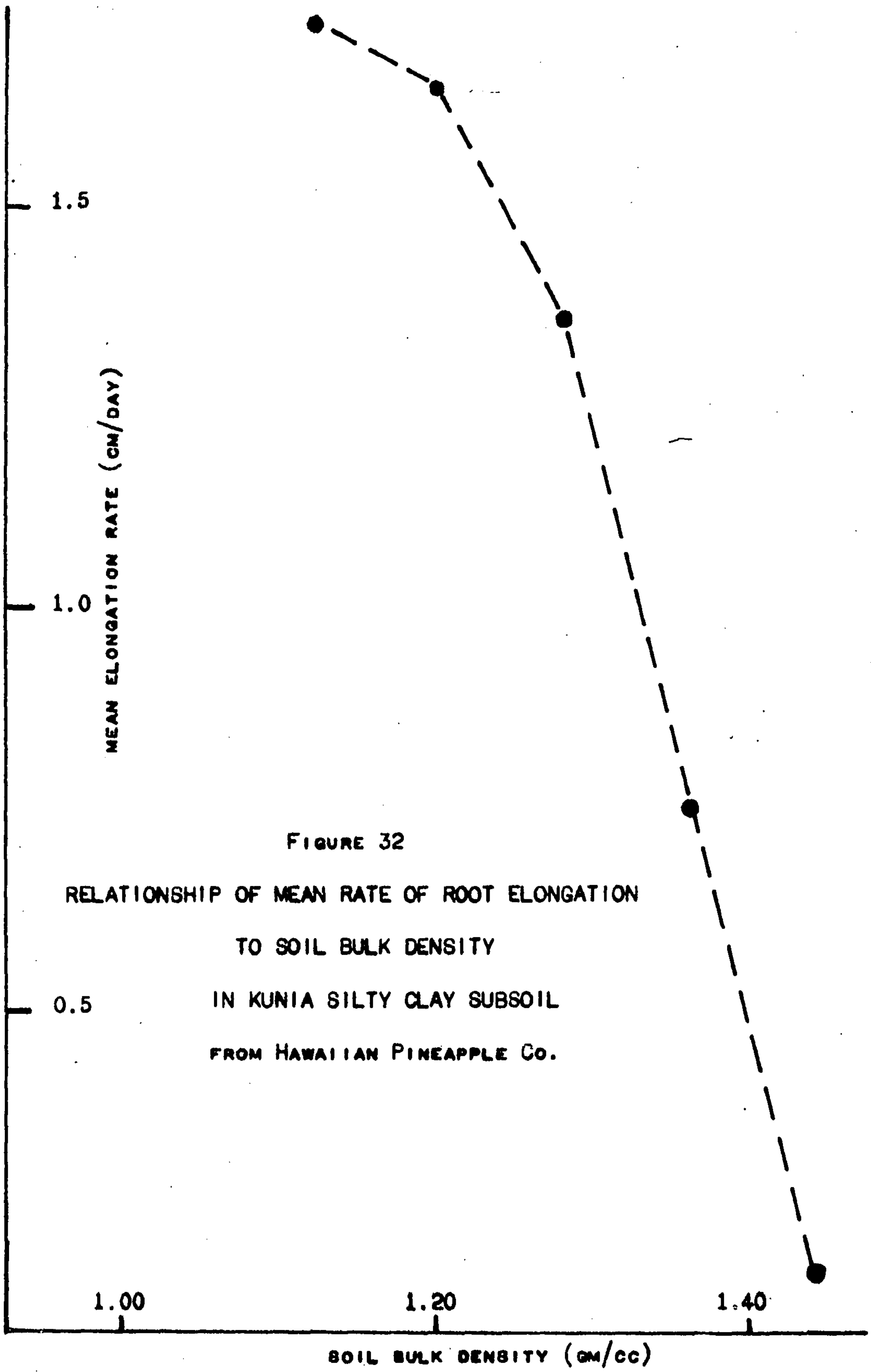


FIGURE 32

RELATIONSHIP OF MEAN RATE OF ROOT ELONGATION TO SOIL BULK DENSITY IN KUNIA SILTY CLAY SUBSOIL FROM HAWAIIAN PINEAPPLE CO.

soil restricts the use of the reported data to comparisons and raises a question as to the validity of the data, per se.

Gill and Miller (9) demonstrated a dual relationship with rates of root elongation for corn seedlings: they found a direct relationship with oxygen content and an inverse relationship with mechanical pressure. Again, under a dynamic situation the mass movement of a dilute oxygen source may be just as effective for root development as a richer oxygen source partially replenished by slower diffusion.

The slower rates of root elongation obtained using the window-box technique may be due to poorer aeration porosity and lower gaseous diffusion in the more dense horizons. Increasing resistance to the physiological pressure of a root forcing the root tip ahead, during cell elongation, may assist in slowing down the rate of root elongation in denser soil horizons. Should the resistance to physiological pressure be a major factor, one might suspect that cells are incapable of full elongation. Therefore, one might further suspect to find smaller cells with, perhaps, thicker cell walls, in roots which developed in denser soil.

j. Cellular Examination: In 1929, Hottes (12) published the findings of his research on the "intimate" relation between cytological functioning and cytological structure of roots. His results led him to believe that, during their period of activity, the cells are subjected to a continuous series of chemical and physical processes induced by internal, and modified by external, conditions: by controlled experimentation one may effect modifications to normal cell structure and functioning. From his studies on effects of pressure on the root tip, he reported that, in the axis normal to the applied pressure, the cells divided mitotically in the region of cell formation but failed to elongate, and the cells became deformed by enlarging into intercullular spaces: in the axis parallel to the applied pressure elongation was more extensive and the cells were more normal in size and shape. An examination of a cross section of such root tips frequently showed distinct evidence of a gliding growth: the cells in the diameter perpendicular to the confining pressure were mechanically prevented from elongation while those parallel to the pressure were free to elongate in that direction. He also describes differences in the cytoplasm and nucleus for the various regions of the root. Recently, Barley (2) substantiated alterations to cellular structure for roots grown under pressure.

From the present study on relationship of root proliferation in soils compressed to various bulk densities, in which both root weight and root density were determined, some suggestion of cellular variations might be apparent. The root volume relationship was investigated on the premise that roots developing in denser soil might, themselves, have an increased volume weight. Should this prove true, then root weight data might be misleading. The results of the root volume and root weight studies, however, show that the mean volume-weight value for sugarcane roots is approximately 1. 30 gm/cc, regardless of the soil bulk density. Figures 33, 34, 35, and 36 show that there is no evidence from this inconclusive study to suspect any

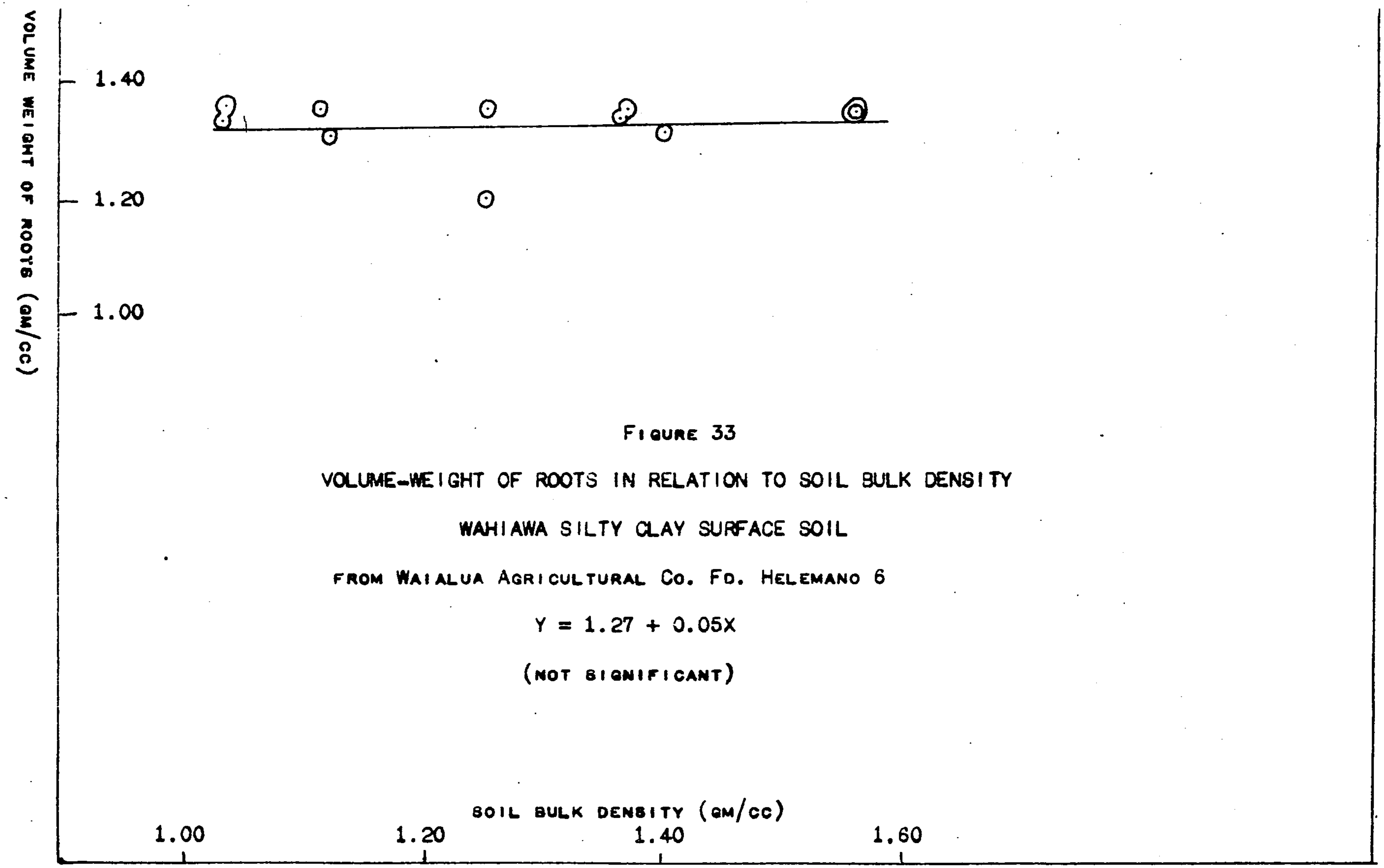


FIGURE 33

VOLUME-WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

WAHIAWA SILTY CLAY SURFACE SOIL

FROM WAIALUA AGRICULTURAL CO. FD. HELEMANO 6

Y = 1.27 + 0.05X

(NOT SIGNIFICANT)

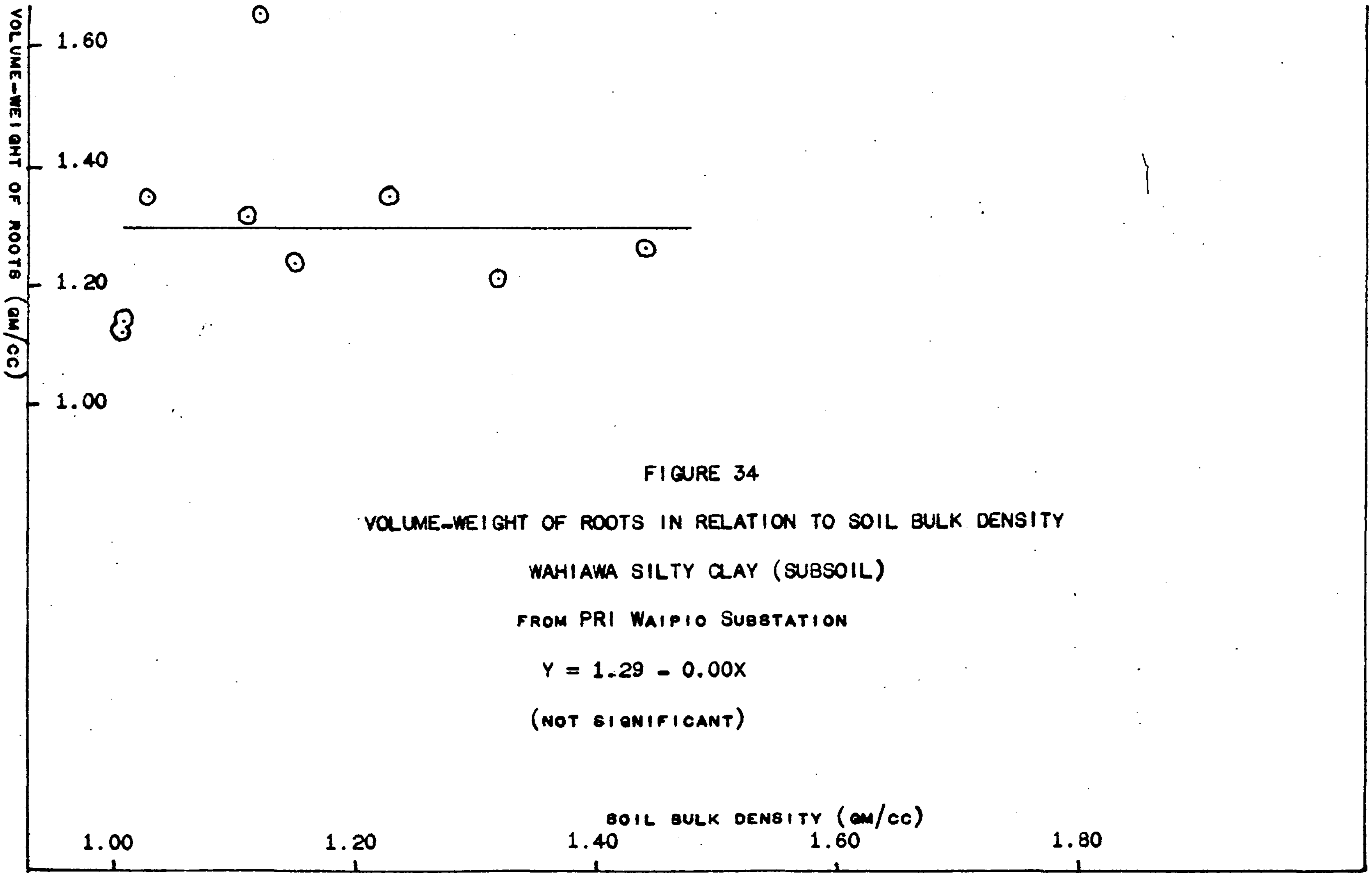


FIGURE 34

VOLUME-WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

WAHIAWA SILTY CLAY (SUBSOIL)

FROM PRI WAIPIO SUBSTATION

$Y = 1.29 - 0.00X$

(NOT SIGNIFICANT)

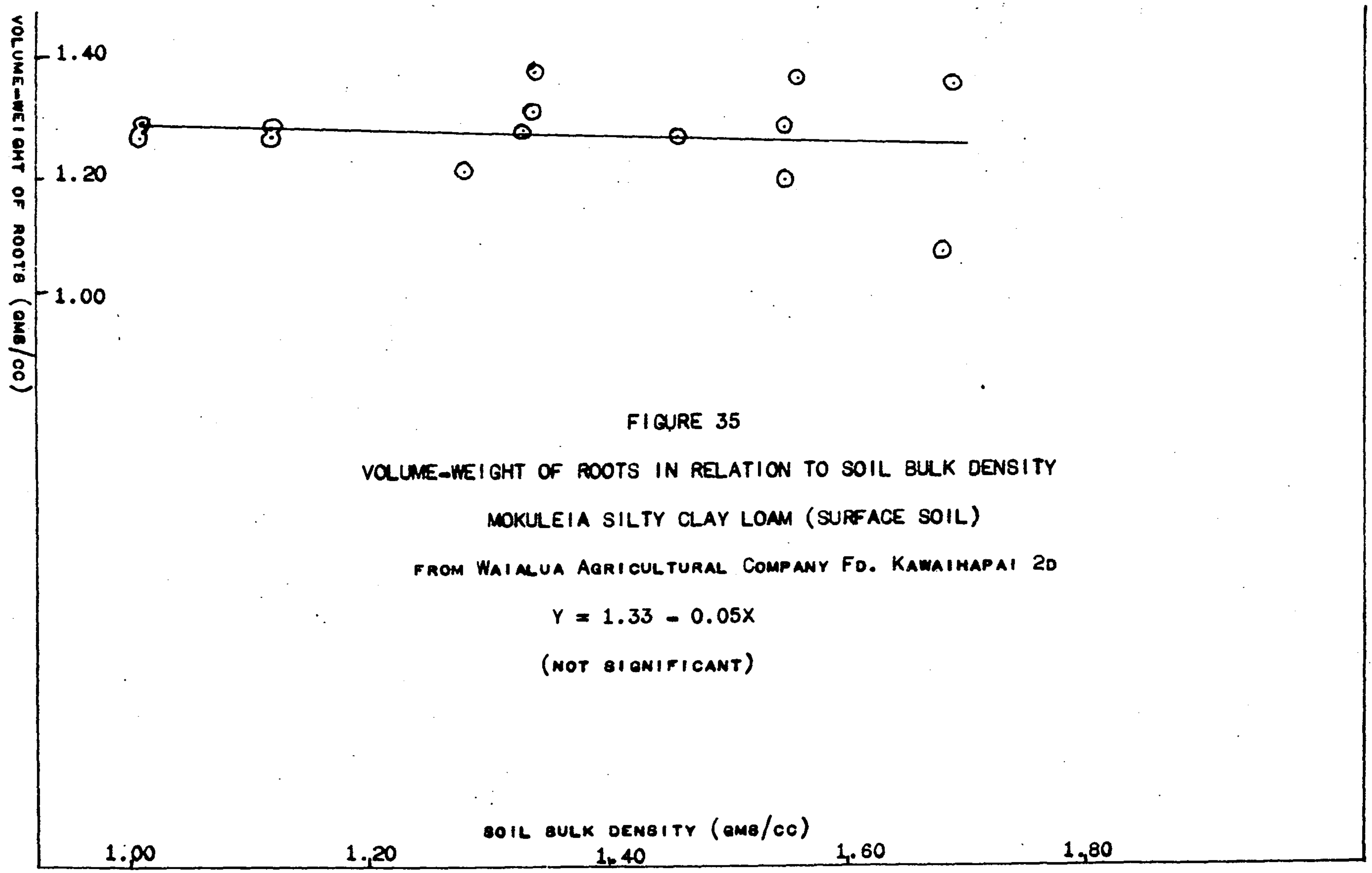


FIGURE 35

VOLUME-WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

MOKULEIA SILTY CLAY LOAM (SURFACE SOIL)

FROM WAIALUA AGRICULTURAL COMPANY FD. KAWAIHAPAI 2D

$Y = 1.33 - 0.05X$

(NOT SIGNIFICANT)

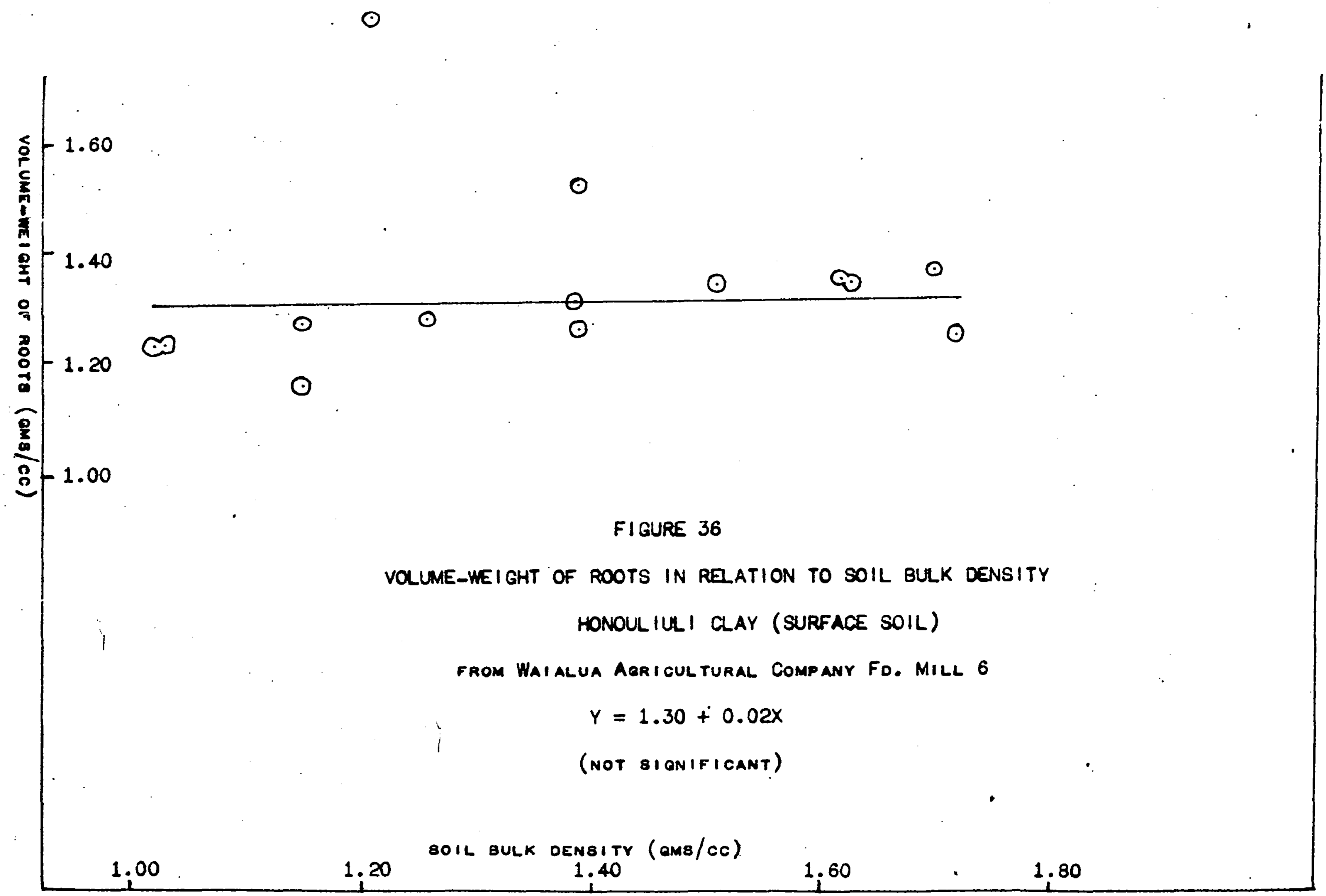


FIGURE 36

VOLUME-WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

HONOULIULI CLAY (SURFACE SOIL)

FROM WAIALUA AGRICULTURAL COMPANY FD. MILL 6

$Y = 1.30 + 0.02X$

(NOT SIGNIFICANT)

differences in cellular construction of roots developing in soil compressed to various bulk densities.

Microscopic examinations of root tissue were utilized to verify the suspicions of the imprecise root volume-weight comparison. These examinations were made on large roots, small roots, and young roots using tissues prepared for cross-sectional and longitudinal observations. After observing some 2,000 sections of cane root tissue grown in soil compressed to various bulk densities, it became obvious that the differentiations reported by Hottes for 5-day-old root tissue of Vicia faba were not as pronounced in the slides prepared using older cane root tissue. Figure 37 illustrates the close association of three sugarcane roots which developed in a fracture in a compressed soil. Observations of cross sections of older sugarcane root tissue which developed in fractures in compressed soil show pronounced flattening in the cortical region of roots. The stele is often flattened slightly, but cells within the cortex and stele do not show a decided flattening. Cortical cells of sugarcane roots tend to disintegrate after a few weeks' growth, thus forming the large chambers visible in the cortex. The roots which develop in loose soil do not show a flattening tendency in the cortex or in the stele although the disintegration of cortical tissue may cause a non-cylindrical contour. Figure 38 illustrates a sugarcane root which developed in loose soil.

Observations of longitudinal and cross sections of tissue of cane roots do not confirm the cell size differences reported by others for other plants. No obvious differences in cell size or cell wall thickness

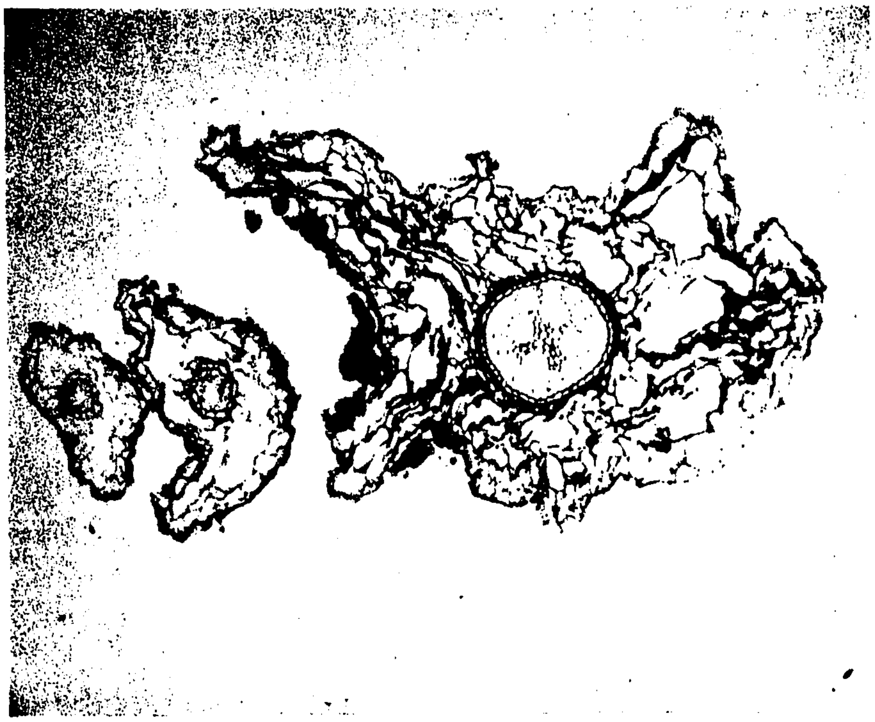


Figure 37. A cross-sectional segment of three roots in direct contact which developed in soil at a bulk density of 1.56 gm/cc. Although the cortex is badly distorted the stele is only slightly distorted and the individual cells show no distinct evidence of distortion.

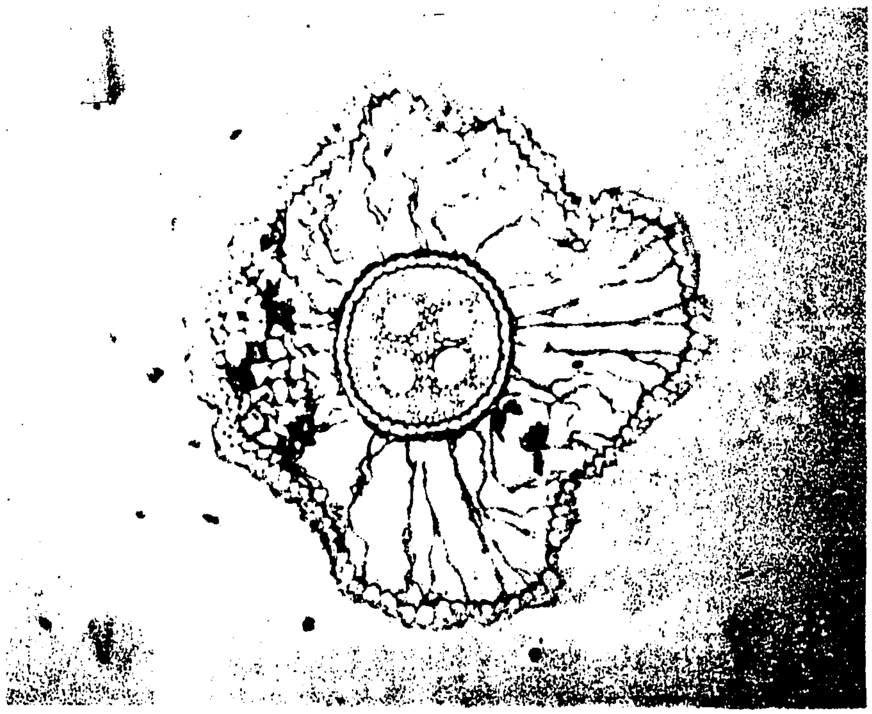


Figure 38. A cross-sectional segment of a normal sugarcane root. The cortical tissue is deteriorating, but the root still exhibits evidence of a circular habit.

were correlated with bulk density of soil in which cane roots developed. The possibility of cells swelling to normal dimensions during the treatment and impregnating process used to prepare the tissue for study was not investigated. However, the cells in the better quick-frozen tissue did not appear different from the impregnated ones.

2. STUDY WITH SOIL PROPERTIES:

a. Field Variability:

(1) Moisture Content: Application of a laboratory-greenhouse technique to study principles involved in increasing soil bulk density allows for accuracy that would not be possible using field studies. To cite an example of field variability, data from three soil sites are presented for soil materials used frequently in this study. Tables V, VI, and VII show the variability of one factor from three relatively flat areas, each of which covered 12 square meters. Twenty samples were taken at each 7.5 cm. level from each site to a depth of 52.5 cm. Although there were no micro-relief fluctuations which would obviously explain moisture variations, two of these tables present an approximate 8 percent moisture variation at each depth delineation. For the Low Humic Latosol Group, a Wahiawa silty clay was used and a Lualualei clay represented the Dark Magnesium Clay Group. The variations in soil moisture are much greater for the Hilo silty clay which represents the Hydrol Humic Latosol Group. The variations in soil moisture within short lateral distances are typical of field conditions in Hawaii: variations are even greater with depth of soil and with topographic variations.

Table V

SOIL MOISTURE VARIATIONS IN A WAHIAWA SILTY CLAY

Stations Gridded 1 Meter Apart—from Wahiawa Forest Site 184

Station	Depth in Centimeters 0-7.5	7.5-15	15-22.5	22.5-30	30-37.5	37.5-45	45-52.5
	SOIL-MOISTURE CONTENT (%)						
A-1	46.9	46.2	49.4	47.1	43.2	38.6	39.6
A-2	45.5	45.1	43.1	40.2	42.7	37.5	35.8
A-3	45.3	43.4	41.0	39.5	36.9	35.9	36.4
A-4	46.8	46.3	39.1	38.8	38.9	37.4	38.1
A-5	54.2	50.7	46.2	42.7	42.3	39.3	38.9
B-1	42.7	44.7	45.2	41.9	39.9	37.6	38.2
B-2	45.1	44.6	46.4	40.3	40.5	37.6	38.1
B-3	47.6	46.9	42.6	38.0	37.8	38.9	38.2
B-4	44.8	45.1	40.7	40.1	37.4	37.5	38.6
B-5	47.6	48.2	46.2	37.5	36.5	38.2	38.0
C-1	46.2	47.2	44.6	38.9	39.9	38.0	37.7
C-2	40.7	43.2	40.5	41.0	41.3	38.6	38.3
C-3	43.8	43.8	38.4	38.5	37.0	36.7	36.6
C-4	43.1	45.4	36.7	36.6	38.0	36.4	37.6
C-5	45.2	47.8	38.4	37.2	36.3	35.3	37.8
D-1	43.7	45.6	42.8	38.9	38.8	40.6	41.6
D-2	43.3	46.8	38.3	37.9	39.9	38.8	37.4
D-3	40.0	43.4	38.0	35.6	37.2	38.0	39.0
D-4	40.9	41.8	36.5	36.6	37.7	36.5	36.3
D-5	44.7	46.3	39.0	37.7	38.9	39.3	39.3
Mean	44.9	45.6	41.7	39.3	39.1	37.8	38.1
C.V. (%)*	6.89	4.50	8.92	6.61	5.39	3.39	3.43

*C.V. = Coefficient of Variability

Table VI

SOIL MOISTURE VARIATIONS IN A LUALUALEI CLAY

Stations Gridded 1 Meter Apart—from Lualualei N.A.D.

	Depth in Centimeters						
Station	0-7.5	7.5-15	15-22.5	22.5-30	30-37.5	37.5-45	45-52.5
			SOIL MOISTURE CONTENT (%)				
A-1	40.9	37.1	32.9	32.6	34.1	34.3	31.1
A-2	43.2	36.1	33.3	38.3	38.9	38.6	35.0
A-3	42.2	37.6	37.0	38.3	38.9	38.4	35.9
A-4	37.9	34.7	36.2	35.1	35.6	35.6	34.4
A-5	43.0	36.0	34.6	34.6	35.1	35.8	35.8
B-1	41.7	32.0	30.2	31.4	33.5	34.7	32.3
B-2	37.2	35.5	33.5	32.6	35.3	37.1	35.8
B-3	39.1	37.8	36.8	39.6	38.6	36.2	36.3
B-4	44.9	37.9	35.7	34.7	35.3	37.2	37.3
B-5	41.1	40.0	40.5	37.9	37.1	35.6	35.0
C-1	39.0	36.4	34.5	33.4	35.5	34.9	33.7
C-2	38.5	34.9	32.4	35.1	36.5	35.9	34.9
C-3	38.7	35.6	36.3	35.5	37.9	36.3	34.1
C-4	38.3	33.7	34.6	35.5	37.3	36.6	35.8
C-5	38.9	36.5	35.8	36.2	35.0	36.5	35.8
D-1	43.1	36.8	34.3	33.5	33.0	33.0	31.5
D-2	38.7	37.4	37.0	38.6	38.4	36.7	33.5
D-3	38.1	34.6	32.9	33.4	34.2	33.3	34.0
D-4	35.6	33.0	35.1	34.5	36.7	34.7	27.2
D-5	37.6	35.4	33.4	33.0	34.0	34.1	31.3
Mean	39.9	36.0	34.9	35.2	36.0	35.8	34.0
C.V. (%)*	6.16	5.17	6.34	6.58	5.16	4.21	6.98

*C.V. = Coefficient of Variability

Table VII

SOIL MOISTURE VARIATIONS IN A HILO SILTY CLAY

Stations Gridded 1 Meter Apart—from Hilo Sugar Company, Ltd. Field 9

Station	Depth in Centimeters 0-7.5	7.5-15	15-22.5	22.5-30	30-37.5	37.5-45	45-52.5
	SOIL MOISTURE CONTENT (%)						
A-1	82.6	95.9	92.8	112.1	189.5	234.7	241.6
A-2	96.5	105.6	97.5	93.7	112.9	219.1	223.7
A-3	94.6	106.3	107.6	128.6	124.6	212.8	255.7
A-4	91.2	120.6	144.2	216.6	205.7	190.8	286.2
A-5	105.8	140.4	127.5	238.5	197.3	259.1	280.8
B-1	82.9	100.7	98.8	116.6	192.4	200.1	254.9
B-2	80.9	102.9	114.7	113.5	197.7	229.1	226.2
B-3	99.1	112.0	207.0	134.8	201.0	215.0	306.4
B-4	106.3	125.6	145.0	166.4	169.8	221.0	285.1
B-5	100.0	162.9	132.1	283.0	175.2	239.7	275.9
C-1	105.9	181.1	112.9	206.1	183.5	237.8	213.3
C-2	101.8	126.5	131.1	157.0	190.0	302.3	269.6
C-3	131.4	137.9	259.4	161.2	233.1	237.3	293.4
C-4	128.8	163.6	295.3	306.6	229.4	234.8	264.4
C-5	100.6	156.3	185.4	206.4	235.4	308.2	295.5
D-1	101.9	116.9	131.1	136.8	240.9	313.1	293.5
D-2	120.1	162.6	195.6	113.8	172.5	231.2	296.4
D-3	107.4	111.4	143.6	132.0	195.2	245.2	289.6
D-4	134.2	186.7	164.6	196.5	222.9	246.7	258.4
D-5	100.9	182.8	168.9	218.1	217.9	260.6	277.1
Mean	103.6	134.9	152.8	171.9	194.3	241.9	269.4
C.V. (%)*	14.64	22.26	35.15	34.80	17.21	13.77	9.90

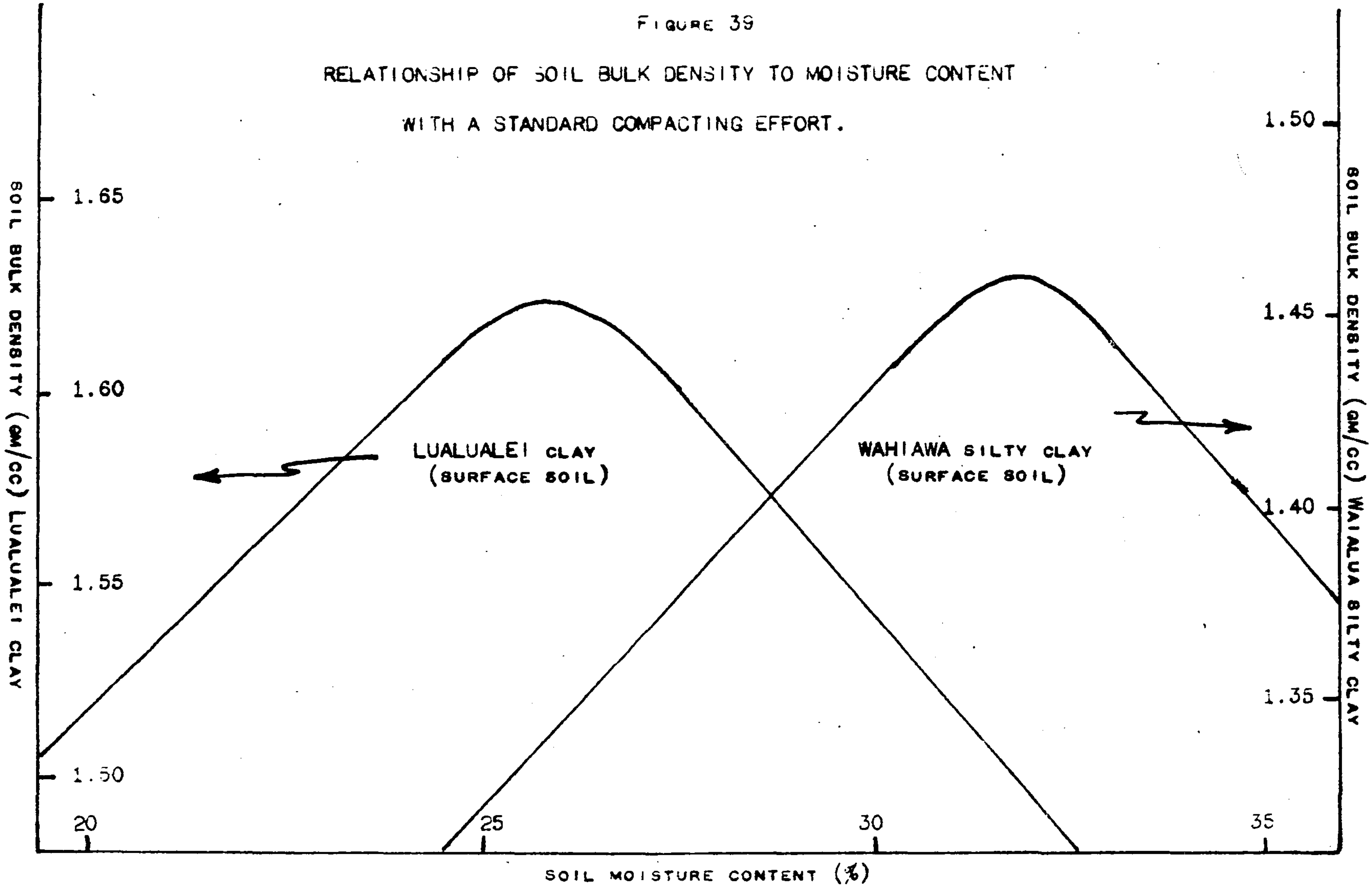
*C.V. = Coefficient of Variability

(2) Bulk Density: Since soil moisture is a dominant factor regulating soil strength (10, 15), it is possible that variations in density would result from vehicular traffic on areas of variable soil moisture. An estimate of variability in bulk density which can be achieved with a standard force can be obtained for the Lualualei clay and for the Wahiawa silty clay from Figure 39. With an 8 percent moisture fluctuation, for example, one can expect as much as a 0.2 gm/cc bulk density variation in these two soils. Considering that the Wahiawa surface soil spans the entire range of root degradation stages with a bulk density change of 0.5 gm/cc and the Wahiawa subsoil does likewise with about 0.4 gm/cc, the 0.2 gm/cc variation cited above is, therefore, excessive for precision research. It should be pointed out that the standard compaction curves presented in Figure 39 flatten out as extremes of soil moisture are encountered so that smaller differences in bulk density would result from pressure acting on soil at these moisture contents.

Associated with variations in moisture content, in horizontal as well as vertical axes, there are soil profile differences with depth: variations in clay content, structural type, structural strength, pre-existing density, etc., exist. The non-uniform compacting effort of a rocking, vibrating vehicle used in field studies introduces additional variables. Figure 40 shows how variable the soil bulk density was after an apparently controlled field test in a Wahiawa silty clay with traffic from one piece of equipment. Following the test, the range in variability of bulk density, for any depth delineation, was

FIGURE 39

RELATIONSHIP OF SOIL BULK DENSITY TO MOISTURE CONTENT WITH A STANDARD COMPACTING EFFORT.



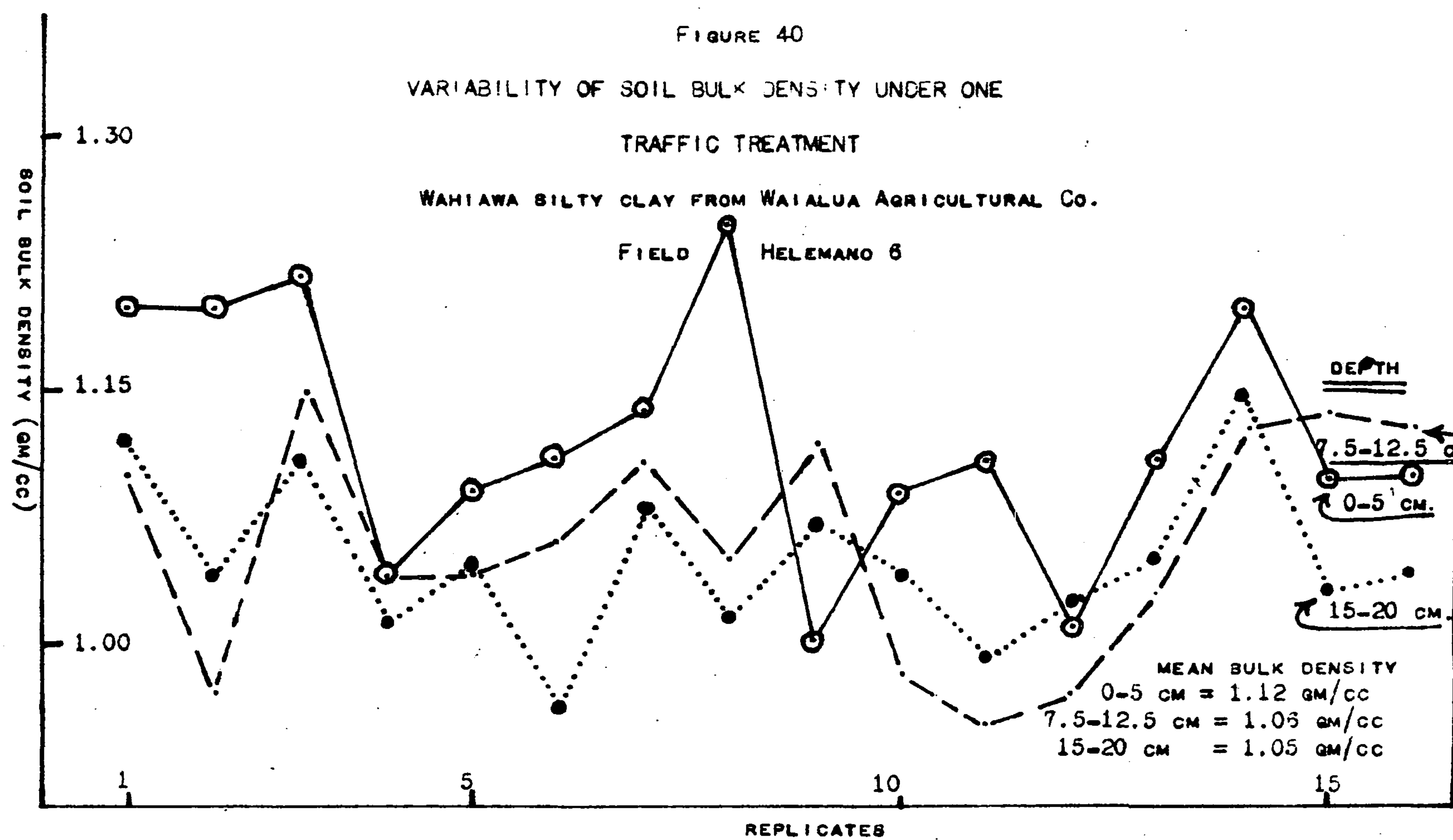


FIGURE 40

VARIABILITY OF SOIL BULK DENSITY UNDER ONE TRAFFIC TREATMENT

WAHIAWA SILTY CLAY FROM WAIALUA AGRICULTURAL CO.

FIELD HELEMANO 6

approximately 0.2 gm/cc; The bulk density replicates for the surface 20 cm. varied over a 0.3 gm/cc range. Although the mean values from 16 replicates did show an increase in bulk density within the surface 12.5 cm. of soil, approximately two-thirds of the samples from the most compressed level (0 to 5 cm.) were similar to those bulk densities found at lower depths. Field experience has guided the writer to expect fair correlation with 12 or more soil bulk density replications.

(3) Water Permeability: Useful information can be obtained from field studies provided that the pertinent variables are carefully considered and limited, and that there are adequate replicates. Frequently a more sensitive measuring criterion can be utilized in the field to show a relationship with fewer replications.

One of the more sensitive techniques for measuring soil deformation is the constant-rate field infiltration-permeability for water. Table VIII shows the relationship of traffic to permeability with just six replicates which are quite variable in themselves, but the mean values show a definite reduction in the rate of flow of water through the soil with increase in traffic. Just one pass of a loaded cane buggy, which had a surface ground contact pressure of 0.48 kg/cc, produced a 20-fold mean reduction in infiltration permeability. With additional traffic, the constant-rate infiltration-permeabilities are further reduced. Rates of reduction were so rapid that a semilogarithmic presentation was required to express the data in Figure 41. Increases in soil bulk density from six replicates of each traffic

Table VIII

RELATIVE SENSITIVITY OF CONSTANT RATE INFILTRATION-PERMEABILITY AND SOIL BULK DENSITY WITH VEHICULAR TRAFFIC

Hilo Silty Clay

Hakalau Plantation Co., Field 131-2

	INFILTRATION-PERMEABILITY (cm/hr) No. of Passes of Cane Buggy					BULK DENSITY AT 5 TO 10 cm. DEPTH (gm/cc) No. of Passes of Cane Buggy				
Replicates	None	1	2	4	8	None	1	2	4	8
1	29.32	0.70	1.16	0.82	0.49	0.71	0.69	0.79	0.82	0.85
2	Leak	5.97	0.52	0.85	0.34	0.71	0.62	0.76	0.77	0.81
3	40.23	1.98	0.21	0.06	1.55	0.51	0.77	0.74	0.74	0.71
4	19.51	2.19	3.75	2.01	0.09	0.68	0.74	0.58	0.68	0.72
5	124.36	1.58	0.52	1.71	0.12	0.58	0.65	0.79	0.78	0.69
6	Leak	0.34	0.34	1.71	0.09	0.62	0.86	0.69	0.84	0.86
Mean	53.36	2.13	1.08	1.19	0.45	0.64	0.72	0.73	0.77	0.77
C.V. (%)*	90.12	94.65	125.00	62.27	80.0	12.50	12.22	11.10	7.40	9.87

*C.V. = Coefficient of Variation

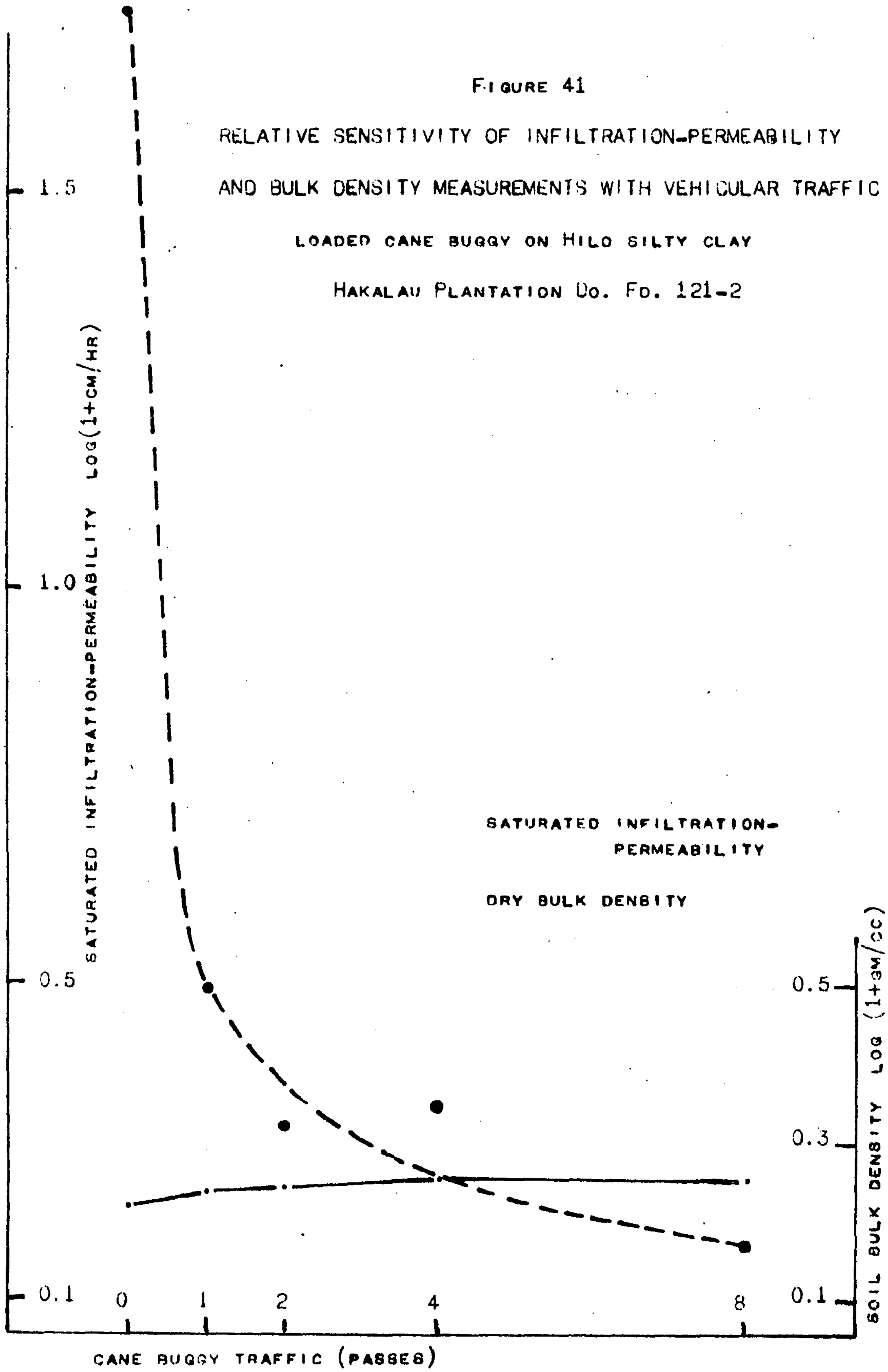


Figure 41
RELATIVE SENSITIVITY OF INFILTRATION-PERMEABILITY
AND BULK DENSITY MEASUREMENTS WITH VEHICULAR TRAFFIC
LOADED CANE BUGGY ON HILO SILTY CLAY
HAKALAU PLANTATION CO. FD. 121-2
SATURATED INFILTRATION-PERMEABILITY LOG(1+CM/HR)
1.5
1.0
0.5
0.1
SATURATED INFILTRATION-PERMEABILITY
DRY BULK DENSITY
SOIL BULK DENSITY LOG (1+GM/CC)
0.5
0.3
0.1
0
1
2
4
8
CANE BUGGY TRAFFIC (PASSES)

treatment were not statistically significant throughout the entire traffic treatment range studied, yet a slight trend of increasing soil bulk density was indicated. In this particular study, germination and early growth of ratooned cane were not reduced until two passes of a cane buggy had traversed the soil. Reductions in germination and early growth were quite spotty, but not excessive, except after eight passes of a cane buggy over the cane line. Thus, it can be seen that, as the infiltration-permeability rates are reduced, there are increases in detriment to the soil, but the detriment is not readily apparent in the crop until certain boundaries are exceeded and these boundaries were found to vary with different soils.

Another example of the effectiveness of the constant-rate field infiltration-permeability in assessing soil deformation can be obtained from Table IX. In this study the traffic was confined to a single pass, but the surface ground contact pressure was varied by use of various pieces of equipment. Although a slight reduction in the mean constant-rate infiltration-permeabilities exists between the untrafficked and the push-rake trafficked areas, there is lack of evidence of a reduction in the mean bulk densities. The deformation to the soil by a grab-loader can be expressed as almost a 17-fold reduction by the infiltration-permeability technique, but an 0. 05-fold increase by bulk density comparisons.

Often, after a certain soil bulk density is obtained, a much greater pressure is required to accomplish a small additional increase in deformation (6). As an example of this situation, a small reduction in

Table IX

RELATIONSHIP OF LOAD* TO THE INFILTRATION-PERMEABILITY RATE AND TO BULK DENSITY OF A HYDROL HUMIC LATOSOL

Honokaa Silty Clay Loam Field 7 Hamakua Mill Company

	INFILTRATION-PERMEABILITY (cm/hr)				BULK DENSITY (gms/cc) 0-20 cm. DEPTH		
Replications	Check	D-2 Push-rake	Model 355 Grab-loader	Empty Kenworth Truck	Check	D-2 Push-rake	M-335 Grab-loader
1	7.62	5.08	0.33	0.08	0.62	0.69	0.73
2	1.78	3.56	0.10	0.08	0.60	0.53	0.61
3	2.54	0.76	0.13	0.18	0.60	0.50	0.41
4	6.86	2.29	0.10	0.13	0.68	0.59	0.75
5	3.30	4.06	0.30	0.18	0.56	0.60	0.64
6	3.56	9.40	0.10	0.08	0.46	0.48	
7	8.13	3.30	0.10	0.46	0.60	0.66	
8	4.06	9.14	0.48	0.18	0.59	0.59	
9	10.16	5.08	0.15		0.64	0.39	
10	7.11	1.27	0.48	0.38	0.62	0.64	
11	6.10	10.92	1.47	0.08	0.56	0.54	
12	2.54	2.79	0.15	0.18	0.63	0.56	
13	3.81	4.32	0.58	0.18			
14	8.64	7.62		0.13			
15	7.11	2.54	0.10				
Mean	5.55	4.81	0.33	0.18	0.60	0.56	0.63
C.V.	46.99	64.24	112.12	65.00	9.17	15.00	23.49

*D-2 push-rake has a ground surface contact pressure of 0.32 kg/cc.
Model 355 grab has a ground surface contact pressure of 0.89 kg/cc.
Kenworth truck has a ground surface contact pressure of 6.69 kg/cc.

the constant-rate infiltration-permeability is obtained for a sevenfold increase in compacting effort when the empty harvest truck is compared with the grab-loader. The constant-rate infiltration-permeability in the empty truck route was about half of that obtained in the path followed by the grab-loader. This study has a weakness typical of field studies in which a change in one treatment will often alter more than one factor. The grab-loader stayed much longer in one location than did the moving truck of the other treatment: the grab-loader also has the added deformation capabilities of vibration and track impact which are much reduced by pneumatic tires on the trucks.

The height of the head used to determine the constant-rate infiltration-permeability did not appear to alter the flow rate significantly when the variations were maintained within 25 cm. and the rate of flow did not exceed 6 cm/hour. Schiff (22) reported on the effect of small variations in height of surface head and upon the lack of need for a double ring under the situations encountered in his study. Many comparisons were made with Hawaiian soils, after increase in soil bulk density, which did not indicate the need for a double ring to determine a constant-rate infiltration-permeability. Variations in flow rate were much greater between the test sites than were the variations due to a changing head height and buffering but, in order to reduce variations, the modified double ring was always employed.

b. <u>Laboratory Studies:</u>

(1) <u>Water Permeability:</u> The constant-rate field infiltration-

permeability measurement technique discussed above is quite applicable to field usage. When soil cores are brought to the laboratory, or when soils are artificially compressed within metal rings, and water permeability is determined by a constant-head permeameter, the results can be correlated with a specific sample. The intrinsic permeability may then be determined for specific bulk densities of a particular soil. Often, additional control of variables by laboratory methods does not appear to give greater precision to permeability measurement. This may, in part, be explained by disturbance of samples during transport, storage, trimming, or while conducting the test. Swelling, due to hydration of clay, causes some plastic deformation of structural units within the rings, and the small size of cores used (35 sq. cm. area by 4.5 cm. height) does not allow adequate lateral movement so that soil height becomes more difficult to maintain.

(2) Air Permeability: Air permeability measurements of soil cores appear to eliminate many of the difficulties encountered with water permeability determinations. Air permeability determinations allow the assessment of pore geometry of a soil at an existing bulk density, without alterations caused by clay swell. Air permeability is a measure of mass flow of air through the pores of a soil and it allows the assessment of the effects of moisture in opening and closing-off pore channels. Although Taylor (25) points out the weakness of measuring velocity of mass flow of air instead of rate of oxygen resupply for plants, there is a relationship between mass flow and diffusion.

The results of limited studies with Hawaiian soils indicated a good relationship of air permeability with root proliferation and development. The pressure of other studies did not allow further pursuit of this very promising, but unscheduled, study.

(3) Bulk Density: Under laboratory control, specimens of compressed soil can be manufactured which are quite uniform within: these specimens may be manufactured so that factors necessary to a study can be varied in the desired proportion while other factors can be either controlled or measured. Although many phases of compression can be better studied by use of laboratory experiments, often the results of such studies are not applicable to field use due to an incomplete understanding of the relationship of contingent factors.

Bulk density of a soil is usually expressed in terms of oven-dried weight of soil per unit volume of soil in the undried state, and is more correctly referred to as the dry bulk density. It is quite common for engineers to express bulk density as the weight of a unit volume of moist soil, or as the wet bulk density. Each expression has utilitarian advantages, but according to two engineers (5), the accepted definition for use with soil compaction is the expression based on oven-dry weights. Dry bulk density is the expression of bulk density with more applicability to agricultural usage and it is the commonly accepted expression of bulk density. Consequently, throughout this report, soil compression will be expressed in terms of bulk density, although bulk density, *per se*, is inadequate.

(a) Effects of Moisture: The bulk density of a particular soil material may be regulated by various means. Although pressure and time are important factors, the soil-moisture content is a most important variable from a practical aspect. Proctor (18) proposes that the effect of moisture ranges from a strictly surface tension phase, in which compression is nil, through a lubrication phase, in which compression is easily accomplished, to a saturation phase, in which water occupies the air space. Proctor developed the type of curves shown in Figure 39 but, unfortunately, he limited his views on ease of compaction to the thicknesses of the films of water around the particles which "lubricate" the particles, so that less energy is transposed to friction. Consequently, with a standard force, the better the "lubrication" the greater the compaction until the pores are completely filled with water. After pores are filled with water (zero voids) any additional moisture would reduce the relative amount of solid material in a sample and a lower bulk density would result. Although Proctor successfully explained his standard compaction curves with this mechanism, he failed to recognize a more important mechanism which will be discussed later. "Lubrication" can be applied to sands, gravels, and other impermeable particles but is only partially applicable to structural soil units which sorb moisture. Its effectiveness with structural units is evident when the compaction of a recently moistened structured soil is compared to compaction obtained with soil after moisture has been fully adsorbed by the structural units. In both of these situations, the moisture content is identical but, in the second case, the film of moisture around the structural units does not adequately assist in lubrication.

An additional effect worthy of comment is that, when the moisture is adequate to produce a zero void condition, calculations indicate some aeration porosity remains. In fact, with increasing moisture, more air is trapped during compression and a lowering of bulk density from the calculated zero void situation becomes greater until a moisture content, close to saturation under normal bulk density conditions, is reached.

(b) Effects of Pressure: Thus far, the effects of moisture on bulk density have been discussed using a standard force. From the standpoint of compaction, pressure can also influence bulk density. By increasing the driving force, instead of reducing resistance as occurs with increasing moisture, solid particles can also be pressed into a smaller volume. It has been demonstrated that, if the compacting pressure is great enough to move particles, or to cause plastic deformation and shattering of structural units, a greater bulk density is obtained at any moisture content than with a lighter pressure (34). When a greater pressure is applied, the maximum compaction point is obtained at a lower soil-moisture content. The zero void condition is also reached at a drier moisture content.

It should be pointed out that the mere fact that pressure has been applied to a soil need not infer that the soil is compressed. A soil may even be strained while under stress and recover when the stress is removed without an increase in bulk density.

(c) Effects of Time: Time is a difficult factor to fully assess. Soil does not completely respond immediately to pressure application; there is a time lag. Soil material also has a fatigue property and, although it may be capable of resisting a pressure for a short time, it is incapable of resisting strain when left under adequate stress for long periods.

When a soil is compressed and contained, the resisting pressure of the soil gradually diminishes. Within limits, if the time is increased before pressure is again applied, the pressure requirement for re-initiation of compression is usually increased. Closely correlated with time is the effect of multiple passes of vehicles: each additional pass increases the time of the pressure application and was found to be similar to the re-initiated compression applications discussed above. In the former case, however, the pressure was not held constant. Rate of pressure application, the length of time the pressure is maintained, and the period of time between repeated pressure applications have been commented upon. There is also a time factor involved with moisture which was discussed earlier. These aspects of time affect the resulting soil bulk density when compression is occurring.

In laboratory studies, it has been found that much less rebound is obtained when a soil is compressed to the desired bulk density and held under the confining pressure for one minute. If the confining pressure is not maintained, the rebound frequently alters the resulting bulk density appreciably. There is also an effect of time involved with the recovery from compression. Although geologists recognize rebound in deep sediment beds, hundreds of years after the removal of load, these are not now of pertinent interest. Compressed soil which is buried within a soil in a mild climate, or is stored in a laboratory where conditions are maintained, will remain at the original bulk density for at least 5 years. It appears that swelling and shrinkage, not time, are required of a compressed soil for reclamation. Naturally, the time factor is involved with the rate of intermittent straining which causes fractures to develop in compressed soil. Slow changes in temperature, or moisture content of large magnitude, or very rapid, small changes, do not appear to be effective in fracturing compressed soil. Lumps of compressed soil left on a soil surface, exposed to sun and rain, will disintegrate into loose "granular" tilth in a matter of months. The loose "granules" are dense fragments of the compressed soil and may not be similar to the original structural units.

(d) Effects of Other Factors: The bulk density of a soil can be increased by additions of naturally occurring, or manufactured, materials to partially fill existing pore spaces. Although materials may be added, this partial filling of pores occurs naturally where predominantly clay, but also lime, iron, etc., are eluviated to a particular horizon. Such action is so slow, however, that it is usually not considered with soil compression.

In recent years chemical additives have been developed which are capable of either reducing or increasing a soil's susceptibility to compaction. Soil additives usually function by reacting with the soil moisture or by affecting the strength of the structural units within a soil by some bonding mechanism. Although such materials are employed in the engineering field, their use in the agricultural field has not been practicable.

Soil bulk density is an important consideration of soil compression, but its measurement is only an expression of total weight of solid material per unit volume and does not necessarily relate pore space, pore geometry, or other important influences to the soil or to a crop.

(4) Total Porosity: Total porosity is an expression of the percent of the volume of a soil not occupied by the solid phase of a soil. Within this phase lie the keys to diffusion of oxygen and many other factors relating to root growth and development. However, the term "total porosity" does not present an indication of the size of the pores, the proportion of various sized groups of pores, the geometry of the pore passageways, nor the amount of moisture within the soil pore system. The moisture retained at the 15 atm. pressure treatment occupies that portion of the total porosity that is made up of fine pores which retain moisture tenaciously: plant roots are incapable of removing much moisture from this fraction of a soil. From a practical standpoint, very little of this portion of the soil volume should be considered as part of the aeration porosity. Pores that can retain moisture between the 15 atm. and the 1/3 atm. pressure treatments may contain the water, or plant roots may remove the moisture from these pores. Moisture retention curves present the percent of the total porosity occupied by pores with an effective size range established between these two pressures: these pores may either contribute to the water-filled pore percentage or they may be part of the aeration porosity. All pores larger than the 1/3 atm. pores are almost always part of the aeration porosity portion of total porosity.

It is generally agreed that the macro-pore sized pores are easily drained of water by gravity and are the pores through which diffusion is most active (16, 17). These macro-pores are considerably larger than the 1/3 atm. pores discussed above. Large pores have been difficult to define: various workers have used tensions of 30, 50, and 60 cm. of water to separate the so-called macro-pores from the micro-pores.

When a soil is compressed the total porosity is decreased. Regardless of bulk density, the water-filled void percentage will increase with increases in soil bulk density. With an increase in soil bulk density, the loss in total porosity is due to the destruction of large pores that compose a portion of the aeration porosity of the soil.

(5) Moisture Retention

a. For Moisture Estimation: The typical moisture-retention curves, as proposed by Richards (20), are utilized for two purposes, but these purposes are both related to the same factors. In the laboratory a technique, using applied pressure to approximate a tension situation existing in nature, is employed to estimate moisture needs of plants. It has been determined that a pressure of 15 atm. will drain enough moisture from a disturbed soil sample, of nearly saturated soil, to approximate the moisture content which exists in nature when a plant with a well-developed root system wilts and will not recover without water being added. At the other extreme, 1/3 atm. pressure will drain enough moisture from a disturbed sample, of nearly saturated soil, to approximate the situation which exists in a deep uniform profile of wet soil which has been allowed to drain by gravity. Moisture retention values obtained from pressures of 1/3 and 2/3 atm. were determined with the pressure membrane apparatus, which was used for greater pressures instead of with the porous plate which was used by Richards (19). It has been established, by unpublished research, that the results from use of the porous plate with Hawaiian soils were: 1. too variable, 2. not aligned with results from the pressure membrane apparatus, and 3. not representative of field moistures. The pressure membrane apparatus at a pressure of 1/3 atm. produced moisture contents close to those existing in the field under field capacity conditions.

The moisture retained between the 1/3 and 15 atm. pressure treatments establishes the range of so-called "available soil moisture" for plant and irrigation use. These moisture treatments also establish the usual range in field moistures for use by the laboratory technician so that testing may be concentrated at the more practical soil-moisture contents. Determination of intermediate pressures, from 1/3 through 15 atm., allow plotting a curve which suggests the pattern of moisture released from the soil to plants. In the primary investigation the moisture content at which the compressed soil cylinders were manufactured was determined from an analysis of both the moisture retention curve and the standard compaction curve for each soil.

b. <u>For Pore Size Estimation:</u> In the section on TOTAL POROSITY (page 118), the use of moisture retention was discussed with reference to pore size in order to relate which portions of the total porosity contained air, air and water, and water. In a later section, the use of pore size, as determined by moisture retention techniques, will be developed further. In general, it is believed that the thickness of moisture films surrounding soil units is determined by the "radius of curvature" of the water in adjacent pores. In a pressure membrane apparatus, the force developed by the radius of curvature of water within the pores will come into equilibrium with the air pressure used and excessive moisture will drain away through the membrane. After an equilibrium condition is obtained and drainage has ceased, the percentage of moisture can be determined for the soil.

It can now be seen that the resulting moisture content is the percent of water retained by certain sized pores in a soil expressed in terms of the dry weight of the soil. This percentage of water can be converted by calculation to an approximation of the volume of pores smaller than a certain effective diameter. The pores have been pictured as fine tubes, but such is not the case for pore geometry of soil. Due to pore geometry, the amount of moisture retained during moisture removal is different from the moisture content drawn in during a "wetting cycle." For this reason, all moisture values were determined on the "drying cycle" and are retained moisture values. What happens to the pores of a soil following an increase in soil bulk density can also be determined by using moisture-tension techniques of analysis, expressed as water percent.

c. <u>With Compressed Soil:</u> Table X was prepared for a Wahiawa silty clay subsoil: the same subsoil which will be discussed under STRUCTURAL DEFORMATION (Page 138). In this study several soils were compressed to bulk densities ranging from 1.00 gm/cc to 1.76 gm/cc, then dried and shattered. The values shown in Table X are the mean moisture-retention determinations, expressed on a weight basis, for the fragments larger than 5 mm., from 2 to 5 mm., and from 1/2 to 2 mm., from soil compressed above 1.00 gm/cc. Increasing the soil bulk density did not alter the volume of pores which retain moisture under the 15 atm. pressure treatment measurably. At a bulk density above 1.60 gm/cc, this soil was massive and all identity of the original structural units was lost to low power optical magnification. Yet, the volume of pores which retain moisture at the 15 atm. pressure treatment was similar to that retained by this soil at much reduced bulk densities. This, then, means that, although portions of the original structural units were deformed, the pore volume in this size range was not reduced by plastic deformation and that, at best, few new pores in this size range were created by destruction of larger pores. The moisture retention of this soil was not altered by compression until a 2/3 atm. pressure was applied. The volume of pores in this size range was reduced by 50 percent when the soil bulk density was increased from 1.00 gm/cc to 1.28 gm/cc. No further alteration in pore volume in this size range was obtained with an increase in soil bulk density from 1.28 to 1.76 gm/cc, under this pressure treatment. Table X

Table X

RELATIONSHIP OF MOISTURE RETENTION
TO SOIL BULK DENSITY
(WEIGHT BASIS)

Wahiawa silty clay subsoil   Wahiawa Forest

	Soil Bulk Density				
Tension	@ 1.00 gm/cc	@ 1.28 gm/cc	@ 1.44 gm/cc	@ 1.60 gm/cc	@ 1.76 gm/cc
	MOISTURE CONTENT (%)				
15 Atm.	29.2	29.2	29.3	29.4	29.2
8 Atm.	30.4	30.1	30.2	30.2	30.3
2/3 Atm.	35.8	33.2	33.2	33.1	33.4
60 cm H_2O	--	48.4	44.4	43.8	43.3
50 cm H_2O	--	48.6	45.9	45.0	45.5
40 cm H_2O	--	53.5	47.9	47.2	47.5
30 cm H_2O	--	64.7	57.9	59.1	57.7

shows that compression of this soil only reduces the larger micro-pores: these pores are easily destroyed with small increases in soil bulk density and the rest of the pores in this size range are unaffected during formation of higher bulk densities.

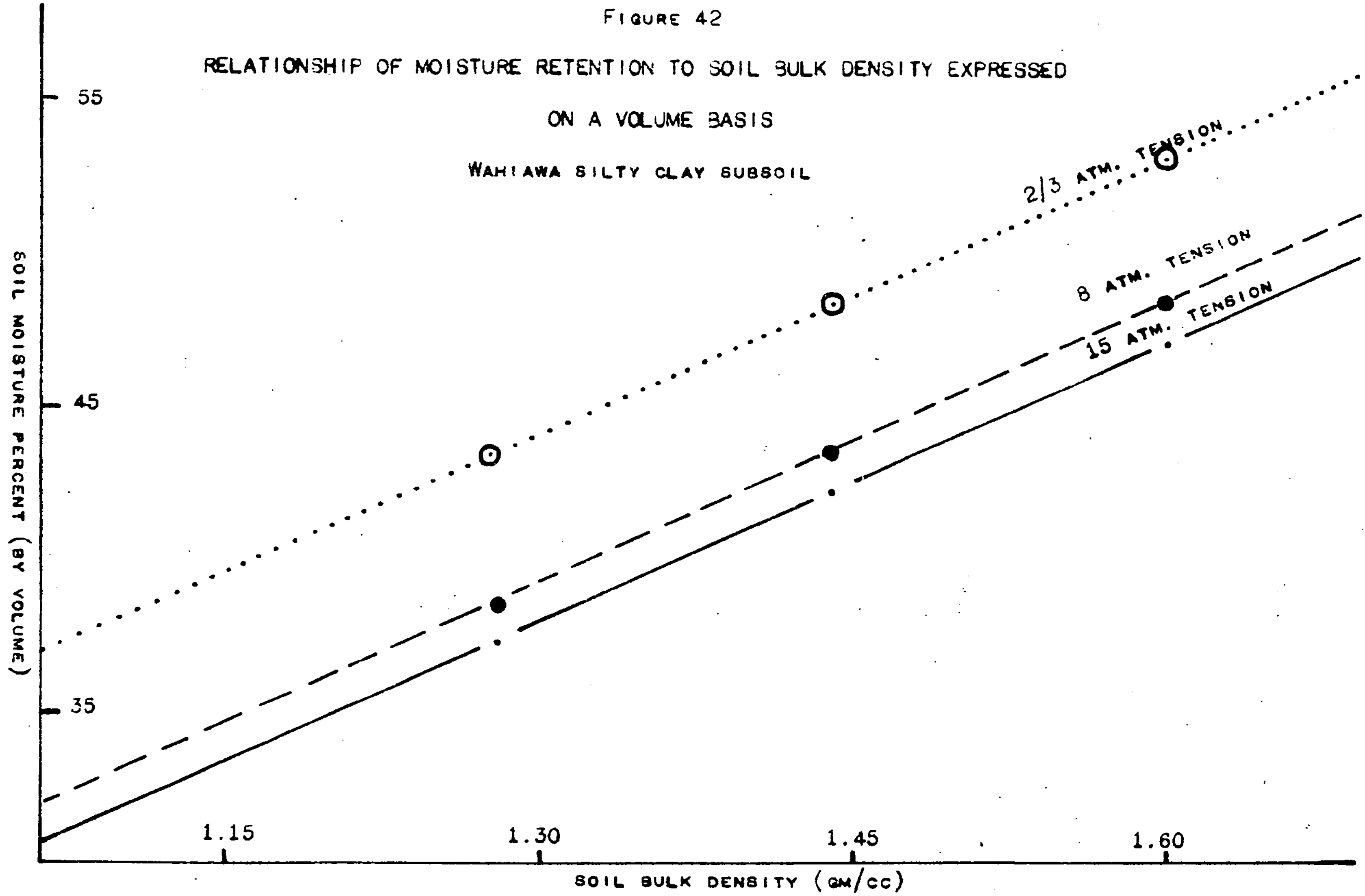
By use of a tension table, tensions were developed from 30 to 60 cm. of water, or approximately 0.03 to 0.06 atm., extending this investigation to the larger pores in the zone of separation between micro-pore and macro-pore. It is with larger micro-pores in this size range and with macro-pores that large volume changes occur when the soil bulk density is increased. Increasing the soil bulk density to 1.44 gm/cc did reduce by about a quarter the volume of pores in the size range between the 0.67 atm. pressure and the 0.03 atm. tension determinations. No additional pore volume loss in this size range was obtained by increasing the soil bulk density further to 1.76 gm/cc. The moisture retention for treatments below 2/3 atm. is partially dependent on moisture around the fragments and in the interfragmental pores. The use of fragmented soil nullifies the absolute value of the moisture content for the 30 to 60 cm. tension treatments.

An initial inspection might indicate that a volumetric examination of these data, with respect to pore volume, would be more meaningful than a determination of pore volume on a weight basis. Figure 42 shows an increase in soil-moisture retention (or pore volume) with an increase in soil bulk density, using the data from Table X expressed on a soil volume basis. The application of such a

Figure 42

RELATIONSHIP OF MOISTURE RETENTION TO SOIL BULK DENSITY EXPRESSED ON A VOLUME BASIS

Wahiawa silty clay subsoil



volumetric presentation of these data is often misleading when discussing soil compaction. During compaction, the soil weight stays constant and the soil volume is decreased. Any real change in pore relationships would be apparent in a weight analysis. The reason more moisture is retained at higher bulk densities in a volumetric analysis is that more soil, with a similar pore size and pore geometry, must be added to the sample to increase the compacted volume to the original soil volume. This added soil is responsible for the increased moisture content. The increased moisture retention is not due to the creation of a larger volume of small pores in soil at a higher bulk density.

The pore analysis discussed in the preceding paragraphs can be applied to all soils. The pore size relationship with bulk density of subsoil of most Low Humic Latosols follows the above pattern quite well. Other soils, composed of units with other strengths and with other pore geometry, may show different results. The moisture retentions at the 1/3 and the 15 atm. pressure treatments and the range between these two treatments present a practical estimate of the volume of pores in an important pore size grouping. Observation of pore volume reduction and deformation of structural units with increasing soil bulk density should supplement this mathematical study.

(6) Structural Deformation: For 12 years, structural deformation, following the application of pressure, has been observed and photographed. In this particular study, the soils were ground and screened through a 2-mm. sieve to eliminate the effect of pre-existing

large lumps of compressed soil. Although sieved soil offers the advantage of more uniformity it does have certain limitations: 1. fragments of structural units do not behave exactly as the natural peds, and 2. the natural porosity and pore geometry of the soil have been destroyed by grinding. With such attempts to create uniformity in the soil samples, uniformity does not result within the structural units or fragments. High magnification of thin section slides indicates that individual structural units do not always exhibit uniform porosity and, therefore, would not exhibit uniform strength. Roots which were allowed to proliferate in the soils created additional non-uniformity when roots move soil aside as they force their way through the soil (1).

To illustrate the effect of pressure on soil structural units, a set of photomicrographs was selected for each of two soils in which sugarcane was grown. These two soils were compared in earlier discussions. Although they have similar particle densities, roots were able to proliferate and develop much better in the Honouliuli clay, at higher soil bulk densities, than in the subsoil of a Wahiawa silty clay. For future reference, it might be well to mention that the moisture retention curves for these soils are different and, therefore, one might expect differences in the volume of pores for corresponding size ranges. Photomicrographs of polished thin sections of soil illustrate porosity better than the photomicrographs presented. The photomicrographs used in this report illustrate compressed soil in "terms" which are more common and more easily understood.

a. In a Honouliuli Clay Surface Soil: At a bulk density of 1.02 gm/cc the aeration porosity is 37.6 percent. In Figure 43, macro-pores larger than a millimeter in diameter can be seen, although most visible pores range between 1/4 to 1/2 mm. in diameter. A polished thin section photomicrograph of this soil is more than 60 percent space and mainly shows space with some segments of structural units. This type of photomicrograph gives a good view of total porosity, but does not illustrate the pore geometry and structural unit contacts as well. At this soil bulk density, the structural units are quite distinct, although some evidence of sub-rounded corners, due to handling, can be noted.

At a bulk density of 1.15 gm/cc, there appears to be a reduction in the pores in the 1/4 to 1/2 mm. range. In Figure 44, most of the structural units are still distinct, although the reorientation of structural units allows less point contacts. The larger pores are definitely distinguishable as root channels. Although this section is concerned with soil properties, some discussion of the action of roots is better explained in association with Figures 44 and 45 which graphically illustrate the compacting ability of roots. Roots have the ability to force soil particles aside or to cause plastic deformation of the structural units. The plastic deformation caused by roots is similar to that reported by Day and Holmgren (6) for mechanical compaction.

Soil movement by roots was confirmed by Barley (1) who described sand grains adjacent to root channels being disposed with

Figure 43. Porosity and arrangement of structural units which exist in a Honouliuli clay at a bulk density of 1.02 gm/cc. Scale is in millimeters.

Figure 44. A reduction in the macro-pores of a Honouliuli clay at a bulk density of 1.15 gm/cc. A loss of 8 percent in aeration porosity was obtained. Note the ring of soil compressed about the large root channel. Scale is in millimeters.

Figure 45. A Honouliuli clay at a bulk density of 1.23 gm/cc. The structural units are quite distinct except where roots have caused additional compression and plastic deformation. Scale is in millimeters.

flatter faces, rather than corners in contact, and with flat faces parallel to root channel boundaries. He also described soil adjacent to root channels of 1 mm. diameter as being more compact than the soil several millimeters removed from the channel. The findings of the writer indicate that all roots move some soil; the larger the diameter of the root or the more dense the soil, the greater the volume or the degree of the compression. These conclusions are limited to situations in which plastic deformation, or individual particle movement, occurs and where the pressure developed by a root does not exceed the shearing strength of the soil surrounding the root.

At a bulk density of 1.23 gm/cc there was a calculated aeration porosity of 25.5 percent. Although structural units are still quite distinct in Figure 45, between root channels, plastic deformation of structural units is obvious surrounding larger root channels and can even be noted surrounding smaller roots.

At a bulk density of 1.39 gm/cc there was a calculated aeration porosity of 17.7 percent. In Figure 46, plastic deformation of the structural units is more obvious and fewer of the macro-pores larger than 1/8 mm. remain. Roots and root channels are quite common at this soil bulk density in this particular soil. Figure 46 shows two sections of root channels which are parallel to the exposed surface: orientation of soil particles along the inner surface of root channels is indicated by the smooth surface and the striations. The inner wall of a root channel is characteristically smooth

Figure 46. A Honouliuli clay at a bulk density of 1.39 gm/cc. Plastic deformation of structural units around the larger roots is almost complete. Some plastic deformation is evident at contact points of structural units. Scale is in millimeters.

if the soil has an adequate clay content and if sufficient plastic deformation occurs. The striations are presumedly caused by the root acropetal of the region of elongation being forced through the soil.

At a bulk density of 1.45 gm/cc, there was a calculated aeration porosity of 11.4 percent. Figure 47 shows that most of the structural units have experienced some plastic deformation and that the original visible macro-pores are less common. The shrinkage cracks suggest the formation of new aggregates. It should be mentioned that, although roots are present, the proliferation is slightly less than that considered desirable for crop production.

At a bulk density of 1.56 gm/cc, the calculated aeration porosity was reduced to 4.2 percent. In Figure 48, the structure appears almost massive, although careful examination does show some pores and allows one to distinguish some fine-line separations between some portions of most structural units. The contact is almost complete between the peripheries of many structural units, as Area A of this photomicrograph indicates, but individual structural units still remain. At this soil bulk density plastic deformation is severe so roots have difficulty in developing.

At a bulk density of 1.62 gm/cc, the calculated aeration porosity was only 1.3 percent. Figure 49 shows that, under such a situation, a few rootlets are still capable of finding a suitable environment in which to develop. It appears that the complete destruction of the structural unit of the Honouliuli clay is difficult to obtain. Extruded

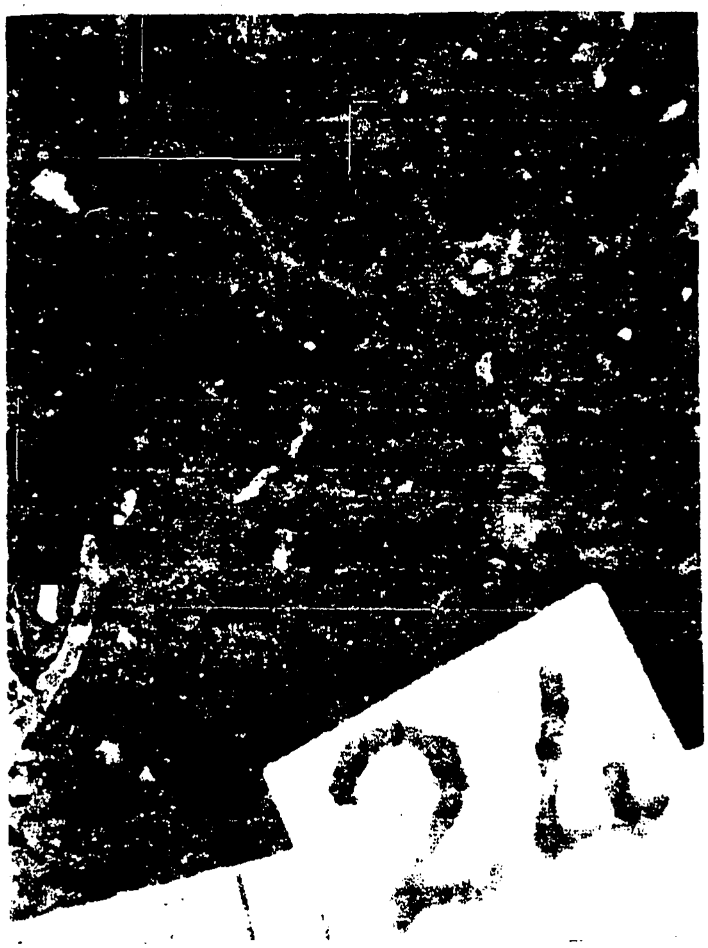


Figure 47. A Honouliuli clay at a bulk density of 1.45 gm/cc. Most of the structural units have undergone some plastic deformation and the original visible macro-pores are less common. Scale is in millimeters.

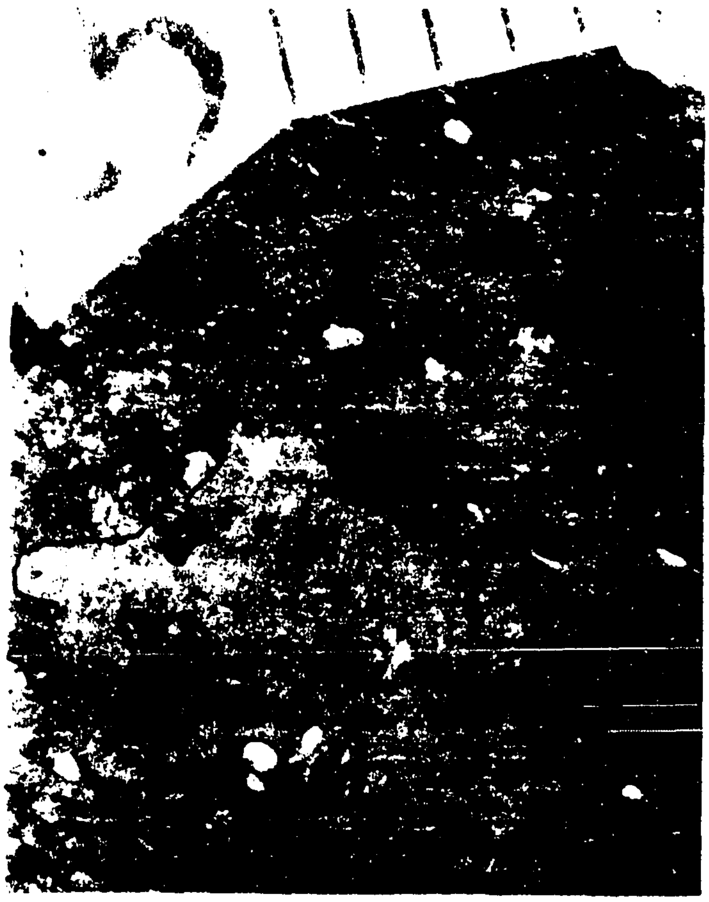


Figure 48. A Honouliuli clay at a soil bulk density of 1.56 gm/cc. The structural units are deformed to form almost complete contact with each other. The cut portion was prepared to illustrate just how complete contact is on a plane surface. Scale is in millimeters.

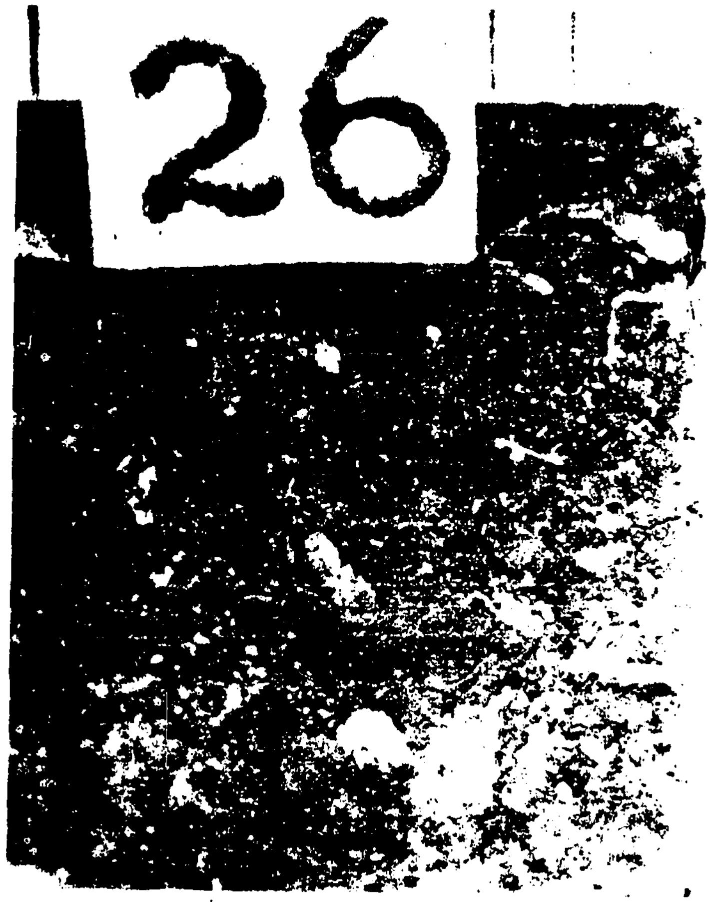


Figure 49. A Honouliuli clay at a bulk density of 1.62 gm/cc. Complete destruction of the structural units is not evident at this bulk density for this soil. Scale is in millimeters.

industrial clays are difficult to bind due to orientation of the clay minerals along the periphery of the extrusion. A similar situation may exist with structural units containing clay with swelling tendencies. Interaction along the periphery of the structural units, due to alternate swelling and shrinking, may orient clay minerals to make binding of such units difficult.

b. In A Wahiawa Silty Clay Subsoil: In order to observe the effects of structural deformation in a soil in which some stages of root degradation are obtained at a low bulk density, a set of photomicrographs of a subsoil horizon (60 to 72 cm.) from a Wahiawa silty clay is presented. This is the same soil which received a mathematical analysis of pore volumes for several effective size ranges on page 122. The real density of both the Honouliuli clay and this soil material is 2.88 gm/cc. The Honouliuli clay was compressed at a moisture content of 26.5 percent, while the Wahiawa silty clay was compressed at 29.6 percent moisture because of this soil's higher moisture content at the 15 atm. pressure treatment. The variations in moisture content should have little effect on the resulting structural changes since the compressive pressures were regulated to produce a specific soil bulk density. The additional moisture will decrease the calculated aeration porosity percentage reported, however.

At a bulk density of 1.01 gm/cc, the calculated aeration porosity is 35.0 percent. The visible pore sizes and structural unit arrangements are very similar to those of the Honouliuli clay at 1.03 gm/cc.

Many macro-pores about 1/4 mm. in diameter are evident. Although most structural units have their natural shape and the units are oriented, somewhat, many point contacts exist. Figure 50 illustrates the angular structural units with large pores around and between the units.

At a bulk density of 1.12 gm/cc, the calculated aeration porosity is 27.9 percent. Figure 51 shows the plastic deformation which is evident in portions of many structural units. There is a decided reduction in the number of larger macro-pores. Most pores larger than 1/8 mm. in diameter are definitely root channels.

At a bulk density of 1.23 gm/cc, the calculated aeration porosity is 20.9 percent. Figure 52 shows that most of the original large macro-pores have been destroyed but there are adequate pores in the 1/8 to 1/16 mm. range. Plastic deformation is quite common in some portions of most structural units. Almost complete plastic deformation occurs in the structural units surrounding the larger root channels. At approximately this bulk density, pore volume in the effective size range of the 2/3 atm. pressure treatment became seriously reduced.

At a bulk density of 1.37 gm/cc, the calculated aeration porosity is 11.8 percent. Figure 53 shows the severe plastic deformation of most of the structural units and that few original macro-pores remain. In fact, few pores which are not root channels remain above 1/16 mm. in diameter. Periphery contact of structural units is quite complete although many structural units still maintain their

Figure 50. A Wahiawa silty clay subsoil at a bulk density of 1.01 gm/cc. Most structural units have their natural shape although the units have been oriented into a tighter arrangement. Scale is in millimeters.

Figure 51. A Wahiawa silty clay subsoil at a bulk density of 1. 12 gm/cc. Plastic deformation is evident in portions of many structural units. Scale is in millimeters.

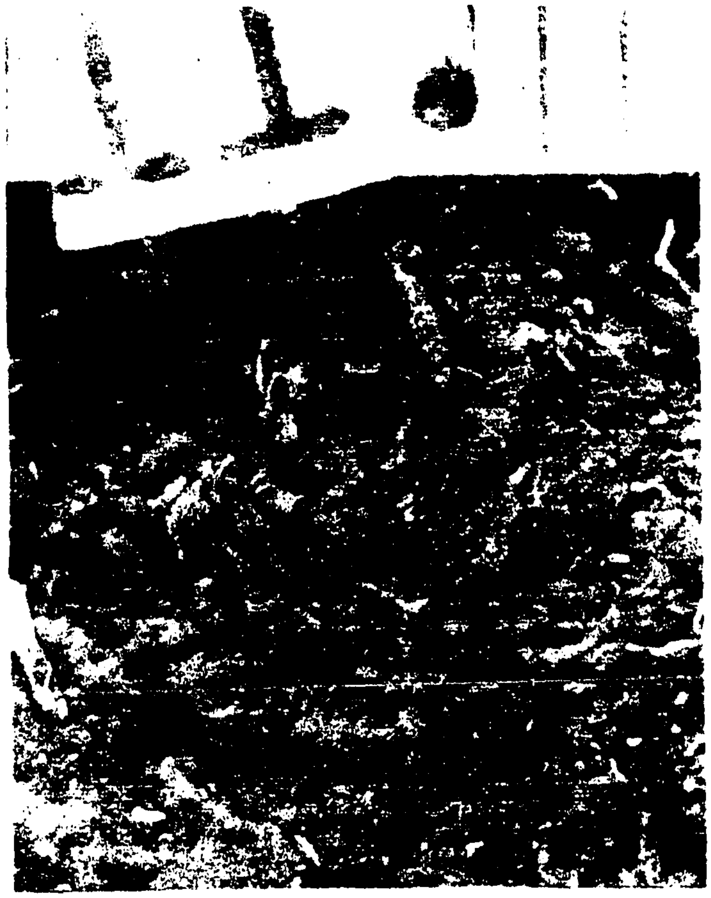


Figure 52. A Wahiawa silty clay subsoil at a bulk density of 1.23 gm/cc. Most of the large macro-pores are destroyed and some plastic deformation of structural units is common. Around large root channels the structural deformation is quite complete. Scale is in millimeters.

Figure 53. A Wahiawa silty clay subsoil at a bulk density of 1.37 gm/cc. Most of the structural units have undergone plastic deformation and few larger macro-pores remain. Scale is in millimeters.

identity. Unfortunately, the soil bordering root channels had undergone plastic deformation sufficiently to eliminate the larger macropores in these areas. Roots and rootlets have difficulty proliferating through the root channel into this soil and the distribution through the soil, therefore, becomes fairly poor. The effectiveness of this soil bulk density in restricting root development is similar to that of the Honouliuli clay compressed to a bulk density of about 1.55 gm/cc.

At a bulk density of 1.45 gm/cc, the calculated aeration porosity is 6.6 percent. Although most of the structural units have undergone severe plastic deformation, and complete periphery contact is common, Figure 54 shows that most structural units have not lost their identity. This soil is dense, but the structure is not massive. Very few roots are capable of locating a favorable environment in which to develop in this soil at this bulk density.

At a bulk density of 1.60 gm/cc, the calculated aeration porosity is -0.4 percent. Figure 55 shows that the structure is massive and that the soil is without a visible macro-pore. No roots were able to enter this soil at a bulk density above 1.60 gm/cc.

c. As Affected by Soil Moisture: To compress soil at various moisture contents to a specific bulk density, the pressure requirement is varied. When the moisture content is varied, the strength of the structural units is thereby altered, but the degree of plastic deformation resulting from compression to a specific soil bulk density appears equal.

Figure 54. A Wahiawa silty clay subsoil at a bulk density of 1.45 gm/cc. The structural units have undergone severe deformation and have almost made complete periphery contact. Scale is in millimeters.

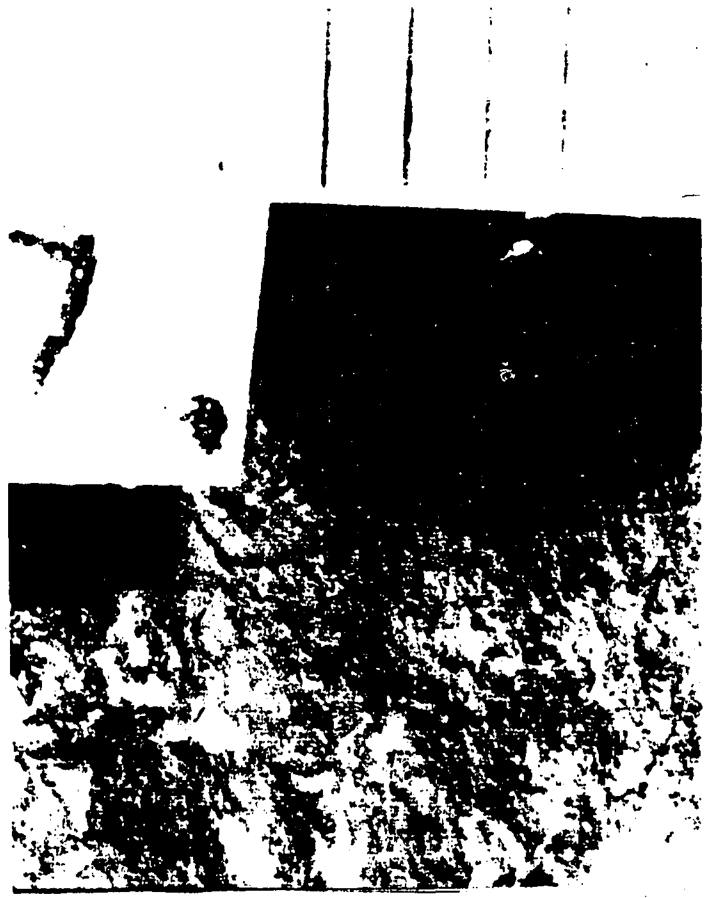


Figure 55. A Wahiawa silty clay subsoil at a bulk density of 1.60 gm/cc. The aeration porosity is reduced to zero and the structure is massive. Scale is in millimeters.

The soil-moisture content was varied from 15 percent to 40 percent by increments of 5 percent in a Honouliuli clay surface soil. The soil was compressed at each moisture content to bulk densities of 1. 28 gm/cc and 1. 57 gm/cc. Examination of the six samples compressed to 1. 28 gm/cc showed no evidence of any differences in pore shape or in plastic deformation of the structural units. The same was true of the five samples above 15 percent soil moisture which were compressed to a bulk density of 1. 57 gm/cc. The 15 percent moisture sample could only be compacted to 1. 53 gm/cc, but, at this bulk density, the structural deformation and pore geometry still appeared very similar to those in the samples compressed to 1. 57 gm/cc.

This study was repeated on 12 other soils with similar results. The deformation with these different soils did not necessarily appear similar to each other at either bulk density. The moisture differences at the time of compression appear to have no effect on structural deformation other than easing deformation. Naturally, if the pressure is held constant, the deformation will be greater in the more moist soils, but the bulk density will also be greater.

A special set of soils was compressed in an air-dry state, with moisture contents of 6. 8 through 9. 4 percent, to see if plastic deformation would occur at moisture contents about 15 to 20 percent below the lower plastic limit. In order to accomplish compression, a 20-ton jack was used, but a bulk density of 1. 28 gm/cc was the highest density achieved. Even in this dry state plastic deformation occurred in these confined samples. The heavy mold was slightly warped by the tremendous pressures required to compress these soils to a bulk density of 1.28 gm/cc, so higher densities were omitted.

(d) As Affected by Free Iron Oxide: Rose (21) reported that "crumbs" formed of pure kaolin broke down easily and that the clay was dispersed under mechanical action of "rain" drops. In his studies with other clay types under similar treatment, he observed practically no breakdown of crumbs and no clay dispersion. Since kaolinite is the dominant mineral of many of the Hawaiian soils used in the present study, a similar breakdown of structural units may be suspected with the mechanical action of stress. In the present study, however, the aggregates of Hawaiian kaolinites did not break down easily.

The presence of free iron oxide in fairly substantial quantities in Hawaiian soils might be suspected as being partially responsible for increasing the strength of the structural units. In Hawaiian kaolinitic soils, free iron oxide contents which varied more than twofold showed no evidence of increased resistance to plastic deformation. The Grey Hydromorphic Clay, which contains some montmorillonite, did resist plastic deformation better than the soils without montmorillonite, but free iron oxide did not appear to be a factor in the range studied.

c. An Estimate of Correlation between Soil Bulk Density and Root Deformation: The primary investigation has established at which soil bulk densities a certain stage of root degradation will occur for some soil series. The completion of this investigation would be relatively costly and a long period of time would be required to establish the limits for each important soil in Hawaii. A better criterion was not established to speed up the results of such a study, although a rough guide has been devised using the usual laboratory determination of physical properties of soil to indicate the soil bulk densities in which Stages D, E, F, and G root degradation will occur.

For a specific soil bulk density, the total porosity can be determined if the particle density is known. From the moisture retention curve for this particular soil material, the moisture retained at the 15 atm. pressure treatment will allow calculation of the volume of water-filled pores expressed as a percent of the whole soil (15 atm. moisture percent X soil bulk density). This value should, then, be subtracted from the total porosity value.

The pores larger than the 15 atm. tension pore are capable of supplying oxygen to the root. When the volume of these pores is less than 5 percent, very few roots can be expected to develop. When the pores larger than the 15 atm. tension pore have a volume between 5 and 15 percent, root degradation Stages D to E can be expected. When the pores larger than the 15 atm. pore occupy 15 to 25 percent of the soil volume, root degradation stages C to D can be expected.

A correction can be applied to soils with a larger than normal volume of "available" moisture. Soils which have a large volume of pores in the 15 to 1/3 atm. pressure range have a large volume of pores which are not easily destroyed by compression. These pores appear to be capable of supplying oxygen to the roots and roots developing in such soils appear in a better stage of root degradation at any specific soil bulk density than the 15 atm. volume percentage indicates.

Table XI shows the calculated values for three common soils in which the effect of increasing bulk density varies the aeration porosity. The estimated stages of root degradation may then be compared with the bulk density values in Table I (page 50). Table I shows that very few roots develop in Wahiawa silty clay subsoil above a bulk density of 1.47 gm/cc: Table XI shows a fair agreement. Very few roots develop in Wahiawa silty clay surface soil above a bulk density of 1.55 gm/cc: Table XI shows a fair agreement. The moisture retention curve of the Honouliuli clay (Figure 56) is shown to contain more available moisture than the Wahiawa silty clay. The curve presented for the Honouliuli clay shows an available range of only 9.6 percent which contains about 3.0 percent less moisture than is typical, but this is the curve for the identical Honouliuli clay presented in Table XI. With an increase of about 30 percent in volume of pores in the 1/3 to 15 atm. range, the roots are capable of developing better than the 15 atm. volume percentage indicates.

To test this system of estimating states of root degradation

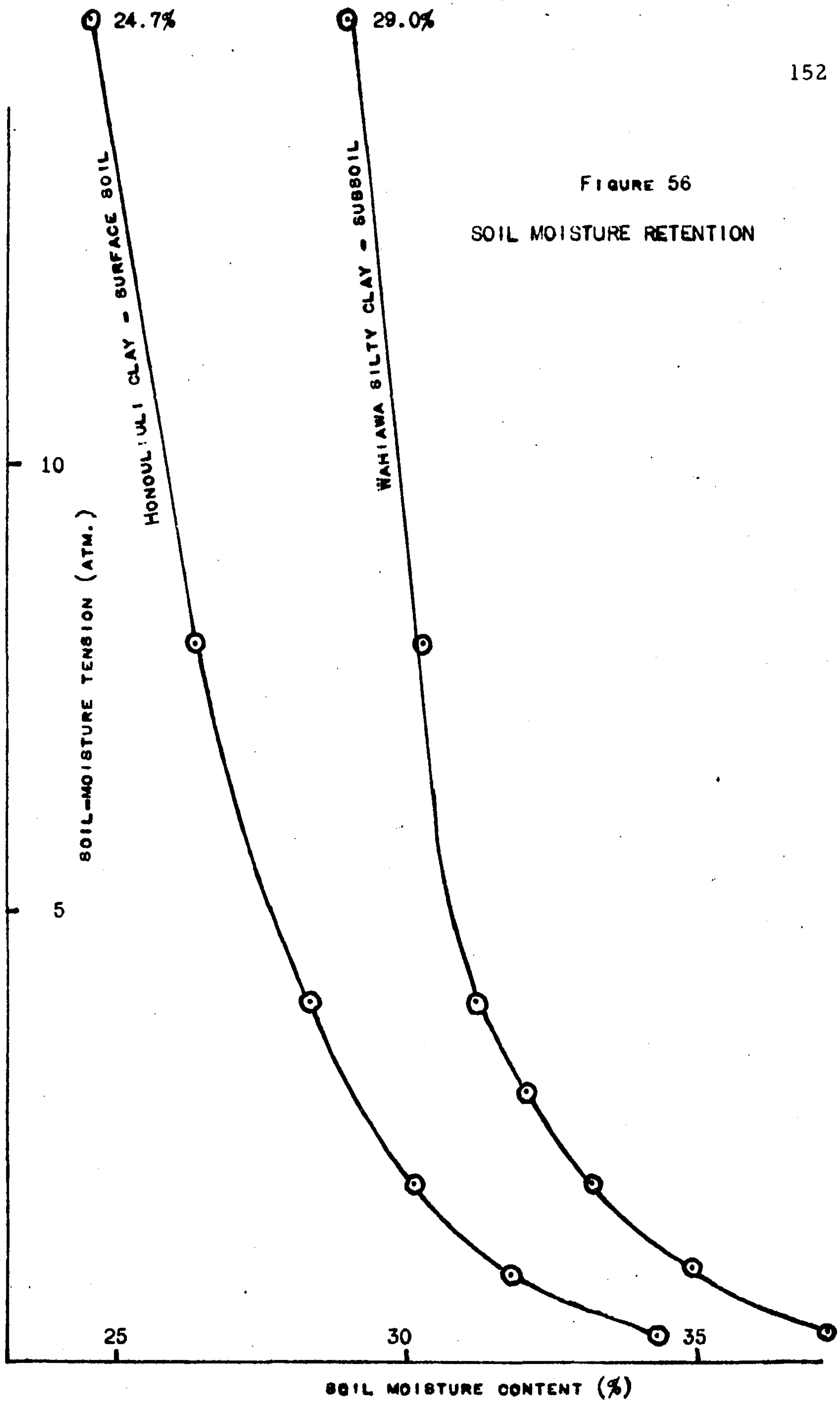
Table XI

RELATIONSHIP OF THE 15 ATMOSPHERE AERATION POROSITY
TO SOIL BULK DENSITY USING 3 SOIL MATERIALS

Soil	Soil Bulk Density (gm/cc) 1.37	1.45	1.56	1.61
	VOLUMETRIC SPACE (%)			
Wahiawa silty clay				
Subsoil				
Solid Material	47.57	50.35	54.17	55.90
Finer than 15 Atm. Pores	39.73	42.05	45.24	46.69
Aeration Porosity	12.70	7.60	0.59	-2.59
Wahiawa silty clay				
Surface Soil				
Solid Material	47.57	50.35	54.17	55.90
Finer than 15 Atm. Pores	34.80	36.83	39.62	40.89
Aeration Porosity	17.63	12.82	6.21	3.21
Honouliuli clay				
Surface Soil				
Solid Material	47.57	50.35	54.17	55.90
Finer than 15 Atm. Pores	33.84	35.82	38.53	39.77
Aeration Porosity	18.59	13.83	7.30	4.33

Figure 56

SOIL MOISTURE RETENTION



under extreme soil conditions, Table XII was prepared. The Hilo silty clay prevents root development at a bulk density of 0.96 gm/cc while the Paaloa silty clay loam allows good to fair root distribution at bulk densities as high as 2.71 gm/cc. The bulk densities presented for the Hilo silty clay are those given in Table III to separate the stages of root degradation. The 15 atm. pore volumes in Table XII are in close agreement with the aeration porosity values presented in Table III. Although the Paaloa silty clay loam was not one of the soils used in the primary investigation, the results in Table XII are in close agreement with field observations.

Table XII

RELATIONSHIP OF THE 15 ATMOSPHERE AERATION POROSITY TO SOIL BULK DENSITY AS EFFECTED BY THE PARTICLE DENSITY

Soil Bulk Density	VOLUMETRIC SPACE (%) Solid Material	Finer than 15 Atm. Pore	Aeration Porosity
Hilo silty clay ρ_p = 2.85 gm/cc 15 Atm. = 71.6%			
0.66	23.16	47.26	29.58
0.74	25.96	52.98	21.06
0.79	27.72	56.56	15.72
0.85	29.82	60.86	9.32
0.91	31.93	65.16	2.91
0.96	33.68	68.74	-2.42
Paaloa silty clay loam (Titanium) ρ_p = 4.01 gm/cc 15 Atm. = 10.8%			
2.65	66.08	28.62	5.30
2.71	67.58	29.27	3.15
2.78	69.33	30.02	0.65
2.84	70.82	30.67	-1.49
2.90	72.32	31.32	-3.64

CONCLUSIONS

Root proliferation and development are affected by soil bulk density. Restrictions to root proliferation and development gradually become more severe over a range of increasing soil densities. Seven stages of root degradation could be recognized for roots of sugarcane and occur in all soils studied. Although the roots of the other plants observed look different, the seven stages of root degradation could still be recognized.

It was determined that mass and volume of roots are decreased as the bulk density is increased; that Hydrol Humic Latosols affect root degradation similarly to other soils, but at much lower bulk densities; that the macro-morphological distortions to roots are increased with increasing soil bulk density; and that roots elongate at a slower rate in denser soils. There was lack of evidence that distorted roots, developing in dense soil, were less capable of physiological functioning. Anatomical effects to the cells were not evident in sugarcane roots which managed to develop in soils at greater bulk densities.

The primary investigation correlated seven stages of root degradation to soil bulk density of 27 soil materials from four soil Groups. Although good agreement of root degradation to soil bulk density was obtained with replicates of the same horizon of the same soil series, soil bulk density, per se, did not affect root degradation. Aeration porosity percentages were calculated for the 27 soil materials. Although a better agreement at each stage of root degradation was obtained for soil Groups with aeration porosity than was obtained with bulk density, it was determined that aeration porosity, per se, did not affect root degradation.

Field and laboratory studies were conducted in order to observe the effects of increasing soil bulk density. It was pointed out that, although field studies contain many unconsidered factors, it is possible, with enough replications, to detect the state of soil compression by determinations of soil bulk density or constant-rate infiltration-permeability. The infiltration-permeability technique proved to be much more sensitive, but the results could not be translated into presently accepted terms of soil compression. It was observed that the number of passes of a vehicle, surface ground contact pressure, soil-moisture content, time of application and structural units affect the resulting soil bulk density.

Total porosity is decreased with increasing soil bulk density. Total porosity is increased for soil at a specific bulk density as particle density is increased. Increased moisture reduces the aeration porosity. Root degradation does not appear to be affected by lower aeration porosity that is due to moisture content; however, the rate of root elongation is reduced. Reduction in soil strength, due to increased moisture, does not affect a "critical" bulk density of a soil with respect to physical impedance.

Pore volumes at the 1/3 and 15 atm. pressures were determined to be near the sizes which allow analysis of porosity for practical use. The 15 atm. pore volume was not affected measurably following plastic deformation of structural units by increasing the soil bulk density. Even that compression which resulted in a massive structure showed no alteration in volume of pores in this size range. Since these pores retain moisture which roots do not remove, they remain water-filled pores. The volume of pores which range between the 1/3 and 15 atm. size is reduced by increasing the soil bulk density somewhat. Some pores in this size range appear to present an environment in which roots can develop: the more of these pores, the better the roots appear to develop. A simple mathematical relationship has been devised from which root development in a particular soil material at a specific bulk density can be roughly estimated.

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APPENDIX

1. AN EXPLANATION OF PARTICLE DENSITY DETERMINATIONS FOR HYDROL HUMIC LATOSOLS:

The particle density of Hydrol Humic Latosols was determined in the standard manner in lieu of a better technique. In nature these soil particles behave as colloidal gels. The water associated with the particle is difficult to distinguish from added moisture since most of both are removed by heating to 110° C. The shrinkage upon drying is tremendous, as is the water loss. The weight of the particles is determined from a value which is "corrected" by the subtraction of the moisture loss from both sources. Determination of the particle volume by the water pycnometer method does not distinguish the water associated within the gel structure from that which is added.

The same difficulties arise with the determination of particle density of hydrated montmorillonities, but with a much reduced magnitude. The accepted measurement for particle density of a montmorillonite is based on the standard determination. Therefore, the particle densities of Hydrol Humic Latosols are presented from standard determinations, realizing that the colloidal gel existing in nature would have a much reduced, but undetermined, particle density.

Table A-XIII

HARVEST-WEIGHT OF CANE IN RELATION TO SOIL BULK DENSITY

Hilo Silty Clay

(Used with Figures 4, 5, 6, 7)

Hilo Field 22		Onomea Field 29		Pepeekeo Field 1B		Hakalau Field 9-1A	
Soil (gm/cc)	Per Mo. (kg)	Soil (gm/cc)	Per Mo. (kg)	Soil (gm/cc)	Per Mo. (kg)	Soil (gm/cc)	Per Mo. (kg)
0.64	0.401	0.66	0.438	0.65	0.454	0.74	0.462
0.66	0.455	0.66	0.408	0.66	0.448	0.74	0.370
0.66	0.472	0.68	0.457	0.67	0.440	0.77	0.362
0.75	0.462	0.76	0.328	0.75	0.444	0.83	0.398
0.75	0.479	0.78	0.446	0.75	0.484	0.85	0.358
0.76	0.455	0.79	0.412	0.76	0.448	0.85	0.460
0.84	0.514	0.80	0.478	0.84	0.364	0.88	0.422
0.84	0.479	0.82	0.384	0.87	0.393	0.91	0.379
0.87	0.404	0.84	0.386	0.87	0.446	0.91	0.384
0.88	0.451	0.85	0.411	0.89	0.484	0.95	0.349
0.89	0.488	0.86	0.423	0.89	0.508	0.96	0.388
0.90	0.522	0.86	0.440	0.92	0.477	0.97	0.356
0.90	0.482	0.88	0.426	0.97	0.468	1.04	0.371
0.91	0.431	0.89	0.413	0.97	0.458	1.04	0.414
0.91	0.438	0.89	0.416			1.04	0.381
Y = 0.40 + 0.08X		Y = 0.45 - 0.04X		Y = 0.41 + 0.05X		Y = 0.47 - 0.09X	
T = 0.84 N.S.		T = -0.32 N.S.		T = 0.50 N.S.		T = -0.95 N.S.	
D.F. = 13		D.F. = 13		D.F. = 12		D.F. = 13	

N.S. = Not Significant

Table A-XIV

WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY[1]

WACO Mill 6 Honouliuli Surface Soil		WACO Kapai 2D Mokuleia Surface Soil		WACO Hele 6 Wahiawa Surface Soil		PRI Substation Wahiawa Subsoil	
Soil Bulk Density (gm/cc)	Root Wt. (mg/cc)	Soil Bulk Density (gm/cc)	Root Wt. (mg/cc)	Soil Bulk Density (gm/cc)	Root Wt. (mg/cc)	Soil Bulk Density (gm/cc)	Root Wt. (mg/cc)
1.02	14.25	1.01	17.86	1.03	29.7	1.01	19.8
1.03	20.26	1.01	31.72	1.03	17.0	1.01	18.2
1.15	17.31	1.12	21.06	1.11	22.3	1.03	9.2
1.15	12.71	1.12	12.12	1.12	52.8	1.11	5.5
1.16	12.66	1.28	14.46	1.25	24.3	1.12	13.1
1.26	16.01	1.33	15.24	1.25	19.3	1.15	10.6
1.39	10.35	1.34	16.43	1.37	17.0	1.23	15.4
1.39	11.89	1.34	15.41	1.37	5.8	1.32	10.3
1.39	10.90	1.46	12.90	1.40	12.1	1.33	9.3
1.51	10.01	1.55	13.97	1.56	2.7	1.44	8.5
1.62	6.06	1.55	11.25	1.56	2.5	1.45	8.8
1.63	7.02	1.56	13.89	Y = 86.95-53.45X		1.50	15.5
1.70	3.86	1.68	12.03	T = -3.05*		1.50	1.9
1.72	3.01	1.69	8.18	D.F. = 9		1.51	
Y = 36.77-18.75X		Y = 39.03-17.32X				1.54	1.3
T = -7.92**		T = -3.57**				1.56	1.7
D.F. = 12		D.F. = 12				1.59	1.2
						1.60	1.6
						Y = 35.37-19.98X	
						T = -3.88**	
						D.F. = 15	

*Statistically significant
**Highly significant, statistically
[1]Used with Figures 24, 25, 26, 27.

Table A-XV

VOLUME OF ROOTS IN RELATION TO SOIL BULK DENSITY[1]

WACO Mill 6 Honouliuli Surface Soil		WACO Kapai 2D Mokuleia Surface Soil		WACO Hele 6 Wahiawa Surface Soil		PRI Substation Wahiawa Subsoil	
Soil Bulk Density (gm/cc)	Root Volume	Soil Bulk Density (gm/cc)	Root Volume	Soil Bulk Density (gm/cc)	Root Volume	Soil Bulk Density (gm/cc)	Root Volume
1.02	1.16%	1.01	1.41%	1.03	2.19%	1.01	1.76%
1.03	1.64	1.01	2.48	1.03	1.28	1.01	1.62
1.15	1.37	1.12	1.65	1.11	1.65	1.03	0.66
1.15	1.10	1.12	0.95	1.12	4.06	1.11	0.42
1.16	0.69	1.28	1.20	1.25	1.80	1.12	0.79
1.26	1.25	1.33	1.20	1.25	1.60	1.15	0.86
1.39	0.82	1.34	1.19	1.37	1.26	1.23	1.15
1.39	0.78	1.34	1.18	1.37	0.43	1.32	0.86
1.39	0.83	1.46	1.02	1.40	0.92	1.33	0.72
1.51	0.75	1.55	1.17	1.56	0.19	1.44	0.68
1.62	0.45	1.55	0.87	1.56	0.18	1.45	0.90
1.63	0.52	1.56	1.02	Y = 6.58-4.04X		1.50	1.56
1.70	0.28	1.68	1.13	T = -2.98*		1.50	0.23
1.72	0.24	1.69	0.60	D.F. = 9		1.51	
Y = 2.58-1.36X		Y = 2.99-1.30X				1.54	0.10
T = -6.65**		T = -3.30**				1.56	0.18
D.F. = 12		D.F. = 12				1.59	
						1.60	0.02
						Y = 2.65-1.43X	
						T = -2.56*	
						D.F. = 14	

*Statistically significant
**Highly significant, statistically
[1]Used with Figures 28, 29, 30, 31.

Table A-XVI

RELATIONSHIP OF THE MEAN RATE OF ROOT ELONGATION
TO SOIL BULK DENSITY

(Used with Figure 32)

Kunia Silty Clay Subsoil — Hawaiian Pineapple Company

Soil Bulk Density	Rate of Root Elongation
1.04 gm/cc	2.00 cm/day
1.12 gm/cc	1.73 cm/day
1.20 gm/cc	1.65 cm/day
1.28 gm/cc	1.36 cm/day
1.36 gm/cc	0.75 cm/day
1.44 gm/cc	0.17 cm/day

Table A-XVII

VOLUME-WEIGHT OF ROOTS IN RELATION TO SOIL BULK DENSITY

(Used with Figures 33, 34, 35, 36)

WACO Hele 6 Wahiawa Surface Soil		PRI Substation Wahiawa Subsoil		WACO Kapai 2D Mokuleia Surface Soil		WACO Mill 6 Honouliuli Surface Soil	
Soil Bulk Density (gm/cc)	Volume-Weight Roots (gm/cc)	Soil Bulk Density (gm/cc)	Volume-Weight Roots (gm/cc)	Soil Bulk Density (gm/cc)	Volume-Weight Roots (gm/cc)	Soil Bulk Density (gm/cc)	Volume-Weight Roots (gm/cc)
1.03	1.35	1.01	1.13	1.01	1.26	1.02	1.23
1.03	1.33	1.01	1.12	1.01	1.28	1.03	1.23
1.11	1.35	1.03	1.39	1.12	1.27	1.15	1.27
1.12	1.30	1.11	1.31	1.28	1.20	1.15	1.16
1.25	1.35	1.12	1.65	1.33	1.27	1.16	1.82
1.25	1.20	1.15	1.23	1.34	1.37	1.26	1.28
1.37	1.34	1.23	1.34	1.34	1.30	1.39	1.26
1.37	1.35	1.32	1.20	1.46	1.26	1.39	1.52
1.40	1.31	1.44	1.25	1.55	1.19	1.39	1.31
1.56	1.36			1.55	1.28	1.51	1.34
1.56	1.36	Y = 1.29 - 0.00X		1.56	1.36	1.62	1.35
Y = 1.27 + 0.05X		T = -0.00 N.S.		1.68	1.06	1.63	1.34
T = 0.57 N.S.		D.F. = 7		1.69	1.35	1.70	1.37
D.F. = 9				Y = 1.33 - 0.05X		1.72	1.25
				T = -0.45 N.S.		Y = 1.30 + 0.02X	
				D.F. = 12		T = 0.13 N.S.	
						D.F. = 12	

N.S. = Statistically Not Significant

Table A-XVIII

RELATIONSHIP OF SOIL BULK DENSITY TO MOISTURE CONTENT
WITH A STANDARD COMPACTING EFFORT

(Used in Figure 39)

Wahiawa Silty Clay Subsoil		Lualualei Clay Surface Soil	
Moisture Content (%)	Soil Bulk Density (gm/cc)	Moisture Content (%)	Soil Bulk Density (gm/cc)
18.8	1.26	15.9	1.44
20.0	1.26	17.7	1.48
22.8	1.25	19.6	1.51
23.7	1.27	21.7	1.54
25.5	1.26	22.2	1.56
28.3	1.34	23.6	1.59
29.1	1.42	24.0	1.60
30.4	1.43	24.8	1.61
32.1	1.46	26.1	1.62
33.5	1.44	27.0	1.61
35.0	1.40	28.3	1.57
37.0	1.35	29.8	1.55
		32.0	1.50
		33.6	1.46

Table A-XIX

VARIABILITY OF SOIL BULK DENSITY UNDER ONE TRAFFIC TREATMENT

(Used with Figure 40)

Wahiawa Silty Clay, Waialua Agricultural Company, Ltd. Field Helemano 6

	Depth (cm.)						
	0-5	7.5-12.5	15-20	22.5-27.5	30-35	37.5-42.5	45-50
Replicates	SOIL BULK DENSITY (gm/cc)						
1	1.20	1.10	1.12	1.14	1.12	1.15	1.19
2	1.20	0.97	1.04	1.11	1.16	1.12	1.21
3	1.22	1.15	1.11	1.06	1.04	1.10	1.13
4	1.04	1.04	1.01	1.01	1.10	1.11	1.14
5	1.09	1.04	1.05	1.14	1.13	1.26	1.20
6	1.11	1.06	0.96	0.95	1.10	1.14	1.31
7	1.14	1.11	1.08	1.03	1.08	1.13	1.14
8	1.25	1.05	1.01	0.96	1.13	1.21	1.20
9	1.00	1.12	1.07	1.04	1.08	1.20	1.25
10	1.09	0.98	1.04	1.14	1.14	1.25	1.21
11	1.11	0.95	0.99	1.12	1.17	1.12	1.15
12	1.01	0.97	1.02	1.12	1.19	1.12	1.19
13	1.11	1.03	1.05	1.08	1.19	1.21	1.27
14	1.20	1.13	1.15	1.20	1.17	1.23	1.20
15	1.10	1.14	1.03	1.11	1.06	1.02	1.05
16	1.10	1.13	1.04	1.02	0.99	1.04	1.05
Mean	1.12	1.06	1.05	1.08	1.12	1.15	1.18
C.V. (%)*	6.61	6.42	4.67	6.57	5.09	6.17	5.93

*C.V. = Coefficient of Variation

Table A-XX

RELATIONSHIP OF MOISTURE RETENTION
TO SOIL BULK DENSITY
(VOLUME BASIS)

(Used with Figure 42)

Wahiawa Silty Clay Subsoil from Wahiawa Forest

Soil Bulk Density (gm/cc)	Soil Material %	MOISTURE CONTENT (VOLUME BASIS) 15 Atm. %	8 Atm. %	2/3 Atm. %
1.76	61.1	51.4	53.3	58.8
1.60	55.6	47.0	48.3	53.0
1.44	50.0	42.2	43.5	47.8
1.28	44.4	37.4	38.5	42.5
1.00	34.7	29.2	30.4	35.8

Table A-XXI

SOIL MOISTURE RETENTION

(Used with Figure 56)

	MOISTURE RETENTION	
Tension (Atm.)	Wahiawa Subsoil (%)	Honouliuli Surface Soil (%)
1/3	37.3	34.3
2/3	35.8	32.6
1	35.0	31.8
2	33.2	30.1
4	31.3	28.4
8	30.4	26.4
15	29.2	24.7