ABSTRACT

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PHYSICAL PROPERTIES AND WATER USE BY MAIZE ON SOME TRINIDAD SOILS

Available water capacities, measured on five Trinidad soils, were greater than those normally quoted in the literature for soils of similar texture.

No significant changes in aggregate stability were observed during wet and dry seasons. Clay soils showed greater seasonal changes in bulk density, macro-porosity, and hydraulic conductivity than loam soils. The change in bulk density after cultivation was dependent on the clay content and mineralogy of the soil, the initial water content and its subsequent change. Uni-dimensional and three dimensional, normal shrinkage was observed in the clay soils. Three dimensional, normal shrinkage occurred only at lower moisture contents in the loam soils.

Differences in growth rate and dry matter distribution of corn, grown on four soils, were not related to rooting depth or water stress. On the soils, water use rates were similar and growth was not limited by water.

PHYSICAL PROPERTIES AND WATER USE BY MAIZE ON SOME TRINIDAD SOILS

by

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I. INTRODUCTION

These studies were made on soils in Trinidad, W.I., using the facilities of the Soil Science Department, University of the West Indies (U.W.I.), St. Augustine, Trinidad.

The Regional Field Experimental Program (R.F.E.P.) of the U.W.I. conducts fertilizer trials on a large number of West Indian soils. Interpretation of the response data has been difficult, partly because of uncontrolled variation in factors other than fertilizer applied. The corn crop is grown in the wet season without irrigation. Rainfall may be adequate, limiting or excessive on different soils, so comparisons of yield data from the soils may reflect the different soil moisture conditions under which the crop was grown.

The five soils studied included four which are used by the R.F.E.P. The fifth soil was selected because of its unusual properties. The objectives of the study were (a) to investigate some of the physical properties with special reference to seasonal changes, and (b) to evaluate growth and water use by corn on the four R.F.E.P. soils to attempt to explain yield differences in some of the R.F.E.P. soils.

II. REVIEW OF LITERATURE

1. Seasonal changes in soil physical properties

In the humid tropics, rainfall is the most variable climatological factor. There is usually an abundance of water in the wet season and a shortage during the dry season. Seasonal wetting and drying may, therefore, greatly affect soil physical properties related to moisture.

1.1. Bulk density and porosity

The effects of wetting and drying on the volume of soil blocks has been studied by several workers since Tempany (1917) and Haines (1923). Three stages of shrinkage have been observed as a soil block is dried from saturation. These are structural, normal and residual shrinkage. Rewetting causes swelling, the volume change being fully or partly reversible depending on the type of clay minerals (Yong and Warkentin, 1966) and the degree of drying.

As soil dries in the field, the reduction in volume causes an increase in bulk density. This volume change is normal (unit volume of water loss resulting in unit soil volume decrease) for soils wetter than the wilting point (Fox, 1964).

Within this range, the volume change is unidimensional above a certain moisture content and three dimensional below this point (Fox, 1964).

Total porosity is determined by particle density and bulk density in the relationship

$$n = 100\ (d-D_b)/d$$

where n is total porosity
d is particle density
and D_b is bulk density

As bulk density increases in response to drying, total porosity decreases.

When soil cores are used, macro-porosity is determined by saturation and subsequent application of suction. It is, therefore, difficult to interpret measured changes in macro-porosity and micro-porosity as the soil dries, since there will be variations in the amount of swelling as the soil is saturated from different moisture contents. Rowles (1948), using soil cores found that the total porosity and macro-porosity of a clay soil increased as the soil dried. The apparent increase in total porosity is probably due to soil variability since total porosity must be decreased. The measured macro-porosity changes were, therefore, influenced not only by variations in swelling but also by soil variability.

As porosity is reduced due to shrinkage, it is likely that macro-porosity will be affected to a greater extent than micro-porosity. This is supported by Gerard et al. (1966) who, observing samples microscopically, found that macro-porosity was decreased by slow drying at 27°C and 80% relative humidity.

1.2. Aggregate stability

Several workers have reported that aggregate stability in water decreased with increasing soil moisture content in the field (Gish and Browning, 1948; Kolodny and Neal, 1941; Wilson et al., 1947). These results were obtained when field samples were air-dried, and the analysis carried out on the air-dry samples. The data of Alderfer (1946) are in agreement with these findings, but also indicate that when the samples were analyzed in the field moist condition, the opposite results were obtained. Since this latter method represents the conditions existing in the field at the time of sampling these results can be considered to be more meaningful.

Evans (1954) found that incubating aggregates for 24 hours, after wetting from the air-dry condition, caused increased wet stability. He suggested that this was due to the hydration of clay particles with a resulting removal of planes of weakness which exist in the dried aggregates.

Cernuda et al. (1954) and Panabokke and Quirk (1957), obtained aggregates at different moisture contents by allowing the aggregates to come to equilibrium at various pF values. Their results indicate that aggregate stability decreases with decreasing soil moisture content. The opposite findings of the earlier workers is, therefore, due to the planes of weakness in the aggregates which develop as the moist soil is air-dried, and which cause breakdown when the aggregates are wetted.

2. Growth and water use of corn

2.1. Reactions of corn growth and yield to soil water conditions

Corn growth and yield react differently to soil water conditions. Kiesselbach and Montgomery (1911) and Kiesselbach (1916) grew corn in potometers under varying soil water conditions. They found that the greatest ear weight was produced at 60% soil saturation, whereas maximum total plant weight was produced at 80% soil saturation.

2.1.1. Effects of water stress

Water stress can be considered to be a plant condition where the rate of water supply to the plant is inadequate to maintain it at full turgidity without compensating physiologic or other damage (Robins _et al_., 1967). Such compensation may be by wilting, by stomatal closure, or by internal adjustment of solute concentration to maintain positive turgor pressure. Water stress is usually associated with a reduction of the soil water content in the root zone to a point where the potential evaporation exceeds the rate at which plant roots can absorb and/or transmit water to the above-ground parts.

The work of Peters (1957) demonstrates that under conditions of low evaporative demand, decreasing soil water content causes very little stress, whereas under conditions of high evaporative demand, stress is caused by slight reductions in soil water content. Moss _et al_. (1961) observed that corn growing in dry soil had slower rates of assimilation at midday than corn growing in soil kept at field capacity, but rates at morning and evening were similar.

Corn leaf growth is more affected by soil moisture fluctuations than any other part of the plant (Miller and Duley, 1925). Baker and Musgrave (1964) found that soil moisture stress reduced the rates of apparent photosynthesis and growth of corn by up to 50% at suctions of less than one atmosphere. Apparent photosynthesis was reduced at or before the stress level was reached where decreases in transpiration occurred. Photosynthetic efficiency always recovered immediately on reduction of the water stress.

Kemper _et al_. (1961) noted that the reduction in growth due to stress was partially compensated by a more rapid growth rate following the release of the moisture stress. The rapid growth rate was reduced in 4 days of the release of stress. Miller and Duley also found that the magnitude of the compensation varied with the stage of growth.

Prolonged or severe stress during early growth resulting in leaf desiccation markedly reduces plant height and vegetative growth (Robins _et al_., 1967). Root growth is less affected by water stress. Harris (1914) found that the shoot-root ratio for corn decreases with decreasing water content.

The shoot weight decreases linearly with decreasing water content. The root weight, however, is at a maximum at about 20% gravimetric water content and decreases as water content is raised or lowered from this point. The 20% value would be specific for the medium used (coarse sand) and does not have any general application. The decreased growth at higher moisture contents is the result of poor aeration, whereas that at lower moisture contents is the result of water stress.

Miller and Duley (1925) studied the influence of varying water supply during the growth period on the shoot-root ratio of corn. Their results show that reducing the soil water content during the last one-third or first one-third of the growth period resulted in a narrowing of the ratio as a result of both reduced top growth and increased root growth.

The effect of water stress on corn growth is modified by the water content. Peters (1957) grew corn on mixtures of a silty clay loam and sand. Results indicate that corn root elongation decreases with decreasing water content at constant water suction. A similar relationship was observed in shoot elongation as water stress was developed under high evaporative demand (Peters, 1960).

Corn can withstand appreciable water stress without loss in yield except during the period from tassel emergence to the completion of pollination (Carlson _et al._, 1961; Howe and Rhoades, 1955; Rhoades _et al._, 1954; Rhoades and Nelson, 1955; Robins and Domingo, 1953). Moisture stress during this period reduces yield greatly. Robins and Domingo (1953) found that a 2-day deficit during this period reduced yield by 22% and a 6-day deficit, reduced yield by 50%. Denmead and Shaw (1960) also reported 50% reductions in yield resulting from water stress during this period. Reduction in yield due to water stress at this time is largely due to pollination failure in which the grains form on only part of the ear (Robins and Domingo, 1953).

Dale (1964) is reported by Shaw and Burrows (1966) to have explained 81% of plot yield variations in corn on the basis of moisture stress occurring between 6 weeks before and 3 weeks after silking. When there were more than 30 stress days (days when the turgor loss point of corn was exceeded) in the period, water stress was the dominant factor reducing yield. When there were fewer stress days, other factors became limiting.

Severe or prolonged water stress with significant wilting of leaves during vegetative growth or during ear development results in a smaller reduction in yield (Robins and Domingo, 1953, Denmead and Shaw, 1960). Decreased yield after water stress during early growth seems to be caused by a reduction in the translocation of photosynthetic products from the leaves to the ears. Decreased yield after water stress during ear development is probably caused by internal competition for water between the ears and the rest of the plant.

2.1.2. Effects of ex~~c~~cessive soil water

Corn is tolerant to soil water contents above the normal field capacity except during the seedling establishment when growth may be reduced by lowered soil temperature and root disease (Robins et al., 1967). However, the findings of Kiesselbach and Montgomery (1911) indicate that prolonged conditions of excessive soil water are likely to reduce growth and yield because of decreased aeration in the rooting zone.

2.2. Water use

Water use by a crop is the loss of water by evaporation between planting and harvesting. In western U.S.A., water use by corn in a season varies from 16 to 25 inches (Robins and Rhoades, 1958). For any crop, this quantity depends on the length of the growing period and on the atmospheric, plant, and soil factors which regulate the movement of water from the soil to the atmosphere.

During early growth when the crop does not completely cover the soil surface, most of the water loss is due to evaporation from the soil surface, whereas later in the season when the crop completely covers the soil, water loss is essentially by transpiration. The portion of the total water used by the corn plant which is due to evaporation from the soil has been estimated as approximately 50% (Harrold et al., 1959; Peters and Russel, 1959).

2.2.1. Factors affecting water use

Soil factors

Peters (1960) grew corn in mixtures of sand and soil. Results indicated that the rate of water use was influenced by both soil moisture content and tension. The cumulative use in the first 7-day period was greater for the soil having high soil moisture content-suction ratios. Similarly Harrold and Dreibelbis (1953) found that water use by corn on a silt loam was less than that on a clay soil. This effect has been attributed to the greater unsaturated hydraulic conductivity in fine-textured soils (Peters and Runkels, 1967).

Plant factors

There is marked variation in the rate of water use with the stage of development of the crop. Kiesselbach (1916) observed that after maximum leaf area was achieved, water use for the next four weeks accounted for almost half the total water used. Holt and van Doren (1961), Doss *et al*. (1962) and others made similar observations. Doss *et al*. (1962), Shaw *et al*. (1958) and Robins and Rhoades (1958) found that during early growth the average water use was about 0.10 in. per day, whereas there was a peak water use of 0.25 to 0.30 in. per day after tasseling, and a subsequent decline.

The depth of rooting and hence the depth from which water is extracted determines the amount of water available for use by the plant. Doss *et al*. (1962) observed that when corn shoots were 18 inches high, water was extracted from an

18 inch depth of a sandy loam soil. The depth of extraction was increased to a maximum of 36 inches by the time of tasseling. However, the amount of water extracted from depths below 24 inches was found to be small. Similarly Gard et al. (1961) found that the water stored below 24 inches on a silt-pan soil was of very limited direct value to the corn crop. Carlson et al. (1959) found that at maturity water was extracted by corn roots from a 4-foot profile of a loam soil. Of the total water used, 75-85% was extracted from the top 2 feet and 90-95% from the top 3 feet.

Greater depths of extraction have also been reported for the period after tasseling (e.g., Holt and van Doren, 1961). Russel and Danielson (1956) observed that whereas rainfall and irrigation affected mainly the top 2 feet of a deep, permeable, well-drained Brunizem soil, an appreciable amount of water was extracted from a depth of 5 feet or more. Linscott et al. (1962) reported water extraction from below the 5-foot depth of loamy sand and silty clay loam soils under dry conditions. Holt and van Doren (1961) concluded that the available water and hence the water use rate determined the depth of extraction of water by corn roots.

Atmospheric factors

The work of Peters (1957) and Denmead and Shaw (1962) indicates that when water is not limiting, water use by corn is determined by the evaporative demand of the atmosphere, i.e., the rate at which water will evaporate from the leaves under given conditions of temperature, relative humidity, radiation and wind speed. However, as water becomes less available to the plants, the lack of water limits the rate of water use.

2.2.2. Effects of water use rate on growth and yield

Schofield (1952) stated that where plant cover is continuous and water is adequate, seasonal use of water is essentially independent of yield. Similarly Shaw and Burrows (1966) stated that yield is decreased with decreasing water used only at low water contents which limit growth.

Letey and Peters (1957) noted that the same amount of available water may be held in the soil at different suctions. Hence, plants although using the same amount of water may experience different conditions of stress, and growth and yield may be different.

III. SOILS AND METHODS

1. Soils used

The soils used in this study were Cunupia silty clay loam, Montserrat clay, Piarco fine sand, River Estate loam and Talparo clay (Chenery, 1952). The grain size distribution of the topsoil of the Piarco site was profoundly changed by cultivation and the texture was found to be sandy clay loam. This soil will be subsequently referred to as Piarco sandy clay loam. Data on the locations of the sites, chemical and physical properties, and mineralogy of the soils are presented in Tables 1 and 2. An area of approximately one-tenth acre was used in each site.

Soil pH was measured in water using a 1:1 soil-water ratio. Grain size distribution was determined by the hydrometer method. Cation exchange capacity was determined by the ammonium acetate method, exchangeable calcium and magnesium by versenate titration and exchangeable potassium by flame photometry. The percent carbon was determined by the method of Walkley and Armstrong Black (1934), and the percent nitrogen by the method of Jackson (1958). Particle density was measured in pycnometers using kerosene as the displacing medium.

Table 1. Chemical and physical properties of the soils

Location	Soils	pH	Grain size distribution: Coarse Sand 2.0–0.20 mm.	Fine Sand 0.20–0.05 mm.	Silt 0.05–0.002 mm.	Clay <0.002 mm.	m. eq./100 g. soil: CEC	Exch. cations: Ca	Mg	K	%C	%N	Truog P ppm	Particle density $g.cm^{-3}$
1.	Cunupia silty clay loam	4.6	--	29	25	46	13.0	3.8	2.0	0.25	1.4	0.17	13	2.56
2.	Montserrat clay	7.3	6	36	10	52	38.1		5.4	0.39	2.0	0.23	26	2.40
3.	Piarco sandy clay loam	4.6	7	55	14	25	6.7	0.5	0.5	0.08	2.0	0.15	8	2.48
4.	River Estate loam	5.5	12	44	22	23	7.2	3.8	0.7	0.12	0.4	0.07	5	2.59
5.	Talparo clay	4.6	--	16	18	68	18.9	1.8	3.4	0.33	1.7	0.15	17	2.49

1. R.F.E.P. site, El Carmen
2. Salvador Estate, Gran Conva
3. R.F.E.P. site, E.C.F.I., Centeno
4. R.F.E.P. site, U.W.I. Field Station
5. R.F.E.P. site, New Grant

Table 2. Mineralogy of the soils (personal communication from N. Ahmad)

Soils	Amorphous material %	Fe_2O_3 %	Kaolinite %	Montmonillonite %	Mica %	Others %
Cunupia silty clay loam	1	5	25	37	17	16
Montserrat clay	1	13	15	47[1]	17	7
Piarco sandy clay loam	6	17	76	11	9	--
River Estate loam	2	8	20	10	52	8
Talparo clay	3	5	45	33	16	3

[1]Not well crystallized and seem to be glauconite-vermiculite intergrades.

2. Methods

Four sample areas were randomly selected within each site. These areas were sampled for measurements of soil moisture, bulk density, porosity, hydraulic conductivity, and aggregate stability. Samples were taken every fortnight during the periods January to May and June to August, 1969, i.e., during dry and wet seasons respectively.

Sampling in the dry period was discontinued when severe desiccation resulted in a loss of cohesion in Cunupia silty clay loam, Piarco sandy clay loam and River Estate loam, and hardening and cracking occurred in Talparo clay. Desiccation was not as severe in Montserrat clay, so this soil was sampled for a longer period in the dry season than the other soils.

In the wet season four cultivated and four uncultivated areas were sampled at each R.F.E.P. site. Maize plants of similar size were selected from the guard rows of control plots and were labelled, six or seven weeks after planting. Four pre-selected plants were sampled every fortnight for growth analysis and rooting depth. Soil moisture, bulk density, porosity, hydraulic conductivity and aggregate stability were also measured on soil samples taken from the vicinity of each of the four plants.

2.1. Soil moisture content

Gravimetric moisture contents were obtained from weighings using soil samples in moisture tins. Four samples of the

0 to 3 inch depth and two samples each of the 3 to 6, 6 to 12, 12 to 18 and 18 to 24 inch depths were taken at each sample area, except at the Montserrat clay site, where an extensive system of large roots restricted sampling to the 12 inch depth. Volumetric moisture contents were calculated by multiplying the gravimetric moisture content by the bulk density.

2.2. Field capacity

An area of soil (1 sq. yd.) was saturated with water and covered with a polythene sheet. The 0 to 6 inch depth was sampled for moisture twenty-four or forty-eight hours after saturation.

2.3. Permanent wilting percentage

The permanent wilting percentage was determined by the 'sunflower method' (Veihmeyer and Hendrickson, 1949) using corn seedlings in place of sunflower seedlings.

2.4. Available water capacity

The available water capacity was calculated as the difference between the volumes of water at field capacity and at permanent wilting in the 6 inch depth of soil and was assumed to be constant to the 2 foot depth.

2.5. Soil moisture retention

Soil moisture retention in the range pF 0 to 2.0 was measured using the Haines apparatus (Haines, 1930), shown in Fig. 1. Air-dry ground soil (2 mm. diam.) was wet to equilibrium at decreasing suctions of 80, 50, 30, 10, 3 and 0 cm. water. Drying was studied by obtaining equilibrium at increasing suctions of 10, 30, and 80 cm. water.

A blank apparatus (containing no soil) was used to estimate evaporation losses. The attainment of equilibrium was considered to be when the rate of change in the pipette reading was equal to that of the blank. The samples were weighed at equilibrium and replaced so that the same samples were used for wetting and then for drying.

Soil moisture retention on drying over the ranges pF 2.0 to 3.5 and pF 3.5 to 4.2 ~~were~~ was measured using the pressure-plate and pressure-membrane apparatus (Soil Moisture Equipment Co.) respectively. Air-dry ground soil (2 mm. diam) was contained in rubber retaining rings (4 cm. diam. and 1 cm. ht.). The soil was saturated with water by shallow flooding on the plate or membrane. This technique is reported to produce higher and more uniform equilibrium moisture contents than those produced by the method of sorption through the plate (Hillel and Mottes, 1966).

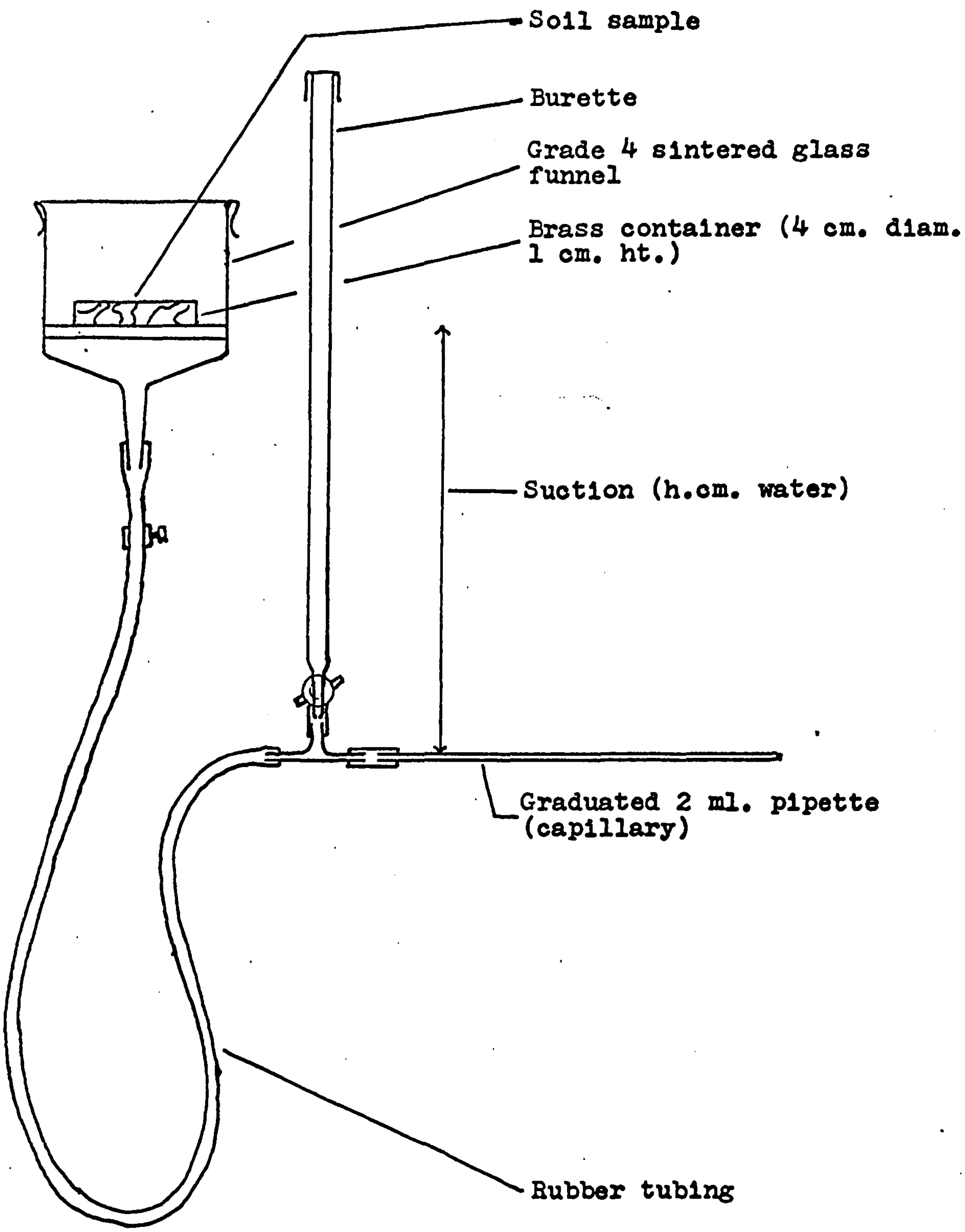

Fig. 1. Diagram of the Haines apparatus used for water retention measurements.

2.6. Bulk density, porosity and hydraulic conductivity

Only the 0 to 6 inch depth was sampled regularly except in the growth and water use studies, where samples were also taken from the lower depths. A brass core (approximately 5 cm. length and 4.75 cm. int. diam.) was used to sample each of the four sample areas. Bulk density, total porosity, macro-porosity and hydraulic conductivity were then measured from each core as follows.

Bulk density

Bulk density was calculated as the oven-dry weight of soil per unit volume of soil *in situ*.

Porosity

Core samples were gradually saturated with water from the bottom to the top in 24 hours and were then weighed. Total pore space was estimated as the difference in weight between the saturated core and the oven-dry core expressed as a percentage of the total soil volume.

Macro-pore space (non-capillary pores) was considered to be the volume of pores drained at 40 cm. water suction (Nelson and Baver, 1940). This was determined by draining the saturated cores at 40 cm. water suction on a Leamer and Shaw apparatus (Leamer and Shaw, 1941) and expressing the air-filled pores as a percentage of the total volume.

Hydraulic conductivity

The saturated hydraulic conductivity was calculated from measurements of the rate of flow of water through a saturated soil core with a 0.5 cm. constant head of water. The saturated core was supported on a Buchner funnel and an empty core was sealed onto the soil core with masking tape. The constant head of water was maintained by a constant level reservoir and the outflow was collected in a graduated cylinder.

2.7. Aggregate stability

Composite samples were produced by bulking the samples from each of the four sample areas. Aggregate stability was determined by two methods.

(a) the instability and permeability test described by Williams and Cooke (1961). Aggregates 4.78 to 5.72 mm were used; and

(b) dry and wet stability of aggregates by sieving. The freezing pre-treatment used in the Williams and Cooke method was also used in these tests. The soil was allowed to thaw and was then air-dried and sieved into aggregates 5.72 to 9.52 mm. and aggregates 1.0 to 2.0 mm.

(i) Dry stability

A twenty-gram sample of air-dry aggregates 5.72 to 9.52 mm. was placed in cylindrical tins and shaken in an end-over-end mechanical shaker oscillating at a speed of 50 r.p.m. for one half-hour. The soil was then sieved for two minutes over sieves of sizes 5.72 mm., 4.78 mm., 2.0 mm., and 1.0 mm.

The aggregates on each sieve were weighed and the mean weight diameter (van Bavel, 1949) of stable aggregates was calculated.

(ii) Wet stability

A twenty-gram sample of air-dry aggregates 1.0 to 2.0 mm. was placed on a 1.0 mm. sieve and oscillated in water at 30 strokes per minute with a stroke of 1.5 inches for two minutes. The soil remaining on the sieve was weighed and expressed as a percentage of the initial weight.

2.8. Dry matter of plants

Ears, when present, were separated from each plant. The separated plant parts were cut into sections of less than 6 in. length, oven-dried at 105°C for 48 hours, and weighed.

2.9. Rooting depth

A spade was used to cut a trench at a radius of two feet from the stem of the plant to a depth of approximately 1 foot. A deeper trench was then dug on one side of the plant, which was then pulled out of the ground. The depth of the root system was then measured on the side of the trench.

2.10. Rainfall

Rainfall records of the raingauges nearest to the sites, were obtained from the Ministry of Works and Hydraulics, Port-of-Spain, for calculating the water use by corn on these soils.

IV. RESULTS AND DISCUSSION

1. Soil moisture retention

The soil moisture characteristics of the five soils are shown in Fig. 2. The moisture contents obtained with the Haines apparatus (pF 0 to 2.0) are means of two values. Those obtained with the pressure-plate and pressure-membrane apparatus (pF 2.0 to 4.2) are means of eight values.

The initial bulk densities and their standard errors for the soils are shown in Table 3. Bulk density values of cores of the cultivated and uncultivated soils are also shown.

Table 3. Initial bulk densities of samples used in moisture retention measurements compared with bulk densities of undisturbed soil cores

Soils	Initial bulk density $g.cm.^{-3}$	Bulk density of soil cores $g.cm.^{-3}$ cultivated	uncultivated
Cunupia silty clay loam	1.52 ± 0.03	1.16	1.28-1.42
Montserrat clay	0.83 ± 0.06	--	0.95-1.08
Piarco sandy clay loam	1.45 ± 0.02	1.15	1.29-1.49
River Estate loam	1.43 ± 0.04	1.26	1.34-1.41
Talparo clay	0.96 ± 0.07	1.06	1.23-1.44

With the exception of Montserrat clay, the wetting and drying curves show increase in moisture content with increasing

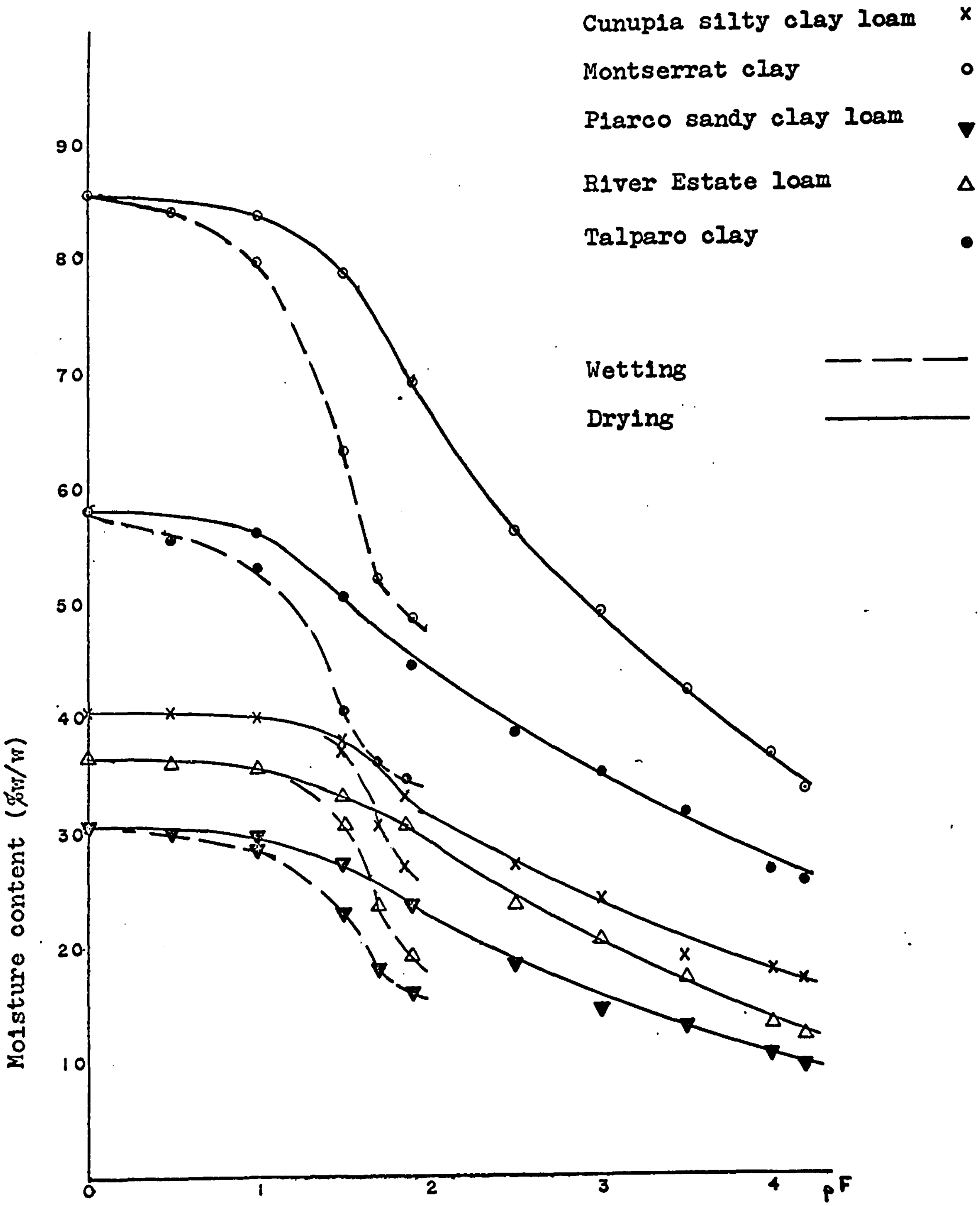

Fig. 2. Moisture retention curves

clay content of the soil. The high moisture contents of Montserrat clay can be attributed to its high swelling properties.

The curves show some discontinuity between the moisture retention measured in the Haines apparatus, the pressure-plate apparatus and the pressure-membrane apparatus. The two factors responsible for this are

(a) the different plate impedences of the three membranes; and

(b) the size of the applied pressure increment.

(a) plate impedence effects

The increasing plate impedence (sintered glass < porous plate < cellophane) increases the time necessary to achieve equilibrium and increases the equilibrium moisture content (Hillel and Mottes, 1966). Hence plate impedence effects tend to cause the equilibrium moisture contents to be increased as pF is increased using sintered glass, porous plate and cellophane membranes. The curves of Montserrat clay and Cunupia silty clay loam seem to have been affected in this manner.

(b) pressure increment effects

The application of any given pressure in one large increment, c.f. several small increments reduces the amount of water retained by a soil (Davidson, et al., 1966). Small increments (3 to 30 cm. water) were made when the Haines apparatus was used, whereas large increments were made when the pressure-plate and pressure-membrane, apparatus were used. Hence the pressure increment effects tend to cause the equilibrium moisture contents to be decreased as pF is increased. The curves of Talparo clay, River Estate loam, and Piarco sandy clay loam seem to have been affected in this manner.

2. Available water capacity

A comparison of the moisture contents of the soils at field capacity and the equivalent pF values is shown in Table 4, which also shows a comparison of the permanent wilting percent and fifteen bar percent values.

Table 4. Comparisons of (a) field capacities and equivalent pF values, and (b) permanent wilting percentages and fifteen bar percentages of the soils

Soils	F.C.	Equiv. pF	P.W.P.	F.B.P.
Cunupia silty clay loam	26±0.54	2.6	17±0.27	17±0.21
Montserrat clay	65±0.50	2.0	34±0.53	34±0.36
Piarco sandy clay loam	23±0.46	1.9	9±0.32	10±0.15
River Estate loam	33±0.61	1.6	11±0.49	12±0.39
Talparo clay	40±0.53	2.3	23±0.45	26±0.24

With the exception of Cunupia silty clay loam, the pF values equivalent to field capacity are generally low (below pF 2.5) and increase with increasing clay content of the soil.

The use of disturbed soil samples may have contributed to the low equivalent pF values because of the lack of natural structure.

The equivalent pF values are also affected by the initial bulk densities of the soils. The initial bulk densities of Cunupia silty clay loam and River Estate loam were higher than the bulk densities of undisturbed soil cores, whereas those of Montserrat clay and Talparo clay were lower than the bulk densities of undisturbed soil cores (Table 3).

Hill and Sumner (1967) indicated that an increase in bulk density affects porosity, and hence water retained in soil by

(1) decreasing the total porosity

(2) decreasing the relative amount of large pores and

(3) increasing the relative amount of small pores.

Studying the effects of bulk density on the moisture content of different soils over the suction range of pF 2.0 to 4.2, Hill and Sumner found _inter alia_ that increasing bulk density in clays and clay loams results in increased moisture content at constant pF, with increasing magnitude as pF increases. Since the initial bulk density of Cunupia silty clay loam was higher than bulk densities in the field, the moisture contents at suctions of pF 2.0 to 4.2 can be expected to be higher than those for lower initial bulk densities similar to those in the field. Therefore at a lower initial bulk density, the equivalent pF value between pF 2.0 and 4.2 for any moisture content is lower. Hence the pF value equivalent to field capacity of Cunupia silty clay loam was increased by the high initial bulk density. Conversely, low initial bulk densities in Montserrat clay and Talparo clay decreased the equivalent pF values.

The initial bulk density of River Estate loam was just higher than the range of bulk densities in the field, so only slight effects can be expected. However, at these low suctions (pF 1.6) when only the large pores are drained, water content is decreased by increased bulk density because of the reduction in total porosity and the relative amount of large pores. Therefore, in this suction range at a lower initial bulk density, the equivalent pF value for any moisture content is higher. Hence the equivalent pF value for River Estate loam may have been decreased by the high bulk density.

The fifteen bar percentages are in agreement with the permanent wilting percentages for the five soils.

The available water capacities of the soils are shown in Table 5. Bulk densities at field capacity were measured directly at the time of sampling. Those at the permanent wilting percent were determined in the field when the gravimetric moisture content approached the permanent wilting percentage. Volumetric moisture contents corresponding to the gravimetric moisture contents at field capacity and the permanent wilting percentages of the soils are also shown in the table.

Table 5. Available water capacities of the soils

Soils	F.C. B.D.	F.C. θ	P.W.P. B.D.	P.W.P. θ	A.W.C. in./ft.
Cunupia silty clay loam	1.32	35.9	1.37	22.7	1.56
Montserrat clay	0.95	63.8	1.08	36.7	3.20
Piarco sandy clay loam	1.32	30.9	1.47	13.4	2.07
River Estate loam	1.38	44.9	1.40	15.4	3.48
Talparo clay	1.23	50.1	1.38	31.7	2.17

The measured available water capacity values for Montserrat clay, Piarco sandy clay loam, River Estate loam and Talparo clay are higher than values normally quoted in the literature for soils of similar texture. Israelsen and Hansen (1962) quote values of 1.0 to 2.7 inches per foot and Marshall (1959) quotes values of 0.6 to 2.2 inches per foot depending on the soil texture. However, Smith (1968) reported that the available water capacity of St. Augustine loam, a soil located between River Estate loam and Piarco sandy clay loam was 5 inches per 18 inches root depth of Axonopus compressus, i.e., higher than the values quoted by Israelsen and Hansen or Marshall.

3. Seasonal variations in physical properties

During the dry season (January to May), soil moisture content varied from field capacity to below the permanent wilting percentage in the five soils. Core sampling was restricted to the range of soil moisture contents above the permanent wilting percentage, when the soil was not too dry. In the period of sampling in the wet season (June to August), there was generally less variation in soil moisture content which tended to be close to field capacity.

The results of bulk density, macro-porosity, hydraulic conductivity and aggregate stability measurements are summarized in Tables 6 and 7.

Table 6. Summary of dry season variations in physical properties of uncultivated soils

Date 1969	Water content w%	Bulk density $g.cm.^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Aggregate stability Dry MWD	Wet %	Instab. factor	Perm. cm./hr.
Cunupia silty clay loam		±0.03	±0.6	±4	±0.06	±2		
10/1	23	1.30	3.6	6	4.98	44.3	14	1.32
24/1	20	1.35	3.1	8	4.97	45.2	16	1.26
7/2	24	1.31	3.9	9	5.03	48.6	14	1.28
21/2	18	1.35	3.0	5	5.17	44.1	17	1.12
8/3	17	1.37	2.9	7	4.91	41.6	15	1.15
21/3	14	1.40	2.8	5	4.69	37.9	19	0.88
5/4	12	--	--	--	4.76	36.5	18	1.01
18/4	8	--	--	--	4.71	38.7	19	0.94
River Estate loam		±0.01	±0.3	±5	±0.04	±2		
15/1	25	1.36	4.7	32	4.73	32.1	20	0.17
29/1	23	1.35	4.9	49	4.71	35.4	22	0.13
12/2	22	1.37	4.3	37	4.63	31.6	21	0.12
26/2	16	1.37	4.1	31	4.29	28.5	25	0.07
12/3	13	1.40	4.2	25	4.34	27.3	24	0.08
27/3	11	--	--	--	4.18	29.4	24	0.10
9/4	9	--	--	--	4.20	25.2	27	0.04
23/4	8	--	--	--	4.16	26.7	28	0.06

Table 6 (continued)

Date 1969	Water content w%	Bulk density g.cm.$^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Dry MWD	Aggregate stability Wet %	Instab. factor	Perm. cm./hr.
Talparo clay								
		±0.02	±1.1	±3	±0.19	±3		
15/1	37	1.28	4.5	6	7.04	68.3	8	3.1
29/1	36	1.28	5.4	11	6.98	72.4	10	3.2
12/2	33	1.33	4.2	6	7.17	79.0	10	3.5
26/2	30	1.37	3.8	7	7.45	43.8	15	1.9
12/3	25	1.38	2.7	2	7.22	61.3	6	2.8
27/3	29	1.38	3.1	1	6.96	69.3	9	2.7
9/4	20	1.42	1.4	1	6.89	63.6	11	2.9
Montserrat clay								
		±0.02	±0.6	±4	±0.12	±4		
15/1	58	0.96	4.9	17	6.36	75.4	-1	6.3
29/1	59	0.95	4.5	18	6.45	76.3	-2	15.8
12/2	57	0.97	4.5	7	6.23	79.0	-1	12.5
26/2	56	0.99	4.3	0	7.38	71.5	-1	18.5
18/3	54	1.02	4.1	1	5.97	70.5	-1	8.0
27/3	52	1.04	3.5	1	6.90	72.8	-2	11.4
9/4	50	1.06	3.0	1	7.30	70.5	-1	6.2
23/4	43	1.07	2.3	1	7.14	68.9	-2	6.8
7/5	35	1.08	2.3	0	7.21	70.8	-2	6.2

Table 6 (continued)

Date 1969	Water content w%	Bulk density g.cm.$^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Aggregate stability Dry MWD	Aggregate stability Wet %	Aggregate stability Instab. factor	Aggregate stability Perm. cm./hr.
Piarco sandy clay loam								
		±0.03	±0.9	±4	±0.07	±2		
10/1	18	1.35	4.7	10	4.33	29.6	23	0.09
24/1	16	1.38	4.1	23	4.87	27.3	22	0.08
7/2	22	1.32	10.1	42	4.87	25.8	26	0.10
21/2	12	1.47	3.7	7	5.67	35.0	27	0.18
8/3	9	1.47	3.3	3	4.99	30.0	29	0.09
21/3	7	--	--	--	4.01	23.6	26	0.05
5/4	5	--	--	--	3.48	21.3	29	0.02
18/4	5	--	--	--	3.20	22.6	35	0.02

Table 7. Summary of wet season variations in physical properties of cultivated and uncultivated soils

Date 1969	Water content w%	Bulk density g.cm.$^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Aggregate stability Dry MWD	Aggregate stability Wet %	Aggregate stability Instab. factor	Aggregate stability Perm. cm./hr.
Cunupia silty clay loam								
Uncultivated		±0.02	±0.9	±3	±0.04	±2		
11/6	20	1.35	3.2	4	4.92	49.3	15	1.36
25/6	21	1.33	3.2	5	4.87	50.2	14	1.39
8/7	22	1.33	3.8	7	4.98	48.6	15	1.29
25/7	25	1.31	3.7	5	5.08	47.3	16	1.23
8/8	25	1.27	3.6	7	4.91	49.4	14	1.32
22/8	27	1.29	3.4	6	4.92	48.3	13	1.30
Cultivated		±0.04	±2.1	±4	±0.10	±3		
11/6	19	1.20	5.7	12	5.21	55.3	11	1.65
25/6	21	1.24	5.2	15	5.18	53.7	13	1.72
8/7	23	1.25	4.9	9	5.09	54.1	14	1.78
25/7	24	1.27	4.6	8	5.23	52.8	14	1.59
8/8	24	1.27	4.5	11	5.26	53.4	13	1.38
22/8	26	1.28	4.9	9	5.08	50.2	15	1.46

Table 7 (continued)

Date 1969	Water content w%	Bulk density g.cm.$^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Aggregate stability			
					Dry MWD	Wet %	Instab. factor	Perm. cm./hr.
Piarco sandy clay loam								
Uncultivated		±0.01	±0.9	±9	±0.12	±2		
11/6	10	1.39	4.2	9	4.13	26.1	26	0.08
25/6	18	1.35	5.8	20	4.26	28.2	25	0.08
8/7	22	1.32	4.7	24	4.53	29.5	24	0.10
25/7	22	1.33	4.1	14	4.47	30.8	26	0.11
8/8	23	1.32	4.5	15	4.29	30.1	24	0.19
Cultivated		±0.02	±1.8	±12	±0.15	±2		
11/6	10	1.19	13.5	53	4.21	29.3	24	0.12
25/6	18	1.17	13.3	29	4.81	29.7	26	0.10
8/7	23	1.20	9.8	28	4.73	27.5	21	0.09
25/7	24	1.18	14.2	31	4.36	31.3	25	0.13
8/8	--	--	--	--	--	--	--	--

Table 7 (continued)

Date 1969	Water content w%	Bulk density g.cm.$^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Dry MWD	Aggregate stability Wet %	Instab. factor	Perm. cm./hr.
River Estate loam								
Uncultivated		±0.01	±0.3	±9	±0.09	±2		
4/7	25	1.35	5.0	39	4.68	33.4	22	0.18
20/7	27	1.38	4.4	32	4.63	29.6	24	0.14
2/8	29	1.37	4.5	36	4.81	32.8	21	0.19
15/8	29	1.36	4.5	37	4.74	31.5	22	0.16
27/8	28	1.38	4.3	33	4.70	33.4	20	0.23
Cultivated		±0.03	±0.8	±9	±0.18	±3		
4/7	25	1.29	5.7	54	4.51	38.3	18	0.31
20/7	27	1.32	5.8	50	4.65	36.5	20	0.18
2/8	28	1.34	4.9	48	4.91	35.4	23	0.15
15/8	28	1.33	5.1	38	4.53	35.0	25	0.14
27/8	28	1.34	4.9	38	4.62	34.6	26	0.18

Table 7 (continued)

Date 1969	Water content w%	Bulk density $g.cm.^{-3}$	Macro-porosity %v	Hydraulic conductivity cm./hr.	Aggregate stability Dry MWD	Aggregate stability Wet %	Aggregate stability Instab. factor	Perm. cm./hr.
Talparo clay								
Uncultivated		±0.02	±0.9	±3	±0.12	±3		
20/6	35	1.28	4.0	7	7.15	73.4	10	2.9
4/7	36	1.28	4.6	6	7.02	68.9	9	3.4
20/7	40	1.26	4.2	6	7.08	74.2	6	3.8
2/8	40	1.25	5.8	8	7.19	72.6	9	3.1
15/8	40	1.24	4.5	5	7.11	73.8	8	3.5
27/8	41	1.23	4.2	7	7.23	74.1	7	7.3
Cultivated		±0.02	±2.1	±4	±0.19	±3		
20/6	37	1.12	9.2	9	7.41	82.1	6	6.2
4/7	35	1.14	6.9	8	7.23	78.5	5	8.4
20/7	41	1.09	6.7	6	7.53	89.3	3	10.3
2/8	41	1.11	7.6	9	7.49	81.9	3	8.6
15/8	42	1.08	7.1	7	7.42	79.2	4	9.5
27/8	43	1.09	5.8	6	7.51	85.6	4	11.8

3.1. Bulk density

Greater changes were observed in the bulk densities of the uncultivated soils during the dry season than during the wet season. During the dry season mean bulk density changes measured in River Estate loam were small (1.36-1.40). Greater changes were measured in the other soils, especially in Montserrat clay (0.96-1.08) and Talparo clay (1.28-1.42). There was a similar trend during the wet season (Tables 6 and 7). ~~Figs. 6 to 10)~~.

Changes in the bulk density of clay soils are the result of volume changes caused by swelling and shrinkage as water is gained or lost. Thus, during the dry season, loss of water causes shrinkage in volume of a unit mass of soil and results in an increase in bulk density. The extent of the bulk density change is, therefore, usually related to the clay content and mineralogy of a soil.

With the exception of Piarco sandy clay loam, the extent of the bulk density change is approximately related to the clay content of the soils (Table 3). The great increase in the bulk density of Montserrat clay can be attributed to its high content of 2:1 clay minerals. The peculiar behaviour of Piarco sandy clay loam, however, cannot be explained on the basis of its clay content or mineralogy (Tables 1 and 2). Furthermore, no appreciable swelling and shrinkage were observed after saturation and oven-drying undisturbed cores of this soil.

A comparison of the standard errors of the bulk densities of uncultivated soils during the wet and dry seasons (Tables 6 and 7) indicates that soil variability at the time of sampling was greater during the dry season than during the wet season. At high moisture contents, soil moisture content is quite uniform in the field, but drying occurs in an uneven manner causing greater variation in soil moisture content. Sampling under these conditions may result in variations in bulk density due to differences in soil moisture content at the time of sampling.

Also, as the soil dries, hardening occurs in clay soils to a certain extent and some loss of cohesion occurs in sandy and loam soils. These factors will tend to decrease the precision of bulk density measurements as the soil dries. The phenomenon of increased bulk density variation at low moisture contents has been reported by Miller (1966). The differences in the standard errors, therefore, may be due to differences in (a) soil variability, and (b) the precision of measurement.

The relationships between bulk density and gravimetric moisture content for Montserrat clay, Piarco sandy clay loam and River Estate loam are shown in Figs. 3, 4 and 5. The measured bulk density values can be considered as estimates of the line or lines drawn for each soil. The rate of increase in bulk density per unit decrease in gravimetric moisture percent and the standard error of the line for each soil is presented in Table 8.

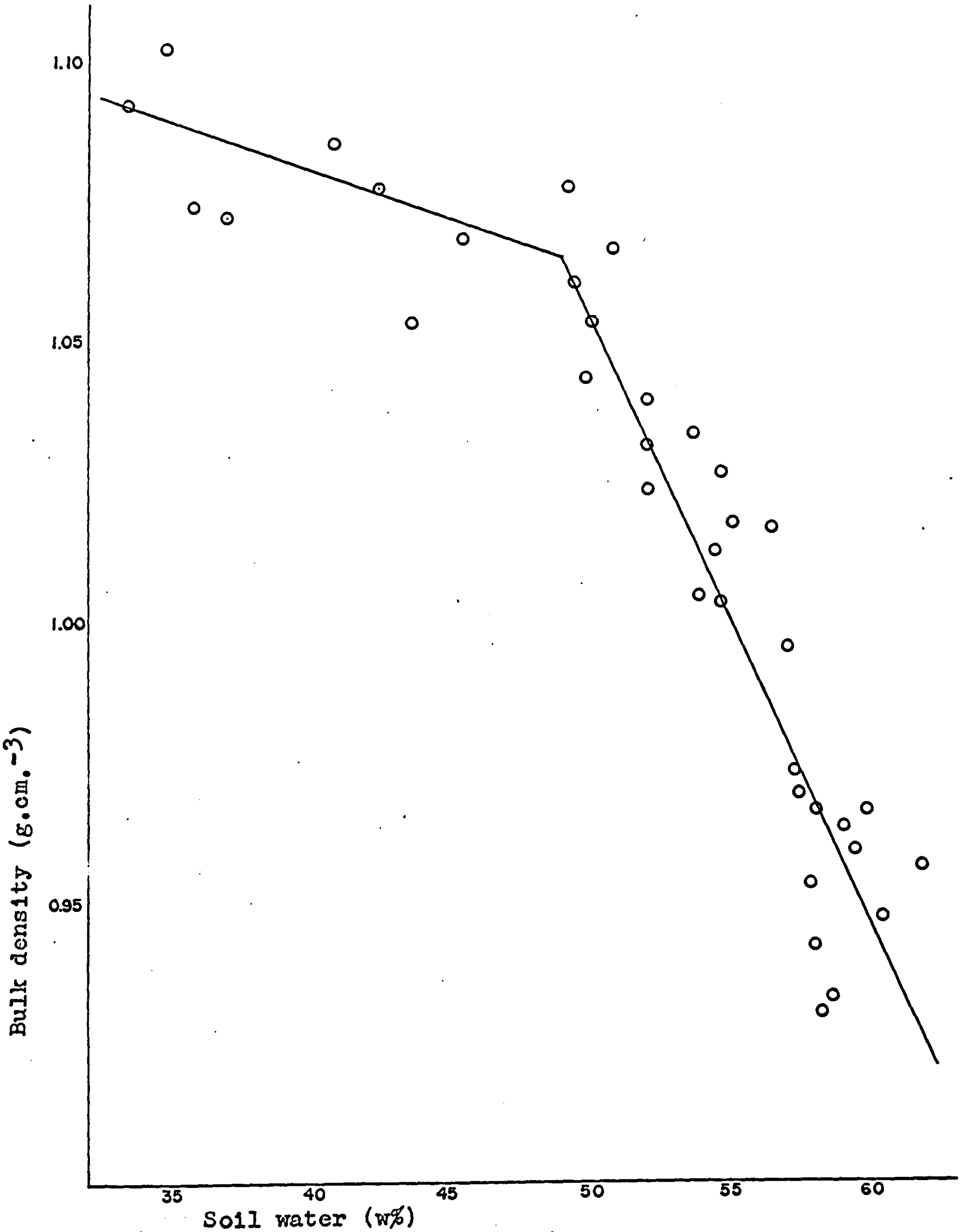

Fig. 3. Bulk density and gravimetric moisture content -- Montserrat clay.

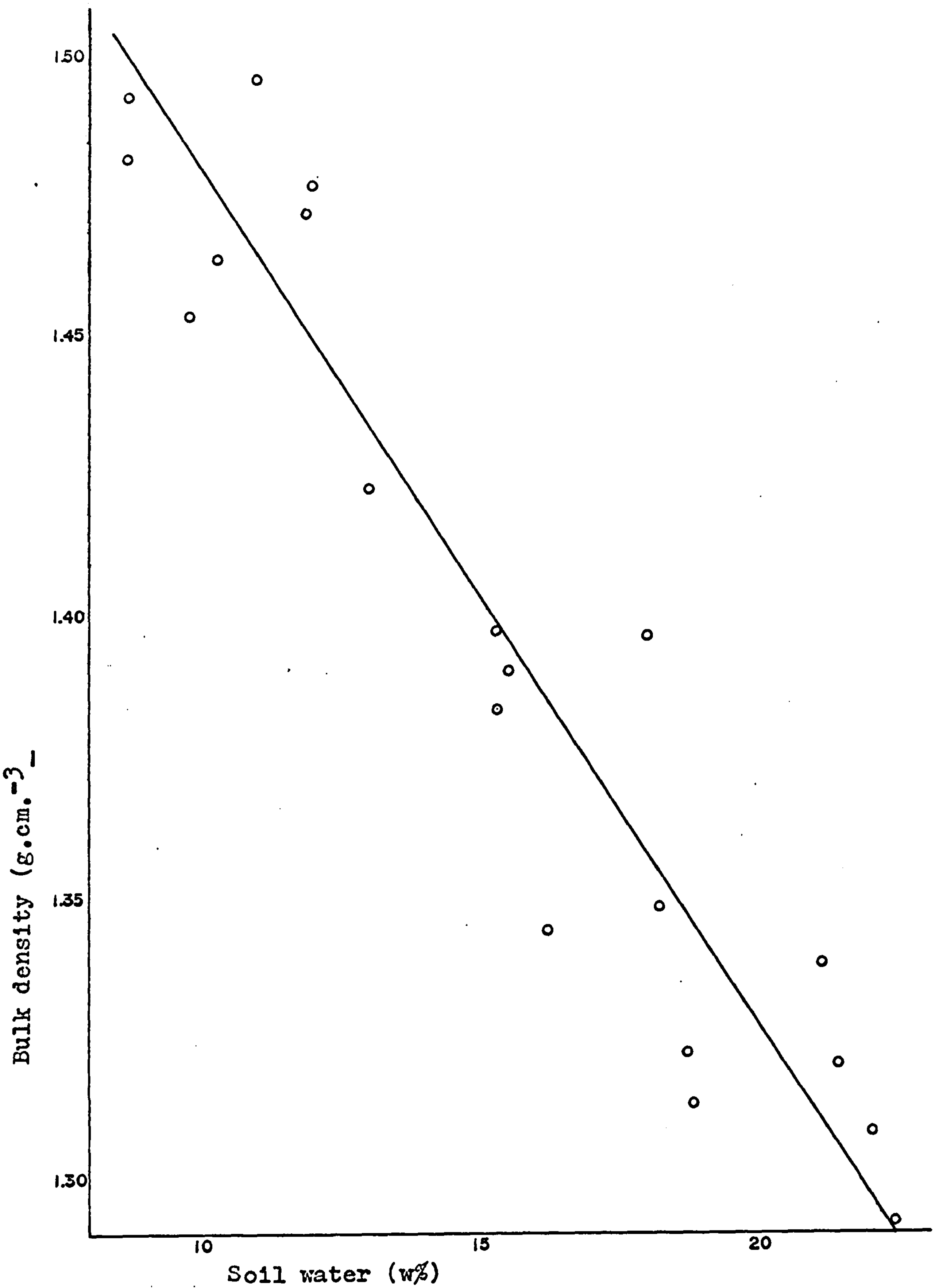

Fig. 4. Bulk density and gravimetric moisture content -- Piarco sandy clay loam.

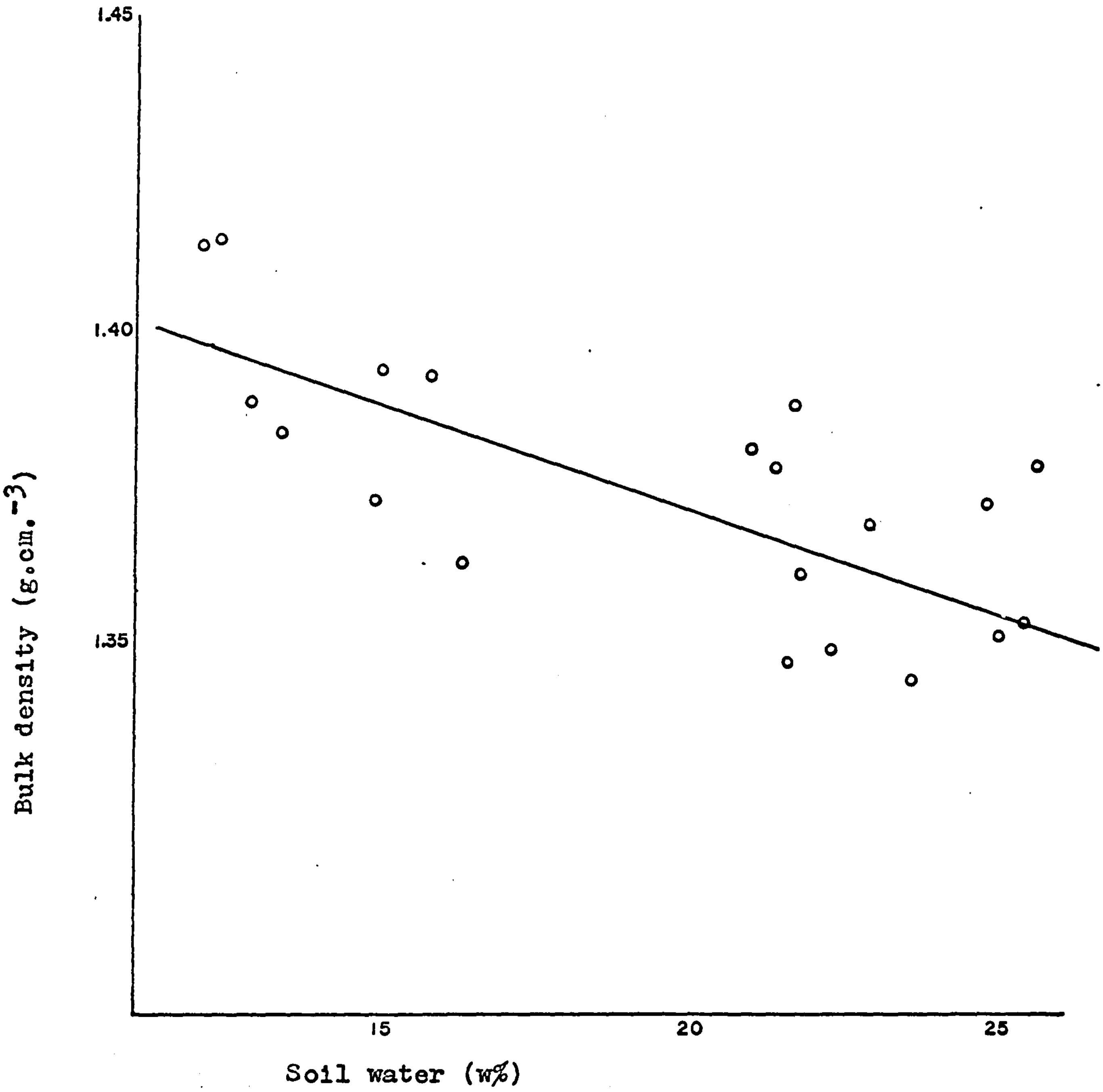

Fig. 5. Bulk density and gravimetric moisture content -- River Estate loam.

Table 8. Rates of increase in bulk density and standard errors

Soil	Bulk density Rate of increase $g.cm.^{-3}/\%$		S.E. $g.cm.^{-3}$
Cunupia silty clay loam	0.0117		0.021
Montserrat clay	0.0118	$w > 49\%$	0.012
	0.0017	$w < 49\%$	0.016
Piarco sandy clay loam	0.0153		0.023
River Estate loam	0.0034		0.013
Talparo clay	0.0162	$w > 31\%$	0.018
	0.0043	$w < 31\%$	0.019

The standard errors in Table 7 indicate that the variability in bulk density at a given moisture content was similar for the soils except Montserrat clay at high moisture contents and River Estate loam which were less variable at a constant moisture content.

The bulk density-moisture content relationships of Montserrat clay and Talparo clay are in agreement with that predicted and measured for a swelling soil by Fox (1964), where the intersection of the two lines corresponds to the transition from one dimensional to three dimensional contraction as the soil dries. The moisture contents at these points, 49 percent in Montserrat clay and 31 percent in Talparo clay, therefore, represent the moisture contents at which cracks should just appear in the field. These values are in fact within the ranges of moisture contents at which cracking was first noticed.

This type of relationship is not obvious in the other soils. There seems to be a simple linear relationship over the entire range of moisture contents sampled, and the soils differ only in the rate of increase of bulk density as water is lost. Cracking was observed in these soils only when the soils were too dry for sampling. Hence, no three dimensional contraction is apparent from the data for these soils because they could not be sampled after such contraction occurred.

During the wet season, although gravimetric moisture contents of cultivated and uncultivated soils were similar, the bulk densities of the cultivated soils were lower than those of the uncultivated soils. This effect is due to the increase in macro-porosity after cultivation.

The effect of cultivation on bulk density can be expected to be greatest immediately after cultivation. However, this condition may be regarded as unstable. If soil moisture content remains constant, there must be a subsequent increase in bulk density with time due to compaction. The rate of bulk density increase will depend on (a) the moisture content, and (b) the extent of the initial decrease by cultivation. If soil moisture content increases after cultivation, the swelling effect of clay will tend to oppose the compaction effect.

Under these conditions the direction of change of the bulk density of cultivated soils will depend on (a) the clay content and mineralogy of the soil, (b) the initial moisture content and the extent of its change, and (c) the extent of the initial decrease by cultivation.

In Cunupia silty clay loam, as water content increased, the bulk density of the cultivated soil increased while that of the uncultivated soil decreased (Table 7). This indicates that compaction effects in this soil after cultivation were great enough to outweigh the swelling effects due to increasing water content.

In Piarco sandy clay loam, as water content increased, the bulk density of uncultivated soil decreased while that of cultivated soil showed no definite change (Table 7). Hence the opposing effects were equal in this soil.

In River Estate loam, the moisture content increased only slightly during the observed period in the wet season (Table 7). Hence, the effect of swelling was limited and the change in bulk density after cultivation was due mainly to compaction.

In Talparo clay, the decreases in bulk density of uncultivated and cultivated soil as moisture content increased (Table 7) indicates that swelling effects dominated the bulk density changes after cultivation.

A comparison of the standard errors of the bulk densities measured during the wet season (Table 7) indicates that bulk densities of uncultivated soils were more uniform than those of cultivated soils. This is due to a combination of (a) increased variability in soil moisture after cultivation, (b) non-uniform increases in porosity by cultivation, and (c) non-uniform compaction after cultivation.

3.1.1. Bulk density and porosity

Mean values of bulk density, macro-porosity and moisture content of the five soils are shown in Figs. 6 to 10.

The changes in macro-porosity were approximately related to the changes in bulk density of the five soils. Very little change was observed in the macro-porosity of Cunupia silty clay loam and River Estate loam soils (Figs. 6 and 9), whereas there were fluctuations in the macro-porosity of Montserrat clay, Piarco sandy clay loam and Talparo clay (Figs. 7, 8 and 10).

Cultivated soils had greater macro-porosities than uncultivated soils. This effect of cultivation was approximately related to the decrease in bulk density due to cultivation. The macro-porosity of cultivated soils fluctuated similarly to that of uncultivated soils.

As a soil core is saturated, swelling occurs. If appreciable swelling occurs, the volume of soil, and hence the porosity, is increased and alterations in void geometry are inevitable. After the application of 40 cm. suction, although only slight shrinkage may occur, the value obtained is a measure of the macro-porosity of the altered core. The accuracy of the macro-porosity measurement will, therefore, depend on the extent

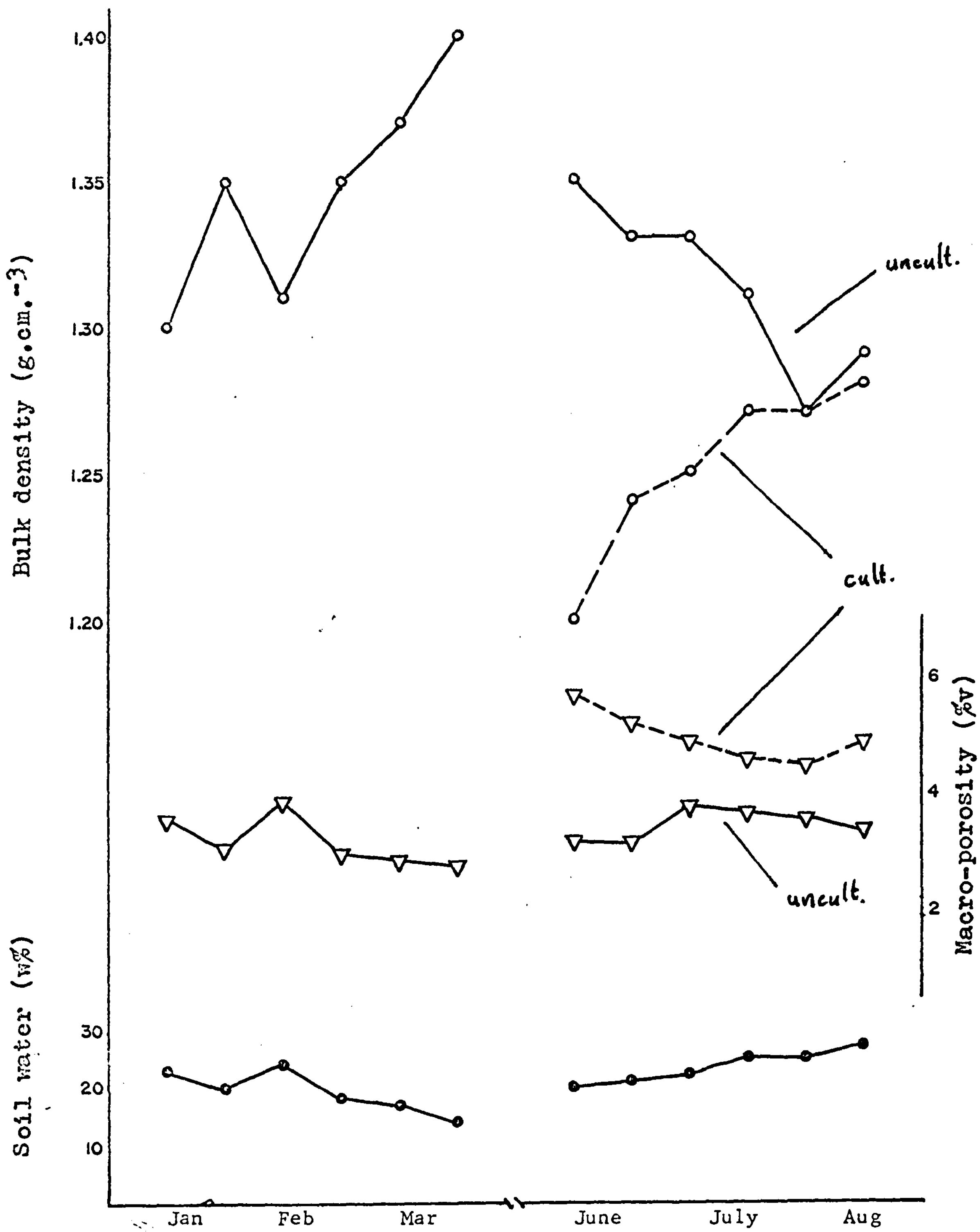

Fig. 6. Seasonal changes in water content, bulk density, and macro-porosity -- Cunupia silty clay loam.

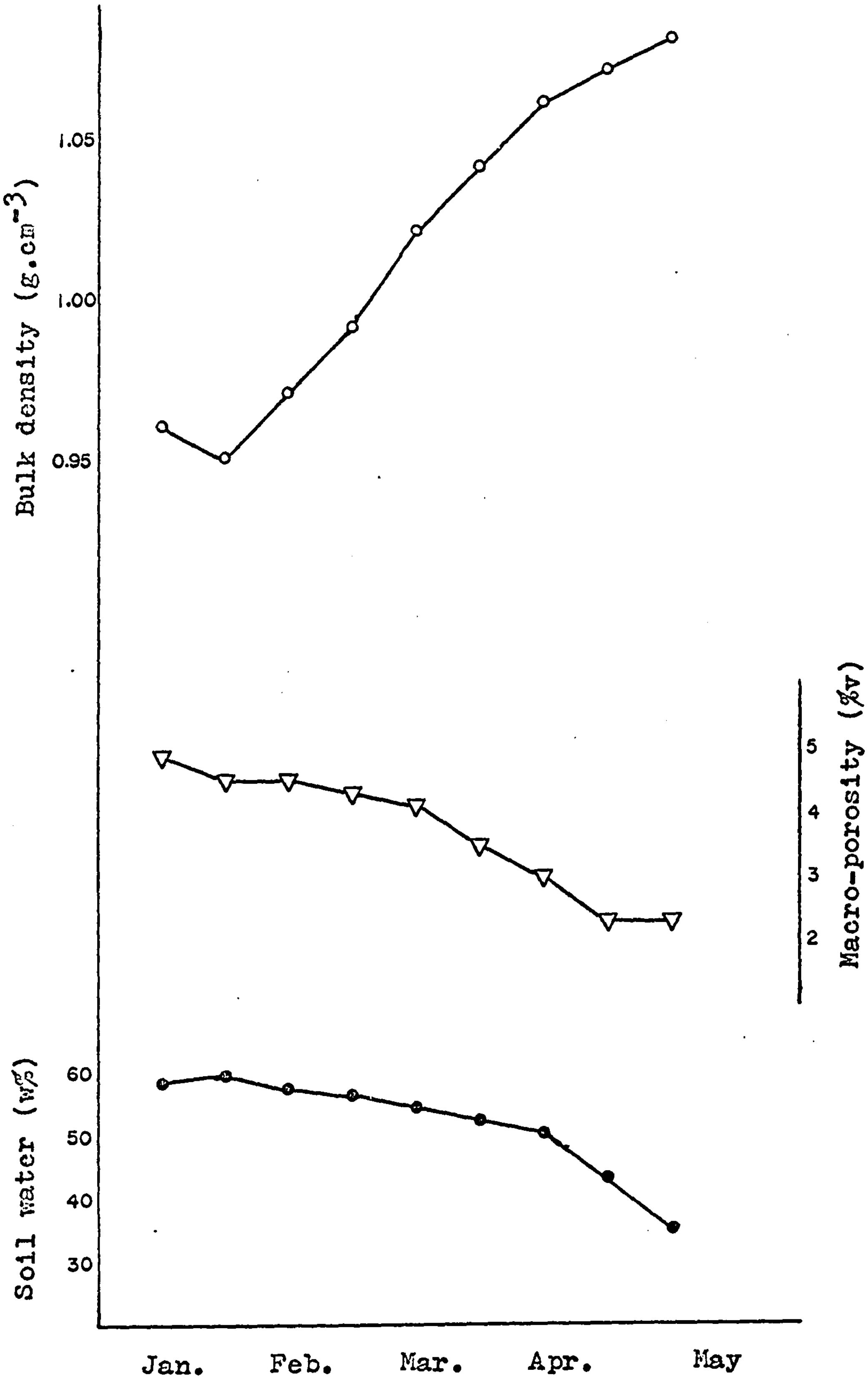

Fig. 7. Seasonal changes in water content, bulk density, and macro-porosity -- Montserrat clay.

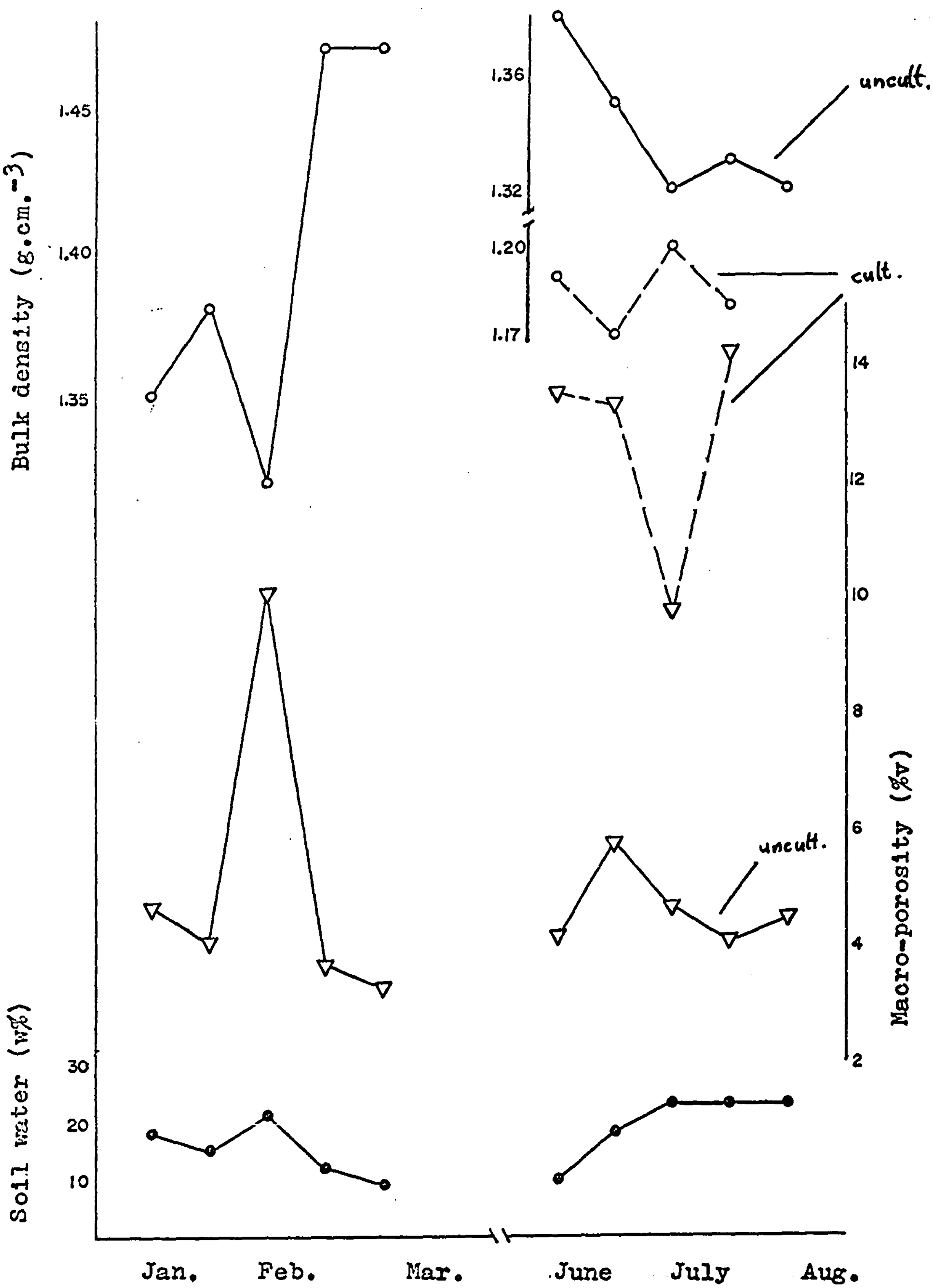

Fig. 8. Seasonal changes in water content, bulk density, and macro-porosity -- Piarco sandy clay loam.

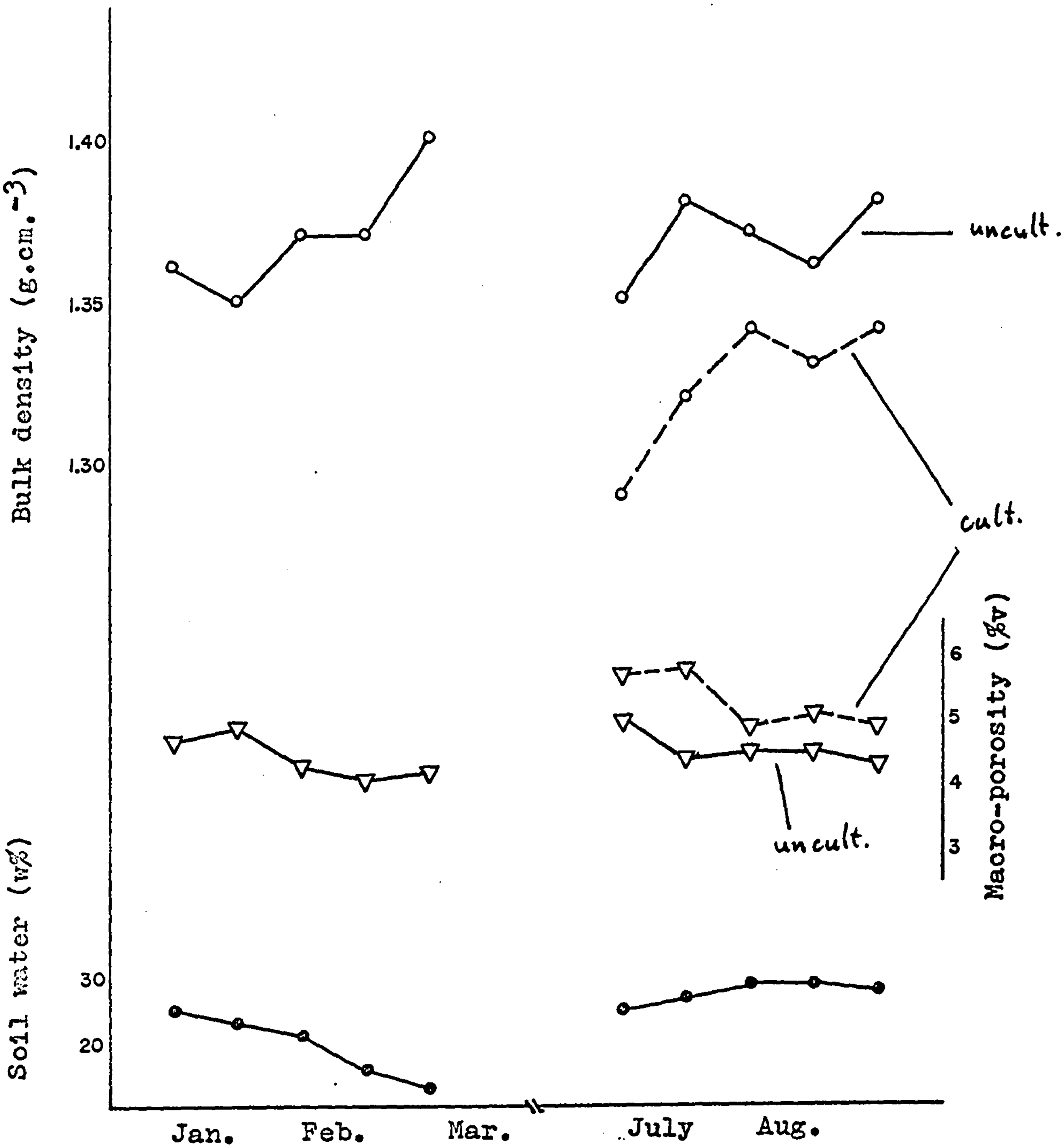

Fig. 9. Seasonal changes in water content, bulk density, and macro-porosity -- River Estate loam.

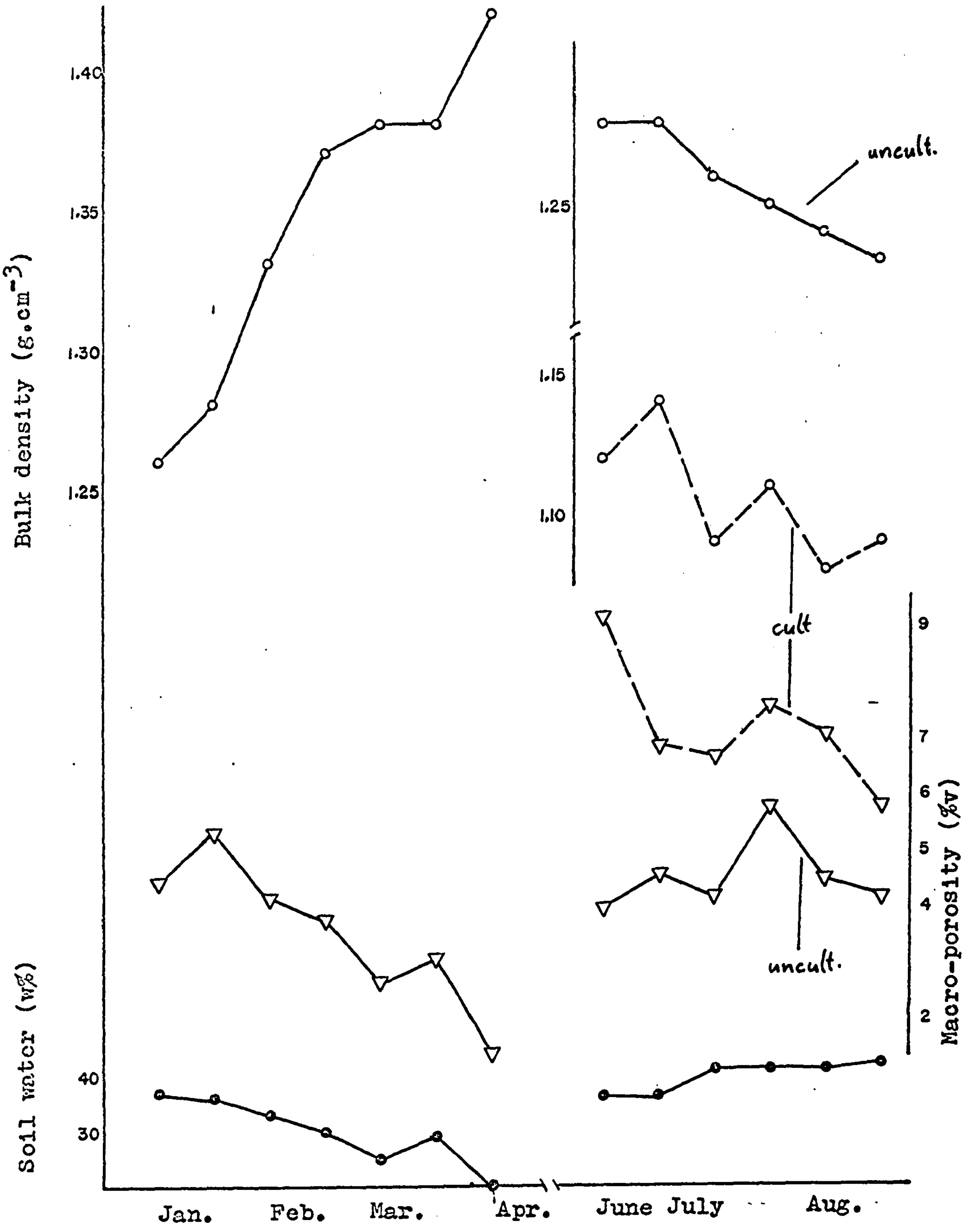

Fig. 10. Seasonal changes in water content, bulk density, and macro-porosity -- Talparo clay.

of core alteration. During oven-drying, shrinkage occurs and the volume of soil is reduced. Thus, the measured total porosity is increased.

An estimate of this effect can be obtained by comparing the measured total porosity values with total porosity values calculated from particle density and bulk density measurements. This comparison is shown in Figs. 11 and 12 for River Estate loam and Talparo clay. Measured total porosity and macroporosity are plotted vs. bulk density values. Calculated total porosity is represented by the straight line. Points lying above the line are due to swelling and shrinkage effects. Points lying below the line are due to plant roots and other low density material present in the sample, or drainage of water from the saturated core just before weighing.

The measured values of total porosity of River Estate loam lie close to the calculated values (Fig. 11). Hence, the porosity measurements in this soil are not greatly affected by swelling and shrinkage.

In Talparo clay (Fig. 12), the measured values of uncultivated soil are greater than the calculated values. Hence, porosity measurements in this soil are seriously affected by swelling and shrinkage. The measured values tend to approach the calculated line as bulk density decreases.

This is partly due to the amount of swelling occurring in the field before sampling. Soil cores sampled at low bulk densities and high moisture contents, when swelling has occurred

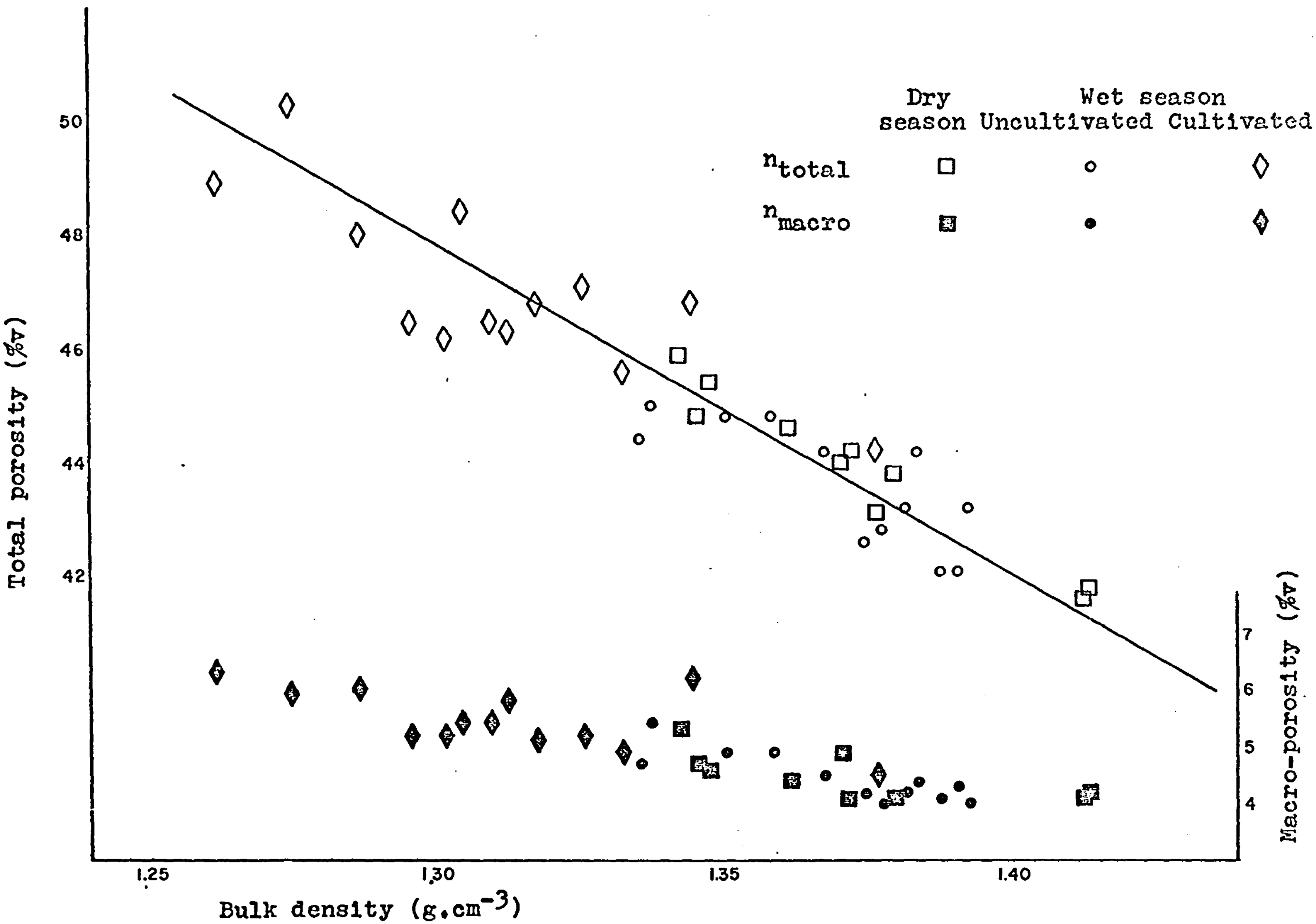

Fig. 11. Bulk density-porosity relationship -- River Estate loam.

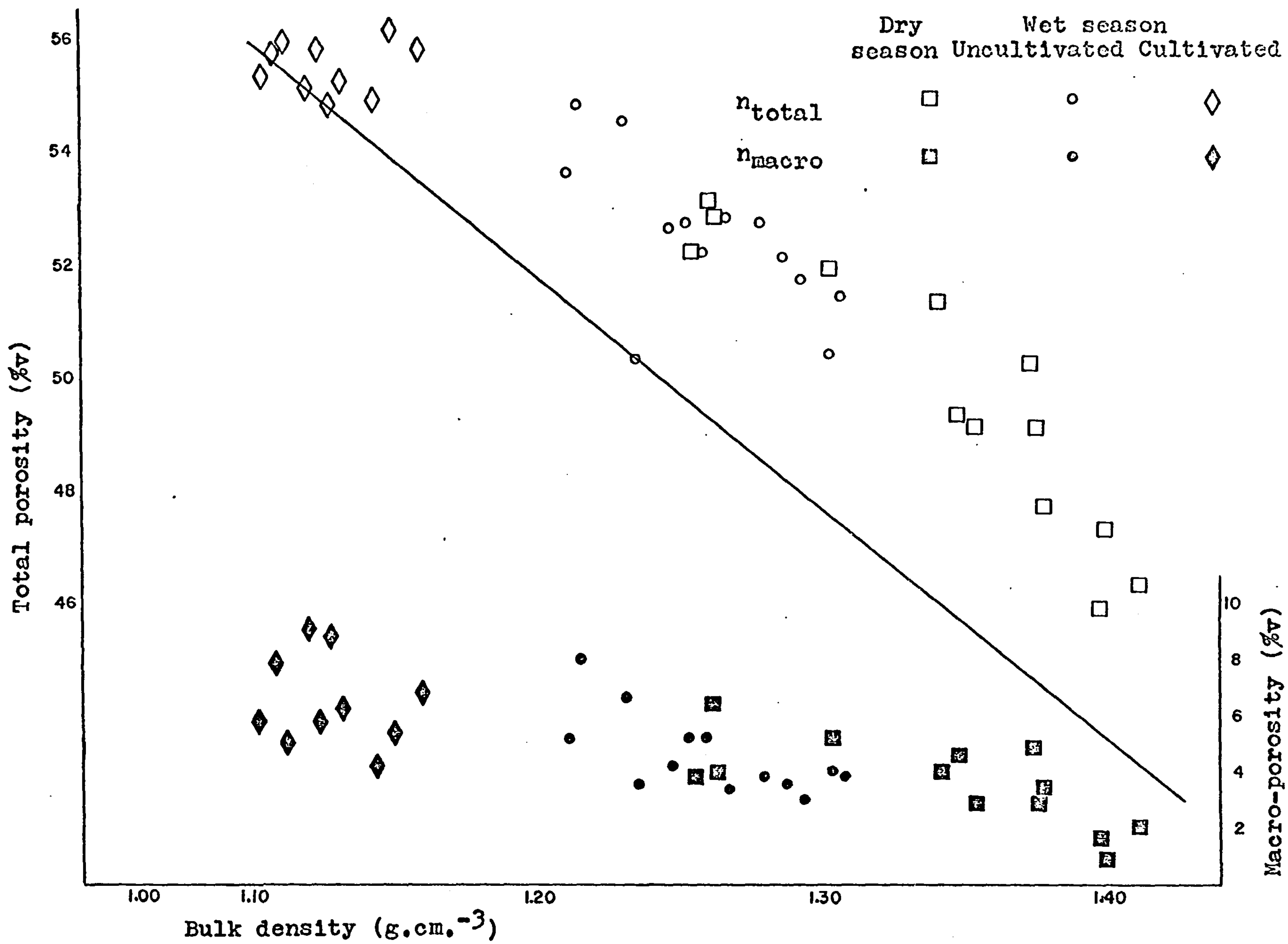

Fig. 12. Bulk density-porosity relationship -- Talparo clay.

to a great extent in the field, can be expected to show only slight volume changes on saturation, whereas cores sampled at low moisture contents and higher bulk densities should produce greater volume changes on saturation. Measured total porosity values of cultivated Talparo clay can, therefore, be expected to be low because of high moisture contents and low bulk densities. The presence of plant roots included in the soil core may also have been partly responsible for the low bulk densities of cultivated Talparo clay soil.

The bulk density-porosity relationships of Cunupia silty clay loam and Piarco sandy clay loam were intermediate between those of River Estate loam and Talparo clay, whereas that of Montserrat clay was similar to that of Talparo clay.

3.1.2. Hydraulic conductivity

The results of hydraulic conductivity measurements are summarized in Tables 6 and 7. The magnitude of the hydraulic conductivity increases with decreasing clay content. Generally, hydraulic conductivity decreased during the dry season and increased during the wet season. The extent of the change was related to the extent of change in macro-porosity. For example, slight changes in macro-porosity measured in Cunupia silty clay loam and River Estate loam are associated with slight changes in hydraulic conductivity, whereas larger changes in the macro-porosities of the other soils are associated with larger changes in hydraulic conductivity.

In the dry season, the hydraulic conductivity of Montserrat clay and Talparo clay decreased to a negligible quantity as the soil dried. This may be due to the alterations of void geometry of the cores by swelling on saturation from conditions of low moisture content and high bulk density.

The effect of cultivation on hydraulic conductivity cannot be easily demonstrated because of the wide variability of this measurement (see standard errors, Table 7). The changes in hydraulic conductivity of the cultivated soils seem to be determined by the extent of compaction. For example, in cultivated Cunupia silty clay loam and River Estate loam soils, where compaction effects were dominant, hydraulic conductivity decreased as the soil became compacted, whereas no decrease in the hydraulic conductivity of cultivated Talparo clay was apparent.

3.2. Aggregate stability

Summarized results of aggregate stability measurements are presented in Tables 6 and 7. The four tests indicate that aggregates of Montserrat clay and Talparo clay were more stable than aggregates of the other soils.

No significant changes ($F_{0.05}$) were observed on any of the soils during wet and dry seasons, nor were there any significant differences between cultivated and uncultivated soils.

Sampling was discontinued when (a) hardening in Montserrat clay and Talparo clay occurred to such an extent that sampling was difficult, and (b) the other soils were so desiccated that, because of a lack of cohesion, there was difficulty in obtaining stable aggregates of a large enough size to be used for dry sieving and the instability and permeability tests.

Hence, as the soil dried, there would have been a tendency to sample the less stable aggregates of Montserrat clay and Talparo clay and the more stable aggregates of the other soils. This suggests that, in fact, the aggregates of Montserrat clay and Talparo clay become more stable as the soil dries, whereas the reverse process occurs in the other soils.

It is interesting to note the different volume change properties of Montserrat clay, Talparo clay and Cunupia silty clay loam in the instability and permeability tests. These soils have high contents of 2:1 clay minerals -- 47, 33, and 37 percent respectively. There was a net increase in volume of Montserrat clay aggregates. Talparo clay and Cunupia silty clay loam aggregates show a relative decrease in volume, the effect being greater in Cunupia silty clay loam aggregates. These effects are due to the different slaking properties of the soils. This is supported by data for the permeability of the slaked aggregates and wet stability, which demonstrate permeability and wet stability decreasing in the order Montserrat clay, Talparo clay, Cunupia silty clay loam.

4. Growth and water use of corn

Soil and plant sampling was discontinued before harvest when the author left Trinidad. The observed periods of growth were 13 weeks on Cunupia silty clay loam and Piarco sandy clay loam, 12 weeks on Talparo clay, and 11 weeks on River Estate loam. Some values for dry matter of ears at harvest have been obtained.

4.1. Growth of corn

Corn growth is expressed as dry matter accumulation of stover, ears, and total aerial plant tissue (Table 9, Fig. 13) and as rooting depth (Table 9). Final dry weights of ears grown on Cunupia silty clay loam, River Estate loam and Talparo clay are also presented (Table 9).

The Piarco site became flooded after 11 weeks growth. The water remained on the site for at least two weeks and the site was later abandoned by the R.F.E.P. The soil is described as imperfectly drained (Chenery, 1952), with low permeability in the subsoil. Under these conditions the open ditch surface drains, which were used, proved to be inadequate. Dry matter accumulation and rooting depth were reduced, with subsequent deterioration of plant tissue. These adverse soil conditions also prevented the estimation of root depth at 13 weeks growth on this soil.

Rooting depth was always less than 2 feet during the

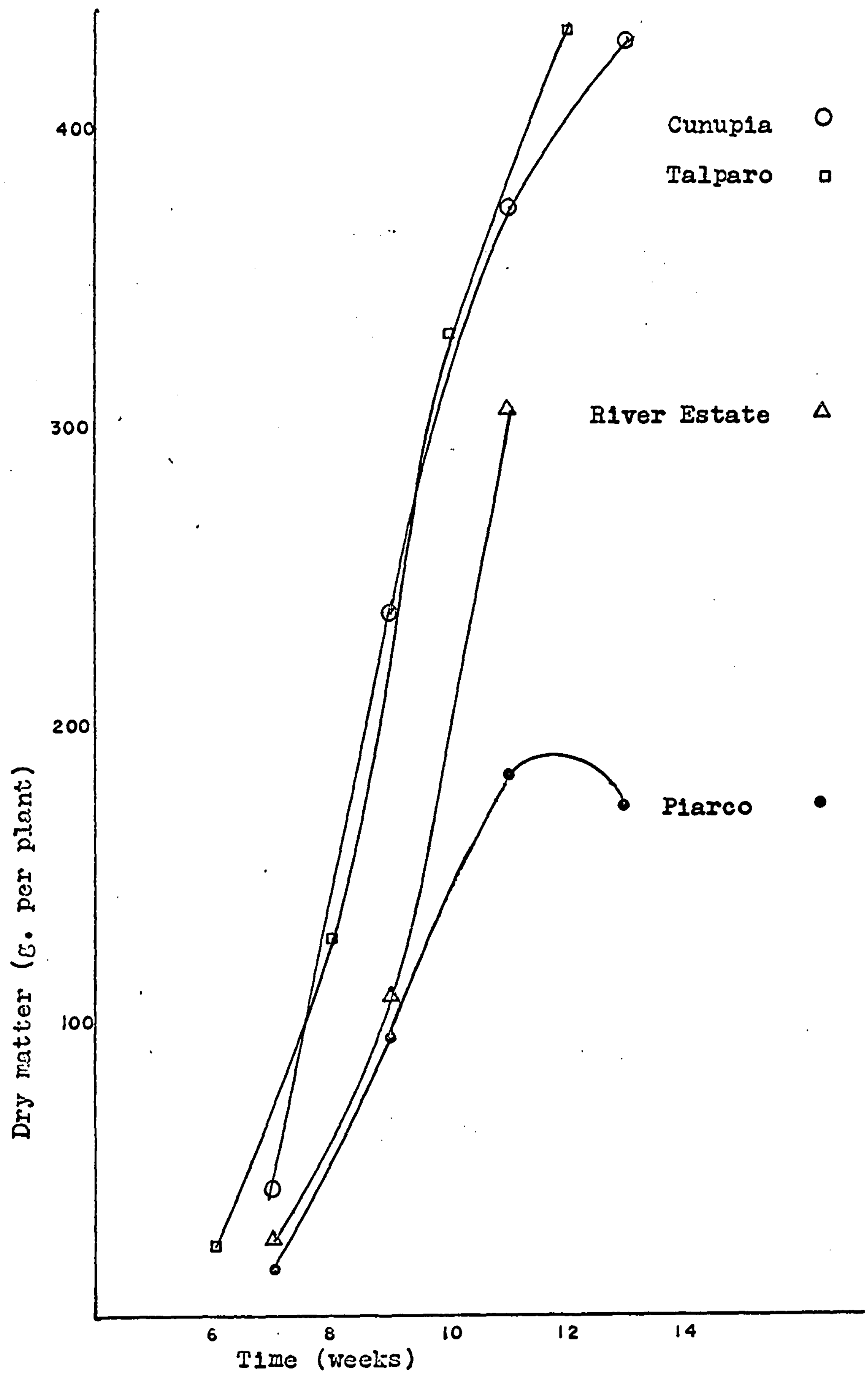

Fig. 13. Dry matter accumulation of corn.

observed period. This is in agreement with the findings of Foth (1962), Baker and Musgrave (1964) and others, that approximately 90 percent of the corn roots by weight are located in the top 12 inch depth of soil. Rooting depth increased at the fastest rate on River Estate loam, reaching 21 in. after 11 weeks.

Dry matter accumulation of total aerial plant tissue and of stover occurred at the fastest rate on Talparo clay and Cunupia silty clay loam soils. Dry matter production of ears also followed this trend. Ears developed earliest on Cunupia silty clay loam, and dry matter of ears exceeded that of stover before 11 weeks of growth. On Talparo clay, dry matter of ears seems to have exceeded that of stover just after 12 weeks of growth. The corresponding time on River Estate loam cannot be determined because the period was too short. However, at the slow rate of growth experienced, this can be expected to be at a much later stage.

In corn, dry matter of ears is produced largely by translocation of photosynthetic products from leaves to the developing ear after pollination (Loomis, 1945). Hence, these differences are probably due to differences in the amount of translocation.

Dry matter production was not related to root depth. The slowest rate of dry matter accumulation occurred on River Estate loam despite the fact that root depth increased at the fastest rate on this soil. Faster rates of dry matter accumulation were achieved on Talparo clay and Cunupia silty clay loam,

Table 9. Rooting depth and dry matter accumulation of aerial plant tissue

Soils	Wks. after planting	Rooting depth (in.)	Dry matter (g. per plant) Stover	Ears	Total
Cunupia silty clay loam	7	9	37	6	43
	9	12	148	89	237
	11	18	178	194	372
	13	21	184	244	428
	Final			485	
Piarco sandy clay loam	7	8	16	0	16
	9	12	68	27	95
	11	15	126	56	182
	13	--	113	59	172
	Final			--	
River Estate loam	7	9	26	0	26
	9	18	81	27	108
	11	21	198	105	303
	Final			233	
Talparo clay	6	6	24	0	24
	8	12	112	15	127
	10	18	209	121	330
	12	18	224	208	432
	Final			266	

although root depth increased at slower rates on these soils.

The atmospheric environment (air temperature, humidity, wind speed, light intensity and day length) can be considered essentially similar on the four soils despite differences in planting date. The different growth and development patterns experienced by corn on these soils must be caused by different soil environment factors. The soil factors affecting growth and yield of a crop can be considered to be (a) availability of water, and (b) availability of nutrients. A soil property or treatment may, therefore, affect these factors either by affecting the concentrations of water and/or nutrients, or by affecting the ability of plants to absorb them.

4.1.1. Availability of nutrients.

It was not within the scope of this thesis to study the effects of different fertilizer treatments on the yield in each soil. However, since only the control plots were used for the growth analyses, nutrient availability was not influenced by fertilizer application. The extent to which yield and growth may have been limited by unavailability of nutrients can be estimated from an analysis of the response to applied fertilizers.

It has been indicated by personal communication with the R.F.E.P. that: (1) there was no significant response to N, P, or K at any level on Cunupia silty clay loam; (2) there was a highly significant response (1% level) to N at the second level on River Estate loam; and (3) there was a highly significant response (1% level) to P at the second level on Talparo clay.

This indicates that growth on Cunupia silty clay loam was not limited by low nutrient status. The lack of available N on River Estate loam would have contributed to the slow rate of growth on this soil. Low soil P status on Talparo clay would have affected the distribution of dry matter between stover and ears by reducing the amount of translocation from leaves to ears.

4.1.2. Availability of water

Since the 2-foot depth of soil was routinely sampled for gravimetric moisture content, and since the root systems were observed to be contained only in this depth of soil during the observed period (Table 9), this depth was taken as the reference depth for the calculation of available water.

Other considerations were:

(a) Although corn has been reported to remove water from soil depths of more than 5 ft. in the later stages of growth (Russel and Danielson, 1956; Linscott et al., 1962), the amount of water extracted from depths below 2 ft. has been found to be relatively small (Carlson et al., 1959; Doss et al., 1962); and

(b) Rainfall and irrigation affect mainly the top 2 ft. of soil (Russel and Danielson, 1956). Thus the use of the 2 ft. depth is justified experimentally.

The bulk densities of the 0 to 6 in. depth of the four soils during the period have been discussed in Section 3.1. (Table 7). Mean bulk densities of the 12 to 18 in depth, sampled at the same times, are presented in Table 10. Soil moisture content and available water in the 2-foot depth of soil were calculated from the bulk density and available water capacity measurements, assuming that the 12 to 18 in. bulk density was representative of the value from 6 to 24 in. (Table 10).

Daily soil moisture contents were also estimated by the method of Thornthwaite (1945). For these calculations, it was arbitrarily assumed that the first heavy rainfall on three or more consecutive days brought the soil to field capacity. This occurred 26 days after planting in Cunupia silty clay loam and Piarco sandy clay loam, 4 days after planting in River Estate loam, and 2 days after planting in Talparo clay. Soil moisture contents were then estimated for the preceding and following periods. These data are presented in Figs. 14 to 17. Estimated values of soil moisture content corresponding to the sample dates are also included in Table 10 for comparison with the measured values.

There was good agreement between the measured and estimated moisture content values for Cunupia silty clay loam and River Estate loam. The difference between measured and estimated values does not exceed 0.6 in. Similar agreement exists in Talparo clay values except at the eighth and tenth

Table 10. Mean bulk densities of the 12 to 18 in. depth, measured and estimated water contents and available water in the 2-foot depth

Soils	Weeks after planting	Bulk density 12-18"	Water content, in. Estimated Thornthwaite	Water content, in. Measured	Available water in.	Available water %
Cunupia silty clay loam	1	1.36	6.09	5.84	0.66	27
	3	1.37	7.22	6.86	1.68	69
	5	1.40	7.43	6.98	1.80	74
	7	1.42	7.60	7.18	2.00	83
	9	1.39	7.34	6.83	1.65	68
	11	1.41	7.41	6.96	1.78	74
	13	1.40	7.48	7.17	1.99	82
Piarco sandy clay loam	1	1.25	6.07	5.56	2.56	54
	3	1.23	7.32	6.83	3.83	81
	5	1.23	7.57	7.21	4.21	89
	7	1.26	7.74	7.86	4.86	103
	9	N.D.[1]	7.48	9.12	6.12	129
	11	N.D.	7.55	10.59	7.59	160
	13	N.D.	--	--	--	--
River Estate loam	1	1.41	10.13	10.08	6.52	94
	3	1.41	9.53	9.97	6.41	92
	5	1.43	9.98	10.19	6.63	95
	7	1.41	8.03	8.46	4.96	71
	9	1.44	10.35	9.94	6.44	93
	11	1.43	10.36	9.81	6.31	91
Talparo clay	0	1.35	8.69	8.21	1.15	37
	2	1.30	10.34	9.76	2.70	88
	4	1.33	9.46	9.48	2.42	79
	6	1.34	9.84	10.06	3.00	97
	8	1.31	9.29	10.34	3.28	106
	10	1.30	8.77	10.86	3.80	123
	12	1.30	10.34	10.65	3.59	117

[1]N.D. -- not done because the soil was too wet.

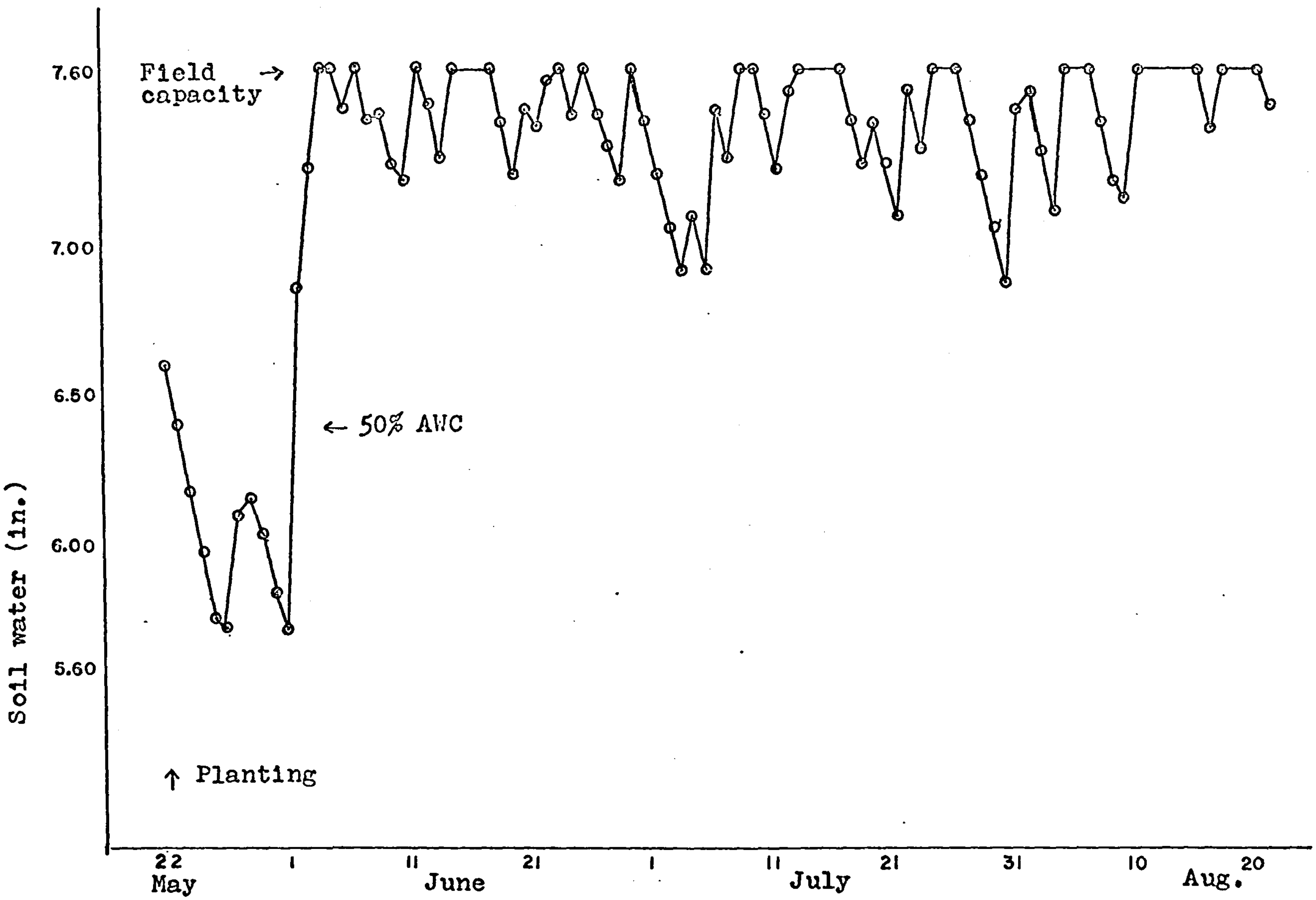

Fig. 14. Estimated daily soil water in Cunupia site.

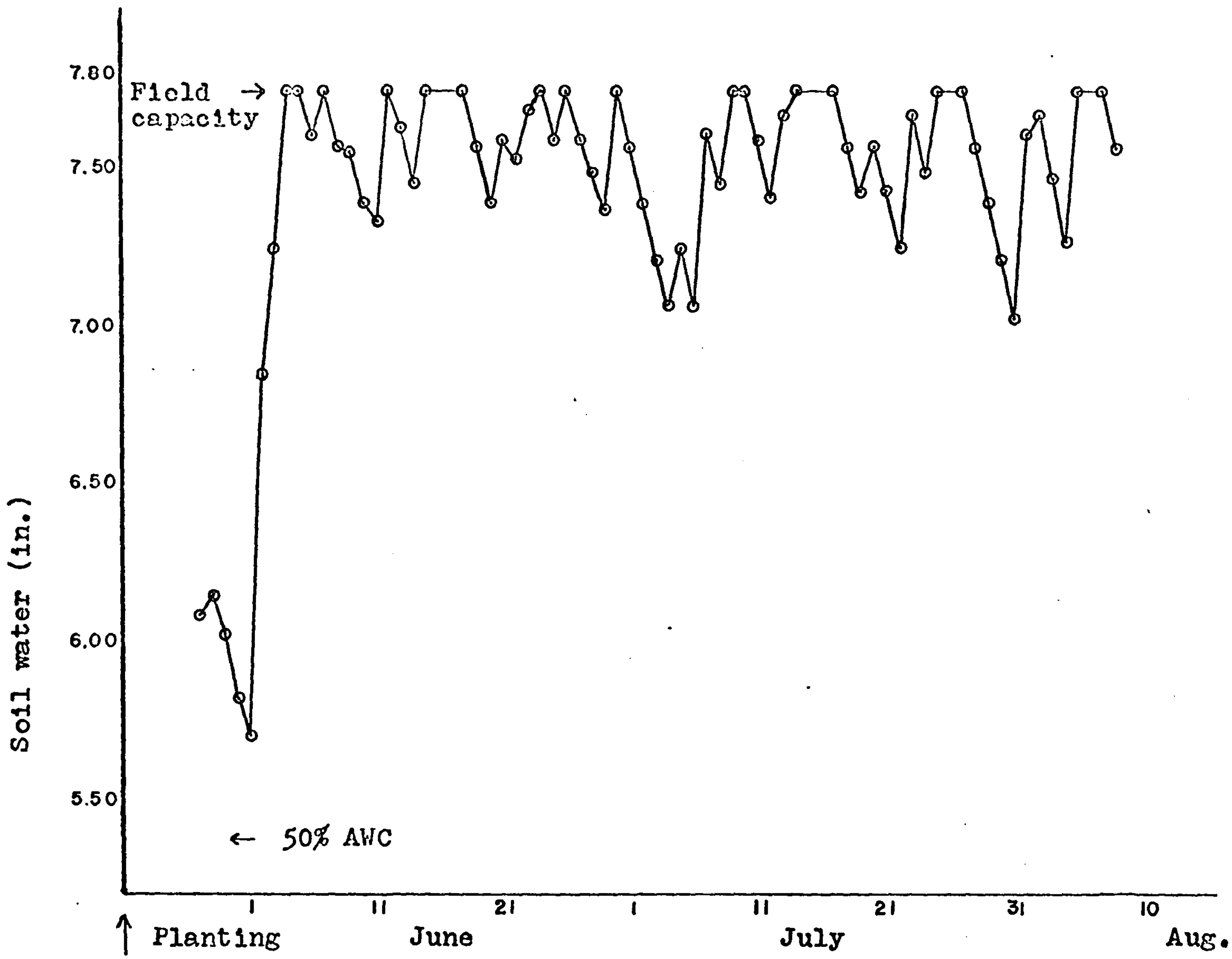

Fig. 15. Estimated daily soil water in Piarco site.

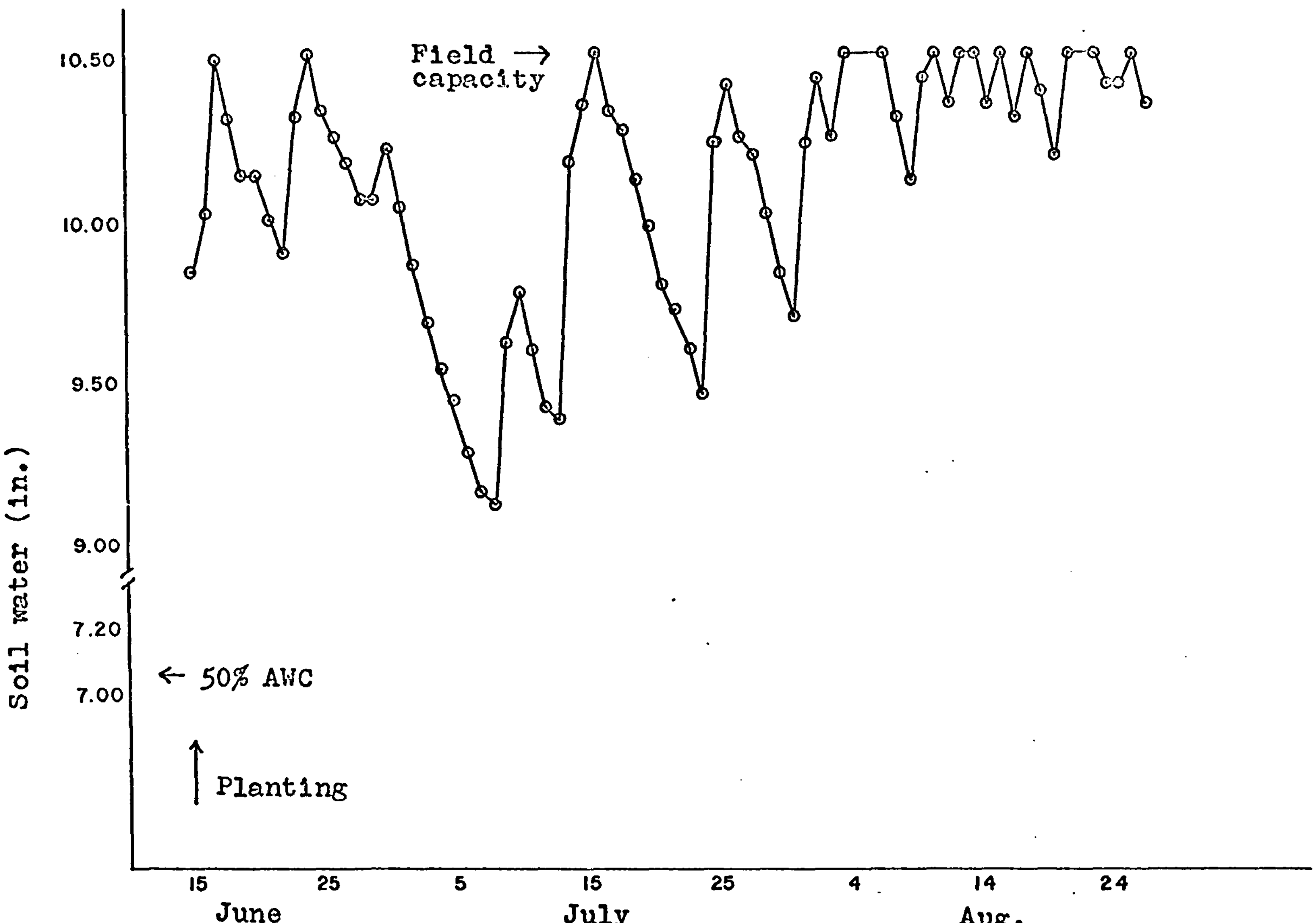

Fig. 16. Estimated daily soil water in River Estate site.

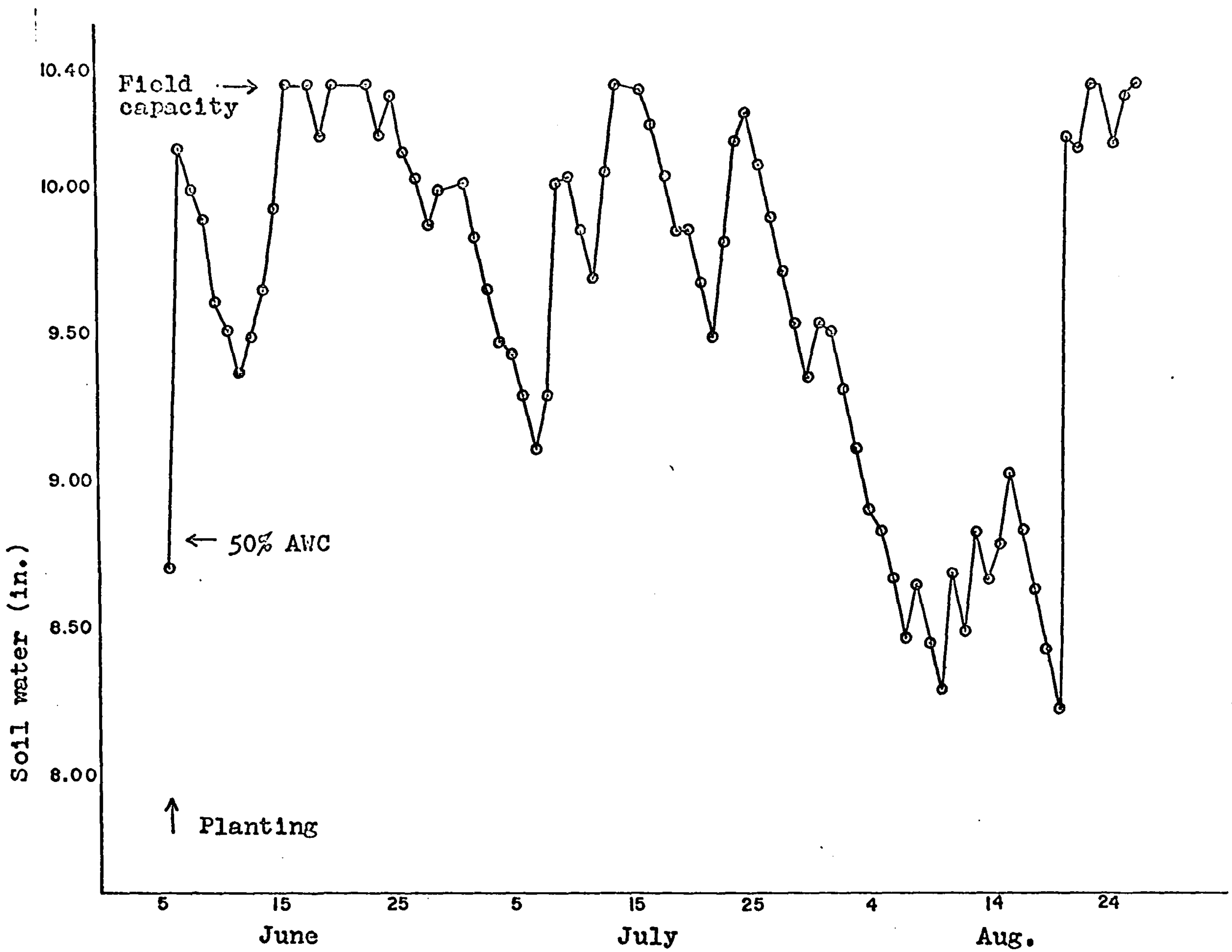

Fig. 17. Estimated daily soil water in Talparo site.

week after planting, when the measured moisture contents exceed the estimated values by 2 in. or more. In Piarco sandy clay loam, there is similar agreement up to 9 weeks after planting, but the last estimated value is more than 3 in. below the measured value.

Differences between measured and estimated moisture contents can be explained on the basis of the assumptions made in the calculations. Measured values may be too high or too low if there are large changes in bulk density with depth between the 6 and 24 in. depth. In each soil, this effect influences every calculation to the same extent, and therefore may cause all the values to be over-estimated or under-estimated. The fact that there were large differences between measured and estimated moisture content values only in a few instances indicates that bulk density changes with depth did not constitute an important source of error. The estimated values may be too low because of impeded drainage, upward flow of ground water or lateral flow within the reference depth from surrounding areas. Under these conditions, there is additional water within the reference depth which is unaccounted for. The estimated moisture contents may be too high if the condition exists that the rainfall rate exceeds the soil infiltration rate. Under these conditions, water which is assumed to enter the soil is lost by run-off.

The under-estimations of soil moisture content in Piarco sandy clay loam and Talparo clay when the measured soil moisture content was above field capacity must be due to impeded drainage. This would prevent excess water from draining through the reference depth.

Generally the estimated moisture content is greater than the measured value. However, the reverse condition exists in River Estate loam soil on the third, fifth and seventh week after planting. This may have been due to upward flow of ground water.

Under the conditions of high temperature, high humidity and low wind speed which exist in Trinidad during the wet season, the atmospheric demand for water was assumed to cause water stress when the soil moisture content was 50 percent of the available water capacity of the soil. If water stress is considered to be this assumed condition, then Figs. 14 to 17 indicate that this condition existed in the reference depth only in Cunupia silty clay loam during the first eleven days after planting, and on the planting day in Talparo clay. The apparent water stress condition in Talparo clay during the period between eight and eleven weeks after planting (Fig. 17) was due to under-estimation because of impeded drainage, since the soil was found to be at field capacity in two measurements made during the period.

Figs. 14 to 16 indicate that there were no great fluctuations in available moisture between samplings. In Fig. 17, the period between 8 and 11 weeks after planting has already been considered to have been under-estimated because of impeded drainage.

Because of the high moisture contents measured at this time, it can be assumed that no great fluctuations in moisture content occurred. It seems, therefore, that available moisture in the 2-foot depth measured at fortnightly intervals during the wet season is a good indication of the changes in soil moisture content occurring in these soils. The same can be assumed for the 0 to 12 in. depth. However, this assumption becomes less valid as the reference depth of soil is reduced because rainfall additions in moisture and evaporation losses cause immediate fluctuations in shallow depths of soil.

During the early growth period when root depth was essentially contained in the 0 to 12 in. depth (0 to 8 weeks in Talparo clay and River Estate loam, 0 to 9 weeks in the other soils)(Table 9), all the water in the 2-foot depth was not directly available to the plants. During this period, growth may be more influenced by the water content in the 0 to 12 in. depth. Water contents and available water in the 0 to 12 in. depth measured during this period are presented in Table 11.

The data in Table 11, therefore, indicate that there was moisture stress in the 0 to 12 in. depth of Cunupia silty clay loam for the first 5 weeks after planting, but there seems to have been no moisture stress in the 0 to 12 in. depth of the other soils during the early growth period.

There is no dominating relationship between dry matter accumulation and the available water status of the 1-foot or

Table 11. Measured water content and available water in the 0 to 12 in. depth during early growth

Soils	Weeks after planting	Water content ins.	Available ins.	Water %
Cunupia silty clay loam	1	2.51	0	0
	3	2.77	0.18	15
	5	3.09	0.50	41
	7	3.20	0.61	50
	9	3.23	0.64	53
Piarco sandy clay loam	1	2.78	1.28	59
	3	2.97	1.47	62
	5	3.42	1.92	81
	7	3.68	2.18	92
	9	4.06	2.56	108
River Estate loam	1	4.00	2.22	64
	3	4.14	2.36	68
	5	4.31	2.53	73
	7	4.39	2.61	75
Talparo clay	0	4.48	0.95	58
	2	5.00	1.47	90
	4	4.74	1.21	74
	6	5.02	1.49	91
	8	5.41	1.88	115

2-foot depths of the soils during the period. In Cunupia silty clay loam, where water stress conditions were experienced for more than 5 weeks and more than 1 week after planting in the 1-foot and 2-foot depths respectively, total dry matter and dry matter of stover accumulated at a faster rate than in River Estate loam and Piarco sandy clay loam (prior to flooding) where there was no water stress. Total dry matter and dry matter of stover accumulated at the fastest rate in Talparo clay, where water stress conditions were restricted to the time of planting.

Similarly, dry matter of ears accumulated at the fastest rate in Cunupia silty clay loam and Talparo clay under the different water stress conditions previously described, whereas dry matter of ears accumulated at a slower rate in River Estate loam despite the high available water existing during the growing period. However, the greater amount of translocation of dry matter from leaves to ears on Cunupia silty clay loam could have been caused by the long period of water stress experienced on this soil.

4.2. Water use

Water use by the crop grown on Cunupia silty clay loam, River Estate loam and Talparo clay soils was calculated from rainfall and estimated soil moisture content data for the observed period of growth. The estimated surplus rainfall was considered to be an estimate of surface run off plus through drainage. Efficiency of water use in terms of the amount of dry matter produced per inch of water used during the first eleven weeks of growth was also calculated. These data are presented in Table 12.

Since the rates of water use on the three soils were similar, while growth rates were different, it follows that the efficiency of water use was directly related to the growth rate.

The differences in the distribution of total dry matter between stover and ears in the plants grown on the three soils have already been discussed. Because of these differences, water use efficiency related to total dry matter production was not directly related to yield.

Table 12. Water use by corn grown on three R.F.E.P. soils during the observed growth period

	Cunupia silty clay loam	River Estate loam	Talparo clay
Soil water at time of planting (in.)	6.59	9.84	8.69
Soil water at end of period (in.)	7.48	10.36	10.34
Change in soil water (in.)	+0.89	+0.52	+1.65
Total rainfall (in.)	35.57	22.67	33.88
Surplus rainfall (in.) (run off + drainage)	17.12	7.42	6.11
Total water used (in.)	17.56	14.73	16.62
Time period (wks.)	13	11	12
Average rate of water use (in./day)	0.193	0.191	0.192
Water use efficiency ave. of first 11 wks. growth (g./plant/in.)	23.86	20.57	27.49

V. SUMMARY

Soil water retention, measured for the five soils showed that moisture contents of the clay soils were higher than those for the sandy and loam soils, due to greater swelling in the clay soils. High values in Montserrat clay due to swelling were attributed to its high content of 2:1 clay and its low bulk density.

Available water capacity values for the soils were found to be greater than the values normally quoted in the literature for soils of similar texture.

Seasonal changes in moisture, bulk density, porosity, hydraulic conductivity, and aggregate stability of the five soils were studied by fortnightly measurements. Uncultivated soils were studied during the dry season and both uncultivated and cultivated soils were studied during the wet season. No studies of Montserrat clay were made during the wet season.

Generally, greater changes in bulk density were observed in the clay soils than in the sandy and loam soils. However, large changes were also observed in Piarco sandy clay loam.

Cultivation caused a decrease in bulk density due to the increase in porosity. The subsequent increase in bulk density was due to the opposing effects of compaction and swelling. The change was, therefore, dependent on the clay content and mineralogy of the soil, the initial water content and the subsequent increase in water content of the soil.

The data indicate that uni-dimensional and three dimensional, normal shrinkage occurred in Montserrat clay and Talparo clay within the moisture range which was sampled in the dry season. Only uni-dimensional, normal shrinkage can be detected in the other soils. This was because cracking occurred at lower moisture contents in these soils, and only a few samples may have been obtained during the three dimensional phase of shrinkage.

Macro-porosity changes followed the same trend as bulk density. Measured total porosity data indicate that the macro-porosity changes in Montserrat clay and Talparo clay were greatly influenced by swelling as the soil cores were saturated from different moisture contents.

Hydraulic conductivity values of the clay soils were lower than those of the loam soils. Changes in hydraulic conductivity were related to changes in macro-porosity. There were small changes in the sandy and loam soils whereas there was a drastic reduction in the clay soils as they dried. This effect in the clay soils was attributed to the alteration of void geometry by swelling on saturation of the soil cores.

Dry and wet aggregate stability changes throughout the wet and dry seasons were not significant ($F_{0.05}$) nor were the effects of cultivation. Differences in the instability factors of Montserrat clay, Talparo clay and Cunupia silty clay loam, soils with similar contents of 2:1 clays were attributed to differences in their slaking properties.

Growth of corn was studied on Cunupia silty clay loam, Piarco sandy clay loam, River Estate loam and Talparo clay. Dry matter of stover and ears and depth of rooting were measured every fortnight. Soil water content was calculated for the 2-foot depth from measurements made at the same time. Daily soil moisture was also estimated by the method of Thornthwaite (1945).

Soil water in the top two feet was greater than 50% of the available water capacity in all the soils for most of the observed period. However, there were differences in the growth rate and the distribution of dry matter on the four soils. There was, therefore, no dominating relationship between growth rate and available water, nor was there a relationship between growth rate and rooting depth.

The effects of different levels of N, P, and K fertilizers indicate that no nutrient was limiting on Cunupia silty clay loam, whereas N, and P were limiting on River Estate and Talparo clay respectively.

Differences in dry matter distribution seem to be due to differences in the amount of translocation of photosynthetic products to the ears from the leaves. The data suggests that this process was impeded in Talparo clay because of low P content, and may have been enhanced in

Cunupia silty clay loam by early water stress in the top 1 foot depth of soil.

The average rates of water use by corn on the four soils was similar, and water was not the limiting factor in corn growth for any of the soils.

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