Bulletin 454 January, 1942

Distribution of Roots of Certain Tree Species in Two Connecticut Soils

GEORGE ILLICHEVSKY GARIN

Connecticut
Agricultural Experiment Station
New Haven

TABLE 1. TREE PLANTING, MORTALITY AND SURVIVAL ON MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM. (Common and scientific names of the tree species follow Sudworth, 1927.)

Tree species		Merrimac loamy sand					Charlton fine sandy loam				
Common name	Scientific name	Number planted April 1933	Number alive August 1934	Number dead August 1934	Number alive July 1940	Number dead July 1940	Number planted April 1933	Number alive August 1934	Number dead August 1934	Number alive July 1940	Number dead July 1940
Arborvitae[2]	*Thuja occidentalis* L.	24	17	7	12	12	21	21	3	14	10
Beech[1]	*Fagus grandifolia* Ehrh.	22	1	21	0	22	25	5	20	2	23
Black birch[1]	*Betula lenta* L.	248	10	238	0	248	223	35	188	0	223
Chestnut oak[1]	*Quercus montana* Willd.	46	14	32	9	37	43	15	28	11	32
Douglas fir[2]	*Pseudotsuga taxifolia* Britton	22	18	4	14	8	23	23	0	20	3
Hard maple[1]	*Acer saccharum* Marsh.	24	8	16	1	23	22	21	1	3	19
Hemlock[2]	*Tsuga canadensis* L.	28	5	23	1	27	42	27	15	14	28
Norway spruce[2]	*Picea excelsa* Link	248	68	180	54	194	253	221	32	207	46
Red oak[1]	*Quercus borealis maxima* Ashe	248	122	126	73	175	223	201	22	96	127
Red pine[2]	*Pinus resinosa* Soland.	24	22	2	21	3	22	20	2	19	3
River birch[1]	*Betula nigra* L.	103	30	73	28	75	209	206	3	159	50
Scotch pine[2]	*Pinus sylvestris* L.	22	22	0	20	2	23	22	1	22	1
Shagbark hickory[1]	*Hicoria ovata* Britton	23	1	22	0	23	22	10	12	3	19
Tuliptree[1]	*Liriodendron tulipifera* L.	24	8	16	3	21	24	20	4	11	13
White ash[1]	*Fraxinus americana* L.	26	23	3	22	4	23	23	0	21	2
White pine[2]	*Pinus strobus* L.	248	177	71	166	82	223	212	11	196	27
White spruce[2]	*Picea glauca* Voss	22	6	16	3	19	22	18	4	17	5
		1402	552	850	427	975	1446	1100	346	815	631

[1] Hardwood stock, 1—0 when planted.

[2] Coniferous stock, 2—1 when planted.

ACKNOWLEDGEMENT

Acknowledgment is made for coöperation, helpful advice, suggestions and criticism during the progress of this investigation to Harold J. Lutz and Walter H. Meyer, Associate Professors of Forestry, Yale University; to Herbert A. Lunt, Associate in Forest Soils, C. I. Bliss, Biometrician, M. F. Morgan, Agronomist in Charge, and H. G. M. Jacobson, Associate Agronomist, Connecticut Agricultural *Experiment Station; to Raymond Kienholz, Silviculturist,* Austin F. Hawes, State Forester, and S. E. Parker, *District* Forester, Connecticut State Park and Forest Commission.

TABLE OF CONTENTS

Distribution of Roots of Certain Tree Species in Two Connecticut Soils[1]

GEORGE ILLICHEVSKY GARIN

A KNOWLEDGE of that portion of a forest stand which is below the ground surface is of great interest to a forester. This knowledge helps to indicate the silvicultural treatment necessary for the best management of the stand. Forest production depends on the proper utilization of a site on which a given forest is growing. Increasing emphasis is now given to soil factors and conditions underground in site utilization. The relationship between soil types, soil horizons, individual soil properties and the roots of trees is receiving much attention in recent years. Because of the many types of soils, species of trees, composition of stands and age classes, only slow progress can be expected. In any event, certain limitations of the scope of the problem must be accepted at the outset of such a study.

The scope of the present investigation was limited to two contrasting soil types and five tree species. The plantations used were established seven years ago on two areas previously cultivated for many years. There was no interference from the remains of the roots of trees which existed there originally. The mixture of species in the evenly spaced plantations offered an opportunity to compare the root distribution of these species. In certain parts of the plantations, where survival was good and trees grew rapidly, the crowns of the trees were about ready to close. It is generally assumed that, with the closure of the stand, competition between trees becomes severe not only above but also below the ground surface. This may have a pronounced influence on the development of roots of trees. It was felt that the effect of soil on root distribution could be studied to better advantage before severe competition had begun. Therefore these two stands were found to be at a suitable stage of growth for the present study.

The objectives of this investigation were to ascertain (A) the differences in the various soil properties between the two soils and several soil horizons, (B) if any of the soil properties were significantly different for the zones of high root concentrations as compared to the zones of low root concentrations, (C) the differences in root distribution in the two soils and soil horizons, (D) the differences in root distribution of the five tree species when considered in relation to the two soils and soil horizons, (E) what effect the two soils would have on root competition.

---

[1] This is a revision of a dissertation presented to the Faculty of the Graduate School of Yale University in candidacy for the degree of Doctor of Philosophy in 1942.

REVIEW OF LITERATURE

There is an abundance of literature on the general subject of roots and the relation existing between roots and soil. The influence of various physical and chemical conditions of soil on root development can be cited at length, but publications dealing with the relation between root distribution and soil horizons are of more recent origin and are rather limited. Root competition between trees in a forest stand has been noted by various observers for a long time, but quantitative studies have been attempted only recently. No attempt will be made to present a complete review of the literature on all the subjects mentioned; only the few contributions having direct bearing on this investigation will be noted.

If the influence of the type of soil on root development is to be taken as a major subject of consideration we can mention several of the more recent writers. Aaltonen (2), in discussing space arrangement in various forest stands, stated that it depends on tree species and quality of site. On poorer types of soil the roots of trees were numerous and extended further both horizontally and vertically than in good soils. Trees required more space on a poor site than on a better one. The same soil space in a poor site represented a smaller amount of food and water than in a better one. It was concluded, therefore, that the growth of trees given equal amounts of space must be greater in the better soil than in the poorer.

Laitakari (19) studied the root system of Scotch pine, Norway spruce and birch. He found that the total length of roots varied according to the nature and fertility of the soil. The most widely spread roots occurred in sandy soil; on clayey soil roots also attained a considerable length, but on morainic and stony gravel soils they spread least of all. The deepest root systems occurred in sandy soil; they decreased in depth in clayey soils, and were most shallow in morainic stony soils. The branching of roots seemed to be abundant where food was available. The volume of soil occupied by roots of an individual tree was smaller for better sites, but was also affected by stand density, being smaller for denser stands.

Aldrich-Blake (4), after reviewing several reports, stated that he was led to believe that poor sandy soils stimulated greater growth in length of roots, with poor branching, while richer soils induced copious branching. In deep, well aerated soil the penetration of the tap root could be great and its form in no way distorted. However, it frequently occurred that a continuous downward growth was frustrated quite near the surface by an impermeable hardpan or high water table. Under these circumstances the tap root persisted only to that depth and grew no further. It might die at this point or turn through a right angle and change to a horizontal root. Root systems and tree crowns appeared to be influenced independently by their respective environments. The root system did not necessarily develop any better on the side on which the tree crown was best developed.

Turner (41) studied the distribution of roots of a 50-year-old short-leaf pine stand by means of transects on three soils in southern Arkansas. The soils were selected because of a contrasting site index.

Although field methods used were similar to those employed in this investigation, the roots were not recorded according to soil horizons but according to the depth from the ground surface. Soils with better aeration and drainage of the lower levels showed a greater percentage of the roots below the upper 18 inches of profile. Soil of the highest site index had the highest numbers and the largest roots; that of the lowest site index had the fewest and smallest roots. Soils of the intermediate site index were intermediate in regard to number and size of roots.

Soil horizons have been recognized by different investigators for some time, but the importance of horizons in forest soils and the general acceptance of this idea is relatively recent. Swetloff (37) investigated roots of pines five to 15 years of age. The soil was carefully removed starting from the top; water was used to facilitate the process. For investigating roots of older trees soil blocks were taken and the roots were divided into three sizes, oven-dried, and weighed. The soils were podzolized sands and loamy sands. He recognized soil horizons and noted that roots, as a rule, spread out in the upper part of well-developed podzol layers and in some cases extended upward into the organic layers. In organic layers the greatest amount of root branching was noted where proportionately more roots, particularly finer ones, were developed. The number of roots in the B_1 horizon was less than that in the A horizon, and in the B_2 horizon there was a marked falling off in root numbers. He also noted instances of new roots following the remains of old roots. He concluded that upper horizons were preferred by roots because of more favorable moisture, nourishment, aeration and temperature.

Coile (9) studied the tree root distribution by methods essentially the same as followed in the present investigation. Several Piedmont soils were compared by horizons. Particular attention was given to the smaller roots, and conclusions were that most of such roots are concentrated in the A and B horizons. Greater root concentration per square foot of profile area was found in finer textured soils. Lutz, et al., (25) made an extensive study of root distribution of white pine as it is influenced by soil profile horizons. The white pine stands investigated were between 35 and 45 years old, growing in soils belonging to the gray-brown podzolic group. The method employed in the field and the quantitative studies of roots used by these authors were essentially the same as those followed by the writer in the present investigation. They showed that the greatest root development occurs in the upper soil layers, and the number of roots per square foot of cross-sectional area in the mineral soil horizons decreased with increasing depth below the ground surface. However, the number of roots per square foot of vertical horizon area was higher in the H layers than in any other horizons. They concluded that, since the A and B horizons have the largest number of roots and the organic layers, except the L layer, have the highest root concentration per square foot, these layers must have the highest ecological significance.

The influence of soil texture on root development has been repeatedly emphasized. Weaver (45) in his intensive root studies concluded that less compact strata of soil invariably allow more lateral branching of roots. Hilf (18) stated that pine roots become more branched with increasing content of finer fractions in the soil. Lutz, et al., (25) pointed out in their investigation the unfavorable influence on root development of extremely coarse textured material which may prevent root development.

Soil moisture always has been recognized as an important factor in root development. Tolski (38) studied the root system of Scotch pine growing on chernozem and sandy soil. In chernozem the roots were principally vertical; in sandy soils lateral roots near the surface were produced. In chernozem, where there is no lack of nutritive substances in any of the soil layers, he believed the roots were guided in their development mostly by moisture, and penetrated deeply into the ground for water. Weaver (45) offered the water content of the forest soil as a logical explanation for forest plants having shallow roots. Hilf (18) attributed the variations of root penetration of Norway spruce to soil moisture. The roots penetrated deeply in dry soils and were relatively shallow in moist soils.

Vater (42) exposed the roots of three species of trees to determine their horizonal spread. He concluded that during the life of a tree considerable changes take place in the root system. Some parts of the roots die and disappear by deterioration; those parts of the roots which come above the surface become covered with bark; and those that are growing may assume forms different from those of the dead roots, thus changing in the course of time the form of the root system of the tree. In his opinion all these activities depend largely on the quality and moisture content of the soil.

Laitakari (19), in his extensive work on tree roots, believed that an explanation of the unusually rich branching of roots can be found in favorable moisture relations. Long branchless roots may be caused by excessive moisture. The depth of the root system depends on the position of the ground water level. Oskamp and Batjer (28) stated that tree roots are usually shallow in soils which have a high water table.

The influence of various physical and chemical soil conditions on root development has been the subject of investigation by many recent authors. Tolski (38), in his study of the roots of Scotch pine in chernozem and sandy soil, stated that the smaller vertical extension of roots in chernozem and the horizontal roots in sandy soils were due to the tendency of roots to develop and spread in those layers which contained in greatest quantities the substances most needed by plants. Sandy soils, as a rule, are richest in their upper layers containing humus; therefore, the roots are superficial in such soils and the bulk of them is found in the top layers. In chernozem, where there is no lack of nutritive substances in any of the layers, the roots were guided in their development mostly by moisture and penetrated deeply for water. Pines grown in chernozem had only half of the total length of roots as compared to those found on trees grown in sandy soil. The activity of the roots was directed toward extracting nutrients from the soil. Consequently, in good soil no great development of roots is needed, but in poorer soil adequate nutrition involves exploitation of the soil in a wide area and numerous roots were necessary.

Stevens (34) stressed the fact that root growth, like so many other biological phenomena, depends upon a combination of factors rather than upon any one factor. He emphasized the importance of at least four such factors: soil moisture, soil temperature, the composition of soil atmosphere and the physical nature of soil. He considered the physical structure of the soil to be of importance in root growth, not only in regard to water holding capacity, but also as to mechanical resistance offered to penetration by roots. West (46), in explaining the concentration of roots in the surface soil, suggested that this may be due to greater availability of nutrients in that zone.

Lutz, et al. (25) were led to the conclusion that root distribution is not appreciably influenced by small variations in hydrogen ion concentration. On the other hand, they pointed out that the nitrogen content generally decreased rapidly with increasing depth below the surface soil and at the same time the number of roots diminished. In their comparison of soil samples containing roots and those where roots were lacking, the difference in total nitrogen was shown to be statistically significant. In investigations of forest soils, they seem to be among the first to give particular consideration to the base exchange properties of soil in relation to root concentration. Their results indicated that roots develop more abundantly in soil material with high base exchange capacity. Base exchange capacity was the highest in organic layers and decreased in the mineral soil horizons with increasing depth. The roots were less numerous in the lower horizons where the total base exchange capacity was low. The exchangeable hydrogen and exchangeable bases gave inconclusive results. Lutz (24), in his later work, found differences in hydrogen ion concentration to be statistically significant between areas on soil mounds which are more favorable for tree growth, and those in adjacent depressions that were less favorable. But he questioned if such differences can be biologically significant. In this work he also noted statistically significant differences in the increase in percentage of base saturation as a result of soil disturbances. It was higher in the disturbed soil and was regarded as being favorable from an ecological point of view.

Root systems of tree species were examined by several investigators to determine their special characteristics as they are seen in three dimensions. Vater (42) stated that no generalization is possible, such as that the root system of spruce is horizontal, that of beech intermediate, and that of pine very deep. He mentioned that spruce roots can penetrate to depths of over 4 feet. The trees of a given stand never follow one pattern or general regularity in root development. Laitakari (19) stated that the root systems of trees which he investigated extended beyond the projections of their crowns. As the tree gets older the root system becomes smaller in proportion to the size of the parts above ground. He also mentioned that spruce has a root system which in total length and area usually exceeds that of pine. Aldrich-Blake (4), in reviewing the literature on roots, pointed out that the root system of a tree is more plastic than its subaerial portions. It is hard to define the normal rooting habit for any species. With regard to spruce he mentioned the fact that, after the seedling stage, tap roots are rarely seen.

Stevens (34), in his study of the root growth of white pine, pointed out that a wide variation in annual growth existed between individual roots. There was no apparent correlation between the amount of root growth and the amount of top growth. He demonstrated that the extent of the crown is but a poor indication of the extent of roots, stating that trees with vigorous tops possessed rapidly growing root systems and vice versa. He examined the largest and best trees in the stand and stated that their crowns not only occupied more space, but their root systems were also more wide-spread and better developed than those of their companions. In other words, the entire tree has grown more rapidly, and he concluded that no tree can achieve and maintain dominance in an even-aged stand unless its root system is of corresponding superiority. Lunes (21) concluded that variation in the root system of the same kind of tree is often greater in different soils than those of different kinds of trees in the same type of soil.

Literature with reference to tree root competition covers numerous observations and some recent attempts of quantitative investigations. Melder (26), in discussing reproduction of pine in a forest growing on dry sandy soils of Courlandia, stated that the root competition of an old stand does not allow the establishment of reproduction until, through loss of vigor or fire, such competition is reduced to allow seedlings to come in under the shade of old trees. Aaltonen (1) has shown that root competition is not confined to the less productive soils, but is present in all qualities of site. In 1926, Aaltonen, in discussing space arrangement of trees in various forest stands, stated that it depends on tree species and quality of site. He presented a hypothesis that the space arrangement of those parts of trees which are above the soil are mainly decided by their root systems and the competition existing between roots for the water and food in the ground. Adams (3) investigated the effect of spacing in a young jack pine plantation on sandy soil and found that competition caused a decided alteration in the form of the root system, changing it from a lateral spreading shape to a short, stubby, much-branched vertical form.

Pearson (29) found that trenching seedlings of western yellow pine benefits them slightly in comparison to seedlings grown in the open, even when the latter are subjected to considerable competition from the roots of older trees. His conclusion was that light, rather than root competition or moisture, is an all-important factor. Grasovsky (16), working with white pine stands in the Yale Forest near Keene, New Hampshire, concluded that the light which reaches the forest floor beneath a fully stocked stand is of sufficient intensity and quality to support reproduction. Light, therefore, was not considered a determining factor in the establishment of white pine reproduction.

The weakened growth and absence of reproduction was believed due to other factors of environment. Craib (10), working in the same forest, demonstrated that root competition with older trees may be the deciding factor in the survival of the reproduction.

Stevens (34) measured the rate of growth in the length of lateral roots of white pine, 4 to 6 years old, planted in open fields. He did not establish a correlation between root growth and weather or soil condition. Finding root growth more rapid on sandy soil, he concluded that, with four-year-old white pines set 6 feet apart on sandy soil, root competition may be expected to start within 5 years after planting. In clayey soil the growth made annually was much smaller and competition was delayed until about the tenth year.

SELECTION OF SOILS AND TREE SPECIES FOR INVESTIGATION

Establishment of the Plantations

Selection of the planting sites and establishment of the plantations were carried out in the spring of 1933 by Raymond Kienholz and H. A. Lunt. In 1940, when the writer joined the staff of the Station, it was felt that the two plantations had advanced in growth sufficiently to permit the study of the spread and penetration of the root systems of the trees.

The two soils selected for planting were Merrimac loamy sand and Charlton fine sandy loam. The plot on the Merrimac soil was in Peoples State Forest in the town of Barkhamsted, Litchfield County, about five miles east of the city of Winsted. It was located on the east side of the West Branch of the Farmington River, on a river terrace without perceptible slope, about 450 feet above sea level. The river valley is surrounded by forested hills rising from 400 to 600 feet above it. The land was formerly cultivated for a number of years, then abandoned. By the time planting was undertaken a thick grass cover with heavy sod had formed.

The Charlton soil plot was located near Bantam Lake on land belonging to the White Memorial Foundation. The general location is about one mile south from the village of Bantam, Connecticut, and about 500 yards north of Bantam Lake. The elevation of this plot is about 900 feet above sea level. The general appearance of the country shows quite unmistakably signs of glaciation, with drumlins forming prominent features. The plot is in a glaciated valley on land with a gentle slope. A conspicuous hill rises to the east of the plot. The land was formerly cultivated and then abandoned. By the time planting was undertaken a thick grass cover with heavy sod was present.

The two plots had been planted by four men between April 20 and April 25, 1933. The planting was at 6 x 6-feet spacing, carefully measured. Where individual trees were planted, the sod was removed for a radius of about 1.5 feet. A hole was dug to accommodate the roots without crowding and, after the roots were inserted, they were carefully covered with soil and well tamped. The planting followed a certain pattern of pure and mixed rows, and the mixed rows in themselves followed a definite plan. However, the original design of planting, made up with rigid regularity, was altered somewhat to meet the supply of planting stock and the shape of the field plots.

An exact record of the source and kind of planting stock is not available. After making several inquiries and examining the trees themselves, the writer has concluded, from the evidence at hand, that the conifers were 2-1 stock, and the hardwoods 1-0 stock. The conifers came from local nurseries. They were grown for one year as transplanted stock at the Connecticut Agricultural Experiment Station Nursery at Windsor, Connecticut, before they were planted in the field. The hardwoods came from the Forest Nursery Company in Tennessee. Since this nursery in all probability secured the seed locally and grew the seedlings, the change of climate involved in transferring the seedlings from Tennessee to Connecticut may account to a large extent for the poor survival of the hardwood trees.

Figure 1. General view of the seven-year-old plantation utilized for root study in this investigation. Plantation on Charlton fine sandy loam, Bantam Lake, Bantam, Connecticut.

In August of 1934 an examination was made of the two plots and a record was made of the mortality and survival of the individual trees. After this examination the two plots received no more attention until the initiation of this investigation.

Condition of the Plantations at the Initiation of the Study

In June, 1940, the two plantations were examined by the writer and, after a preliminary inspection, plans were made to conduct the root investigations presented in this paper. The two plantations at this time were seven years old and afforded views as in Figures 1 and 2. In certain parts of these plantations, where survival was good and trees grew rapidly, the crowns of the trees were about ready to close.

TABLE 1. TREE PLANTING, MORTALITY AND SURVIVAL ON MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM.
(Common and scientific names of the tree species follow Sudworth, 1927.)

Tree species		Merrimac loamy sand					Charlton fine sandy loam				
Common name	Scientific name	Number planted April 1933	Number alive August 1934	Number dead August 1934	Number alive July 1940	Number dead July 1940	Number planted April 1933	Number alive August 1934	Number dead August 1934	Number alive July 1940	Number dead July 1940
Arborvitae[2]	*Thuja occidentalis* L.	24	17	7	12	12	21	21	3	14	10
Beech[1]	*Fagus grandifolia* Ehrh.	22	1	21	0	22	25	5	20	2	23
Black birch[1]	*Betula lenta* L.	248	10	238	0	248	223	35	188	0	223
Chestnut oak[1]	*Quercus montana* Willd.	46	14	32	9	37	43	15	28	11	32
Douglas fir[2]	*Pseudotsuga taxifolia* Britton	22	18	4	14	8	23	23	0	20	3
Hard maple[1]	*Acer saccharum* Marsh.	24	8	16	1	23	22	21	1	3	19
Hemlock[2]	*Tsuga canadensis* L.	28	5	23	1	27	42	27	15	14	28
Norway spruce[2]	*Picea excelsa* Link	248	68	180	54	194	253	221	32	207	46
Red oak[1]	*Quercus borealis maxima* Ashe	248	122	126	73	175	223	201	22	96	127
Red pine[2]	*Pinus resinosa* Soland.	24	22	2	21	3	22	20	2	19	3
River birch[1]	*Betula nigra* L.	103	30	73	28	75	209	206	3	159	50
Scotch pine[2]	*Pinus sylvestris* L.	22	22	0	20	2	23	22	1	22	1
Shagbark hickory[1]	*Hicoria ovata* Britton	23	1	22	0	23	22	10	12	3	19
Tuliptree[1]	*Liriodendron tulipifera* L.	24	8	16	3	21	24	20	4	11	13
White ash[1]	*Fraxinus americana* L.	26	23	3	22	4	23	23	0	21	2
White pine[2]	*Pinus strobus* L.	248	177	71	166	82	223	212	11	196	27
White spruce[2]	*Picea glauca* Voss	22	6	16	3	19	22	18	4	17	5
		1402	552	850	427	975	1446	1100	346	815	631

[1] Hardwood stock, 1—0 when planted.

[2] Coniferous stock, 2—1 when planted.

Other parts presented open growth with a heavy grass cover between the individual trees.

Local climate perhaps was a factor in the survival of the planted trees, but data on local climatic conditions in the two areas were not available. It would appear from casual observation that there were dissimilarities: the area of Merrimac loamy sand was in a valley protected from the wind on two sides; the plantation on Charlton fine sandy loam was exposed and was swept by winds from all sides. This exposed condition probably created other slight local variations in atmospheric factors. However, it can be assumed that the survival and development of the trees was more affected by the differences in the two soils than by other environmental factors.

Figure 2. General view of the seven-year-old plantation after excavation of soil transects around the trees was well under way. Excavation in Merrimac loamy sand, Peoples Forest, Pleasant Valley, Connecticut.

Table 1 gives the record of trees which were planted, those which died and those which survived on the two soils. About 30 percent of the trees survived on Merrimac loamy sand and 56 percent on Charlton fine sandy loam. Norway spruce and river birch showed noticeably better survival on Charlton fine sandy loam than on Merrimac loamy sand. Conifers and hardwoods both showed better survival on Charlton soil. Black birch was a total failure on both areas. The Charlton soil was more favorable for the growth of conifers in general, and the Merrimac soil for that of hardwoods.

Selection of Trees to be Studied

After the preliminary examination it was concluded that no less than eight and preferably ten trees of each species should be studied in order to give a good representation. Later on it became evident that the amount of work involved in conducting the field excavation and charting of roots would not permit the investigation of more than eight trees of each species on both plots if work was to be finished within one season. The work was started in the field on July 15 when the most active growth for the season was coming to an end. It was completed on November 1 of the same year, thus making all field data come within one season.

In the selection of species from the group of trees that survived, several points were considered. Both conifers and hardwoods were to be represented. The species selected were to have no less than eight individual trees surviving on each plot. These eight trees were to be predominantly of good vigor and height growth, since such trees may be expected to show good root growth, and have a much greater chance to survive as dominants in the final stand. Although the plantations examined were young, they were examined as a prospective forest stand. Trees having a low chance of survival were not considered. Selected trees were to be surrounded by other trees, preferably of other species if they were to show the influence of root competition in a mixed stand. For this reason river birch, for example, was not considered since it occurred for the most part in pure rows at one end of the plantation.

The above considerations eliminated all species but six; namely, Norway spruce, red oak, red pine, Scotch pine, white ash, and white pine. Finally Scotch pine was eliminated since it is an exotic species and two native ones were available. The selected group of trees was of slightly better average height growth on Charlton fine sandy loam than on Merrimac loamy sand. Red oak was the only exception to this general rule.

METHODS OF PROCEDURE AND FIELD WORK

Methods of Procedure

The first phase of field work consisted in recording the location, height and vigor of each tree. Eight trees of the five species to be investigated were selected. Trees of the best vigor and height growth, not adjacent to one another and surrounded by the largest number of other trees, were marked for investigation by consecutive numbers. The numbering was done with shipping tags securely attached to the stem of each tree.

In selecting the method for field study several considerations were kept in mind. It was necessary to show to what extent the available ground was occupied by the tree roots, and the size and the spread of roots by soil horizons. The presence of root competition between the trees, as well as places of high and low root concentration or the absence of roots, were to be noted.

A considerable amount of research has been done by excavating carefully individual trees and following all of their roots through the soil in three dimensions. This method makes it possible to measure the length of the root system, the area and volume occupied by the root system, root distribution by horizons, and a comparison of the number of vertical and horizontal roots. This is the method used by Tolski (38), Laitakari (19), Swetloff (37), and by many others. The method gives much quantitative data but it is laborious and very time-consuming. It requires the training of common labor and considerable technical help. It is accurate within certain limits but falls short of theoretical accuracy under field conditions, as each of the above investigators pointed out in his report.

The transect method which was developed by Weaver (45) in studying root systems of grasses has had some application and was used by Turner (41), Coile (9), Lutz, et al. (25), and, with some variation, by others. A trench was made on a straight line and offered one, or, if desired, two long faces of the soil profile for examination. The vertical sides of the trench, after being cleaned and smoothed, offered an excellent view of soil horizons and showed the roots that were cut in that vertical plane. It is a method that can be used for quantitative studies because it gives precise information concerning root distribution by horizons, and root classification according to sizes, and shows areas of high and low root concentration. This method does not require special training of common labor, demands less technical supervision, and is more rapid in accumulating field data. This procedure was refined and perfected in the work done by Ely (12), Little (20), and Lutz, et al. (25). This scheme was chosen as most suitable under the conditions of the present study.

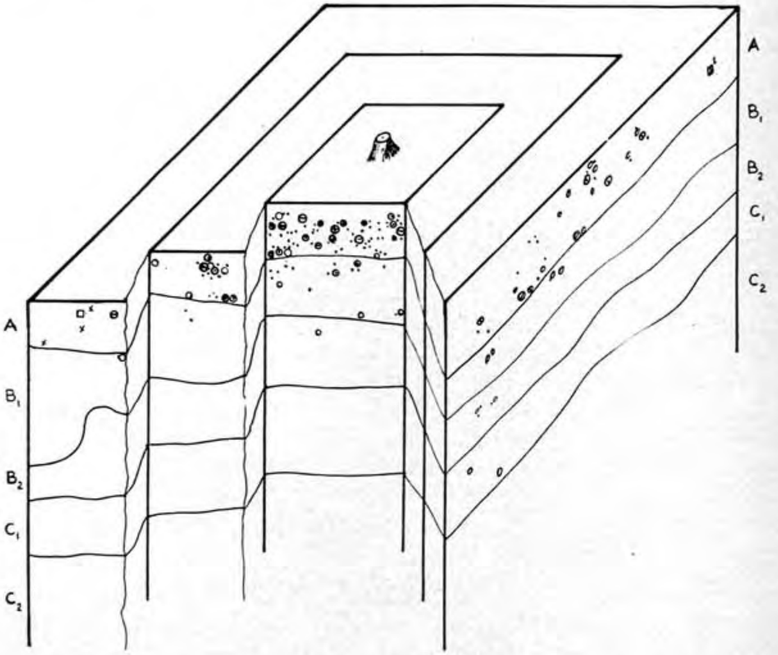

Figure 3. Oblique projection of the block of soil which was isolated around an individual tree. Three sets of soil transects, 1 foot apart, were made. Each set of transects formed a square with the tree at its geometrical center.

Field Work

An area of 36 square feet would be allotted to each tree in a plantation spaced 6 x 6 feet. The boundaries of this area would be half way between two trees, i. e., 3 feet from each one of them. The length of the boundary on each side would be 6 feet. It was decided that the roots of each tree would be investigated within this space. This required digging a trench on all four sides of a tree with the tree stem at the geometrical center of the square. The sides of the square were parallel to the rows of planted trees in two directions. In order to provide a working space around the square bounded by the trenches, they were made 2.5 feet in width and slightly longer than 6 feet in length. The depth of the trenches was from 3.5 to 7 feet depending on root penetration and soil horizon thickness. Two additional transects were made around the tree. The second cut was 2 feet and the third cut 1 foot from the tree. The sides of these smaller squares were oriented parallel to the sides of the original squares. A view of the position of trenches and sides of the square block of soil can be gained from Figure 3.

The digging of the first trenches around each tree proved to be the most difficult job, while the opening up of the two additional profiles was not nearly so laborious a task. All in all, the digging of trenches, opening of additional profiles and covering up the holes after the work was done amounted to considerable labor. The work was made possible by the use of members of the Civilian Conservation Corps, provided through the courtesy of the State Forester's office. A crew of approximately ten men was busy performing this work for a period of about 3½ months.

Along the side of each transect to be investigated digging was done with caution. When completed, the profile was cleaned and smoothed to, as nearly as possible, a vertical plane. The larger rocks were allowed to remain in place in order that the profile face would not be greatly disturbed by their removal. Of several tools tried, including kitchen knife, hunting knife and trowel, the machete proved to be the most efficient for this work. This tool has a long cutting surface, making it possible to do the work rapidly, and a wide blade which permits the strokes to follow with ease the plane of the transect. Its sharply pointed tip makes it convenient to work around rocks and in narrow places. This tool proved to be particularly efficient in smoothing out profiles in sand, a few strokes sufficing to produce a large clean area.

Mapping of Soil Profiles

The exposed soil profiles were mapped on cross-section paper with a scale of 1 inch to a foot. Three representative maps or charts are shown in Figures 4, 5 and 6. On these charts are indicated four sides of each set of transects, one next to the other. Corresponding sides of the next set are shown above the first one, and a third set above this one. Each interval between the graduations, along the sides and bottom of charts of the transects, represents one foot. Horizon boun-

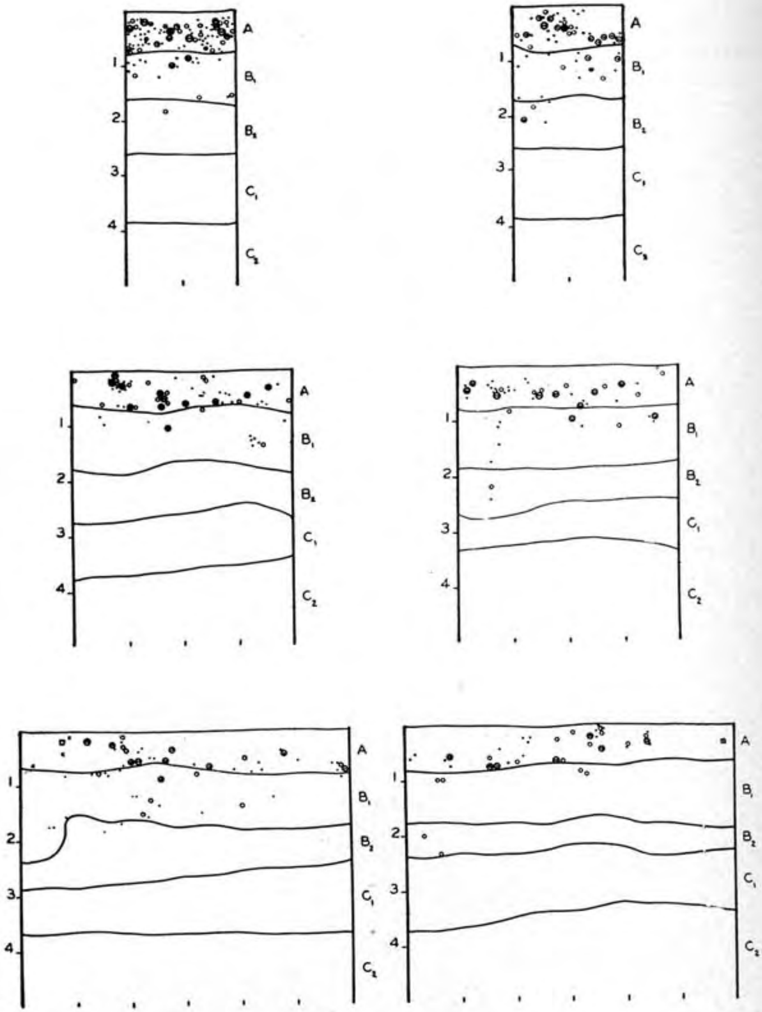

Figure 4. Horizon features and root distribution in the typical soil profile of Merrimac loamy sand. This set of transects was made around a white pine tree 7.8 feet in height. (Continued on page 117)

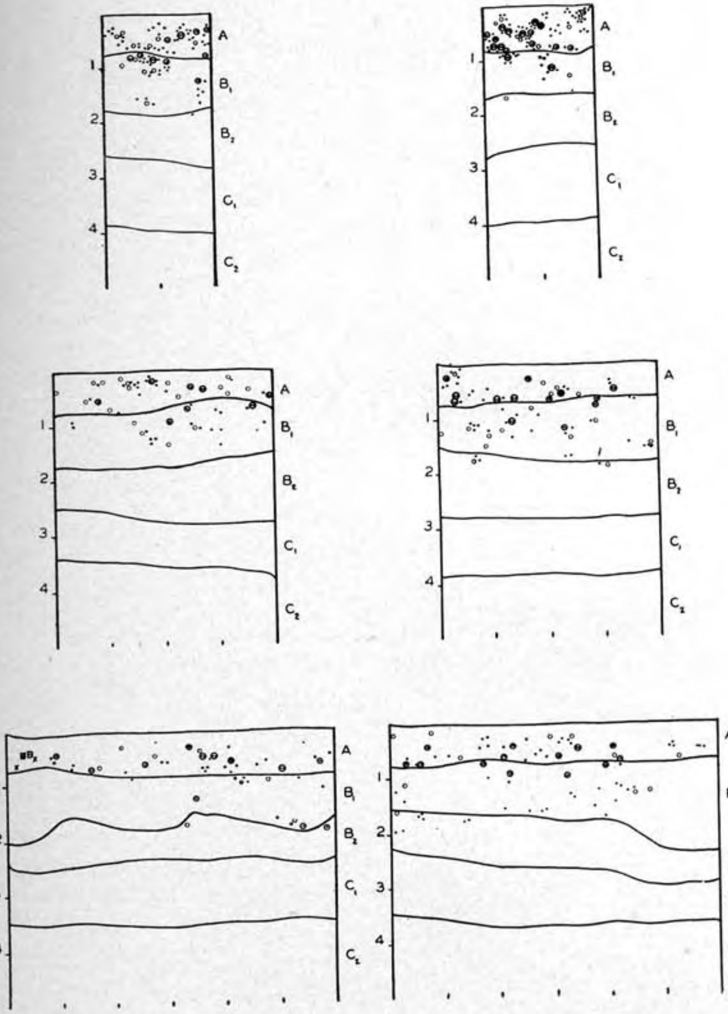

Figure 4. (Continued.)

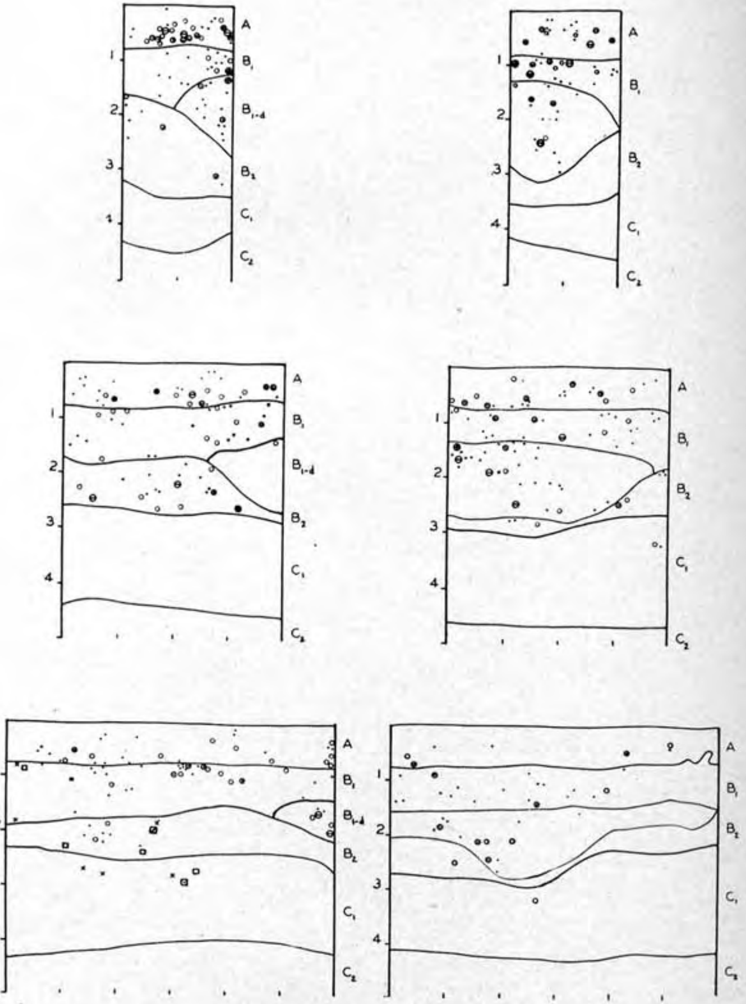

Figure 5. Horizon features and root distribution in Merrimac loamy sand. Patchy appearance of the atypical profile is shown. This set of transects was made around a red pine tree 7.7 feet in height. (Continued on page 119.)

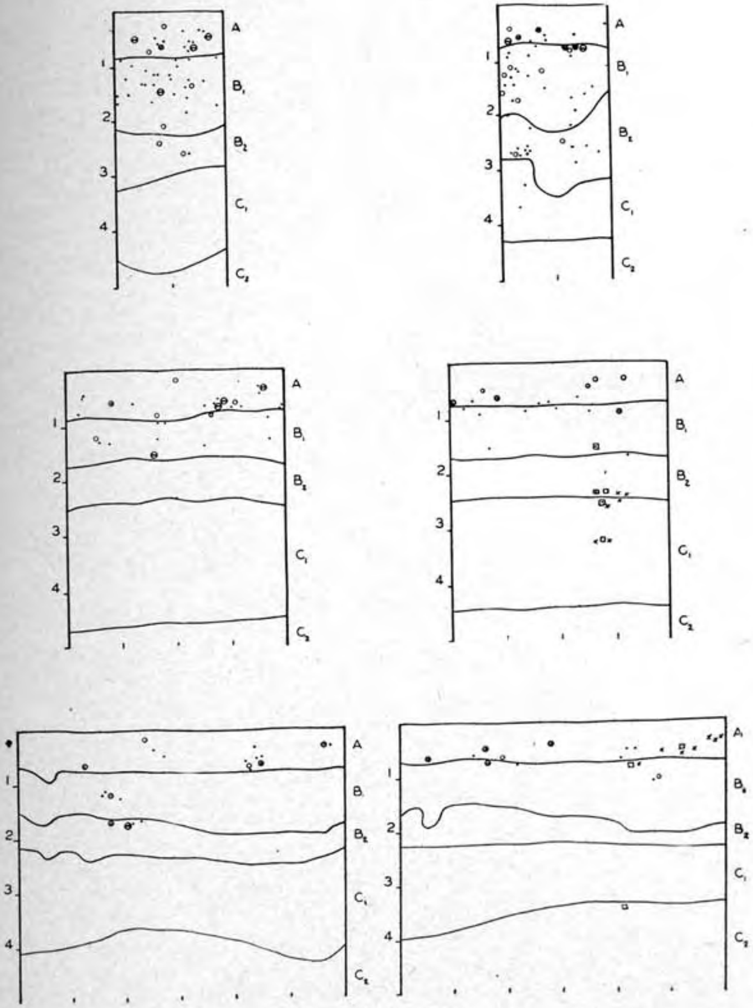

Figure 5. (Continued.)

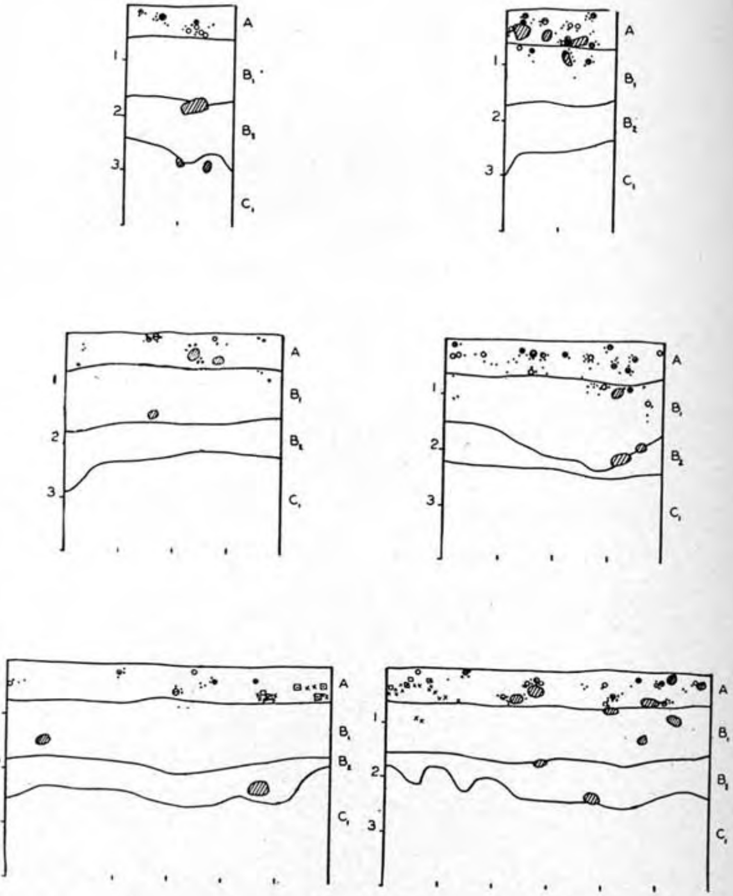

Figure 6. Horizon features and root distribution in Charlton fine sandy loam. This set of transects was made around a Norway spruce tree 7.4 feet in height. (Continued on page 121.)

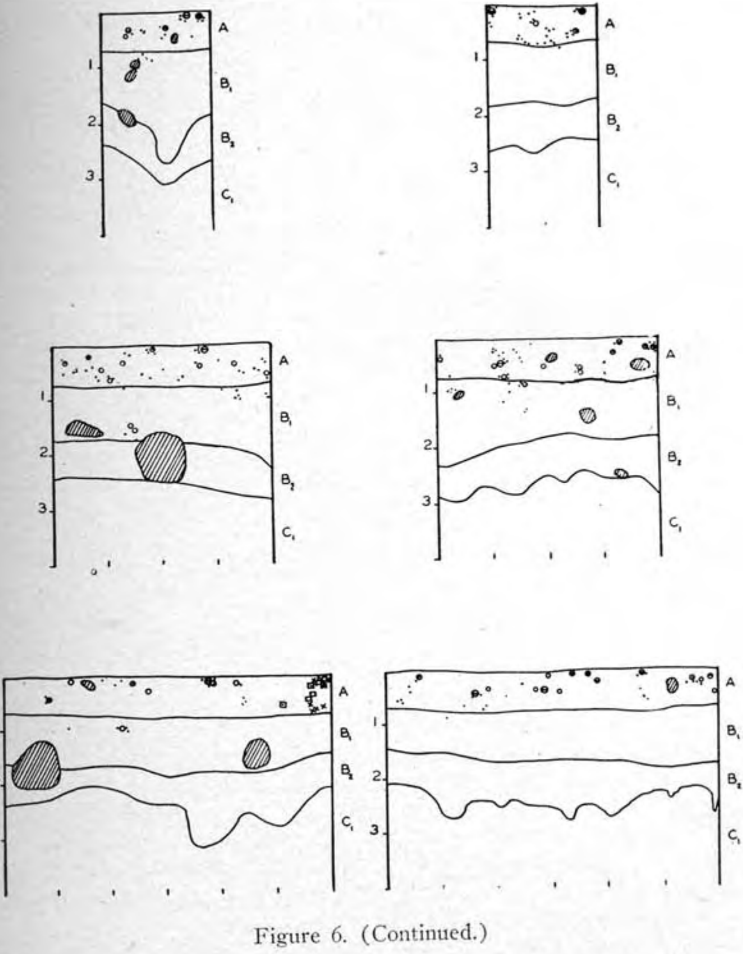

Figure 6. (Continued.)

daries are indicated by lines, horizons are lettered, and large rocks, which were mapped to scale, are cross-hatched. Roots of trees were mapped according to five size classes with the following symbols indicating root sizes.

Diameter of root	Roots of trees under investigation	Roots of trees other than those investigated
up to 0.05 inch	•	×
0.05 to 0.1 inch	○	◻
0.1 to 0.2 inch	⊙	⊡
0.2 to 0.5 inch	⊖	⧄
0.5 to 1.0 inch	⊕	⊠

In order that mapping could be done accurately a frame 3.5 feet long and 2 feet wide was constructed. This frame and its application is essentially the same as that described by Ely (12). Thin wire was used in preference to string for subdividing the frame into smaller squares because wire gave rigidity to the frame and kept the lines from saging. Wires 6 inches apart were sufficient for orientation in mapping. With the aid of an ordinary foot ruler the mapping could be done with accuracy. The frame, fitted against the exposed profile, was used as a guide in mapping the roots to scale, as illustrated in Figure 7.

As the work on root charting proceeded, the exposed horizons were studied and described. The succession of horizons on the two areas followed a certain general pattern but all deviations and variations from the usual pattern were noted for each tree.

Collection of Soil Samples

Immediately following the mapping of roots two main series of soil samples were taken. One set was collected by horizons for the entire plot. On Merrimac loamy sand two patterns of soil horizon succession appeared to be evident, one of which was more general and far more widespread than the other. As the work progressed it became apparent that, except for one modification occurring only in patches, the two patterns were essentially the same. On Charlton fine sandy loam one common type of horizon pattern prevailed throughout. The general soil samples collected for the two areas consisted of one set for Charlton fine sandy loam and two sets for Merrimac loamy sand, one from the typical and one from the atypical profile pattern. These sets were taken in paper bags in small lots as the work progressed to give a good representation of the entire area. The resulting composite soil samples were accumulated from not less than 40 different places. All samples were thoroughly mixed before any laboratory analysis was begun.

The other set was collected by soil horizons also, but in pairs rather than by individual samples. One sample of the pair was taken from or near areas where roots showed particularly heavy concentration. The other taken from areas in the same horizon, at about the same level, where there were no roots at all or where they were very scarce. Soil samples collected from typical profiles of both soils were kept separate for each tree species. An exception was made in the case of the atypical profile on Merrimac loamy sand. Due to the fact that areas of atypical profiles occurred irregularly and were rather limited in extent, it was decided to maintain root concentration divisions irrespective of species. Soil was taken in small lots and was mixed to form composite samples. Such composite samples were made up from not less than five separate lots and as a rule represented at least twenty individual portions.

In addition to the above, three special sets of soil samples were collected from each area. One set was taken from the A and B_1 horizons, at four random places on each area. These were put into air-tight glass fruit jars. This set was used for the aggregate analysis. The second set consisted of soil samples taken from the middle of the A and B_1 horizons in each area at six random places by means of 250 cc. soil cylinders. These cylinders were of the same type as described by Coile (8). The technique of taking the soil samples was also according to Coile's suggestions. These soil samples represented undisturbed soil and were used for physical analyses. The third set of special samples consisted of three specimens taken one under the other at specified depths below the surface of the soil, from five random places in each area. Undisturbed core samples representing a volume of one liter were drawn with steel cylinders, following the technique of Lutz (24). These samples also were used for the physical analyses of the two soils.

Photographing the Roots

After the mapping of roots and collection of soil samples, each tree was left standing on a square block of soil measuring 2 feet on a side (Figures 8 and 9). At this stage the trees were removed from the soil, care being taken not to disturb the roots as the soil was dug away. A white board with lines 6 inches apart was used as a background in photographing the exposed roots. The central root mass of each tree of the different species in the two soils was then photographed against this board.

FIELD OBSERVATIONS

In this investigation very young forest stands were utilized in which top layers of the forest floor had not yet accumulated. Humus layers were absent except for very limited areas around the trunks of the largest trees. Soil horizons were uncovered in the transects down to the C_1 or C_2 layers.

The two soils and soil horizons were described in great detail in field notes included in the author's dissertation.[1] Consistent outstanding differences between the two soils were observed. Merrimac loamy sand was developed from water-deposited material of coarse texture; the parent rocks were granites, some gneisses and schists. Gravel

---

[1] Yale University, Graduate School and School of Forestry, Doctor's thesis. 179 pp.

was found in the C_2 horizon in the majority of cases. Coarse sand, often white in color, was also encountered in the C_2 horizon. Charlton fine sandy loam, on the other hand, was derived from parent material consisting of a heavy, well-disintegrated mass of glacial till in which schist fragments were predominant. Erratics up to occasional large boulders were found in this soil.

Figure 7. View of the frame used for field mapping. The frame is fitted against the 2 x 2 foot block of soil. Note cross-wires, 0.5 foot apart, which were used as reference lines. Exposure of typical profile in Charlton fine sandy loam, Bantam Lake, Bantam, Connecticut.

Another conspicuous difference between the two soils was the difference in drainage. Merrimac loamy sand, owing to the texture of its subsoil, allowed excellent drainage and the water table was approximately 10 feet below the surface. Yellow and brown color prevailed throughout the B and C_1 horizons and indicated good aeration. Charlton fine sandy loam offered good drainage only as deep as the B_1 horizon but, below that, due to the compact glacial till in the C_1 horizon, drainage was slow and the water table was only 3 to 5 feet below the surface. An olive color in the B_2 horizon was common, and blue or green colors indicating poor drainage were often found in the C_1 horizon. The roots of trees did not reach into this horizon in Charlton soil while only a very few penetrated into the C_1 horizon in Merrimac soil.

The A horizons in the two soils were similar in color, being very dark brown, approaching a blackish brown. The color of the A horizon was slightly lighter in Merrimac loamy sand and this horizon was thicker, with coarser and more friable soil than in Charlton fine sandy loam. Certain similarities existed in the B_1 horizons of the two soils. These horizons were light yellow to yellowish brown in color, being somewhat lighter in Charlton fine sandy loam. In Merrimac loamy sand the B_1 horizon was thicker, having coarser and more friable soil. The differences in the B_2 horizons between the two soils were very pronounced. The B_2 horizon in Merrimac soil was similar to the B_1 horizon. It was brownish yellow, and the soil was coarse in texture and very friable. In Charlton soil the B_2 horizon was quite different from the overlying B_1 horizon but similar to the C_1 horizon. It was of a yellowish olive color and was slightly compact. In this soil the boundary between the B_2 and C_1 horizons was gradual and very irregular, while the boundary between the B_1 and B_2 horizon was abrupt and wavy. In Merrimac soil the boundary between the B_1 and B_2 and the B_2 and C_1 horizons was gradual and wavy.

There was practically no catastrophic deformation of profiles in Charlton fine sandy loam. Occasionally in Merrimac loamy sand deformations were encountered that perhaps were due to man's activity. In this soil, in addition to these few cases, a quite common and uniform type of deformity was often encountered during the excavation. In more or less extensive areas of the transects the B_1 horizon was subdivided into two parts which were designated as B_1 and B_{1-d}. The B_1 layer which constituted the upper portion was similar to the usual B_1 horizon. The only differences noted in the field were that it was somewhat reddish in color and of finer texture than the usual B_1 horizon. The B_{1-d} horizon was distinctly different from any other layer of the profile. Occurring only in spots, it was very dark blackish brown in color and more compact than any other horizon in this soil. It is difficult to explain this irregularity but, considering that charcoal was found in the B_{1-d} horizon, it is believed that the burning of quantities of wood at the time the land was cleared may be the explanation. This burning probably took place a long time ago. While this land was under cultivation, the A horizon recovered its normal appearance. From photographs of the horizons which were taken in the field, and are shown on Figures 7, 8 and 9, some of the above described differences can be seen.

In addition to these differences, more biological activity, as evidenced by a greater number of earthworm and insect holes, was observed in the Charlton than in Merrimac soil. However, the activity of earthworms was confined to a shallower depth in the Charlton soil, owing to poor drainage and aeration conditions and heavier texture.

LABORATORY METHODS

The laboratory analyses of soil samples collected in the field were divided into three parts. The first consisted in aggregate and physical analyses of the special samples collected for this purpose from the two soils under investigation. The second part related to chemical analyses of the general samples collected by horizons from the two soils. The third part consisted of a limited number of tests on soil samples collected in pairs according to root concentrations, tree species and soil horizons. General soil samples were also included in the third set of tests.

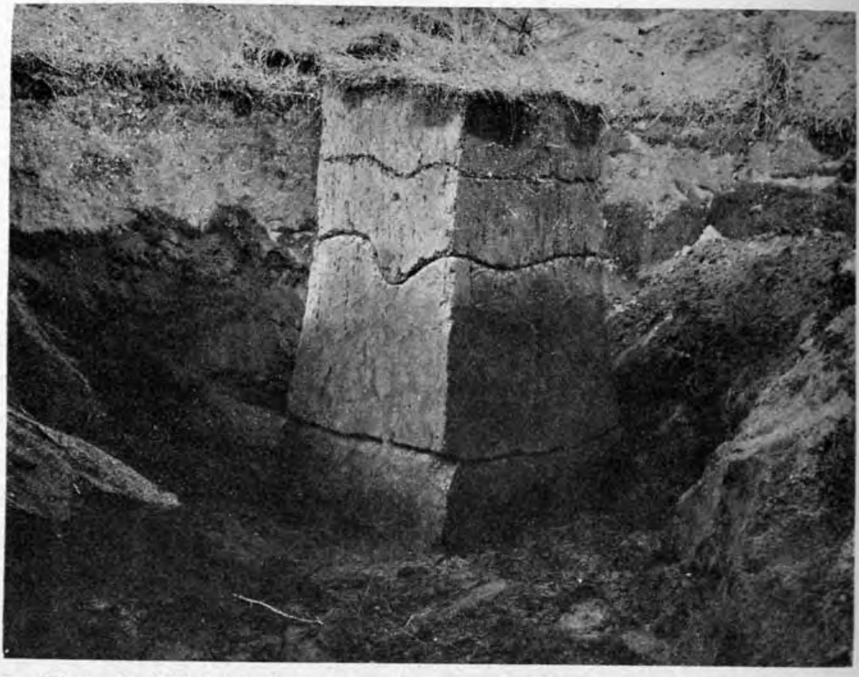

Figure 8. View of the 2 x 2 foot block of soil left around a white ash tree after final excavation. Soil horizon boundaries are marked. From this block of soil the central root mass was removed and photographed. Exposure of typical profile in Merrimac loamy sand, Peoples Forest, Pleasant Valley, Connecticut.

The method used for aggregate analysis was a modification of the one described by Dittrich (11) and by Russell and Tamhane (31). This analysis was done on duplicate samples of 50 grams each. Net aggregate fractions were expressed in percentage of oven dry weight of the soil sample used. The two sets of soil samples taken for investigating physical properties of the two soils were soil-in-place samples and were treated and analyzed in the laboratory in the same manner; i. e., by the method described by Lutz (24).

Chemical analyses of the general soil samples collected by horizons were all done in duplicate, for only the most important chemical elements in the soil. Total calcium, potassium and magnesium were determined by the official methods of the Association of Official Agricultural Chemists (5). Other methods used were as follows: total phosphorus by the perchloric acid method of Volk and Jones (44); exchangeable calcium and replaceable potassium by the modified Williams (47, 48) methods; and readily soluble phosphorus by the Truog and Meyer (40) modified method.

In the next series of determinations all of the soil samples were used. The entire set consisted of 93 soil samples. Mechanical analysis was carried out by the Bouyoucos (6) hydrometer method. General soil samples, in addition to the usual treatment, were used to determine the amount of material coarser than 2 mm. Moisture equivalent values were determined in a Briggs and McLane centrifuge according to the method of Veihmeyer, et al. (43). Other methods used were as follows: Loss on ignition according to the general procedure given by Wright (49); total nitrogen according to the Kjeldahl method as modified by Stubblefield and DeTurk (35); hydrogen ion concentration, pH values, by using a glass electrode pH meter; exchangeable hydrogen by the Pierre and Scarseth (30) method, with modification; exchangeable bases by the Chandler (7) method, modified by Lunt (23); exchangeable bases were obtained by subtracting the two base exchange values thus secured and base saturation percentage was calculated.

STATISTICAL ANALYSIS

After the field work was completed, transect charts of the roots of the 80 trees investigated formed a ready reference. The roots were recorded in five size classes, and the roots of others not under investigation were recorded by different symbols. Each horizon boundary was shown on these charts. Since three series of transects, 1 foot apart, were made around each tree, every tree had three sets of maps for its root record and each set had four maps corresponding to four sides of the square. A count of the number of roots recorded on the maps gave the total number of roots in each class per tree. It was also possible to determine the vertical areas of horizons because all mapping was done to scale. From the areas of the horizons the number of roots could be expressed per square foot of each horizon.

An examination of the tables gives useful information from which conclusions can be drawn. To ascertain the validity of such conclusions the data were examined statistically by the analysis of variance as described by Fisher (13, 14) and Snedecor (32, 33). The analysis of variance has the objective of determining whether a given difference is enough larger than that ascribable to chance alone for it to be considered significant. This is ascertained by referring the variance ratio or "F" value in question to statistical tables which show how large a value could be expected by chance alone, once in 20 trials and once in 100 trials. If the observed F is larger than that expected at odds of one in 20, the factor is called significant; if larger than that at odds of one in 100, it is called highly significant.

Figure 9. Close view of the 2 x 2 foot block of soil left around a Norway spruce tree after final excavation. These transects expose the atypical soil profile in Merrimac loamy sand. Soil horizon boundaries are marked. Note wide and dark B_{1-4} horizon which is the third from the surface. Peoples Forest, Pleasant Valley, Connecticut.

For the analysis of variance of root data three separate values, one for each transect around an individual tree, were combined because the separate values did not represent any uniform distance from the stem of the tree. Once this was done it was felt that the large size roots could not be included, because such roots might have been recorded more than once in various transects. Furthermore, the small roots should indicate only feeding roots of trees and as such are of special interest. The C_1 horizon was eliminated from consideration because only a few roots were found in this horizon in Merrimac loamy sand and none at all in Charlton fine sandy loam. The B_1 and B_2

horizons were combined into one B horizon because of the extreme scarcity of roots in the B_2 horizon in Charlton loam. If the B_2 horizon was eliminated instead of combining it with the B_1 horizon the comparison between the two soils would be thrown out of balance. Root numbers in the A and B horizons in the two soils were compared as in an experiment with split plots.

The series of tests that were conducted on the soil samples in the laboratory produced a considerable amount of data. Some of these data, such as chemical tests on the two soils, served as unreplicated descriptive material. Other tests based upon individual random samples, were evaluated by the analysis of variance.

The statistical analysis of soil properties differed from the usual procedure in that there were no true replicates from which an error term could be computed. Two samples of soil were taken from each horizon about each tree in the study, one from a zone with many roots and the other from a zone with few or no roots. All samples from the same zone, horizon, species of tree and type of soil were combined for soil analysis, giving 60 measurements in all of each soil factor. The analysis of variance was divided into two parts. The first was based upon the sums of the paired values from the two zones of high and low root concentration. These sums were used to differentiate the Merrimac loamy sand from the Charlton sandy loam by comparing the principal differences between them and the first order interactions between the main effects with the second order interactions which served as the error. The second part was based upon the differences in each soil property about the same trees between the zone with many and that with few roots. This part of the analysis determined which soil factors favored root growth, again in comparison with the higher order interactions.

In all of these calculations, however, each soil property was treated in a separate analysis of variance, although the different factors were not independent of one another. The objective was to relate soil characteristics as commonly measured to root development. Some of these relations no doubt could be explained largely if not entirely by the interrelations between factors. The independent effect of each factor upon root development could be determined by covariance and related techniques, but this lies outside the scope of the present investigation and should be based upon more extensive data with true replicates.

DISCUSSION AND INTERPRETATION OF RESULTS

Physical Soil Properties

Physical properties of the two soils received special attention in this investigation. It has been pointed out in the review of literature that there is more or less general agreement among investigators that physical properties of forest soils are very important from the point of view of forest growth and development of tree roots.

Aggregate Analysis

Methods of aggregate analyses are not as yet established on a firm basis. In analyzing aggregates, they were subdivided originally into five size classes. Although the latter proved rather erratic, the sum of all aggregates, expressed as a percentage of the dry weight of soil sample, clearly differentiated the two soils. The results of four random samples from both the A and B_1 horizons in the two soil types are shown in Table 2.

TABLE 2. AGGREGATE ANALYSIS OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM SOILS.
(Values are based on four random samples analyzed in duplicate)

Soil type	Soil horizon	Total of the five aggregate size classes in percentage of dry weight of soil sample				Average
Merrimac	A	6.72	10.75	5.91	4.72	7.02
loamy sand	B_1	1.68	3.57	4.08	3.73	3.26
Charlton fine	A	23.39	31.11	24.87	34.60	30.49
sandy loam	B_1	6.97	19.41	13.48	11.58	12.86

The data in Table 2 have been analyzed statistically in Table 3. Charlton fine sandy loam contained more aggregate than the Merrimac loamy sand and in both soil types a higher proportion of aggregates was present in horizon A than in horizon B_1. Both differences were highly significant in comparison with their respective errors. The ratio of the aggregates in horizon A to those in B_1, however, did not differ between soil types. By transforming the percentages in Table 2 to their logarithms before computing the analysis of variance in Table 3, the variance was stabilized and the variability in the ratios of the aggregates could be tested critically by the interaction between soils and horizons.

TABLE 3. ANALYSIS OF VARIANCE FOR TOTAL AGGREGATES IN PERCENTAGES OF OVEN DRY WEIGHT OF SOIL SAMPLES IN A AND B_1 HORIZONS OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM
(Based upon the data in Table 2 transformed to logarithms)

Variation due to	Degrees of freedom	Mean square	Observed F
Types of soil	1	1.53357	50.08[1]
Plot error	6	0.03062	
Soil horizons	1	0.53213	28.25[1]
Interaction between soils and horizons	1	0.00725	0.39
Subplot error	6	0.01884	
Total	15		

[1] Significant at the 1 percent level.

Physical Properties of Soil-in-place Samples

Data for physical properties of soil-in-place samples were obtained from analyses of samples taken with 250 cc. cylinders from the middle of the A and B_1 horizons and from samples taken with 1000 cc. cylinders at three fixed depths below the surface. The results of these two samplings are not strictly comparable. The difference in the size of cylinders was responsible for some discrepancies. It might be expected that the smaller cylinders would allow a relatively greater amount of side play and, as a consequence, air capacity and pore volume percentages would be greater. Deductions from Table 4 prove this to be the case. Difference in the method of spacing the samples, one above another, was responsible for another portion of the discrepancies. One set was taken from the middle of the A and B_1 horizons, while the other set was taken at 2, 8 and 14 inches below the surface. In the first set soil horizons were mixed, particularly at the 8-inch depth, because these samples were taken with cylinders 10 cm. in height and came from the zone where the boundary between the A and B_1 horizons was encountered.

TABLE 4. PHYSICAL PROPERTIES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM SOILS.

Soil type	Soil horizon	Depth of sample below surface inches	Pore volume percent	Air capacity percent	Water holding capacity percent		Apparent specific gravity (Volume weight)	True specific gravity
					Volume basis	Weight basis		
Merrimac loamy sand[1]	A	....	55.45	9.63	45.81	41.65	1.093	2.47
	B_1	....	52.07	9.60	42.47	36.98	1.149	2.40
Charlton fine sandy loam[1]	A	....	61.08	13.63	47.45	51.02	0.918	2.39
	B_1	....	48.59	10.20	38.39	30.85	1.226	2.53
Merrimac loamy sand[2]	A	2-6	53.13	6.88	46.25	40.72	1.135	2.42
	A-B_1	8-12	49.58	6.64	42.94	36.46	1.180	2.34
	B_1	14-18	47.57	6.88	40.69	33.42	1.226	2.34
Charlton fine sandy loam[2]	A	2-6	59.40	12.64	46.76	52.20	0.866	2.19
	A-B_1	8-12	50.78	6.98	43.80	39.70	1.067	2.23
	B_1	14-18	45.95	6.10	39.85	32.20	1.205	2.28

[1] Values represent the average of six random samples collected in 250 cc. cylinders from the middle of the horizons at variable depths below the surface of the soil.

[2] Values represent the average of five random samples collected in 1000 cc. cylinders at a fixed depth below the surface of the soil.

Analysis of variance of the physical properties of the two soils is shown in Table 5 separately for the two sets of samples. Pore volume, water-holding capacity and apparent specific gravity have been selected for this study since they were determined largely from independent measurements and adequately represented the entire set of physical properties. Some purely arithmetic correlations could be expected from the remaining values since three initial measurements were used to give six criteria.

The three measurements analyzed in Table 5 represent different aspects of the same physical properties as measured by three criteria in common use. The two series corroborated one another very well and the differences between them could be ascribed largely to the man-

TABLE 5. PHYSICAL PROPERTIES OF THE SOIL-IN-PLACE SAMPLES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM. (Based upon data from which the means in Table 4 were computed)

Samples collected in	Variation due to	Degrees of freedom	Pore volume percent		Water holding capacity on weight basis, percent		Apparent sq. gr. (volume weight)	
			Mean Square	Observed F	Mean Square	Observed F	Mean Square	Observed F
250 cc. cylinders from the middle of the horizons at various depths below the surface of the soil	Types of soil	1	6.96	3.88	15.69	2.74	0.01416	8.33[1]
	Plot error	10	1.79		5.72		0.00170	
	Soil horizons	1	377.94	53.07[2]	925.04	110.65[2]	0.19929	81.88[2]
	Interaction of soils and horizons	1	124.58	17.49[2]	360.37	43.11[2]	0.09538	39.91[2]
	Subplot error	10	7.12		8.36		0.00243	
	Total	23						
1,000 cc. cylinders at a fixed depth below the surface of the soil	Types of soil	1	28.52	5.42[1]	151.87	10.10[1]	0.13574	35.53[2]
	Plot error	8	5.27		15.03		0.00382	
	Depths below surface	2	231.78	45.40[2]	473.87	40.54[2]	0.11693	63.55[2]
	Interaction of soils and depths	2	39.96	7.83[2]	103.78	8.88[2]	0.03925	21.33[2]
	Subplot error	16	5.11		11.69		0.00184	
	Total	29						

[1] Significant at the 5 percent level.

[2] Significant at the 1 percent level.

ner of collecting the samples. With the 1000 cc. cylinders and hence larger, less-distorted samples, the differences between soil types were all significant as compared with their errors. With the smaller samples collected in cylinders one-fourth as large, the differences between soil types were not well enough established to be significant, except for the apparent specific gravity.

The use of fixed depths with the larger cylinders, on the other hand, did not isolate the characteristics of the soil horizons as well as the smaller cylinders, where each horizon was sampled separately. All three criteria differed between horizons or depths very significantly and these differences were unequal in the two soil types to a high level of certainty for both sizes of cylinders.

The analysis in Table 5 led to the following conclusions. Combining depths or horizons, Charlton fine sandy loam had higher pore volume percentages, greater water-holding capacity and smaller apparent specific gravity than Merrimac loamy sand. Both the percentage of pore volume and of water-holding capacity decreased at greater depths or lower horizons, while the apparent specific gravity increased. The change in these same characteristics with depth or horizon was consistently greater in the Charlton fine sandy loam than in the Merrimac loamy sand.

TABLE 6. MECHANICAL ANALYSIS AND MOISTURE EQUIVALENT VALUES FOR MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM SOILS. (Values represent percentages of dry weight; based on composite samples.)

Soil type and profile	Soil horizon	Gravel 2 mm percent	Composition of material less than 2mm.				Moisture equivalent percent
			Sand percent	Silt percent	Clay percent	Bouyoucos colloid equivalent percent	
Merrimac loamy sand (Typical profile)	A	0.35	74.6	20.2	5.2	10.0	13.11
	B_1	0.50	79.5	16.6	3.9	7.3	8.82
	B_2	1.46	85.7	12.0	2.3	4.4	4.59
	C_1	3.67	88.7	9.8	1.5	3.2	3.88
Merrimac loamy sand (Atypical profile)	A	0.33	75.1	19.8	5.1	10.2	13.56
	B_1	0.42	74.4	20.6	5.0	10.0	11.56
	B_1-d	0.23	79.0	17.1	3.9	8.0	9.50
	B_2	1.10	85.7	12.0	2.3	5.4	5.40
	C_1	2.37	88.4	9.8	1.8	3.2	3.76
Charlton fine sandy loam (Typical profile)	A	4.01	56.6	33.5	9.9	22.4	21.48
	B_1	5.42	58.8	29.4	11.8	21.2	13.68
	B_2	6.00	63.0	24.7	12.3	17.9	10.33
	C_1	5.77	60.6	21.0	18.4	25.1	13.08

All physical properties of soil-in-place samples, with the exception of water-holding capacity on a weight basis, tended to differ in the A horizons of both soils more than in the B_1 horizons. In seeking an explanation of this condition it must be noted that Charlton soil showed signs of greater biological activity than the Merrimac soil. Higher total nitrogen percentages in the Charlton soil, which will be discussed later, also point to the greater biological activity in this soil.

TABLE 7. MECHANICAL ANALYSIS AND MOISTURE EQUIVALENT VALUES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM IN THE DIFFERENT HORIZONS FOR SOIL MATERIAL FOR ZONES OF ROOT CONCENTRATIONS AND FROM ADJACENT ZONES WHERE ROOTS WERE FEW OR LACKING.

(Based on composite samples collected separately for five tree species)

Soil type and profile	Tree species	Soil horizon	Soil material from zones of root concentration					Soil material from zones with few or no roots				
			Sand percent	Silt percent	Clay percent	Bouyoucos colloid equiv. percent	Moisture equiv. percent	Sand percent	Silt percent	Clay percent	Bouyoucos colicid equiv. percent	Moisture equiv. percent
Merrimac loamy sand (Typical profile)	WP	A	75.9	19.3	4.8	9.1	12.08	77.3	18.5	4.2	9.1	12.46
		B_1	81.6	14.4	4.0	7.2	7.63	82.7	14.7	2.6	6.2	6.59
		B_2	86.5	11.1	2.4	4.6	4.36	88.5	9.9	1.6	3.5	3.93
	RP	A	75.5	19.3	5.2	10.7	12.96	77.8	16.6	5.6	10.4	13.44
		B_1	81.0	15.6	3.4	7.3	7.81	83.3	14.0	2.7	5.5	7.58
		B_2	86.7	10.9	2.4	4.0	4.69	88.5	9.7	1.8	3.5	4.35
	NS	A	77.7	18.4	3.9	8.6	13.13	75.8	19.8	4.4	9.0	13.09
		B_1	81.1	16.4	2.5	6.9	7.90	81.6	15.4	3.0	6.9	8.88
		B_2	87.4	10.9	1.7	4.1	4.38	87.9	10.9	1.2	2.9	4.73
	WA	A	77.8	18.8	3.4	8.1	12.15	77.8	18.0	4.2	8.6	12.00
		B_1	81.2	15.7	3.1	7.4	8.23	80.7	15.5	3.8	6.8	8.58
		B_2	87.7	10.6	1.7	3.5	3.98	91.5	7.3	1.2	2.7	3.51
	RO	A	76.8	19.1	4.1	8.8	13.16	77.0	19.7	3.3	8.5	13.11
		B_1	82.5	14.9	2.6	5.9	8.41	82.7	14.5	2.8	6.3	7.53
		B_2	89.8	9.2	1.0	3.2	4.09	89.6	8.8	1.6	3.8	4.34
	Average of five species	A	76.7	19.0	4.3	9.1	12.70	77.1	18.6	4.3	9.1	12.82
		B_1	81.5	15.4	3.1	6.9	8.00	82.2	14.8	3.0	6.3	7.83
		B_2	87.6	10.6	1.8	3.9	4.30	89.2	9.3	1.5	3.3	4.17
Merrimac loamy sand (Atypical profile)	Irrespective of species	A	75.9	19.6	4.5	9.7	13.48	76.1	19.6	4.3	9.2	13.48
		B_1	75.5	20.6	3.9	9.3	11.38	75.7	21.0	3.3	8.9	11.88
		B_1-d	81.3	16.1	2.6	7.1	8.85	79.7	17.7	2.6	6.6	9.58
		B_2	85.3	12.4	2.3	4.8	5.62	86.2	11.9	1.9	4.4	5.33

Charlton fine sandy loam (Typical profile)	WP	A	55.9	33.1	11.0	21.8	22.42	55.6	37.0	7.4	19.6	21.96
		B_1	56.4	32.2	11.4	23.1	17.06	54.1	35.0	10.9	22.0	16.08
		B_2	63.5	25.7	10.8	17.8	10.78	63.4	24.6	12.0	18.1	10.23
	RP	A	57.6	34.2	8.2	17.5	20.93	57.4	34.2	8.4	20.1	21.30
		B_1	58.4	31.0	10.6	21.5	15.54	61.0	30.8	8.2	17.6	14.46
		B_2	63.0	26.9	10.1	19.3	11.83	62.7	26.4	10.9	17.8	10.92
	NS	A	57.0	35.5	7.5	19.7	21.67	55.6	37.3	7.1	18.7	21.78
		B_1	59.2	31.7	9.1	19.0	15.44	60.5	30.1	9.4	20.5	14.11
		B_2	60.5	28.5	11.0	21.2	11.91	62.5	26.9	10.6	22.4	11.80
	WA	A	54.4	36.2	9.4	21.6	22.08	56.4	35.4	8.2	19.6	22.02
		B_1	56.2	33.5	10.3	19.0	17.00	57.8	30.4	11.8	21.4	14.24
		B_2	60.6	27.5	11.9	21.6	11.88	60.0	26.2	13.8	21.8	11.10
	RO	A	56.8	34.8	8.4	20.7	21.55	57.0	32.2	10.8	21.0	21.97
		B_1	58.9	31.1	10.0	18.2	15.20	57.0	31.2	11.8	19.8	14.28
		B_2	60.7	26.8	12.5	20.1	11.22	59.0	27.3	13.7	21.7	11.62
	Average of five species	A	56.3	34.8	8.9	20.3	21.73	56.4	35.2	8.4	19.8	21.81
		B_1	57.8	31.9	10.3	20.2	16.05	58.1	31.5	10.4	20.3	14.63
		B_2	61.7	27.0	11.3	20.0	11.52	61.5	26.3	12.2	20.4	11.13

All differences of physical properties between horizons ascertained from the analyses of soil-in-place samples point to the much more favorable conditions for root growth in the A horizon. Highly significant interactions between horizons and soils indicate more rapid changes in the physical conditions of Charlton soil from the A to B_1 horizon in comparison to Merrimac soil.

Mechanical Analysis

Textural differences between the two soils were quite pronounced. This can be seen from the field description and from examination of Tables 6 and 7. Gravel coarser than 2 mm. was present in the C_1 horizons in both soils but the amount in Charlton soil was almost twice as great as in Merrimac soil. In the A horizons the two soils differed even more in their gravel content. In Charlton soil it was still high but in Merrimac soil the quantity present was negligible. The three soil fractions of sand, silt, and clay are given as percentages in Table 7. The two controlling components, the sand and clay, reflected the existing differences and have been analyzed statistically in Table 8. The percentage of silt and the Bouyoucos colloid equivalent, which included the clay and the finer part of the silt, are given for descriptive purposes. For the differentiation of soil types, the data from zones with many roots have been added to those from zones with few or no roots for the computations in the upper part of Table 8.

The outstanding difference between the two soil types was the higher percentage of sand and smaller percentage of clay in the Merrimac loamy sand. The percentage of sand rose with increasing depth in both soils but more sharply in the Merrimac loamy sand, both trends being highly significant. The percentage of clay, on the other hand, decreased with depth in Merrimac loamy sand but increased with depth to nearly the same extent in Charlton sandy loam, as shown by a mean square for soil horizons hardly larger than the error coupled with a very significant variance ratio or F for the interaction between soils and horizons. The percentages in the two soils of sand and clay and also of the correlated silt and Bouyoucos colloid equivalent agreed most nearly in the A horizons and diverged progressively at the lower horizons or depths. Field records also had noted a smaller difference in the two soil types in the A than in the C_1 horizon.

The above observations are consistent with the modern theories of pedology. Glinka (15) has shown that, regardless of the parent material, undisturbed soils under the same climatic conditions will in time become essentially the same. The two soils in this investigation have different parent material, but they were located only 20 miles apart. Since there was a variation of some 450 feet in elevation between the two areas, some local climatic differences undoubtedly existed, but the general climantic conditions were very much alike; hence the two soils tended to become similar. The A horizons, being most exposed to the elements, showed the greatest response to the climate; B_1 horizons, being more protected, displayed effects of climate to a lesser degree, and the C_1 horizons least of all.

TABLE 8. ANALYSIS OF VARIANCE FOR MECHANICAL ANALYSIS AND MOISTURE EQUIVALENT VALUES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM IN THE DIFFERENT HORIZONS FOR SOIL MATERIAL FROM ZONES OF ROOT CONCENTRATION AND FROM ADJACENT ZONES WHERE ROOTS WERE FEW OR LACKING.

(Based upon the data in Table 7)

Variation due to	Degrees of freedom	Sand percent		Clay percent		Moisture equivalent percent	
		Mean Square	Observed F	Mean Square	Observed F	Mean Square	Observed F
Types of soil	1	8,468.07	2,288.67[2]	784.817	2,864.30[2]	922.768	1,178.509[2]
Soil horizons	2	354.00	95.68[2]	0.331	1.21	454.742	580.77 [2]
Tree species	4	1.83	0.49	2.147	7.84[2]	0.137	0.02
Interaction between							
soils and horizons	2	48.89	13.21[2]	41.201	150.37[2]	5.244	6.70 [1]
soils and species	4	5.34	1.44	3.890	14.20[2]	0.946	1.21
horizons and species	8	1.57	0.42	0.502	1.83	0.382	0.05
Error (interaction of soils, horizons, and species)	8	3.70		0.274		0.783	
Zones of root concentration differences	1	3.46	3.23	0.007	0.01	1.498	9.73 [2]
Interaction between zones of root concentration							
and soils	1	2.65	2.48	0.416	0.62	1.014	6.58 [1]
and horizons	2	0.30	0.28	0.339	0.50	1.001	6.50 [2]
and tree species	4	1.77	1.65	1.606	2.39	0.209	1.36
and soils and horizons	2	0.73	0.68	1.107	1.65	0.514	3.34
Error (other interactions)	20	1.07		0.672		0.154	
Total	59						

[1] Significant at the 5 percent level.

[2] Significant at the 1 percent level.

No relation would be expected between species of tree and soil texture if the trees were well interspersed in the planting on each soil. The percentage of sand did not differ between species, but the percentage of clay showed a highly significant variation between soil types for the five species. The relatively larger interaction between species and soils alone would indicate an unequal distribution of trees selected for study rather than differential survival related to the percentage of clay.

In contrast with the relation between tree species and their interaction with the type of soil, the textural differences between zones of high and low root concentration are of direct biological interest. If any of the mean squares in the lower half of Table 8 for percentage of sand or of clay were significant, it would indicate that the growth of roots responded to differences in soil texture. Since none of the differences exceeded their errors significantly, the roots of these 5 species did not react differentially to soil texture in this investigation.

Moisture Equivalent

Moisture equivalent values are considered to be of importance as an indication of the capacity of soil to hold water. A high content of organic and inorganic colloids results in high moisture equivalent values. Moisture equivalent values for Merrimac loamy sand and Charlton fine sandy loam are shown in Tables 6 and 7. Analysis of variance of 60 soil samples is presented in Table 8.

Moisture equivalent values for the Charlton soil were much higher than those for the Merrimac soil and in both types dropped off sharply in the lower horizons, both effects being highly significant. Not only were the moisture equivalent percentages smaller in the Merrimac loamy sand but they fell off more rapidly in the lower horizons. The atypical profiles of the Merrimac soil showed larger moisture equivalent values in all horizons than the typical profiles, especially in the B_1 and $B_{1\text{-}d}$ levels (Table 6). Presumably the atypical profiles had more favorable moisture relations for root development. In the C_1 horizon, which was not included in the statistical analysis, the moisture equivalent in Charlton soil exceeded that for the B_2 horizon, which may be attributed to the high percentage of inorganic colloids in the glacial till of the C_1 layer.

Moisture equivalent values averaged significantly higher in zones with many roots than in neighboring soil zones with few or no roots, emphasizing the importance of soil moisture in the economy of trees. The contrast in moisture equivalent between the two zones was several times more marked in the heavier Charlton fine sandy loam with its two-fold high percentage of moisture equivalent values than in the lighter Merrimac loamy sand. Root growth proved more sensitive to moisture relations in the heavier soil. The significant interaction in Table 8 between root zones and soil horizons showed that the response varied with depth. Two zones of root concentration had nearly the same moisture equivalent in the A horizon, but differed markedly in the B horizons, the difference being most pronounced at the B_1 level in the heavier Charlton soil and at the B_2 level in the lighter Merrimac loamy sand. This finding is consistent with that of Lutz et al. (25), who found that moisture equivalent values were unmistakably higher for zones with many roots, especially in the lower soil horizons.

Several investigators, Morgan (27) and others, have noted that a degree of correlation exists between moisture equivalent values and other properties of soils. The large number of soil samples analyzed in this investigation offered an opportunity to test the direct correlation existing between moisture equivalent values and other soil properties. The highest correlation coefficient ($r = 0.907$) was found for the loss on ignition. Since loss on ignition largely reflects the presence of organic matter in the soil, it can be well understood why it was closely related to the moisture equivalent. The content of organic matter in turn may account for the related values of total nitrogen and of total base capacity found in the soil sample analyses. The correlation coefficient between moisture equivalent and total nitrogen was 0.834, and between moisture equivalent and total base capacity it was 0.871. Moisutre equivalent with Bouyoucos colloid equivalent values gave a smaller correlation coefficient of 0.778 which would be expected, since not only organic colloids but also inorganic colloids are involved in the latter. All of the correlations thus found to exist between moisture equivalent and other soil properties are in general agreement with those given by Morgan (27).

Chemical Properties

Analyses of Certain Chemical Elements in the Two Soils

Earlier authors placed more stress on the chemical relationships of forest soils than is done now. Exception is made in the case of nitrogen which is still considered to be important. It was decided to compare the two soils under investigation for some of the more important chemical elements. The results of these analyses are shown in Table 9.

The A horizons of the two soils agreed closely with respect to total calcium, potassium, magnesium and phosphorus. The first three of these elements did not vary to any appreciable extent between horizons in Merrimac loamy sand. In Charlton fine sandy loam there was some increase in these elements from the A to B_2 horizon, but a very sharp rise occurred in the C_1 horizon. The percentage of total phosphorus decreased in both soils from the A to lower horizons, but in Charlton soil increased again in the C_1 horizon. The total amounts of calcium, potassium, magnesium and phosphorus in the two soils and several horizons differed much less than the physical properties. Differences in the distribution of tree roots between the two soils and the soil horizons, which will be discussed later, were not related to the amounts of these chemical elements in the soil.

The absence of differences in these elements in the A horizons of the two soils is not in harmony with the fact that the parent material of the two soils differs in mineral composition, as attested by the chemical differences in the C_1 horizons. Total calcium, potassium,

TABLE 9. CHEMICAL PROPERTIES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM SOILS.
(Values represent percentages or parts per million of dry weight; based on composite samples.)

Soil Type and Profile	Soil horizon	Loss on ignition percent	Total calcium percent	Total potassium percent	Total magnesium percent	Total phosphorus percent	Total nitrogen percent	Exchangeable calcium p. p. m.	Replaceable potassium p. p. m.	Soluble phosphorus p. p. m.	Hydrogen ion concentration (pH)	Total exchange capacity m. e.[1]	Base saturation percent
Merrimac loamy sand (Typical profile)	A	4.42	1.02	2.07	0.45	0.085	0.130	156	30	21	5.28	8.08	29.83
	B_1	2.33	0.91	2.00	0.44	0.062	0.045	98	24	25	5.51	3.54	30.51
	B_2	1.06	0.97	1.92	0.41	0.040	0.014	79	24	23	5.62	2.14	46.73
	C_1	0.77	0.89	2.11	0.45	0.036	0.010	65	19	18	5.68	1.20	33.33
Merrimac loamy sand (Atypical profile)	A	4.71	0.94	1.87	0.48	0.091	0.132	231	31	20	5.28	8.75	35.20
	B_1	3.10	0.82	2.02	0.47	0.067	0.068	154	25	21	5.47	5.33	31.89
	B_{1-d}	2.92	0.90	1.96	0.53	0.066	0.058	185	50	22	5.52	6.31	41.52
	B_2	1.37	0.92	1.97	0.50	0.044	0.022	101	22	21	5.59	2.50	45.60
	C_1	0.86	0.83	2.05	0.42	0.041	0.011	68	18	17	5.64	1.53	36.60
Charlton fine sandy loam (Typical profile)	A	7.94	0.94	2.09	0.46	0.090	0.242	205	67	10	5.16	11.55	29.18
	B_1	2.83	0.92	2.34	0.62	0.046	0.042	147	38	13	5.41	3.58	25.42
	B_2	1.64	0.99	2.85	0.64	0.049	0.012	218	67	35	5.48	3.08	30.19
	C_1	1.70	1.75	2.99	0.84	0.056	0.005	782	189	79	5.56	5.23	63.29

[1] m. e. signifies milligram equivalents per 100 grams of dry soil.

magnesium and phosphorus were considerably higher in this horizon for Charlton fine sandy loam. Differences in the amounts of these elements in the two soils were to a considerable degree obliterated in the process of soil formation, just as in the case of the differences in texture.

Values for exchangeable calcium and potassium were considerably lower in the Merrimac soil and decreased gradually from the A to the C_1 horizon. This indicates some improvement in the A horizon. In Charlton soil with higher levels of the two elements, the lowest values for exchangeable calcium and potassium existed in the B_1 horizon. The A and B_2 horizons agreed closely, but exceptionally high values for exchangeable calcium and potassium were recorded in the C_1 horizon of Charlton fine sandy loam. This appears to be due to a high content of exchangeable calcium and potassium in the glacial till of this horizon.

The atypical profile of Merrimac soil showed a greater amount of calcium in all horizons. There was an especially noticeable increase in exchangeable calcium and potassium in the dark $B_{1\text{-}d}$ horizon. This layer had an abundance of these two elements in an available form. Values for soluble phosphorus were almost the same for all horizons for both the typical and atypical profiles in Merrimac soil.

Soluble phosphorus was higher in the B_1 horizon in Merrimac soil, and it fell in the A and other horizons. The A horizon in Charlton soil had less soluble phosphorus than the A horizon in Merrimac soil. In proceeding from the A to C_1 horizon in this soil there was an increase in soluble phosphorus. In Charlton fine sandy loam this element was highest of all in the C_1 horizon, paralleling replaceable potassium and calcium in this respect.

Loss on Ignition

Loss on ignition depends on the organic matter of the soil, clay materials containing combined water, and changes in the state of oxidation of the soil constituents. It serves as a useful joint measure of the organic matter and a portion of the inorganic colloids. It is only a rough measure of the soil organic matter. Loss on ignition for the two soils is shown in Tables 9 and 10. The analysis of variance of 60 soil samples is shown in Table 11.

The differences between the two soils, between the soil horizons, and interaction between soils and horizons were highly significant. Loss on ignition was much higher for the Charlton fine sandy loam than for Merrimac loamy sand and decreased rapidly from the A to the lower horizons. Values in the A horizon for the two soils were quite different, being higher for Charlton fine sandy loam. However, the loss on ignition for this soil decreased in the B_2 horizon to values approaching those obtained in the Merrimac soil. The atypical profile of Merrimac's soil showed higher values in the B_1 and $B_{1\text{-}d}$ horizons, as compared to the typical B_1 horizon. In Charlton soil high loss on ignition in the C_1 horizon should be especially noted. It cannot be due to the organic matter. Apparently the high percentage

TABLE 10. CHEMICAL PROPERTIES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM IN THE DIFFERENT HORIZONS FOR SOIL MATERIAL FROM ZONES OF ROOT CONCENTRATION AND ADJACENT ZONES WHERE ROOTS WERE FEW OR LACKING.

(Based on composite soil samples collected separately for five tree species.)

Soil type and profile	Tree species	Soil horizon	Soil material from zones of root concentration					Soil material from zones with few or no roots				
			Loss on ignition percent	Total nitrogen percent	pH values	Total exchange capacity m. e.[1]	Base saturation percent	Loss on ignition percent	Total nitrogen, percent	pH values	Total exchange capacity, m. e.	Base saturation percent
Merrimac loamy sand (Typical profile)	WP	A	4.70	0.122	5.27	7.50	28.9	4.40	0.120	5.30	7.58	30.7
		B_1	2.36	0.042	5.46	3.54	32.8	2.02	0.042	5.53	3.15	34.0
		B_2	1.20	0.015	5.61	1.36	23.5	1.00	0.017	5.57	1.21	23.1
	RP	A	4.62	0.127	5.29	8.17	30.6	4.53	0.123	5.30	8.08	32.4
		B_1	2.40	0.042	5.49	3.65	35.3	2.14	0.041	5.50	3.65	34.8
		B_2	1.59	0.022	5.56	1.57	24.8	1.11	0.015	5.55	1.57	29.3
	NS	A	4.72	0.124	5.30	8.25	35.9	4.58	0.118	5.29	8.25	36.4
		B_1	2.16	0.036	5.52	3.62	34.3	2.27	0.037	5.60	4.08	41.7
		B_2	1.22	0.016	5.66	2.14	53.3	1.15	0.013	5.68	2.07	44.9
	WA	A	4.46	0.126	5.25	7.42	33.2	4.31	0.115	5.28	7.25	31.0
		B_1	2.19	0.037	5.50	3.77	37.4	2.11	0.042	5.50	3.62	32.0
		B_2	1.23	0.017	5.60	1.93	51.8	0.70	0.013	5.64	1.57	45.2
	RO	A	4.38	0.123	5.29	7.67	28.3	4.38	0.124	5.20	7.17	23.9
		B_1	2.13	0.043	5.58	3.69	33.3	1.81	0.038	5.53	3.08	27.6
		B_2	0.96	0.014	5.64	1.93	51.8	1.11	0.015	5.61	1.71	37.4
	Average of five species	A	4.58	0.124	5.28	7.80	31.4	4.44	0.120	5.27	7.67	31.2
		B_1	2.25	0.040	5.51	3.65	34.5	2.07	0.040	5.53	3.52	34.4
		B_2	1.24	0.017	5.61	1.79	43.0	1.01	0.015	5.61	1.63	37.4
Merrimac loamy sand (Atypical profile)	Irrespective of species	A	4.64	0.121	5.31	8.55	34.7	4.56	0.128	5.32	8.33	34.9
		B_1	3.43	0.077	5.24	5.58	31.4	3.32	0.070	5.44	5.25	30.9
		B_1-d	2.69	0.062	5.55	6.38	42.2	2.99	0.066	5.53	6.96	43.7
		B_2	1.34	0.027	5.60	2.75	45.5	1.33	0.021	5.56	2.50	45.6

Charlton fine sandy loam (Typical profile)	WP	A	8.08	0.247	5.15	11.73	31.0	7.90	0.230	5.17	11.41	31.5
		B_1	4.11	0.068	5.39	4.83	25.9	3.69	0.063	5.43	4.58	25.3
		B_2	2.26	0.018	5.43	3.08	32.5	1.95	0.011	5.44	3.38	38.5
	RP	A	7.47	0.229	5.13	10.82	29.4	7.21	0.227	5.18	11.45	31.7
		B_1	3.11	0.053	5.41	4.17	26.1	2.81	0.047	5.42	3.58	34.9
		B_2	2.03	0.017	5.47	3.54	28.3	1.79	0.012	5.52	3.23	33.4
	NS	A	8.12	0.236	5.13	12.09	32.3	7.66	0.227	5.19	11.82	30.8
		B_1	3.67	0.061	5.41	4.17	34.0	2.92	0.038	5.42	3.96	35.9
		B_2	2.11	0.008	5.51	2.46	32.9	2.00	0.008	5.50	3.23	39.3
	WA	A	9.04	0.259	5.29	12.00	35.6	8.43	0.241	5.29	12.18	37.3
		B_1	3.98	0.079	5.48	6.25	44.0	3.56	0.064	5.49	5.00	30.0
		B_2	2.30	0.016	5.52	4.15	44.3	1.74	0.008	5.58	3.85	48.0
	RO	A	8.40	0.240	5.20	12.00	31.8	8.36	0.223	5.21	12.45	34.3
		B_1	3.26	0.057	5.44	4.33	26.8	2.48	0.046	5.39	3.50	21.4
		B_2	1.80	0.009	5.50	3.54	47.7	1.64	0.006	5.52	2.92	35.6
	Average of five species	A	8.22	0.242	5.18	11.73	32.1	7.91	0.230	5.21	11.86	33.1
		B_1	3.63	0.064	5.43	4.75	32.2	3.09	0.052	5.43	4.12	29.4
		B_2	2.10	0.014	5.49	3.35	37.6	1.82	0.009	5.51	3.32	39.5

---

[1] m. e. stands for milligram equivalents per 100 gms. of soil.

TABLE 11. ANALYSIS OF VARIANCE FOR CHEMICAL PROPERTIES OF MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM IN THE DIFFERENT HORIZONS FOR SOIL MATERIAL FROM ZONES OF ROOT CONCENTRATION AND FROM ADJACENT ZONES WHERE ROOTS WERE FEW OR LACKING.

(Based upon the data in Table 10)

Variation due to	Degrees of freedom	Loss on ignition percent		Total nitrogen percent		Hydrogen ion concentration pH values		Total exchange capacity, m. e.[1]		Base saturation percent	
		Mean Square	Observed F	Mean Square	Observed F	Mean Square	Observed F	Mean Square	Observed F	Mean Square	Observed F
Types of soil	1	52.155	478.92[2]	0.0268394	997.75[2]	0.13920	79.36[2]	71.395	301.45[2]	14.00	0.33
Soil horizons	2	121.405	1114.83[2]	0.1520596	5652.77[2]	0.55361	315.63[2]	292.579	1235.36[2]	256.19	6.07[3]
Tree species	4	0.203	1.86	0.0001309	4.87[3]	0.00642	3.66	0.481	2.03	201.38	4.77[3]
Interaction between											
soils and horizons	2	10.932	100.39[2]	0.0197224	733.17[2]	0.00117	0.66	14.005	59.13[2]	36.32	0.86
soils and species	4	0.418	3.84[3]	0.0001545	5.74[3]	0.00689	3.93[3]	1.014	4.28[3]	36.63	0.87
horizons and species	8	0.147	1.35	0.0000342	1.27	0.00104	0.59	0.258	1.09	84.90	2.01
Error (interaction of soils, horizons an species)	8	0.109		0.0000269		0.00175		0.237		42.18	
Zones of root concentration differences	1	1.148	51.03[2]	0.0005340	37.61[2]	0.00204	3.71	0.383	5.83[3]	10.84	0.90
Interaction between zones of root concentration											
and soils	1	0.140	6.23[2]	0.0002128	14.99[2]	0.00088	1.60	0.003	0.05	21.48	1.78
and horizons	2	0.025	1.09	0.0000326	2.30	0.00001	0.01	0.197	2.92	5.07	0.42
and tree species	4	0.017	0.75	0.0000086	0.61	0.00177	3.21[3]	0.128	1.95	53.01	4.40[3]
and soils and horizons	2	0.030	1.32	0.0000292	2.06	0.00105	1.90	0.203	3.09	21.36	1.77
Error (other interactions)	20	0.023		0.0000142		0.00055		0.066		12.03	
Total	59										

[1] m. e. stands for milligram equivalents per 100 gms. of soil.

[2] Significant at the 1 percent level.

[3] Significant at the 5 percent level.

of hydrated inorganic colloids in the C_1 horizon influenced the loss on ignition values for this soil.

The difference in loss on ignition between zones of root concentration and soil zones lacking roots was highly significant. It indicated that the roots were concentrated in the zones with greater content of organic matter. The significant interaction between the two soils and root zones was due to a relatively greater difference in Charlton fine sandy loam than in Merrimac loamy sand.

Total Nitrogen

Total nitrogen in the soil is of considerable importance and has a bearing on its fertility. Nitrogen is an element important for plant growth. Total nitrogen percentages for Merrimac loamy sand and Charlton fine sandy loam are given in Tables 9 and 10. Analysis of variance of total nitrogen for 60 soil samples is given in Table 11. The difference between the two soils was highly significant, the total nitrogen being much higher in Charlton fine sandy loam.

The fall in total nitrogen from horizon A to B_1 and B_2 was exceptionally large and approximately in geometric proportion. High significance of the interaction between the two soils and horizons was due to a much sharper drop in nitrogen from A to B_2 in Charlton fine sandy loam than in the Merrimac soil. Nitrogen values for the two soils in the B_2 horizon were nearly alike, but in the A layer they were about twice as high for Charlton soil. In C_1 total nitrogen for Charlton soil was even less than in Merrimac soil. The atypical profile of Merrimac soil showed considerably more nitrogen in the B_1 and $B_{1\text{-}d}$ horizons, as compared to the typical B_1 horizon.

Several investigators have pointed out the favorable influence of nitrogen on tree root development. When roots die they contribute organic matter to the soil. Organic matter and decomposition products increase the nitrogen content. Total nitrogen in the soil zones of high root concentration can be either the cause or the effect of the roots present. In the young forest stand used for this study higher total nitrogen percentages occurred in the zones of root concentration than in the soil zones where roots were few or lacking. The difference in total nitrogen values between soil samples from the two zones was statistically highly significant.

In Merrimac loamy sand the difference in total nitrogen between areas of high root concentration and those of low root concentration was rather small, but in Charlton fine sandy loam the difference was significantly larger. Mycorrhizae were present in the Merrimac soil in conspicuously large numbers. At times, in the open transects in the field, it appeared that almost all small roots in this soil were mycorrhizal. According to Hatch (17) mycorrhizal roots, by means of the increased absorbing surface, are able to extract the needed nutrients from the soil more effectively than other types of roots. Thus large differences in nitrogen between the two zones would be less expected in Merrimac soil. In the Charlton soil, where mycorrhizae were few, the association of high nitrogen values with the zones of root concentration was more in evidence, a reasonable result from the above assumption.

Differences in total nitrogen percentages between the tree species and interaction between tree species and the types of soil were significant. For white pine and white ash, the soil samples from the zones of high root concentration, showed more total nitrogen, particularly in the Charlton soil, in comparison to corresponding samples for the other tree species. The larger size of the white pine and the greater tendency of white ash trees to build up nitrogen may explain the situation. Soil samples taken around red pine roots on Merrimac soil showed high values; those taken in Charlton soil showed low values as compared to other species.

Hydrogen Ion Concentration (pH Values)

Slight variations in acidity within the limits usually found in nature are not considered decisive, as has been indicated in the review of literature. Acidity is readily measured with modern pH meters and is considered necessary for a complete description of any soil. Hydrogen ion concentration (pH values) for the two soils is given in Tables 9 and 10. Analysis of variance of pH readings for the 60 soil samples in Table 10 is given in Table 11. The higher pH of Merrimac loamy sand was highly significant in comparison to Charlton fine sandy loam, indicating that the latter was the more acid.

The differences in pH between horizons were highly significant but the interaction between soils and horizons was less than the "error." The two soils paralleled one another in showing a relatively high acidity in the top layers, which decreased with increasing depth. The two soils investigated belong to the Brown Podzolic group, and similar soils were classified by Lunt (22) as having a mull type of humus layer. In this type of soil a somewhat higher acidity would be expected in the top layers than in the parent material of the C horizon. The atypical profile in Merrimac soil showed practically no difference in the acidity of its B_1 and B_{1-4} horizons as compared to the B_1 horizon of the typical profile.

The average difference in pH between zones of high and low root concentration was too small to be considered significant, but a comparison of the five species showed in both soils a higher acidity in zones with many roots than in zones with few roots for all species except red oak. In red oak this relation was reversed, the zones with many roots being significantly less acid.

Base Exchange Values

Base exchange relations are receiving increasing attention in more recent investigations, as has been pointed out in the review of literature. Total exchange capacity, exchangeable hydrogen, exchangeable bases and percentages of base saturation were given attention in this investigation. Data concerning the base exchange values for the two soils are given in Tables 9 and 10, and the analysis of variance of 60 soil samples in Table 11.

The total exchange capacity was significantly higher for Charlton fine sandy loam than for Merrimac loamy sand but in the percentage of base saturation the two soils were alike. Total exchange capacity decreased sharply from the A to C_1 horizon, while base saturation percentage increased with increasing depth. There was an exception in the B_1 horizon for Charlton soil, which was due presumably to the low content of exchangeable calcium and potassium noted before. In the atypical profile of Merrimac soil the B_1 and particularly the B_{1-d} horizons showed exceptionally high base saturation values. This again coincides with the exceptional values for exchangeable calcium and potassium in this horizon. The total exchange capacity in Charlton fine loamy sand dropped notably between the A and B_1 horizons, and comparatively little from B_1 to B_2, while in Merrimac loamy sand it decreased at a geometric rate from the A to C_1 horizon.

The total exchange capacity differed significantly between the zones of high and low root concentration and was relatively high in the zones with many roots. These results support the conclusion reached by Lutz, et al. (25), who found in older stands of white pine a significantly higher total exchange capacity in the zones of high root concentration than in the soil zones with few or no roots. They concluded that high values of this property favored the development of roots. Although closely similar in the A horizons, in the B_2 and particularly in the B_1 horizons total base capacity in the zones with many roots was considerably higher than in comparable soil zones with few or no roots. Apparently base exchange values were of greater importance for the development of the roots of trees in the lower soil layers. Significance of interaction between soil types and tree species brings out the facts that total exchange capacity values in the Merrimac soil were high for Norway spruce and low for white pine as compared to other species. In the Charlton soil these values were high for white ash and low for red pine.

Differences in the percentage of base saturation between zones with few and many roots varied significantly with the species of tree. The zones of high root concentration for white ash and red oak had a higher percentage of base saturation than zones with few or no roots, while the reverse was true for red pine. White pine and Norway spruce showed no apparent "preference."

From the data on the various soil properties it can be concluded that, aside from a few chemical similarities, the Merrimac loamy sand and the Charlton fine sandy loam differed in practically all soil qualities investigated. Differences in some of the soil properties definitely favored the concentration of tree roots.

Root Distribution in the Two Soils

Maps or root charts prepared in the field offered an opportunity to study variations in the distribution of tree roots. After defining the differences between the two soils and several soil horizons and measuring their significance, it was concluded that not one soil property, but the entire complex of properties, was responsible for the differences in root distribution.

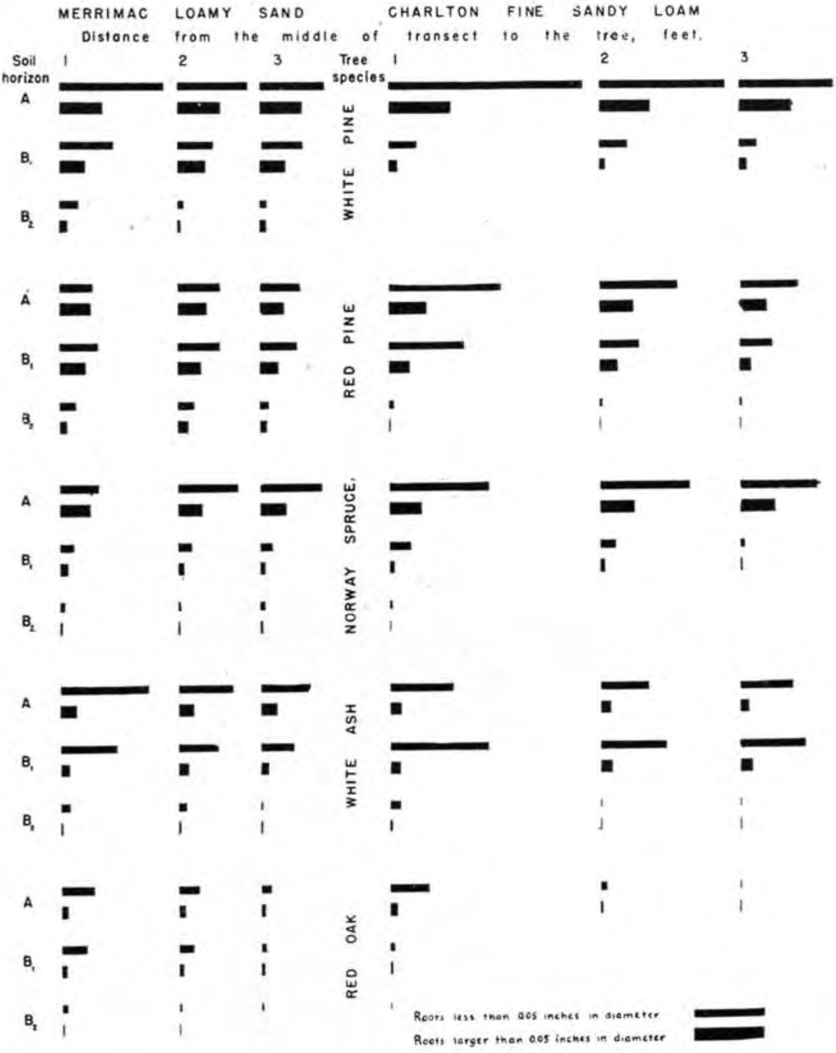

Figure 10. Number of roots in two size classes in vertical sections of soil profile horizons in Merrimac loamy sand and Charlton fine sandy loam. (Based on the count of roots in vertical cross-sections surrounding eight trees of each species.)

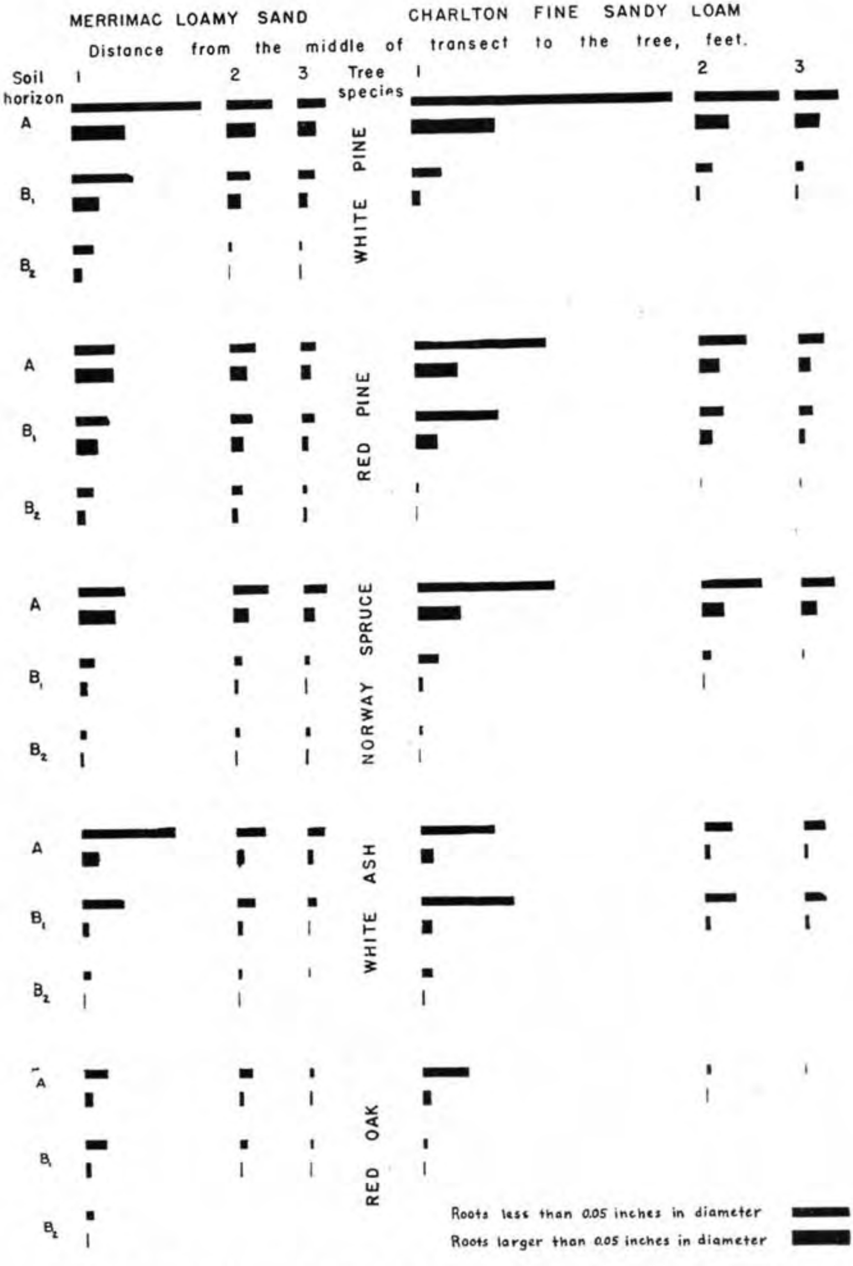

Figure 11. Number of roots in two size classes per square foot of areas of soil profile horizons in Merrimac loamy sand and Charlton fine sandy loam. (Based on vertical cross-sections surrounding eight trees of each species.)

Three sample root charts are given in Figures 4, 5 and 6. Root maps prepared in the field were used to count tree roots and to determine soil horizon areas. The number of tree roots and the roots per square foot of exposed soil horizon were tabulated. The resulting data are presented graphically in Figures 10 and 11. Photographs of the central root mass, (Figures 12 to 21, inclusive), illustrate the root distribution. In these photographs the small flexible roots do not retain their horizontal position but droop down under their own weight, thus giving the suggestion of somewhat deeper root penetration than was actually the case.

Distribution of All Roots

The maps and diagrams show that roots in Merrimac loamy sand reached much deeper than they did in Charlton fine sandy loam. Roots of trees in this sandy soil not only penetrated the A and B_1 horizons in larger numbers but even reached the C_1 horizon. Comparison of photographs of the central root mass confirms this observation. In the review of literature Laitakari (19) was cited as expressing the view that the deepest root systems occurred in sandy soils and that they decreased in depth in clayey soils. This fact stands out clearly in the present investigation. This also was an important factor contributing to the development of shallow root systems in that soil.

There was a proportionately greater number of large roots in Merrimac loamy sand than in the Charlton soil. This fact leads to another conclusion, previously expressed by Laitakari (19), i. e., roots of trees growing on light sandy soils do not branch as much as they do in rich soils. More large roots were encountered in the transects in Merrimac loamy sand than in other soils. As the photographs show, branching in this soil was not as extensive as in the other soil, but the roots that were present were larger in size and more widespread.

A very rapid decrease in the total number of small and large roots from the A to B_1 and B_2 horizons stands out clearly. This supports the conclusion reached by Lutz, et al., (25) that most of the tree roots are found in the A and B horizons in forest soils. However, the proportion of large roots in the lower horizons was greater than in the top soil layers. The decrease in the number of roots in the lower horizon was even more noticeable in their distribution per square foot of vertical horizon areas. The rate of decrease between horizons was much more rapid in the Charlton than in the Merrimac soil.

Comparisons of root distribution in three transects, at 1, 2 and 3-foot distances from the trees, showed that the trees in Merrimac loamy sand have a proportionately greater number of roots at a greater distance from the stems than is the case in Charlton soil. This is particularly true for the large size roots. It supports the view of Aaltonen (2) that roots of trees spread widely in light sandy soils which are poor in nutrients; in heavy soils, rich in nutrients, the root spread is less. The fact that roots reached deeper in Merrimac loamy sand indicated that the total volume of soil occupied by the roots of an individual tree was much greater in the Merrimac loamy sand than in Charlton fine sandy loam.

A comparison of the three transects, 1, 2 and 3 feet from the tree, showed that the number of roots differed less between horizons at the greater distances from the tree. The roots penetrate more deeply and a relatively smaller number of them remained in the A and B_1 horizons, as compared to the B_2. This held true both for the total number of roots and for the number of roots per square foot of the vertical areas. At the same time the proportion of large roots increased at the greater distances.

In addition to these observations there was a tendency for the root crowns in Charlton soil to produce heavy branching in two horizontal planes. Not all trees showed this but there were enough of them to make it noticeable. On examining corresponding field maps of the transects these two planes appeared to be at a more or less consistent depth. Heavy branching was in evidence in the A horizon just under the sod and at the boundary of the A and B_1 horizons. This resulted in a very distinct two-layered root system for some trees. Evidently the heavier branching occurred at those levels where the greatest quantity of nutrients was available.

In Merrimac soil special attention was given to the atypical sections of the soil profile. In counting roots of trees on the root charts, sections of transects having the atypical pattern were separated so that they could be compared with the typical profiles. Three tree species—red pine, white ash and red oak—had a heavier concentration of roots in the B_1 and B_{1-d} horizons of the atypical section of profiles, in comparison to the corresponding B_1 horizon of the typical sections of profiles. As shown later, these species had a higher proportion of their roots in the B_1 horizon. Red pine showed a most pronounced tendency in this respect. Moreover, red pine roots not only concentrated in the B_1 and B_{1-d} horizons of the atypical sections of profiles, but they were fewer in the A horizon of the atypical profiles than in the A horizon of the typical profiles. It must be recalled that in the analyses of several soil properties the B_1 and, especially, the B_{1-d} horizons proved to be richer in nutrients than the B_1 horizon of the typical profile pattern. On this evidence it can be stated that, if the areas of soil horizons having particularly favorable properties are within the reach of the roots of trees, the roots will have a tendency to concentrate in such areas. The presence of such areas in the lower horizons offers special opportunity for the species of trees with deep root systems.

Distribution of Small Roots

Data pertaining to the small roots were selected for statistical analysis, omitting those pertaining to large roots for reasons previously mentioned under the heading of statistical analysis. Furthermore, there are important differences in the physiological functions of the two types of roots. There is a generally accepted view that large roots have as their function the anchorage of the trees and conduction of nutrients. Small roots are mainly feeding roots. At what

TABLE 12. HEIGHTS OF INDIVIDUAL TREES, TOTAL NUMBER OF SMALL ROOTS (LESS THAN 0.05 IN. IN SIZE), AND NUMBER OF SMALL ROOTS PER SQUARE FOOT OF VERTICAL HORIZON AREAS IN MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM. (Roots were recorded by soil horizons in three square transects at a distance of one, two and three feet from the middle of each side of transect to the tree).

Tree species	Merrimac loamy sand					Charlton fine sandy loam				
	Height of tree, feet	Number of roots		Number of roots per square foot		Height of tree, feet	Number of roots		Number of roots per square foot	
		Soil horizon					Soil horizon			
		A	B	A	B		A	B	A	B
White pine	5.0	159	31	4.2	0.5	6.0	346	114	10.9	1.7
	8.2	138	350	4.0	4.7	9.0	528	99	16.3	1.6
	6.4	152	62	4.5	0.7	6.7	617	55	17.4	0.7
	6.4	342	117	9.5	1.4	7.8	424	130	15.1	2.2
	7.8	313	172	9.3	1.9	7.1	570	55	14.5	0.7
	8.0	420	323	11.4	3.4	7.1	421	60	12.8	1.0
	6.2	118	86	3.4	0.9	5.2	338	55	10.4	0.8
	6.0	371	473	11.0	4.8	6.3	288	59	8.0	0.9
Av.	6.8	252	202	7.2	2.3	6.9	442	78	13.2	1.2
Red pine	8.5	185	305	4.2	3.3	5.3	143	5	3.5	0.1
	5.0	145	169	4.2	2.6	7.2	415	198	12.1	2.4
	6.8	129	108	3.5	1.8	6.9	243	158	7.6	2.7
	8.3	49	179	1.4	2.1	6.4	217	179	6.4	3.3
	4.7	92	60	6.6	0.9	7.6	258	289	7.4	4.3
	7.7	113	254	3.0	2.8	6.4	349	87	9.1	1.4
	6.0	198	171	5.2	2.1	6.4	243	263	6.6	3.3
	5.0	45	63	1.1	0.7	6.0	258	93	5.7	1.2
Av.	6.5	119	164	3.1	2.1	6.5	266	159	7.2	2.3
Norway spruce	4.7	166	53	2.8	0.5	6.0	131	44	4.1	0.6
	3.6	168	56	4.3	0.9	6.0	239	39	7.1	0.7
	8.9	152	86	4.5	1.6	6.4	470	44	11.0	0.5
	4.2	124	17	3.4	0.3	6.3	285	6	8.1	0.1
	5.3	208	54	5.8	0.9	6.6	233	35	7.0	0.6
	4.2	285	37	7.9	0.7	7.4	301	60	8.9	0.7
	6.0	182	73	5.4	1.4	6.4	214	41	6.8	0.5
	4.7	62	34	1.8	0.6	4.8	412	75	11.9	0.9
Av.	5.2	168	51	4.4	0.8	6.2	286	43	8.3	0.6

White ash		4.6	358	236	6.0	1.5	6.0	169	233	3.7	2.4
		6.5	169	291	5.3	2.0	3.3	47	61	1.4	0.9
		4.0	192	150	4.2	1.6	5.4	300	349	8.5	4.8
		5.1	191	83	5.5	0.9	4.0	229	138	6.7	1.4
		4.5	228	145	4.0	1.3	5.7	234	394	5.2	3.6
		4.0	181	140	5.4	1.3	6.0	216	316	5.5	4.5
		3.4	190	83	4.7	0.7	5.4	121	391	3.2	3.8
		2.4	91	87	2.6	0.9	3.6	73	165	1.8	1.7
	Av.	4.6	200	152	4.7	1.5	4.9	174	256	4.5	2.8
Red ash		2.4	7	3	0.2	0.1	3.2	99	1	2.5	
		4.0	57	62	1.3	0.7	1.4	13	9	0.4	0.1
		2.0	47	18	1.4	0.2	1.2	27	1	0.7	
		4.5	30	131	0.8	1.5	2.4	52	2	1.5	
		3.4	103	47	2.3	0.5	1.0	18	1	0.4	
		4.7	98	106	3.1	1.0	1.4	61	2	1.9	
		2.0	77	19	2.2	0.2	3.8	99	21	3.1	0.3
		2.2	107	44	2.8	0.5	2.0	21	1	0.4	
	Av.	3.2	66	54	1.8	0.6	2.1	49	5	1.3	0.1

root diameter class this distinction must be made is hard to decide. It is fairly safe to assume that all of the smallest were feeding roots.

Data for small roots are given in Table 12, separately for the two soils, five tree species and for the eight individual trees of each species. Roots are reported both in total numbers and in the number of roots per square foot of the vertical horizon areas. Results of the analysis of variance are given in Table 13.

The number of roots was significantly greater in Charlton fine sandy loam than in Merrimac loamy sand. This supports the previous conclusion that, in the richer Charlton soil, copious branching of roots occurred, resulting in a large number of small roots. At this point it will be observed that Merrimac soil, poor in nutrients, supported trees of the same age and about the same size with a lesser number of feeding roots than was the case for Charlton soil. The difference in the total number of small roots in the two soils was significant but the results cannot be considered decisive in view of the fact that there was a difference in the type of small roots in the two soils. In Merrimac loamy sand small roots were predominantly mycorrhizal with large absorbing surface, and in consequence a lesser number of these roots was required to support the trees than in Charlton fine sandy loam. It is believed that the influence of soil fertility is evident primarily in the type of roots developed, and thus only indirectly in the number of roots.

TABLE 13. ANALYSIS OF VARIANCE FOR TOTAL NUMBER OF SMALL ROOTS (LESS THAN 0.05 IN. IN SIZE) AND NUMBER OF SMALL ROOTS OF TREES PER SQUARE FOOT IN VERTICAL SECTIONS OF SOIL PROFILES IN MERRIMAC LOAMY SAND AND CHARLTON FINE SANDY LOAM.

(Based Upon the Data in Table 12)

Variance based on	Variation due to	Dgrees of freedom	Number of small roots		Number of roots per square foot of horizon areas	
			Mean Square	Observed F	Mean Square	Observed F
The number of roots in both A and B horizons	Types of soil	1	87,120	4.69[1]	125.53	17.38[2]
	Tree species	4	362,946	19.54[2]	203.46	27.52[2]
	Interaction between soils and tree species	4	25,130	1.35	21.71	2.94[1]
	Error	70	18,572		7.39	
	Total	79				
The difference of number of roots in the A and B horizons	Difference in A and B horizons	1	293,951	65.29[2]	709.81	307.01[2]
	Interaction between A and B differences					
	and soil types	1	96,531	21.44[2]	64.26	27.80[2]
	and tree species	4	80,618	17.91[2]	64.27	27.80[2]
	and soils and species	4	53,198	11.82[2]	24.08	10.42[2]
	Error in A and B difference	70	4,502		2.31	
	Total	80				
	Grand total	159				

[1] Significant at the 5 percent level.

[2] Significant at the 1 percent level.

There was a highly significant difference between the two types of soil in the numbers of small roots per square foot of the vertical horizon areas. It was much greater in Charlton fine sandy loam than in Merrimac loamy sand. This leads us to a conclusion reached by other investigators, as cited in the review of literature, that rich soils induce more copious branching and produce a higher concentration of small roots in a given volume of soil. The presence of a heavy concentration of small roots in Charlton fine sandy loam is confirmed by the photographs of root crowns.

Highly significant differences existed between the A and B horizons in the total number and the numbers of roots per square foot of horizon areas. The number of small roots in the A horizon was greater than in the B horizon. Interactions between the A and B differences and soils were also highly significant. A relatively greater number of small roots occurred in the A horizon of Charlton soil than in the A horizon of the Merrimac soil. Thus it is true that small roots of trees on heavy Charlton soil not only had greater concentration in a given volume of soil, but this concentration was most pronounced in the A horizon of this soil.

Root Distribution of the Five Tree Species

Some differences in root distribution between the five tree species can be noted from the examination of the root distribution diagrams and tables. In analyzing statistically the total number of small roots and the numbers of small roots per square foot of the horizon areas, with reference to the tree species, the significance of the differences in the two cases paralleled one another. The differences were highly significant between tree species, in the first order interaction between tree species and horizons, and in the second order interaction between species, soils and horizons. Results of the statistical analysis indicated that the differences between the five tree species in the distribution of small roots were real and substantial.

Root Distribution

White pine trees had the greatest number of roots of all sizes. This was true in both soils. White pine roots concentrated mostly in the A horizon and were reduced in numbers in the B_1 and B_2 horizons, falling off to insignificant numbers in the C_1 horizon in Merrimac loamy sand. In Charlton fine sandy loam the concentration of roots fell off rapidly in the B_1 horizon, and were negligible in the B_2 horizon. White pine roots reduced gradually in number with a greater and greater proportion of them extending into the deeper horizons of transects farther away from trees in Merrimac soil. This was true for the total numbers of roots and for roots per square foot of transects. This reduction in numbers at a greater distance from the trees with increasing proportions of roots in lower horizons was attained more rapidly in Charlton soil.

Red pine trees ranked next to white pine in number of roots but they had considerably fewer roots. Red pine roots were almost evenly distributed between the A and B_1 horizons, but fell off considerably in the B_2 horizon in Merrimac soil. In Charlton soil the concentration of red pine roots was greater in the A horizon, but a larger proportion of them extended into the B_1 horizon than was the case for white pine roots. Only a few reached into the B_2 horizon. The number of red pine roots in Merrimac soil remained almost unchanged but gradually diminished per square foot in the transects farther away from the trees. In Charlton fine sandy loam the number of roots gradually decreased with increase in distance from the trees.

Norway spruce was next to the lowest in the total number of roots of all sizes. The proportion of small roots was slightly greater in this species than in the two pines. Norway spruce roots showed the greatest concentration in the A horizon; they fell off very rapidly in the B_1 horizon, and were extremely few in the B_2 horizon in both soils. Norway spruce roots did not fall off in numbers with the increase in distance from the trees, but showed a slight increase in Merrimac soil; on a square foot basis, there was a gradual reduction in numbers. Fewer roots at greater distances from the trees were recorded in the Charlton soil.

White ash occupied the middle position among the five tree species investigated for the total number of roots. The proportion of small roots was considerably greater for this species as compared to others. In Merrimac loamy sand, roots of white ash were more numerous in the A horizon, fell off slightly in the B_1 horizon, and were reduced sharply in the B_2 layer. In Charlton fine sandy loam the largest number of roots was found in the B_1 horizon, slightly less in the A horizon, and only a few were found in the B_2 horizon. In both soils the number of roots was greatest in the transects at one foot distance from the trees. In the other two transects, the number remained almost the same. The number of roots per square foot in the two areas gradually, declined, the greater the distance from the trees.

Red oak had the smallest number of roots in both soils, in comparison to the other four species. The proportion of small roots in red oak was almost as high as it was in white ash. The number of roots in Merrimac loamy sand was the largest in the A horizon. It fell off slightly in the B_1 horizon, and was negligible in the B_2 horizon. In Charlton fine sandy loam the largest number was in the A horizon and it fell sharply in the B_1 layer. In both soils the number of roots gradually diminished, the greater the distances from the trees. In Charlton soil red oak roots were not found in the B_1 horizon in outer transects. This can be attributed to the very small size of these trees.

Root Arrangement in the Central Root Mass

Representative photographs of the central root mass for each species of trees, one on each soil, are given in Figures 12 and 13. Opinions have been expressed that root crowns of individual trees of the same species may differ to a greater extent among themselves than they do from other species. An examination of the entire set of 80 photographs revealed that although individual trees varied within the species, the species differed one from another appreciably.

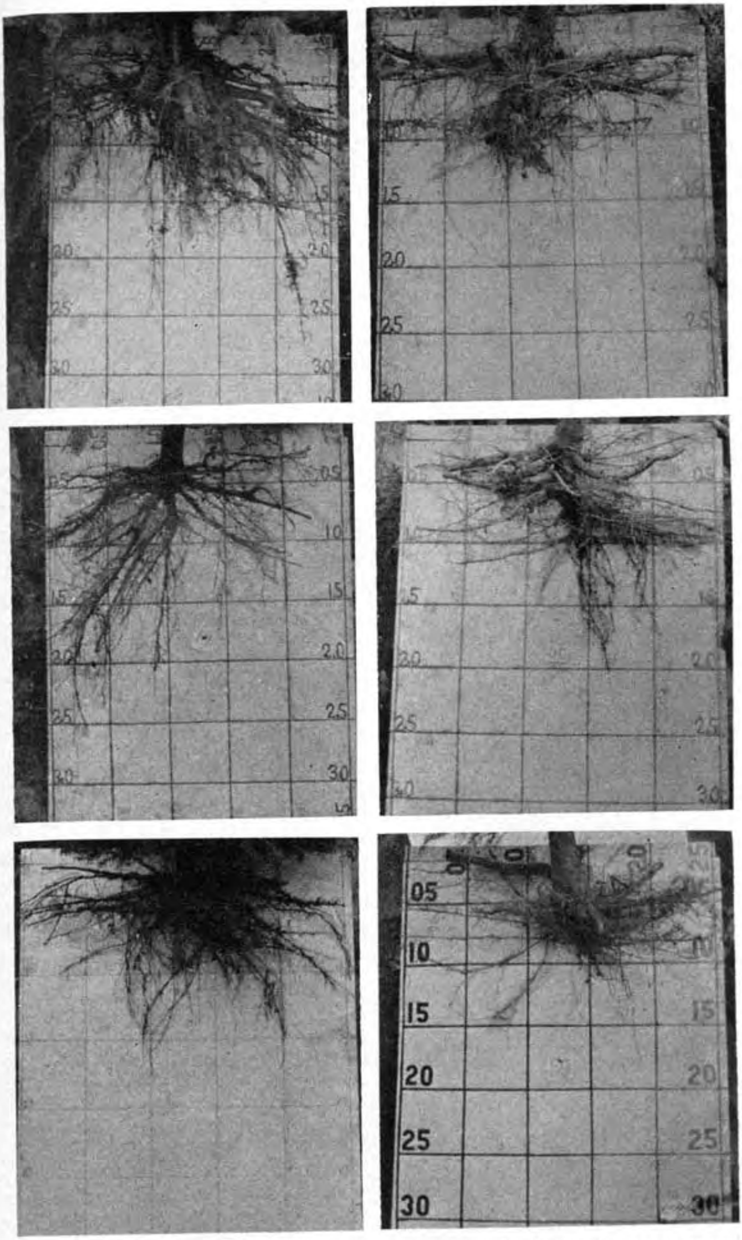

Figure 12. Upper left, central root mass of white pine tree growing in Merrimac loamy sand and, upper right, in Charlton fine sandy loam.

Center left, central root mass of red pine tree growing in Merrimac loamy sand and, center right, in Charlton fine sandy loam.

Bottom left, central root mass of Norway spruce tree growing in Merrimac loamy sand and, bottom right, in Charlton fine sandy loam.

White pine showed a short stubby tap root which in some cases was difficult to distinguish. Heavy branching occurred immediately under the root collar, with large roots extending into the soil in all directions. Small roots formed a heavy mass around the root crown. On Merrimac soil roots reached much deeper under the center of the tree than in Charlton soil, and main branch roots turned more sharply downward. Root crowns were more shallow in Charlton soil, and lateral roots did not go into deeper layers of the soil in the immediate vicinity of the root crowns. In white pine small branches were very numerous, with a few exceptions. One of the root crowns shown

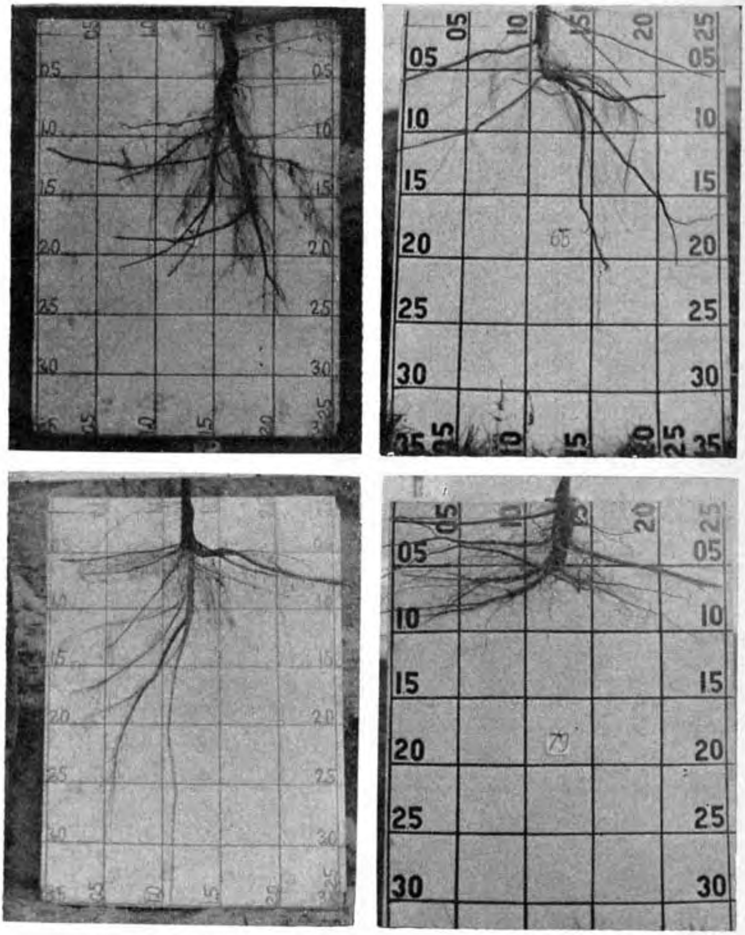

Figure 13. Upper left, central root mass of white ash tree growing in Merrimac loamy sand and, upper right, in Charlton fine sandy loam.

Lower left, central root mass of red oak tree growing in Merrimac loamy sand and, lower right, in Charlton fine sandy loam.

for Charlton soil had the two-layered effect which was mentioned before.

Red pine indicated a strong tendency to form a tap root, but this was not always present, or at least it was not always a prominent feature of the root system. Heavy branching occurred immediately under the root collar, but large roots assumed a downward trend more sharply than in white pine. Small roots did not form as heavy and compact a mass as they did in white pine. In Charlton soil lateral roots displayed a tendency to spread out in a more level plane than they did in Merrimac soil. The root crowns in Charlton soil were shallow but less so than in the case of white pine.

Norway spruce did not show any tap root in the true sense of the word. Lateral branching occurred almost wholly from one common point at the base of the tree. Lateral roots remained near the surface and did not assume a prominent downward trend as they did on the two pines. Small branches formed a considerable mass of roots but this mass was quite shallow. It would be well to recall that the roots of Norway spruce remained in the A horizon. This conclusion is supported by the photographs.

White ash, as a rule, had a tap root which branched into a few heavy roots maintaining their conspicuous downward trend. In Charlton soil, in a few cases, the tap root was practically absent, but some prominent branches always maintained their downward trend with the same type of vertical rooting habit. From these characteristic vertical roots single lateral branches were developed at intervals. Lateral branches did not come out in a mass as they did in conifers. They maintained their size unusually well. Lateral branches proceeded outward horizontally or assumed a gradual downward trend, and in turn produced some vertical, long branches, small in diameter. As a result of this angular branching small roots never formed a compact mass but were hanging in long strings.

Red oak definitely showed the presence of a tap root, which in some cases turned horizontally and continued its development on the same plane. This horizontal trend of the tap root was an exception in Merrimac soil, but vertical branching of the tap root was common. In Charlton soil, it was the long vertical tap root that was an exception. High water table and compactness of Charlton soil did not allow the development of deep roots by any species. The tap root of red oak, because of these conditions, could not continue its downward trend. The turning of the tap root of this tree in Charlton soil frequently gave a stunted appearance of its root system. The poor growth of red oak on this soil was perhaps a result of retarded root development. The two-layered root system could be seen in oak as well as in other species. Lateral branching of red oak roots was quite extensive. These roots developed in large numbers and in groups in contrast to the single branching of white ash. Lateral roots as a rule maintained a more or less horizontal position. Small roots were scattered and never formed a closely woven mass, but were more numerous and not as long as in white ash.

SILVICULTURAL DISCUSSION

Within the 36 square feet of ground area around each tree investigated in the field, a number of roots of adjoining trees of the same or different species were found. These roots are represented by different symbols listed in the tables in the author's dissertation. The vigor and height growth of trees on adjacent ground were invariably less than the trees under study. Consequently, the neighboring trees did not have nearly as extensive or well developed root systems as those under investigation. Stevens (34) indicated that crown development is related to the extension of the root system. This view was supported by the fact that in the outermost transect, which was on a theoretical boundary between two trees, the larger number of roots were those of the tree under investigation.

Other facts can be observed from the field maps and the tables. The number of roots coming into the transects from the outside was considerably greater in Merrimac than in Charlton soil. This is one additional fact in support of the conclusion already reached that trees have more spreading root systems in the lighter Merrimac soil than in heavier Charlton soil. A proportionately larger number of roots coming into the transects from the outside was found in lower horizons. This again sustains the previous conclusion that more roots of trees reach into deeper horizons at a greater distance from the trees. The number of roots coming into the transects from outside trees increased when the trees under study were smaller. Such smaller trees had fewer roots of their own and it was to be expected that the roots of other trees would invade the soil around them more promptly. The number of roots coming into the transects from the outside decreased from the first transect, 3 feet away from the tree, to the third one which was only 1 foot from the tree. This was due to the obvious fact that the soil was already well occupied by roots of trees under investigation and the distance from other trees was increasingly great.

The roots of other trees frequently extended well within the area occupied by those under investigation. Since the crowns of the trees did not come in contact with each other, it can be said that the roots of trees extend well beyond the radius of their crown projections and that intermingling of the roots of adjacent trees occurs sooner than does closing of the crowns. The development of roots underground, and their competition with those of other trees, were found to progress at a faster rate than do those of tree crowns. But this invasion may not mean early competition because the soil offers opportunities for the development of roots in 3 dimensions. If the roots of trees occupy parts of soil in proximity one to another, they are not necessarily in the state of competition.

These observations tend to support the view expressed by Coile (8) that under given forest and climatic conditions every forest soil has its "root capacity." Consequently, at about the time the root capacity is reached, true root competition must begin. Such competition may start in one part of the forested area before it becomes more general, but it must be reached at about the same time in an evenly spaced plantation.

Root development of a forest plantation can be pictured as passing through four stages. The first stage is that of free root growth, when roots have space in which to develop without coming near the territory occupied by those of other trees. The second is that of root invasion, when the expanding root systems begin to intermingle and invade areas adjacent to other trees. This stage is reached at a very early age in the forest plantation. The third period, that of root competition, begins when root capacity is reached. In some soils this may be much sooner than in others. On poor dry soils this period, in most cases, precedes the closing of the tree crowns above the ground. Observations show that, in poor soils, roots of trees of about the same height and the same age spread more widely and occupy a much larger volume of soil than those in richer soils. On rich soils the stage of root competition may follow the closing of the crowns. The third period would prevail throughout the greater part of the life of the stand. A fourth stage, that of release from root competition, begins when mature trees start to die and release a sufficiently large area from root competition so the new reproduction can become established. Trees at this stage do not have the vigor to replace to the point of "root capacity" the areas release by dead trees, before new reproduction becomes established.

Considering these four stages of root development, the stands under investigation were found to be in the stage of root invasion, not in that of root competition. This is evidenced by the intermingling of roots of the individual trees and the lack of complete occupation of the soil to the point of root capacity. Root capacity is an approximate constant with respect to the number or weight of the small roots in top soil layers in a soil under given forest and climatic conditions. It can be measured on the basis of weight of the small roots in the surface soil or on the basis of numbers of small roots per vertical unit area of the A horizon. In this investigation data for root distribution, on the basis of the numbers of roots per square foot of horizon areas, indicated great variation and were far from reaching a constant value.

Stevens (34), in discussing young white pine plantations, expressed the view that root competition begins very early because roots extend into all parts of the area at an early age. The present writer takes exception to this view and, on the basis of the ideas just presented, feels that on good sites true competition between roots may not begin until well after the tree crowns have been closed.

The view expressed by the writer is in no way in opposition to the conclusions reached by Grasovsky (16) that other factors besides light are determining ones in the survival of the reproduction under competition conditions. The conclusions reached by Craib (10) were that soil factors, particularly that of moisture, were most important in root competition. It is natural to suspect that root competition is an important factor in suppressing the individual trees of open forest stands on poor sites. Here elimination of the weak trees begins before competition for light is in evidence. On good sites with high "root capacity" root competition and elimination of weak trees do not start until well after the closing of the tree crowns. Competition for light, so apparent above the ground under these conditions, can easily divert the attention of an observer from the importance of root competition. This is also true of the expression of dominance of trees on poor and good sites. Stevens (34) concluded on valid evidence that there can be no true dominance in a tree without a corresponding superiority of its root system. Although light cannot be disregarded in the ecological complex of a forest stand, root competition may be essentially the most important factor in the suppression or dominance of trees on either good or poor sites.

The information concerning root systems and root distribution of the 5 tree species investigated, as influenced by various properties of the two soil types, can serve as a background with which to formulate some silvicultural practices. It is suggested that, in devising a proper mixture of tree species, consideration be given to a combination of those with a shallow and deep root systems, of those forming compact and spreading root masses and of those having a tendency to either build up or lower the acidity in the soil. The use of some tree species on shallow or rich soils and others on poor or deep soils is suggested. The information can also be utilized in diagnosing poor or good growth of the tree species involved on certain sites, in mixture or in pure stands. No attempt can be made, due to the limited scope of the problem studied, to make any specific recommendations, except that in applied silviculture it is well to be familiar with the aspects of soil and root relationships of the tree species so that such knowledge can be used as one of the factors in deciding on certain silvicultural practices.

SUMMARY

Seventeen tree species were planted in mixture on Merrimac loamy sand and Charlton fine sandy loam in April, 1933. Seven years after planting five species were selected for root study: white pine, red pine, Norway spruce, white ash and red oak. On each soil type eight tall vigorous trees of each species were used in a study of root distribution. The field investigation consisted in surrounding each tree on four sides by three sets of trenches, 1, 2 and 3 feet from the tree. These trenches exposed the soil horizons and the roots, which were plotted to scale on the maps according to five size classes. After the last examination, the trees were removed with their roots and photographs were taken of the central root mass.

Composite soil samples were collected by horizons while the field work was in progress. One set of soil samples was a general series for each of the two soil types. Samples of another set were collected in pairs from zones of high root concentration and from zones where roots were few or absent. The third set consisted of soil-in-place samples collected from the two soil types for the analysis of physical properties. One more set was taken for the aggregate analysis of the two soils.

Root charts made in the field were utilized to count tree roots and to determine soil horizon areas. The number of tree roots and the

roots per square foot of soil horizon areas were tabulated. The analysis of variance technique was used in the statistical analysis of data for small roots of the individual trees. The same technique was also applied to the laboratory data for the various soil properties investigated.

Outstanding differences between the two soils observed in the field were discussed.

In the laboratory, aggregate analysis was carried out with the soil samples collected for this purpose. Soil-in-place samples were used to determine pore volume, air capacity, water holding capacity on volume and weight bases, apparent specific gravity and true specific gravity. General soil samples were subjected to chemical analyses to determine total calcium, potassium, magnesium and phosphorus. Exchangeable calcium, replaceable potassium and soluble phosphorus were also determined.

Considerable differences existed between the two soils selected for this investigation and between soil horizons within the two soil types. These were observed both in the field, and in laboratory studies involving a great majority of the soils investigated. Certain differences in the soil properties in the A horizons of the two soils increased while others decreased in the lower soil layers.

Soil samples collected in pairs from zones of high root concentration and from zones where roots were few or absent were subjected to mechanical analysis, to ascertain percentages of sand, silt, clay and Bouyoucos colloidal equivalent. These samples were also subjected to moisture equivalent measurements and chemical analysis to determine loss on ignition, total nitrogen, hydrogen ion concentration (pH values), total base capacity, exchangeable hydrogen, exchangeable bases and relative base saturation.

Some soil properties proved to be significantly different in the zones of high root concentration in comparison to the zones where tree roots were few or lacking. Moisture equivalent values, loss on ignition, total nitrogen, and total exchange capacity were higher for the zones of greater tree root concentration. Soil acidity and base saturation percentages in the zones of root concentration were found to differ significantly between the five tree species investigated.

In the Charlton fine sandy loam fewer mycorrhizal roots were observed than in the other soil, in the zone of high root concentration. However, this zone showed a greater superiority in total nitrogen for the former soil type. Field maps with tables and diagrams were used as a basis for the discussion of root distribution. Attention was given to the following: total number of roots and numbers of roots per square foot of horizon areas; distribution of small and large roots; and to the roots of trees under investigation in relation to the roots of other trees appearing in the field maps.

Roots of trees in Merrimac loamy sand penetrated into deeper soil layers than in the Charlton fine sandy loam. Roots of the individual trees showed greater lateral spread in Merrimac loamy sand than in Charlton fine sandy loam. As a consequence of the deeper penetration and the wider spread of tree roots in Merrimac loamy sand, the volume of soil occupied by the roots of the individual trees was much greater in this soil than in the richer Charlton fine sandy loam. The number of tree roots decreased with increasing depth below the soil surface, the decrease being greatest in Charlton fine sandy loam.

The proportion of large roots to small roots increased in the lower soil horizons. Small roots were concentrated near the soil surface and large roots penetrated deep into the soil without forming small feeding roots. The proportion of roots in the lower soil layers and the proportion of large roots to small roots both increased with distance from the base of the tree. Thus small feeding roots were concentrated near the soil surface and were more numerous near the trees.

Large roots were present in a proportionately greater number in Merrimac loamy sand than in Charlton fine sandy loam. The total number of small roots was significantly greater in Charlton than in Merrimac soil. This indicated more copious branching of the tree roots in the heavier and richer Charlton fine sandy loam. The vertical change in numbers of small roots per square foot differed very significantly between the two soils. Although differences in the number of small roots in the two soils were not marked there were great differences in distribution of the roots in the soil body. The number of small feeding roots per square foot was greater in Charlton than in Merrimac soil, particularly in the A horizon.

Some pronounced differences existed between the five trees species in the total number of all roots and of small feeding roots, in the proportion of large to small roots, in root penetration and spread, and in the distribution of roots in the two soils and several soil horizons. Deep-rooted tree species, particularly red pine, showed a tendency to concentrate their roots in sections of the B_1 horizon which were rich in nutrients.

Photographs of the central root masses of trees were used to show the differences existing between the five tree species investigated. The tree species differed in tap root formation, density of central root mass, type of root branching, and manner of spreading of roots from the tree. Vigorous trees had better root development than poor individuals of the same age.

Root distribution in relation to roots of bordering trees which occurred in the transects served as a basis for the discussion of root competition in a forest stand. The root development of a forest stand was suggested to be divided into four stages: free root growth, period of invasion, period of root competition, and period of release from competition. In the seven-year-old plantations investigated the roots of trees spread more widely than the boundaries of their crown projections, invading areas adjacent to the neighboring trees. The stands under investigation were placed in the second stage because it was shown in the root charts that root density of small roots in the A horizon did not approach a constant; therefore the "soil capacity" for roots was not reached, and the period of root competition had not begun.

The period of root competition in a forest stand may precede or follow the closing of tree crowns above the ground depending on the site quality. Root competition frequently must be the most important factor of suppression and dominance of trees in a forest stand on good and poor sites alike.

Information made available with regard to root systems, root distribution, and root distribution as influenced by soil properties and two soil types of the five tree species investigated, can serve as a background on which to formulate some silvicultural practices.

LITERATURE CITED

1. AALTONEN, V. T. Über die Ausbreitung und den Reichtum der Baumwurzeln in den Heidewäldern Lapplands. Acta Forestalia Fennica **14**:1-55. 1920.
2. ——————. On the space arrangement of trees and root competition, Jour. of For. **24**:627-644. 1926.
3. ADAMS, W. R. Effect of spacing in a jack pine plantation. Vermont Agr. Exp. Sta. Bul. **282**. 51 pp. 1928.
4. ALDRICH-BLAKE, R. N. Recent research on the root systems of trees. Forestry **3**:66-70. 1929.
5. Association of Official Agricultural Chemists. Official and tentative methods of analysis 2nd ed. Washington, D. C. 535 pp. 1925.
6. BOUYOUCOS, GEORGE JOHN. Directions for making mechanical analysis of soils by the hydrometer method. Soil Science **42**:225-229. 1936.
7. CHANDLER, R. F. JR. Cation exchange properties of certain forest soils in the Adirondack section. Jour. Agr. Res. **59**:491-506. 1939.
8. COILE, T. S. Soil samplers. Soil Science **42**:139-142. 1936.
9. ————. Distribution of forest tree roots in North Carolina Piedmont soils. Jour. of For. **35**:247-257. 1937.
10. CRAIB, I. J. Some aspects of soil moisture in the forest. Yale Univ. School For. Bul. **35**. 61 pp. 1929.
11. DITTRICH, HEINRICH VON. Untersuchungen über die Bodengare. Bodenkunde und Pflanzenernäherung. Verlag Chemie. **16** (61):16-50. 1939.
12. ELY, JOSEPH B. Root distribution of white pine in relation to certain physical characteristics of soil profile horizons. Yale Univ. School For. Master's Thesis. 35 pp. 1935.
13. FISHER, R. A. Statistical methods for research workers. 6th ed. xiii + 339 pp., Oliver and Boyd, London. 1936.
14. ————. The design of experiments. 2nd ed. xi + 260 pp., Oliver and Boyd, London. 1937.
15. GLINKA, K. D. The great soil groups of the world and their development. Translated from the German by C. F. Marbut. Mimeographed copy. 235 pp., Edwards Brothers, Ann Arbor, Mich. 1927.
16. GRASOVSKY, A. Some aspects of light in the forest. Yale Univ. School For. Bul. 23. 23 pp. 1929.
17. HATCH, A. B. The physical basis of mycotrophy in *Pinus*. Black Rock Forest Bul. **6**. 168 pp. 1937.
18. HILF, H. H. Wurzelstudien an Waldbäumen. Die Wurzelausbreitung und ihre waldbauliche Bedeutung. 121 pp., M. and H. Schaper, Hannover. 1927.
19. LAITAKARI, ERKKI Männyn juuristo. Morfologinen tutkimus. (The root system of pine, *Pinus silvestris*.) (English summary, pp. 307-380.) Acta Forestalia Fennica **33**:1-380. 1929.
20. LITTLE, SILAS, JR. Root distribution of white pine in relation to certain physical characteristics of soil profile horizons. Yale Univ. School For. Master's Thesis. 51 pp. 1936.
21. LUNCS, G. Reshershes récentes sur les racines des arbres forestier. Bullitin de la Soci̧ęté Centrale Forestièr de Belgique **38**:531-538, 1931.
22. LUNT, HERBERT A. Profile characteristics of New England forest soils. Connecticut Agr. Exp. Sta. Bul. **342**, pp. 743-836. 1932.

23. ————————. Soil analyses significant in forest soils investigations and methods of determination: I. Exchangeable bases, exchangeable hydrogen, and total base capacity. Soil Science Society of America. Proceedings, 1940, **5**: 344-347. 1940.
24. Lutz, Harold J. Disturbance of forest soil resulting from the uprooting of trees. Yale Univ. School For. Bul. **45**. 37 pp. 1940.
25. ————————, Ely, Joseph B., Jr., and Little, Silas, Jr. The influence of soil profile horizons on root distribution of white pine. Yale Univ. School For. Bul. **44**. 75 pp. 1937.
26. Melder, Chr. Vlianie kornevoy systemy na raspredelenie podrosta okolo sosnovych semennikov v suchom boru. (Influence of root system of seed trees on distribution of reproduction in a forest growing on dry sandy soil.) Izvestia Imperatorskago Lesnogo Institut. Issue **21**. St. Petersburg. pp. 215-246. 1911.
27. Morgan, M. F. Base exchange capacity and related characteristics of Connecticut soils. Soil Science Society of America. Proceedings, 1939, **4**:145-149. 1939.
28. Oskamp, Joseph, and Batjer, L. P. Soils in relation to fruit growing in New York. Part III. Some physical and chemical properties of the soils of the Hilton and Monroe areas, Monroe County, and their relation to orchard performance. New York Agr. Exp. Sta., Ithaca. Bul. **575**. 34 pp. 1933.
29. Pearson, G. A. The other side of the light question. Jour. of For. **27**: 807-812. 1929.
30. Pierre, W. H. and Scarseth, G. D. Determination of the percentage base saturation of soils and its value in different soils at definite pH values. Soil Science **31**:99-114. 1931.
31. Russell, E. W. and Tamhane, R. V. The determination of the size distribution of soil clods and crumbs. Jour. of Agr. Science **30**:210-234. 1940.
32. Snedecor, G. W. Calculation and interpretation of analysis of variance and covariance. 96 pp. Collegiate Press Inc., Ames, Iowa. 1934.
33. ————————. Statistical methods applied to experiments in agriculture and biology. xiii + 341 pp. Collegiate Press Inc., Ames, Iowa. 1937.
34. Stevens, Clark Leavitt. Root growth of white pine (*Pinus strobus* L.). Yale Univ. School For. Bul. **32**. 62 pp. 1931.
35. Stubblefield, F. M. and Deturk, E. E. Effect of ferric sulphate in shortening Kjeldahl digestion. Indust. and Eng. Chem., Anal. Ed. **12**:396-399. 1940.
36. Sudworth, G. B. Check list of the forest trees of the United States, their names and ranges. U. S. Dept. of Agr. Misc. Circ. **92**. 295 pp. 1927.
37. Swetloff, N. F. Issledovanie vliyania usloviy mestoproizrostania na kornevouyu sistemu sosny v institutskom (b. pargolovskom) uchebnom lespromchoze. (Investigation of the influence of the site conditions on the root system of pine in the experimental forest of Leningrad Forest Academy.) Troudy lesotechnicheskoy academii, lesovodstvennyi tzikl. Issue **1** (**38**). Leningrad. pp. 103-126. 1931.
38. Tolski, A. P. Materialy po izucheniyou formy e razvitiya korney sosny e drugich drevesnych porod. (Materials on the investigation of form and development of root system of pine and other trees.) Troudy Opytnich Lesnichestv. Issue **3**. St. Petersburg. 1905.
39. ————————. Materialy po izoucheniyou stroeniya e jisnedeyatelnosty korney sosny. (Materials on the study of form and functions of pine roots.) Troudy po Lesnomu Opitnomu Delu v Rossii. Issue **3**. St. Petersburg. 118 pp. 1907.
40. Truog, Emil and Meyer, A. H. Improvements in the Deniges colorimetric method for phosphorus and arsenic. Indust. and Eng. Chem., Anal. Ed. **1**: 136-139. 1929.
41. Turner, Lewis M. A comparison of roots of southern shortleaf pine in three soils. Ecology **17**:649-658. 1936.
42. Vater, H. Die Bewurzelung der Kiefer, Fichte und Buche. Tharandter Forstliches Jahrbuch **78**:65-85. 1927.

43. Veihmeyer, F. J., Oserkowsky, J., and Teeter, R. B. Some factors affecting the moisture equivalent of soils. Proceedings and Papers of the First International Congress of Soil Science, 1927. Part 2, Comm. 1. pp. 512-534. 1928.

44. Volk, Garth W. and Jones, Randall. The use of perchloric acid in the determination of total phosphorus in soils. Proc. of Soil Science Society **2**: 197-200. 1937.

45. Weaver, John E. The ecological relations of roots. Carnegie Institution of Washington (D. C.) Pub. **286.** vii + 128 pp. 1919.

46. West, Eric S. The root distribution of some agricultural plants. Jour. of the Council for Scientific and Industrial Research (Commonwealth of Australia). **7**:87-93. 1934.

47. Williams, Rice. The determination of exchangeable calcium in carbonate-free soils. Jour. of Agr. Science **18**:439-445. 1928.

48. ——————. The determination of exchangeable bases in soils. Magnesium, potassium and total bases. Jour. of Agr. Science **19**:589-599. 1929.

49. Wright, C. H. Soil analysis and chemical methods. A handbook of physical and chemical methods. 2nd ed. 276 pp. Thomas Murby and Co., London. 1939.