

The Effect of a Dense Soil Layer and Varying Air-Water Relations on the Growth, Root Development, and Nutrient Uptake of Cotton in Commerce Silt Loam¹

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ABSTRACT

Studies were made of a Commerce silt loam traffic pan soil at St. Joseph, La., to determine the cause of the poor productivity in droughty field areas locally known as "hotspots". The pan in the problem area was only slightly more dense and less permeable than that of the productive areas. Large cylinders (10 by 24 inches) of soil were cut undisturbed and placed in a covered pit with the surface exposed. Restricted drainage, with a water table maintained at 24 inches, reduced oxygen diffusion and retarded the growth of cotton planted in the cylinders. Supplemental aeration provided by perforating some of the walls of the cylinders had very little effect on oxygen diffusion or plant growth. Reduced oxygen diffusion in this soil was associated with lower nitrogen uptake but had little effect on the uptake of potassium since the soil supply was sufficient to allow for luxury consumption by the cotton plants. It appears that a combination of factors affecting air-water relationships and root extension are responsible for these problem areas in fields of the lower Mississippi River Delta areas.

THE work reported herein was begun in an effort to learn more about the soil conditions in the "hot spot"³ areas that appear in Mississippi River Delta fields during droughty periods. The plants in these

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spots in a field of cotton, soybeans, or other crops, wilt during a drought somewhat before those in the rest of the field. They are variable in area, though usually less than an acre in size. They are often associated with slight depressions where the rain water tends to pond. The local term "hot spot" indicated those problem areas more susceptible to the effect of drought during hot, dry weather.

In April of 1954, studies were made of both problem and nearby good areas in a soybean field on Commerce silt loam at the Northeast Louisiana Substation. Duplicate core samples were taken at various depths at 4 sites in a problem area and at 3 sites in the surrounding good area. The bulk density, field moisture and moisture retention at 0.06, 0.33 and 15 atm. tension were determined for each sample. The difference between the 15 atm. and field moistures was taken to represent stored available moisture. For this soil the

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³Droughty areas of low productivity surrounded by areas of normal production.

0.33 atm. values usually agreed closely with the field capacity. At this time the soil profile was felt to be near the field capacity value. There were some dry pockets observed at depths of 18 inches or more in the problem area. The moisture retained between the field moisture and 0.06 atm. value was considered as "temporarily available" since it would drain in a few days after the soil was wetted to such a low tension.

In other soils of the Southeastern United States the 0.06 atm. value has been a better approximation of the field capacity than 0.33 atm. The amount of water released in the 0.06 to 0.33 atm. range by this soil is of interest. Above a restricting pan layer one may expect the pore space in this range to be water filled for some time after a prolonged period of rainfall. The mean volume percent of each of these was plotted against soil depth for the two areas and is shown in the soil space diagram in figure 1. The good area soil has a definite traffic pan layer from about 5 to 8 inches. The percentage of unavailable water is moderate and available water relatively high. This is readily understood since this soil is very high in silt content and should have high available moisture storage capacity. The mean total for the good area sampling was 4.2 inches in the surface 2 feet of the profile. This partly accounts for the unusually high productivity of this soil. If conditions favor water entry into the soil rather than excessive runoff, so that the available moisture storage capacity of this soil is filled during the winter and spring months, a good crop of cotton may be grown with little or no summer rainfall. Over 50% of the water held by this soil at field capacity is available, which is somewhat higher than for most soils in the United States. The percentage of large (usually air-filled) pores was low for this soil in the good area, especially in the hardpan.

The soil in the problem area also had a definite traffic pan layer, not noticeably more dense than in the good area. As in the good area the large pores and unavailable water was low. Although the available

water storage was high, as compared with other soils, it was only about 80% as much as that for the good area. Separate tests for hydraulic conductivity of the pan layer showed it to be only slightly lower than that of the good area.

The soil both in the problem and the good area was resistant to wetting when dry. The surface soil seemed to be less wettable than the subsoil. No studies of this or of the reasons for it were made. The surface soil was noticeably low in structure stability in that surface crusts formed after rains. The field studies thus far had indicated only one appreciable difference between the problem and the good areas. Even though the available moisture storage in the upper 2 feet of the profile was only 3.4 inches in the problem area as compared with 4.2 inches in the good area, there is some question whether this factor alone will account for cotton growth differences. Even 1.7 inches per foot is excellent if other soil conditions are such that plant roots have ready access to the supply. A dense traffic pan layer may restrict root growth and reduce the effectiveness of the stored moisture. The growth restriction into and through the pan may be due to poor air-water relations or to growth impedance. It was felt that a direct study of the soil in the problem area was needed. This would entail close measurement or control of soil-air-water conditions either in place or in large undisturbed samples placed in an accessible and more nearly controlled environment. Facilities at the U. S. Tillage Laboratory at Auburn, Ala., seemed to offer an excellent means of doing the latter. To get further information on air-water relations in this soil, the soil cylinder experiment reported here was planned and executed.

Experimental Procedure

An attempt was made to vary air-water relations in large core samples of the soil from the problem area and to study the effect on the root development and growth of cotton. Heavy gage, galvanized stove pipe sections, 24 inches long and 10 inches in diameter, were used to take the cores. The plow layer was removed from a 3 by 30 foot strip in a problem area. To take each core a system of cutting away the soil outside the wall and jacking beneath a tractor was used to remove the large cores in a very nearly undisturbed state. After 25 were taken, each being from the 6 to 24 inch depth so as to fill the lower 18 inches of each cylinder, the topsoil that had been removed to cut the cores was mixed thoroughly and 6 inches added to the top of each cylinder—thus restoring the plow layer in a "cultivated" condition to its place above the traffic pan. The cylinders were transported to the U. S. Tillage Laboratory at Auburn, Alabama, where they were installed in place in a pit especially prepared for the study.

The pit was a trench 45 feet long and 4 feet wide cut along the side of a slope at the south side of the Laboratory property. The earth removed from the pit was used to fill a double lumber retaining wall that formed the upper part of the south bank of the pit. Drainage from the pit was provided by grading the floor toward the ends which were cut open down slope. The pit was protected from runoff from above by a diversion ditch. The north side of the pit was an earth bench upon which the soil cylinders were set. A wooden framework and chicken wire covered with pine needles was used to cover the pit and shade the cylinder walls from the sun. The cylinder tops were exposed to the sunlight through openings cut in the chicken wire. The pit walls were sprayed with water daily in an attempt to maintain high relative humidity in the pit.

Two types of drainage were provided for the cylinders. The water table of some was maintained at 24 inches by setting these cylinders in shallow pans which were kept filled by replenishment of the supply in inverted flasks tied to the cylinders. The other cylinders were set on a bed of silt over successive layers of sand and gravel to the floor level which allowed for a capil-

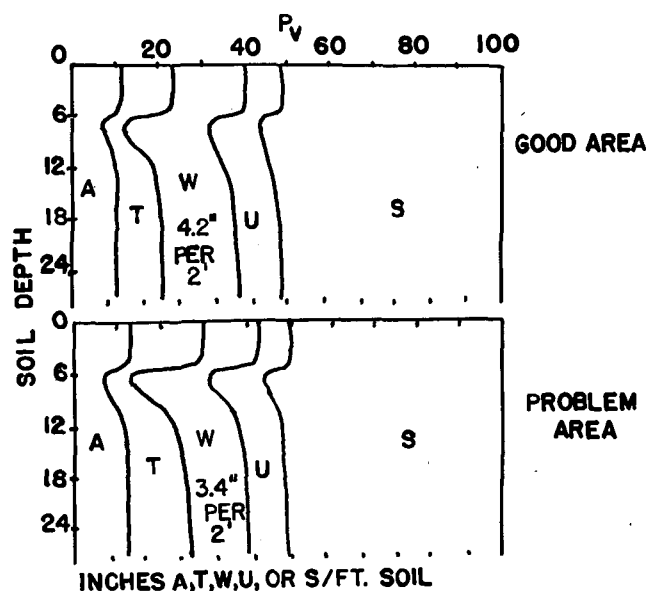


FIG. 1.—Air-water-solid space relations compared for a "hotspot" and a surrounding good soil area. The letters A, T, W, U, and S indicate volume of air, "temporarily" available water, available water, unavailable water, and solid space, respectively.

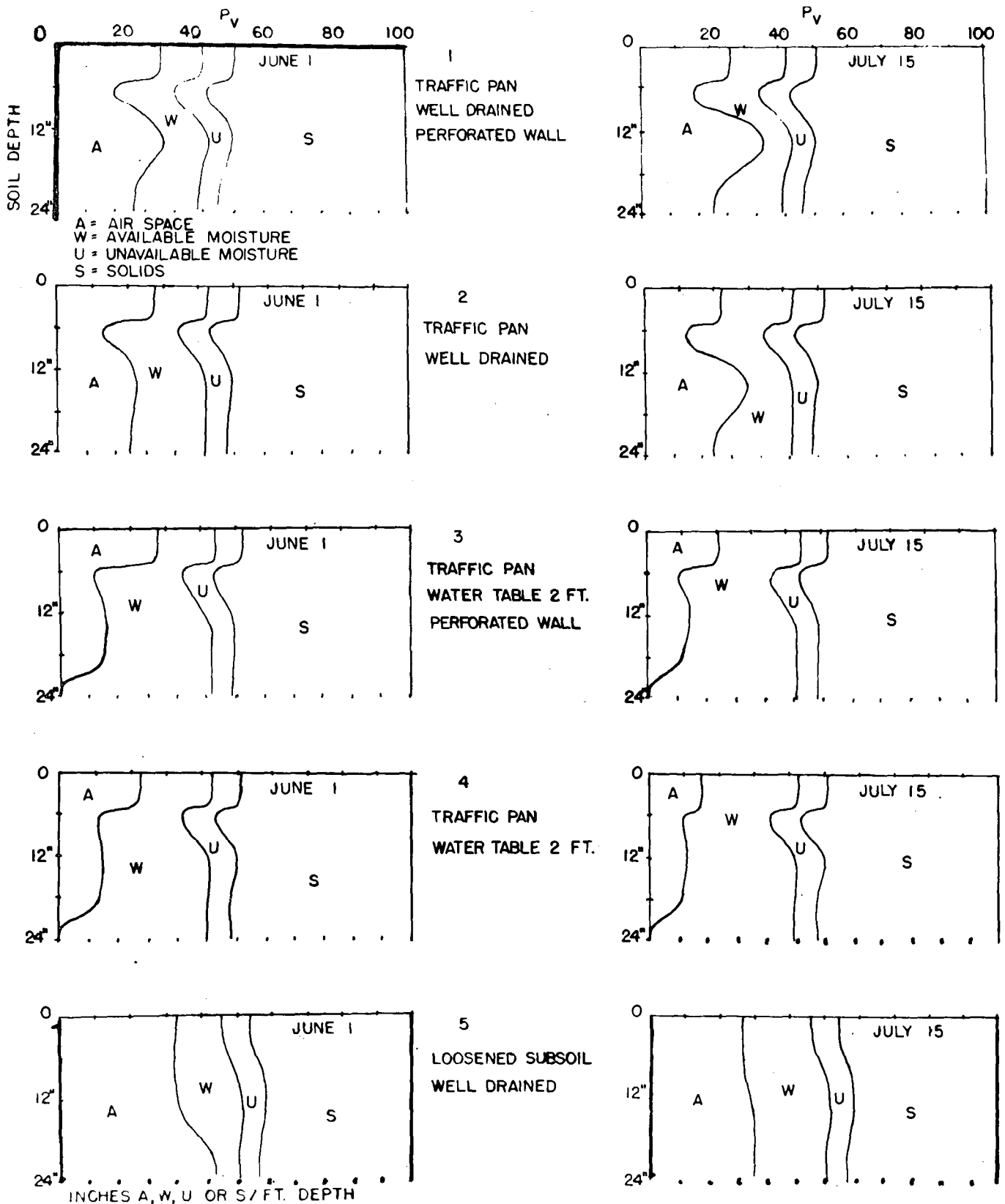


FIG. 2.—Mean air-water-solid space relations for the various soil cylinder treatments at the start and end of the experiment.

lary drainage depth of 52 inches. The cylinders were set 15 inches apart from center to center.

TREATMENTS

The 5 treatments, as listed in table 1, consisted of a 2 by 2 factorial involving the degree of drainage and "supplemental aeration" plus a treatment in which the subsoil was loosened. These treatments were replicated 5 times in a randomized block design with care being taken to minimize the "end effects" by placing an extra cylinder with plants at the end of each row. The supplemental aeration was provided by drilling $\frac{1}{4}$ inch holes in a pattern of 1 per square inch in each cylinder wall from the soil surface to the base.

For treatment 5, the subsoil was removed in 10 pound increments, pulverized through a 0.5 inch screen and then after the cylinder was emptied, 7.75 pound aliquots of each of the increments were returned to the cylinder in proper order, each aliquot being brought to the previous height by tapping the cylinder until it settled.

After the cylinders were set in place, the soil was wetted thoroughly by several "irrigations" of $\frac{1}{2}$ inch increments applied to the soil surface and drainage allowed to continue for 3 days. To get a measure of the moisture status at the start of the experiment and of oxygen diffusion rates during the experiment, each of the cylinder walls for all treatments was drilled with $\frac{1}{2}$ inch holes at 3, 7, 14, and 21 inches below the soil surface. Soil moisture samples were removed with a $\frac{1}{2}$ inch cork borer and the tube of a small modification of the Ramey oxygen diffusion chamber (6) inserted in each hole where it was firmly clamped and sealed in the wall. Cotton was planted in each cylinder on May 26 and thinned to 2 plants in each on June 3. No fertilizer was applied. No fertilizer other than nitrogen is needed to produce an excellent cotton crop on this soil with favorable weather conditions. Since a fairly good crop can be produced with no nitrogen, it was felt that by using no fertilizer, the low level of nitrogen should make the plants sensitive indicators of soil aeration through leaf color and tissue analyses.

Table 1.—Treatments used in cylinder experiment with Commerce silt loam.

Treatment number	Drainage	Subsoil	"supplemental aeration"
1	Unrestricted	Compact	Yes
2	Unrestricted	Compact	No
3	Water table 24 inches	Compact	Yes
4	Water table 24 inches	Compact	No
5	Unrestricted	Loose	No

Table 2.—Effect of soil conditions on growth of cotton in cylinders of Commerce silt loam.

Growth measurements	Drainage					LSD 0.05	LSD 0.01
	Shallow		Deep		Loose Deep		
	"supplemental aeration"						
	Yes	No	Yes	No	No		
	Treatment No.						
	3	4	1	2	5		
Plant color (July 12)	1.8	1.4	3.6†	3.4†	3.4†	0.5	0.7
Percent K in dry matter	1.70	1.76	1.70	1.61	1.81	0.23	—
Total nitrogen	1.30	1.31	2.47†	2.25†	2.33†	0.30	0.42
Nitrate nitrogen in petioles (July 15)	0.2	0.2	1.4†	0.6	2.2†	0.9	1.2
Oxygen partial pressure (July 6, 2 days after N ₂ flush)	119	90	140	122	139	54	—
Mean height increase Cm. (July 1-7)	4.6	3.8	5.2*	5.8†	5.6†	1.1	1.6
Dry weight—g. (July 15)	14.3	12.7	12.9	17.9	18.1	5.8	—
"Yields"—No. squares (July 15)	3.6	4.8	6.6	9.0*	9.0*	4.3	—

*Significantly different than the lowest (boldface) value at the 0.05 probability level.

†Significantly different than the lowest (boldface) value at the 0.01 probability level.

MEASUREMENTS

Measurements of plant height and number of "true leaves" (over 0.5 inch long) were made at weekly intervals. Oxygen diffusion measurements were made during the wet interval July 1 to 7 (see rainfall data, figure 3). The drought was broken by an artificially applied "rain" of 2.94 inches on June 30 followed by 0.59 inch on July 4. Plant color was judged on a 1 to 4 yellow to dark green scale by two independent observers, who agreed quite closely. The plants were harvested July 15, the number of squares being counted for "yields". Nitrate nitrogen was determined in the petioles, dry weight of tops was determined and analyses for percent K and total nitrogen in the dry matter were made. The cylinders were cut open and soil cores were removed for moisture and bulk density measurements. The roots were carefully washed from the soil and photographed.

Results and Discussion

The soil traffic pan layer (figure 2, treatments 1 to 4) on both June 1 and July 15 had higher moisture by volume than the surface or deeper subsoil. The soil air in this layer was only 12 to 15% by volume. The high water table soils had a high moisture supply, at the expense of air content, especially in the subsoil. The loosened soil was well supplied with air, there being a limited supply of available moisture in the 18 to 24 inch layer. The volume of the cylinders was fixed and soil had to be removed to lower the bulk density. In practice, subsoiling and plowing would increase the volume occupied by a given weight of soil but would not reduce the quantity of soil available for moisture and nutrient supplies. For this reason, treatment 5 was hardly a fair test of the effect of loosening the soil. Comparison of treatments 1 and 2 on June 1 indicates that the wall perforations were causing moisture evaporation losses in spite of the attempt to maintain relative humidity in the pit. The same is true for the surface soil in treatment 3 as compared with that of treatment 4 where the water table was kept at 24 inches.

The shortage of moisture supply due to evaporation through the wall perforations is further shown in figure 3 by the plant growth curve for treatment 1.

The potassium analyses were made by Dr. R. D. Rouse and the nitrogen by Dr. C. E. Scarsbrook, both of the A. P. I. Agronomy staff, Auburn, Alabama.

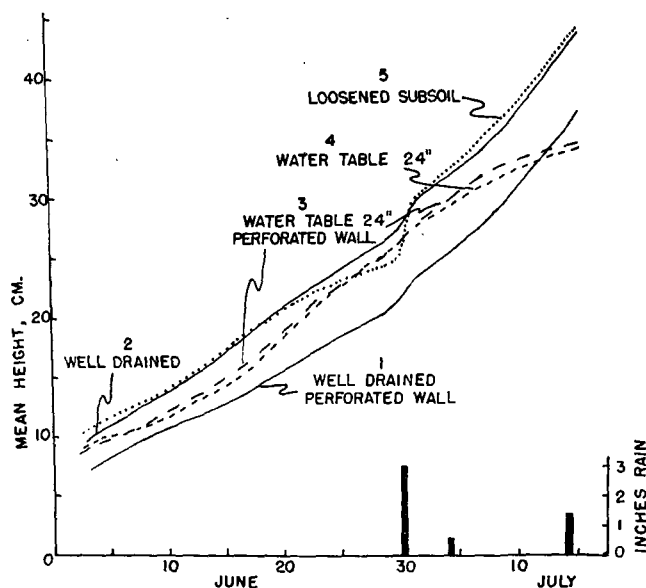


FIG. 3.—Mean cotton plant height curves for the five treatments in the cylinder experiment showing the effect of the moisture applied as artificial and natural rainfall.

The curve for the development of number of "true leaves" is very similar and so is not shown. Plant variability was so great that some of the mean differences shown are not significant. However, the growth surge made after artificial rain was applied on June 30 by plants in treatments 1, 2 and 5 shows that moisture was limiting growth in the deep drained cylinders—especially where the moisture storage capacity was reduced by loosening the subsoil. The plants in treatment 5 would soon have been the shortest of all if water hadn't been added. When water was added as needed, this treatment led the others in plant height measurements as shown in figure 3.

The wall perforations were of little effect in providing oxygen to the roots of the high water table treatments. Plants in treatment 3 made only slightly better growth than those in 4. Other plant measurements and analyses showed little difference for "supplemental aeration". This method is not very effective in improving aeration except through the removal of moisture by evaporation. This is not surprising since one should expect gaseous exchange through the soil air to be much more rapid than by diffusion in solution in soil water. Measurements of gaseous diffusion in soil by Blake and Page (1) indicate that the over-all rate depends on total air space porosity. It is also apparent from these results that mere exposure of a clod of soil to the air will not necessarily insure good aeration to the interior of the mass.

The most significant plant differences, in yields, height, dry weight, nitrate nitrogen in the petioles and plant color, were between deep and shallow drainage treatments as shown in table 2. Since the potassium is very high, the plants all showed evidence of luxury uptake (more than 1%) of K regardless of oxygen supply. The differences in K uptake were small and not significant, though that of total nitrogen in the plant tops at the end of the experiment was significantly higher (at the 0.01 probability level) in the deep, than it was in the shallow drained cylinders. Air exposure through wall perforations had little effect on total N.

These results are interesting in light of results reported elsewhere. Russell (5) reviewed the work of several workers showing that oxygen supply to plant roots affects the uptake of nutrients. It is evident that energy derived from root respiration is involved in the concentration of nutrients against a gradient in plant tissues. The work of Woodford and Gregory (7) with barley plants in nutrient culture clearly shows that not only is oxygen supply important, but also the concentration of any particular nutrient in the substrate. The Commerce silt loam used here was well supplied with available potassium,⁵ but the supply of nitrogen was limited. In order to reconcile these results with those of Larsen (3), Lawton (4) and others, one is led to believe that the supply of exchangeable potassium in the soil they used was at least marginal since potassium uptake appeared to be noticeably affected by soil aeration. Graham (2) suggests that for good potassium fertility, the saturation of a soil with potassium should be between 2 and 5% for most clay soils, depending upon the exchange capacity and nature of the dominant clay minerals.

The marginal supply of nitrogen in this soil served as a sensitive indicator of aeration as shown in table 2. It is generally recognized that the uptake of nitrogen by plants is affected by soil aeration through the effect of oxygen on soil micro-organisms and hence upon the supply and available forms of nitrogen present in the soil, as well as through the direct effect of oxygen on root respiration.

The differences in height increases for the wet July 1 to 7 period are interesting. Even though treatment 1 had the highest mean rate of oxygen diffusion, the rate of growth was less than in treatments 2 and 5 where the walls were intact. Here it is evident that the benefits of better aeration were partly offset by moisture losses. The relationships between oxygen diffusion (as shown by partial pressures after flushing chambers with nitrogen) and growth rate during this period are shown in table 3. It is clear that oxygen was a limiting factor for growth in some of the cylinders during this period. It is conceivable that conditions may exist, as in the dense traffic pan, where moisture tension may be so high and oxygen supply may concurrently be so low as to limit growth. In such a compact layer the moisture tension may be fairly high without the presence of an adequate supply of air space to supply oxygen. However, with those treatments where aeration was good, moisture rather than air supply limited growth just before the July 1 to 7 wet period. The marked growth increase in these treatments with the

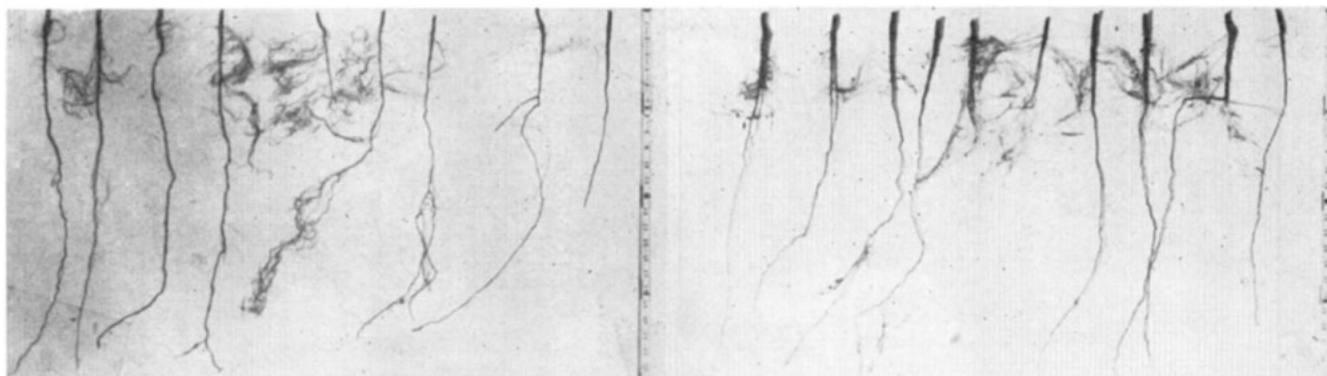
⁵Although analyses of this soil for exchangeable K have not been made, records of several years tests show no response to applied K on this soil for cotton and other crops at the N. E. Louisiana Exp. Sta.

Table 3.—The relationships between oxygen diffusion and plant height increase during the period July 1 to 7.

Comparison	Correlation coefficient
Height increase vs. mean D/D_0 July 6	+0.59†
Height increase vs. mean D/D_0 July 7	+0.49*
Height increase vs. D/D_0 July 6 at 7-inch depth	+0.60†

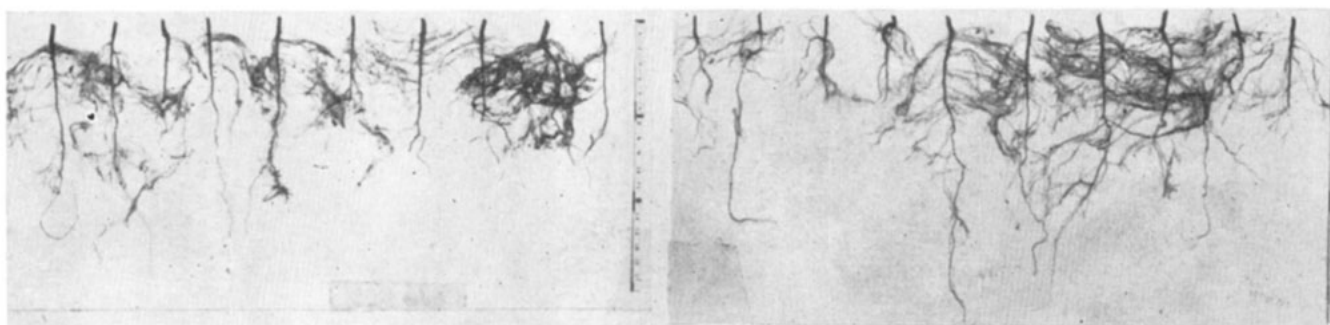
*Significant at 0.05 probability level.
†Significant at 0.01 probability level.

Fig. 4.—Comparison of cotton root growth with the five different treatments in the cylinder experiment.



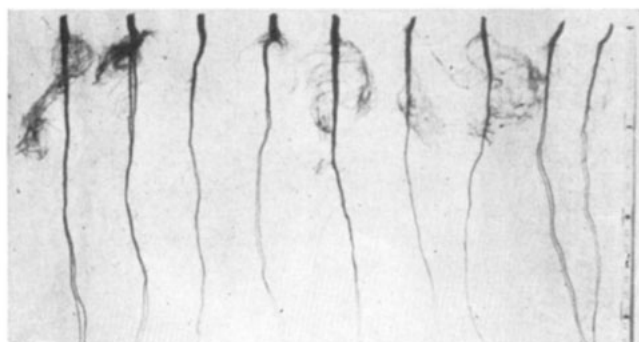
TREATMENT I.—Natural compact structure, well drained, supplemental aeration. Root length extends to 24 inches.

TREATMENT II.—Natural compact structure, well drained, no supplemental aeration. Root length extends to 23 inches.



TREATMENT III.—Natural compact structure, 60-cm. water table, supplemental aeration. Root length extends to 18 inches.

TREATMENT IV.—Natural compact structure, 60-cm. water table, no supplemental aeration. Root length extends to 20 inches.



TREATMENT V.—Loose soil, well drained, no supplemental aeration. Root length extends to 24 inches.

June 30 irrigation was a response to moisture rather than air supply as shown in figure 3. However, in the treatments that had poor aeration due to the high water table, the irrigation suppressed growth.

All of the cotton roots removed from the cylinders are shown in figure 4. It is clear that the roots were not greatly retarded by the traffic pan even where the water table was at 24 inches (60 cm.). Exposure to the air through wall perforations seemed detrimental to the growth of plant roots in the well drained soil, but appeared beneficial to those with the high water table. The roots in the loosened subsoil (treatment 5) are generally smoother and less tortuous than in the undisturbed subsoil. Even in treatment 5 there are some deformities that are not accounted for. As usual with

plant studies, extreme variation within each treatment is wide and disconcerting.

The information gathered thus far shows no single factor to be dominant in causing the poor growth in the problem areas as compared with the surrounding areas. The difference must be due to an accumulation of effects mostly rising from the dense traffic pan layer. The pan layer in the good area in the field studied was nearly as dense and only slightly more permeable than in the problem area. Yet, these and other factors combined to reduce the moisture stored from winter rains in the problem area profile to about 80% of that in the productive areas. This difference in available moisture during summer droughts, and poor aeration in the root zone above the pan during brief wet periods, must act in combination to restrict growth through either inadequate air or water in the root zone.

Conclusions

It is often difficult to determine when one or both water and oxygen supply may limit growth in soil-air-water-plant relationships.

Wall perforations as used here effectively improved aeration only where evaporation losses were high. Then the moisture supply may be so low (or the tension so high) as to limit plant growth. Supplying air around a dense, wet, though small body of soil may not greatly improve aeration within the soil mass.

When a nutrient ion is marginal in supply its uptake by plants will serve as a more sensitive indicator of soil aeration than if the supply is more adequate. In a fertile soil well supplied with exchangeable potas-

sium, cotton may exhibit luxury consumption of K, even when the soil is wet and poorly aerated.

Although cotton root extension is affected by a compact soil layer in the root zone, except at very high densities, the influence probably arises more from air-water relationships than from physical resistance to root penetration.

It is evident that a combination of factors affecting root extension and plant growth through reduction of soil aeration and moisture storage are responsible for the less productive problem areas in cotton and soybean fields of the Mississippi River Delta areas.

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