HILGARDIA

A JOURNAL OF AGRICULTURAL SCIENCE PUBLISHED BY
THE CALIFORNIA AGRICULTURAL EXPERIMENT STATION

Volume 39, Number 5 • May, 1968

Plant Growth as a Function of Soil Texture in the Hanford Series

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At the Kearney Horticultural Field Station, in soils of the Hanford series, cantaloupe plant growth and yield varied from excellent to poor as the sand content of the soil varied from about 40 per cent to 70 per cent. Experiments described here indicated that tendencies to moisture stress or nutritional deficiency were not the primary factors limiting plant growth on the coarser soil. Observations upon roots indicated a greater mechanical impedance to root growth in the coarser soil, although this was not reflected in penetrometer measurements, and although the rate of water percolation was higher for the coarser than for the finer soil. Since, in response to textural variation, plant development in pot culture was analogous to that in the field, the field profile did not appear to be a principal factor in the response phenomenon. A two-point hypothesis which fits all the observations is offered to explain the relationship between soil texture and plant growth: (1) for cantaloupe, pore sizes in both the coarser and finer members of this soil were too small for root extension; (2) adequate root extension occurred in the finer soil *via* fractures which developed during moisture loss. Fractures do not develop in the coarser soil. The response of cotton and of some woody species to textural variations in this soil is similar to that of cantaloupe.

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Plant Growth as a Function of Soil Texture in the Hanford Series¹

IN 1963, COMPARABLE CANTALOUPE plantings were made on soils of the Panoche, San Joaquin, and Hanford series represented at three University of California field stations in the central San Joaquin Valley. Plant growth and yield were notably the least at the Kearney Horticultural Field Station (Reedley, California). The soils at this station were classed as Hanford sandy or fine sandy loams which have high productivity ratings on the Storie Index (Storie *et al.*, 1940).

At the station, the soil exhibits a low infiltration rate (0.1 to 0.3 inch of water per hour). Since cantaloupes beds are wide (80 inches from furrow center to furrow center), and the plant row is in line with the bed center, it was reasonable to suppose, first, that soil moisture was not supplied adequately by

furrow irrigation. It was reasonable to suppose, second, that the poor growth and yield might be due to effects of soil structure on aeration and root penetration. The soil is notably loose and friable under tillage, but after wetting it assumes the appearance of extreme consolidation, *i.e.*, a single grain matrix with little pore space.

This paper reports the results of two field experiments and one greenhouse experiment designed to assign the plant growth phenomenon to one or more of the following: soil moisture, soil aeration, physical impedance to root growth, or some other factor. Such an assignment is essential if someday we are to have a measure of the soil property which has such an exceptionally strong influence on plant growth.

Field Experiments

General procedure

Field plot designs were appropriate for randomized complete block analyses. Culture and fertilization of cantaloupe (*Cucumis melo*, L., cultivar PMR 45) followed practices used in California (Lingle and Wight, 1964).

The experimental area in 1964 was located on Kearney field number 26. It had been cleared of peach trees in 1963, and the soil had been ripped in two directions to a depth of 2 feet before winter rains. The soil was treated with 100

pounds per acre of a fumigant (DD) in split applications, winter and early spring. The planting date was April 15.

The experimental area in 1965 (field number 45) had been cleared of grape vines in 1963 and ripped in one direction. It was kept fallow during 1964 and was fumigated as described for field 26. The planting date was April 27.

Blocks of cantaloupe plants to be sprinkler-irrigated were left unfurrowed. Application by sprinkler at the rate of about 0.1 inch per hour was de-

¹ Submitted for publication October 27, 1967.

TABLE 1
VARIATION OF SOIL-MOISTURE TENSION WITH IRRIGATION TREATMENT,
ELECTRICAL RESISTANCE-BLOCK PLACEMENT, AND DATE,* 1964

Irrigation treatment	Block placed (18" deep):	Moisture tension on:						
		7/1†	7/9‡	7/13	7/20‡	7/23§	7/27	8/3
		bar	bar	bar	bar	bar	bar	bar
Sprinkler.....	In row	.18	.64	.17	.45	.15	.18	.60
	20 inches from row	.16	.36	.16	.26	.16	.17	.25
Furrow.....	In row	.15	1.00	.64	1.04	1.10	.87	1.07
	20 inches from row	.15	.21	.16	.24	.18	.21	.34

* An LSD of .23 may be used reliably at the .05 level between any two values in the table.
† Moisture tension on July 1 is representative of previous measurements.
‡ Plots were irrigated on these dates, just after block resistances were recorded.
§ Fruits were harvested from July 24 to August 4.

signed to be as evenly distributed as possible. Standard soil moisture measurements and leaf analyses were made. To examine roots in the field after harvest, trenches 3 feet deep were dug across several plant beds of each treatment. The soil was slowly washed away by spraying to note root distribution.

Fruit quality measurements were made as described by Davis, Baker and Kasmire (1964).

In the 1964 irrigation experiment, response of cantaloupe plants to sprinkler and furrow irrigation was observed, to test the hypothesis that moisture was not supplied adequately in this soil by furrow irrigation. Table 1 presents soil-moisture tensions calculated

from electrical resistance-block measurements for several dates. The young plants assumed an appearance of water stress, although tensiometers and resistance blocks indicated adequate soil moisture (<0.2 bar tension) on all plots.

The yield of melons was low (1.64 melons per lineal foot of row)^a and did not vary between treatments. However, important variations in melon characteristics occurred between replications. Replication means for fruit characteristics are shown in table 2. On a replication basis, contrary to expectation, smaller plants having smaller melons with thinner flesh were associated with lower soil moisture tensions (fig. 1). Figure 1 shows also that the poorer

^a This is total yield of all fruits, including culls.

TABLE 2
VARIATIONS IN MELON CHARACTERISTICS AND SOIL MOISTURE,
DUE TO REPLICATION, 1964

Variable	Replication*				LSD (.05)
	A	B	C	D	
1. Ratio of flesh thickness to cavity diameter.....	.66	.61	.62	.63	.03
2. Cross diameter (cm).....	12.7	12.3	13.0	12.7	.4
3. Per cent of melons less than 10 cm in diameter.....	.7	8.7	1.4	3.8	2.2
4. Ratio of melon length to cross diameter (Item 2).....	1.07	1.00	1.03	1.05	.03
5. Soil moisture tension (bar), seasonal mean.....	.48	.20	.43	.45	.18

* Means for irrigation treatments combined.

Fig. 1. Ratio of melon flesh thickness to cavity diameter as a function of seasonal mean moisture tension, when classed on the basis of irrigation method and replication. Field experiment, 1964.

quality melons were associated with sprinkler irrigation in each replication. Soil samples taken from several depths during the season indicated no excessive soil moisture at any time.

Root growth was poor for both treatments, but somewhat better under furrow irrigation than under sprinkler irrigation. The soil was dense and difficult to erode without breaking roots. The greatest proliferation of roots occurred in the shoulders of irrigation furrows, which had remained friable during the growing season. This region of plant beds must have been subjected to wide variations in soil moisture between irrigations, yet roots here were healthy and vigorous.

Acetic acid-soluble nitrate nitrogen in small plants was 570 ppm, far less than the critical level (5,000 ppm) indicated by Lingle and Wight (1964) or the level of 2,000 ppm found by Tyler

and Lorenz (1964) for unfertilized plants of comparable age.

The failure of plants to grow and produce more fruit when soil moisture was higher, and the inverse correlation between soil moisture and fruit quality contradicted the hypothesis that moisture stress under furrow irrigation was the primary factor limiting plant growth in this soil.

Suppose, tentatively, that some unmeasured factor depressed plant growth—perhaps by limiting root growth—and this, in turn, restricted water and nutrient uptake. If this factor varied in intensity between replications, then soil moisture would be highest in the replications having the smallest plants, and this was the case. The additionally depressing effect of sprinkler irrigation on root growth and fruit quality suggested that sprinkling possibly intensified the naturally occurring growth-suppressing factor.

In the 1965 irrigation-tillage-species experiment, the comparison of sprinkler and furrow irrigation was repeated. Normal tillage was compared with precision tillage (ripping the soil under the anticipated plant row to a depth of 2 feet) (Carter *et al.*, 1965).^a Comparative plots of cotton (*Gossypium hirsutum*, L., cultivar Acala 4-42) were planted in conjunction with the cantaloupe.

In addition to the measurements and procedures described earlier, cantaloupe plant growth was estimated six weeks after planting, and just before harvest, by measuring the length of branches of replicated sets of plants in each plot. On July 15, penetrometer readings were made for each row of each species at distances of 0, ± 10 , and ± 20 inches from each row to a depth of 3 feet with a continuous recording penetrometer (Carter, 1967).

^a There was an additional ripping line midway between (or 40 inches from) each cantaloupe row.

TABLE 3
CORRELATIONS ACROSS PLOTS BETWEEN CANTALOUPE YIELDS,
TREATMENTS, AND SELECTED INDICATORS OF SOIL VARIABILITY,
1965

Indicator variables	Correlation with yield*			Range or coding of variables
	Zero order		Multiple†	
	r	Significance level	Significance level	
Tillage method.....	.22	NS	.001	Nonripped = 1, ripped = 2
Irrigation method.....	-.28	NS	.01	Furrow = 1, sprinkler = 2
Leaf analysis:				
Na.....	.67	.001	...	.12 to .36 per cent, dry wt.
HAc sol. NO ₃ -N.....	.57	.001	NS	1890 to 7630 ppm, dry wt.
HAc sol. PO ₄ -P.....	.42	.02	...	1070 to 3970 ppm, dry wt.
Plot location:				
By tier number.....	.80	.001	.001	1 to 4, west to east
By column number.....	.30	NS	.02	1 to 4, south to north
Penetrometer index:				
10 inches out.....	.25	NS	NS	150 to 800 psi
20 inches out.....	.21	NS	...	190 to 440 psi
In plant row.....	.32	NS	...	10 to 800 psi
Soil moisture tension:				
Season mean, 20 inches out.....	.79	.001	NS	.1 to 1.0 bar
July 16, 20 inches out.....	.63	.001	...	.2 to .7 bar
Season mean, in row.....	.20	NS	NS	.3 to 3.1 bar
July 16, in row.....	.31	NS	...	.2 to 2.8 bar
Plant branch length:				
Six weeks after planting.....	.64	.001	...	5 to 23 inches
At harvest.....	.74	.001	...	15 to 50 inches
		Multiple R = .929		

* Range of cantaloupe yields among plots was .72 to 3.57 melons per lineal foot of row.

† For multivariate analyses, addition of more variables than those entered here did not reduce the residual error. All foliar nutrient variates responded to multivariate analysis as did nitrate nitrogen.

‡ Out = away from row. Penetrometer index = the summation of penetrometer exertion pressure between 1- and 2-foot depths.

Cotton yield,⁴ cantaloupe plant growth, yield, and fruit dimensions were positively correlated. Cotton plant growth, by casual observation, exhibited a pattern parallel to that of cantaloupe plant growth. Since detailed measurements and foliar analyses of cotton plants were not made, the discussion will center on cantaloupe plant growth and yield.

Cantaloupe plant measurements soon indicated great variations within the planting, due to plot position in the experimental area. Reconnaissance of the experimental area showed that the soil texture varied from a Hanford sandy loam (see table 5 for a mechani-

cal analysis) to a Hanford loam. The poorest growth occurred on the coarsest soil.

Soil texture changed so rapidly and continuously within the experimental area that it profoundly influenced the detectable effect of the ripping treatment. Texture changed along the length of plant rows, and since the ripping treatment was placed at random on one or the other half of each row, it was sometimes placed on more productive and sometimes on less productive soil. By dividing the area into four numbered columns from south to north and four numbered tiers from west to east, the position of each plot was defined

⁴ The yield of seed cotton, dried at 80° C, ranged from 575 to 2,770 pounds per acre.

TABLE 4

SEASONAL MEAN MOISTURE TENSION AS AFFECTED BY TILLAGE METHOD, IRRIGATION METHOD, AND DISTANCE FROM PLANT ROW,* 1965

Tillage method:	Soil moisture tension†			
	In plant row		20" from plant row	
	Furrow irrigated	Sprinkler irrigated	Furrow irrigated	Sprinkler irrigated
	<i>bar</i>	<i>bar</i>	<i>bar</i>	<i>bar</i>
Nonripped.....	1.95	.39	.49	.24
Precision ripped.....	2.30	1.21	.54	.39

* An LSD of .19 may be used reliably at the .05 level between any two values in the table.

† As indicated by electrical resistance in gypsum blocks placed 18 inches below the mean soil surface.

by two numbers and the data seemed suited to analysis by multivariate regression analysis.

The result of a multivariate analysis utilizing a minimum number of important variables is indicated in table 3, third column, by the probability levels of significance (null hypothesis) for each selected variable. Other combinations of variables were analyzed, some more extensive than the example shown, and all indicated that tillage, irrigation method, and plot position were the significant variables correlated with cantaloupe yield.

Note (table 3) that although the associations of yield with tillage and irrigation method were highly significant when considered in multiple with plot position, this significance was not detectable in the zero-order coefficients. The converse was true of leaf-nitrate and soil moisture tension, indicating that their apparently significant correlations with yield were actually reflecting some factor or set of factors associated with plot position—that is, they were dependent, not independent, variables. Penetrometer readings were not correlated with yield on any analytical basis. They were closely correlated with soil moisture tension as affected by location of plot, irrigation treatment, and plant species.

At harvest, the soil was massively consolidated, even in the sprinkled plots. A void commonly remained at the lowest point of the ripped channels. Ripping greatly benefited root growth on both furrow and sprinkler-irrigated plots. As in 1964, root growth was more restricted under sprinkler irrigation. As a result, root growth was greatest under furrow irrigation on ripped plots, and least under sprinkler irrigation on unripped plots. Variations in soil moisture tension were closely associated with these observations (table 4).

Plant growth on the least productive, coarsest soil, showed the greatest proportionate increase in response to precision ripping (fig. 2). Nevertheless, while the yield of ripped, and even unripped plots, on the finer soil would be considered excellent, even the improved yield on the coarser soil, due to ripping, was not commercially satisfactory.

All observations and analyses demonstrated that poor root growth, poor plant growth, and poor yield were associated significantly with higher soil moisture. Soil saturation was not involved. As in 1964, soil moisture stress again was shown not to be the dominant cause of poor growth. Poor root growth and high soil moisture were associated not only with coarser soil, but with

Fig. 2. The response of cantaloupe plant growth to precision tillage (ripping) as a function of plant growth on contiguous, unripped subplots. The response index is mean branch length on a ripped subplot divided by the mean branch length on the contiguous unripped subplot.

sprinkler irrigation and the nonrip tillage method.

Discussion

Plot yields in 1965 varied from poor to excellent (less than one to more than three melons per lineal foot of row), with poorer production on the sandier soil. A scan of field 26, used in 1964, showed that replications with poorer quality melons and lower moisture tensions also were located on the sandier portions of that field. However, the characteristic of the coarser soils that was responsible for poor plant growth was not clarified.

Poor root growth and the beneficial effect of precision ripping enhanced the notion that mechanical root impedance was a dominating factor in the phenomenon. The adverse effect of sprinkler irrigation on plant and root growth did not contradict this supposition. The soil was observed to be consolidated by water action, even under the slow rate of sprinkling; conceivably, sprinkler application caused consolidation closer to the plant crown than did furrow application. Root impedance is commonly considered to be associated with elevated penetrometer readings, but this association was not detectable in

this case, even by a multivariate analysis which included soil moisture measurements.

It was possible that the sandier soil was deficient in mineral nutrients, even though applications of nitrogen, phosphate, and potash were at the rates of 70 pounds per acre each in 1964 and 100 pounds per acre each in 1965, and banded as recommended by Lingle and Wight (1964). If nutrients were lacking, one would not expect the positive response to precision ripping. Zinc in

leaves was negatively correlated with growth and yield. Plants were free of soil-borne pests and pathogens.

It would have been difficult to elucidate further the relationship between plant growth and soil texture by field observations. Since yield was closely correlated with vegetative growth, it was considered that the investigation could be pursued with greater refinement by observing vegetative growth in short-term greenhouse pot experiments.

Greenhouse Experiment

General procedure

Two sites were selected in field 45, one having the coarsest, the other having the finest textured soil. Three large samples of each were removed from depths of 1 to 2 feet. Each sample was divided into two subsamples, into one of which was mixed a complete fertilizer⁵ at a concentration equivalent to

960 pounds of fertilizer per acre mixed in the upper 1.25 feet of soil in the field. Pots of soil were prepared according to four treatments from each of the twelve subsamples.

The pots were blued sheet steel stovepipes, 6 inches in diameter and 12 inches high, set on individual flat wood bases (fig. 3). Plastic 120-cc bottles were

Fig. 3. Root distributions at termination of the greenhouse experiment.
See text for treatment details.

⁵ "Super Veg-Cropper" by Best, containing the following elements: N (12%), P (8%), K (5%), S (18%), Ca (2%), Fe (1.5%), Zn (1.0%), Mn (0.1%).

taped on the pots of treatments 1 and 4, as water reservoirs for irrigation wicks. These wicks (one per pot), of 3-inch-wide cheesecloth strips folded lengthwise, were placed before filling the pots with soil. They extended from the bottles down the inner sides and 2 inches below the lower edges of the pots. While the plants were growing, the bottles were filled once daily.

At the end of the experiment, the pots were cut open from the top down, for root examination, by an oxyacetylene cutting torch, with negligible damage to the soil core.

During the experiment, the sides of the pots were shaded to prevent abnormal solar heating of the soil. Brown paper sleeves, 2 inches high, were used as container lips during the experiment, to maintain uniform light at the soil surface for all treatments.

Seeds of cantaloupe cultivar PMR 45 were planted on January 26, 1967. Emergence was uniform and practically complete by February 1. On February 2 and 3, the plants were thinned to four per pot.

Sufficient measurements were made during soil preparation to establish a gravimetric basis on which per cent soil moisture could be determined for each pot by weighing. Plant size was determined on certain dates by measuring all plants from the sharp juncture of the cotyledons at the stem to the tip of the earliest developing true leaf. Other dimensions were measured, but were well represented by the one described.

Differential treatments

The general methods of preparing soil are shown in figure 3. The term "water-settled soil" refers to soil prepared in pots by crumbling fairly dry soil into water; *i.e.*, slowly filling pots to the desired soil level by adding soil and water alternately without tamping.

The term "moist aggregate" refers to soil prepared before placement in pots by mixing soil and water to the point of maximum crumb aggregation, or to what might be called a garden seedbed tilth and moisture content.

Treatment 1. On the planting date, the pots were filled with moist aggregate. Wick irrigation was started when emergence was practically complete.

Treatment 2. On the day before planting, pots were filled to a depth of 8 inches with water-settled soil which was permitted to drain for 24 hours. Then after scarifying the surface of the water-settled layer, a 5.5-inch layer of moist aggregate was added. The superfluous 1.5 inches were contained by a removable sleeve. The sleeve was removed later when the soil was settled by surface flooding. On February 10, ten days after emergence, enough water was added to bring soil moisture slightly above field capacity. The 5.5-inch layer of crumb aggregate collapsed, displacing the roots with an accordion-like compression.

Treatment 3. On the day before planting, pots were filled to a depth of 10 inches with water-settled soil. After the 24-hour draining period, a layer of moist aggregate 1.5 inches deep was added—the surface of the water-settled soil first being scarified slightly to minimize an interface effect between the two layers. Pots of this treatment were not irrigated subsequently.

Treatment 4. Six weeks before planting, pots were filled with water-settled soil. On December 22, 1966, and again on January 9, 1967, the soil was rewet to saturation by surface flooding. Then it was permitted to lose moisture slowly until the planting date, January 26, when the surface 1.5-inch layer in each pot was moistened slightly and stirred to make a seedbed. Wick irrigation was started after emergence was complete.

Results of the greenhouse experiment

Growth increments and soil moisture determinations for several dates are shown in table 5. Measurements are not shown for plants growing in pots containing unfertilized soil. Plants in the coarse soil responded more to fertilization than did plants in the fine soil. Growth of plants in fertilized treatments alone will be considered here, since the results indicated that, for them, nutrition was eliminated as a factor differentiating the two soil types.

Shoot growth. With important exceptions, plants shoots of treatments 1, 2, and 3 grew equally well and faster than those of treatment 4. For treatment 4, shoots of plants in the coarse soil grew consistently more slowly than those in the fine soil.

In treatment 2, shoots of plants in both soils grew equally well until the final period, when growth on the fine soil exceeded that on the coarse. This variation was associated with difference in root penetration (fig. 3), and failure of roots to obtain moisture in the coarse soil. The same type of variation occurred in treatment 3 for which moisture was not added after the planting date. In treatment 1, plants grew equally well in both soils throughout the experiment. The most rapid growth of the series occurred in treatment 2 for a brief period immediately after the surface flooding.

Root growth. Only under treatment 1 did roots become as widely distributed in the coarse soil as in the fine soil (fig. 3). The aggregate structure of the soil in treatment 1 was successfully maintained by wick irrigation. In treatment 4, a few roots penetrated the interface between the seedbed layer and the water-settled layer in the fine soil, rarely in the coarse soil. In treatment 2, roots became well distributed in the upper bed of crumb aggregate, but only

in the finer soil did they penetrate into the water-settled layer. Although dead roots were found in the upper collapsed layer, the viable root system apparently used the existing water supply efficiently. Except for treatment 1, deepest root penetration for the coarse soil occurred in treatment 3, but even here roots did not extend to the lowest soil levels by the time the wilting point was reached (the terminal date of the experiment).

At the termination of the experiment, the cores of fine soil in pots of treatments 2, 3, and 4 seemed at least as dense and hard as cores of coarse soil. An exception was the collapsed aggregate layer of treatment 2, which was extremely dry and cinder-like in the coarse soil. Here, furthermore, the surface zone of the underlying water-settled soil was hard and dense. Soil cores of treatment 4 were more moist and soft than those of treatments 2 and 3.

Deep penetration of roots in the fine soil of treatments 2, 3, and 4 more often than not appeared to be associated with soil fractures. Comparatively large volumes of soil were devoid of roots. When soil cores were broken for observation, roots came free with root hairs intact in the fine soil, not the coarse.

Discussion

The greenhouse results support a hypothesis that the coarse soil presents a more impermeable barrier to root growth than the fine soil. The best root growth for both soils occurred in treatment 1, in which root impedance must have been minimum. Nothing in theory, results, or calculations of air space at successive soil moisture levels (table 5) indicates that deficient aeration constitutes the barrier, in contrast to Bushnell's (1953) interpretation of observations upon potato production in Wooster silt loam. When the crumb aggregate collapsed upon flooding in treatment 2, shoots grew rapidly, con-

TABLE 5
PLANT GROWTH, SOIL MOISTURE, AND PHYSICAL PROPERTIES AS AFFECTED BY
SOIL TEXTURE AND TREATMENT IN GREENHOUSE POT CULTURE

Hanford soil texture:	Mechanical analysis			Field capacity (0.1 bar)	Treat- ment number	Plant size increments between:					Soil moisture on:				Soil density and air volume*		
	Sand	Silt	Clay	Water		Feb. 6-8	Feb. 8-10	Feb. 10-13	Feb. 13-16	Feb. 16-20	Jan.† 25	Feb. 6	Feb. 10	Feb. 20	D	V _d	V ₁₆
					per cent	per cent	per cent	per cent	mm	mm	mm	mm	mm	per cent	per cent	per cent	per cent
Fine (loam).....	38	41	21	22	1	4.4	7.3	20.7	15.1	13.7	.14	.13	.12	.10	.98	.63	.8
					2	5.3	8.3	26.9	17.3	15.4	.20	.14	.12-.22†	.11	¶	¶	.1
					3	4.8	7.5	24.8	15.0	11.9	.21	.15	.13	.07	1.34	.50	.21
					4	4.4	5.4	18.6	8.7	10.6	.11	.14	.15	.16	1.46	.45	.13
Coarse (sandy loam).....	68	17	15	15	1	6.1	7.8	24.3	15.1	15.6	.09	.09	.10	.11	1.03	.61	.8
					2	5.7	8.4	28.2	17.5	10.5	.13	.07	.05-.15†	.04	¶	¶	.1
					3	5.9	6.7	22.8	11.9	3.1	.15	.08	.06	.02	1.58	.41	.17
					4	3.2	3.7	12.3	7.2	5.5	.08	.11	.12	.14	1.57	.41	.18
	LSD (.05) within date						1.1	1.5	4.9	3.0	2.5						

* D = bulk density at planting time in pots prepared as described under Greenhouse Procedure. V_a = void or air space as a per cent of dry soil (volume basis). Calculated from D using an assumed particle density of 2.67. V_{te} = void or air space as a per cent of soil at field capacity (volume basis).

† Planting date.

‡ On February 10, pots of treatment 2 were moistened to field capacity.

§ Aggregate structure of soil in treatment 1 would collapse if it were moistened to field capacity.

¶ Treatment 2 might be considered as consisting of a layer of treatment 1-type soil structure on top of a layer of treatment 3-type soil structure.

tradicting a supposition of deficient aeration. The same inference was drawn by Veihmeyer and Hendrickson (1948) upon contrasting root growth in compacted soil and saturated, water-settled soil. The evidence of treatment 2 indicates that roots can function efficiently in the water-settled soil if they are ramified extensively before the soil becomes settled. That the barrier to root extension is physical is the explanation that best fits all the observations made in the field and greenhouse experiments reported here.

Soil pore size is a major component of root growth impedance. Hilgard (1911) describes a sandy soil in California at "a culture station of the University,"⁶ the particles of which are so distributed in shape and size that pore space is virtually absent. Bodman and Constantin (1965) place the relationship between particle size distribution and pore space on a quantitative basis. Wiersum (1957) reports on experiments that elucidated the relationship between pore size and root growth. In the coarse, water-settled Hanford soil, root growth resistance appeared to be intensified by even slight moisture loss. Pore size would be expected to diminish with the shrinkage attending moisture loss (Keen 1931), and there might be irreversible shifts in the physical condition of colloids (Hilgard, 1911). The extremely poor root growth in treatment 4 may be attributed to the several wetting and drying cycles of the pre-planting treatment. This soil has the well recognized characteristic of failing to regain a former volume upon drying and rewetting (Keen, 1931). The soil in pots of treatment 4 was probably more nearly analogous than that of other treatments to field soil conditions, particularly those below tillage depth and under sprinkler irrigation.

However, the comparatively poor root growth in the coarse soil cannot be attributed to a smaller pore size in the coarse than in the fine soil. The converse must be the case. Observations upon root hairs (see Greenhouse Results) indicate that they extended into the pores of the coarse soil but not into the pores of the fine soil. Steady-state percolation rates were higher for the coarse than for the fine soil.⁷ In addition, although pore size must decrease more in the fine soil than in the coarse during moisture loss, it seems that the intensification of root impedance which accompanies moisture loss in the coarse soil is somehow alleviated in the fine soil (fig. 3).

Carter *et al.* (1965), in explaining the more pronounced effect of precision tillage in coarse soils refer to evidence in the literature that coarse-textured soils develop extreme pore space rigidity (Meredith and Patrick, 1961). Laboratory studies have shown that pore space rigidity can influence root growth (Gill and Miller, 1956; Wiersum, 1957). When Carter *et al.* (1965), grew cotton on artificially compacted soils, they found a close correlation between yield and penetrometer readings. Taylor (1963) also describes relationships between soil strength as measured by penetrometer, bulk density as established by mechanical compaction, and cotton root growth. Root penetration, soil density, compaction, and infiltration of water have been studied and discussed by Doneen and Henderson (1952) and Veihmeyer and Hendrickson (1948).

Somewhat different conditions were encountered in these tests:

(1) Soils of identical source and age but of different textures were compared rather than different compaction treatments on the same soil.

⁶ The Kearney station was not then established.

⁷ For 45-mm columns under a 20-mm head, percolation rates were established at time of water-settling and again after slight moisture loss. For the coarse soil, before and after rates were 1.65 and 1.52 mm H₂O/hour. For the fine soil, they were 1.35 and 0.59 mm H₂O/hour.

(2) Penetrometer readings were not correlated with yields in the field, even on the basis of a multivariate analysis which included soil moisture data.

(3) Greenhouse experiments indicated no obvious relationship between root growth and soil-core rigidity as they varied between soils.

In none of the six soils studied by Veihmeyer and Hendrickson did roots fail to penetrate the water-settled soil. To that extent the coarse soil studied herein represents a separate class.

In consideration of all the information gathered from the field and greenhouse experiments, the commonly recognized explanations of poor plant growth on sandy soils must be rejected in the case of the coarse soil described here. These explanations in summary are: a tendency toward moisture stress, a tendency toward nutritional deficiency, and a tendency toward pore space rigidity. In addition, since growth in pot culture was analogous to growth in the field, a differentiating factor must have been present in the soil apart from any possible profile differences in the field.

Only one set of observations offers an explanation of the response of root and plant growth to soil texture in this case: In the fine soil, root extension was associated with soil fractures (see Greenhouse Results). When the soils in fields 26 and 45 are drying after winter rains, the coarsest soils exhibit no surface cracking over large areas, 20 by 20 feet or greater. A discontinuous network of cracks, mostly under $\frac{1}{4}$ inch in width, spaced at intervals of 12 to 15 inches, appears on the surface of the fine soils.

Greater root penetration which occurs in the fine soil must be at least partly due to the fracturing characteristic of the fine soil during moisture loss. No other factor, such as pore space rigidity, appears to contribute to the variation in root permeability asso-

ciated with soil texture. Greater pore space rigidity might obtain in the coarse soil at moisture levels equivalent to or below those of the fine soil, but in the field experiments, moisture was never extracted by plants to as high a tension in the coarse soil as in the fine.

To explain the plant growth phenomenon, it may be inferred from these experiments, that: (1) Soil pore size, on the micro-structural level, limits root growth, hence plant growth, of cantaloupe in both the finer and coarser soils of the Kearney station. (2) Root growth, hence plant growth, is better in the finer-textured soils, because root impedance is alleviated by the fracturing of such soils which occurs during moisture loss.

Doneen and Henderson (1952), in their studies with clay and sandy soils from the standpoint of sodium dispersion, mention the difficulty of distinguishing between sodium dispersion and compaction on sandy soils that exhibit little cracking. From their observations that most plants will develop roots under sodium dispersion, we must infer, as we did from Veihmeyer and Hendrickson's results (1948), that the coarse soil under study here must be put in a separate class. The differentiating cracking property may possibly be overlooked in some laboratory studies of root development, in which care is exerted to minimize or eliminate cracking. Also, it is important to recognize that cracking would not be a factor in root penetration in soils where pore sizes are not in themselves limiting.

Hanford sandy loam is extensive and noted for its productivity for vineyards and orchards. An interaction possibly may occur between soils and species, perhaps because of differences between primary root diameters (Kampe, 1929). The response of at least some woody species to varying textures within this soil has been observed to be similar to those reported here for cataloupe and

cotton. The same growth pattern described herein for cantaloupe and cotton on the experimental area in 1965 was present in the vineyard that previously occupied the site. (The pattern is presently extending itself into an adjacent planting of young plum trees.)

Multivariate analysis is becoming a useful tool in agricultural research (Weeks and Snyder, 1957). Soil characteristics discussed herein—pore size and soil cracking—are usually not included in such analyses. The most useful element considered in the analysis of the 1965 field experiment was the position of the plot on the experimental site. Position was particularly useful

in discounting mineral nutrients and soil moisture as independent factors, but it is a poor substitute for meaningful soil measures to indicate root penetrability.

The observations described here direct attention to the need for indicators of root penetrability in addition to penetrometer measurements. A measure of water-stable pore size appears to be fundamental; and since adequate root growth evidently is permitted by the cracking characteristic of some soils having small pore sizes, a measure of cracking or some associated factor seems essential for a completely reliable analysis or prediction of productivity.

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