DEEP TILLAGE AND ROOT GROWTH

A Study of Tobacco Growing in Sandy Loam Soil

H. C. De Roo

Bulletin 644

June 1961

THE CONNECTICUT AGRICULTURAL EXPERIMENT STATION

New Haven

Contents

DEEP TILLAGE AND ROOT GROWTH

A STUDY OF TOBACCO GROWING IN SANDY LOAM SOIL

H. C. DE ROO

Most cultural practices are directed to the roots of our plants. Yet, because roots are rarely seen and difficult to extricate from the soil, our knowledge of the rooting habits of plants is limited.

A plant obtains water and nutrients through the roots which anchor it in the soil. Therefore, one assumes that greater root room and broader roots will tap a greater reservoir and provide a larger and more reliable supply of nutrients and water, which in turn will result in consistently higher yields. Although each species has an inherited root pattern (58), this pattern is changed by soil compaction (14), and we turn to deep tillage for the enlargement of the root room. But, because roots and hardpans are buried out of sight we rarely know whether the compacted soil was improved, whether the improvement persisted, or whether the roots responded to the tillage.

This Bulletin presents direct observations of cigar tobacco roots growing in the intensively cultivated sandy soils of Connecticut. We observed the usual distribution of these roots, the enlargement of the root room by deep tillage, the maintenance of the enlargement, and the benefits to the plants.

ROOT DEVELOPMENT AND SOIL LOOSENESS

Each plant species has a more or less characteristic root system. It may be sparse, or fibrous and dense; it may be shallow or deep (58). These rooting habits, however, are quite flexible and can be modified considerably by the soil environment, especially by a barrier of compact soil (14, 34, 56). Therefore, if we want to see the maximum spread attainable by the roots of a species and how it may be restricted, we should examine the roots under optimum as well as under the usual soil conditions of a commercial field.

The optimum soil is assumed to be porous, friable, and fertile, so that roots are not restricted in their free growth and development. The soil usually encountered in a commercial field is compact because soil and crop management operations with heavy machinery tend to compress soils (22, 35). This problem is widely recognized, and as a result, research in soil compaction, its prevention and amelioration, is proceeding in many parts of the world (2, 43).

Root-restricting hardpans induced by tillage and traffic are most common in coarse to medium textured soils (33, 43). The direct cause of root restriction in compact soils is often hard to identify because compaction affects air and water movement in the soil when it creates a physical barrier. In coarse to medium textured soils, however, mechanical resistance appears to be of primary importance. This resistance is increased because of reduction in the larger pores and an increased mechanical strength of the soil mass or a rigidity of the pore structure (24, 41, 59).

The research on tobacco root growth was reviewed in 1940 (21). In America only one study of the development and distribution of tobacco roots was reported (11). Abroad, particularly in Germany and the Balkans, much more work had been done.

In a study of tobacco plants grown in North Carolina fields there was no evident correlation between root distribution and either pH or moisture equivalent, but the distribution seemed to be limited by factors associated with soil texture (21). These observations did indicate, however, that shallow root systems were, at least partially, the result of shallow cultivation. For normal development of roots, a loosened soil was necessary.

Root growth and activity have recently been traced through the use of radioactive phosphorus (26). Evidently the growth of the roots and a marked increase in nutrient uptake precede the rapid growth of the plant shoot. Further, in the friable, fertile deep phase Norfolk sandy loam, flue-cured tobacco is evidently a deep-rooted plant.

In Connecticut, where for many years three types of cigar tobacco have been grown, practically no research had been done on the root systems. Most work on tobacco roots was incidental to the study of injuries caused by two of the major field and soil-borne diseases: brown and black root rot (1). However, a survey of the well-drained and well-aerated tobacco soils in the Connecticut Valley showed us that the effective rooting depth of tobacco is generally shallow (Figure 1).

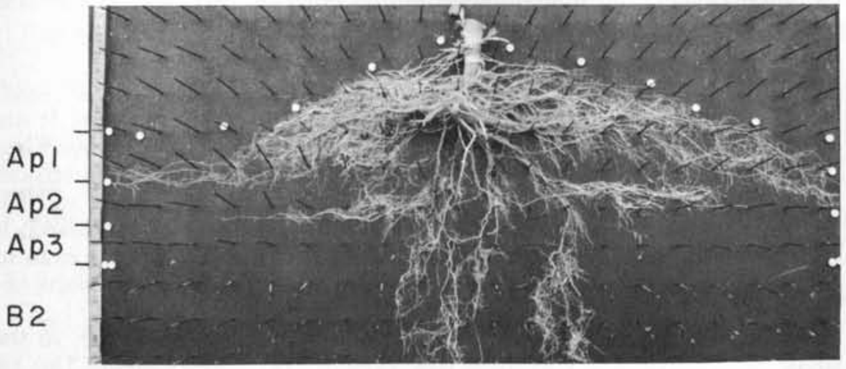


Figure 1. Roots of a shade type of tobacco. The shallowness and distribution of the roots within and below the plow layer (Ap) are typical for the rooting of tobacco in the Connecticut Valley.

Materials and Methods

We sought to create optimum soil conditions for root extension by loosening the soil carefully and deeply, by doubling the layer of the surface soil or topsoil, by adding fertilizer to the subsoil, and by restricting compaction by traffic and machinery through the use of manual labor. Thus in 1954 a small-plot experiment was designed, with the treatments and soil profile modifications established by hand. After the precise, manual establishment of the test conditions, the deep looseness of

the various profiles was preserved as well as possible by setting the tobacco transplants by hand and cultivating them with a hoe. All operations were performed at the times customary in the Connecticut Valley (1).

Soil. The soil was typical tobacco soil, a Merrimac sandy loam at the Tobacco Laboratory of The Connecticut Agricultural Experiment Station in Windsor. An extensive description of this soil, the predominant soil type on the experimental farm, can be found in our introduction to these studies (14).

The soil was plowed 8 to 9 inches deep and disk-harrowed twice. To facilitate the study and cleaning of the tobacco root samples, no cover crop had been grown. Beneath the recent plow zone of 8 to 9 inches depth lay the compact, platy, older plow zone, which had not recently been plowed. The thickness of this layer of sub-surface soil varied from about 1 to 6 inches in this field. The upper subsoil comprised the main body of the compaction pan. The depth of the subsoil, B-horizon, averaged 24 inches. The mechanical composition of the soil in the pan and in the layers above the pan was essentially the same; with depth, the layers below the pan became coarser textured and looser. The topsoil, as well as the subsoil layers, had a pH of about 5.5, which is favorable for tobacco. The nutrient status of the subsoil varied from very low to medium for phosphoric acid and low to medium for potash.

Treatments. The plots measured 40 by 90 inches and gave room for one row of 5 tobacco plants. The treatments (Table 1), replicated 4 times, were applied after the topsoil, 0 to about 10 or 15 inches, was removed by spade and laid aside (Figure 2).

Table 1. Outline of treatments—nature of profile, depth of loosening, and fertilization in the hand-tilled plots

Soil profile and treatment	Approximate depth beneath ridged tobacco row of		
	Top soil	Shattering	Fertilization[1]
	Inches	*Inches*	*Inches*
I (control)	12	8 (plowed)	0 to 6
IS	12	24	0 to 6
ISF	12	24	0 to C and 12 to 16
IIS	24	24	0 to 6
IISF	24	24	0 to 6 and 12 to 16
OS	0	24	0 to 6
OSF	0	24	0 to 6 and 12 to 16

[1] 0-6 inches: standard surface fertilization.
12-16 inches: deep fertilization, duplication of surface fertilization.

Deep shattering —S— was performed with a fork by loosening the compaction pan and lower subsoil over a depth of about 12 inches; this was done with a minimum of soil inversion, thus leaving the subsoil layers in their natural order.

Deep placement of fertilizer —F— was accomplished by broadcasting fertilizer upon the surface of the exposed and loosened subsoil and mixing it with a fork to a depth of 4 inches. Thereafter, on the plots IS and ISF the original topsoil was replaced. On the O plots no topsoil was

Figure 2. Small field-plot on Merrimac sandy loam with topsoil or Ap horizon removed. The plow pan in the upper subsoil is here roughly shattered so that the block-like clods may demonstrate the compactness of this layer.

replaced, but it was exchanged for the subsoil of the II plots which required a double layer of topsoil. The deep fertilizer on the plots IISF was placed upon the topsoil that replaced the subsoil and also was worked in about 4 inches. The II plots were completed by replacing their topsoil.

The deeply placed fertilizer was applied at the same rate as the surface application, 3,500 pounds of 6-3-6 per acre, plus phosphate, potash, and landplaster, added according to Morgan soil tests (51). This complete fertilization of the layer 12 to 16 inches below the hilled tobacco row was designed to reveal the impact upon the development and distribution of the tobacco roots of a buried layer of soil highly enriched with nutrients. Thus the plots with deep fertilizer, ISF, IISF, and OSF, received at least twice the amount of fertilizer applied to the other plots, I, IS, IIS, and OS. The 6-3-6 grade of mixed fertilizer was made up of materials commonly used for Connecticut tobacco; castor pomace plus cottonhull ash formed the main sources of nitrogen and potash. The surface fertilization was also applied by hand and mixed with a fork to a depth of 4 to 6 inches.

Havana Seed tobacco (Var. K1) seedlings, 4 to 6 inches tall, were transplanted in the first week of June.

Measurements. After a predominantly dry, rather cool season (Table 6) the plants of each plot were harvested in the middle of August and cured in the customary way. The leaf samples of the three center plants of each plot were graded for quality, counted and weighed. Later the leaves were analyzed for dry matter, total nitrogen, protein nitrogen, nicotine, nitrate nitrogen, ammonia nitrogen, and iron.

The soil profiles were sampled to determine the residues of the fertilizations.

The response of the roots of the tobacco plants was determined by the pinboard method (14). This method gives a graphic and detailed picture of the pattern of root development which can be related to the details of the soil environment in the plots. An undisturbed monolith of soil with a cross sectional area of 6 by 40 inches was taken to a depth of 20 to 24 inches, depending upon the depth of root penetration. At the same time soil profile descriptions were made and undisturbed soil samples of measured volume were taken with a modified Lutz core sampler (53). Many profiles were sampled to provide a background for our understanding of the behavior of these roots. In this report we shall present the root system of the plant in the center of a plot from each treatment. These root studies and samplings were made immediately after the stalks of the tobacco were harvested.

After the root profiles were photographed, quantitative observations were made of the roots within horizons. The roots were sampled by horizons in the control plot I and by layers of approximately the same depth in the deeply loosened S plots. Depths were measured from the top of the ridged tobacco row. The horizon designation, approximate depth in inches and nature of the soil were:

Ap1	0 to 6	topsoil—hilled and cultivated.
Ap2	6 to 10	topsoil—lower part of recent plow zone, not cultivated.
Ap3	10 to 12	topsoil—compacted portion of plow zone, not recently plowed.
B21	12 to 18	upper subsoil—with main body of plow pan.
B22	18 to 24	lower subsoil—less compact than B21.

The roots in the thin Ap3 horizon were combined with those in the Ap2 horizon.

The weight of roots in each horizon does not provide an easy basis for comparison of the treatments. These weights vary with the depth of the profile horizons and with the size of the plant, as well as with the root penetration which is our interest. Therefore, we defined a number that would more quickly reveal the root distribution and penetration into deeper horizons. First, the roots in the cultivated zone, 0 to 6 inches or Ap1 horizon, were excluded because a few thick woody roots would completely overbalance the weight of the younger, absorbing portion of the root system. Then the number was defined as the proportion of the root system below the Ap1 horizon which is present in each inch of profile. This number, the relative root weight, was calculated by dividing the root weight in a horizon by the depth of the horizon and by the total weight of the roots beneath the 6-inch Ap1 horizon:

$$\text{Rel. Root Wt.} = \frac{\text{Weight of roots in horizon} \times 100}{(\text{Weight of roots in Ap2, Ap3, B2}) \times \text{Depth of horizon}}$$

Clearly a higher relative root weight in the lower horizon is an indication of deeper root penetration.

Response of Roots to Soil Looseness and Fertility

The root profiles in the small plots showed, first of all, a scarcity of roots beneath the depth of plowing on the control plots I. The root profile shown in Figure 3A demonstrates a definite inhibition of root growth by the plowsole hardpan, Figure 3B and C. On the other hand, the root profiles from the other plots, which were all deeply shattered –S–, showed profuse rooting beneath the plowed horizon, Ap, or its equivalent soil profile depth. The root profiles from the plots IS, OSF, and IISF, pictured in Figures 4A, 4B, 5, and 6A, show this quite clearly. The other S profiles not pictured here all showed the same pattern of dense and deep rooting to the bottom of the monolith. The loosened soil can be clearly seen in Figures 6B and C.

From the root weight data in Table 2, the same observations can be made. In the control plot I a relative root weight of only 1.1 was found in the so-called 12- to 18-inch zone, much less than the 3.6 to 5.0 found in the corresponding zones of the deeply-loosened S plots. In fact, the relative root weights in the 12- to 24-inch zones of the loosened S plots were greater than the weights in the shallower 12- to 18-inch zone of the check plot I.

Table 2. The distribution of roots from mature plants in the hand-tilled plots

Soil profile and treatment	Approximate depth in inches beneath hilled tobacco row						
	0-6	6-12[1]		12-18[2]		18-24	
	Grams[3]	Grams	Relative	Grams	Relative	Grams	Relative
I (control)	42.5	2.79	15.1	0.28	1.1	0	0
IS	33.0	3.14	9.7	1.63	5.0	.65	2.0
ISF	54.0	4.90	10.8	1.80	4.0	.90	2.0
IIS	45.4	5.21	11.1	1.69	3.6	.93	2.0
IISF	40.8	5.30	9.4	2.75	4.9	1.39	2.5
OS	27.3	3.29	10.8	1.24	4.1	.55	1.8
OSF	43.0	4.41	10.8	1.71	4.2	.67	1.7

[1] On 1 (control 6-10 inches: 2.40 g.; plowsole pan at 10 inches depth.
10-12 inches: 0.39 g.; old plow zone or Ap3 horizon.
[2] On 1 (control 12-20 inches: 0.28 g.; no roots below 20 inches depth.
[3] Oven-dry weights.

The cause of the inhibited root growth in plot I with the usual soil condition can be seen in the physical properties of the soil (Table 3). The compaction of the soil is expressed as bulk density, the weight in grams of a cubic centimeter of undisturbed dry soil. The porosity is expressed as the percentage of the soil volume occupied by the soil pores. These soil pores are divided into capillary and non-capillary pores, the large pores from which water is drained by 60 cm. of tension. The hardness of the soil is expressed in resistance to penetration or penetrability, the number of strokes required to drive the sampler into the soil.

The topsoil in the check plots I, sampled at a depth of 7 to 9 inches, showed the highest density, 1.40, of all plots at that depth (Table 3). However, this Ap2 horizon of plots I had not been worked after the field was plowed and disk-harrowed. Therefore, within plow depth as well as below the physical conditions of the soil profiles in the control plots I were similar to those commonly found in comparable soils, when used

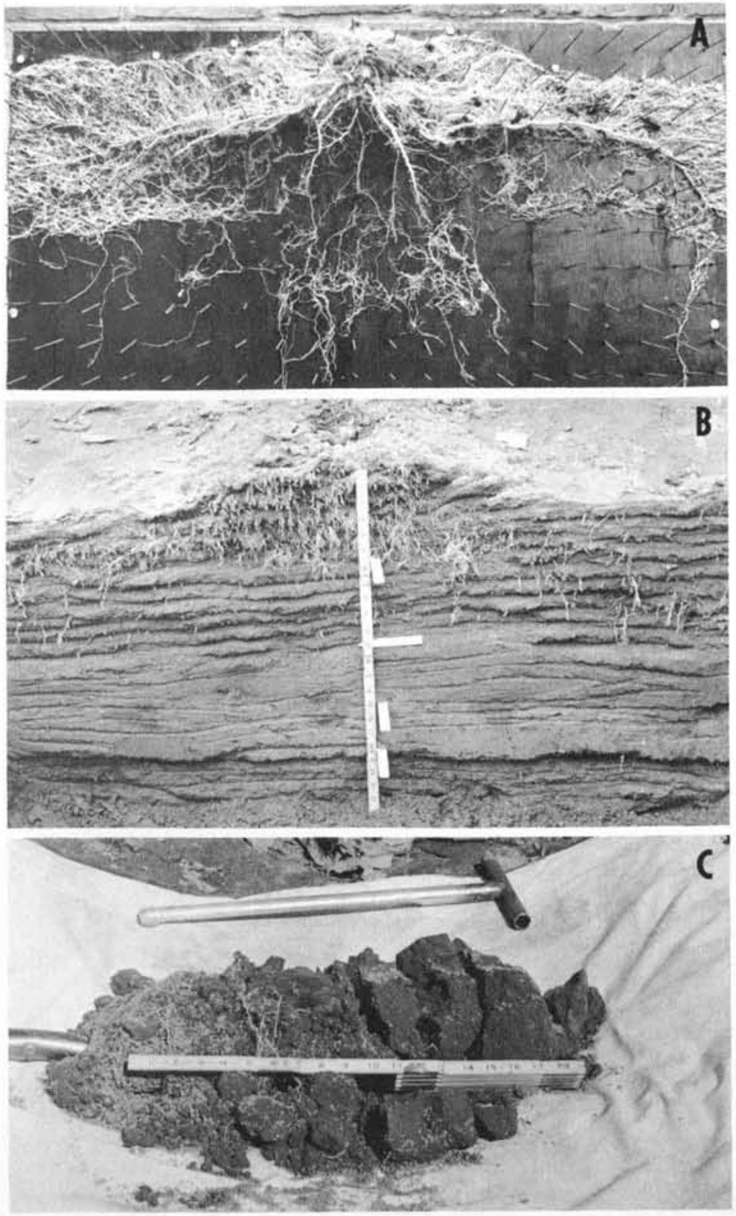


Figure 3. A. Root system from plot I: normal soil (control). B. Soil profile from which root monolith was taken, showing compactness and root development in the different horizons which are described on page 7. C. Spade test demonstrates soil tilth in the various horizons: Ap1, crumbly; Ap2, cloddy or subangular blocky; Ap3 and B2, large angular blocks of the plow pan.

Table 3. Soil physical properties in the hand-tilled plots at harvest time

Soil profile and treatment	Core sample depth beneath hill[1]	Bulk density	Porosity: Capillary	Porosity: Non-capillary	Resistance to penetration, strokes[2]	Soil moisture[3]
	Inches	*g./c.c.*	*Per cent*	*Per cent*	*No.*	*Per cent*
I (control)	7-9	1.40	29	16	8	12
	11-13	1.63	29	8	23	12
	16-18	1.56	31	10	16	11
IS	7-9	1.30	28	21	2	14
	12-14	1.34	30	19	2	14
	18-20	1.46	28	16	5	14
ISF	7-9	1.30	28	20	4	13
	12-14	1.31	27	22	2	12
	18-20	1.39	31	16	4	13
IIS	7-9	1.27	28	22	3	13
	12-14	1.29	28	22	2	14
	18-20	1.27	28	24	2	14
IISF	7-9	1.27	29	21	3	13
	12-14	1.30	29	21	2	14
	18-20	1.30	30	21	3	13
OS	7-9	1.34	29	18	3	12
	13-15	1.40	31	16	4	12
	18-20	1.36	33	16	4	13
OSF	7-9	1.38	30	16	3	11
	12-14	1.36	30	18	4	12
	18-20	1.44	31	14	7	13

[1] Average of 4 determinations.
[2] Number of times a 12-pound hammer was dropped 2 feet to drive a 3⁵⁄₁₆-inch diameter core sampler 3⅜ inches into the soil (53).
[3] Moisture in soil when sampled.

for commercial tobacco growing.

The compaction pan in plot I, lying 10 to 17 inches beneath the hill, was sampled at a depth of 11 to 13 inches. The soil in this layer had a high bulk density, 1.63, and a great resistance to penetration, 23 strokes at a moisture content of 12 per cent, i.e. about 75 per cent of its field capacity. This compact soil had a low non-capillary porosity, 8.4 per cent. The reduction in porosity took place almost completely at the expense of these larger soil pores, the most important ones for the free growth and development of roots (59).

In sharp contrast to this dense compact layer of the check plot I, complete shattering of the pan in the plots IS, ISF, OS, and OSF produced B2 horizons of much lower bulk densities, 1.31 to 1.46, and higher non-capillary porosity, 16 to 22 per cent. In this loosened soil only 2 to 7 strokes were required to drive the core sampler into the soil.

Soil aeration was only slightly affected by the deep loosening. The rate of oxygen diffusion was estimated in the different plots by means of the Raney diffusion chamber (42). The higher the diffusion rates, the better the aeration. The measurements were taken at depths of 12 and 20 inches; in the normal profiles of plots I these sampling depths were located within and below the compaction pan (Table 3). The rates of oxygen diffusion in the check plots I were high in spite of the compacted plowpan or great depth of sampling, approaching values measured in sand (10), and indicating a minor effect, if any, of the pan on soil aeration under the dry conditions of this experiment. Nevertheless, the deep loosening in the S plots increased these diffusion rates somewhat and this to such an extent that the diffusion apparatus was incapable of measuring the difference between the diffusion rate through these loosened porous S plots and that through free air.

The loosening with a fork of the compacted B21 horizons was not always complete. A small part of the hardpan was often left unshattered, as was demonstrated by the root profiles (Figure 4B). The removal by spade of the B2 horizons in the II plots and their replacement by topsoil resulted in a complete loosening of the soil at the 12- to 24-inch depth (Figure 6B, C).

The porosity in the topsoil buried at 12 to 24 inches in the II plots was 50 to 52 per cent, which was higher than found at this depth in the subsoil of the other plots. The organic matter in the all-topsoil profiles probably helped maintain the high porosity in the II plots to the end of the growing season. In agreement with this, we found that the subsoil layers placed at the usual topsoil depth in the OS plots had become more dense by the end of the season than the topsoil at the same depths in the other S plots: about 1.36 at 7 to 9 inches in the OS plots compared to about 1.28 in the others. In all S plots these layers had been completely shattered when they were removed or exchanged from plot to plot, but the soil most lacking in organic matter was the one that had become most compact by the end of the season.

Fertility of the soil, either in the form of native nutrients and humus or added fertilizer, had little effect upon the root distribution. The relative root weights of Table 2 show no remarkable changes in the lower portions of the root systems due to fertility. For example, the deep placement of the humus and fertility inherent in topsoil in plot IIS was not

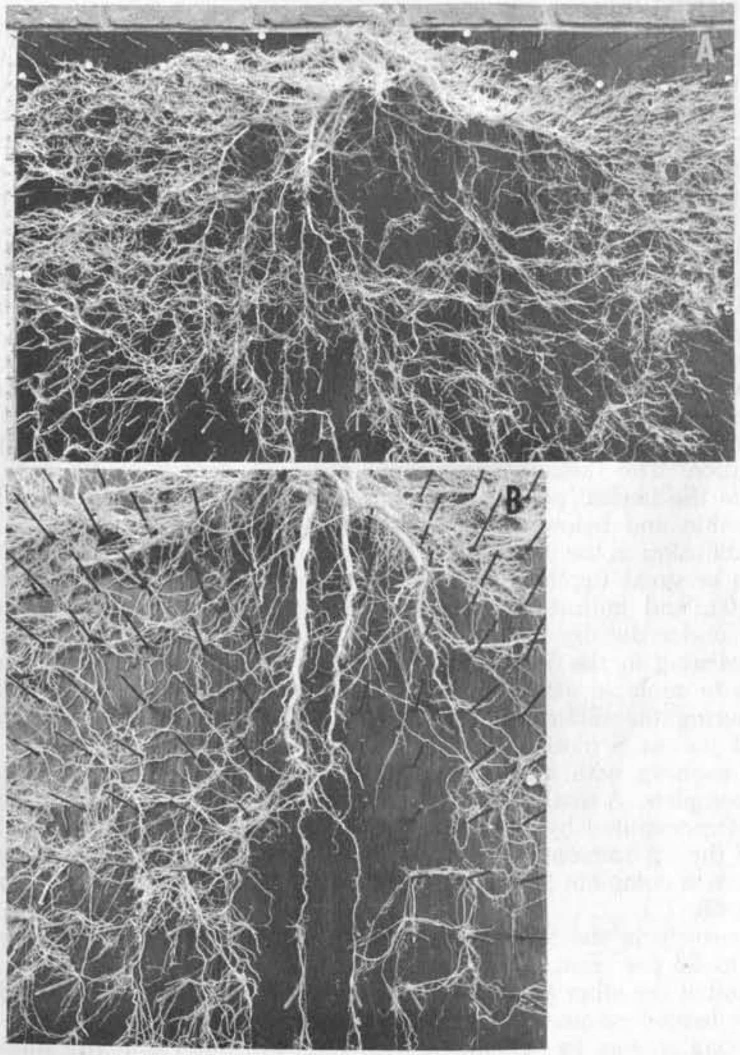


Figure 4. A. Root system from plot IS: normal profile, deeply loosened. B. Uneven root distribution caused by incomplete shattering of the plow pan; note the two "screwed" primary roots striking on this undisturbed lump of soil.

more effective in shifting the roots to lower depths than deep shattering alone in the subsoil of plot IS. The relative root weights of 11.1-3.6-2.0 in the all-topsoil profile IIS were surprisingly close to those of 9.7-5.0-2.0 in the topsoil and subsoil profile IS. Only in the low native fertility of the all-subsoil O plots, a tendency was noticeable toward slightly lower relative root weights; we observed 1.7 and 1.8 in the 18- to 24-inch zone.

Deep placement of fertilizer also failed to affect markedly the root distribution or penetration. As demonstrated by Figure 5, even in the

relatively infertile all-subsoil profiles, OSF, the two highly fertilized layers at depths of 0 to 4 and 12 to 16 inches did not produce notably greater root development or more profuse branching; nor did they retard deeper rooting. In most soil profiles the soil tests showed considerable residues of the deep fertilization: medium to high levels for nitrates, phosphoric acid, and potash.

This lack of response is surprising because it is well known that plants grown in soils with alternate layers enriched with nutrients have roots that branch much more profusely in these layers and also produce less roots below such layers (23, 58). Our tobacco plants, of course, were

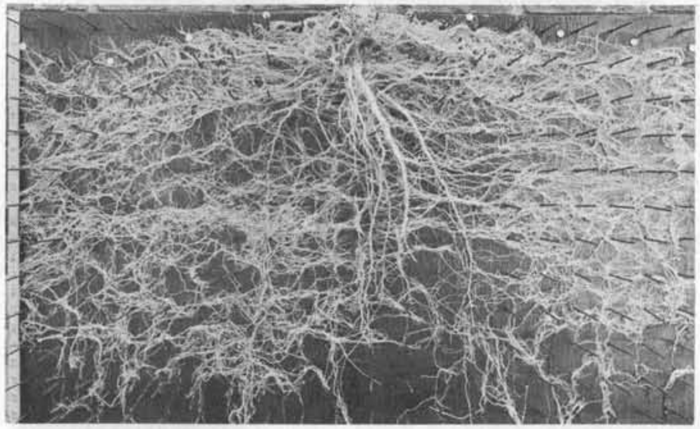


Figure 5. Root system from plot OSF: all-subsoil profile, deeply loosened and fertilized, consisting of a duplication of the surface fertilization at a depth of 12 to 16 inches.

full-grown and mature when sampled for these root pictures and weights. Thus, it was possible that 1) the root systems, when younger, were more clearly influenced by the fertility pattern in the small plots, and that 2) these well fertilized plants, as they grew older, filled the loose and unfertilized soil layers with roots. We had an opportunity to investigate this possibility on an additional set of plots ISF, which were planned at the outset of the experiment for the purpose of root examinations and samplings at intermediate stages of growth of the plants. These studies of the younger root systems, however, also did not show any higher concentration of roots in the layers with the high levels of nutrients (Figure 7).

Another explanation for the lack of root response to the placement of fertilizer could have been the occurence of excessive rains during the experiment, which would have washed the fertilizer salts from the enriched layers down into the unfertilized soil layers. This factor, however, was negligible: the rainfall during the greater part of the growing season was far below normal and the first leaching rain occured only 8 days before the plants were harvested.

Although fertility, either in the form of topsoil or fertilizer, had no discernable influence upon the root distribution or relative root weights

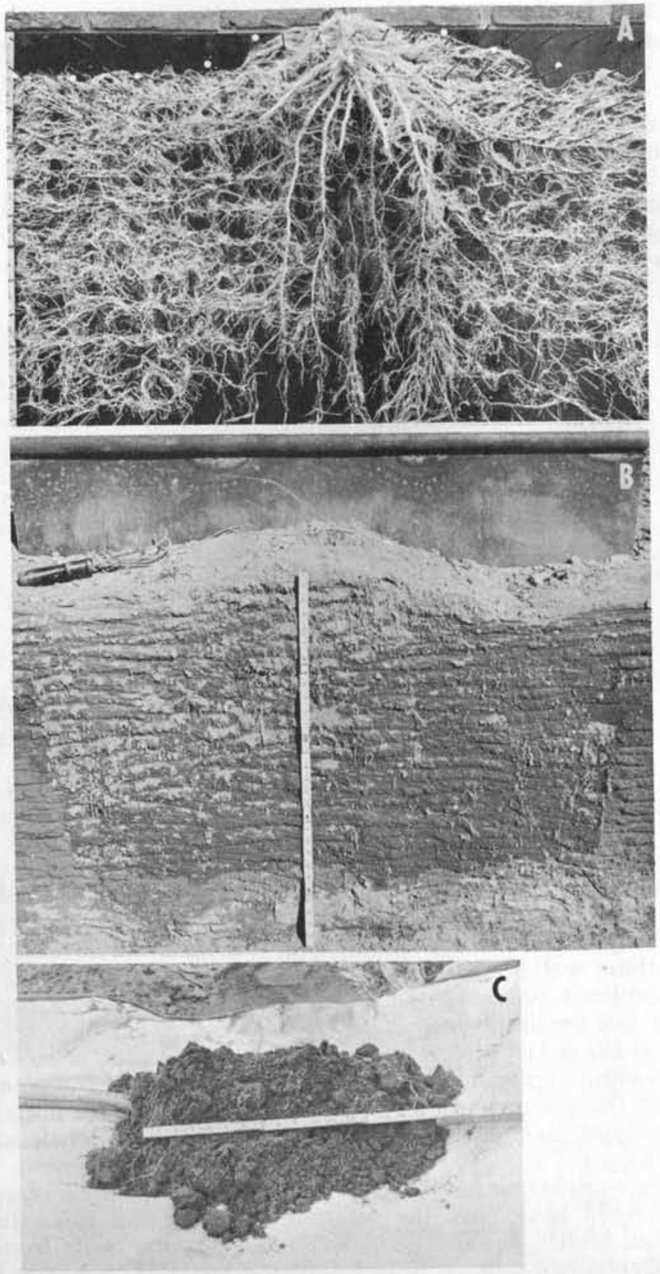


Figure 6. A. Root system from plot IISF: all-topsoil profile, loose and deeply fertilized, consisting of a duplication of the surface fertilization at a depth of 12 to 16 inches. B. Trench dug across plot IISF showing all-topsoil profile, from which root monolith was taken. C. Spade test shows that soil has good tilth and breaks up easily into rounded, porous crumbs.

in the deeply loosened S plots, it remarkably increased the root yields or absolute root weights in the 6- to 24-inch profile zones. The change in total root growth below 6 inches, expressed in oven-dry weight, was pronounced, Table 2: the higher the fertility level, produced by topsoil or by fertilization, the larger the amount of roots in the 6- to 24-inch zone (Figure 6A).

Clearly, the lowest root yield below 6 inches was found in the unloosened check plot I. First of all, the plowpan inhibited the development of deeper roots, and furthermore the soil within the zone of 6 inches to plowpan depth, the Ap2 horizon, was less loose in the I plots than in the comparable zone in the S plots.

In conclusion then, the root studies in the hand-tilled plots showed that deep rooting of tobacco was primarily effected by deep loosening, that is by breaking the resistance to root penetration by a compaction pan at the plow depth. Shallow roots were not an inherent characteristic of tobacco. The weight of roots in the soil monolith below the 6-inch depth of cultivation was, of course, markedly increased by the fertility status of the soil profile. But neither the penetration nor distribution of the roots was greatly influenced by fertility, either in the form of topsoil or of added fertilizers.

Now, let us see what effect, if any, the expanded and increased root growth in the different soil layers of the small plots had on the yield, commercial quality, and composition of the leaves.

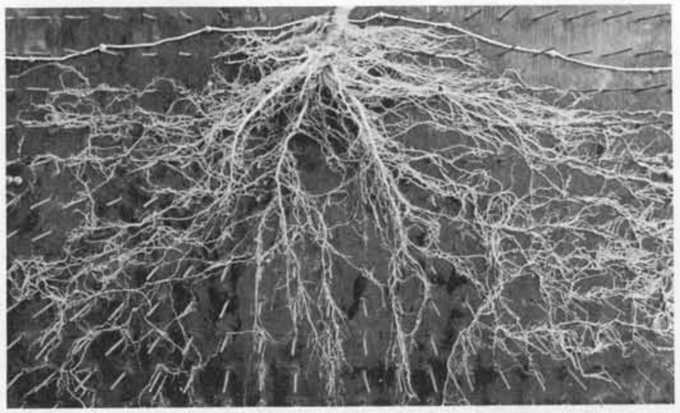


Figure 7. Young root system (7 weeks after transplanting) taken from plot ISF: normal profile, deeply loosened plus deep fertilization.

ROOT DEVELOPMENT AND THE YIELD AND COMPOSITION OF LEAVES

Effect of Deeper Root Distribution on Leaf Yield and Quality

The mean yields of air-cured leaves of the tobacco plants grown on the hand-tilled plots are summarized in Table 4. They tend to increase

Table 4. The root weights and the yields, quality, and composition of air-cured leaves of plants grown in the hand-tilled plots

Soil profile and treatment	Root weight 6-24 inches depth		Leaf yield[1]		Quality[2]	Leaf composition		
	Oven dry	Percentage	Weight	Percentage		NO3-N	Nicotine	Iron
	g.	Per cent	g.	Per cent		Per cent	Per cent	Per cent
I (control)	3.07	100	276	100	.502	.68	1.39	.088
IS	5.42	177	297	108	.492	.52	1.56	.086
ISF	7.60	248	343	124	.578	1.03	1.32	.081
IIS	7.83	255	312	113	.562	.83	1.73	.084
IISF	9.44	308	344	125	.542	1.22	1.63	.080
OS	5.08	165	309	112	.508	.76	1.24	.116
OSF	6.79	221	336	122	.530	1.12	1.38	.112
L.S.D. (.05)			40		.057	.15	.26	.014

[1] Leaves stripped from the three center plants of each plot.
[2] The larger the figure (grade index), the better the quality.

with deep shattering –S– and with fertility, either produced by an additional topsoil layer –II– or by deep fertilization –F–. These effects of the treatments and soil profile modifications on leaf yields were essentially similar to those on the absolute root weights in the 6- to 24-inch zone of the soil monoliths, as discussed in our last chapter.

Indeed comparing the leaf yields to the root yields, Table 4, we see a proportionality between them, although the effects of deep shattering and fertility on leaf yields are less pronounced than those on root weights. This relationship was further analyzed and we found a highly significant, linear association, $r=0.87^{**}$, between root and leaf yields (Figure 8). Although it is realized that the root weight data represent only the response of one plant to each of the treatments and soil profile modifications, our many root observations in these plots and the degree of correlation suggest a true interrelationship: the higher the root weights in the 6- to 24-inch profile zone in the plots, the higher the leaf yields.

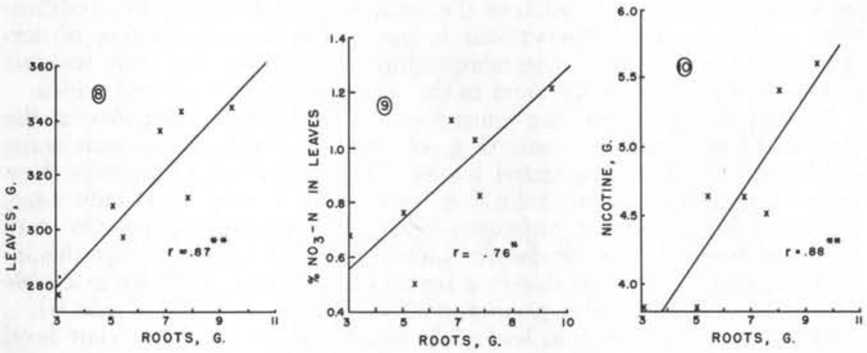
The tobacco plants on the control plots I, with root impedance at the 10-inch plow depth and only 3 g. of roots in the 6- to 24-inch zone, produced only 276 g. of cured leaves. The plots IS and OS, with their deeply loosened soil and fully 5 g. of roots in the 6- to 24-inch zone, produced 297 and 309 g. of leaves. Since the all-subsoil profiles OS were more productive than the control plots, one must conclude that the increased productivity was due to a better utilization of moisture available in the subsoil during this predominantly dry season, 1954 (Table 6).

However, an increase in leaf yield significant at the 5 per cent level was obtained only in the plots that received treatment F: a duplication of the surface fertilization placed at a depth of 12 to 16 inches. Whether the amount or placement of this fertilization was the critical matter cannot be stated because the experiment was not designed to test this question. Rather the treatment F was designed to reveal any qualitative change in root distribution following the placement of a large quantity of fertilizer at the bottom of the topsoil layer or Ap horizon: as we have already seen, it did not. It did, however, increase root growth at all depths and this was reflected in a significant increase in leaf production.

Growing the tobacco in pure subsoil or in a double layer of topsoil made no significant difference in leaf yields. The profile modification O was applied to test whether a full exposure of the subsoil to the roots would be detrimental; deep tillage not only would cause the roots to penetrate the subsoil, but it might bring subsoil to the surface. Clearly, if the plant was not harmed by growing in the pure subsoil of profile O, it would not be harmed by growing in the subsoil of a normal profile which had been shattered by deep tillage. The profile modification II was applied to test whether great advantage would follow the creation of an "ideal" profile wholly composed of humus-laden topsoil. We noted that treatment II did increase the root weight greatly although it did not change their distribution. In Table 4 we see no significant differences among OS, IS, and IIS, on the one hand, or among OSF, ISF, and IISF, on the other. This indicates that the amount of subsoil or topsoil had little effect. Thus the effects of more or less fertility in the form of more or less topsoil were much smaller than the effect of extra fertilizer, as applied by treatment F.

The commercial quality of the cured leaves was not affected in a consistent manner by the treatments and soil profile modifications. The grading results are also shown in Table 4. This failure to detect any response in leaf quality may be due to the fact that small quantities of tobacco, such as the leaf samples of this experiment, are hard to sort into commercial grades. In normal sorting operations it is found as a rule that the quality of the leaves is proportional to the yields: the higher the yields, the better the quality. The data in Table 4 show this trend to some degree.

Next we turned to the chemical composition of the leaves, which is an index of nutrition and has an important bearing on the quality and market value of tobacco.



Figures 8, 9, & 10. The relation between the characteristics of the air-cured leaves of three tobacco plants and the dry weight of roots below 6 inches, middle plant. Figure 8. Yield of leaves and root weight. Figure 9. Nitrate nitrogen concentration in leaves and root weight. Figure 10. Nicotine yield in leaves and root weight.

Effect of Deeper Root Distribution Upon Nitrogen and Nicotine in the Leaves

The leaves were analyzed to determine the quantities of nitrogen absorbed by the plants grown on the different plots. Nitrogen is of great influence on several elements of quality in the cured leaf (20).

Of the various forms of nitrogen found in cured leaves, the protein fraction and ammonia concentrations were not affected by the treatments and soil profile modifications; the total nitrogen concentration of the leaves also failed to show any significant response. Ammonia and protein in tobacco, however, are known to be influenced markedly in curing and fermentation, and a close relationship was not expected between the concentrations in the cured leaves and the soil environment in which the plant grew.

Nitrate nitrogen (6) was most clearly affected (Table 4). The presence of nitrate nitrogen in the growing crop and the cured leaf depends primarily on the conditions of nutrition, and the nitrate analyses show this expected trend.

Deep shattering of the subsoil in the plots IS, however, decreased the nitrate nitrogen concentration of the leaves significantly. It also decreased the amount of nitrate nitrogen yielded in leaves. What caused this de-

pressive effect is not clear, as leaching of fertilizer salts was practically absent during the season. Possibly the microorganisms decomposing organic materials appropriated some of the available nitrogen. The great looseness of the topsoil in these hand-tilled plots might have favored a breakdown of its organic matter, in particular of any undecomposed organic materials released by the complete shattering of the compacted subsurface soil of the Ap3 horizon. This hypothesis also could explain why the nitrate nitrogen concentration of the leaves on the plots OS, deeply loosened but without any topsoil present, was so much higher than that on the plots IS. Thus, deep shattering alone might sometimes put a temporary extra demand on the nitrogen supply, making it desirable to compensate with additional nitrogen fertilizer.

The extra topsoil-fertility placed at a depth of 12 to 24 inches in the plots IIS increased the nitrate nitrogen concentration of the cured leaves to a level that was just statistically significant.

The big increases in nitrate nitrogen concentrations in the leaves, however, were shown by the plants grown on the F plots, which received the double amount of fertilization and luxuriously consumed part of the additional nitrogen available. Leaves grown on the plots IISF with maximum fertility clearly showed the highest nitrate nitrogen concentration; with an excess the tobacco plant is capable of storing considerable quantities of nitrate nitrogen. And since treatment F increased both nitrate nitrogen concentrations and leaf yield, extra fertilization —F— obviously increased the amount of nitrate nitrogen taken up by the plant.

Nitrogen promotes root growth (23), and although we did not observe a greater concentration or more profuse branching of roots in the highly fertilized layers of the S plots, the weight of the deeper roots, 6 to 24 inches deep, were higher with increasing fertilization and soil fertility. Thus as one could expect, the concentration of nitrogen in the leaves, indicative of the available nitrogen level of the soil in the various plots, was closely correlated (r=.76*) with the root yields in the 6- to 24-inch zone of these plots (Figure 9). And of course, since we found a highly significant, positive association between root and leaf yields, the amounts of nitrate nitrogen accumulated in the plants were surely closely correlated with the root weights.

Nicotine is a nitrogenous compound, which is the most characteristic chemical constituent of tobacco. Although it is most abundant in the leaves, it is predominantly synthesized in the roots (20).

Understandably, as soon as we found the remarkable effect of deep shattering and fertility on the root development, we were anxious to know what effect, if any, this greatly increased root growth would have on the nicotine content of the leaves. Thus the nicotine analyses, shown in Table 4, were made (12). The nicotine contents of the leaves were the highest on the plots IIS and IISF, although only the increase on the plots IIS was significant. The root weights in the 6- to 24-inch profile zones of these plots were also the highest: 2.5 to 3 times as high as the amount of roots in the comparable zone of the control plot I. And yet, a further statistical analysis showed that although there was a correlation of the nicotine concentrations of the leaves with those root weights, the coefficient (r=.49) was not significant. A second look at this relationship of roots and nicotine, however, brought out a highly significant correlation ($r=.88^{**}$) between root weights on the different plots and the amount or yield of nicotine, i.e. the nicotine concentration in the leaves times the leaf production.

Thus in conclusion, the effect of the treatments and soil profile modifications on the nicotine concentration of the leaves was not important and as a result apparently did not affect the commercial quality of the leaves. The production or yield of nicotine by the plants, however, was clearly affected by soil looseness and fertility, and highly significantly correlated with the root yields.

Effect of Deeper Root Distribution and Exposure to Subsoil Upon the Uptake of a Marker of the Subsoil, Iron

After observing the greatly expanded root growth into the subsoil layers in the deeply loosened plots, we wondered what effect this would have on the mineral nutrition of the plant and ultimately on the quality of the tobacco leaves. If the different soil horizons had different micronutrient concentrations, the micronutrient concentration of the leaves, grown on plants in the deep-shattered and modified soil profiles, would conceivably be changed by the altered root distribution.

Under certain conditions, deeply rooted plants exhaust the soil moisture to the depth of the roots. A possible effect of such deep rooting, of course, is absorbtion and utilization of subsoil nutrients. For example, late in the season, flue-cured tobacco grown in a deep sandy loam absorbed appreciable quantities of P32 from soil as deep as 14 to 18 inches, while the relative importance of the top 6 inches of soil continually dwindled (26).

Now, phosphorus and other macronutrients, although used in relatively large amounts by the plants, would not reveal the contribution of the subsoil to the nutrition of the plant; any supply of native macronutrients by the subsoil undoubtedly would have been obscured by the relatively high amounts of these elements supplied by the annual, heavy fertilization of the topsoil. The micronutrient contents of the soil, on the other hand, tend to be influenced by the parent materials from which the soils are formed. And so, the subsoil, being younger and less depleted by constant cropping than the topsoil, might supply higher concentration of some of these elements than the older, more weathered topsoil layer. Micronutrients, however, are only needed in small amounts and deficiencies of these nutrients have never been reported to occur in the tobacco soils of Connecticut. Therefore, the feasibility of correcting micronutrient deficiencies by subsoiling was not our immediate practical concern, although it is important to know if this might be feasible elsewhere. Our primary concern was the possibility that after shattering the subsoil and exposing it to the permeating roots, the supply of some of these elements would be excessive for normal crop growth. After all, the range of concentration of micronutrients in which plants will grow satisfactorily is narrow, and all are harmful when supplied in large quantities.

The conditions for the study of these phenomena were present in our experiment. First of all, a suitable indicator or marker was present, namely the micronutrient iron. In the upper subsoil or B22 horizon of

the Merrimac soil, the so-called free iron oxide concentration is about one-eighth to one-fifth higher than in the topsoil and is also higher than in the underlying horizons (49, 54). Secondly, chemical analyses of leaf samples in connection with clinical work at the Tobacco Laboratory showed that tobacco can accumulate iron concentrations in the leaves which are many times as high as normally found. When soils are high in free iron or become strongly acid (37), the available iron increases, the tobacco absorbs more than is essential for normal growth, and the iron content rises, lowering the quality of the cured leaves (32).

The growth of roots in pure subsoil profiles increased the concentration of this micronutrient in the leaves as shown in the spectrographic analyses, (Table 4). Shattering —S— alone, however, did not increase the iron in the leaves; it took the all-subsoil profiles of plots OS and OSF to work this change. These all-subsoil plots, however, did not increase the iron concentration in the leaves enough to deteriorate quality. Therefore, it is not surprising that a mere shattering of the subsoil failed to change quality (Table 4).

Apparently the amount of available iron in a single layer of subsoil, as in the plots IS and ISF, was not high enough to produce such an excess in the total iron supply as to induce the plant to absorb iron above its needs; after all, the free iron oxide content of the Merrimac subsoil is only about one-eighth to one-fifth greater than that of the topsoil. The acceptance of this hypothesis demands that the roots in the 0- to 12-inch layer be of overwhelming influence in nutrition, at least in the absorption of iron. The upper half (0 to 12 inches) of the root systems in the plots OS and OSF was exposed to subsoil, while in the plots IS and ISF only the lower half (12 to 24 inches) of the root system was exposed to subsoil. The relative root weights in both sets of plots were about the same in the different profile zones (Table 2). Unfortunately for this hypothesis, we know that the roots in the 12- to 16-inch zones were sufficiently active to benefit significantly from increased fertilization —F— in this zone. Further, the roots of flue-cured tobacco were shown to be effective in this deep zone (26).

Another hypothesis to explain why only the plants grown in the all-subsoil profiles OS and OSF increased their iron uptake significantly, would state: "Increasing the iron supply in the early development of the plant determines the iron concentration in the leaves." In other words, the iron-rich subsoil at the top of the all-subsoil plots is the controlling factor: the roots in the plots OS and OSF were exposed to iron-rich subsoil from the very moment of transplanting, while in the I plots the early root growth after transplanting took place in 12 inches of topsoil; in the II plots, of course, nearly the full root development occurred in the topsoil, which was 24 inches deep. This hypothesis implies that the concentration of iron, one of the most immobile elements in plants, should be relatively great in the lower leaves which grew early upon the all-subsoil plots. This was not the case: 1) on all plots the lower and older leaves had higher iron concentrations than the upper and younger leaves, 2) this decrease in iron content on the all-subsoil plots was the same as that on the rest of the plots, namely a little over a third. Thus, the hypothesis that the early uptake of iron is the determining factor in the iron metabolism of the plant is untenable.

Alternatively we could consider the known (36, 55) competitive effect of calcium and magnesium upon the absorption of iron by the plant. By removing the topsoil and replacing it with subsoil on the OS and OSF plots we not only increased the iron supply in these plots, but at the same time the supply of such elements as magnesium and calcium was reduced. The data for Merrimac soils, obtained from a forested profile (8) and two cultivated soils in Massachusetts (49), show that the topsoil layers contain about 2.5 times as much calcium plus magnesium as the B-horizon. Thus, the exchange of the topsoil for subsoil on the OS and OSF plots clearly changed the antagonistic situation in these profiles, in spite of the fact that the subsoil was amended for the tobacco according to soil tests. The amendment of the subsoil at the surface consisted of the application of landplaster, 300 pounds per acre, and superphosphate, 500 pounds per acre. However, the analyses of the leaves did not show any differences in concentrations of calcium and magnesium related to the treatments or soil profile modifications, and we cannot accept this hypothesis.

Finally we could consider the possible changes in the subsoil layers when they were placed at the surface and exposed to the air. However, this also will not explain the increased iron uptake by the plants on the all-subsoil profiles. As a matter of fact, it is easier to postulate that at least some of the active iron in the surfaced subsoil of the plots OS and OSF was rendered unavailable for the plants. First of all, the better aeration at the surface undoubtedly depressed the supply of iron available to the plants. Secondly, the soil tests at the end of the growing season pointed in the same direction: 1) they did not indicate a greater availability of iron in the surfaced subsoil of the O plots than in the normal surface soil of the other plots, 2) the only marked difference was that, despite extra superphosphate, the phosphoric acid level of the O plots was lower than in the I and II plots, the readings varying from very low to medium in the O plots as against medium high to high in the others. This suggests that the iron-rich subsoil converted phosphorus to an unavailable form, while making at least some of the active iron at the surface of the O plots unavailable for the plants.

In short then, the iron concentration in the leaves and the quality of the leaves was not affected by shattering the subsoil –S–: exposing the roots in the 12- to 24-inch zone of the plots IS (Figure 4A) and ISF to subsoil, with its somewhat higher concentration of so-called free iron oxide, did not increase the iron content of the leaves. Only exposing the roots to all-subsoil profiles—treatments and soil profile modifications OS and OSF—increased the iron concentration in the leaves significantly. The distribution of iron was not affected by the treatments or soil profiles, the lower leaves always containing about one-third more iron than the upper leaves.

Possible Achievements of a Deeper Root Distribution

The costs of shattering hardpans by subsoiling or deep plowing are high. Therefore it may be wise to recapitulate the achievements which were attained under the conditions of maximum soil looseness and high fertility in the small plots, tilled and managed by hand. The results should be indicative of the benefits that farmers could expect from deep tillage under the similar conditions of a moderately coarse-textured soil in a dry season.

Deep shattering –S– greatly expanded the effective rooting zone and considerably increased the root weights in the 6- to 24-inch zone. However, shattering alone produced a leaf yield on plot IS only an insignificant 8 per cent above the control I.

Adding deep fertilization –F– to deep shattering –S– not only increased root weights further, it also produced a leaf yield on plot ISF that was a significant 24 per cent above the check I. Therefore, in our field experiments we expect small benefit from deep tillage save where deep fertilization is added.

All subsoil –O– did not decrease root weight and leaf yields: plots OS and OSF produced a leaf yield about equal to the yields from the normal profiles IS and ISF or the all-topsoil profiles IIS and IISF. Therefore, when deep tillage brings subsoil to the surface and dilutes the topsoil with subsoil, we do not expect that it will affect leaf production.

None of the treatments or profile modifications had any large and consistent effect on the commercial quality of the tobacco.

Of the various forms of nitrogenous compounds found in the cured leaves, only the nitrate nitrogen concentrations were clearly affected by the treatments and soil profile modifications, generally reflecting the nutritional conditions in the different plots. Under all soil profile conditions, deep shattering plus additional fertilization –SF– caused significant increases in nitrate nitrogen concentrations in the leaves, while only in a normal profile did deep shattering alone –S– decrease nitrates below those from usual tillage I. Nicotine concentration of the leaves was insignificantly affected; the production or yield of nicotine in the leaves, however, was clearly affected by soil looseness and fertility and was significantly correlated with the root yields. Nicotine is synthesized predominently in the roots.

The observations made on the iron uptake indicated that an oversupply of micronutrients native to the subsoil will not affect the chemical composition or quality of the leaves, unless the soil profile is drastically changed. The iron concentrations of the leaves increased significantly only when the plants were grown in all-subsoil profiles OS and OSF, and even then the commercial quality of the cured leaves was not affected.

Thus, in our field scale experiments with deep tillage we expect no ill effects and small benefits except where deep placement of fertilizer is added.

DEEP TILLAGE WITH MACHINERY UNDER PRACTICAL CONDITIONS

Deep tillage is any tillage below the normal plow layer. Practically it can be accomplished in several ways with different degrees of inversion of soil horizons: 1) by subsoiling, which loosens the soil by lifting or displacement without inversion; 2) by chiseling, which stirs without appreciable inversion; 3) by deep plowing, which completely shatters the soil through an inversion and mixing (3).

Of old, deep tillage, in particular subsoiling, has appealed to farmers who would shatter pans to allow deeper root penetration and percolation of moisture. However, the practice of deep or subsoil tillage is still a controversial subject, with exact observations often showing few and impractical benefits.

The achievements attained in our hand-tilled plots of the previous chapter, however, encouraged us to such an extent that we wanted to apply these findings to field scale and machinery. Before reporting on this work, let us first review briefly what results are generally obtained with deep tillage.

The literature on deep tillage, its effects on crop performance, soil characteristics, and soil and water conservation is voluminous. Several reviews appeared between 1950 and 1956 (34, 35, 38, 43, 60). Much of this renewed interest in the loosening of subsoil was aroused by increasing soil compaction. With the mechanization of agriculture, and accompanying heavy traffic on the land during intensified tillage, cultivation, and spraying, the amelioration of compacted layers induced in once-loose soils is being studied more and more (2, 4, 43).

Most improved plant growth following deep tillage is reported on the medium to moderately coarse-textured soils, which compact most firmly under intensive row-crop farming (33, 43). A shattering of induced pans increased yields of cotton and sugar cane in years with below average or poorly distributed rainfall (44, 46). However, if profitable at all, best responses in root growth and yields of corn, cotton, and alfalfa were generally obtained from a combination of deep tillage and deep fertilization and not from deep tillage alone (23, 31, 40, 45). On soils with strongly acid subsoils, applying lime in addition to deep fertilization improved root penetration and crop growth (17, 45). Deep placement of fertilizer often resulted in higher yields than applying the same amount of fertilizer to the normal plow layer, although the differences were not always significant and depended upon the chemical composition of the soil profile and upon the rainfall distribution (45).

In the Connecticut Valley, most intensively cultivated soils are moderately coarse to medium textured soils and are classified as Brown Podzolic; most belong to the Merrimac, Agawam, Enfield, and Hartford soil series (48). The tobacco soils range from loamy sand to silt loam, are naturally weakly structured and readily compressed when they are intensively tilled and cultivated. The depth of root penetration of tobacco predominantly coincides with the depth of plowing and in most cases the bulk of the root system is restricted to the zone of secondary tillage (14). A characteristic tobacco root profile is shown in Figure 1.

The benefits of deep tillage are usually found to be transitory and may be limited to a single season (45). However, expectations are that benefits from deep tillage will accumulate over the years: roots each year contribute to the organic matter and improved structure in the subsoil (17, 31). As an example, work has begun on stablizing subsoil channels by placing crop residues in them (50). In the Connecticut Valley the many operations of its intensive agriculture will almost certainly quickly destroy any improved tilth.

Tobacco is known to be particularly susceptible to poor tilth. However, experimental results on deep tillage for tobacco are limited. The investigations in North Carolina (26) clearly suggested that it would be

desirable to search for methods of subsoil preparation and deep placement of fertilizer which would efficiently exploit the capacity of the tobacco root system to absorb nutrients from deep soil layers. This work apparently led to deep modification and fertilization of sandy textured soils with a large disk plow (18). In India, flue-cured Virginia tobacco responded profitably to deep plowing, 9 inches deep, particularly when supplemented with fertilizer "placed at such a depth in the main root zone, 6 to 9 inches deep, where there was adequate moisture and where the roots fed during the active period of plant growth" (7).

Exact observations on deep tillage of tobacco land in Connecticut are lacking and the only report (5) we are aware of, discusses the subsoiling with dynamite of so-called plowsole hardpans in moderately well to poorly drained soils, which resulted in improved drainage where suitable water-outlets were available.

Thus, several factors encouraged our work on deep tillage and fertilization: 1) the promising effects upon root and shoot growth observed in our hand-tilled plots, 2) the favorable results often obtained with other crops in comparable soils, and 3) the lack of information on the response of tobacco to such practices.

Materials and Methods

Soil. The field-scale experiment was located close to the small, hand-tilled experiment. The soil was the same, uniform Merrimac sandy loam with a plowsole pan at a depth of 8 to 9 inches. Of old, this field, like the rest of the farm, had been used for intensive tobacco growing. Under the intensive fertilization of continuous tobacco growing, the fertility of the plowlayer was high, and even the upper subsoil was relatively fertile as indicated by a medium level of available phosphorus according to the Morgan test. Both top and subsoil had a favorable pH for tobacco: 5.6 to 6.3.

Just before transplanting tobacco each spring, 3,600 pounds per acre of the standard 6-3-6 tobacco fertilizer was broadcast. It was supplemented with calcium hydroxide and sulfate as indicated by the Morgan test and our knowledge of the nutrient requirements of tobacco.

Pests. The field proved to be infested with soil-borne pests. The main trouble was a basal stem rot, believed to be caused by various fungi and bacteria; but brown root rot, caused by parasitic meadow nematodes, was also present. In an attempt to control these pests, the soil had to be tilled. In the spring of 1955 the soil was plowed and then fumigated with a nematocide by means of an applicator whose narrow cultivator-like teeth were spaced 12 inches apart and extended to a depth of 6 to 8 inches (1). The fumigation was repeated in the fall of 1955. Thus the entire field was plowed in both the spring and fall of 1955, regardless of the experimental treatment.

Cover crop. In the fall of 1955 the usual oat cover crop was replaced by a mixture of oats and rye. Therefore in the spring of 1956 all plots were again plowed to bury the overwintered rye cover.

Plot arrangement. Thirty-three plots extending 25 x 90 feet were arranged in three replicates of eleven. The rows were at intervals of 3 feet and each plot permitted six rows and a barrier of 5 feet.

Table 5. Tillage and fertilization procedures in the machine-tilled plots

Treatment		
Ps	spring(s)	: plow (P) 8 inches.
PCs	"	: plow 8 inches plus chisel (C) 7 inches below furrow bottom.
PCFs	"	: plow 8 inches plus chisel 7 inches plus deep placement of additional fertilizer (F) at about 11 and 15 inches.
PCf	fall	: plow 8 inches plus chisel 7 inches.
PCFf	"	: plow 8 inches plus chisel 7 inches plus deep placement of additional fertilizer at about 11 and 15 inches.
SfPs	"	: subsoil (S) 18 inches at 18 to 24 inch intervals; spring: plow.
SFfPs	"	: subsoil 18 inches at 18 to 24 inch intervals plus deep placement of additional fertilizer at about 14 and 18 inches; spring: plow.
PTs	spring	: subbase plow (T) 8 plus 4 inches.
PTBs	"	: broadcast (B) half surface fertilizer, then disk harrow, finally subbase plow 8 plus 4 inches.
PBs	"	: broadcast half surface fertilizer, then disk harrow, finally plow 8 inches.
Df	fall	: deep plow 15 to 16 inches.

Treatments. The customary primary tillage for tobacco in the Connecticut Valley is spring plowing to a depth of 8 inches. This is the control treatment Ps as shown in Table 5.

In treatment PC, the furrow bottom was chiseled with an experimental machine to a depth of about 15 inches below the surface of the field. This was accomplished with a heavy duty, chisel-point subsoiler carried by a straight, rigid shank behind the wheel in a position designed to preserve the loosened condition of the compaction pan. The machine has been described elsewhere (13) and is shown in Figure 11C. Treatment PC was accomplished in both spring and fall as indicated by the subscripts "s" and "f" in Table 5; this permitted a comparison of spring and fall treatment.

At intervals of 18 to 24 inches across the field subsoiling –S– was carried to a depth of 18 inches below the land surface by means of a chisel-point subsoiler carried by a straight, rigid shank (Figure 11A and B). As shown by the subscript "f" in Table 5, subsoiling was only done in the fall, a time when we hoped that soil dryness would cause maximum shattering of the pan. The following spring the soil was plowed in the customary way, making the completed treatment SfPs.

Subbase plowing PT, the deep tillage of the furrow bottom, loosened the soil to a depth of about 12 inches without carrying an appreciable amount of subsoil to the surface. The lower bases of the subbase or T.N.T. plow were set to chisel a 4-inch deep groove in the bottom of the furrows turned by the regular bases (Figure 11D). This treatment was accomplished only in the spring, PTs, because sandy soils drain readily and are seldom too wet in the spring for this deep tillage (13).

Deep plowing D to 16 inches provided a nearly complete destruction of the compaction pan to that depth. It was accomplished in the fall only, Df.

The deep placement of fertilizer, treatment F, was begun in the spring

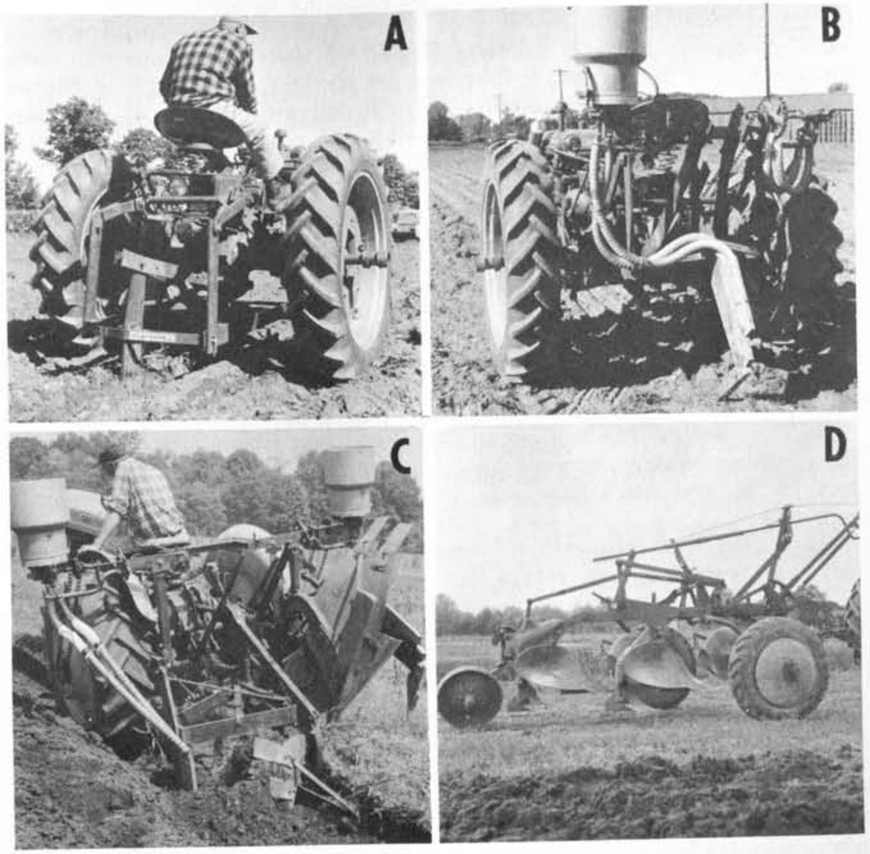


Figure 11. Deep tillage equipment used in large-scale experiment: A. Subsoiler, shattering –S– the plow pan to a depth of about 18 inches. B. Subsoiler with attachment and fertilizer hopper for the deep placement of fertilizers –F–. C. Experimental machine for plowing plus chiseling from the furrow bottom –PC–, with and without deep placement of fertilizer. D. Subbase or T.N.T. plow –PT–, used with and without plowing down fertilizer –B–.

of 1955. At first we applied a mixture of potassium nitrate and triple superphosphate that added 18 pounds of nitrogen, 188 pounds of phosphoric acid and 61 pounds of potash to each acre. In 1957 and treatment PCFs, we substituted a mixture of a standard 6-3-6 tobacco fertilizer and triple superphosphate that added 84 pounds per acre of each of the above nutrients. These fertilizers were placed at a depth of 11 to 15 inches by means of chutes attached to the back of the subsoiler shanks.

Plowing down one-half the broadcast surface fertilizer, treatment B, placed it deeper than is customary in the Valley. This fertilizer was plowed down by the regular moldboard plow, treatment PBs, as well as by the subbase plow, treatment PTBs, permitting a comparison of –B– in normally compact and deeply loosened soil.

Secondary tillage and transplanting. Each fall or spring after the deep tillage or plowing, the whole field was prepared in the usual way for tobacco. In the fall the soil was disked at least once, and oats were disked in once by a harrow that was set straight. In the spring the soil was smoothed by disking, fertilizer was broadcast and then incorporated by an overlapping or crossways disking. At planting time the surface had sometimes become compact, and it was loosened by a spring-tooth harrow just ahead of the transplanter.

In early June each year, Havana Seed tobacco seedlings, Variety K1, were set mechanically at intervals of 18 inches in rows that were 36 inches apart. Thereafter the fields were managed in the customary way (1).

Weather. The rainfall and average temperature during the experimental period is summarized in Table 6. Moisture was often scanty and the plots were irrigated as is customary in the tobacco husbandry of the Valley.

In May of 1955 the soil became dry and was difficult to till. Because July and early August were hot and dry, the plots were irrigated on July 16, 24, and August 2. Then, just 5 days before harvest, a torrential rain fell.

July, 1956, was extraordinarily cool. Rain was deficient in August, and the plots were irrigated 7 to 9 days before harvest.

The 1957 season was extraordinarily dry, with rainfall deficient in every month. The month of June was hot. Therefore, the plots were irrigated during transplanting and on July 8, 19, and 26.

Measurements. After the customary harvest and curing of the tobacco (1), the yield and the commercial quality of the cured leaf were determined. Because the growth of the shoot is less directly related to the treatments than is the behavior of the roots, root monoliths of the harvested plants were taken with the pinboard (14) for a more direct evaluation of the tillage and fertilizer placement. These monoliths were always located across the rows, i.e. perpendicular to the direction in which the treatments were applied. Undisturbed core samples were taken from the same profile pits.

Table 6. Deviations from normal rainfall and temperature during the tobacco tillage and growing seasons.

	April	May	June	July	Aug.	Sept.	Oct.	Seasonal Total	
1954	−0.09	+1.72	−1.54	−1.48	+ 2.32	+2.41	−1.71	+ 1.63	inches
	+2.3	−1.7	+1.0	−1.1	− 3.0	−2.4	+3.7	− 1.2	degrees F.
1955	+1.06	−1.45	−0.23	−2.19	+14.41	+0.70	+8.77	+21.07	inches
	+2.0	+3.3	−1.5	+4.0	+ 3.2	−1.5	0.0	+ 9.5	degrees F.
1956	−0.70	−1.90	−0.08	0	− 3.06	+1.29	−1.61	− 6.06	inches
	−4.9	−4.2	+0.9	−3.1	− 1.1	−5.3	−2.3	−20.0	degrees F.
1957	+0.72	−1.50	−2.60	−0.80	− 2.45	−2.04	−0.60	− 9.27	inches
	+2.3	+0.2	+4.0	−1.0	− 3.2	+0.1	−2.3	+ 0.1	degrees F.
1905-58[1]	3.70	3.56	3.47	3.67	4.01	3.43	3.00		
	47.8	58.7	67.6	73.0	70.7	63.6	53.5		

[1] Mean rainfall and temperature, Hartford, Conn.

Effect of Deep Tillage and Deep Fertilization on Yield and Quality

The results are given in Table 7. Despite fumigation, patches of uneven growth were evident in the field. This caused variability in the results, especially in 1957 when a 15 per cent increase in yield was required to demonstrate significance at the 5 per cent level. Nevertheless, several inferences can be drawn from the yields and quality indices in Table 7.

Over the three years, yields were consistently increased by springtime deep chiseling from the furrow bottom with deep placement of fertilizer, PCFs, and springtime subbase plowing and deeper incorporation of one-half the broadcast fertilizer, PTBs. In 1955 the growth of the crop was poor, but PCFs caused a significant increase in yield and PTBs caused a smaller increase. In 1956 these same two treatments produced the largest yields, and that year both increases were significant. In 1957 variability was great, as already mentioned, due to the necessity of replacing some transplants and to the patchy distribution of rot disorders. Further, frequent irrigation likely minimized the benefits of deeper rooting. Nevertheless, treatments PCFs and PTBs were again the most productive.

The other subbase plowing in the spring, PTs, lacked the deeper incorporation of one-half the broadcast fertilizer. But it, too, performed well, producing a significant increase in yield in 1956 and small increases in the other years.

Finally, fall subsoiling with deep placement of fertilizer followed by spring plowing, SFfPs, produced a significant increase in 1956; it was the only falltime deep tillage to produce such an increase in any one year.

The quality of the tobacco, as revealed by the grade indices in Table 7, was improved by the two treatments that had consistently increased yields; these are PCFs and PTBs. This follows the usual correlation between yield and quality. However, none of the improvements in quality was significant.

Thus, the *deep tillage in the spring*, PCFs, PTBs, and occasionally PTs, gave the most favorable effects during the 3-year trial. The two most successful deep tillage operations, PCFs and PTBs, were essentially the chiseling of the compaction pan from the bottom of each furrow in combination with normal plowing –P– and some form of deep fertilization –F– or –B–.

The experimental machine placed fertilizer –F– in a vertical band, which extended from slightly below the middle of the furrow bottom to a depth of about 15 inches (13). It consisted of additional fertilizer: in 1955 and 1956 a small amount was used which increased the yields significantly, while in 1957 a heavy application produced an insignificant yield increase.

No additional fertilizer was used in –B–, the plowing down of half the regular fertilizer. The exact distribution of this fertilizer over the tilled 12 inches is difficult to determine. Within the plow layer distribution depends on the degree of inversion of the furrow slice: the greater the inversion, the larger the portion of fertilizer which is distributed deeply; below the plow layer distribution depends upon the exchange

Table 7. Effect of various methods of deep tillage and deep fertilization on the yield and quality of Havana Seed tobacco on Merrimac sandy loam

Treatment	Yield per acre, pounds cured leaves 1955[1]	1956[2]	1957	Mean	Difference[3]	Quality grade index 1955	1956	1957	Mean
Ps	1639	1784	1929	1784	0	.42	.44	.41	.42
PCs	1655	1816	1879	1783	-1	.40	.44	.41	.42
PCFs	1811	2040	2082	1978	194	.44	.46	.44	.45
PCf	1691	1902	1945	1846	62	.41	.43	.43	.42
PCFf	......	1925	1744	......	.....	....	.44	.40	....
SfPs	1624	1835	2039	1853	69	.41	.44	.43	.43
SFfPs	......	1973	1932	......	.....	....	.44	.42	....
PTs	1773	1948	2062	1928	144	.43	.46	.43	.44
PTBs	1771	2111	2081	1988	204	.43	.46	.45	.45
PBs	1777	1893	1787	1819	35	.42	.45	.36	.44
Df	......	1927	1837	......	.....	....	.45	.40	....
L.S.D. (0.05)	144	148	282	......	.....	.05	.03	.09	....

[1] Whole field plowed in spring and fall for fumigation.
[2] Whole field plowed in spring to bury rye cover crop.
[3] Difference: increase over untreated.

of top and subsoil caused by the subbase plow. In 1956 this practice B combined with deep tillage resulted in the highest yield obtained from any treatment during the three years.

The success of plowing down fertilizer in combination with springtime chiseling from the furrow bottom, PTBs, suggests that the critical matter in the springtime deep fertilization with the experimental machine, PCFs, is the placement and not the simple addition of more fertilizer. Apparently, it was profitable to place some fertilizer in or near the deep-tilled zone below the normal plow layer, whether this was part of or in addition to the usual fertilizer. But here again, this experiment was not designed to answer detailed questions about the proper placement and supply of fertilization.

Without deep fertilization both PCs and PTs were less favorable. Spring plowing plus chiseling to a depth of 15 inches, PCs, was ineffective over the 3-year period, while subbase plowing to a depth of 12 inches, PTs, produced consistently small yield increases, just significant in 1956.

Without deep tillage plowing down half the surface fertilization, PBs, produced yield increases in only two years and these were insignificant. These results are in agreement with the small yield increases which were obtained in another experiment where one-half the fertilizer was placed on the plowsole and the other half was harrowed into the upper soil in the usual way (52). Clearly maximum benefit demands combined deep tillage and fertilization.

Now, let us look at *deep tillage in the fall.* This was less beneficial than springtime deep tillage (Table 7).

Without deep placement of additional fertilizer the responses of the tobacco to chiseling from the furrow bottom, PCf, and to subsoiling SfPs, were consistently insignificant over the 3-year period.

With deep fertilization, tested only in 1956 and 1957, subsoiling in the fall, SFfPs, produced a yield increase in 1956 that was just significant. Deep fertilization in combination with chiseling from the furrow bottom, PCFf, affected an insignificant yield increase in 1956. In 1957, PCFf decreased the yield because the soil was not plowed in the spring, the year and soil were dry, the plantbed was imperfect, and the stands were poor in one replicate. On the other hand, the plots tilled with SFfPs were plowed in the spring after fall subsoiling. In 1956, of course, all plots were plowed in the spring to bury the rye cover crop.

Falltime deep plowing Df, also tested for only two years, began well in 1956 with a yield increase that was almost significant; in 1957, however, the effect was disappointing.

The failure of deep plowing in 1957 is easy to understand. As mentioned above, the lack of spring plowing in 1957 caused poor stands and poor yields.

Now let us discuss why the benefit of deep plowing in 1956 was less than we hoped. The chief factor in our failure to secure a significant yield increase undoubtedly was insufficient fertilization or amendment of the turned-up subsoil in these plots. Tobacco is fast-growing and any depression of growth, even in the early stages, will be felt at harvest time. Our small plot experiment proved that when an all-subsoil profile is heavily fertilized, it could out-produce a normal soil with standard treatment. In our machine-tilled plots the deep-plowed soil did not receive any additional nutrients because the soil tests, as described above, had indicated a reasonable fertility and favorable pH in the subsoil. Evidently these few samples of subsoil taken before plowing were misleading.

Also, increasing the depth of plowing from 8 to 16 inches, in one step, might have lessened the benefit of deep plowing in 1956. In this way much light-colored subsoil was carried to the surface at once, increasing the transpiration of the young tobacco plants (57), and drought became more frequent. One might also expect that the turning up of subsoil, poor in organic matter, would decrease the moisture-holding capacity of the surface layer; this can be disregarded, however, because the capacity available to plants of this soil depends not upon organic matter but upon silt and capillary porosity (28) which are not poorer in the plow pan than in the usual plow layer.

These possible causes of disappointment in deep plowing could be cancelled by proper fertilization and by increasing the depth of plowing in several steps, e.g. 2 to 3 inches at a time. This method, then, could be further improved by plowing to an intermediate depth of 12 to 15 inches, the depth to which the two most profitable treatments, PTBs and PCFs, stirred the soil.

Finally, as already mentioned, it was evident that deep tillage in the fall was less effective than deep tillage in the spring (Table 7). For example, our most successful spring treatment PCFs was ineffective when applied in the fall, treatment PCFf. Several causes of ineffectiveness of the deep tillage in the fall can be listed: 1) leaching during the winter and early spring in this sandy loam (15) certainly wasted much of the deep fertilization applied in the fall; and maximum benefit demands combined deep tillage and fertilization; 2) recompaction of this weakly structured sandy loam under resettling and rain overwinter nullified some of the tilth or looseness established by the deep tillage in the fall (14); 3) lack of spring plowing may require intensified harrowing for plant bed preparation under adverse conditions, aggravating the formation of a disk pan, which may block root penetration (14, and following chapter).

Green manuring with winter cover crops will counteract these causes of ineffectiveness of deep tillage in the fall: 1) it conserves plant nutrients against winter leaching (15), 2) it improves and preserves tilth established in the fall by intercepting rainfall, by root growth in the shattered subsurface layers, and by the cushion effect of its plowed under top growth, that helps to minimize the recompaction under secondary tillage in the spring and following cultivation operations and traffic (14, and following chapter). Deep tillage in the spring, of course, also benefits from plowed-under winter-cover crops as far as they conserve nutrients, penetrate the compaction pan and subsoil with their roots, improve the tilth, and help prevent the development of compaction zones within the plow layer. These beneficial effects probably are found in the generally favorable results with deep tillage for the 1956 tobacco crop, the only year an overwintered rye cover crop was plowed under: three spring deep-tillage treatments (PCFs, PTs, and PTBs) and one falltime deep-tillage treatment (SFfPs) produced significant yield increases (Table 7).

In conclusion then, improved growth of tobacco through deep tillage evidently depends upon springtime operations of medium depth and the incorporation of fertilizer into the deep-tilled soil. Over the 3-year period the most effective treatments, PCFs, and PTBs, increased yields about 11 per cent above those obtained in the normally tilled control plots; the highest yield increase by any treatment during the years 1955-1957 was the 15 per cent by PTBs in 1956. These yield increases are modest compared with the 24 per cent yield increase that was obtained with deep loosening plus deep fertilization on the plots tilled and managed by hand. Of course, between these two experiments several factors may have contributed to this big difference in effect of deep shattering plus fertilization. The difference due to season must be small because 1954, the season of the small plots and large increase, was moderately dry, relatively cool, and not too different from the 1956 season. The difference due to fertilizer was not large because, although the deep fertilization was much higher in the small plots a great increase in deep fertilization had no effect in the machine-tilled plots. Thus, it appears we have to search for a factor which will more fully explain this great difference in results between the two tests. Now, if our working hypothesis stated in the general introduction is valid and there is a true relationship between growth above and below the ground, as was strongly indicated by the results of the hand-tilled plots, then we should not limit the comparison of the results of both experiments to the above-ground parts of the plants. A look below the surface of the soil, studying the direct response of plants to tillage, may offer a clearer explanation for the relatively poor benefits seen in the machine-tilled plots.

Root Development as Affected by Machine Tillage

The patterns of roots grown in soil that was subjected to the same treatment varied from plot to plot and year to year. A complete survey of all treatments was not made in a single year. Therefore, we cannot correlate yields with roots as before. Nevertheless, important qualitative differences can be seen, revealing the consequences of the tillage methods.

We shall see that these roots in this sandy loam are restricted by bulk densities of soil of 1.52 to 1.54, not by fertility. Also, deep tillage seldom results in uniform loosening and rooting, the soil recompacts easily, and two zones of root activity are produced: maximum growth within the zone of secondary tillage and deeper roots in the loosened regions of subsoil.

The looseness created by tillage in the hand-tilled plots determined whether roots would penetrate the soil. As we studied the root profiles from the various types of machine tillage, the same relation between soil density and root penetration was evident as the determinant of success and failure of the method. Nutritional fertility, either in the form of topsoil or added fertilizer, seemed of secondary importance. This was demonstrated by tabulating the 80 observations of bulk density and root growth that were taken in the tillage experiment.

The tabulation, Table 9, clearly shows that roots are rare at densities above 1.52. This is clearly demonstrated despite the differences between years and fertilizer practices and despite difficulties encountered in dry

1957 in the collection of undisturbed cores. Therefore, as we begin our examination of individual profiles, we can expect that the distribution of roots will depend upon whether the soil was loosened below 1.52 and whether this looseness was preserved throughout the season.

The usual root system found in a commercial field resembles that from the control plot, treatment Ps, Figure 12 and Table 8.

Table 8. The root distribution of mature plants in the machine-tilled plots

Photograph, Figure	Treatment	Approximate depth in inches beneath hilled tobacco row: 6-12 Ap2 – hor.		12-18 Ap3 + B2 – hor.		18-24 B2 – hor.	
		Grams	*Relative*	*Grams*	*Relative*	*Grams*	*Relative*
12	Ps[1]	1.24	21.1	.23[2]	.6	....	....
13A	PCs	5.62	9.8	2.73	4.7	1.24	2.2
15	PCFs	8.43	9.7	4.39	5.1	1.60	1.9
16	PCFf	6.13	12.9	1.58	3.3	.24	.5
17	PBs	3.60[3]	24.1	.13[2]	.6	....	....
18A	Df	4.27	9.2	2.19	4.7	1.31	2.8
18B	Df[4]	.80	15.0	.45	5.6	.08	1.0

[1] In Ps: Apl is 0 to 8 inches; root weight 6 to 8 inches, 2.00 g.
[2] All roots deeper than Ap2 horizon.
[3] In PBs: Ap2 is 6 to 10 inches; root weight 6 to 10 inches, 3.60 g.
[4] In Df, B: Apl is 0-8 inches; root weight 6 to 8 inches, 3.30 g.

Loosening by machine is rarely uniform and the roots are rarely distributed uniformly. Hence, we did not observe the same profuse and uniformly distributed rooting over the whole tilled depth that was attained with the maximum soil looseness in our small plot experiment (Figures 4A, 5 and 6A). The most uniform root penetration over the depth of normal plus deep tillage that was found in sampling the machine-tilled plots is shown in Figure 13. The soil had been deeply tilled without deep placement of fertilizer according to treatment PCs and consequently it did not increase leaf yield because no deep fertilization was applied.

The root system in Figure 13A is relatively uniform and dense within the plow layer, particularly in the Ap2 and Ap3 horizons. The bulk

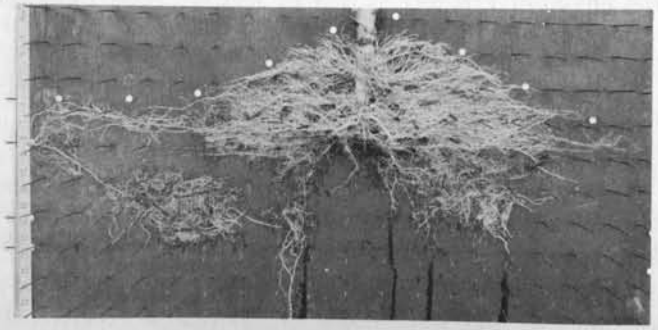


Figure 12. Root system of plant grown under normal conditions on plot Ps. Most roots are restricted to the plant hill by a disk pan; below this level roots followed and concentrated around buried trash or residues of preceding tobacco crops.

density of the soil ranged from a mean of 1.27 in the Apl horizon to 1.40 in the Ap2 horizon. However, in the chiseled subsoil or B2 horizon, the root distribution generally coincides laterally with the chisel paths. The areas most recently chiseled are visible in the soil profile, Figure 13B, and are marked by pairs of white dots at the bottom of the root system, Figure 13A. The bulk densities of the root-inhabited chisel channels averaged 1.37, while in the rootless dikes or beams between these loosened trenches the density averaged 1.54. Although somewhat non-uniform laterally, the vertical distribution of the roots as indicated by

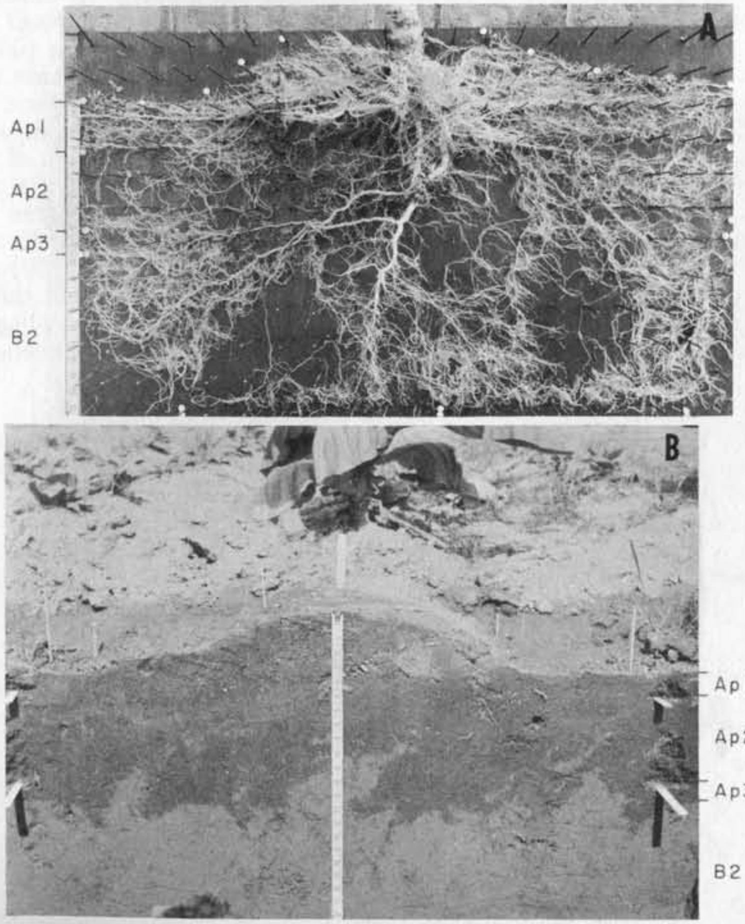


Figure 13. A. Root system that shows a relatively uniform distribution of roots over the whole depth of tillage. B. The profile from which above root monolith was taken; dug across a row of harvested tobacco on a plot, that for three years had been deeply tilled: spring plowing plus chiseling from the furrow bottom, PCs. The latest runs by the chisel are marked by light-colored subsoil mixed into the plow layer or Ap horizon.

the relative root weights, Table 8, compares favorably with those of the hand-tilled plots, Table 2.

The lateral distribution of the roots in the subsoil, of course, depended upon the tillage method. Completely shattering and mixing the plow pan with the normal plow layer by deep plowing produced a root environment which, at least in its lower part, was similar to that in the small plots where the pan was fully loosened. The uniform lateral distributions of roots with deep plowing and hand tillage are seen in Figures 4A and 18A. Chiseling and subsoiling, on the other hand, shattered the pan at intervals of 14 to 22 inches (Figure 14). After three seasons, one would expect that the whole soil mass would be cracked, resulting in an even lateral root distribution, but this was seldom the case. The reason for this uneven looseness could have been the following: each year deep tillage started from the same point or side of the plot; on these narrow plots this put the chisel paths in about the same place each time, preventing a complete shattering of the compaction pan. Another reason, as we shall see, could have been the easy recompaction of these sandy soils. At any rate, this uneven lateral distribution of roots in the subsoil is not our main concern. As a matter of fact, in a deep-tilled Merrimac sandy loam with its low retention capacity, some compactness of soil as is found in these dikes of subsoil between the loosened areas should increase its available moisture-holding capacity (30).

Recompaction was the chief obstacle to our accomplishment through tillage of an even vertical distribution of roots. Secondary tillage or "cultivation" and tractor traffic readily recompact the soil loosened or

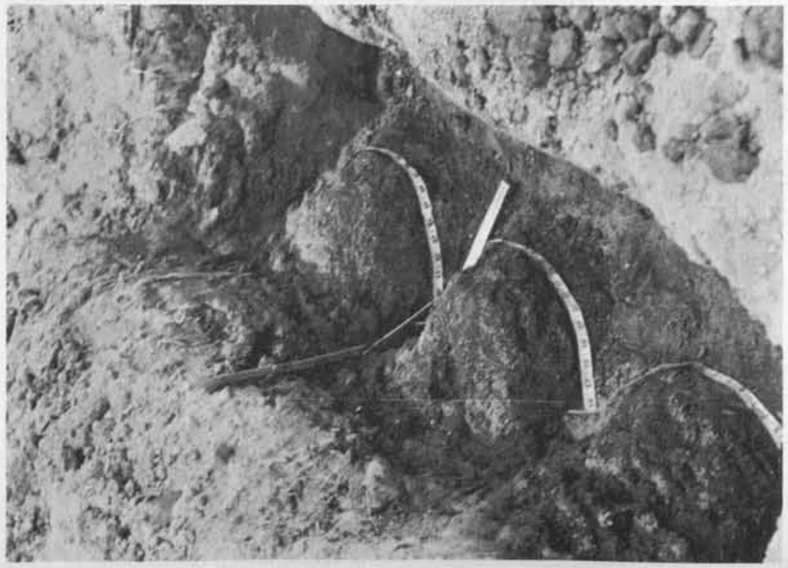


Figure 14. A trench dug across a plot subsoiled the previous fall, Sf, showing the beams or dikes of unloosened soil between the shattered areas or grooves of the plow pan and subsoil.

fluffed up by tillage. This important problem was emphasized in our preliminary report (4).

The study of the tobacco root systems grown in the present plots again demonstrated that disking was particularly effective in forming a compacted zone, the disk pan, within a plow layer. Root extension into this pan was hampered, and this restriction often prevented deeper root development. Another weaker zone of recompaction was sometimes found at plow depth; it was caused by the pressure exerted by the plow and traffic on the furrow bottom when the soil was plowed after deep tillage. A third region of renewed compaction was more local. It was formed by the inter-row traffic and cultivations and started with the transplanting operation. This compaction, of course, affected predominantly the horizontal root development in the plow layer.

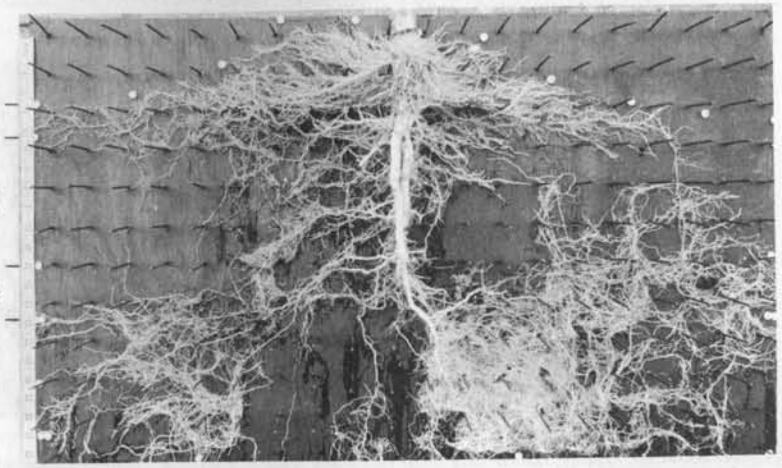


Figure 15. Root system taken from soil tilled by PCFs: spring plowing plus chiseling and deep fertilization from the furrow bottom.

Stratification of the root systems by recompaction could be generally observed, its intensity depending upon the tillage procedure and the moisture content of the soil during tillage. An average amount of recompaction within the plow layer is shown in Figure 15, treatment PCFs or spring plowing and chiseling from the furrow bottom plus deep fertilization. The rooting in the Ap1 horizon is mainly restricted to the plant hill, few roots growing into the compacted inter-row areas. In the Ap2 horizon, whole areas have few roots, particularly in the disk pan underlying the Ap1 horizon. In the deep-tilled Ap3 and B2 horizons are found the normal concentration of roots in and around the chiseled areas. Deep fertilization greatly increased the root growth in these areas, as a comparison of Figure 15 and Figure 13A illustrates and Table 8 indicates. This effect is in agreement with the conclusion of the small plot experiment: the higher the fertility of the subsoil, the higher the weight of the roots below 6 inches. Whether the deep fertilization had any effect on the lateral distribution of the roots in the subsoil is difficult to tell; the bulk density of the dike of soil between the two chisel paths was 1.55, which, as we have seen, usually blocks penetration of tobacco roots in this soil. This root system was taken from a plot deep-tilled according to our most effective spring-time treatment PCFs. Let us now see how recompaction affected a root system grown in a plot treated in the same way, but in the fall.

Figure 16 pictures a root profile taken from such a plot in 1957. The soil was chiseled with deep placement of fertilizer from the furrow bottom during fall plowing, and spring tillage was restricted to disk and springtooth harrowing. At the transition between the Ap1 and Ap2 horizons, this profile shows a very abrupt break which was caused by the disk pan. Even the very fibrous roots of the chickweed plants (*Stellaria media*) that are noticeable along the surface, did not break through the disk pan. In 1957, when special difficulties were experienced in establishing a plantbed, this disk and traffic pan was undoubtedly aggravated

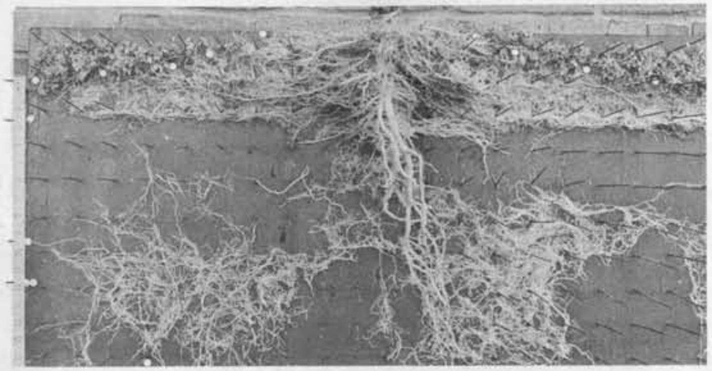


Figure 16. Root system taken from soil tilled by PCFf: falltime plowing plus chiseling and deep fertilization. Plot preparation in the spring was restricted to disk and springtooth harrowing. Very abrupt break at about 6 inches marks upper boundary of disk pan.

by the intensified harrowing. Of course, natural forces, such as rainfall and the weight of the soil itself, resettled the plow layer during the winter. In the lower part of the Ap2 horizon and beneath, looseness was better preserved and root distribution was similar to that shown in Figure 13A and 15.

An attempt was made to measure the density of the restricted disk pan. Core samples were taken at a depth of 8 inches beneath the plant hill, i.e. about 2 inches below the transition between the Ap1 and Ap2 horizons with its sharp break in root penetration. At that depth the bulk density varied from 1.42 to 1.44, which densities normally are not detrimental to tobacco root growth in the soil (Table 9). Apparently the soil layer most severely affected by disking was thin, not much more than 2 inches. Nevertheless, it was adequate to stop abundant root penetration.

Another disadvantage of fall treatment is the rapidity of leaching of deeply-placed fertilizer in this sandy soil. A comparison of the root

weights, Table 8, for treatments PCFs and PCFf shows that falltime treatment is less effective.

The evidence of easy recompaction indicates that its prevention is essential to the success of deep tillage. Obviously, eliminating unnecessary secondary tillage and traffic is crucial. Further we found that the burial of a winter cover crop was useful in preserving the tilth of the usual plow layer. In the spring of 1956 a rye cover was plowed under. Figure 17 shows a uniformly profuse rooting to plow depth, PBs. The rye cover plowed under apparently cushioned the compacting action

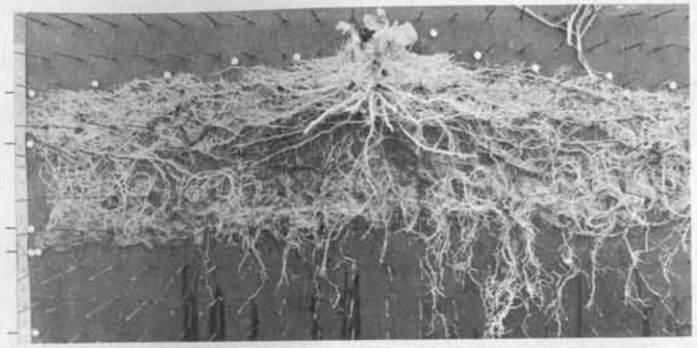


Figure 17. Root system taken from soil where a rye cover crop plus half the surface fertilization was plowed under: PBs, in 1956.

of the following operations and prevented the formation of a disk pan and the compaction in the inter-row areas within the usual plow layer. In and just above the Ap3 horizon on the left side of the root profile, a mat of old rye roots is clearly visible. This uniform rooting following the burial of a cover crop can be compared to Figure 12 where no cover crop was buried. The beneficial effect of cover cropping on a plot plowed deeply in the fall before seeding the rye cover crop, Df, is shown in Figure 18A. The rye overwintered and permeated the loosened soil with a fibrous mass of roots, here and there still visible in the Apf horizon; spring plowing incorporated the topgrowth of the rye into the Aps layer. This root pattern of the tobacco can be compared to that shown in Figure 18B where no cover crop was grown and plowed under

Table 9. Observations of the density of root growth in relation to soil compaction

Bulk density	Density of roots		
	Many	Some	Few or none
< 1.40	30	2	...
1.41 - 1.44	3	4	3
1.45 - 1.48	2	6	3
1.49 - 1.52	4	7	1
1.53 - 1.56	1	3	5
1.57 - 1.60	....	..	4
> 1.61	....	..	11

in the spring; spring tillage was restricted to disk and spring-tooth harrowing.

Clearly the growth and residue of roots and shoots from the winter cover helped maintain tilth, resulting in a more uniformly profuse deep rooting of the tobacco. Apparently this beneficial effect extended itself to the shoots, because in 1956, several deep tillage treatments produced significant yield increases (Table 7).

Recompaction decreased the looseness created by deep tillage, but seldom nullified it completely. The root investigations on the deep-tilled plots always showed that at least a few roots were able to reach and spread out into the shattered, open-structured zones in the subsoil. In contrast to this, on control plots that were not deeply tilled, such an extension into the subsoil was not observed, Figure 12. The bulk density of the compaction pan at plow depth was uniformly about 1.60 and higher to a depth of about 17 inches. Only few roots, following worm burrows or channels of old roots, penetrated into the plow pan, as is also shown in Figures 1, 3A, and 17.

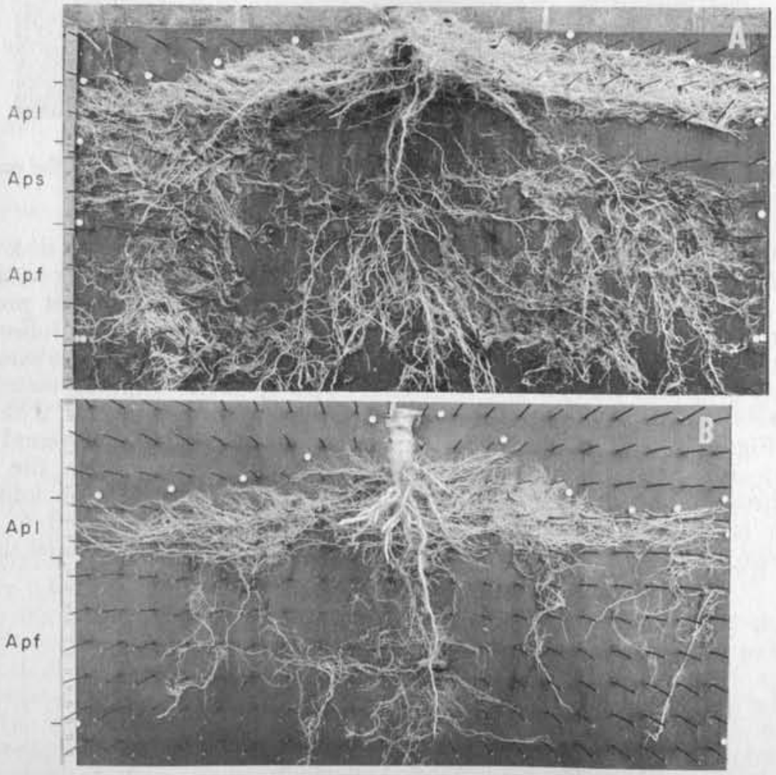


Figure 18. A. Root system grown in plot deep-plowed in the fall, about 16 inches deep, followed by normal plowing in the spring, 8 to 9 inches deep, to incorporate the rye cover crop: Df, in 1956. B. Root system taken from soil tilled by Df: deep plowing in the fall, 15 to 16 inches deep. No cover crop was grown and buried; plantbed preparation in the spring was restricted to disk and spring-tooth harrowing.

In conclusion, root behavior has clearly shown that bulk densities above 1.52 restrict root distribution, while nutrients affect root amount. Their behavior also showed that deep tillage seldom caused uniform loosening and rooting. Because the soil was easily recompacted, two zones of root concentration were produced: one within the zone of secondary tillage and one within subsoil regions loosened by subsoiling, chiseling, and deep plowing.

With this picture of root development we can understand the ineffectiveness of deep tillage combined with the standard practice of concentrating all fertilizer in the shallow surface or Ap1 horizon where the moisture is limited and variable. And we understand why the placement of some fertilizer in or near the deeper rooting zone, which has a more reliable water supply, consistently increased leaf yields. Finally, it is understandable why these increases were modest as compared to those in the hand-tilled plots, where the feeding area of the roots in deeply tilled soil was unrestricted by recompaction in the top soil.

TURNING UP CLEAN SOIL BY DEEP PLOWING

Deep plowing not only shatters the plow pan, it may also invert the soil layers. A deep furrow slice, well turned over, rotates the soil, bringing clean, uninfested soil to the surface, while the old plow layers, carrying trash, weed seeds, and any soil-borne pests, is buried beyond the reach of most roots. The soil is rotated, vertically. We tested this sanitation through deep plowing by attempting to control brown root rot, a major disease of Connecticut tobacco caused by nematodes (1).

The exposure of less fertile subsoil will not nullify any benefits of the inversion if the subsoil is adequately fertilized, as were the all-subsoil plots OS and OSF in the hand-tilled plots.

Brown root rot was present in the soil of the machine-tilled plots described in the preceding chapter. However, the infestation was too erratic and the degree of soil inversion was too incomplete to permit an adequate test of vertical rotation. Hence we turned to another, more thoroughly infested field of the Laboratory farm.

Materials, the Disease, and Methods

Soil. This field was predominantly Merrimac sandy loam and one block or replicate of plots was Sudbury sandy loam, the moderately well drained soil of the Merrimac catena. Again, the recent plow layer of about 8 inches was underlain by a definite plow pan, consisting of a subsurface or Ap3 horizon of 0 to 8 inches thickness and a subsoil or B2 horizon.

The disease. For many years this field had annually produced tobacco, and examination of the tobacco roots had disclosed intensive damage from the brown-root-rot nematodes (*Pratylenchus* sp.). Actual counts of parasitic nematodes in the soil showed that they were generally present in this field at a destructive level; it was the most thoroughly infested field on the farm, the best for our experiment.

Infested root systems consisted mostly of bushy tufts of short, brown, dead, fibrous roots at the base of the stalk occasionally with a few normal roots near the surface of the soil (1). Naturally, such a reduced root system cannot supply the necessary water and nutrients for the shoots, and the above-ground symptoms of the disease are early wilting, slow growth, stunting, and chlorosis caused by nutritional deficiency (Figure 19). As described in the previous experiment, good control of the disease can be obtained by soil fumigation.

Treatments. Whole plot treatments were normal plowings, Ps, 7 to 8 inches deep and deep plowing, Df or Ds, 14 to 16 inches deep with a moldboard plow provided with an extended wing. With a minimum of mixing, deep plowing replaced the normal plow layer of about 7 to 8 inches with a layer of inverted, fresh, and uninfested soil of about the same depth. The whole plots were eight rows or 24 feet wide and 67 feet long; they were replicated four times. For 1956, these plots were plowed and deep plowed in the fall of 1955; then spring preparation was restricted to disk and spring-tooth harrowing. In 1957 the plowing and deep plowing were carried out on the same plots in the spring, the usual time for plowing.

After tillage, half of each whole plot, i.e. four rows or 12 feet, was treated uniformly with a nematocide, providing a standard for comparison. In the fall of 1955, we fumigated with 15 gallons per acre of ethylene dibromide W-40; in the spring of 1957, with 4.5 gallons per acre of ethylene dibromide W-85.

Figure 19. Brown root rot or nematode infestation in normally plowed plot, Ps, nonfumigated. Above-ground symptoms are clearly noticeable: uneven, stunted growth and wilting.

During the fall of 1954 a cover crop of oats was grown; during the second fall and winter, a mixture of oats and rye. The overwintered rye cover was plowed under when the plots were tilled in the spring of 1957.

Fertilizer and lime were applied to whole plots according to Morgan soil tests, adjusting the fertility of the plots as uniformly favorable for tobacco as possible. Secondary tillage, planting, cultivation, and harvesting were done with conventional field implements. Once again, the test crop was Havana Seed tobacco, var. K1.

Effect of Soil Inversion and Fumigation on Yield

The effects of deep plowing and of fumigation as well as their interaction on yield were all highly significant. The results are summarized in Table 10.

Fumigation of the normally plowed soil increased yield in both years. This is evidence of the high nematode population in these plots, of the damage which was being caused by the nematodes, and also of the effectiveness of the fumigation. Fumigation of the deep-plowed plots increased yields little.

Deep plowing or burying the highly infested soil was also effective in increasing yields: in 1957 deep plowing increased yields as much as did fumigation of the normal plow layer; in 1956, 68 per cent as much. There was no additional increase in yield, compared with fumigated soil normally plowed, when deep-plowed soil was also fumigated. Evidently deep plowing and fumigation gave essentially equal control of nematodes.

Because deep plowing did not significantly increase the yield from fumigated soil, we conclude that deep loosening itself was ineffective. This agrees with our observations in the previous experiment where plowing to 16 inches also failed to increase yields significantly.

More importantly this experiment in vertical rotation did indicate that deep plowing can help control soil-borne pests by turning up fresh, uninfested soil. The second deep plowing in the spring of 1957 was just as effective as fumigation, indicating that this practice could provide a vertical rotation of the plow layer in addition to the deep loosening of the profile.

Table 10. Yield of Havana Seed tobacco in pounds per acre as affected by deep plowing and fumigation

Year	Normal plowing, Ps		Deep plowing, Df or Ds	
	Non-fumigated	Fumigated	Non-fumigated	Fumigated
1956	1670	1960	1870	1990
1957	1580	1770	1770	1850

CONCLUSIONS AND SUMMARY

This Bulletin deals primarily with the improvement of rooting depth. The coarse to medium textured soils of the Connecticut Valley are intensively used for the production of row crops. In these weakly-structured soils normal tillage induces hardpans just below the recent plow layer, and these plow pans inhibit root penetration. Our studies were made in the Merrimac sandy loams typical of the well-drained and well-aerated tobacco soils in the Valley. A survey of these soils had shown that most crops were shallow-rooted, especially tobacco, whose roots were generally so shallow that it seemed to be an inherent characteristic (Figure 1).

Small field-plots were used to learn which root habits were inherent and which were controlled by environment, thus gathering basic information on deep tillage. These plots were established and managed by hand (Figure 2), guaranteeing precise loosening and precise placement of fertilizer and topsoil and assuring maximum soil looseness throughout the season.

The principal conclusions were:

1. Tobacco can be deeply rooted: breaking the plow pan permitted deep profuse rooting (Figures 3 and 4). Deep rooting was evident in all deeply loosened soil, whether topsoil or subsoil. Neither the penetration nor the distribution of the roots was greatly influenced by fertility, either in the form of topsoil or of added fertilizers (Figures 5, 6, and 7). However, the weight of roots below the 6-inch depth of cultivation, as distinct from their distribution, was markedly increased by the fertility from a deep placement of additional fertilizer or from a doubling of the depth of topsoil (Figure 6 and Table 2).

2. Expanded and increased root growth produced heavier shoots: the higher the root weights in the 6- to 24-inch zone, the higher the leaf yields (Figure 8). Adding fertility in the form of topsoil was less effective than adding fertilizer, deeply placed (Table 4).

3. None of the treatments or profile modifications had any large and consistent effect on the commercial quality of the cured tobacco leaves (Table 4).

4. The nutritional fertility of the soil was reflected in the nitrate nitrogen concentration of the leaves, which was closely correlated with the amount of roots (Figure 9). In the leaves, the quantity of nicotine, which is synthesized predominantly in the roots, was clearly affected by soil looseness and fertility and significantly correlated with the root yields (Figure 10). The concentration of nicotine was unaffected.

5. A micronutrient native to the subsoil was not oversupplied nor was the chemical composition or quality of the leaves affected through deep tillage unless the soil profile was drastically changed. The iron concentrations of leaves increased significantly only when the plants were grown in pure subsoil profiles, and even then the commercial quality of the cured leaves was not affected.

Thus, for our field-scale experiments in mechanized deep tillage, we expected no ill effects and small benefits except where deep placement of fertilizer was added. We had found that shattering of the plow pan produced only an insignificant 8 per cent increase in yield above the yield from normally plowed soil; adding deep fertilization to deep shattering, however, produced a leaf yield that was 24 per cent above the control. Further, when deep tillage brought subsoil to the surface and diluted the topsoil with subsoil, it did not affect leaf production.

On the machine-tilled plots the following practices were explored for three years: 1) subsoiling with and without deep placement of additional fertilizer, 2) chiseling from the furrow bottom with and without deep placement of additional fertilizer or chiseling from the furrow bottom with half the surface fertilizer plowed down, 3) deep plowing (Table 5 and Figure 11).

The following conclusions and practical considerations are based on the more important findings:

1. Springtime deep tillage combined with deep fertilization increased the leaf yields consistently, although not always significantly. Most successful was spring plowing plus chiseling from the furrow bottom with deep placement of additional fertilizer. Also beneficial was subbase plowing and deeper incorporation of half the broadcasted surface fertilizer. Both treatments improved the quality of the tobacco, but not significantly (Table 7).

2. Falltime deep tillage was less beneficial, particularly when springtime plowing was omitted. Without spring plowing, dry soil made intensified harrowing necessary for the preparation of a proper plantbed. Besides, in most years, fertilizer placed in the fall will be leached by winter and early spring rains.

3. Effect of deep tillage and plowing is transitory because recompaction of this sandy loam soil is easy. Rain and resettling overwinter recompact the soil, but the most severe recompaction is due to secondary tillage, which forms a disk pan within the plow layer (Figures 3, 12, 15, 16). Green manuring with winter cover helped to minimize this recompaction and might improve the tilth of the soil (compare Figures 17 and 12; Figures 18A and 18B).

4. Roots are restricted by bulk densities of the soil above about 1.52 (Table 9), while fertilizer affects amount of roots (compare Figure 15 and 13A).

5. Deep tillage with machinery seldom produced the uniformly profuse rooting throughout the tilled soil which we had observed following deep tillage by hand (Figures 4A and 6A). Recompaction of the soil just below the depth of secondary tillage limited the feeding area within the topsoil and was probably responsible for the smallness of the yield increases from machine tillage, which, over the 3-year period, did not exceed 11 per cent.

6. Deep plowing to a great depth, for example 16 inches, turns up much subsoil and demands great additions of fertilizer, phosphate, and lime.

7. Deep plowing can turn up fresh, uninfested soil and this "vertical rotation" can control brown root rot as effectively as fumigation (Figure 19 and Table 10).

8. Because intermediately deep tillage, 12 to 15 inches, was beneficial, because recompaction destroys the established tilth, and because costs of deep tillage increase with depth, tillage to intermediate depths seems most sensible. Plowing at different depths each year can slow down the formation of a plow pan. Limiting all secondary tillage and cultivation to a minimum causes less soil compaction, requires less labor and costs less; it is a prerequisite for any successful attempt to deepen the effective rooting depth.

Through logic, one is easily convinced that a uniform root penetration with large concentrations of roots at lower depths will mean less irrigation and less loss of nutrients by leaching and hence optimum, uninterrupted growth. Our observations established the magnitude of the benefits, revealed the problems that accompany deep tillage and explain some of the failures.

BIBLIOGRAPHY

1. ANDERSON, P. J. Growing tobacco in Connecticut. Conn. Agr. Expt. Sta. Bul. 564. 1953.
2. AM. SOC. AGR. ENG. SOIL COMPACTION COMMITTEE. Annotated bibliography on soil compaction. St. Joseph, Mich. 31 p. 1958.
3. AM. SOC. AGR. ENG. Definitions of tillage operations and equipment. Trans. Am. Soc. Agr. Eng. 1(1):57. 1958.
4. AM. SOC. AGR. ENG. SOIL COMPACTION COMMITTEE. Soil compaction research. Trans. Am. Soc. Agr. Eng. 1(1):58-64. 1958.
5. BARTLETT, G. D. Subsoiling with dynamite. Effects on Connecticut tobacco lands. Farm. Eng. 4:4-5. 1916.
6. BEAR, F. E., and R. M. SALTER. Methods in soil analysis. West V. Agr. Expt. Sta. Bul. 159. 1916.
7. BHAT, N. R. New methods bring handsome profits in flue-cured Virginia tobacco. Indian Tobacco 8 (3):159-161. 1958.
8. BOURBEAU, G. A., and C. L. W. SWANSON. The morphology, mineralogy and genesis of two southern New England soils. Conn. Agr. Expt. Sta. Bul. 584. 1954.

9. BRIND, W. D. Some recent work on depth of plowing. Soils and Fertilizers 20(5):241-245. 1957.
10. BRUCE, R. R., and L. R. WEBBER. The use of a diffusion chamber as a measure of the rate of oxygen supplied by a soil. Can. J. Agr. Sci. 33:430-436. 1953.
11. BRUNER, W. E. Root development of cotton, peanuts, and tobacco in central Oklahoma. Proc. Oklahoma Acad. Sci. 12:20-37. 1932.
12. CUNDIFF, R. H., and R. C. MARKUNES. Determination of nicotine, nornicotine and total alkaloids in tobacco. Anal. Chem. 27:1650-1653. 1955.
13. DE ROO, H. C. Subsoiling, plowing, and deep placement of lime or fertilizer in one operation. Agron. J. 48:476-477. 1956.
14. DE ROO, H. C. Root growth in Connecticut tobacco soils. Conn. Agr. Expt. Sta. Bul. 608. 1957.
15. DE ROO, H. C. Fertilizing Connecticut tobacco. New methods for new needs. Conn. Agr. Expt. Sta. Bul. 613. 1958.
16. DE ROO, H. C., and P. E. WAGGONER. Root development of potatoes. Agron. J. 53(1):15-17. 1961.
17. ENGELBERT, L. E., and E. TRUOG. Crop response to deep tillage with lime and fertilizer. Proc. Soil Sci. Soc. Am. 20:50-54. 1956.
18. FITTS, J. W., and W. V. BARTHOLOMEW. Modifying the soil profile for deeper root penetration. Better Crops with Plant Food. Vol. 44(5):52-57. 1960.
19. FREE, G. R. Minimum tillage for soil and water conservation. Agr. Eng. 41(2):96-99, 103. 1960.
20. GARNER, W. W. The production of tobacco. The Blakiston Co. N. Y. 1951.
21. GIER, L. J. Root systems of Bright Belt tobacco. Am. J. Botany 27(9):780-787. 1940.
22. GILL, W. R. Soil compaction by traffic. Agr. Eng. 40(7):392-394, 400, 402. 1959.
23. GLIEMEROTH, G. Bearbeitung und Düngung des Unterbodens in iher Wirking auf Wurzelentwicklung, Stoffaufnahme und Pflanzenleistung. Z. Acker- u. Pflanzenbau 96:1-44. 1953.
24. GOEDEWAAGEN, M. A. J. *et al.* Root development in soils consisting of a top layer of clay and a sandy subsoil. (In Dutch). Verslag. Landbouwk. Onderzoek. No. 61. 7. 's-Gravenhage. 1955.
25. GOLD, T. S. Eleventh Annual Report Connecticut Board of Agriculture, 1877-8: 15-48, 133-160. Hartford, 1878.
26. HALL, N. *et al.* A tracer technique to measure growth and activity of plant root systems. N. Carolina Agr. Expt. Sta. Tech. Bul. 101. 1953.
27. HARPER, H. J. The accurate determination of nitrates in soils. Phenoldisulfonic acid method. Ind. Eng. Chem. 16(2):180. 1924.
28. HILL, D. E. The storage of moisture in Connecticut soils. Conn. Agr. Expt. Sta. Bul. 627. 1959.
29. HUGHES, M. B. The effect of subsoiling on the yield of several tomato varieties and its relation to soil fumigation. Proc. Am. Soc. Hort. Sci. 75:595-600. 1960.
30. JAMISON, V. C. Changes in air-water relationships due to structural improvement of soils. Soil Sci. 76:143-151. 1953.
31. KOHNKE, H., and A. R. BERTRAND. Fertilizing the subsoil for better water utilization. Proc. Soil Sci. Soc. Am. 20(4):581-586. 1956.
32. LE COMPTE, S. B., JR. Studies on black tobacco. Conn. Agr. Expt. Sta. Bul. 444:270-278. 1940; Bul. 469:130-155. 1942; Bul. 478:114-117. 1943.
33. LULL, H. W. Soil compaction on forest and range lands. U. S. Dept. Agr. Misc. Publ. 768. 1959.
34. LUTZ, J. F. Mechanical impedance and plant growth, p. 43-71. *In* B. T. Shaw, [ed.], Soil physical conditions and plant growth. Academic Press, N. Y. 1952.

35. MIDDLETON, H. F. Modifying the physical properties of soil, p. 24-41. *In* B. T. Shaw, [ed.], Soil physical conditions and plant growth. Academic Press, N. Y. 1952.

36. OLSEN, C. Iron absorption in different plant species as a function of the pH value of the solution. Compt. rend. trav. lab. Carlsberg 31(4). 1958.

37. OLSEN, R. V. Iron solubility in soils as affected by pH and free iron oxide content. Proc. Soil Sci. Soc. Am. 12:153-157. 1948.

38. PANEL. Does deep tillage pay? What's New in Crops and Soils. 9(1):9-12. 1956.

39. PANEL. Where do we stand on minimum tillage? Crops and Soils. 12(7):7-9, 18. 1960.

40. PATRICK, W. H., JR. *et al.* Response of cotton and corn to deep placement of fertilizer and deep tillage. Proc. Soil Sci. Soc. Am. 23(4):307-310. 1959.

41. PHILLIPS, R. E. Soil compaction and corn growth. Agron. Abstr., A.S.A. 1959

42. RANEY, W. A. Field measurement of oxygen diffusion through soil. Proc. Soil Sci. Soc. Am. 14:61-65. 1949.

43. RANEY, W. A. *et al.* Current status of research in soil compaction. Proc. Soil Sci. Soc. Am. 19:423-438. 1955.

44. RANEY, W. A. *et al.* Study of soil compaction on Mississippi River delta soils. 6 Congr. Intern. Soil Sci. Rapp. 7:520-524. 1956.

45. ROBERTSON, W. K. *et al.* Results from subsoiling and deep fertilization of corn for 2 years. Proc. Soil. Sci. Soc. Am. 21:340-346. 1957.

46. SAVESON, I. L., and Z. F. LUND. Deep tillage for crop production. Trans. Am. Soc. Agr. Eng. 1(1):40-42. 1958.

47. SHAH, V. H., and R. M. PATEL. Desirability or otherwise of interculturing in row crops. Indian J. Agr. Sci. 29(1):1-9. 1960.

48. SHEARIN, A. E. *et al.* Soil survey of Hartford County, in ms. Aerial photo mosaic maps, scale 1/20,000.

49. SOIL CONSERVATION SERVICE. Laboratory characterization report of soils collected in Massachusetts. U. S. Dept. Agr., Beltsville, Maryland. 1960.

50. SPAIN, J. M., and D. L. MCCUNE. Something new in subsoiling. Agron. J. 48:192-193. 1956.

51. SWANBACK, T. R., and P. J. ANDERSON. Fertilizing Connecticut tobacco. Conn. Agr. Expt. Sta. Bul. 503. 1947.

52. SWANBACK, T. R., and P. J. ANDERSON. Fertilizer placement for Connecticut tobacco. Conn. Agr. Expt. Sta. Bul. 561. 1952.

53. SWANSON, C. L. W. A portable soil core sampler and penetrometer. Agron. J. 42:447-451. 1950.

54. TAMURA, T. Physical, chemical, and mineralogical properties of brown podzolic soils in Southern New England: Paxton and Merrimac series. Soil Sci. 81:287-299. 1956.

55. TWYMAN, E. S. The effect of iron supply on the yield and composition of leaves of tomato plants. Plant and Soil 10(4):375-388. 1959.

56. VEIHMEYER, F. J., and A. H. HENDRICKSON. Soil density and root penetration. Soil Sci. 65:487-493. 1948.

57. WAGGONER, P. E. *et al.* Plastic mulching. Principles and benefits. Conn. Agr. Expt. Sta. Bul. 634. 1960.

58. WEAVER, J. E. Root development of field crops. McGraw-Hill Book Co., Inc. N. Y. 1926.

59. WIERSUM, L. K. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9(1):75-85. 1957.

60. WINTERS, E., and R. W. SIMONSON. The subsoil. Advances in Agron. Academic Press, N. Y. 3:1-92. 1951.