AN INVESTIGATION INTO THE RELATION OF SOIL COMPACTION AND SOIL FERTILITY AS AFFECTING ROOT DEVELOPMENT IN SOILS

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AN INVESTIGATION INTO THE RELATION OF

SOIL COMPACTION AND SOIL FERTILITY

AS AFFECTING ROOT DEVELOPMENT IN SOILS

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INTRODUCTION

In the past few years, several members of the Agronomy Staff at the University of Massachusetts have observed that the roots of various crops grown in the Connecticut River Valley do not develop extensively below the plow layer. Since it is felt that more extensive root systems are desirable, this investigation was proposed as an attempt to isolate or correlate the factor or factors which are foremost in limiting the development of root systems in this area.

Field examinations had established the presence of a zone of compacted soil, called a plow sole, which is located at the base of the plow layer. The extent and effect of this compacted zone was not known and the first objective of this study was to determine how much of a barrier such a compact soil layer would offer to root development under local soil conditions. In undertaking this study, the possibility had to be considered that the plow sole did not seriously impede root penetration but that other factors might be instrumental in limiting root development.

In the light of local experiences, the other likely factor was thought to be the relatively low fertility of the sandy subsoils. This trend of thought had been strengthened by previous deep plowing experiments at this Station where the subsoils, when brought to the surface, had proved unfavorable for crop growth.

It was decided, in consideration of these two factors, that the best approach would be a combination of fertility and compaction experiments both in the field and greenhouse. Field investigations were started in the summer of 1955 and were followed by greenhouse work under more controled conditions during the following winter.

REVIEW OF LITERATURE

Various investigators have studied the subsoil since it became apparent that plants, through their root systems were vitally associated with it. The awareness of the importance of the lower soil layers grew as evidence accumulated to show that these layers contained important potential reserves of water and plant nutrients. The fact that plants are physiologically able to utilize subsoil moisture has been demonstrated by at least two investigators, Kiessalbach et al. (19) and Hunter et al. (15).

Kiessalbach and his associates showed that alfalfa was dependent upon subsoil water when rainfall failed to replenish surface moisture. Hunter and his co-workers demonstrated that some plants are capable of transporting water and nutrients from the water table to the surface through several feet of soil at the permanent wilting point.

That some plants were prevented from benefiting from subsoil water and fertility reserves due to the restricting influence of subsurface hard pans, was shown by Weaver and Crist (32) in their studies on root penetration. An important observation made by Weaver and his associate was that the plants most likely to be deprived of moisture were the small grain crops such as wheat whose root systems were not in existence long enough to penetrate the pan during the season when the pan was moist and soft.

The work of Weaver and his associates was carried out in sections of the United States where the problem of dense soil layers is one presented by naturally occuring clay and hard pans. While some of these research studies are not directly applicable to eastern conditions, they do form a valuable background in an approach to a common problem - that of overcoming compact subsoil layers and other conditions which inhibit deeper and fuller root development.

In the past the simplest solution to the problem of compact layers and pan formations seemed to lie along the lines of a physical approach. This means the destruction of the dense layer by subsoil chiseling or other deep tillage operations. In 1888 Goff (14), working in New York State, tilled field corn plots at six inch depth intervals to a total depth of two and one-half feet. He mixed subsoil and topsoil evenly throughout the depth of tillage with the most favorable results appearing on the plots which received the deepest tillage. Goff's experiment, in spite of its positive results, could hardly prove practical under field conditions due to the large amount of hand labor required.

The mixing of top and subsoil did not always have such favorable effects. Both Smith (29) and Woodruff et al. (35), working in different areas of the Midwest, found that even small quantities of subsoil reduced yields when it became mixed with the topsoil during their subsoiling operations. The experiments of Chilcott and Cole (5) on the Great Plains also showed a decrease in yield on some subsoil tillage experiments.

When only mechanical methods were used in breaking up hard pans or clay pans, the experiments of Chilcott et al. (5), Mosier et al. (26), and Smith (29) failed to increase the downward movement of water or the capacity of the subsoil to hold water. These three authors and Beeson et al. (2) found that the breaking of clay pans was futile as the pans quickly returned to their previous state soon after the first heavy rain.

Concurrently with the mechanical attempts to solve the problem of compacted soil layers, there developed an interest in the subsoil's ability to supply nutrient elements for plant use. Millar (24) found that corn made little growth on untreated subsoils and that placing fertilizer in sandy subsoils did not stimulate root development. In his later work with alfalfa, however, Millar (25) discovered nutrient solutions placed at depth did encourage root development and that plants growing in 15 inches of subsoil drew water successfully from such soils. In spite of these results Millar felt that satisfactory plant growth in his experiments was primarily due to the utilization of stored food reserves.

McMiller (23) stated that the "rawness" causing unproductivity in some Minnesota subsoils was due to a lack of available phosphorus and potassium. Conner (6), on the other hand, discovered that the total phosphorus content of some Indiana subsoils was as high as that of the overlying topsoil. The availability of the phosphorus in these subsoils was not as great as in the corresponding topsoils. Potassium was equally abundant and available in both the top and subsoils studied by Conner. He concluded that subsoils, in general, contain less nutrients than topsoils and that these nutrients are at a lower level of availability.

Crist and Weaver (7) found that barley grown in containers of subsoil 30 inches deep utilized water and nutrients from the entire volume of the container although maximum uptake occurred near the surface.

Their conclusions were that subsoils are important in the later stages of the barley crop when the surface supply of moisture and nutrients are depleted. Hunter and Omer also showed that plants extract water from surface soil layers even when it is more readily available at lower depths.

Weaver (33) showed that nitrates can be utilized from subsoil depths down to five feet. He pointed out that maximum root development occurs in areas where fertility is located and that concentrations of nutrients tend to inhibit root penetration to deeper depths. Weaver concluded that subsoils constitute an important potential fertility reserve and therefore cultural practices encouraging deep root penetration are desirable.

During the period of subsoil nutrient investigations, subsoil pH was also studied. Watenpough (31) reported that the root development of alfalfa was related to the pH of the soil horizon. The optimum for root development occurred within the pH range of 5.5 - 6.2 and decreased down to pH 4.8 which stopped root development completely.

Woodruff and Smith (35) shattered a subsoil pan and placed fertilizer and lime at a depth of 16 to 20 inches in a series of crop production experiments which had significant results. Where the pan had been shattered without liming, the tap roots turned aside and did not enter the loosened area. Where lime had been applied to the broken pan, tap roots penetrated deeper into the shattered area. Corn plants growing under these subsoiled conditions were able to utilize the water in the former hard pan zone during drought periods.

Beeson and Murphy (2) found that lime increased the water holding capacity of the first two feet of soil and decreased the resistance to root penetration in the second foot of soil. When lime alone was applied, the roots just entered into the broken hard pan but did not penetrate all the way through it. When lime was combined with manure the greatest development of roots through the pan took place. When manure was applied alone, the tap roots were again able to traverse the broken pan section and extend deeply into the porous lower subsoil.

Similar results were obtained by Longenecker and Merkle (21) who found that maximum fibrous root development took place in the presence of lime. Because soil structure was also improved, their conclusions were that lime compounds should be thoroughly mixed throughout the entire root zone. These authors noted that tap roots can penetrate through areas of unfavorable fertility but that feeding roots do not develop unless the lime is present. Pohlman (27), also working with lime, reported a 50 percent increase in alfalfa roots in the 8-16 inch layer when this layer was limed to neutrality.

Working with potatoes, Bushnell (4) found that the addition of urea and cyanamid stimulated potato root development in the subsoil. The phosphates of calcium, magnesium and ammonium, in addition to superphosphate, also increased subsoil root development. Manure produced greater root development than that produced by the chemical fertilizers. The yield of tubers was not increased by any of the fertility treatments.

Fox and Lipps (13), studying the effect produced by nutrients on alfalfa root development, showed that the presence of nutrients greatly influenced root distribution even when water was adequate throughout the profile. In some instances, the roots had extensive development just above the ground water table and were using this supply to provide for most of their water requirements. When plants are feeding at depth due to favorable water conditions, the authors concluded that to be effective fertilizers should be placed where the water supply occurs.

Russel (28) agrees with the investigators who claim that phosphorus stimulates root growth. He emphasizes that phosphorus does not directly stimulate root development but that the increased root growth is a result of the beneficial effect of phosphorus upon the entire plant.

Farris (9) pointed out that when roots find adequate nutrients in the upper soil layers, this fertility inhibits root development at lower layers. Therefore he stresses that fertilizers should be placed deeply if they are to encourage deep root development. Ferrant and Sprague (11) reported similar results from their studies. They found that topsoil fertilization inhibited deep root penetration even when the subsoil had been thoroughly tilled.

The trend of literature over the years shows that investigators have turned away from approaching the problems of dense soil layers and root penetration on the solely physical basis of subsoiling and deep tillage. Increasing evidence shows that the solution of such soil problems will be found in the coordinated application of soil chemistry and soil tillage techniques.

DESCRIPTION OF SOIL CONDITIONS

A detailed soil analysis forms an essential background for any soil compaction study. Therefore, one of the first steps in this investigation was to carry out such an analysis to determine the physical and chemical characteristics of the soil in which the work was carried on.

The experimental plots were located on the east bank of the Connecticut River in Sunderland, Massachusetts one quarter mile north of the Sunderland-Deerfield bridge. The soil at this location is classified by the Soil Survey of Franklin County, Massachusetts (20) as a Hadley very fine sandy loam which is considered to be one of the best agricultural soils in the locality.

METHODS OF SOIL ANALYSIS

Mechanical Analysis

Representative composite samples of the top and subsoils were taken with a shovel and brought to the laboratory for detailed processing. The coarser mineral separates were determined by screening and the silt and clay fractions by the pipette method (16). Loss on ignition was run by the A.O.A.C. (2) method to determine the approximate organic content of the soil. Results of these analyses are listed in table 1.

Nutrient Analysis

Both the top and subsoils were tested to check the quantity and kind of nutrients present in the soil profile. The tests were conducted by the method of Lunt et al. (22) and the results are reported in table 2.

Field Capacity Data

The water holding capacity of the soil was determined by the tension method described by Uhland et al. (30). The results of this test and the data are contained in table 3.

Bulk Density Tests

Two methods of taking bulk density samples were used to meet both field and greenhouse conditions. The first method consisted of taking sample cores 3 inches in diameter and 3 inches deep using the procedure described by Uhland et al. (30). For taking samples from the profile boxes of the greenhouse studies and from the sides of the field excavation pits, a smaller, handier type of sampler was needed. A small cylinder, just under 2 inches in diameter, with a volume of 100 cc. was patterned after that of Joffe et al. (17) for this type of work. The sampler was pressed into the soil and a core withdrawn. After trimming to the correct volume, the core was removed from the cylinder for drying and weighing. In the sandy soils studied, this type of sampler proved very successful.

The field bulk density figures, obtained from both types of sampling operations, are presented in tables 4 and 5.

pH Test

pH readings for both the top and subsoil were obtained by using the standard Beckman pH meter on samples taken at random throughout the test plots. The composite pH for the topsoil was 5.70 and for the subsoil 5.48. The results from the individual pH samples are listed in table 6 and show the uniformity of the field with respect to the pH variation.

PROFILE OBSERVATIONS

Before and during the root excavations in the field, the nature of the soil profile was noted and recorded. The presence of the compaction layers was detected by probing with a sampling tube. Detailed examinations were made during excavation. The observations obtained are incorporated in the "Summary of Soil Conditions" and other discussions in this paper.

TABLE 1.

Results of Mechanical Analysis

	Topsoil	Subsoil
Sand Fractions		
500 microns	.85%	.08%
500-250 "	2.76%	3.37%
250-100 "	34.00%	42.12%
100-50 "	26.79%	23.25%
Total sand	64.40%	68.82%
Silt Fractions		
Coarse silt > 5 microns	32.30%	28.83%
Fine silt < 5 microns	1.40%	1.39%
Total silt	33.70%	30.22%
Clay Fractions		
Clay 2 microns	.73%	.38%
Clay 1 micron	1.17%	.58%
Total clay	1.90%	.96%
	100.00%	100.00%

Loss on Ignition

	Topsoil	Subsoil
Approximate organic matter content as determined by loss on ignition.	2.31%	1.70%

TABLE 2.

SOIL NUTRIENTS

Nutrients Expressed in Approximate Parts Per Million

Nutrient	Topsoil		Subsoil
NO_3	10 (medium)	less than	5 (very low)
NH_3	12 (low)		12 (low)
P	100 (high)		50 (medium high)
K	180 (medium high)		60 (low)
Ca	500 (low)	less than	500 (very low)
Mg	125 (high)		125 (high)

TABLE 3.

FIELD CAPACITY DATA

	TOPSOIL		SUBSOIL	
	% Field Capacity	Inches of Water per Foot of soil	% Field Capacity	Inches of Water per Foot of Soil
	22.0%	4.12"	17.5%	3.02"
	22.8%	4.27"	18.9%	3.30"
	22.8%	4.18"	19.6%	3.36"
	22.0%	4.03"	17.6%	3.00"
	19.1%	3.41"	19.3%	3.19"
	19.6%	3.36"	19.2%	3.25"
Average	21.4%	3.89"	18.7%	3.18"

TABLE 4.

Soil Profile Bulk Density Data

Sampled with 3-inch Uhland Cylinders

Depth Description		Control Row		Subsoiled Row	
		1.370		1.318	
Surface		1.344		1.266	
		1.331		1.292	
		1.331		1.266	
	Average		1.34		1.29
		1.462		1.370	
Disk Compaction		1.488		1.305	
Depth		1.475		1.292	
		1.462		1.357	
	Average		1.47		1.33
		1.422		1.357	
Transition between		1.499		1.350	
Disk and Plow		1.435		1.357	
Compaction		1.422		1.409	
	Average		1.44		1.37
		1.462		1.331	
Plow Compaction		1.422		1.357	
		1.422		1.383	
		1.475		1.344	
	Average		1.45		1.35
		1.357		1.331	
Below Compaction		1.370		1.357	
Layers		1.383		1.344	
		1.396		1.357	
	Average		1.38		1.35

TABLE 5.

Soil Profile Bulk Density Data

Sampled with 100 cc. cylinder

Depth Description	Control Row		Subsoiled Row	
	1.316		1.199	
Surface	1.387		1.235	
	1.365		1.217	
	1.355		1.173	
Average		1.36		1.21
	1.443		1.337	
Just above	1.395		1.352	
Compaction Layer	1.421		1.236	
	1.407		1.394	
Average		1.42		1.33
	1.468		1.356	
Upper part of	1.457		1.397	
Compaction Layer	1.461		1.372	
	1.472		1.314	
Average		1.46		1.36
	1.442		1.288	
Lower part of	1.444		1.271	
Compaction Layer	1.437		1.336	
	1.428		1.237	
Average		1.44		1.28
	1.337		1.363	
Below Compaction Layer	1.357		1.359	
	1.350		1.351	
	1.395		1.370	
Average		1.36		1.36

TABLE 6.

Soil pH and Limestone Requirement

	Topsoil pH	Subsoil pH
	5.73	5.40
	5.66	5.46
	5.74	5.48
	5.73	5.48
	5.68	5.47
	5.71	5.50
	5.66	5.50
	5.69	5.52
	5.69	5.49
	5.73	5.53
Composite	5.70	5.48

Topsoil Limestone Requirement	Subsoil Limestone Requirement
2000 lbs./acre	1000 lbs./acre

SUMMARY OF SOIL DATA

The mechanical analysis shows the soil to be a fine sandy loam. It belongs to the Hadley series. The profile itself consists of a dark brown A horizon of low organic content averaging 9 to 11 inches in depth overlaying a yellowish subsoil. The top 6 to 8 inches of the subsoil is slightly heavier than the lower portions but retains the sandy character of the subsoil.

Examination of this soil profile revealed a plow sole compaction layer which averaged four inches in thickness. This layer was from 9 to 13 inches below the surface beginning at the base of the plowed zone. As the data in tables 4 and 5 indicate, this compaction layer is located in an area of increased bulk density.

Table 4 indicates a disk compaction layer from one to three inches thick located at a depth varying from four to six inches below the surface. This disk compaction layer is created by local cultural practices which feature repeated disk harrowing in the early spring. At this time of year, soil moisture is at optimum for maximum compaction and a compact layer is formed by the action of the disks repeatedly pressing at the same depth.

The presence of the compaction layers throughout the plots was checked by probing with a tubular soil sampler. Both the disk compaction and the plow sole offered resistance to probing. The disk compaction could be penetrated by several hard thrusts but the plow sole could not be penetrated until the weight of a 150 pound man was concentrated upon the tubular sampler.

Plate 1 shows the compaction layer where it fractured off during the excavation of a pit. The illustration shows the roots being forced to extend laterally along this layer. In many instances these roots were flattened in cross section.

Nutrient tests indicate the soil to be low in ammonia nitrogen and calcium; medium in nitrates; and high in phosphorus, potassium, and magnesium. The subsoil content was lower in all nutrients except magnesium and ammonium which were equal to that of the topsoil.

The composite pH of the topsoil is 5.70 and of the subsoil 5.48 The topsoil contains a greater potential hydrogen ion reserve than the subsoil as indicated by a limestone requirement of 2000 pounds per acre compared to the subsoil requirement of 1000 pounds per acre.

The field capacity of the topsoil to hold water averages 21.4 percent and the subsoil 18.7 percent. When converted, these percentages show that the topsoil has a field capacity of 3.89 inches of water per foot of soil while the subsoil has a field capacity of 3.18 inches per foot. This indicates that the subsoil forms a valuable moisture reserve providing the roots develop deeply enough to draw upon it.

PLATE 1.

The compaction layer at a depth of about nine inches. The topsoil was removed revealing the flattened roots growing along the surface of the layer.

EXPERIMENTAL PROCEDURE

FIELD METHODS

The root development of two crops, tobacco and tomatoes, was investigated intensively under field conditions. The plots for each crop were located on the same soil type on adjoining areas.

The preparation of the plots started with plowing to a depth of about nine inches; the average plow depth for the area. This was followed by broadcast treatments (tobacco fertilizer 6-3-6-2 at 3500 pounds per acre; 10-10-10-2 at 2000 pounds per acre for tomatoes) which were disked into the surface soil. The subsoil fertilizer treatments were in addition to those above and were at the same rate.

The subsoil compaction study plots consisted of ten rows of tilled subsoil and two control rows where the soil was not disturbed at depth. Five of the rows were treated to a depth of 15 to 18 inches by using a subsoil tillage machine. This machine, shown in plates 2 and 3 could place fertilizer in a band behind the implement point. This feature proved very useful in putting the fertilizer treatments down into the subsoil. In the remaining five rows, the topsoil was removed by shoveling a trench the length of the row. The compaction was then broken at the bottom of the trench by a tractor drawn cultivator. Where fertilizer was added, it was placed in the trench just prior to this cultivation operation which served to mix the fertilizer with the subsoil.

The subsoil fertility treatments were handled in the same manner for both tomatoes and tobacco; the only difference being in the type of fertilizer applied (see above). Where lime was placed in the subsoil,

PLATE 2.

A view of the subsoiling machine used in the field experiments. A known amount of fertilizer is placed on a belt in the long box at the top of the machine. The belt moves toward the rear of the machine emptying the fertilizer into the placement tube. The V shaped top of the tube is to the right of the handwheel

PLATE 3.

The subsoiling machine in position for subsoil tillage. The point of the chisel is 18 inches below the surface.

it was in the form of dolomitic limestone at the rate of 2000 pounds per acre. Each of the machine tilled rows received one of the following treatments: no fertilizer or lime, fertilizer only, lime only, fertilizer and lime, and fertilizer and lime at a double rate.

The cultivated subsoil section of the plot had one row of each of the following fertility treatments: fertilizer, lime, fertilizer and lime. In addition this plot had two special row treatments. One, a deep profile made by mixing top and subsoil to a depth of 18 inches. Secondly, an inverted profile made by trenching and reversing the position of the topsoil and subsoil. These special rows received no fertilizer or lime other than that applied broadcast to the plot as a whole.

Tobacco and tomato transplants were set, in their respective plots, directly over each treated row. Both crops were allowed to grow to maturity before examination of their root systems.

To insure adequate water supply and to observe the effect of water on crop quality and yield, three levels of irrigation were applied when soil moisture blocks and observation of the plants indicated a need for moisture. Water was applied through perforated pipe at 0 inch, 1/2 inch, and 1 inch per hour. During the dry period of early August 1955 the supplemental water was added on three different occasions for one hour periods.

After the crops had grown to maturity, samples of the root systems were taken from each of the rows. This was done by the DeRoo "Needle Board" method (8). The equipment used in the sampling operation is shown in plate 4. The needle board illustrated is two feet square and

PLATE 4.

Equipment for taking field root samples. The needle board for impaling the root systems in place is to the left of the iron used to slice out the block of soil.

has steel prongs six inches long set two inches apart. These prongs serve to hold the roots in place during sampling and subsequent washing operations. The slicing iron is constructed from a piece of sheet steel with a bar welded along the top edge to serve as re-enforcing and handles.

The sampling operation begins by digging a trench 30 inches deep across the row about eight inches from the stem of the plant to be sampled. Five inches of this face is used to examine soil conditions to see what changes subsoil tillage may have brought about. After examination, the face of the pit is cut and smoothed to within three inches of the stem. The needle board is then driven into the face of the pit to impale the roots in place. The board is braced in position and the block of earth equal to the area of the board and the depth of the prongs cut off by means of the slicing iron driven by a sledge hammer. Next, the earth block, now mounted on the board, is moved for the washing operation.

The process of removing the soil from the roots is carried out in the washing operation. First the soil block containing the roots is placed in a tank and allowed to soak until soft. The soil is then carefully washed away in order to expose the roots with as little disturbance as possible. After washing, the boards with mounted roots are allowed to dry for examination and photographing. In the final operation the roots were removed from the board at successive two inch levels to determine their oven dry weights at these intervals.

GREENHOUSE METHODS

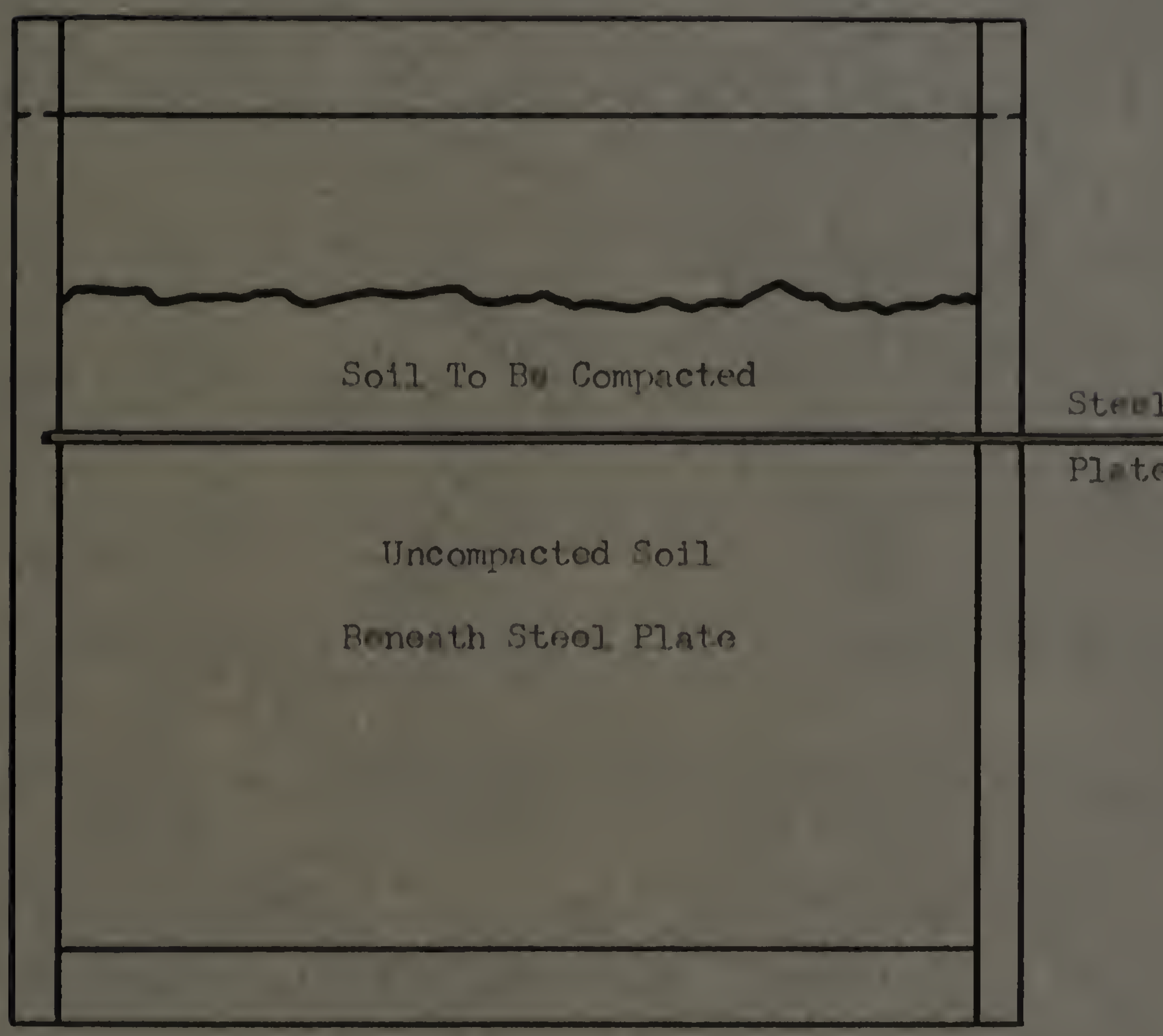
In the greenhouse experiments, tobacco was used for the crop as it proved to be sensitive to soil compaction in the field. Fertilizer treatments consisted of fertilizer at 3500 pounds per acre and dolomitic limestone at 6000 pounds per acre. Two replications were grown in soil profile boxes with inside dimensions of 19" x 24" x 3 1/4". These boxes contained both topsoil and subsoil taken from the field site and separately screened and mixed for uniformity. The boxes were packed to give an eight inch topsoil horizon and a ten inch subsoil horizon.

Artificial compaction layers were formed in two-thirds of the boxes in the following manner. First, the soil up to the base of the compaction area was placed in the box. Then a steel plate was inserted through the side of the box at the base of the area to be compacted and engaged in a notch in the opposite side (See diagram 1). The soil to be compacted was spread out on top of the plate and tamped to hardness with a tamper the width of the box. After hand tamping, the tamper was driven by a sledge hammer until the soil on the plate was uniformly compacted. The plate was then removed and the compacted soil pressed into contact with the soil below it using a pusher which moved the compaction layer as a unit and thus prevented cracking. When the layer had been pressed down into contact with the soil below, several sharp blows with tamper and sledge on the pusher sealed the layer to the soil underneath. The soil for the remainder of the profile was then placed above the compaction layer. Compaction layers with bulk densities consistently in the vicinity of 1.55 were obtained using this method.

Each of the profile boxes received one of these fertilizer treatments. No fertilizer, fertilizer in topsoil only, fertilizer in subsoil only, fertilizer in topsoil and subsoil, fertilizer in the topsoil with

DIAGRAM 1.

SCHEMATIC DRAWING SHOWING THE METHOD OF COMPACTING SOIL FOR GREENHOUSE STUDIES



After the soil above the plate has been compacted, the steel plate is removed and the compaction layer pressed down in contact with the soil below. The soil for the remainder of the profile is then added.

lime in the subsoil, and fertilizer in the topsoil with lime and fertilizer in the subsoil.

Tobacco transplants one month old were planted and allowed to grow for 56 days before harvesting. Measurements of plant heights were taken during the growth period to compare the growth rates of the different treatments.

Harvesting was carried out in the following manner. The tops of the plants were cut off, chopped up, oven dried, and weighed for yield. Roots were processed in much the same manner as in the field. One side of the box was first removed and any surface roots removed. The boxed profile was then impaled on a needle board and placed in the washing tank. At this point the rest of the box was removed leaving the sample supported upon the needle board. The newly exposed surface was then examined and any surface roots scraped away.

The removal of the surface roots from the profile was necessary before washing in order to accurately determine which roots actually penetrated the compaction layer and those which forced their way down between the wall of the box and the soil.

The washing and sampling operation is carried on in the same way as described for the field procedure.

RESULTS FROM FIELD EXPERIMENTS

Effect of Subsoil Tillage Upon the Soil Profile

Examination of the treated profiles at the end of the growing season revealed changes due to the subsoil treatments. The most striking of these was the longtongue like intrusion of the topsoil down into the opening created by the subsoiling chisel. This feature, in some form, was characteristic of all rows which had been treated by the subsoil chiseling machine. In each case the topsoil in the intrusion had good structure and aeration and was in a loose friable condition.

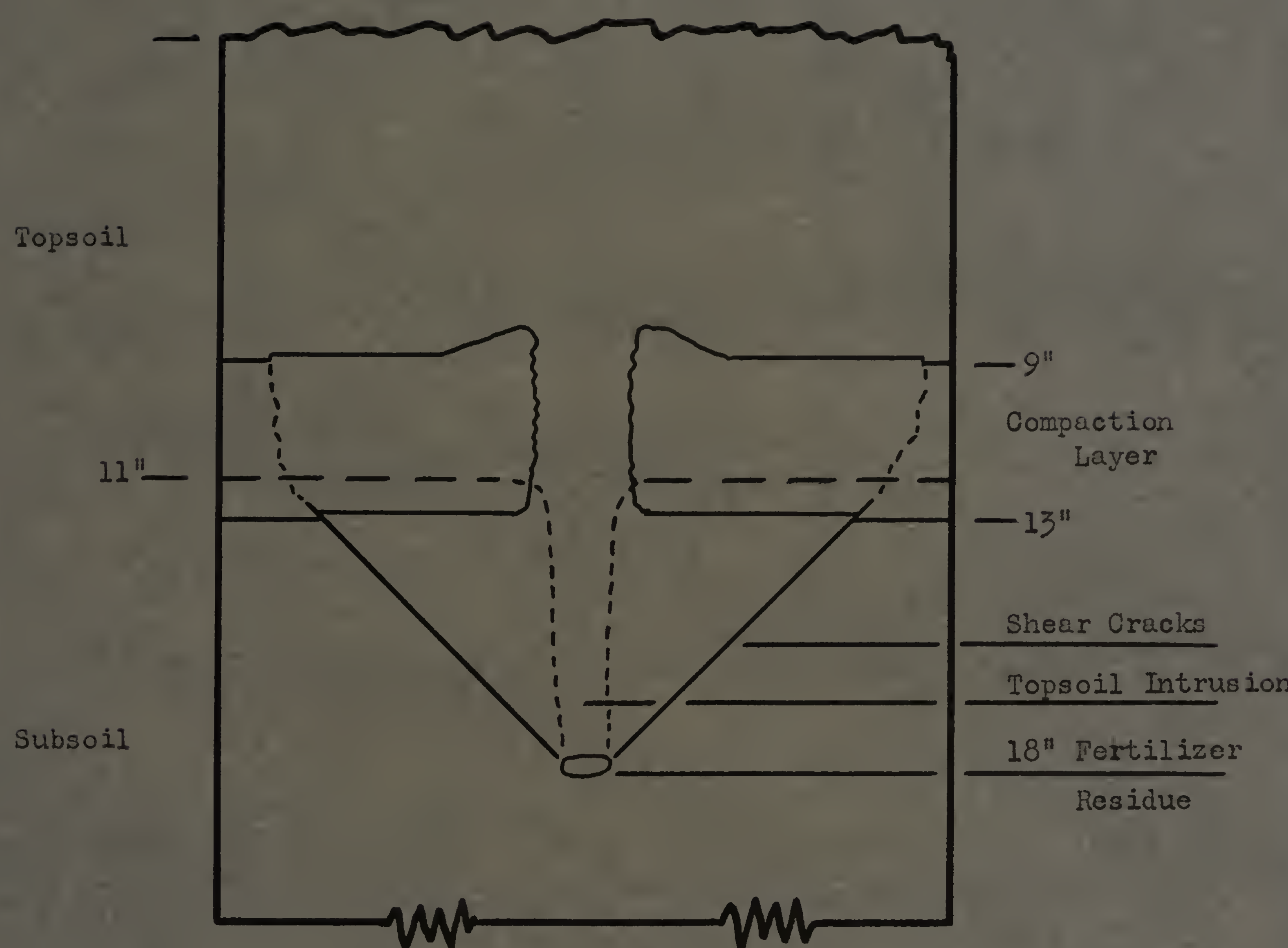
Two other features were noticeable during the examination of the profiles. The first of these was the residue of the fertilizer banded during the chiseling operation (see plates 5 and 10). This took the shape of a gray mass 1 x 2 inches in cross section and was surrounded by feeding roots put out from the base of the tap roots. The other feature was the presence of sheer planes which started at the base of the chisel mark and angled upwards toward the topsoil at about 45° from vertical. In some instances the subsoil had been offset up to an inch along these planes. If these sheer planes reached the topsoil, the topsoil would sometimes intrude down the crack thus encouraging root development along this line. That these sheer cracks were important in enabling water to penetrate to depths was shown by the subsoil being damper along these cracks than elsewhere. Diagram 2 illustrates the features of the machine subsoiled profile.

Excavation of the cultivated subsoil rows showed different results than the results of the chiseled rows. The compaction was broken where the subsoil at the base of the excavation had been cultivated but remained intact elsewhere. At the point of contact between the A and B horizons, a three to five inch area of top and subsoil intermixing occurred. The condition of the cultivated subsoil was looser than before treatment but was not as friable as the topsoil found in the chisel opening. On the other hand, the width of the loosened area was wider where the subsoil had been cultivated. The general decrease of the

PLATE 5.

A portion of the subsoil chisel path. The fertilizer residues are about two inches wide. Extending about four inches above the fertilizer, is a small block of intruded topsoil.

DIAGRAM 2



A SCHEMATIC DRAWING SHOWING THE EFFECTS OF THE MACHINE SUBSOILER UPON THE SOIL PROFILE bulk densities in the subsoil treated rows is seen in the data presented in tables 4 and 5.

Effect of Subsoil Tillage Upon Root Development

Tobacco Root Development

Tobacco, grown under Connecticut River Valley conditions, is a shallow rooted plant and this general characteristic remained even after the tillage treatments. Table 7 indicates that the greatest weight of roots was found in the upper portion of the A horizon.

Where the subsoil treatments had been applied by machine, the main roots of the tobacco plants tended to penetrate down the topsoil enriched chisel opening. Lateral roots were produced from these tap roots particularly where nutrients had been placed in the subsoil. Control rows showed little root development beyond the noncompacted topsoil. The beneficial value of breaking the compaction layer can be seen by a comparison of plates 6 and 7.

Where fertilizer was applied during the subsoiling operation, root development increased. When separately banded by machine, both lime and fertilizer increased the weights of roots produced in the subsoil. A greater increase in subsoil root weight is seen where the nutrients were banded in combination and the highest root weight occurs where lime and fertilizer were banded at double rate. Plates 8 and 9 illustrate root development occurring where the lime and fertilizer were banded together.

When lime and fertilizer were cultivated into the subsoil the results were slightly different. Lime alone produced the greatest weight increase in subsoil roots. Fertilizer alone and in combination

TABLE 7.

RESULTS OF FIELD EXPERIMENT

WEIGHTS OF TOBACCO ROOT SAMPLES FOR VARIOUS ROW TREATMENTS

(In Grams)

Depth	1	2	3	4	5	6
0-2"	1.98	5.53	3.87	4.17	7.02	2.16
2-4"	4.42	4.54	3.70	4.80	3.84	4.12
4-6"	2.78	3.25	2.48	2.19	1.91	2.54
6-8"	3.11	1.52	2.48	.82	2.11	1.11
8-10"	.56	1.89	.74	.07	1.62	.74
10-14"	1.00	1.68	1.53	.09	1.23	1.76
14-18"	.86	.51	.28	.08	1.07	.97
18-24"	.41	.24	.03	----	.23	1.21
Total wt. 0-10"	12.85	16.73	13.27	12.05	16.50	10.67
Total wt. 10-24"	2.27	2.43	1.84	.17	2.53	3.94

Depth	7	8	9	10	11	12
0-2"	10.77	4.31	3.97	5.71	3.26	2.74
2-4"	2.85	3.73	5.18	6.07	4.90	4.87
4-6"	1.31	1.75	1.93	3.68	3.30	2.16
6-8"	.25	1.25	.60	.41	.79	.93
8-10"	.11	1.25	.35	.23	.17	1.14
10-14"	.49	.10	.35	.30	1.83	.99
14-18"	.32	.16	.90	.18	1.62	1.90
18-24"	----	.04	.25	.30	.56	4.41
Total wt. 0-10"	15.29	12.29	12.03	16.10	12.42	11.84
Total wt. 10-24"	.81	.30	1.50	.78	4.01	7.30

Row Treatments

1. Machine subsoiled to 18"; no fertilizer.
2. Machine subsoiled to 18"; with fertilizer.
3. Machine subsoiled to 18"; with lime.
4. Control row; no treatments.
5. Machine subsoiled to 18"; with lime and fertilizer.
6. Machine subsoiled to 18"; with lime and fertilizer at double rate.
7. Cultivator mixed subsoil; with fertilizer
8. Cultivator mixed subsoil; with fertilizer and lime.
9. Cultivator mixed subsoil; with lime.
10. Control row; no treatments.
11. Inverted profile (subsoil over topsoil).
12. Deep profile (topsoil and subsoil mixed through 18" depth).

PLATE 6.

Tobacco root development is restricted largely to the topsoil where the profile has not been subsoiled.

PLATE 7.

Tobacco root development in a machine subsoiled row without the addition of fertilizer. This photo shows the value of breaking the compaction layer even when no fertility is added.

PLATE 8.

Extensive subsoil tobacco root development where lime and fertilizer have been placed in a machine subsoiled row.

PLATE 9.

Extreme penetration of tobacco tap roots in a machine subsoiled row with a double application of lime and fertilizer.

with lime failed to stimulate as much root development as when these two nutrients were banded by machine. The effect of lime was almost as great when cultivated into the subsoil as when applied in a band.

The rapidity of root penetration to the fertilizer placed in the subsoil was indicated by the early increase in size of the tobacco plants receiving the double fertility treatments.

The two special rows produced interesting results. In the inverted profile, topsoil was found at the surface where cultivation operations had spread it over the surfaced subsoil and from 10 to 18 inches below the surface where it had been placed when the profile was inverted. It was in the areas where the topsoil occurred that the best root development took place in the inverted profile. As the weights in table 7 indicate, the roots seemed to avoid the subsoil placed at the surface and utilized the nutrients in the buried topsoil.

The deep profile treatment produced good root development throughout its area. This indicates that a general deepening of the profile may be possible without roots being effected by the mixing of the two soil horizons. The tobacco plants in the deep profile row were equally as well developed as the plants in the nearby control row.

Tomato Root Development

The tomato plot was characterized by the same general root development patterns as the tobacco plot but without the distinct pattern found in the tobacco. The greatest increase in tomato root weight at lower levels is found in the machine tilled rows while the cultivated subsoil rows have less development in the subsoil. Treatments 1, 2, and 3 have similar weights at the lowest levels but rows 2 and 3 with nutrients placed in the subsoil show heavier weights at the intermediate levels.

The control rows 4 and 10 show that tomato root development is limited by the compaction layer. In these two rows the roots are definitely restricted to the A horizon.

Where nutrients were placed in the subsoil at double rates extensive fibrous root development took place in the vicinity of the fertilizer. This development is indicated in the root weights of table 8 and illustrated in plate 10. The addition of lime to the subsoil favored tomato root development as can be seen by the root weights of plants grown in rows 3 and 9 in table 8.

Effects of Subsoil Fertility Treatments Upon Tobacco Growth and Yield

The early response of the tobacco receiving the double fertilizer treatment has been referred to previously. Throughout the growing season this row continued to maintain its growth lead over the other tobacco treatments. In general, the top growth of tobacco plants was in direct proportion to the plant's root development. Thus the tobacco rows receiving single nutrient treatments (2 and 3) were about the same size while those receiving the combination of lime and fertilizer (5 and 6) produced larger tops. The plants in the rows where the subsoil had been cultivated did not develop large tops; this is indicated by their lower root weights. Plates 11, 12, and 13 illustrate the top growth produced by the tobacco treatments.

Table 9 presents the yield, grade index, and crop index for the tobacco treatments at three levels of irrigation. Because treatments 1 through 6 produced the best results at all levels of water application, the comparisons following will be made between these treatments only.

TABLE 8.

RESULTS OF FIELD EXPERIMENT

WEIGHTS OF TOMATO ROOT SAMPLES FOR VARIOUS ROW TREATMENTS

(In Grams)

Depth	1	2	3	4	5	6
0-2"	3.37	.73	.62	2.47	2.47	2.64
2-4"	2.06	2.18	1.73	1.07	1.80	1.63
4-6"	1.36	2.61	3.43	1.26	4.41	2.84
6-8"	.74	3.59	3.03	1.10	1.86	2.76
8-10"	.40	1.73	1.76	.57	.82	1.30
10-14"	.83	2.24	2.21	.21	.92	2.34
14-18"	1.00	1.80	1.30	.31	.92	.90
18-24"	1.13	.41	1.51	----	.84	1.90
Total wt. 0-10"	7.93	10.84	10.57	6.47	11.36	11.17
Total wt. 10-24"	2.96	4.45	5.02	.52	2.68	5.14

Depth	7	8	9	10	11	12
0-2"	1.99	1.32	1.51	2.21	.88	4.46
2-4"	1.36	1.78	1.17	2.68	.71	2.51
4-6"	1.73	1.06	1.10	2.40	.80	1.35
6-8"	.32	.51	1.96	2.24	1.04	1.80
8-10"	.17	.30	.52	2.35	.53	.74
10-14"	.26	.52	1.28	.69	1.02	1.53
14-18"	.42	.13	1.24	.46	.73	1.76
18-24"	.50	.56	.73	.65	.41	.62

Row Treatments

1. Machine subsoiled to 18"; no fertilizer.
2. Machine subsoiled to 18"; with fertilizer.
3. Machine subsoiled to 18"; with lime.
4. Control row; no treatments.
5. Machine subsoiled to 18"; with lime and fertilizer.
6. Machine subsoiled to 18"; with lime and fertilizer at double rate.
7. Cultivator mixed subsoil; with fertilizer.
8. Cultivator mixed subsoil; with fertilizer and lime.
9. Cultivator mixed subsoil; with lime.
10. Control row; no treatments.
11. Inverted profile (subsoil over topsoil).
12. Deep profile (topsoil and subsoil mixed through 18" depth).

PLATE 10.

Extensive root development from a tomato plant where the profile was machine subsoiled and a double rate of lime and fertilizer added. This treatment produced far greater root development than where lime and fertilizer were not added to the subsoil.

PLATE 11.

Tobacco grown on the following treatments from left to right: 2 fertilizer subsoiled, 3 lime subsoiled, 4 control row - no fertility or subsoil treatments. Both fertility treatments of the subsoil produced better growth than the control row.

PLATE 12.

Tobacco grown on the following treatments left to right: row 5 - fertilizer and lime subsoiled; row 6 - fertilizer and lime subsoiled at a double rate; row 7 - fertilizer cultivated into the subsoil. The row treated with the double rate of lime and fertilizer produced the greatest amount of top growth.

PLATE 13.

Tobacco grown on the following treatments left to right: row 8 - lime and fertilizer cultivated into the subsoil; row 9 - lime cultivated into the subsoil; row 10 - control row with no subsoil or fertility treatments. The control row produced less top growth than the treated rows.

TABLE 9

YIELD AND QUALITY OF FIELD GROWN TOBACCO TREATMENTS

Treatment	PLOT A 1" water per application			PLOT B No water applied			PLOT C 1/2" water per application		
	Yield Acre (lbs)	Grade* Index	Crop** Index	Yield Acre (lbs)	Grade Index	Crop Index	Yield Acre (lbs)	Grade Index	Crop Index
1. Machine subsoiled; no fertilizer	2,147	.488	1,048	2,063	.405	836	2,241	.436	977
2. Machine subsoiled; fertilizer added	2,276	.452	1,029	1,847	.369	682	2,335	.402	939
3. Machine subsoiled; lime added.	2,101	.485	1,019	1,892	.380	719	2,181	.465	1,014
4. Control row	1,934	.490	947	1,655	.386	639	1,833	.440	807
5. Machine subsoiled; lime and fertilizer	2,296	.483	1,109	1,976	.420	830	2,391	.408	976
6. Machine subsoiled; lime and fertilizer at double rate	2,293	.438	1,004	2,241	.385	863	2,039	.395	805
7. Machine cultivated subsoil with fert.	1,906	.480	915	1,934	.445	861	1,917	.487	934
8. Machine cultivated subsoil with lime and fertilizer	1,519	.428	650	1,457	.355	517	1,753	.436	764
9. Machine cultivated subsoil with lime	1,641	.478	784	1,701	.427	726	1,843	.416	767
10. Control row	1,561	.479	748	1,460	.334	488	1,830	.377	690
11. Inverted Profile	1,575	.449	707	1,760	.356	627	1,913	.392	750
12. Deep Profile	1,830	.479	877	1,805	.394	711	1,962	.350	687

*Grade Index is determined by multiplying the weight (in percent) of each grade of tobacco by the grade rating and then totaling the products.
**Crop Index is obtained by multiplying the yield per acre by the grade index.

In the tobacco plot receiving the highest amount of water (plot A) the rows with the most nutrients in the subsoil (rows 5 and 6) produced the greatest yield. The quality of tobacco leaf from these two treatments was low as shown by a grade index of .483 for treatment 5 and .438 for treatment 6.

Treatment 4 produced the lowest yield of plot A but had the highest quality leaf with a grade index of .490.

Crop index data for treatments 4, 5, and 6 shows the value of these fertility treatments based on a combination of quality and quantity of yield. Fertility treatment 5 (lime and fertilizer subsoiled) has the highest crop index due to a high yield being only slightly offset by a moderately low leaf quality. The high yield of treatment 6 (lime and fertilizer at double rate) is offset by low leaf quality and treatment six therefore has the second lowest crop index. Treatment 4 (control row) has the lowest crop index; the higher quality leaf being counteracted by a very low yield.

In plot B, which received no irrigation, fertility treatment 6 produced both a high yield and quality of leaf. Because of the high yield and quality, the crop index for treatment 6 was the best in plot B.

In plot B, which received no irrigation, fertility treatment 6 had high yield and good quality. Treatment 5 had a medium yield and good quality. Both treatments 5 and 6 had good crop indexes due to their combination of quality and yield. The control row, treatment 4, produced a low yield and medium quality leaf; a combination which gave the lowest crop index for plot B.

A comparison of irrigation plots A and B shows that supplemental water increased the overall yield and quality but lowered the leaf quality of the plants receiving the high subsoil fertility treatments. The plot which had no supplemental water had low overall yield and quality but the high subsoil fertility treatments produced the highest yield and quality within the plot.

The irrigation plot receiving supplemental water at the rate of one-half inch per application was intermediate in yield and quality between plots A and B. The effect of water upon the individual fertility treatments at this level of irrigation (one-half inch per application) did not produce a yield and quality pattern which could be compared with either of the patterns found the other irrigation plots.

Effects of Subsoil Fertility Treatments Upon Tomato Yield

The effects of the subsoil treatments upon the tomato yields were difficult to determine. The plants were allowed to grow untrellised and the vines became intermixed. Yields were obtained from the plots but it was not possible to harvest the plots uniformly and therefore differences in yield could not be determined satisfactorily.

RESULTS OF GREENHOUSE EXPERIMENTS

Effects of Soil Compaction Upon Tobacco Root Pattern

The pattern of tobacco root development varied with the different compaction treatments. Where there was no compaction, the roots produced a well developed system throughout the profile. In general these unrestricted root systems were heavier in the topsoil while the denseness of the entire system was determined by the available fertility.

The pattern produced by an unrestricted root system is illustrated by plates 14 and 15.

The compaction layers at 4 to 8 and 8 to 12 inches below the surface disrupted the root pattern found in the boxes where such layers were not present. A root pattern similar to that found in the field was encountered where the 8 to 12 inch compaction was present. The roots above the compaction layer were distributed throughout the topsoil in much the same manner as the roots of the noncompacted soil profile. However, where the compaction layer was encountered, root penetration abruptly stopped; the roots being unable to enter the dense soil (plates 16 and 17).

On meeting the compact layer, the roots turned aside and forced their way between the soil and the side of the soil profile boxes. Once past the compaction layer these roots were free to develop in the softer subsoil beneath. Only in this manner were the roots able to bypass the compact layer.

The compaction at 4 to 8 inches below the surface also stopped root penetration resulting in a restriction of the topsoil available to the plant. Here again, the roots were able to bypass the compaction layer to utilize nutrients and moisture from the lower part of the profile. Typical root development patterns are shown in plates 15, 17, 18, and 19.

Effects of Soil Compaction and Nutrients Upon Tobacco Plant Growth

The direct effects of fertility are seen by comparison of the tobacco grown on the noncompacted treatments. When averaged together the weights of these plants give the following results. The weight of

PLATE 14.

Top growth of tobacco produced in an uncompacted profile with no fertilizer added.

PLATE 15.

Roots produced by the tobacco plant shown above. Notice the heavier growth in the topsoil section. (Indicated by the white dot markers)

PLATE 16.

Growth produced by tobacco with no fertilizer and compaction layer between eight to twelve inches below the surface.

PLATE 17.

Roots of the plant shown above. Notice the restriction of the roots to the area above the compaction. The compacted area is indicated by the double white markers.

PLATE 18.

Growth produced by tobacco with no fertilizer and compaction between four and eight inches below the surface.

PLATE 19.

Tobacco roots produced by the compaction treatment shown above. No roots entered the compact layer indicated by the double white markers. The lower roots forced their way between the side of the box and the compacted layer.

tobacco tops increased where fertilizer was added to the topsoil and showed a decrease when the fertilizer was placed in the subsoil. The remaining fertilizer treatments produced the top weights of tobacco equal to, or higher than, that produced by fertilizer placed in the topsoil only. These tobacco top weights are plotted graphically in diagram 3.

Growth charts (diagrams 4, 5, and 6) show that equal fertilizer treatments, did not produce equal growth rates. In the no fertilizer replication (diagram 4) the plants with no compaction to hinder their root development maintained a growth lead over the two compacted treatments. These two compacted treatments show less growth at a given period of time due to the restriction of their root systems. The tobacco plant growing over the compaction layer at 8 to 12 inches produced less top growth than the plant growing over the compact layer extending from 4 to 8 inches below the surface. This was an unexpected result as the plant growing above the deeper of the two compaction layers had the larger amount of soil to draw upon for water and nutrients. Plates 14, 16, and 18 illustrate the differences in top growth produced by the effects of the compaction layers.

The pattern of top growth described above is repeated in those profile studies where fertilizer was placed in the subsoil only (diagram 6). The main difference between the two fertility treatments (no fertilizer, diagram 4; with fertilizer, diagram 6) is the greater amount of top growth produced where the fertilizer was added. The unrestricted roots of treatment 8 enable the plant to reach the fertilizer sooner giving this plant a faster growth rate and a greater size than the other plants in this fertilizer replication.

DIAGRAM 3.

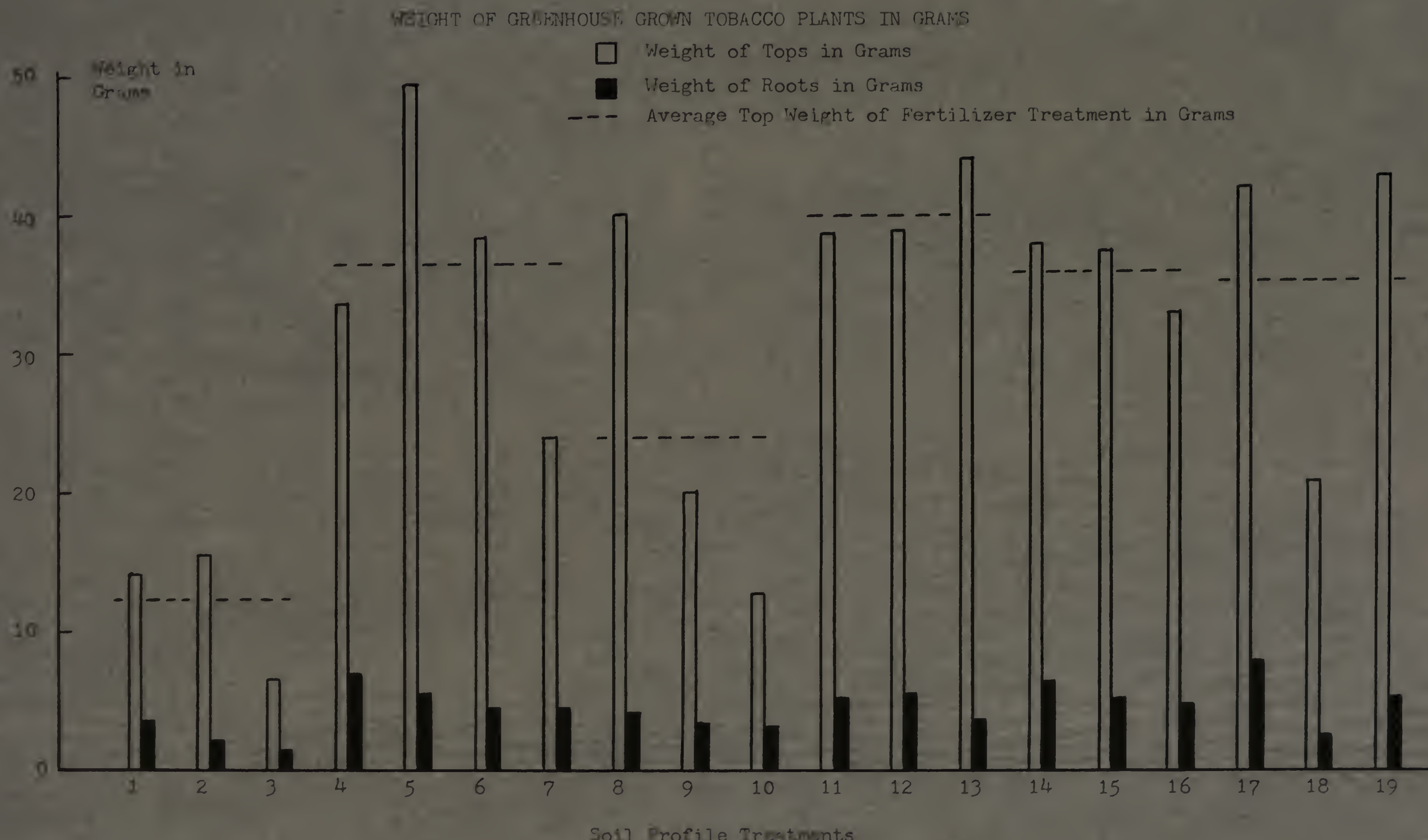
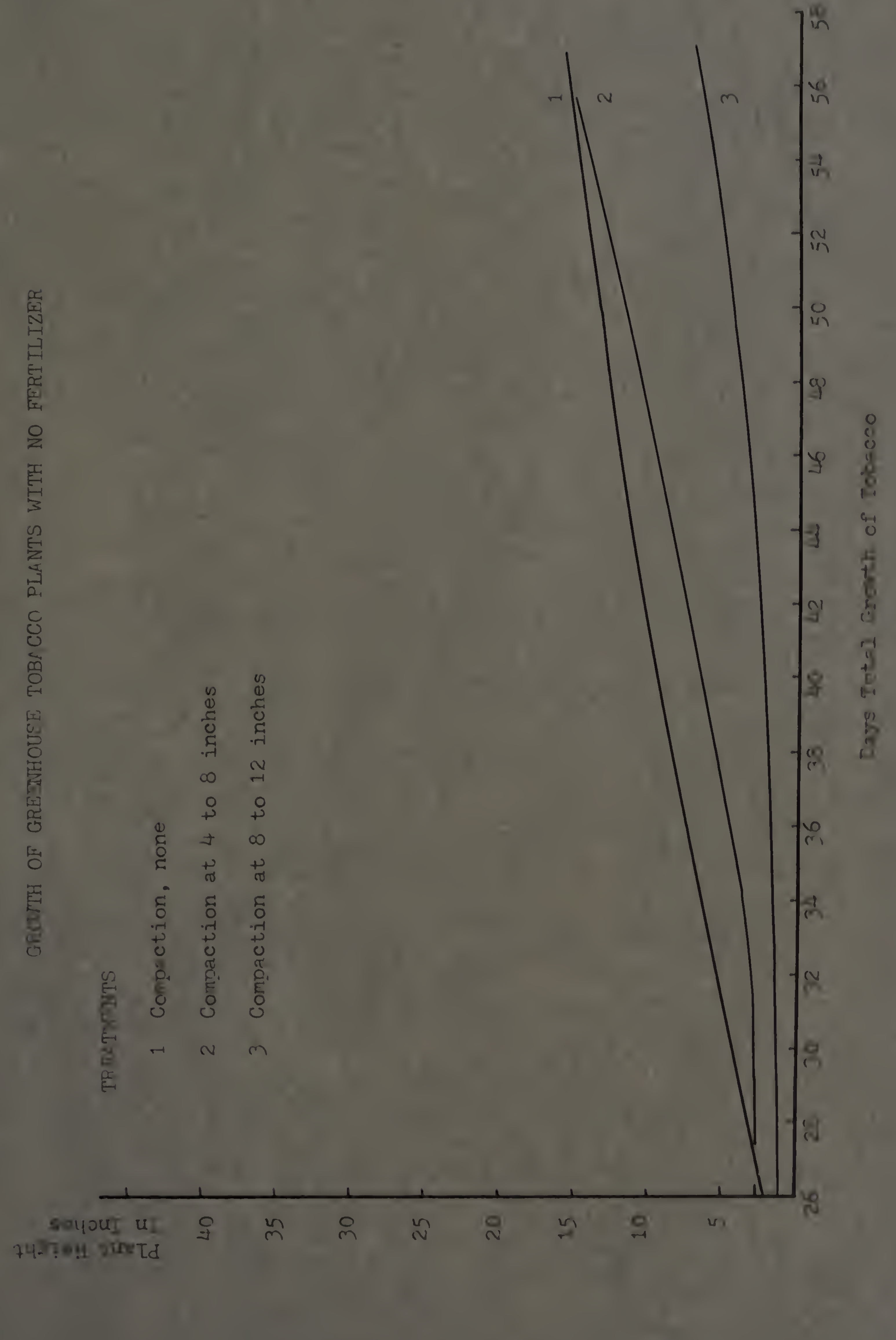
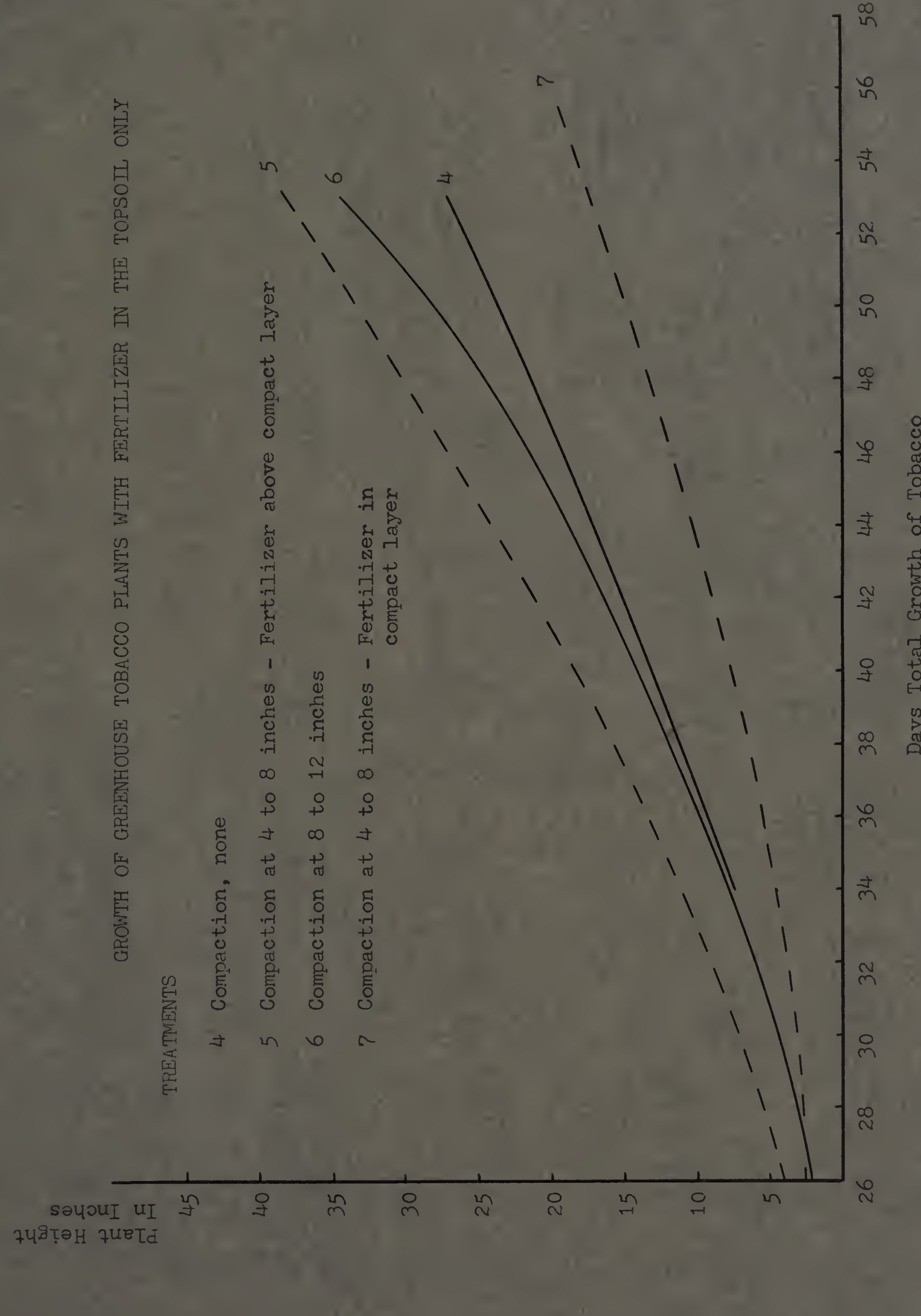

WEIGHT OF GREENHOUSE GROWN TOBACCO PLANTS IN GRAMS
Weight of Tops in Grams
Weight of Roots in Grams
Average Top Weight of Fertilizer Treatment in Grams
Weight in Grams
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Soil Profile Treatments

DIAGRAM 4.



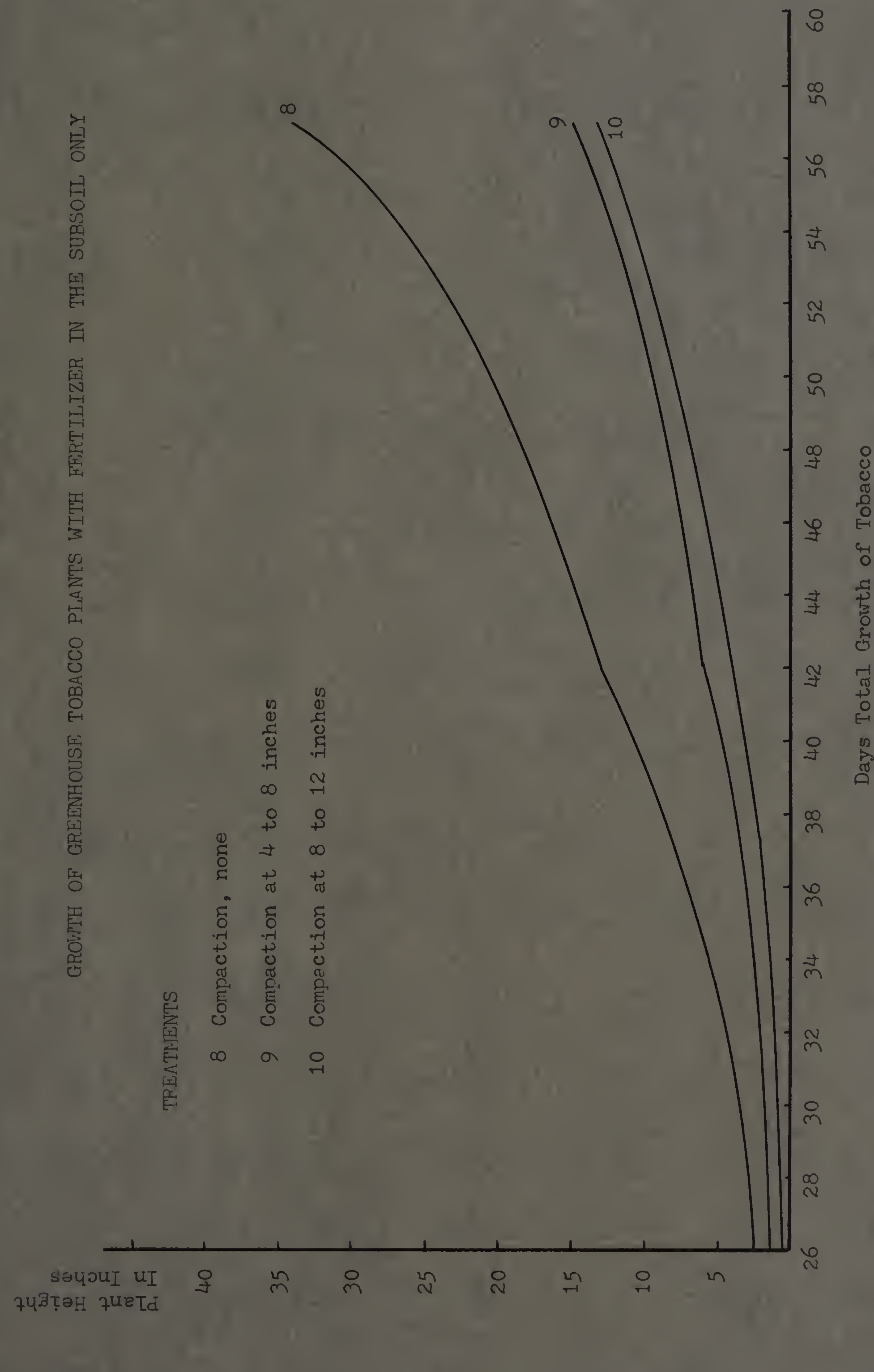
GROWTH OF GREENHOUSE TOBACCO PLANTS WITH NO FERTILIZER

DIAGRAM 5.



GROWTH OF GREENHOUSE TOBACCO PLANTS WITH FERTILIZER IN THE TOPSOIL ONLY

DIAGRAM 6.


GROWTH OF GREENHOUSE TOBACCO PLANTS WITH FERTILIZER IN THE SUBSOIL ONLY
TREATMENTS
8 Compaction, none
9 Compaction at 4 to 8 inches
10 Compaction at 8 to 12 inches
Plant Height In Inches
40
35
30
25
20
15
10
5
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
Days Total Growth of Tobacco
8
9
10

Where fertilizer was placed in the topsoil only, the following results were obtained. Treatments 4 and 6 which have no compaction layers are of comparable sizes although treatment 6 is slightly larger. Striking differences in top growth are seen in treatments 5 and 7 where fertilizer was placed above and in the compaction layer. Treatment 5 resulted in large top growth due to the fertilizer being concentrated above the compaction layer where it was readily available. Treatment 7, on the other hand, had the fertilizer "locked" in the compaction layer where the roots could not reach it. It was found that treatment 7 produced the smallest plants of this fertilizer replication. Plate 20 shows the size of the plant when fertilizer was above the compaction layer and plate 21 the size of top growth produced when the fertilizer was placed in the compaction layer.

Treatment 7 with fertilizer in the compaction layer, produced a heavier top (21 grams dry weight) than treatment 1 (11 grams dry weight) which had neither compaction or added fertilizer. This is because treatment 7 was able to utilize the fertilizer leached from the compaction layer to the roots which had by passed the layer.

With fertilizer placed in both the top and subsoils, (treatments 11, 12, and 13) the top growth pattern due to the position of fertilizer in the profile becomes indistinct as adequate fertility is present at all levels. Where both lime and fertilizer were added to the profile boxes the growth rates were essentially the same as where fertilizer was added to both the topsoil and subsoil. The growth measurements for treatments 11 through 19 are given in table 10.

PLATE 20.

Tobacco top growth produced when fertilizer was placed above the compaction layer.

PLATE 21.

Tobacco top growth produced when the same amount of fertilizer as in Plate 20 was placed in the compaction layer.

TABLE 10 - Part 1

GROWTH OF GREENHOUSE TOBACCO PLANTS

(Plant Height in Inches)

Days Total Growth	Treatments 1	2	3	4	5	6	7	8	9	10
26	2	2 1/4	1	2	4	2	2 1/2	2 1/4	1 1/4	1/2
32	5	2 3/4	1	3	9	5 3/4	3 3/4	4 1/4	1	1 1/4
34	6	3 1/4	1 1/2	7	10 3/4	7 1/4	4 1/2	5	2 1/2	1 1/2
36	7 1/4	4 1/4	1 1/2	8 3/4	13 1/2	9 1/4	5 1/4	7	2 3/4	1 3/4
38	8	4 3/4	1 3/4	11	15 1/2	11 1/2	6	8 1/2	3 1/2	2 1/4
40	8 3/4	6 3/4	2 1/2	13 1/2	19 1/4	15	7 3/4	10 3/4	4 1/2	3
42	10 1/4	7 1/4	2 1/2	16 1/4	22	17	9	13	6	3 3/4
44	11	8 1/4	2 3/4	17 1/2	24 1/2	19 1/4	10 3/4	14 1/4	6 1/2	4 1/2
47	12	10	3 1/2	20 1/2	28	22 1/2	12 1/4	17	8	6 1/2
49	13	11 1/4	4	22 1/2	31 3/4	25 3/4	13 3/4	18 3/4	9	7 1/2
51	13 1/2	12 1/4	4 1/2	24 1/2	35	30	15 1/2	21 3/4	10 1/4	9
53	14 1/4	13 1/4	5	27 1/4	38	34	17 1/4	24 3/4	11 1/2	10
57	15 3/4	15 3/4	7	-----	-----	42	21 1/4	34	15	13 1/4

Treatment Identification

1 No fertilizer; no compaction
2 No fertilizer; 4-8 compaction
3 No fertilizer; 8-12" compaction
4 Fertilizer in topsoil; no compaction
5 Fertilizer in topsoil (above comp.); 4-8" comp.
6 Fertilizer in topsoil; 8-12" compaction
7 Fertilizer in topsoil (in comp); 4-8" comp.
8 Fertilizer in subsoil; no compaction
9 Fertilizer in subsoil; 4-8" compaction
10 Fertilizer in subsoil; 8-12" compaction

TABLE 10 - Part 2.

GROWTH OF GREENHOUSE TOBACCO PLANTS
(Plant Height in Inches)

Days Total Growth	Treatments 11	12	13	14	15	16	17	18	19
26	2	2	1 1/2	3 1/2	2 1/4	3	1 1/2	3/4	2 3/4
32	4	7 3/4	3 3/4	7 1/2	5 1/2	7 1/4	3 3/4	1	6 1/2
34	5 1/4	9 1/2	5 3/4	9 3/4	6 1/2	10	5 1/4	1 1/4	7 3/4
36	7	12	7 3/4	12	9	12 3/4	7 1/2	1 1/2	10
38	9 1/2	14	9 1/2	14 1/4	10 1/2	15	9 1/2	1 1/2	12
40	11 3/4	15 1/2	12 1/2	16 1/2	13 3/4	17 3/4	11 3/4	2 1/2	14 3/4
42	13 1/4	18 1/2	15	18 3/4	16 1/2	20 1/2	14 1/2	3	17 1/4
44	14 1/2	20 1/2	17 1/4	20 1/4	18	22	16 1/2	3 3/4	19 3/4
47	16	23 1/2	20 1/2	22 1/2	19 1/4	26	19 3/4	5 1/4	23 3/4
49	18	25 1/2	23	25 3/4	26 1/2	28 1/4	22	6 1/4	26 1/4
51	21 1/4	29	26 1/2	30	28 1/2	31 1/4	26	7 1/2	29 1/4
53	21 1/2	31 1/2	30 3/4	34	30 1/2	35 1/2	29	8 3/4	34
57	28 1/2	40	-----	-----	40	40	-----	12 1/4	-----

Treatment Identification

11 Fertilizer in topsoil and subsoil; no compaction
12 Fertilizer in topsoil and subsoil; 4-8" compaction
13 Fertilizer in topsoil and subsoil; 8-12" compaction
14 Fertilizer in topsoil, lime in subsoil; no compaction
15 Fertilizer in topsoil, lime in subsoil; 4-8" compaction
16 Fertilizer in topsoil, lime in subsoil; 8-12" compaction
17 Fertilizer in topsoil, lime and fertilizer in subsoil; no compaction
18 Fertilizer in topsoil, lime and fertilizer in subsoil; 4-8" compaction
19 Fertilizer in topsoil, lime and fertilizer in subsoil; 8-12" compaction

Effects of Soil Profile Inversion Upon Greenhouse Tobacco Plants

Inversion of the soil profile produced root development patterns and plant sizes directly related to the presence or absence of fertilizer. Where fertilizer was placed in the inverted subsoil, excellent top and root growth resulted. Where fertilizer was absent, the tobacco transplants barely survived and did not grow until their root systems managed to reach the buried topsoil. Tobacco growth where both lime and fertilizer were added was less than with fertilizer alone, but showed a root weight increase of 500 percent over the plant where no fertilizer was available.

The plants described above are illustrated in plates 22 through 27. Diagram 7 presents the growth curves of plants growing in the inverted profile from the measurements listed in table 12.

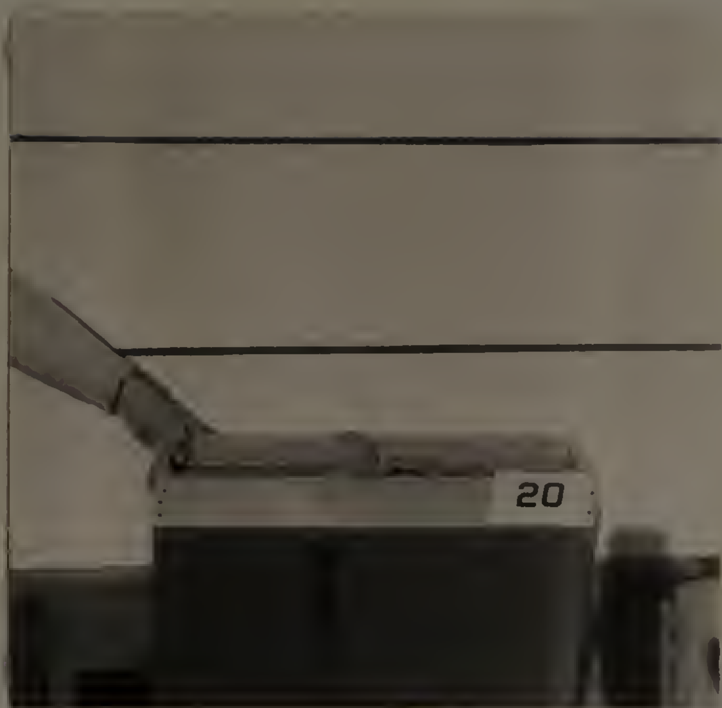
DISCUSSION

The discussion of the experimental results will be divided into two sections: (1) The alteration of the profile by subsoiling treatments and (2) The effect of subsoiling and fertility treatments upon root development.

Alteration of the Soil Profile by Subsoiling Treatments

Subsoiling, like other tillage operations, is done in order to alter the soil conditions so that they will become more favorable for plant growth. Several Midwestern investigators (2), (5), (26), and (29) found that mechanical subsoiling did little to increase water retention and infiltration or to alter the profile. This was due to the clay pan soils with which they worked flowing together before any permanent benefits could result.

PLATE 22.



Tobacco top growth produced after 53 days growth in an inverted profile with unfertilized subsoil.

PLATE 23.

Roots produced by the plant above. The white dot markers indicate the surface of the soil and the division between the inverted profiles.

PLATE 24.

Tobacco top growth produced where fertilizer was added to the subsoil in the inverted position.

PLATE 25.

Roots from the plant shown above. This photo, when compared with Plate 23, shows the favorable effect of fertilizer upon root development in an otherwise infertile soil.

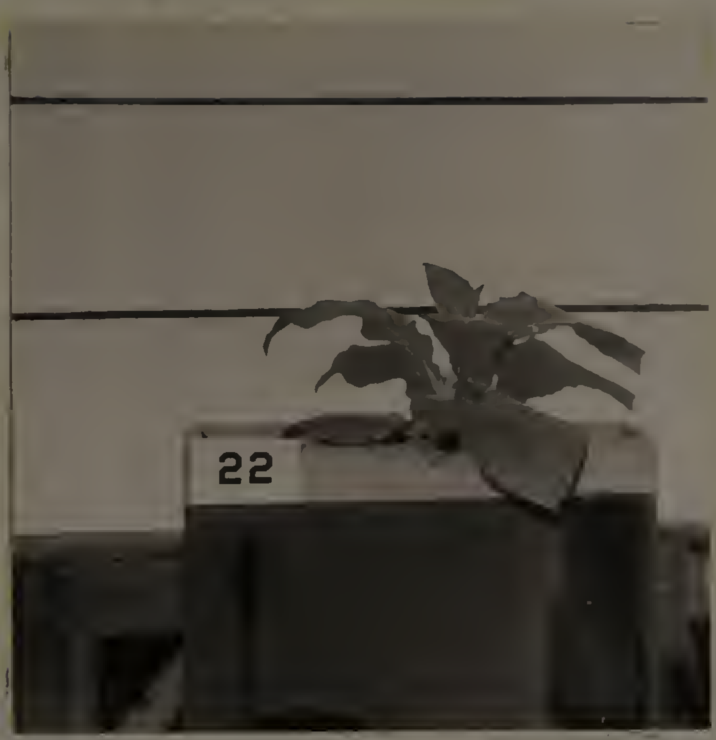


PLATE 26.

Tobacco top growth produced in the inverted profile where lime and fertilizer were added. The top weight of this plant was 25 times greater than the plant shown in Plate 25.

PLATE 27.

Roots from the plant above. Here again the addition of fertility made the development of a good system possible.

DIAGRAM 7.

GROWTH OF GREENHOUSE TOBACCO PLANTS IN INVERTED PROFILE

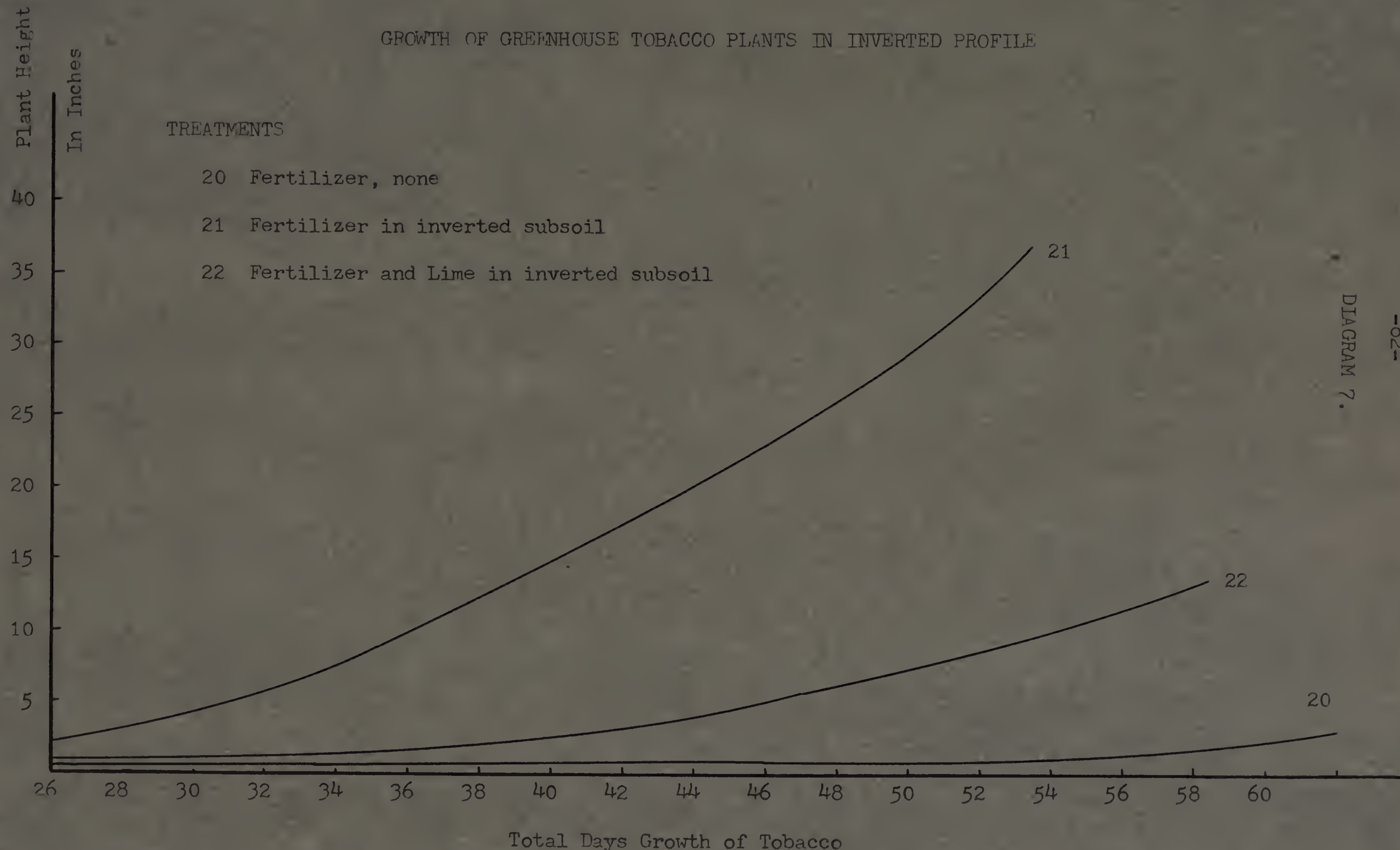


TABLE 11

GROWTH OF TOBACCO PLANTS IN GREENHOUSE

(Inverted Profile Experiment)

Plant Height in Inches

Days Total Tobacco Growth	Treatments #20	#21	#22
26	1/2	2	3/4
32	3/4	5 1/2	1
34	3/4	7 1/4	1 1/2
36	3/4	9 3/4	1 1/2
38	3/4	12	2
40	1	14 1/2	2 1/2
42	1	17 1/2	3
44	1	19 1/4	4
47	1	22 1/2	5 1/2
49	1	27 3/4	6 1/2
51	1	31 3/4	7 3/4
53	1	36	9 1/2
57	1 3/4	---	12 1/2
61	2 3/4	---	---

Treatment Identification

#20 Inverted Profile; no fertilizer in subsoil.

#21 Inverted Profile; fertilizer in subsoil.

#22 Inverted Profile; lime and fertilizer in subsoil.

On the sandy loam soils investigated here in the Connecticut River Valley, two techniques were used to break the compact layer with different results. The first method was subsoil cultivation after removal of the topsoil. This method left the profile essentially unchanged except for a slight mixing at the boundary of the A and B horizons.

The second method, that of chiseling with a subsoiling machine, produced results which were different than those obtained in the Midwest. At the time of the subsoiling operation, it was noted that the chisel left a very definite opening which sometimes did not close at the surface until the pressure of the tractor working on the next row pressed it together. These chisel openings could be detected two weeks later by probing indicating that a passage for aeration and water infiltration was in existence. Further proof of the existence of these openings was provided when excavation of the subsoiled rows revealed deep intrusions of topsoil where the subsoiler implement had passed through the profile. The feature of topsoil infiltration was characteristic of all rows which had been machine subsoiled and produced several important changes in the profile. First, the topsoil with its nutrients and organic matter, is distributed to new depths. Secondly, this topsoil is in a loose, well aerated condition and forms a channel for water infiltration.

If subsoiling operations are carried out each year in this manner, and adequate organic matter and nutrients are added to the soil, such topsoil infiltration should gradually mix the A and B horizons resulting in a deeper zone favorable for root penetration.

The feasibility of mixing the topsoil and subsoil to deepen the profile was demonstrated by the deep profile row where equal amounts of topsoil and subsoil were blended. While the size of tobacco top growth in this row did not equal the top growth of tobacco in the fertilizer rows, it was comparable in size to the control row and its roots were better than those of the control row. These results are similar to the experiments of Goff (14) who had good root and top growth of corn upon mixing top and subsoils to a depth of 2 1/2 feet.

Under local conditions the best method of mixing the two soil horizons would seem to be, in the opinion of this author, subsoil chiseling with subsequent topsoil infiltration. The reasons for this statement are: (1) Subsoiling can be carried out at the same time as plowing. (2) The mixing of topsoil and subsoil under such conditions is a gradual process where a minimum of low fertility is incorporated at once. (3) Deep plowing would not be satisfactory as it brings up large quantities of subsoil in which plants do not grow well. The absence of roots in the subsoil portion of the inverted profile, both in the field and greenhouse experiments, shows that roots will not develop in the subsoil.

Effect of Compaction and Fertility Upon Root Development

Both in the field and in the greenhouse experiments, the root development was limited by the presence of a dense soil layer. As a result of this soil condition, the roots were largely limited to the area above the compact layer unless some break in the layer permitted root penetration. In the case of the greenhouse tobacco plants, this break existed in the form of the crack between the side of the box and the soil. This opening permitted root penetration to lower levels and, in some cases, utilization of nutrients which otherwise would have been unavailable.

In the field experiments, few such cracks existed naturally and had to be created by subsoiling and subtillage techniques. Where the compaction layer was left undistrubed, the root development of the plants was largely lateral while where the pan had been broken, the root pattern changed from horizontal to vertical. This indicates that a fuller and deeper root system would develop if the restricting layer were not present. Further evidence in this connection was seen in the greenhouse studies where a fully developed root system grew throughout the profile box in the absence of a compact layer (plate 12).

Below the compaction layer in the field the bulk density of the soil averaged 1.36; a value close to the bulk density figure for the surface soil. As there was no lack of moisture in the subsoil, the conclusion is that the absence of fertility was the main factor restricting tobacco root development in the subsoil.

Where the roots penetrated to a considerable depth, tobacco plant development was proportional to the available fertility. Where subsoiling was carried out without placing of fertilizer, the intruded topsoil supplied some fertility in itself. The total fertility supplied by a topsoil intrusion could be only a portion of the fertility contained in the topsoil. Tobacco top development in rows where the only deep fertility addition was provided by the topsoil intrusion was better than in the control row but did not equal the top growth of the subsoiled fertilized rows.

The manner of application influenced the effectiveness of lime or fertilizer in the subsoil. Where cultivated into the subsoil, lime and fertilizer were less efficient than when banded by the subsoiling machine. The reduced effectiveness may be due to the application being spread, and therefore diluted, through a larger volume of soil when cultivated into the subsoil. In addition, subsoil cultivation left no channel for easy root penetration to the fertility placed in the subsoil.

The data show an increase in the weight of tobacco tops and roots when lime and fertilizer were banded separately, or in combination, by the subsoiling machine. When placed by machine, fertility treatments were concentrated at the bottom of an area of easy root penetration. As would be expected, the tap roots penetrated down the channel formed by the subsoiling implement and produced a concentration of feeding roots in the vicinity of the fertility placement.

If the banding of fertilizer leads to a concentration of roots in a restricted volume of soil, such banding would seem to defeat the purpose of subtillage which is to enable the roots to extend throughout the entire volume of cultivated soil. A restriction of roots to a small volume of soil means the roots have available to them only the water present in this volume. Actually the roots produced around the fertilizer band lie in the path of easiest water infiltration and therefore are not likely to suffer from a restricted water supply.

In the field experiments where lime was placed in the subsoil, the growth of tomato roots was greatly increased. The favorable effects of lime in promoting root growth in the subsoil has been noted by other investigators (2) and (35).

The effects of calcium in the local sandy subsoils are probably the raising of the pH with a consequent increase of the availability of phosphorus. Both of these effects would promote good tomato root growth. The effect of lime in the greenhouse experiments was masked by the effects of the fertilizer.

In the field, the best top and root growth of tobacco took place where both lime and fertilizer were applied in the subsoil. The early response of the plants receiving the double rate of these materials indicated that their roots penetrated rapidly to the nutrients placed in the subsoil. Here again, the greatest root development took place in the area nearest the fertilizer concentration.

In both the field and greenhouse experiments, the size of plants produced depended upon the amount of fertilizer applied. In the field experiments the supplemental fertility was applied in the subsoil. The question as to whether the additional fertility would be more valuable broadcast in a conventional manner is a valid one. A case can be made for broadcasting this additional fertilizer where shallow rooted plants are located where their water requirements can be met by irrigation. While applying fertilizer to the top few inches of soil may produce satisfactory growth in a naturally shallow root system, this author feels that deep placement of fertilizer is necessary for deep root development in the subsoils studied in the Connecticut River Valley.

SUMMARY AND CONCLUSIONS

This investigation was carried out to determine the factors which restrict the deep root penetration of crops in the Connecticut River Valley soils. Previous investigators had found a compact soil layer at the base of the plowed zone and a subsoil with a low fertility level.

Two field methods of subsoiling to break the compaction layer combined with subsoil fertility treatments produced the following results:

(1) Where the compact layer was not broken plant roots were restricted to the soil above the compaction.

(2) Where the compact layer was broken by subsoil chiseling, the topsoil filled the chisel opening to create a good avenue for root penetration and consequent development. No path for root penetration was made when the compaction layer was broken by stirring with a cultivator.

(3) The best root and crop development as measured by yield and quality took place where the lime and fertilizer were banded together in the subsoil.

In the greenhouse experiments, combinations of artificial compaction layers and fertility treatments produced results similar to those in the field.

The results summarized above lead to the following conclusions:

(1) Crop roots will develop at depth to utilize subsoil water and nutrients provided they are not restricted by adverse soil conditions such as compact soil layers and low fertility levels.

(2) Fertilizer and lime supplements are necessary to encourage and stimulate good root development in low pH subsoils.

(3) Chisel subsoiling and deep banding of fertilizers is a satisfactory method to simultaneously deal with the compaction and fertility problems of Connecticut River Valley soils.

(4) The intrusion of the topsoil into the chisel opening provides a valuable channel for water infiltration and root penetration in addition to gradually mixing the topsoil and subsoil into a deeper profile.

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