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SCHULTZ, John David, 1934-
THE VERTICAL ROOTING HABIT IN BLACK SPRUCE, WHITE SPRUCE, AND BALSAM FIR.

The University of Michigan, Ph.D., 1969
Agriculture, forestry and wildlife

University Microfilms, Inc., Ann Arbor, Michigan

THE VERTICAL ROOTING HABIT IN BLACK SPRUCE, WHITE SPRUCE, AND BALSAM FIR

by
John David Schultz

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in
The University of Michigan
1969

Doctoral Committee:

Professor Robert Zahner, Chairman
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Professor Samuel A. Graham (deceased)

ABSTRACT

THE VERTICAL ROOTING HABIT IN BLACK SPRUCE,
WHITE SPRUCE, AND BALSAM FIR

by
John David Schultz

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Little has been known about the nature of the vertical rooting habits on upland sites of black spruce (Picea mariana (Mill.) B. S. P.), white spruce (Picea glauca (Moench) Voss), and balsam fir (Abies balsamea (L.) Mill.). The purpose of this investigation was to provide information on the occurrence of vertical roots and to correlate their depths of penetration with soil conditions where such roots were produced.

Excavations and examinations of root systems in the field were conducted in natural stands and in spruce plantations located in the Lake Superior region during the summers of 1958 through 1960. In 28 natural stands, the stumps of 40 black spruces, 32 white spruces, and 36 balsam firs were either dug out by hand, washed out, or examined at the site of logging road construction where trees had been uprooted by heavy machinery. Ages of trees ranged between four and 181 years. Thirty-one white spruces and 14 black spruces were excavated by hand in 22 different plantations in Michigan, Wisconsin, and Minnesota. These trees ranged in age from eight to 20 years.

The sites where these 153 trees grew were classified according to land-form. Soil texture and bulk density were determined through the soil profile to depths where roots terminated.

In a greenhouse experiment, 64 two-year-old seedlings of each species grew for nearly 10 months in four different soil environments which simulated various conditions of aeration, drainage, and compaction. Forty-four black

spruces, 51 white spruces, and 16 balsam firs survived.

White spruce and balsam fir produced prominent tap roots and vertical sinker roots in all field conditions and in the greenhouse soils. The average depths attained by such roots in natural stands were greater than 30 inches for both species, and many were from six to 10 feet deep. Both species consistently exhibited greatest vertical root penetration in coarse textured sandy soils. In natural stands, vertical roots on white spruce averaged more than 40 inches deep in sands, and balsam fir averaged over 30 inches deep. In plantations, white spruce averaged more than 31 inches deep on the sandy soils.

Black spruce trees commonly had a tap root and some small sinker roots, but most of these vertical roots were feebly developed and averaged less than 18 inches deep in natural stands. All such roots of black spruce were shallower than 18 inches in plantations.

In the greenhouse, vertical root growth of all seedlings was impeded by a compact loam layer underlying a sandy loam. Greatest vertical penetration for all trees was attained in a coarse textured sand which represented excessive drainage and aeration conditions.

It should be recognized that prominent tap roots and vertical sinker roots are produced in abundance by white spruce and balsam fir on upland sites. Coarse textured soils appear to favor greatest expression of this habit for both species.

ACKNOWLEDGMENTS

I would like to express my deep appreciation to the late Professor Samuel A. Graham for his considerate and continuous guidance during most of this study. Dr. Graham's wise counsel and steadfast confidence in me and in the value of the study were a continuous source of inspiration.

To each of the other committee members, grateful thanks is given for their readily available counsel; but appreciation is especially expressed to Dr. Robert Zahner who took over as Chairman of my committee after Dr. Graham died and who served to encourage me in the final phases of the study.

This investigation would not have been carried out were it not for the splendid opportunity afforded me by the Kimberly-Clark Corporation in the way of two research fellowships for the academic years 1958-59 and 1959-60. The Company also sponsored the field research by providing me with summer employment in 1959 and 1960. Particular thanks are expressed to all of the Kimberly-Clark employees, in the Lake States and in Ontario, who provided assistance in various ways during the summer field seasons.

A University Fellowship awarded by the Horace H. Rackham School of Graduate Studies, The University of Michigan, enabled me to complete the final year of academic preparation during 1960-61. I am very grateful for this.

Finally, but by no means least, my deep expression of appreciation goes to all of my family and friends who have assisted in untold ways over the years this investigation has taken place.

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CHAPTER I

INTRODUCTION

Purpose and Scope of Study

Black spruce (Picea mariana (Mill.) B. S. P.), white spruce (Picea glauca (Moench) Voss), and balsam fir (Abies balsamea (L.) Mill.) are important forest trees of North America but relatively little is known about their rooting habits. All three are generally considered to be shallow rooted and this belief appears to be well founded because many reports of this are present in the literature pertaining to these species. A few studies, however, have shown that white spruce and balsam fir sometimes have well developed vertical roots. Much of the existing information about spruce and fir rooting habits has been derived from the study of trees growing in wetland situations where root development is usually restricted. All three trees occupy vast acreages of wet lands in North America, but they are also important on many upland sites which are not classified as swamps or seepages.

Numerous vertical roots were found on several white spruces and balsam firs which the author excavated on an

upland site as a preliminary part of this study. A subsequent search of literature pertaining to spruce and fir revealed that much confusion seems to exist about the extent of vertical root development in all three species (Schultz, 1960).

Some tree species possess an inherited tendency to produce a tap root or other prominent vertical roots such as sinker roots, but this trait may be masked by conditions of the site where the trees grow. It is not known whether black and white spruce and balsam fir, as species, have such an inherent tendency nor is it within the scope of this study to determine whether such a genetic trait exists. This investigation was undertaken to determine under what site conditions these species do develop vertical roots and to determine how abundant and how prominent vertical roots may be.

Three physical site factors were selected for evaluation of their effects on vertical root growth and the study was designed to incorporate as wide a variety of these as possible. The factors were: (1) physiography or landform, (2) soil texture, and (3) soil bulk density. All three relate to the moisture, aeration, and penetrability conditions within the soil mass which affect vertical root development. Because high water tables are known to

inhibit vertical root growth of these three species, the study was restricted to upland sites where this factor would not normally be dominant.

In natural stands of spruce and fir growing in the Upper Peninsula of Michigan, northern Minnesota, and northern Ontario, over 100 trees were examined during the summers of 1959 and 1960. Many of these trees were excavated in place, and some were examined at the site of logging operations or road-building operations where trees had been uprooted by heavy equipment. The roots of an additional 45 trees of black and white spruce in 4- to 16-year-old plantations were excavated in Michigan, Wisconsin, and Minnesota.

Because the study was concerned with the effects exerted by a variety of site conditions, an attempt was made to examine the trees in as many different locations throughout the Lake Superior region as possible. I chose not to study any one site condition intensively; hence, the results reflect the rooting habits of a few selected trees and not the entire population of trees at a given location.

Field observation of roots of seedlings in natural stands indicated that distinct vertical roots are usually produced initially by white spruce and balsam fir but not often by black spruce. The development of vertical roots on two-year-old seedlings of all three species was studied

in a greenhouse experiment.

Distribution and Ecological Importance of Species

Black spruce, white spruce, and balsam fir are all commercially important trees within their natural ranges. They are even more important ecologically because they are the dominant coniferous species in the boreal forest region of North America. Their geographic distributions are illustrated in Figures 1, 2, and 3. Both spruces are more widely distributed than balsam fir; and, within their ranges, black spruce occupies more land area than white spruce.

The Society of American Foresters (1962) reports that black spruce is a dominant species in six forest types of



Fig. 1.--Natural range of black spruce. (Map courtesy of U. S. Forest Service.)



Fig. 2.--Natural range of white spruce.
(Map courtesy of U. S. Forest Service.)

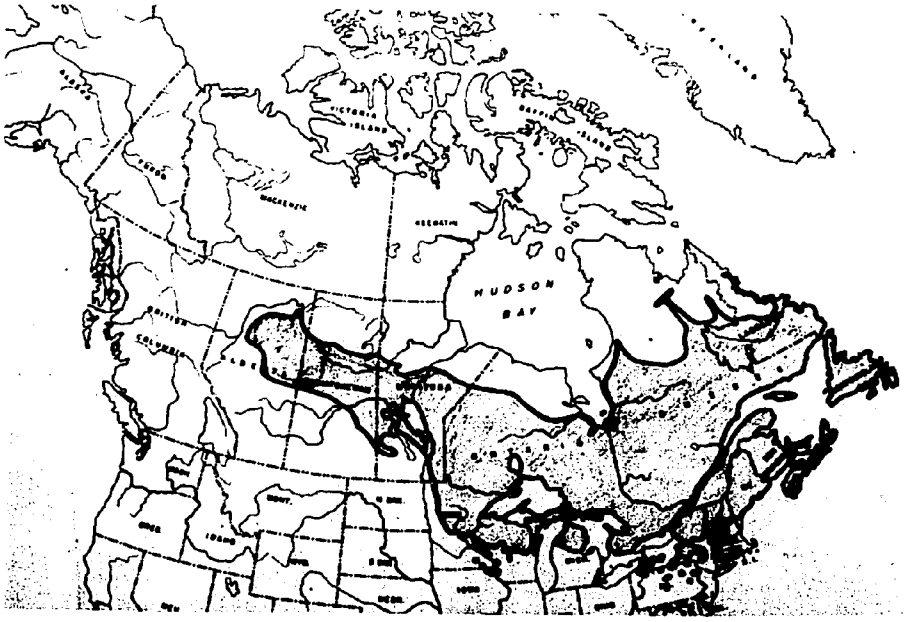


Fig. 3.--Natural range of balsam fir.
(Map courtesy of U. S. Forest Service.)

North America and an associate in 12 others. White spruce dominates in six types and plays a lesser role in 12 others. Balsam fir is a major species in seven forest types and it occurs as an associate in 16 others. The major spruce and fir types are listed in Table 1.

TABLE 1

FOREST TYPES IN WHICH BLACK SPRUCE, WHITE SPRUCE, AND BALSAM FIR ARE MAJOR SPECIES

Species	Type Numbers and Cover Types[a]	
Black spruce	2	Black spruce-white spruce
	6	Jack pine-black spruce
	7	Black spruce-balsam fir
	10	Black spruce-aspen
	12	Black spruce
	13	Black spruce-tamarack
	204[b]	Black spruce
White spruce	2	Black spruce-white spruce
	4	White spruce-balsam fir
	9	White spruce-balsam fir-aspen
	36	White spruce-balsam fir-paper birch
	201	White spruce
	202	White spruce-birch
Balsam fir	4	White spruce-balsam fir
	5	Balsam fir
	7	Black spruce-balsam fir
	9	White spruce-balsam fir-aspen
	33	Red spruce-balsam fir
	35	Paper birch-red spruce-balsam fir
	36	White spruce-balsam fir-paper birch

[a] Taken from: Forest Cover Types of North America (Exclusive of Mexico). 1962. Soc. Amer. Foresters.

[b] Types which are numbered over 200 occur in western North America; those less than 200 are in eastern North America.

All spruce and fir data are grouped into two major classifications by the North Central Forest Experiment Station, U. S. Forest Service, when forest survey statistics are presented (Cunningham, Horn, and Quinney, 1958; Findell, Pfeifer, Horn, and Tubbs, 1960; and Stone and Thorne, 1961). These classifications and their definitions are: (1) Spruce-Fir Type---mixed hardwood-conifer stands in which 50 percent or more is white spruce and balsam fir, singly or in combination; and (2) Black Spruce Type---swamp conifer forest stands in which 50 percent or more of the stand is black spruce. Common associates in the former "type" include black spruce, white-cedar, American elm, aspen, red maple, and paper birch. Associates commonly found in the latter "type" include tamarack, balsam fir, and white-cedar. Other American descriptions of spruce and fir types can be found in Cheyney (1942), Westveld (1949), Barrett (1962), and Fowells (1965).

Two of the forest regions of Canada, according to Rowe (1959), are found in the general area of Lake Superior with which this investigation is concerned. These are the Boreal Forest Region and the Great Lakes-St. Lawrence Forest Region. The forest regions are broad designations applied to major geographic belts or zones "characterized vegetationally by a broad uniformity both in physiognomy and in the composition of the dominant tree species." White and black spruce are

both characteristic of the Boreal region across the continent, and balsam fir is typical in the forests of the eastern and central parts of the region. In the Great Lakes-St. Lawrence region the spruces and balsam fir are "boreal" species which grow intermixed with white and red pines, hemlock, and yellow birch. Tamarack, jack pine, aspens, paper birch, white-cedar, and many of the northern hardwoods are also associated species.

Review of Literature Pertaining to Vertical Rooting in Spruce and Fir

Roots of most tree species are concentrated within the upper two feet of the soil profile. In addition, however, many develop a tap root or sinker root system which serves several distinct functions. It can permit the tree to gain an initial foothold in mineral soil soon after seed germination. It can develop extensively to anchor the tree. And, such a rooting habit may permit the tree to obtain moisture and nutrients on sites which are nutritionally poor or tend to be dry in periods of drought.

According to Pulling (1918), some species of trees have what could be termed rigid or inflexible root habits, meaning that the typical root system is maintained no matter what site the species grows on. Others, however, have a decidedly flexible root habit and these species often adapt to the particular soil environment in which the tree first

becomes established. Pulling considered trees to be deep rooted if the inherited habit centers about a main, deeply penetrating tap root or if one or more vertical sinking roots ("sinkers") descend from lateral roots near the stem of the tree. When such roots are absent and most roots remain near the soil surface, the root system is classed as shallow. Various degrees of transition may be observed between these two extremes, and the species which has the ability to develop a flexible root habit may exhibit all degrees between the extremes. Because all three trees considered in this study are known to produce some vertical roots, they would necessarily be classed as having flexible root habits according to the definitions of Pulling.

References which mention anything about the rooting habits of spruce and fir can be separated readily into those which declare that black spruce, white spruce, and balsam fir are almost invariably shallow rooted and those which discuss the presence of some vertical roots. A more complete treatment of the literature published prior to 1960 can be found in the Master's thesis which was a preliminary part of the present investigation (Schultz, 1960).

The Shallow Root Habit

Nearly all of the earlier editions of tree guides, if they referred to root system traits at all, reported that

both spruces and balsam fir are predominantly shallow rooted and this habit predisposes them to windthrow. Current editions of the most popular of these guides (Harlow and Harrar, 1968; Preston, 1966) provide the same information. White spruce is said to have a "shallow, spreading root system" (Preston, 1966) and "silvical and other features similar to those of black spruce" (Harlow and Harrar, 1968). Balsam fir has a "shallow root system" (Preston, 1966) and a "shallow, wide-spreading root system" (Harlow and Harrar, 1968).

Most publications which discuss spruce and fir management refer to the shallow root habit of all three species, but no clear definition is given as to what is meant by such a habit. Does it mean, as Pulling (1918) stated, that no tap root or sinker roots exist? Or, does it mean that most of the roots are surficial and extend horizontally with perhaps a few descending as distinct vertical roots? Regardless of what definitions are chosen for deep rooting and shallow rooting, it is clear that black and white spruce and balsam fir are considered to be shallow rooted.

Only rarely are vertical roots mentioned in the management and silvical publications which refer to spruce and fir (Fowells, 1965; Bakuzis and Hansen, 1965). In several research papers published over the years, however, vertical roots have been described. Unfortunately, some authors have

considered such roots to be abnormal and they have often dismissed them as being of no consequence in describing spruce and fir rooting habits. The reports of vertical rooting are where this study must begin, however, so on the pages which follow much of what is presently known about vertical rooting habits of these species is presented.

Reports of Vertical Rooting

Black Spruce

Little can be found in the literature of black spruce about vertical roots, but a few observations are worth noting. It is reported in Agricultural Handbook No. 271 (Fowells, 1965) that black spruce "root development is characteristically shallow and it has no taproot." On some older trees "sinker" roots one or two feet long may be present.

Bannan (1940) excavated 10 mature black spruce trees on a deep sand plain north of Lake Superior. He concluded that the black spruces had shallow lateral roots and feeble tap roots. Small vertical roots sometimes dropped from the laterals but they soon divided and did not descend deeply.

LeBarron (1945) reported that slender sinker roots may extend down from the prominent laterals for as much as two feet, but he also stated that the usual tendency was for the root system to take the form of a mat-like pedestal. In addition, he said that the species has no definite tap roots.

In a study of black spruce in the Clay Belt of northern Ontario, Millar (1936) found that numerous small secondary roots "go straight down for one or two feet" from the large lateral roots. These vertical roots were from one-quarter to one-half inch in diameter.

Curry (1961) examined the stumps of numerous mature black spruce trees which had been uprooted in road construction near Longlac, north of Lake Superior in Ontario. On a sand and gravel soil, he found some vertical sinker roots which were broken off at 18 inches below ground. On a silty sand site, he found vertical roots 15, 26, and 44 inches below ground at their point of breakage. And, on a silty clay soil, one black spruce tree had a vertical root 24 inches long. Each tree stump had only a few of these vertical roots as compared with white spruces which he examined and which had several such roots on each tree.

These observations about vertical root development in mature black spruce trees are virtually all that can be found in published works. They do, however, illustrate that some observers have recognized the presence of sinker roots and an occasional tap root in this species. There appears to be no real agreement about whether tap roots are common.

White Spruce

Vertical roots have been observed in white spruce trees

by many investigators so there is little need to question whether the species produces roots which descend. The main concern, then, is about their abundance, the depths reached, and under what site conditions they are produced. In addition, it needs to be known whether a persistent tap root is found.

In an investigation conducted in northern Ontario and northern Wisconsin more than 50 years ago, Pulling (1918) examined the thesis that tree distribution was related to the form of the root system on different soils. He concluded that trees with flexible rooting habits are often able to survive and grow well under conditions which might otherwise be unfavorable for their development. They are thus able to compete more favorably on certain sites with trees which possess rigid rooting habits. On deep soils, he found vertical roots of white spruce able to penetrate nearly a meter below ground. He stated that white spruce possesses a tap root in deep soils but lacks one in shallow soils, and he classified white spruce as a tree with flexible root habits.

Bannan (1940) excavated 10 mature white spruce trees on the same sand plain in northern Ontario where he studied the black spruces mentioned earlier. Six of these had recognizable tap roots which were usually branched. The branched divisions diverged but grew to depths of two or three feet in some of the trees, and they followed a parallel course to

a maximum depth of four and one-half feet in the others. The trees which lacked distinct tap roots had strong vertical roots which descended from the laterals to a depth of four feet. He concluded that the development of vertical roots from the lateral system of mature white spruce trees either supplements the tap roots or supplants them when tap roots are absent.

Paine (1956) found that vigorously growing white spruce trees in a Quebec plantation on a sandy soil produced deep roots which reached the ground water table.

On a seepage in the western Upper Peninsula of Michigan, Satterlund (1960) observed two poorly developed sinker roots on a white spruce tree. These roots penetrated to a depth of 26 inches in a weakly gleized horizon and ended abruptly without branching.

At the same road construction sites where he examined black spruce in northern Ontario, Curry (1961) reported on 15 white spruce trees. On the sand and gravel soil, he found vertical roots descending from 40 to 60 inches below ground. Some of these roots were greater than one inch in diameter at the point of breakage. White spruce vertical roots ranged between 42 and 65 inches deep in the silty sand soil. And, in the silty clay soil, roots from six trees ranged between 28 and 50 inches to the point of breakage. One white spruce

tree growing in fine sand produced vertical roots to a depth of 20 inches at the point where the root was broken off.

The foregoing observations represent most of the published information about vertical roots in white spruce prior to the appearance of an excellent bulletin in 1967. Wagg (1967) examined, in detail, the roots of immature[1] white spruce trees taken from a variety of sites in west-central Alberta and in the southern part of the Northwest Territories, Canada. Observations on several hundred root systems exposed on recent burns supplements the detailed work. His observations on the morphology of white spruce root-forms are more complete and more useful than descriptions of any root systems this author has encountered in searching the literature. Wagg's main conclusion was that no single root-form is inherent to immature white spruce in the areas he studied. He recognized four principal root-forms in the region: (1) elongated tap root-form, (2) restricted tap root-form, (3) monolayered root-form, and (4) multilayered root-form. Variations of these typical forms were encountered in any area. Those on which distinct vertical roots occur are the elongated and restricted root-forms, although

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[1]The ages (in years) of the 12 trees which Wagg examined were as follows: 31, 33, 35, 35, 38, 42, 43, 45, 50, 56, 60, and 88. They ranged in height from 18.0 to 32.9 feet, and their d.b.h. values ranged from 2.5 to 4.9 inches.

vestigial tap roots are sometimes found on the other two principal forms.

Wagg was also concerned with the effects of the soil environment on vertical root development and his summary with respect to the various root-forms encountered is worth paraphrasing. He concluded that the elongated tap root-form is found on well drained podzolic soils where soil texture, structure, or drainage do not restrict growth of the tap root. In well drained podzolic, regosolic, and solonetzic soils, growth of the tap root and proximal roots may be aborted or contorted where textural changes between horizons occur or where compaction of the underlying soil may restrict the growth of these roots. Rapid growth of a complete whorl of secondary lateral roots around the rootstock may also restrict tap root development. Early horizontal growth of the tap root through decayed logs, humus, or wet soil layers may also produce a contorted variant. These conditions all apply to the so-called restricted tap root-form.

The monolayered root-form usually results when the tap root is aborted or degenerate in the seedling because of restriction by a rock or gley layer or from a degenerating lower part of the root system caused by a fluctuating water table. In this root-form, the horizontal whorl of lateral roots becomes very prominent. The form is most common in imperfectly

drained to poorly drained podzolic and gleysolic soils.

The multilayered root-form usually has little or no vertical root development because of the restrictions which occur in the other forms. It is found usually on sites where water tables rise, lacustrine or alluvial deposits are laid down around the trees, or where thick layers of moss and humus accumulate. These situations are commonly found on well drained to imperfectly drained regosols, very poorly drained gleysols, and poorly drained podzols.

Although Wagg (1967) presents complete diagrams of the root systems of the trees he examined, no data are given concerning the vertical depths attained by the tap roots and other vertical roots. His discussion and conclusions about white spruce root-forms, nevertheless, are the best available on the topic.

With the information presented in the paragraphs above, it would now be difficult for one to retain the conviction that white spruce produces only shallow, horizontal roots. The principal question that might be raised, however, is "What is meant by shallow rooted and deep rooted?" This can better be answered after an examination is made of the literature describing vertical roots in balsam fir.

Balsam Fir

Relatively little has been written about the rooting

habits of balsam fir other than to convey the impression that the species is essentially shallow rooted. A few statements pertaining to vertical rooting are available, however. One of the earliest detailed discussions of balsam fir was given by Zon (1914). He observed that roots were able to penetrate to depths of two or two and one-half feet only on well drained sites where good growth occurs, but he made no mention of distinct vertical roots.

In a study of seedling development, Moore (1922) reported that balsam firs frequently produce a heavy central root which resembles a tap root. He also stated that mature balsam fir trees send down "anchorage roots" which may reach the water table.

Bannan (1940) excavated 10 mature balsam firs on the sand plain in northern Ontario where he studied other root systems. He presented no data for balsam fir rooting but he did state that tap roots were found and that considerable variation existed in the vertical distribution of the root system.

Cheyney (1942) reported that balsam produces a comparatively short tap root during the first few years, but this habit is soon abandoned in favor of a strong lateral system.

Satterlund's studies (1960) of ground water and swamp

forests included some observations about vertical roots in balsam fir. He stated that the weak tap root on young balsam firs appeared to cease development soon after it penetrated the gley horizon in swamps where water levels fluctuate widely. Sinker roots on mature trees penetrated downward below the higher water levels. Each sinker root ended abruptly by dividing into a brushy mass within the soil layer that was often saturated by ground water. On transition sites between swamp and upland, he found that vertical roots of balsam fir penetrated to depths where the soil was almost permanently saturated.

Fowells (1965) reports only that balsam fir seedlings possess longer tap roots and consequently have better opportunities of reaching a permanent moisture supply than do those of spruce seedlings.

The balsam fir monograph by Bakuzis and Hansen (1965) refers to most of the work conducted on the species. In several instances they report relative windfirmness by this species on well drained soils, but little is said about the size or depth of penetration of vertical roots.

The foregoing statements represent the bulk of what is presently reported about vertical rooting habits of black spruce, white spruce, and balsam fir. Clearly a shortage of evidence exists to permit definitive statements to be made about the nature of vertical rooting by these species.

Definitions: Shallow Rooting Versus Deep Rooting

Unless trees have large roots, including tap roots, sinker roots, and lateral roots, which grow vertically or descend diagonally to depths of eight feet or more,[2] authors generally consider them to be shallow rooted. By this it is usually meant that the root system is mainly confined to the upper foot or two of the soil profile. Occasional vertical roots may be produced on shallow rooted trees but they are neither large in diameter nor do they penetrate deeply. No clear line of demarcation exists between what is a large diameter and what is a small diameter for roots which descend deeply into the soil. Likewise, no clear definition exists as to what is "deep" and what is "shallow."

Pulling (1918) considered that any tree with prominent vertical roots, meaning tap root and sinkers, was deep rooted regardless of the extent or size of the lateral roots. But, he did not specify what depth these vertical roots needed to attain to achieve that definition.

Wagg (1967) pointed out for white spruce that it is sometimes difficult to determine whether a vertical root which

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[2] This is purely an arbitrary depth because some reports of deep rooting refer to trees with roots only five or six feet deep in the soil. Most authors consider this to be moderately deep.

descends from the central area of the root mass is a true tap root (primary vertical root). For this study, such a root has been considered to be a tap root if it was prominently developed. Sinker roots are defined by some authors, e.g., Wagg (1967), as only those roots which clearly descend from lateral roots and not from the central root mass. In this study, any well developed distinct vertical root which is probably not the tap root is considered to be a sinker root. It may descend from the proximity of the tap root or from one of the lateral roots which grow out from the central root mass.

At this point, I shall avoid concluding whether black and white spruce and balsam fir are anything but shallow rooted. By Pulling's definition, white spruce and balsam fir could easily be considered deep rooted. Black spruce might always be considered shallow rooted. Where and under what conditions these trees produce prominent vertical roots is the substance of this investigation.

CHAPTER II

RESEARCH AREAS AND METHODS

Study Areas

Field excavations of 108 spruce and fir trees were conducted in natural stands across the full length of the Upper Peninsula of Michigan, in northern Minnesota, and at several places in the vicinity of Longlac, Ontario, north of Lake Superior. The 45 planted spruces which were excavated were located in 22 plantations established by the Kimberly-Clark Corporation. Five of the plantations are in northern Minnesota, one is in northern Wisconsin, and the remaining 16 are in the Upper Peninsula of Michigan. Approximate locations of these study sites are depicted in Figure 4, and their geographic locations are provided in Appendix Tables 1 and 3.

Much of the preliminary work in this study was carried out in the vicinity of the summer forestry station, Camp Filibert Roth, of The University of Michigan in the western portion of Iron County, Michigan. Rudimentary facilities were available there for laboratory analysis of soils. The study of seedling root development was conducted at the old Botanical

Gardens of The University of Michigan in Ann Arbor.

Because the main object of the investigation was to study vertical root development in relation to site factors, the choice of study areas was important. Spruce and fir occur on an exceptionally wide variety of upland and transition sites in the Lake Superior region; therefore, it was necessary to select approximate study areas in advance of excavation. In Michigan, the surficial geology map of the Upper Peninsula (Martin, 1957) was used to locate approximately certain broad landform classes. Further local

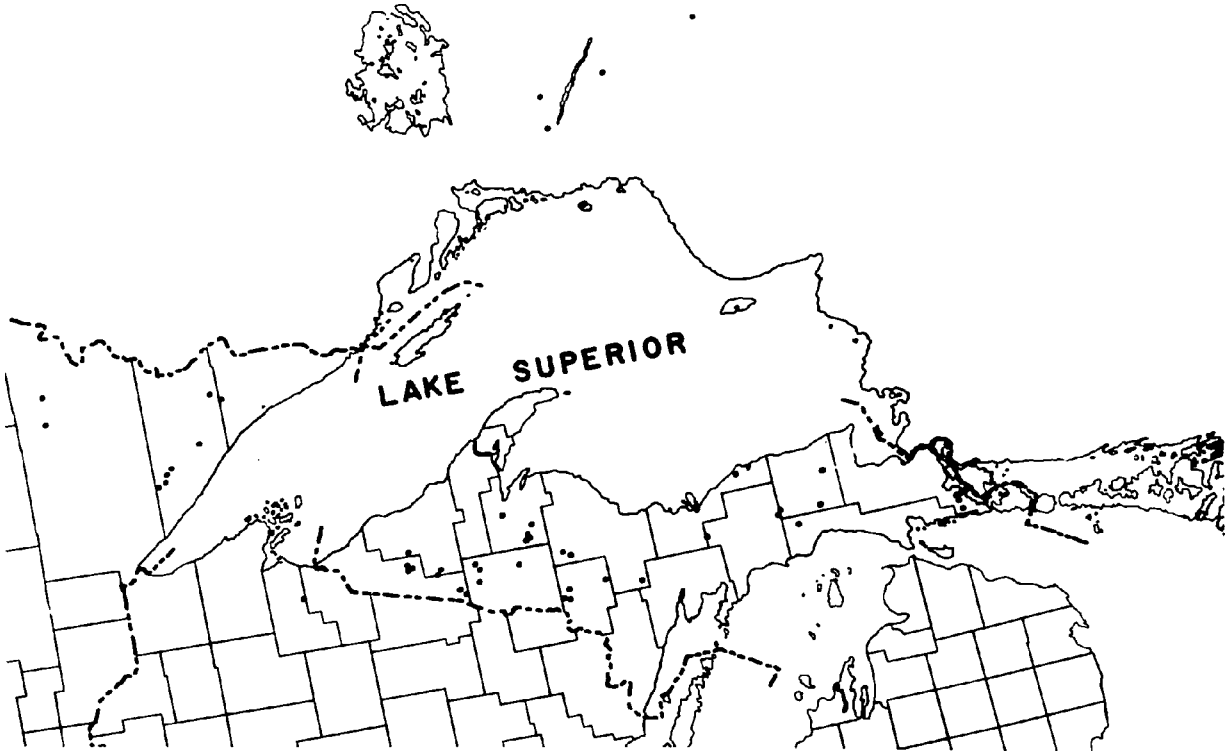


Fig. 4.--Generalized locations of spruce and fir excavation sites in the Lake Superior region. Each dot represents the approximate location of a study site.

consultation with district foresters of the Kimberly-Clark Corporation, the Michigan Department of Conservation, and the U. S. Forest Service helped locate desirable places where specific soil conditions were likely to occur. The same procedure was followed for site selection in the Kimberly-Clark plantations in Michigan. Records of the plantation histories were available from the offices of the Chief Forester, Kimberly-Clark of Michigan, Incorporated.

Plantation data for the Wisconsin plantation and the five in Minnesota were also provided by Kimberly-Clark personnel. The few natural stands visited in Minnesota and Ontario were selected after consultation with Kimberly-Clark foresters also. Landform and soil texture classes for the study sites are listed in Table 2.

Physical Characteristics of Spruce and Fir Sites

Most of the land area within 100 miles of Lake Superior belongs to the physiographic province called the Superior Upland (Hansen, 1962). This is actually an extension of the Laurentian Upland of Canada. The general pre-Pleistocene landform is largely obscured by the results of extensive glaciation. Therefore, except where Precambrian rock outcrops occur, the physiography consists of virtually every feature associated with glacial action.

Features such as swamps and bogs, morainic deposits,

TABLE 2

PHYSIOGRAPHY AND SOIL TEXTURE AT STUDY SITES

Physiographic Feature	Texture of Upper Soil Profile		Study Areas[a]
	0 - 6 inches	6 - 24 inches	
Till plain	loamy sand	sandy loam	52-S-1 (Minn.)
	sandy loam	loamy sand	N-1, N-20, N-22 53-S-4 (Mich.)
	sandy loam	sandy loam	N-2, N-5, N-6, N-7 52-S-2 (Minn.)
	loam	sandy loam	N-3
	loam	loam	N-26
	silt loam	sand	N-25
	silt loam	loam	N-27
Moraine	sand	sand	56-S-2 (Mich.)
	loamy sand	sand	54-S-3 (Mich.) 56-S-2 (Mich.)
	loamy sand	loamy sand	N-21
	sandy loam	loamy sand	53-S-6 (Mich.)
	sandy loam	sandy loam	N-4 45-S-1 (Wis.)
	silt loam	silt loam	53-S-6 (Mich.)

[a]Study areas designated by a prefix N are natural stands; the others are Kimberly-Clark plantations. For example, 52-S-1 (Minn.) means that the plantation was established in the spring (S) of 1952 (52), and it was the first plantation established by the Corporation in Minnesota that year.

TABLE 2--Continued

Physiographic Feature	Texture of Upper Soil Profile		Study Areas
	0 - 6 inches	6 - 24 inches	
Moraine deposited in water or later covered by glacial lake	sand	sand	N-13 52-F-14 (Mich.) 54-F-20 (Mich.) 54-F-21 (Mich.)
	loamy sand	sand	52-F-18 (Mich.)
	silt loam	loam	53-S-10 (Mich.)
	silt loam	silt loam	52-F-16 (Mich.)
Ice-contact ridge	loamy sand	loamy sand	N-17, N-18, N-19 N-28
	sandy loam	sandy loam	N-16
Outwash plain	sand	sand	N-11
	loamy sand	loamy sand	44-S-1 (Mich.)
	loamy sand	sandy loam	54-F-8 (Minn.)
	sandy loam	loamy sand	44-S-1 (Mich.) 54-S-4 (Minn.)
	sandy loam	sandy loam	N-8, N-9, N-10 53-S-5 (Mich.)
	sandy loam	loam	54-S-10 (Mich.)
Thin drift over rock	loam	sandy loam	N-12
	clay loam	clay	N-23
Swamp complex of dunes, recessional sand bars, etc.	sand	sand	N-15
	sandy loam	loamy sand	53-S-11 (Mich.)

TABLE 2--Continued

Physiographic Feature	Texture of Upper Soil Profile		Study Areas
	0 - 6 inches	6 - 24 inches	
Lake bed	sand	sand	N-14 54-F-19 (Mich.)
	clay loam	clay	52-S-1 (Mich.)
	silty clay loam	silt loam	N-24
	clay	clay	53-F-5 (Minn.)

outwash plains and fans, till plains, kames and kettles, eskers, ice-contact ridges, and glacial lake deposits and beaches are found throughout the region. Other physiographic features, not all glacial in origin, include sand dunes, other eolian deposits, and alluvial flats and terraces of major rivers. Black spruce, white spruce, and balsam fir are found growing on all of these features of the landscape.

The discussion below of the more typical site conditions in which spruce and fir are found serves to indicate just how wide a variation one might expect to encounter in the field. The site conditions listed in Table 2 represent a fair number of those which might be found but certainly not all.

Black Spruce Sites

On the Laurentian Shield portion of northeastern

Minnesota and adjacent Ontario, black spruce occurs on gravelly and bouldery loams and on shallow soils overlying bedrock (Fowells, 1965). Its growth appears to be best where slopes are gentle and moisture is abundant. South and east of the area of Precambrian rock outcrops, black spruce grows on mineral soils bordering swamps and in other areas with a high water table.

The better stands of black spruce occur on moist to somewhat wet clay loams and clays typical of the Clay Belt region on long, gentle slopes and on lowlands north of Lake Superior in Ontario. Podzolized and gley soils derived from clayey glacial till or from the unmodified pro-glacial lake clays are common. The maximum growth rates are obtained on loams and clay loams with better drainage.

White Spruce Sites

White spruce grows best on loamy soils (Fowells, 1965). The species also grows well on sands and clays where moisture is not limiting. When moisture is lacking on the sands or is too abundant on the clays, growth may be stunted and scrubby. Maximum development is obtained in any soil only when the roots are continuously supplied with fresh water.

Wilde, Wilson, and White (1949) stated that white spruce occurs on sandy podzols, loam podzols, podzolized gley loams, strongly podzolized clays, gley-podzol clays, and stream-bottom

soils in the podzol region of Wisconsin. Its best development there is reached on the podzolized gamma gley loams and strongly podzolized clays. On the sandy podzols its importance is minor. Wilde, Voigt, and Pierce (1954) report that the species is a major forest component on the calcareous podzol loams and clays in the Algoma District of Ontario. Exceptionally good development is found there on melanized loams and clays.

Balsam Fir Sites

Balsam fir grows on many different soil types and over a wide range of drainage conditions (Fowells, 1965). Soils range from silt loams derived from lacustrine deposits to stony loams developed from glacial till. The species makes comparatively slow growth on gravelly sands. Best development appears where soils are deep and well drained but abundantly supplied with moisture.

Major soil groups on which balsam is found in the Lake Superior region include true podzols, brown podzolic soils, gray brown podzolic soils, gray wooded soils, and organic soils (Bakuzis and Hansen, 1965). Textural classes vary from heavy clay soils to loams, sandy loams, gley loams, sandy glacial till, lake sand, and skeletal soils atop rock outcrops.

Methods

Root System Excavations

Exposure of the Root System

Three different methods were used to examine the gross morphology of spruce and fir root systems. They were the following: (1) hand, shovel, and ice pick excavation; (2) examination of trees uprooted in road-building work; and (3) hydraulic washing technique.

Removal of mineral soil and organic matter from around the roots of trees is customarily done by hand-and-shovel excavation. Some investigators have dug pits around the bases of trees in order to study the development of tap roots or sinker roots, and this is what was done in the present study. The pits were begun by shovel and the earth surrounding the roots was then pried away with sticks, ice picks, or other implements. An example of such an excavation can be seen in Figure 5. The method is very time consuming and tedious, but in this study it was used on 17 trees in natural stands and on all 45 of the spruces in plantations.

Another dry method useful for studying the gross morphology of tree root systems was used extensively in this study, but no references to this method have been found in published works treating root studies. When logging roads are constructed in forested regions many trees are usually



Fig. 5.--Young white spruce tree excavated by hand. Ontonagon County, Michigan.

cut and removed from the site of the road grade. Sometimes trees are merely pushed over and uprooted by a bulldozer and shoved to one side. In these instances, many roots are broken off but many remain intact. Because one main objective of this study was to determine if strong vertical roots are produced by spruce and fir, examination of uprooted tree stumps often provided substantial amounts of information. Observations were made on 71 different spruce and fir trees by this method. It was usually necessary to employ a sharp-pointed instrument to dislodge much of the soil which adhered to the root mass, but the presence or absence of vertical roots could be determined with confidence and measurements could be made after the soil was

removed. The exposed root systems of two trees examined by this method can be seen in Figures 6 and 7.

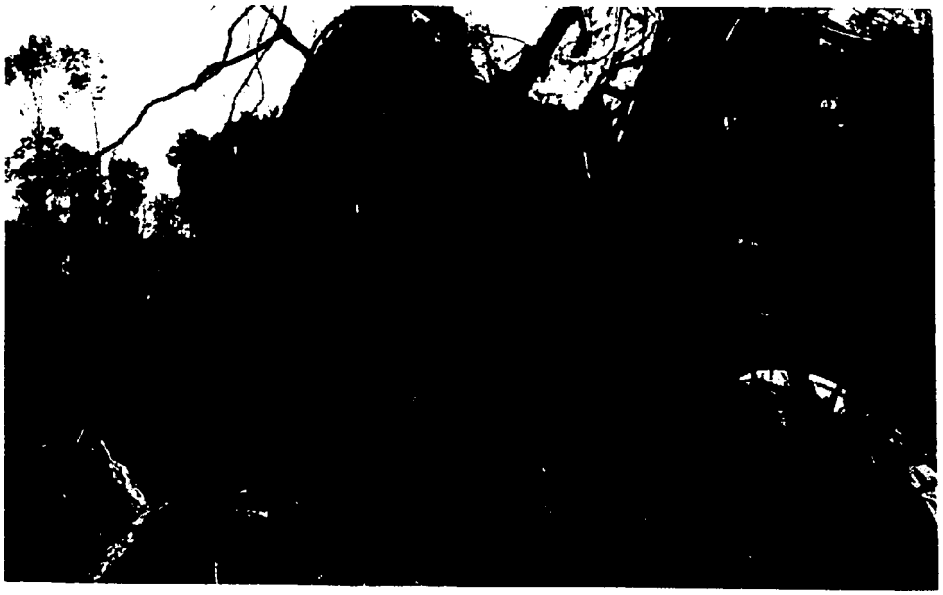


Fig. 6.--Root system of black spruce tree exposed in road construction. Ontario, Canada.



Fig. 7.--Root system of white spruce tree exposed in road construction. Ontario, Canada.

Stoeckeler and Kluender (1938) were among the first to describe thoroughly the hydraulic method of exposing plant roots. A jet of water is used to wash away the mineral soil and other material in which the roots of a plant are embedded. An abundant source of water is required, and a pump capable of forcing a strong jet of water through a washing nozzle must also be available. Unless the site has a slope of at least 20 percent, too much debris usually clogs up the washing area and renders the operation unsatisfactory. Two white spruce trees which were excavated by the hydraulic method in this study are seen in Figure 8. The method, like the hand-and-shovel technique, is also time consuming and tedious. For this reason, the roots of only 20 different trees were washed out.



Fig. 8.--Two white spruce trees excavated by the hydraulic method. Iron County, Michigan.

The pump used in this study was a portable fire-fighting pump driven by a two-cycle engine. Up to 200 feet of one-and-one-half-inch fire hose was used to transport water from the pump to the excavation site. A standard one-quarter-inch fire nozzle was used to direct the stream of water.

Measurements of Root Development

On each of the 153 trees examined in this part of the study, the main concern was for vertical root development. Several measurements were taken on the root system of each tree after it was dug out of the soil. On those trees examined along logging roads, measurements were made after soil was removed from the overturned root mass. The first feature sought was a primary vertical root, or tap root, beneath the tree stem. Any other prominent vertical roots, such as sinkers, were also noted. If a tap root was found, the distance from the soil surface to its unbroken or broken terminus was measured. This distance was accurately determined on those root systems which were excavated by hand or washed out, but obviously it had to be estimated on stumps uprooted in road construction.

In addition, diameter measurements were obtained with calipers at each of several locations on each vertical root. The first of these was taken at a point on the root where it

became distinctly separated from the main root mass. Other diameters were measured at 12-inch increments descending below that initial point, and a final diameter measurement was made at the root terminus. These data were used to establish a relative measure of root taper which was later used to estimate the possible total length of broken roots. This technique is discussed in Chapter III. The distance below the soil surface to the initial diameter measurement was also noted.

Measurements of this kind were obtained on the tap root and on as many as four other strong vertical roots, if that many were found, on each tree. If no tap root were found, or if trees did not have four other prominent vertical roots, these facts were recorded. Some trees, particularly balsam firs, had a dozen or more prominent vertical roots. In these instances, the most prominent ones were measured. Where no distinct vertical roots were encountered, measurements were taken on any roots which descended below the main root mass. Black spruce trees expressed this form more commonly than did the other two species.

In those excavations done by hand and by water, some measurements were made while the root system was still in the soil. Thus, it was possible to observe root proliferation in various soil strata in some of the larger excavations. For

example, a hole 10 feet deep was dug beneath one balsam fir tree in Iron County, Michigan.

Measurements of Soil Factors

Soil bulk density and texture were the two main soil variables of concern at each study site. Notations were made, however, of soil profile development and of such characteristics as depth to rock, hardpan, or water.

In situ soil samples were taken at each study site for the measurement of bulk density. The following depths in the mineral soil were sampled: 0-3 inches, 3-6 inches, 6-12 inches, and one-foot increments thereafter to bedrock, water, or the greatest depth attained by tree roots measured. The core samples had a volume of 148.0 cc and they were taken at the midpoint of the depths listed above. In addition, loose samples of soil were obtained at each of these depths for mechanical analysis. Soil texture was determined by the Bouyoucos hydrometer method.

Soil samples were taken from the excavation hole of each tree which was excavated by hand or by water. For those root systems which were exposed by road building, soil samples were taken as near the stumps as possible. In some instances, these samples may not correctly represent the soils in which the trees grew. Selection of the various stumps for study was partly based on the relative uniformity

of site for the area, however.

Seedling Root Development Study

One hundred nursery-grown seedlings each of black spruce, white spruce, and balsam fir--all two years old--were obtained in the spring of 1960. The source of the seed was unspecified by the two nurseries except that it was from the Great Lakes region. Black spruce seedlings came from Grand Haven, Michigan; and the white spruce and balsam fir came from Sturgeon Bay, Wisconsin.

Four different soil environments were prepared for the seedlings so that root development could be studied under several conditions of soil texture and bulk density. The treatments and their descriptions follow. Treatment 1. A loosely packed, coarse soil composed of washed sand and gravel was used to simulate a well aerated soil with excessive moisture drainage. Its average bulk density was 1.70 g/cc.[3] Treatment 2. Intermediate drainage and aeration conditions were simulated by a loosely packed sandy clay loam with an average bulk density of 0.92. Treatment 3. Another soil with intermediate drainage and aeration, but with a restricting hard pan, was prepared from a loose sandy

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[3]Henceforth, bulk density will be referred to without giving the units; it should be understood that g/cc is meant each time a numerical value is presented.

loam with average bulk density of 1.06 for the upper six inches and a highly compacted loam (average bulk density of 1.62) for the lower six inches of the artificial profile.

Treatment 4. The fourth condition simulated was one of poor drainage and aeration. This was accomplished by using a somewhat compacted sandy clay loam with an average bulk density of 1.24. Each of these four soil conditions was replicated four times for each of the three tree species.

A wooden frame four feet wide, ten feet long, and one foot deep was constructed atop a concrete workbench in one of the Botanical Gardens greenhouses. This box was partitioned inside so that 16 compartments resulted. Each of these was 12 inches deep, 12 inches wide, and 30 inches long. Free drainage was permitted for each of the compartments. The four soil treatments were randomly assigned positions in a Latin square design so that analysis of variance could be used to evaluate root development in these conditions.

Texture of the soil in the various compartments was determined at the time this greenhouse study was begun, but other physical attributes of the soil were determined at the termination of the seedling growth period. At that time, volumetric soil samples were taken from the 0- to 6-inch depth and 6- to 12-inch depth at two places in each of the 16 compartments. Bulk density was determined from these.

In April, 1960, four seedlings of each species were planted carefully in each of the 16 compartments. The 64 seedlings of each species were selected on a random basis from the 100 seedlings originally obtained. For the next nine and one-half months the seedlings were watered at weekly intervals until moisture began to appear at the soil surface. No artificial light was used; all seedlings grew under the natural photoperiod for the latitude of Ann Arbor. Greenhouse temperature was maintained at close to 70 F.

Initial Measurements Taken on Seedlings

Before any seedling was planted, certain measurements were obtained pertinent to roots and top of the tree. If a distinct tap root or other main vertical root was evident, its length was measured and recorded. In the event that no main vertical root was found on the tree, a measurement was made on one root which exhibited a tendency to descend. Also, on each seedling, total length measurements were made on the three uppermost lateral roots of the tree. All root measurements, vertical and lateral, were made from the root collar zone to the terminus of each root. All measurements were recorded to the nearest one-eighth inch.

The 36 residual seedlings of each species which were not planted were utilized to provide an index of top and root dry weights of planted seedlings prior to development in the

four soil environments. Tree heights were measured and then the trees were cut in two at the root collar. Tops and roots were oven dried separately at 105 C for 24 hours and weighed.

Final Measurements Taken in Greenhouse Study

At the end of the second week of February, 1961, approximately nine and one-half months after planting, the surviving seedlings were removed carefully from the study boxes. One side of each compartment was removed and an ice pick was used to extricate each seedling, one at a time, from the soil. (See Figures 9 and 10.) At this time, the depth reached by the main vertical root was recorded. After each seedling was removed from the soil, it was spread out on a gridded sheet and photographed. (See Figure 11.) The total lengths of the three uppermost lateral roots were measured. (When one of the uppermost roots was obviously of recent adventitious origin it was not included among the three measured.) Final tree heights were also obtained.

After each tree was measured and photographed it was cut in two at the root collar. Each top and each root mass was then placed in a separate container and dried in an oven for 24 hours at 105 C. Final weighings were made to 0.001 g.

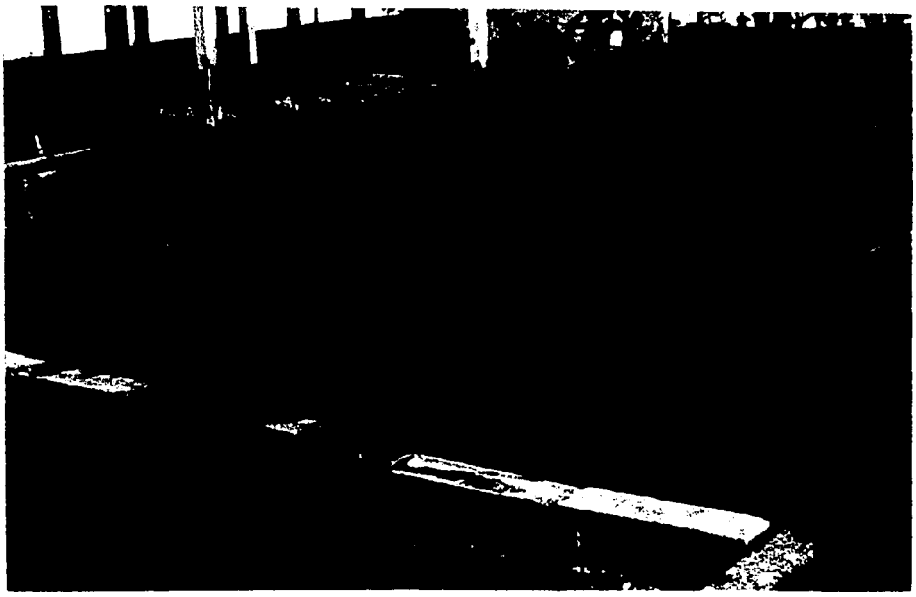


Fig. 9.--Exposure of the ends of four different soil profiles in the seedling study.



Fig. 10.--White spruce seedling (on left) being extricated from sandy clay loam soil with bulk density of 0.94.

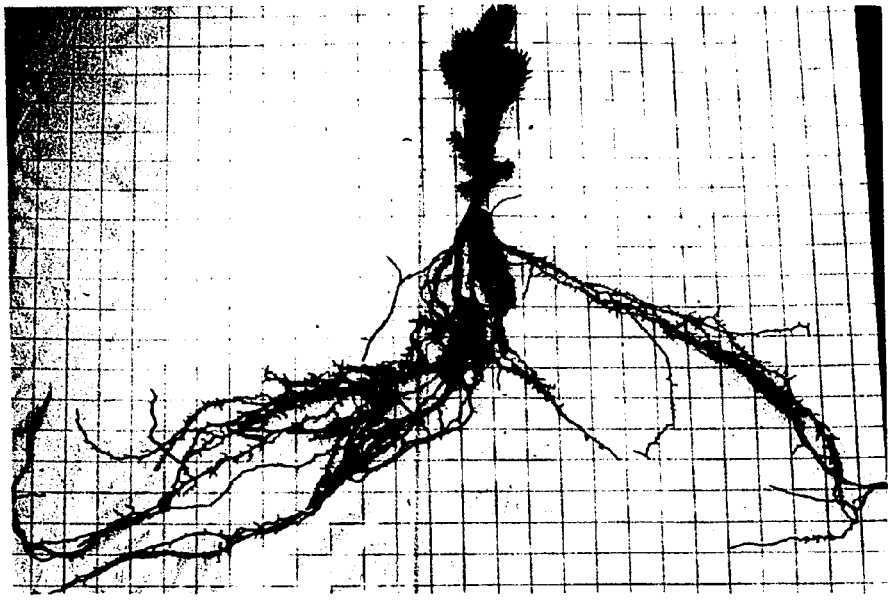


Fig. 11.--White spruce seedling after growing nine and one-half months in a sandy soil with bulk density of 1.76. Grid is in one-inch squares.

CHAPTER III

BLACK SPRUCE ROOT EXCAVATIONS

Trees which develop from seed in natural stands may or may not exhibit rooting habits which differ from planted trees. The results which are presented in the following pages are treated separately, however, according to whether the trees were studied in natural stand conditions, in plantations, or in the greenhouse seedling study. In natural stands, 40 different black spruce trees were examined in some detail. Fourteen plantation trees were excavated, and 44 seedlings survived (out of 64 planted) the greenhouse experiment and were examined.

Black Spruce Trees in Natural Stands

The 40 black spruce trees were examined at 19 different sites. Eight were exposed using the hydraulic method, 21 were examined on road construction or logging sites, and the other 11 were excavated by hand (Table 3). Each of the roots for which information is reported terminated at the depth indicated below ground or its estimated depth of greatest penetration is indicated. The bulk density values represent

TABLE 3

SOIL CHARACTERISTICS AND VERTICAL ROOT PENETRATION OF BLACK SPRUCE TREES IN NATURAL STANDS

Site No.[a]	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-11	Sand	Sand	1	32	4.2	16(17)1.70	10(12)1.59			
			2	32	3.7	12(20)1.70	11(12)1.59	11(12)1.59	11(12)1.59	
N-14	Sand	Sand	1	52	5.3	c	26(26)1.56	18(19)1.49	20(21)1.49	20(22)1.49
N-15	Sand	Sand	1	34	2.0	c	32(34)1.54	14(18)1.48	15(17)1.48	33(36)1.54
			2	33	1.2	33(34)1.54	20(22)1.48	17(18)1.48	39(39)1.55	18(18)1.48
N-17	Loamy sand	Loamy sand	1	63	4.3	c	16(17)1.53	12(13)1.53		

[a]A more complete site description is given in Appendix Table 1. Data presented in this table are arrayed by soil texture classes and range from the coarsest to the finest textures.

[b]Numbers listed first are the depths of roots below ground either at the point of breakage or the unbroken terminus; numbers in parentheses are the estimated total vertical depths reached when calculated by the method of Dittmer (1959); and the final numbers are the bulk density at greatest root depth attained.

[c]No distinct main vertical root was found on this tree.

TABLE 3--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density		
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]	
N-18	Loamy sand	Loamy sand	1	50	3.4	11(12)1.48	13(14)1.68	12(13)1.68
			2	72	4.8	c	12(13)1.68	10(11)1.48
N-19	Loamy sand	Loamy sand	1	61	4.2	15(16)1.58	11(12)1.67	9(10)1.67
N-21	Loamy sand	Loamy sand	1	4	d	3(3)1.30	2(2)1.30	2(2)1.30
			2	4	d	5(5)1.22	4(4)1.22	
			3	4	d	2(2)1.30		
			4	4	d	2(2)1.30	2(2)1.30	
N-28	Loamy sand	Loamy sand	1	71	4.8	13(15)1.58	12(13)1.58	14(15)1.58
			2	51	3.4	12(14)1.58	11(13)1.58	15(16)1.58
			3	39	2.6	c	10(11)1.67	11(12)1.58
			4	57	3.7	9(11)1.67	11(13)1.58	

[d]Tree was a seedling less than two feet in height.

TABLE 3--Continued

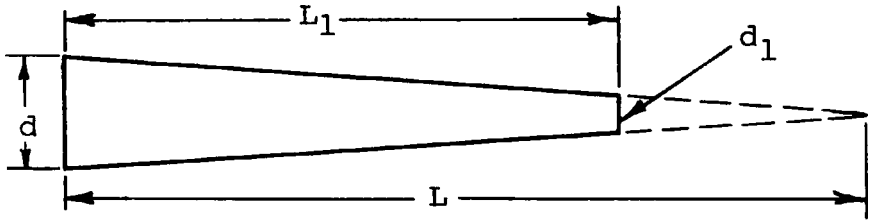
Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-22	Sandy loam	Loamy sand	1	43	3.2	c	9(11)1.14	10(12)1.62	11(13)1.62	
N-2	Sandy loam	Sandy loam	1	37	4.8	13(14)1.51	19(21)1.51	16(17)1.51	18(20)1.51	14(16)1.51
			2	36	4.3	c	10(11)1.63			
			3	35	4.0	14(15)1.51	12(13)1.51			
			4	38	5.0	c	14(15)1.51	11(12)1.63		
N-9	Sandy loam	Sandy loam	1	35	7.0	28(29)1.41	33(34)1.41	27(28)1.41	24(25)1.41	40(44)1.41
			2	33	5.9	30(31)1.41	44(48)1.41	26(26)1.41		
N-16	Sandy loam	Sandy loam	1	57	3.6	18(19)1.52	19(20)1.52	16(16)1.52	20(20)1.52	19(20)1.52
N-3	Loam	Sandy loam	1	42	6.9	c	24(25)1.70	19(20)1.34	16(17)1.34	
			2	35	5.2	14(15)1.34	23(28)1.70	16(17)1.34		
N-12	Loam	Sandy loam	1	61	6.2	c	13(13)1.58	24(25)1.65	14(16)1.58	14(15)1.58
			2	57	4.7	13(13)1.58	13(13)1.58			

TABLE 3--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density		
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]	
N-26	Loam	Loam	1	147	12.0	c	12(14)2.24	13(15)2.24
			2	138	11.7	c	16(18)2.24	18(21)2.24
			3	154	12.1	c	18(20)2.24	16(19)2.24
N-25	Silt loam	Sand	1	51	7.0	c	18(22)1.86	16(20)1.86
			2	37	4.0	c	10(12)1.59	11(13)1.86
			3	43	4.0	c	11(13)1.86	12(14)1.86
N-27	Silt loam	Loam	1	51	5.9	26(28)2.24	22(24)2.24	25(28)2.24
			2	119	10.0	c	44(47)2.24	22(26)2.24
N-24	Silty clay loam	Silt loam	1	137	12.0	24(26)1.94	15(26)1.94	16(18)1.94
			2	30	2.1	c	12(14)1.94	13(14)1.94
N-23	Clay loam	Clay	1	91	9.3	c	29(30)1.49	

the average obtained at the particular soil depth where the root terminated.

Since data were obtained on the diameters of individual roots at specific depths below ground, a taper factor was calculated for those roots which were broken off above the root terminus. Dittmer (1959) reported on a method he used with success to estimate total vertical root length as well as total length of certain lateral roots. The following formula and sketch illustrate the relationship which he used.



$$L = \frac{L_1 \ (d)}{d - d_1}$$

L = total estimated length of root
L_1 = actual length of broken root
d = root diameter at base of plant
d_1 = root diameter at broken end

Dittmer discussed that its reliability was generally restricted to roots which were not gnarled and twisted or abnormally enlarged where the root left the central root mass of the tree. On checks made against actual length of many roots, he found the error to be less than 10 percent. The

same method was used in the present study, and most estimates were found to be within five percent error on all three species studied. In Table 3, both estimated and actual lengths are given so that either may be considered. Diameter measurements of roots at different depths are shown in Appendix Table 5.

By examining the data in Table 3, one can see that 19 of the 40 trees exhibited no type of root which could be called a tap root, but most trees did possess one or more sinker-type roots. Twenty-one of the trees had a tap root descending from the central root mass, but on only one tree was this root prominent. The stump of this tree is illustrated in Figure 12. Even this large root did not descend deeply (30 inches) into the sandy loam soil before it pursued a horizontal course. The bulk density of 1.41, while being moderately high, does not represent impenetrable conditions. Only five of the 21 trees had tap roots which penetrated below two feet, and the deepest any one of these attained was 33 inches. No distinct changes in texture or bulk density of the soil seem to account for this generally shallow penetration of tap roots. (Bulk density and texture data for each soil depth at each study site are presented in Appendix Table 2.)

The sinker roots examined on these 40 trees exhibit



Fig. 12.--Prominent tap root on black spruce tree growing in natural stand at Site No. N-9, Baraga County, Michigan.

the same shallow penetration. Of the 87 different sinker roots on which observations were made, only four penetrated deeper than 36 inches. The deepest of these was 44 inches below the soil surface. Numbers of roots observed, according to depth of penetration, are summarized in Table 4 along with the numbers of trees according to their greatest depth of penetration. Out of a total of 108 vertical roots examined, 85 of them, or nearly 79 percent terminated within the upper two feet of soil.

No relationship was found between root depth and soil bulk density at the root terminus. Several different ways of analyzing the data to establish such a relationship were tried, but none gave anything except a random scatter of points on a

TABLE 4

SUMMARY OF VERTICAL PENETRATION BY ROOTS OF FORTY BLACK SPRUCE TREES GROWING IN NATURAL STANDS

Maximum Depth of Penetration	Number of Roots Observed[a]		Number of Trees[b]
	Tap Roots	Sinker Roots	
0 - 12 inches	6	18	6[c]
12 - 24 inches	10	51	22
24 - 36 inches	5	14	8
36 - 48 inches	---	4	4
Total	21	87	40

[a]If the estimated depth of penetration of a root was in a next higher depth class, the root was tallied in that class; borderline cases were tallied in the lower class.

[b]This is the number of trees for which the greatest depth of root penetration was in the depth class shown.

[c]Four of these trees were four-year-old seedlings.

graph. It seems possible to conclude temporarily that bulk density of the soil does not, by itself, reflect conditions which inhibit vertical root development of black spruce trees which grow on upland sites in natural stands.

Most of the vertical roots which were observed on these 40 black spruces were not prominent roots, except for the one tap root illustrated in Figure 12. Typical sinker

roots were, as those shown in Figures 13 through 19, similar to those described by Bannan (1940) and LeBarron (1945). A tap root may also be seen on some of these trees, but it was most often aborted or poorly developed.

Black spruce seedlings which were only a few years old did not produce any distinct vertical roots. In addition, it was not possible to correlate age of tree and vertical root penetration by older trees. Soil texture and bulk density undoubtedly have some bearing on the depth to which roots are able to penetrate, but no direct relationship between these variables was apparent in this phase of the study.



Fig. 13.--Inverted root system of black spruce tree showing small vertical roots. This tree grew in sand and the deepest root terminated 26 inches below ground. Site No. N-14, Alger County, Michigan.



Fig. 14.--Inverted stump of black spruce tree showing typical short, branched sinker roots. Tree grew in sandy loam and deepest root was 20 inches below soil surface. Site No. N-16, Iron County, Michigan.



Fig. 15.--Numerous sinker roots and tap root on black spruce tree growing in sandy loam. Tap root was 13 inches deep and deepest sinker descended 19 inches. Site No. N-2, Menominee County, Michigan.



Fig. 16.--Close-up view of tap root which descended short distance before growing horizontally. Same black spruce as shown in Figure 15.

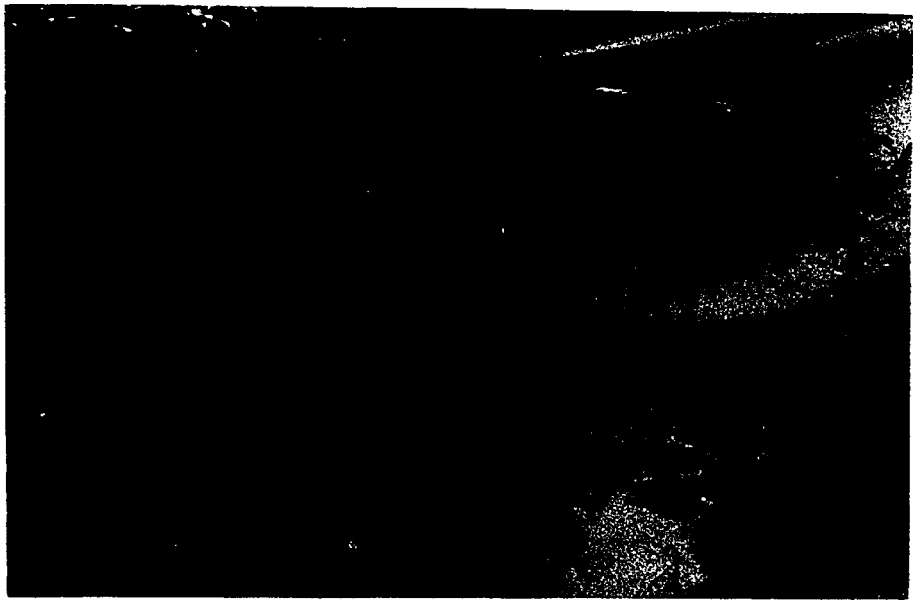


Fig. 17.--Slender sinker roots on black spruce growing in pure sand. Deepest root was 33 inches below ground level. No tap root was present. Site No. N-15, Luce County, Michigan.



Fig. 18.--Tap root on black spruce growing in pure sand. Penetration was 16 inches below surface. Site No. N-11, Baraga County, Michigan.



Fig. 19.--Feeble sinker roots and aborted tap root on large black spruce tree near Longlac, Ontario.

Equally deep vertical roots were encountered both in sandy soil and in the finer texture classes. As stated earlier, bulk density and root depth did not appear to be closely related. The conclusion reached after examining the data collected on upland black spruce trees would seem to be that growth of vertical roots may be restricted by soil environmental factors but the species seems to produce limited vertical roots under any circumstance. Weakly developed tap roots were found in numerous instances but these were never very large.

Black Spruce Trees in Plantations

The 14 trees of this species which were excavated by hand in Kimberly-Clark spruce plantations ranged in age from 8 to 20 years. One tree was 20 years old and the others were from eight to 11 years old. The eight-year-old trees had grown in the plantation environment for five growing seasons, and all others had grown longer than that. Ample time for adjustment to the soil conditions should have passed, and the tree rooting habits found are likely to be representative of those developed by plantation trees in general on similar sites.

Data presented in Table 5 and Appendix Table 6 are similar to those of Table 3 and Appendix Table 5 for black

TABLE 5

SOIL CHARACTERISTICS AND ROOT PENETRATION OF BLACK SPRUCE TREES IN PLANTATIONS, EXCAVATED 1960

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
54-F-19 Mich.	Sand	Sand	1	10	72	c	15(1.59)Sa		
54-F-20 Mich.	Sand	Sand	1	10	59	6(1.20)Sa	6(1.20)Sa	5(1.20)Sa	
54-F-21 Mich.	Sand	Sand	1	10	70	c	8(1.45)Sa	8(1.45)Sa	8(1.45)Sa

[a]Plantation designations are those used by the Kimberly-Clark Corporation. For example, 54-F-19 means that the plantation was established in the fall (F) of 1954 (54), and it was the nineteenth plantation established by the Corporation in Michigan that year.

[b]Numbers listed first are the depths of roots below ground at their terminus; those in parentheses are the soil bulk density at that depth; and the letters indicate the soil texture at the root terminus. Sa is sand, Si is silt, Cl is clay, and Lo is loam. SiLo indicates silt loam.

[c]No distinct main vertical root was found on this tree.

TABLE 5--Continued

Plantation No.[a]	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
56-S-2 Mich.	Sand	Sand	1	8	42	16(1.57)Sa	11(1.31)Sa		
54-S-3 Mich.	Loamy sand	Sand	1	9	50	9(1.57)Sa	15(1.63)Sa		
			2	9	74	6(1.30)Sa	7(1.57)Sa	15(1.63)Sa	
56-S-2 Mich.	Loamy sand	Sand	1	8	39	5(1.31)LoSa	5(1.31)LoSa		
52-S-1 Minn.	Loamy sand	Sandy loam	1	11	104	7(1.44)SaLo	14(1.61)SaLo	14(1.61)SaLo	11(1 44)SaLo
54-F-8 Minn.	Loamy sand	Sandy loam	1	10	39	c	5(1.44)SaLo		
45-S-1 Wis.	Sandy loam	Sandy loam	1	20	214	c	11(1.26)SaLo	10(1.26)SaLo	
52-S-2 Minn.	Sandy loam	Sandy loam	1	11	101	14(1.69)SaLo	8(1.22)SaLo		

TABLE 5--Continued

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
53-S-5 Mich.	Sandy loam	Sandy loam	1	10	72	7(1.26)SaLo	6(1.41)SaLo	6(1.41)SaLo	
			2	10	60	8(1.26)SaLo	7(1.26)SaLo	7(1.26)SaLo	8(1.26)SaLo
54-S-10 Mich.	Sandy loam	Loam	1	9	65	8(1.63)SaLo	13(1.75)Lo	13(1.75)Lo	6(1.52)SaLo

spruces in natural stands. The main exceptions are that: (1) no estimated root depths are given because all roots were excavated completely, and (2) soil texture at the root terminus is shown. Additional soils data are presented in Appendix Table 4.

Past experience by Kimberly-Clark foresters had indicated that black spruce plantations developed best on soils of relatively coarse or medium texture; therefore, most of the Corporation spruce plantations were established on such sites. With one tree as an exception, the roots of all trees terminated in soil which was either sand, loamy sand, or sandy loam in texture. This exception was a tree which grew on a site where the soil was loamy in texture below 12 inches and relatively compact at all depths.

Ten of the 14 trees possessed distinct tap roots, but none of these penetrated deeper than 16 inches. The average penetration of the 10 tap roots was about eight and one-half inches. No other vertical roots were found below 15 inches in the soil. A summary of these data is presented in Table 6. Because the soils did not vary greatly in texture, it would seem that bulk density might be a more significant factor affecting rooting depth. Analysis of depth of penetration versus bulk density, however, revealed no apparent relation between the two. In fact, a few of the deeper roots

TABLE 6

SUMMARY OF VERTICAL PENETRATION BY ROOTS OF FOURTEEN BLACK SPRUCE TREES GROWING IN PLANTATIONS

Maximum Depth of Penetration	Number of Roots Observed		Number of Trees[a]
	Tap Roots	Other Vertical Roots	
0 - 6 inches	3	7	3
6 - 12 inches	5	12	4
12 - 18 inches	2	7	7
Total	10	26	14

[a]This is the number of trees for which the greatest depth of root penetration was in the depth class shown.

were found at higher bulk densities than were the shallower roots. The maximum depth of 16 inches cannot really be considered "deep" however.

In coarse textured soils which inherently have high bulk density, increasing bulk density with depth often represents greater compaction. This often improves the water relations of these soils because the pore spaces tend to be smaller and more water is retained around individual soil particles. If the pore spaces were too small for the rootlets of black spruce to penetrate, however, bulk density would be a limiting factor. Again, however, the 14 black spruce trees examined did not produce prominent vertical

roots even though 10 distinct tap roots were observed. No apparent relation can be seen between penetration and bulk density for these trees. Several of them can be seen in Figures 20 through 24.

The ages of these plantation trees may have had a bearing on the development of vertical roots, but this is not apparent from an examination of the data. One other factor may have been even more important. Regardless of the care used to plant seedlings in the field environment, many of the roots usually are twisted when the tree is thrust into the soil. Most of the trees examined in the plantation studies were planted by machine, although a few were hand-planted with the aid of a grub hoe, mattock, or planting bar.

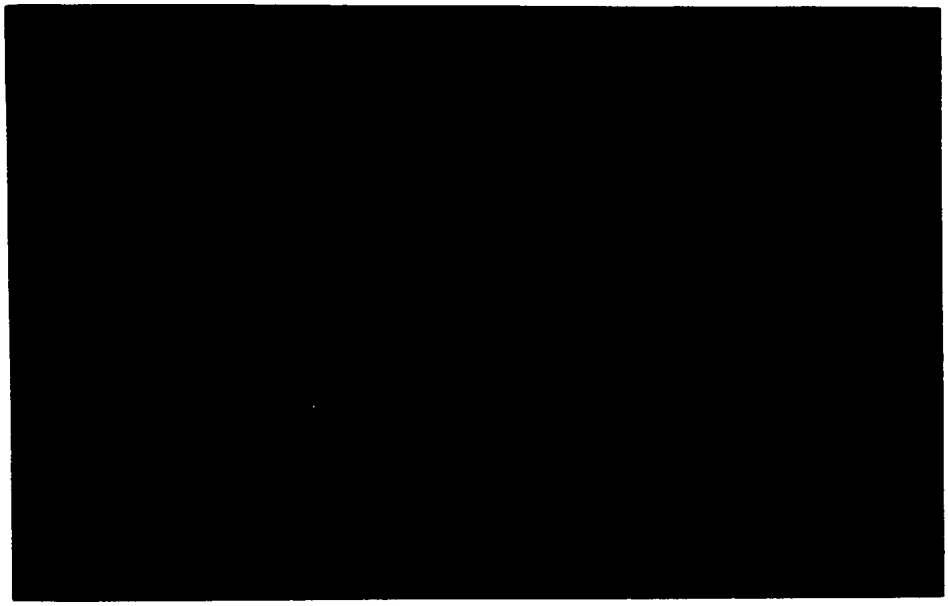


Fig. 20.--Root system of a nine-year-old black spruce tree growing in a sandy soil. Plantation No. 54-S-3, Ontonagon County, Michigan.



Fig. 21.--Root system of an eight-year-old black spruce tree growing in a sandy soil. Plantation No. 56-S-2, Marquette County, Michigan.



Fig. 22.--Root system of a ten-year-old black spruce tree growing in a sandy soil. Plantation No. 54-F-20, Chippewa County, Michigan.

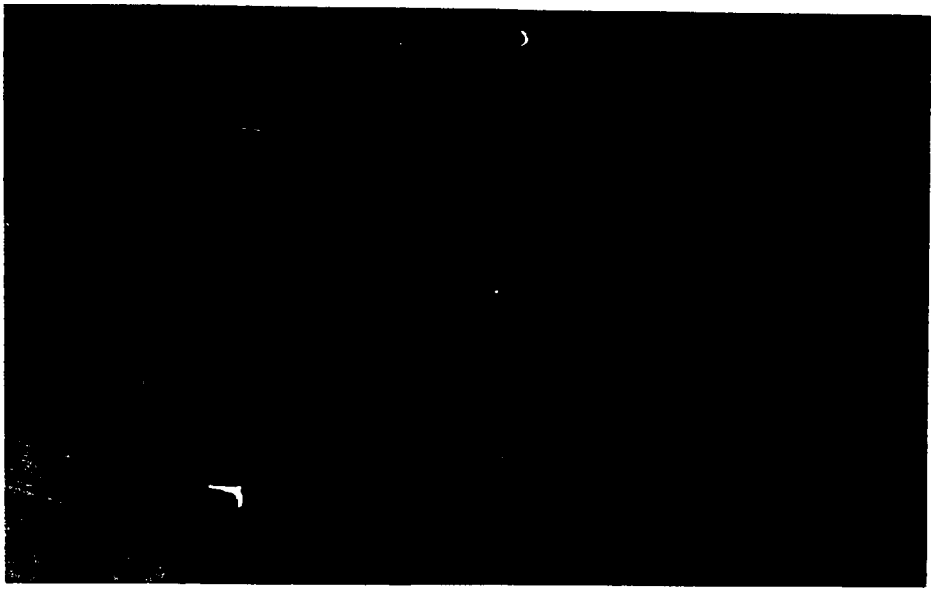


Fig. 23.--Root system of a ten-year-old black spruce tree growing in pure sand. Plantation No. 54-F-19, Luce County, Michigan.

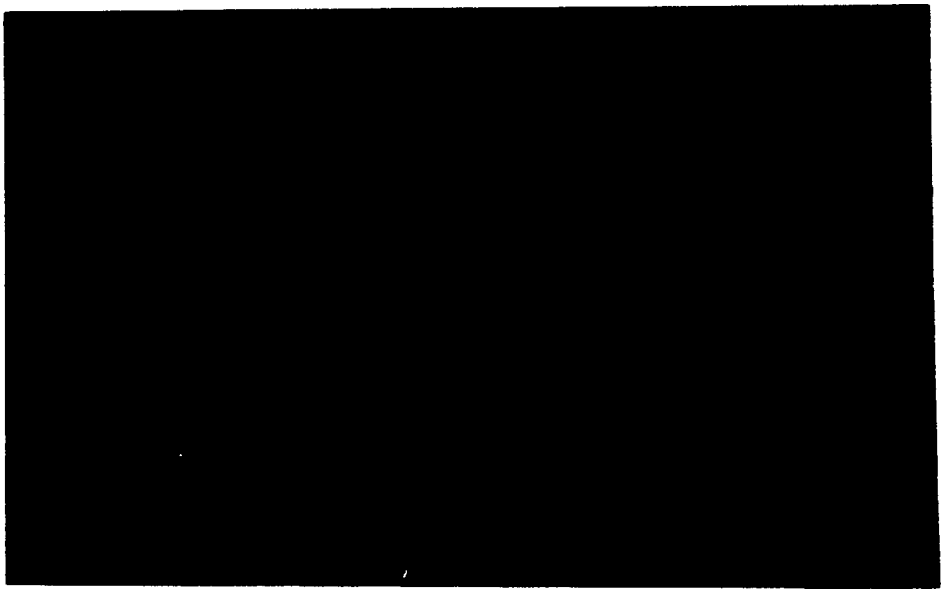


Fig. 24.--Inverted root system of a nine-year-old black spruce tree growing in a sandy soil. Plantation No. 54-S-3, Ontonagon County, Michigan.

The twisting of the seedling root mass which frequently results from machine or rough hand-planting appears to persist throughout the life of the tree. This can easily be seen on the trees shown in Figures 21 and 22. In fact, black spruce often produces adventitious lateral roots above the mass of roots which is twisted at the original time of planting. These adventitious roots were apparent on nearly all trees excavated in plantations, but they are not as obvious on natural-grown trees. From this, one might surmise that black spruce trees in plantations could fail to develop vertical roots because of the abnormal initial treatment of their root systems. Even on the 10 trees which did have tap roots, none were more than one-quarter inch in diameter at 10 inches below ground.

Considerable care was used in the planting of black spruce seedlings in the greenhouse study which is described next. Those results strengthen even more the belief that vertical rooting is not a dominant feature of the black spruce root system even though a tap root is frequently produced.

Black Spruce Seedlings in Greenhouse Experiment

Within a few days after the 64 seedlings were planted in April, 1960, their buds expanded and new foliage was produced. Elongation proceeded for several weeks and then a

period of dormancy began. Growth in height resumed again and additional foliage was produced before the trees were excavated in February, 1961.

Sixteen trees had been planted in each of the four different soil environments, and 44 of the 64 survived. Survival, in numbers of trees, was as follows for each treatment.

Treatment Number	Soil Texture	Average Bulk Density (g/cc)	Surviving Trees (number)
1	Sand	1.70	16
2	Sandy clay loam	0.90	8
3	Sandy loam loam	1.06 1.62	10
4	Sandy clay loam	1.24	10

Textural analyses, with mean percentages of sand, silt, and clay fraction, respectively, were as follows for each of the treatments:[4]

1---95.5 sand, 2.0 silt, 2.5 clay

2---49.5 sand, 25.5 silt, 25.0 clay

3---72.0 sand, 14.0 silt, 14.0 clay (0-6 in.)
40.0 sand, 36.0 silt, 24.0 clay (6-12 in.)

4---50.5 sand, 29.5 silt, 20.0 clay

[4] Means are rounded off to the nearest one-half percent.

Results of vertical root growth are presented in Table 7. In this study, only one main vertical root was measured initially. At the conclusion of the study, a measurement was taken on the depth of penetration of the one most prominent vertical root on each surviving tree. Because the soil in each 12-inch-deep box had settled somewhat over the course of the experiment, the root collar of each tree was approximately one inch below the top of the box. That meant that a maximum of 11 inches was possible for vertical root penetration by any tree.

The mean depths of penetration by black spruce seedlings gives a good indication of what effects the soil environment exerted on these trees. Only in the compartments which contained treatment 3, with a compact layer in the lower six inches of the profile, was root growth different from the other soil conditions. Analysis of the data, using the "t" test, shows that the mean depths of penetration in soil treatments 1, 2, and 4 are not significantly different from one another. The mean depths of penetration in treatments 2 and 4, however, are significantly different from the mean depth of penetration in treatment 3 at the five percent level of probability. The mean rooting depth in treatment 1 lies between the five and ten percent probability levels of being different from the mean in treatment 3. The initial

TABLE 7

INITIAL AND FINAL VERTICAL ROOT PENETRATION BY BLACK SPRUCE SEEDLINGS GROWN IN GREENHOUSE EXPERIMENT

Tree No.	Vertical Root Penetration in Different Soil Treatments[a]							
	1		2		3		4	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	(inches)							
1	3.4	5.5	3.5	3.5	2.9	3.5	2.8	7.0
2	2.8	3.0	4.0	5.0	3.9	3.9	3.5	4.0
3	0.9	6.0	5.5	6.0	3.1	6.0	4.0	9.0
4	6.0	6.0	3.5	8.0	4.4	6.0	4.5	4.5
5	2.5	5.0	2.3	6.0	1.3	2.0	3.1	7.0
6	5.3	5.3	3.8	10.0	6.6	6.6	5.1	6.0
7	3.8	5.3	2.5	8.0	1.9	6.0	4.0	11.0
8	4.3	4.3	2.4	6.0	4.5	5.0	4.6	6.0
9	4.3	11.0			4.0	6.0	4.3	6.0
10	2.0	11.0			2.0	6.0	2.3	6.0
11	2.5	11.0						
12	2.5	11.0						
13	2.5	4.0						
14	2.5	4.0						
15	2.9	5.0						
16	6.3	6.3						
Means	3.4	6.5	3.4	6.6	3.5	5.1	3.8	6.7

[a]Treatment 1 is a sand with average bulk density of 1.70; 2 is a sandy clay loam with bulk density of 0.90; 3 is a sandy loam with bulk density of 1.06 over a packed loam with bulk density of 1.62; and 4 is a sandy clay loam with bulk density of 1.24.

mean depths were not significantly different for any set of trees.

One anomaly appears in the data of Table 7. This pertains to the depths reached by the roots of four black spruce trees growing in soil treatment 1--the sandy soil. Trees 9

through 12 all grew in the same compartment and they all attained the maximum depth possible in that box. Inasmuch as only one other black spruce tree grew that deep, the question arises as to why these four trees did. An examination of the soil texture and bulk density data for that particular compartment of soil does not reveal the answer because the values do not differ from the values of the other three replicates of the same treatment. There does not seem to be an interaction among the roots of the white spruce and balsam fir seedlings and those of black spruce because this situation is not repeated in any other compartment where the trees grew together. It should be noted, however, that the balsam fir and white spruce trees in that same compartment also attained the maximum depth. This fact does not aid in detecting the cause however, because those two species attained the maximum depth in several other compartments. This situation may simply have to be considered a chance occurrence. The greater depth of the roots of those four trees does influence the mean depth for seedlings which grew in the sandy soil, however, and so the difference between root penetration in treatment 1 and treatment 3 would not be nearly as pronounced if those four had not grown so deeply.

Figures 25 and 26 depict eight of the 44 black spruce seedlings which survived the greenhouse study. Those chosen

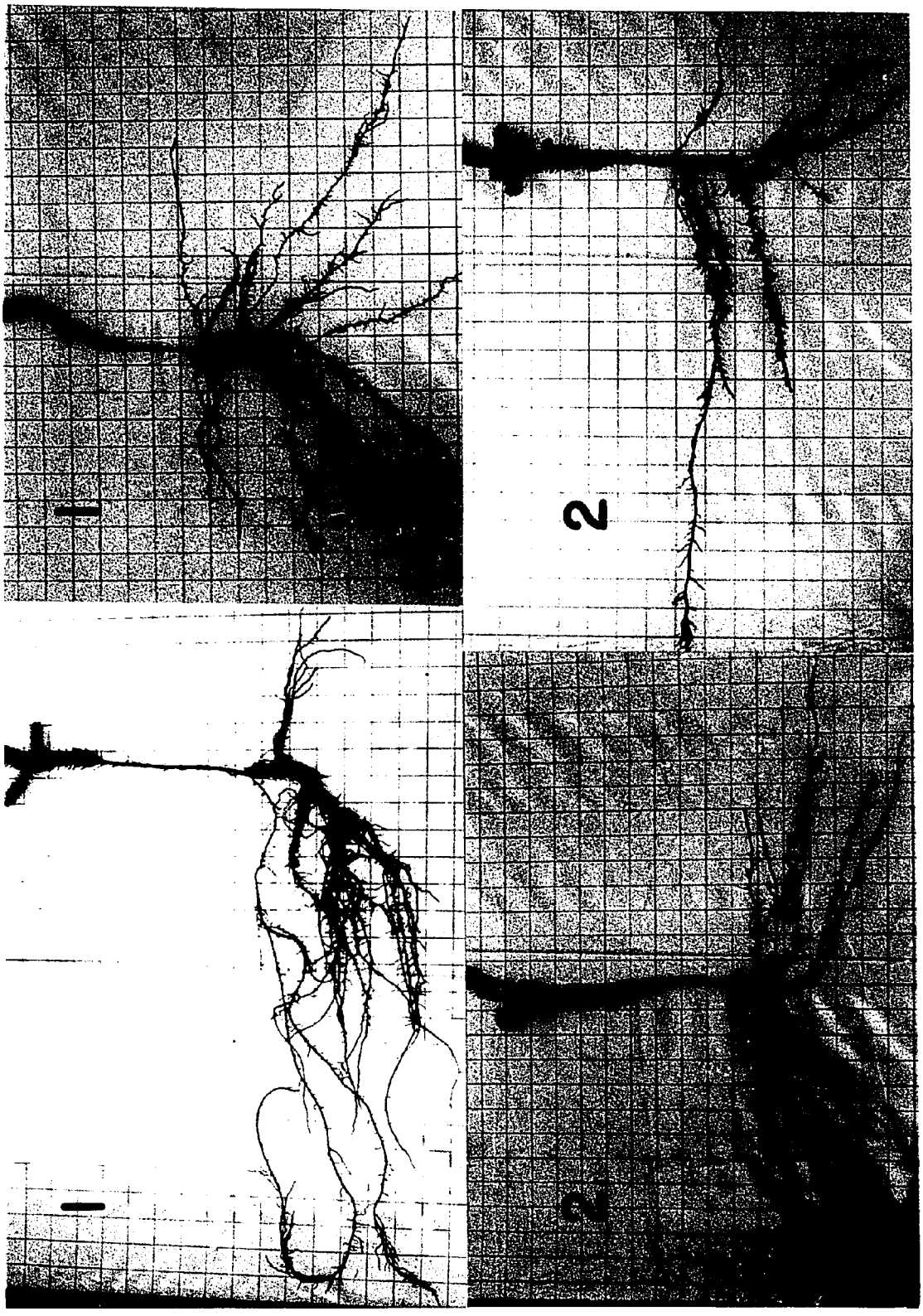


Fig. 25.--Selected typical black spruce seedlings which grew in soil treatment 1--sand (bulk density 1.70) and soil treatment 2--sandy clay loam (bulk density 0.90).

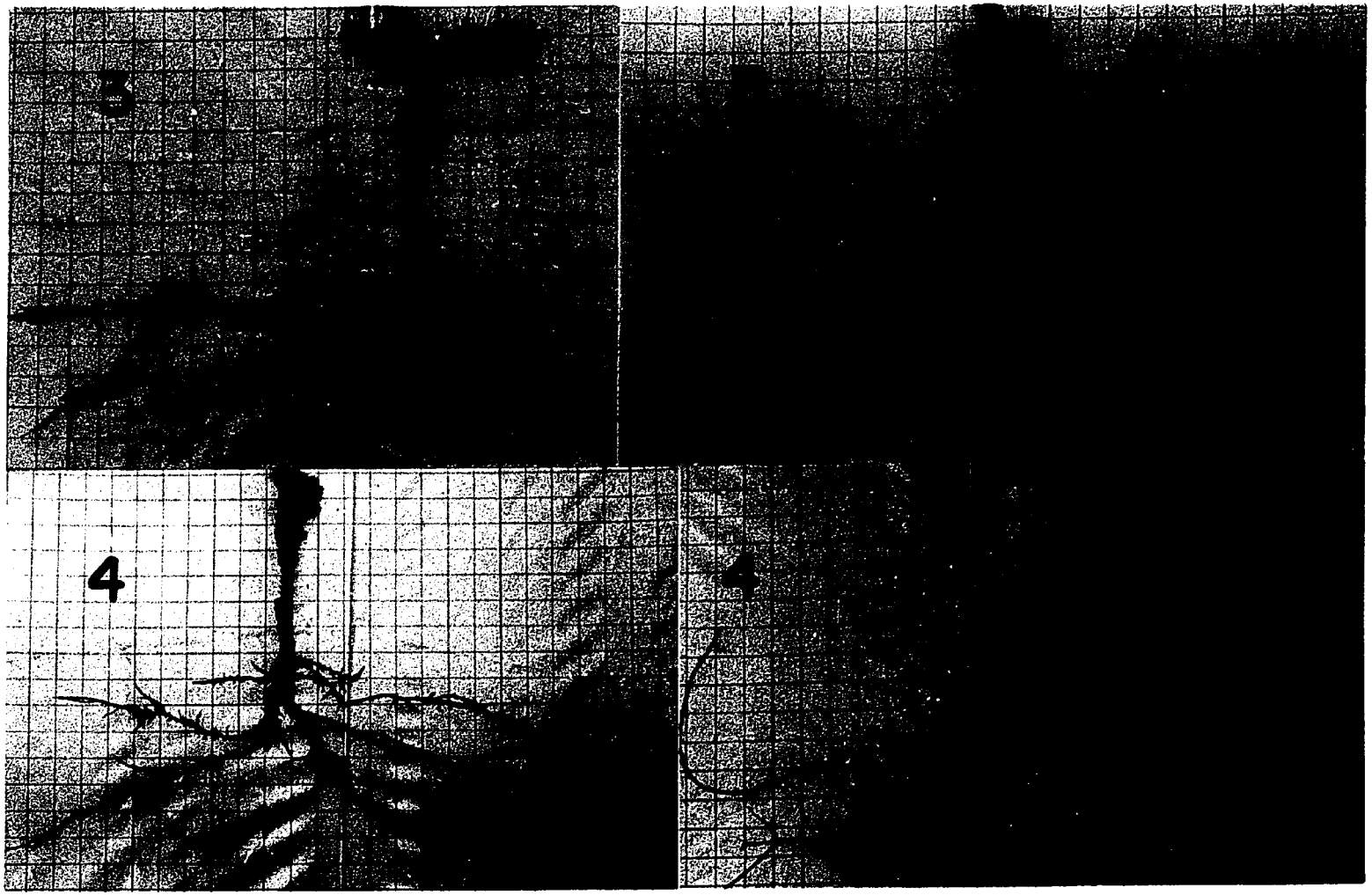


Fig. 26.--Selected typical black spruce seedlings which grew in soil treatment 3--sandy loam (bulk density 1.06) over compact loam (bulk density 1.62) and soil treatment 4--sandy clay loam (bulk density 1.24).

are typical of the ones which grew in each of the four different soil environments. The presence of a distinct tap root cannot be detected on most of the black spruce trees examined. Distinct vertical roots in general are difficult to find. Some variation was encountered in the mass of root material produced on different trees in each of the soils, but no one soil seemed to have trees with considerably more or less root material. The observation which emerges from visual examination of the surviving seedlings is that a pronounced vertical rooting habit cannot be detected. This differs from that found for both white spruce and balsam fir seedlings which grew in the same soil environments. It is entirely possible that vertical roots simply had not had sufficient time to develop on these seedlings. Tap roots and sinkers were observed on mature trees in the natural stand condition.

Summary and Conclusions about Vertical Rooting in Black Spruce

The 98 black spruce trees which were examined in detail in this study represent age classes from three-year-old seedlings to a mature tree 154 years old. A relatively wide range of upland site conditions, as pertains to the soil environment in particular, was sampled. One conclusion is clear from the observations obtained. Black spruce trees do not produce

many roots which penetrate deeply into the soil. In only a few instances were roots found below a depth of three feet in any soil situation. Because tap roots and distinct vertical sinker roots were found, it cannot be concluded that the species produces only shallow lateral roots. But, none of the vertical roots found were both large in diameter and deeply embedded in the soil. Nearly all were confined to the upper three feet and most were within 24 inches of the soil surface.

Vertical roots which were observed on black spruce trees did not seem to be produced in response to any particular combination of site factors which were examined, nor did age of the tree appear to be important in this respect. Most young trees, including seedlings, which were examined had only feeble tap roots if they had any at all. Where such a root was observed on older trees, it often was aborted and only a dead stub remained. (See Figure 27.) Short sinker roots were produced in most soil environments examined, but the typical "pedestal" form of this root (as shown in Figure 14, page 53) was found only in relatively porous sandy soils. These pedestal roots are short vertical roots which branch extensively in a horizontal plane at their lower end.

Implications of these conclusions about vertical rooting, or its modest expression, in black spruce are discussed

in Chapter VI.



Fig. 27.--Pronounced lateral root system of mature black spruce tree showing aborted stub of a dead tap root. Loamy sand soil, Site No. N-19, Iron County, Michigan.

CHAPTER IV

WHITE SPRUCE ROOT EXCAVATIONS

A distinctly different conclusion is reached about vertical rooting habits in white spruce when the species is compared with black spruce. In natural stands, 32 white spruce trees were examined; 31 planted trees were excavated in plantations; and 51 seedlings were examined at the termination of the greenhouse study.

White Spruce Trees in Natural Stands

The 32 white spruce trees were examined at 13 different sites. Four were washed out, three were dug out by hand, and the other 25 were examined at road construction or logging sites. Data pertaining to the vertical penetration of roots, to soil characteristics, and to root diameters are presented in Table 8 and Appendix Tables 2 and 7.

All white spruce trees examined in natural stand conditions, including the three seedlings at Site No. N-21, had distinct tap roots. Some of these roots were not well developed and some were grotesquely twisted where vertical growth had been impeded by rock or other barriers encountered in the

TABLE 8

SOIL CHARACTERISTICS AND VERTICAL ROOT PENETRATION OF WHITE SPRUCE TREES IN NATURAL STANDS

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density	
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]
N-19	Loamy sand	Loamy sand	1	58	6.2	18(22)1.58	72(74)1.89 60(64)1.89
N-21	Loamy sand	Loamy sand	1	4	c	6(6)1.22	
			2	4	c	4(4)1.22	
			3	5	c	3(3)1.22	2(2)1.22

[a] A more complete site description is given in Appendix Table 1. Data presented in this table are arranged by soil texture classes and range from the coarsest to the finest textures.

[b] Numbers listed first are the depths of roots below ground either at the point of breakage or the unbroken terminus; numbers in parentheses are the estimated total vertical depths reached when calculated by the method of Dittmer (1959); and the final numbers are the bulk density at greatest root depth attained.

[c] Tree was a seedling less than two feet in height.

TABLE 8--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-1	Sandy loam	Loamy sand	1	42	4.8	35(35)1.64	38(40)1.48			
			2	37	5.2	20(24)1.54	32(44)1.48	22(30)1.64		
			3	39	5.1	15(22)1.54	19(20)1.54	22(26)1.64		
			4	44	5.8	30(31)1.64	32(33)1.64	28(28)1.64	24(25)1.64	21(23)1.54
N-20	Sandy loam	Loamy sand	1	41	5.8	27(30)1.76	38(40)1.76	19(22)1.76		
			2	48	6.2	30(32)1.76	34(35)1.76	20(21)1.76		
			3	29	4.7	19(22)1.76	18(21)1.76			
N-2	Sandy loam	Sandy loam	1	35	5.8	7(10)1.63	19(22)1.51			
N-4	Sandy loam	Sandy loam	1	25	2.4	18(20)1.35	20(23)1.35			
			2	27	4.1	7(10)1.28	31(33)1.47	27(28)1.47	24(25)1.47	

TABLE 8--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-6	Sandy loam	Sandy loam	1	146	12.5	30(34)1.43	33(36)1.43	32(33)1.43	35(37)1.43	33(35)1.43
N-7	Sandy loam	Sandy loam	1	95	10.8	28(30)1.39	31(33)1.39			
N-8	Sandy loam	Sandy loam	1	53	7.8	29(30)1.41	35(37)1.41	35(36)1.41	32(33)1.41	27(29)1.41
			2	53	4.9	35(36)1.41	35(40)1.41			
N-10	Sandy loam	Sandy loam	1	57	4.8	34(36)1.41	31(34)1.41	27(29)1.41	21(22)1.51	27(32)1.41
N-25	Silt loam	Sand	1	165	10.0	58(63)1.82	32(35)1.82	27(30)1.82		
			2	181	16.0	56(62)1.82	62(68)1.82	48(52)1.82		
			3	162	13.0	44(50)1.82	40(47)1.82	53(56)1.82	39(43)1.82	
			4	173	25.0	60(65)1.82	49(53)1.82	46(48)1.82	45(50)1.82	
			5	159	13.0	61(67)1.82	54(59)1.82	48(52)1.82		

TABLE 8--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density			
	0-6 in.	6-24 in.				Main Vertical Root	Other Roots		
				(yr.)	(in.)	(inches below ground and grams/cc)[b]			
N-27	Silt loam	Loam	1	151	13.0	42(47)1.94	51(54)1.94	49(51)1.94	
			2	84	13.0	65(70)1.94	48(51)1.94	53(58)1.94	
N-24	Silty clay loam	Silt	1	52	5.0	27(30)1.94	29(32)1.94	27(29)1.94	
			2	63	5.6	28(32)1.94	39(43)1.94	33(35)1.94	
			3	78	5.2	28(31)1.94	24(27)1.94		
			4	85	7.7	41(47)1.94	45(49)1.94	42(44)1.94	
			5	117	11.0	37(40)1.94	50(58)1.94	50(56)1.94	48(51)1.94
			6	111	10.5	39(41)1.94	49(53)1.94		

soil. Depths attained by these roots varied from less than one foot below the soil surface to as great a depth as 65 inches to the point where the root was broken. The projected vertical penetration of that root, using Dittmer's (1959) method, was 70 inches. Examples of several distinct tap roots are illustrated in Figures 28 through 32.

Sinker roots were prominent features of white spruce root systems. Every juvenile and mature tree examined had at least one distinct sinker root. Many trees had several such roots. The deepest one encountered in this investigation was 72 inches below the soil surface and it is shown in Figure 33. A summary of vertical root penetration by white spruce trees in natural stands is given in Table 9. Twenty-nine of the 63 sinker roots observed on these white spruces were found at least three feet below the soil surface, and 76 out of all 95 vertical roots examined (80 percent) were deeper than two feet below the soil surface where they terminated. This compares with nearly 80 percent of the black spruce roots terminating above two feet.

Several linear regression analyses were made of the relationship between depth of root penetration and soil bulk density. All of these analyses yielded positive correlations which were significant at the 95 or 99 percent levels of probability. In other words, greater root depths were found in



Fig. 28.--Prominent tap root on 25-year-old white spruce tree which grew in a sandy loam soil. Site No. N-4, Dickinson County, Michigan.



Fig. 29.--Large tap root and sinker root on 85-year-old white spruce tree which grew in a silt loam soil. Site No. N-24, near Longlac, Ontario.

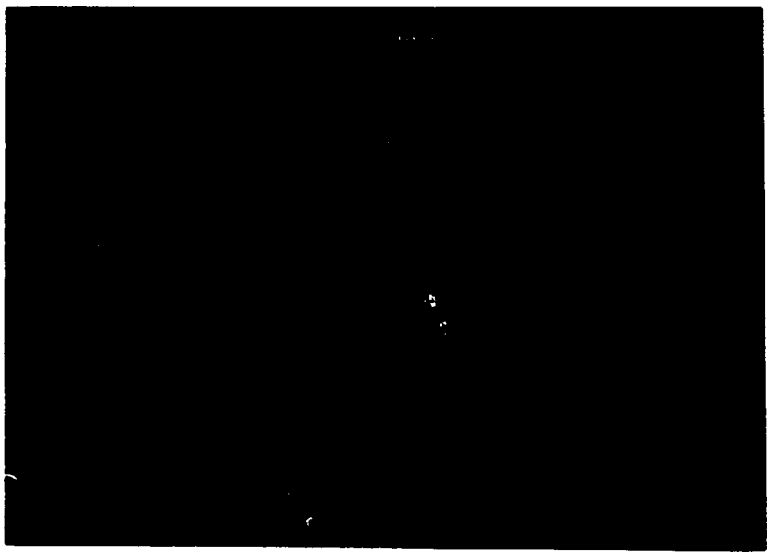


Fig. 30.--Branched tap root on 29-year-old white spruce tree which grew in a sandy soil. Site No. N-20, Iron County, Michigan.



Fig. 31.--Prominent vertical roots on inverted stump of 162-year-old white spruce tree which grew in a sandy soil. Site No. N-25, near Longlac, Ontario.

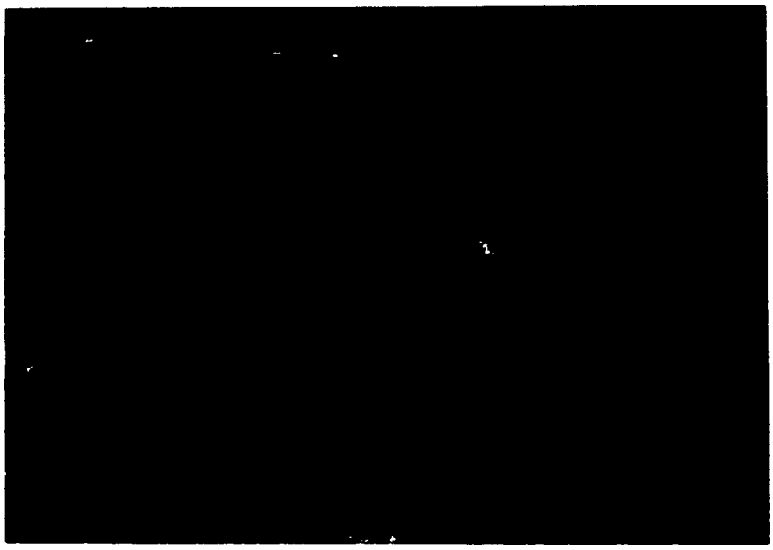


Fig. 32.--Sinker roots on a 48-year-old white spruce tree which grew in a sandy soil. Site No. N-20, Iron County, Michigan.



Fig. 33.--Prominent sinker root found on 58-year-old white spruce tree which grew in a sandy soil. Root descended more than 72 inches into the soil. Site No. N-19, Iron County, Michigan.

TABLE 9

SUMMARY OF VERTICAL PENETRATION BY ROOTS OF THIRTY-TWO WHITE SPRUCE TREES GROWING IN NATURAL STANDS

Maximum Depth of Penetration	Number of Roots Observed[a]		Number of Trees[b]
	Tap Roots	Sinker Roots	
0 - 12 inches	5	1	3[c]
12 - 24 inches	5	8	3
24 - 36 inches	12	25	8
36 - 48 inches	4	11	7
48 - 60 inches	1	15	5
60 - 72 inches	5	2	5
72 - 84 inches	---	1	1
Total	32	63	32

[a]If the estimated depth of penetration of a root was in a next higher depth class, the root was tallied in that class; borderline cases were tallied in the lower class.

[b]This is the number of trees for which the greatest depth of root penetration was in the depth class shown.

[c]These three trees were no older than five years.

soils with high bulk densities than in those with low bulk densities.

The three seedlings at Site No. N-21 were not included in these analyses because too great a disparity existed between their ages or stage of development and the ages of the 29 larger trees examined. Six different relationships were

examined as outlined below, and the regression equations and correlation coefficients are presented in Table 10.

Relationship Reference No.	Variables Tested (Y)		(X)
1	Depths of all 29 tap roots	vs.	Bulk density at end of each tap root
2	Depths of all 62 sinker roots	vs.	Bulk density at end of each sinker root
3	Depths of all 91 vertical roots examined	vs.	Bulk density at end of each vertical root
4	Depths of the one deepest tap root at each site (12 sites)	vs.	Bulk density at end of deepest tap root at each site
5	Depths of the one deepest sinker root at each site (12 sites)	vs.	Bulk density at end of deepest sinker root at each site
6	Depths of the one deepest vertical root at each site (12 sites)	vs.	Bulk density at end of deepest vertical root at each site

Because vertical rooting depth is correlated positively with bulk density of the soils examined in this study, it appears that a causal relationship may exist. Soil texture, however, is one of the most important soil factors affecting vertical root development, and an inherent relationship

TABLE 10

REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS OF ROOT PENETRATION BY WHITE SPRUCE TREES IN NATURAL STANDS VERSUS SOIL BULK DENSITY AT ROOT TERMINUS

Relationship Reference No.[a]	Regression Equation[b]	r^2	Significance[c]
1	$\hat{Y} = 37.4\ X - 30.0$	0.280	**
2	$\hat{Y} = 32.2\ X - 18.5$	0.303	**
3	$\hat{Y} = 33.9\ X - 22.2$	0.289	**
4	$\hat{Y} = 45.8\ X - 40.1$	0.354	*
5	$\hat{Y} = 52.8\ X - 44.3$	0.633	**
6	$\hat{Y} = 58.4\ X - 52.1$	0.679	**

[a] Reference numbers pertain to the variables listed in the outline on the previous page.

[b] $\hat{Y}$ is the estimated depth of root penetration, in inches; and X is the soil bulk density at the root terminus, in grams per cc.

[c] A single asterisk indicates that the correlation coefficient, r, is significant at the 95 percent level of probability; and two asterisks indicate significance at the 99 percent level of probability.

exists between soil texture and bulk density. In most soil profiles it is known that bulk density increases with soil depth, but it also increases with particle size (texture). Within a particular soil texture class this relationship is important from the standpoint of moisture availability, and this may well be the most important factor affecting vertical penetration by white spruce roots. The texture-bulk density relationship makes it difficult to untangle the

relative importance of either factor by itself.

Moisture and aeration conditions in coarse sands could be more favorable for roots at greater depths where greater bulk densities occur. The tighter packing of the mineral soil fragments results in pore spaces which retain water more readily available to roots at these depths than higher in the soil where bulk density is likely to be lower. Low bulk density in coarse soils may reflect conditions of excessive aeration and drainage; but bulk density, by itself, may not necessarily reflect aeration, drainage, or resistance to penetration in such soils. On the other hand, bulk density in sandy loams and silt loams is indicative of soil aeration and of physical resistance to penetration by roots.

Mean depths of the roots examined on 29 trees are presented in Table 11 according to the soil texture class at the root terminus. Complete information on the soil texture and bulk density at the root terminus is found in Appendix Table 2. Deepest vertical penetration was observed in sand and silt loam texture classes, and bulk density was greater in these than in the sandy loam and loamy sand classes.

The complexity of the bulk density-texture relationship for sand and loamy sand makes it hazardous to state that greater root depth occurred in sand because of bulk density. It is better simply to state that greatest depths were attained in sands.

TABLE 11

MEAN DEPTH OF WHITE SPRUCE ROOTS IN RELATION TO SOIL TEXTURE AT ROOT TERMINUS, NATURAL STANDS

Soil Texture at Root Terminus	Mean Depths and Numbers of Roots Examined[a]		
	Tap Roots	Sinker Roots	All Vertical Roots
	(inches and numbers of roots)		
Sand	45.5 (8)	38.5 (18)	40.5 (26)
Loamy sand	22.0 (5)	34.0 (11)	30.5 (16)
Sandy loam	29.5 (10)	33.5 (22)	32.0 (32)
Silt loam	33.5 (6)	39.5 (11)	37.5 (17)
Grand Mean	33.5 (29)	36.0 (62)	35.0 (91)

[a]Means are to the nearest one-half inch; numbers in parentheses represent the numbers of roots measured in each category.

It may be possible, however, to examine this relationship for sandy loams and silt loams. Possibly smaller pore space conditions in the silt loams were favorable for white spruce root development and did not impede it until high bulk density occurred at greater depths. In the sandy loams, this vertical development may not have been as great because adequate moisture-aeration conditions existed higher in the soil where bulk density was less.

The means in Table 11 indicate that white spruce tap roots do not descend quite as deeply as the sinker roots. It is true, for most of the 29 larger trees examined, that at

least one of the sinker roots penetrated more deeply than the tap root. This situation was found in 21 of the 29 trees; the tap root was as long as or longer than the longest sinker root in only eight of the trees.

In this part of the study of vertical roots in white spruce it must be concluded that prominent roots of this kind are commonly produced in natural stands on upland sites throughout the Lake Superior region.

White Spruce Trees in Plantations

Ages of the 31 white spruce trees which were excavated in Kimberly-Clark plantations ranged from 10 to 20 years. Two trees were 20 years old, eight were 12 years old, 13 were 11 years old, and the other eight were 10 years old. All had been growing in the plantation environment for at least six growing seasons prior to their excavation. Even though these trees should have become adjusted to the soil conditions of the plantations, results are treated separately from those of trees studied in natural stands. Nevertheless, results are strikingly similar in both instances.

The data in Table 12 and Appendix Tables 4 and 8 are presented in the same way as similar data were treated for black spruce trees in plantations. A wider range of soil conditions was encountered in the excavations of white spruce trees in plantations, and several trees had roots which ended

TABLE 12

SOIL CHARACTERISTICS AND ROOT PENETRATION OF WHITE SPRUCE TREES IN PLANTATIONS, EXCAVATED 1960

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
52-F-14 Mich.	Sand	Sand	1	12	88	59(1.76)Sa	45(1.63)Sa	37(1.63)Sa	17(1.60)Sa
			2	12	77	21(1.53)Sa	30(1.56)Sa	36(1.67)Sa	16(1.53)Sa
54-F-19 Mich.	Sand	Sand	1	10	70	10(1.38)Sa	60(1.70)Sa	50(1.70)Sa	37(1.68)Sa
54-F-20 Mich.	Sand	Sand	1	10	47	6(1.20)Sa	14(1.56)LoSa	14(1.56)LoSa	
54-F-21 Mich.	Sand	Sand	1	10	51	34(1.76)Sa	28(1.76)Sa		

[a] Plantation designations are those used by the Kimberly Clark Corporation. For example, 52-F-14 means that the plantation was established in the fall (F) of 1952 (52), and it was the fourteenth plantation established by the Corporation in Michigan that year.

[b] Numbers listed first are the depths of roots below ground at their terminus; those in parentheses are the soil bulk density at that depth; and the letters indicate the soil texture at the root terminus. Sa is sand, Si is silt, Cl is clay, and Lo is loam. SiLo indicates silt loam.

TABLE 12--Continued

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
52-F-18 Mich.	Loamy sand	Sand	1	12	54	11(1.79)Sa	29(1.82)Sa	8(1.79)Sa	
54-S-3 Mich.	Loamy sand	Sand	1	10	59	11(1.45)Sa	15(1.49)Sa	13(1.49)Sa	
			2	10	23	22(1.77)Sa	22(1.77)Sa	19(1.77)Sa	17(1.77)Sa
44-S-1 Mich.	Loamy sand	Loamy sand	1	20	88	65(1.65)Sa	19(1.41)SaLo	23(1.41)SaLo	15(1.41)SaLo
54-F-8 Minn.	Loamy sand	Sandy loam	1	10	33	10(1.68)SaLo	7(1.68)SaLo	11(1.68)SaLo	
			2	10	32	5(1.44)SaLo			
44-S-1 Mich.	Sandy loam	Loamy sand	1	20	152	105(1.70)Sa	96(1.70)Sa	70(1.65)Sa	
53-S-4 Mich.	Sandy loam	Loamy sand	1	11	64	9(1.43)LoSa	8(1.43)LoSa	8(1.43)LoSa	8(1.43)LoSa
			2	11	72	9(1.43)LoSa	11(1.43)LoSa		
			3	11	55	5(1.31)SaLo	5(1.31)SaLo		

TABLE 12--Continued

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root			
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]		
53-S-6 Mich.	Sandy loam	Loamy sand	1	11	58	11(1.26)LoSa	18(1.64)Sa	13(1.64)Sa	
53-S-11 Mich.	Sandy loam	Loamy sand	1	11	62	8(1.73)Sa	9(1.73)Sa	10(1.73)Sa	
54-S-4 Minn.	Sandy loam	Loamy sand	1	10	51	18(2.43)LoSa	8(1.49)SaLo		
52-S-2 Minn.	Sandy loam	Sandy loam	1	11	40	14(1.69)SaLo	14(1.69)SaLo	14(1.69)SaLo	9(1.22)SaLo
53-S-5 Mich.	Sandy loam	Sandy loam	1	11	45	9(1.26)SaLo			
			2	11	49	24(1.93)SiLo	15(1.47)SiLo	13(1.47)SiLo	6(1.41)SaLo
53-S-10 Mich.	Silt loam	Loam	1	11	55	6(1.29)SiLo	7(1.29)SiLo	5(0.98)SiLo	
52-F-16 Mich.	Silt loam	Silt loam	1	12	60	32(1.54)SiLo	26(1.54)SiLo	23(1.43)SiLo	21(1.43)SiLo

TABLE 12--Continued

Plantation[a] No.	Soil Texture		Tree No.	Tree Age	Tree Ht.	Depths Reached by Principal Vertical Roots and Bulk Density and Soil Texture at Terminus of Root		
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground--grams/cc--texture)[b]	
53-S-6 Mich.	Silt loam	Silt loam	1	11	50	10(1.23)SiLo	14(1.36)SiLo	10(1.23)SiLo
			2	11	76	37(1.71)Sa	49(1.71)Sa	21(1.36)SiLo
52-S-1 Mich.	Clay loam	Clay	1	12	58	9(1.48)Cl	5(1.27)Cl	
			2	12	42	7(1.48)Cl	8(1.48)Cl	
			3	12	53	8(1.48)Cl	6(1.48)Cl	
			4	12	62	10(1.48)Cl	8(1.48)Cl	
53-F-5 Minn.	Clay	Clay	1	11	56	14(1.48)Cl	14(1.48)Cl	
			2	11	37	14(1.48)Cl	11(1.48)Cl	5(1.36)Cl

in clay and silt loam soil textures. In practice, white spruce is planted on a wider variety of sites than is black spruce.

All of the trees possessed distinct tap roots, and 29 of the 31 trees also had at least one prominent sinker root. A summary of these data is provided in Table 13. Photographic evidence of the nature of vertical root development on these plantation trees is given in Figures 34 through 39. It is obvious, again, that white spruce produces prominent vertical roots where conditions permit.

On many trees where well developed vertical roots were not found, the methods of initial planting might well have contributed to the twisted mass of roots which resulted near the base of the tree. This feature can be seen easily in Figures 36, 38, and 39. It is understandable that the roots of seedlings planted in a compact clay soil might develop into a contorted mass as is shown in Figure 38, but those planted in a loamy sand or sandy loam with relatively low bulk density should not develop similarly unless they were twisted initially when planted.

Because these plantation trees were still in a period of rapid growth and were not nearly as old as most of the trees examined in natural stands, it is hardly legitimate to compare the percentages of roots examined with respect to

their maximum depths attained. Nonetheless, 21 percent (19 out of 89 vertical roots) of the roots examined were deeper than two feet below the soil surface. This compares with no vertical roots being found below 18 inches on all of the plantation-grown black spruce trees.

Three linear regressions were run between depth of root penetration and soil bulk density at root terminus.

TABLE 13

SUMMARY OF VERTICAL PENETRATION BY ROOTS OF THIRTY-ONE WHITE SPRUCE TREES GROWING IN PLANTATIONS

Maximum Depth of Penetration	Number of Roots Observed		Number of Trees[a]
	Tap Roots	Other Vertical Roots	
0 - 12 inches	18	22	12
12 - 24 inches	7	23	10
24 - 36 inches	2	5	4
36 - 48 inches	1	3	---
48 - 60 inches	1	3	3
60 - 72 inches	1	1	1
72 - 84 inches	---	---	---
84 - 96 inches	---	1	---
96 - 108 inches	1	---	1
Total	31	58	31

[a] This is the number of trees for which the greatest depth of root penetration was in the depth class shown.

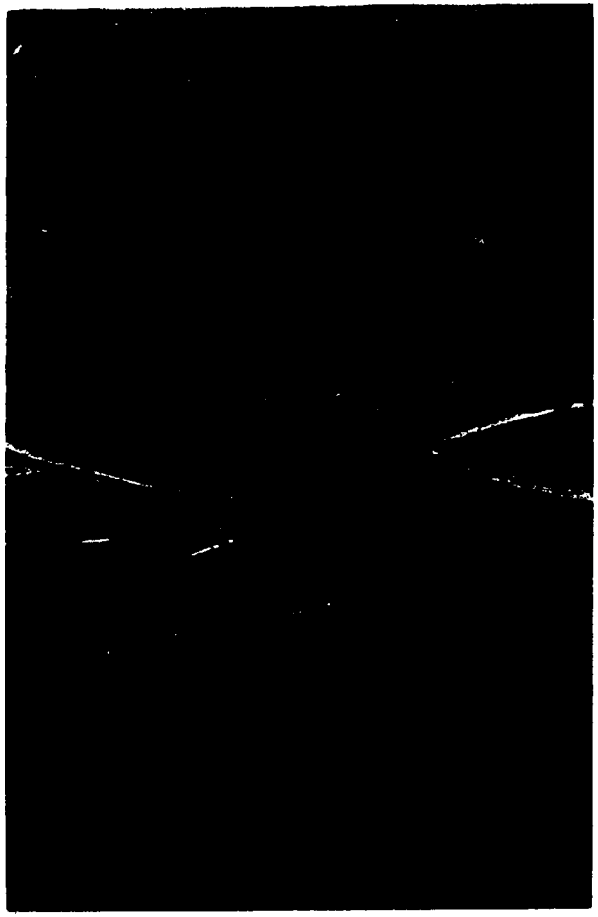


Fig. 34.--Distinct tap root on 20-year-old white spruce tree which grew in a sandy soil. Root descended to a depth of 105 inches. Plantation No. 44-S-1, Ontonagon County, Michigan.



Fig. 35.--Tap root on 20-year-old white spruce tree which grew in a sandy soil. Root descended to a depth of 65 inches. Plantation No. 44-S-1, Ontonagon County, Michigan.

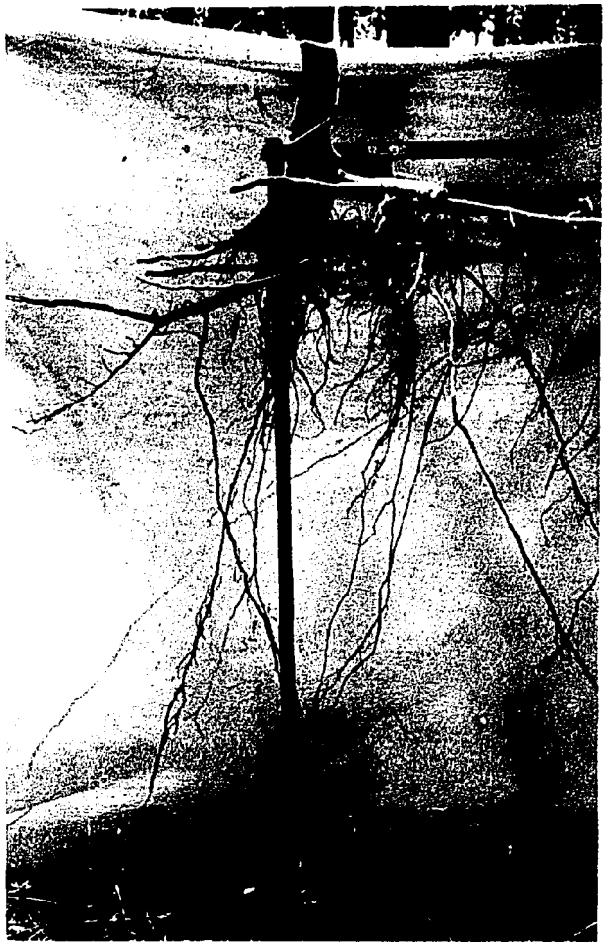


Fig. 36.--Ten-year-old white spruce tree with numerous deep sinker roots but short tap root growing in a sandy soil. Plantation No. 54-F-19, Luce County, Michigan.



Fig. 37.--Tap root on a 12-year-old white spruce tree growing in a sandy soil. Root reached water table at 59 inches below soil surface. Plantation No. 52-F-14, Mackinaw County, Michigan.

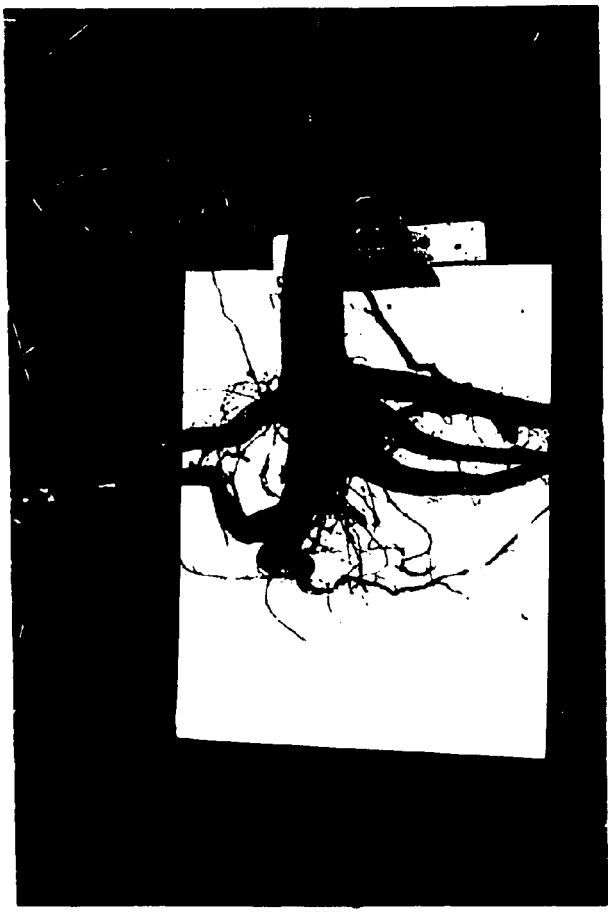


Fig. 38.--Contorted tap root on an 11-year-old white spruce tree which grew in a sandy soil. Deepest vertical root on this tree descended five inches. Plantation No. 53-S-4, Dickinson County, Mich.

All of these, as was true for white spruce in natural stand conditions, yielded positive correlations which were significant at least at the 95 percent level of probability. The amount of explained variation (r^2), however, was much lower. The relationships examined were as listed below, and the regression equations and correlation coefficients are presented in Table 14.

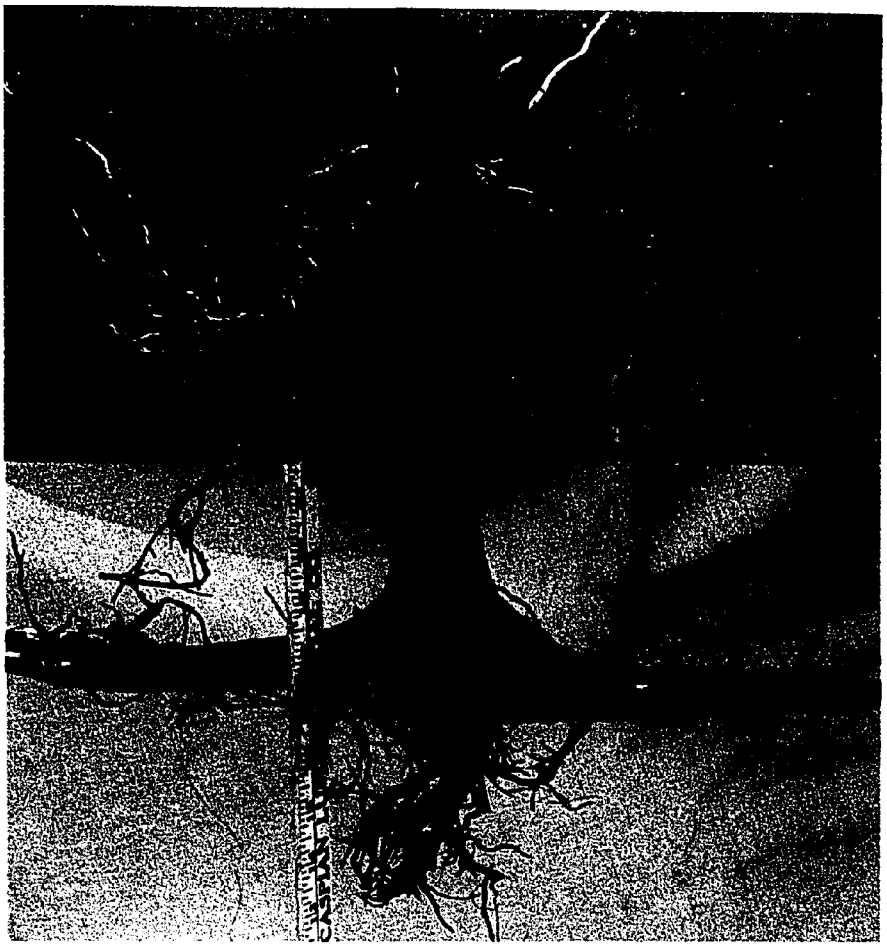


Fig. 39.--Contorted tap roots on two 12-year-old white spruce trees which grew in a clay soil. No vertical roots were found deeper than 10 inches in the soil. Plantation No. 52-S-1, Ontonagon County, Michigan.

Relationship Reference No.	Variables Tested (Y)		(X)
1	Depths of all 31 tap roots	vs.	Bulk density at end of each tap root
2	Depths of all 58 sinker roots	vs.	Bulk density at end of each sinker root
3	Depths of all 89 vertical roots examined	vs.	Bulk density at end of each vertical root

TABLE 14

REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS OF ROOT PENETRATION BY WHITE SPRUCE TREES IN PLANTATIONS VERSUS SOIL BULK DENSITY AT ROOT TERMINUS

Relationship Reference No.[a]	Regression Equation[b]	r^2	Significance[c]
1	$\hat{Y} = 30.4\ X - 27.6$	0.124	*
2	$\hat{Y} = 44.4\ X - 48.3$	0.192	**
3	$\hat{Y} = 36.9\ X - 37.1$	0.155	**

[a]Reference numbers pertain to the variables listed on the previous page.

[b]$\hat{Y}$ is the estimated depth of root penetration, in inches; and X is the soil bulk density at the root terminus, in grams per cc.

[c]A single asterisk indicates significance of the correlation coefficient, r, at the 95 percent level of probability; and two asterisks indicate significance at the 99 percent level.

The same comments may be made about bulk density and texture effects on vertical root growth by plantation-grown white spruces as was said for trees in the natural stands. In this respect, consistent results appeared for white spruce trees studied under both situations. Soil texture and root penetration are treated similarly and the means of plantation root growth are shown for different textures in Table 15.

The means shown in Table 15 indicate that the tap roots on white spruce trees descend slightly deeper than the sinker roots in all of the soils except those classified as sandy

TABLE 15

MEAN DEPTH OF WHITE SPRUCE ROOTS IN RELATION TO SOIL TEXTURE AT ROOT TERMINUS, PLANTATIONS

Soil Texture at Root Terminus	Mean Depths and Numbers of Roots Examined[a]		
	Tap Roots	Sinker Roots	All Vertical Roots
	(inches and numbers of roots)		
Sand	32.5 (12)	31.0 (24)	31.5 (36)
Loamy sand	12.0 (4)	10.5 (6)	11.0 (10)
Sandy loam	8.5 (5)	12.0 (11)	11.0 (16)
Silt loam	18.0 (4)	15.5 (10)	16.0 (14)
Clay	10.5 (6)	8.0 (7)	9.0 (13)
Grand Mean	20.0 (31)	20.0 (58)	20.0 (89)

[a] Means are to the nearest one-half inch; numbers in parentheses represent the numbers of roots measured in each category.

loam. In sandy loam, the sinkers average several inches deeper. The main differences between the trees in natural stands and those in plantations are of degree. In sands, the penetration by young trees was notably greater than in the other texture classes. The clay soils provide the poorest conditions of aeration, drainage, and penetrability; and in these vertical growth is least.

Just as it was concluded that vertical roots are prominent features on white spruce trees which grow in natural stands, the same may be said for plantation trees. Even in

relatively unfavorable soil environments, distinct vertical roots are produced. In the section which follows, it is clear that white spruce seedlings also produce distinct vertical root growth.

White Spruce Seedlings in Greenhouse Experiment

In the soil boxes of the greenhouse study, 51 of the original 64 white spruce seedlings survived. Survival results, according to soil treatment, are as follows:

Treatment Number	Soil Texture	Surviving Trees
1	Sand	16
2	Sandy clay loam	10
3	Sandy loam loam pan	11
4	Sandy clay loam	14

Textural analyses, with mean percentages of sand, silt, and clay fraction, respectively, were as follows for each treatment:

1---95.5 sand, 2.0 silt, 2.5 clay

2---50.0 sand, 25.0 silt, 25.0 clay

3---72.0 sand, 14.0 silt, 14.0 clay (0-6 in.)
40.0 sand, 36.0 silt, 24.0 clay (6-12 in.)

4---50.5 sand, 29.5 silt, 20.0 clay

TABLE 16

INITIAL AND FINAL VERTICAL ROOT PENETRATION BY WHITE SPRUCE SEEDLINGS GROWN IN GREENHOUSE EXPERIMENT

Tree No.	Vertical Root Penetration in Different Soil Treatments[a]							
	1		2		3		4	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	(inches)							
1	2.5	11.0	1.9	11.0	3.5	7.5	1.8	9.0
2	3.3	11.0	7.3	11.0	4.5	8.0	4.6	9.0
3	4.0	11.0	3.8	11.0	3.4	7.0	3.1	8.0
4	6.5	11.0	6.0	11.0	3.5	5.5	2.0	10.0
5	4.4	9.0	2.0	5.0	7.0	7.0	4.0	5.0
6	2.8	8.0	3.3	11.0	6.8	6.8	3.9	11.0
7	2.5	9.0	6.5	11.0	4.1	6.0	3.0	6.0
8	2.6	9.0	5.0	11.0	3.0	7.0	3.6	11.0
9	5.0	11.0	3.9	11.0	3.1	8.0	2.5	11.0
10	5.1	11.0	2.3	5.0	6.3	7.0	4.0	10.0
11	2.8	11.0			4.5	7.0	2.9	10.0
12	5.0	11.0					3.3	11.0
13	3.0	11.0					6.0	11.0
14	5.0	11.0					3.3	10.0
15	2.0	11.0						
16	6.8	11.0						
Means	4.0	10.4	4.2	9.8	4.5	7.0	3.4	9.4

[a]Treatment 1 is a sand with average bulk density of 1.70; 2 is a sandy clay loam with bulk density of 0.92; 3 is a sandy loam with bulk density of 1.05 over a packed loam with bulk density of 1.64; and 4 is a sandy clay loam with bulk density of 1.24.

Results of vertical root growth are presented in Table 16. The mean depths of penetration by the main vertical root (usually the tap root) differ slightly when treatments 1, 2, and 4 are compared with each other, but "t" tests of the differences show that none are statistically significant at the

95 percent level or higher. All three of these treatment means do differ significantly from those attained by trees which grew in soil treatment 3. Apparently the compact loam layer did effectively prohibit white spruce roots from penetrating into it very far. Several of the 11 trees which survived in that treatment, however, did grow two or three inches into the loam. Whether the failure of trees to penetrate this layer was due to excessively wet moisture conditions or merely to the inability of roots to penetrate the soil with a bulk density of 1.64 is not known. White spruce trees in natural stands and in plantations were able to penetrate soils of finer texture and high bulk densities, so it may be possible that insufficient time had elapsed in this greenhouse study to enable the white spruces to penetrate completely through the loam pan. The fact that roots were found well within the upper two or three inches indicates that penetration might ultimately have occurred completely.

Results of this study seem to indicate that white spruce trees do have a definite tendency to produce vertical root growth when they are seedlings. No soil conditions used in this study were completely effective in prohibiting vertical root growth. Numerous vertical roots can be seen in the pictures of white spruce seedlings which are shown in Figures 40 and 41.

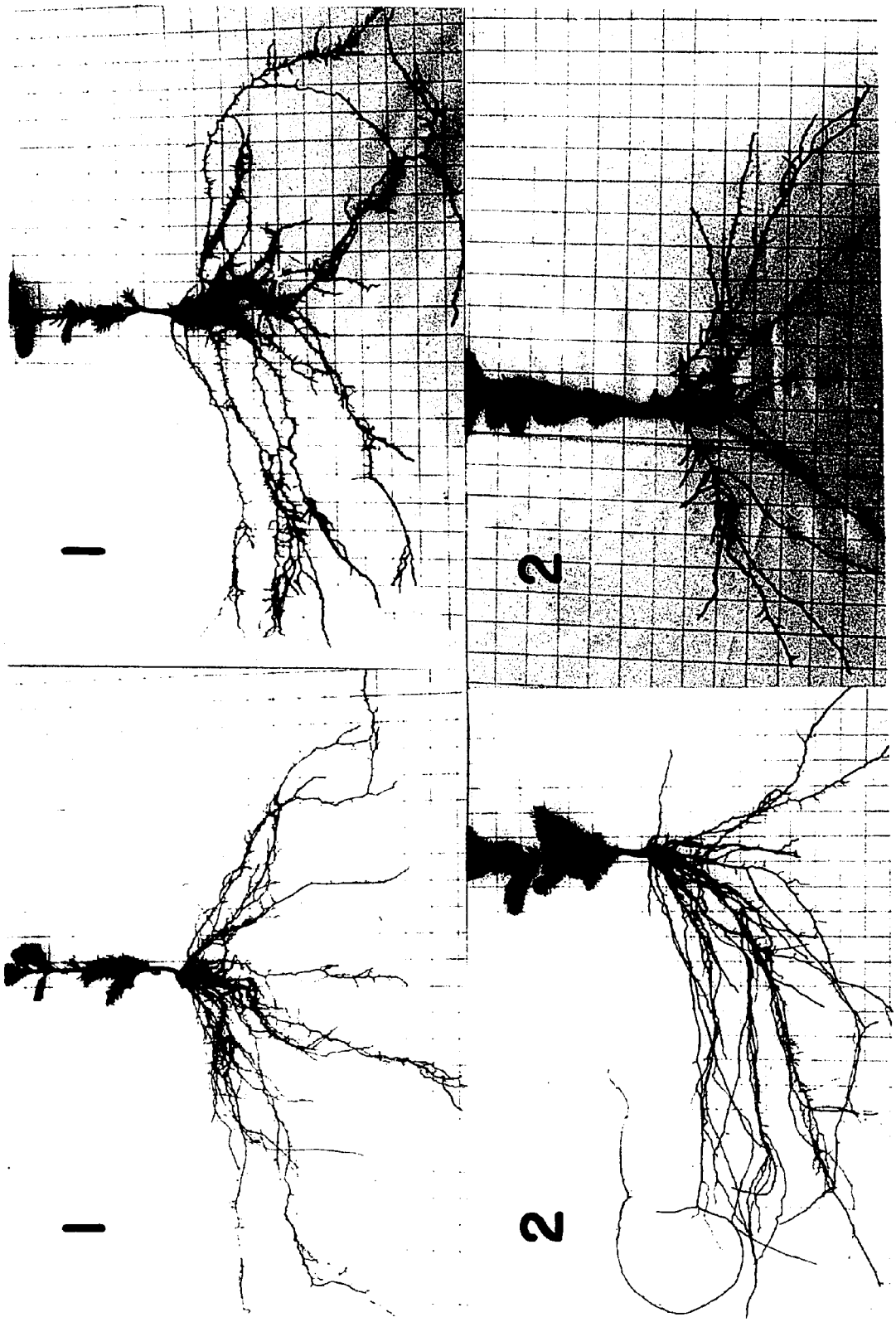


Fig. 40.--Selected typical white spruce seedlings which grew in soil treatment 1--sand (bulk density 1.70) and soil treatment 2--sandy clay loam (bulk density 0.92).

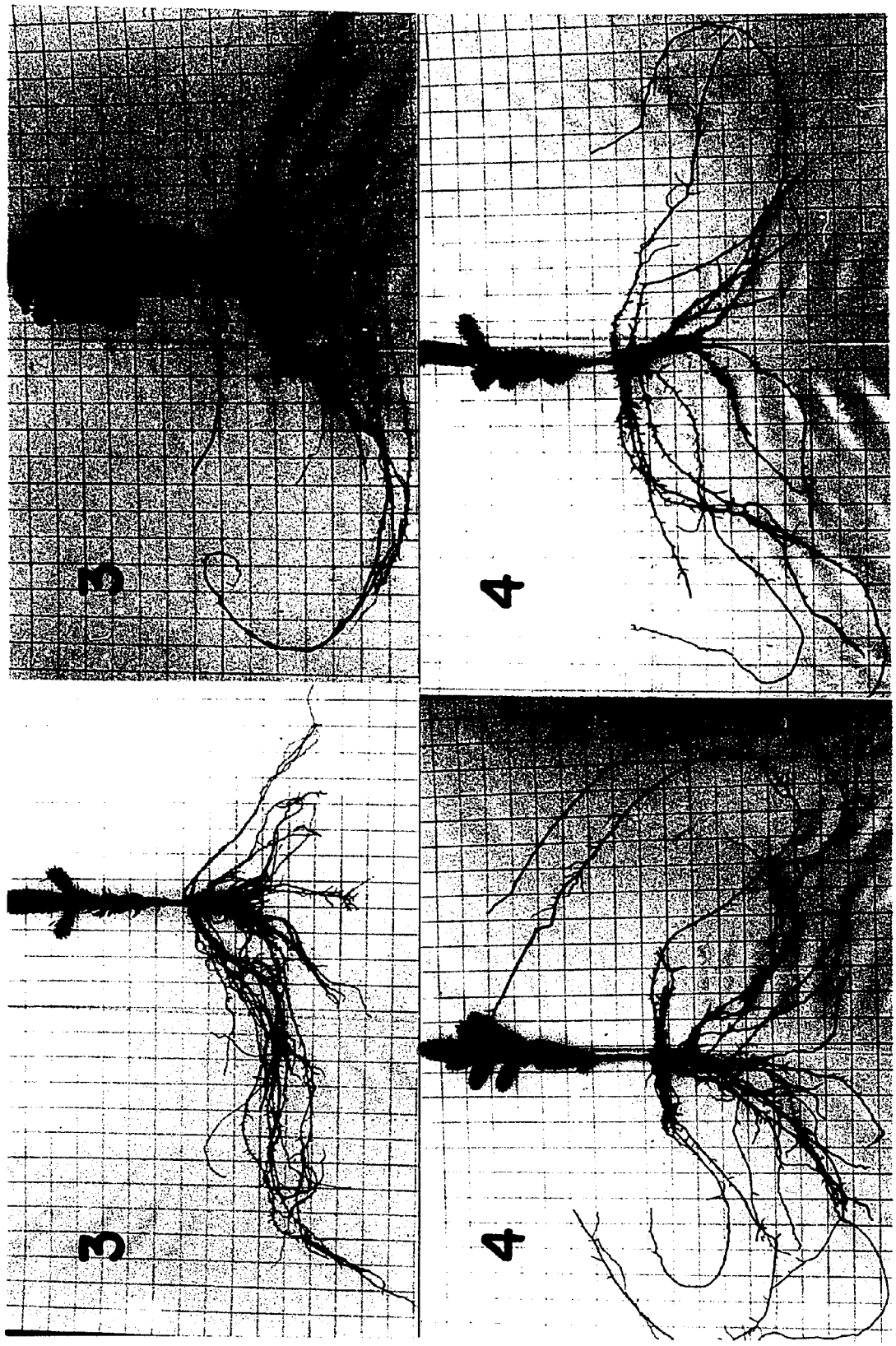


Fig. 41.--Selected typical white spruce seedlings which grew in soil treatment 3--sandy loam (bulk density 1.05) over compact loam (bulk density 1.64) and soil treatment 4--sandy clay loam (bulk density 1.24).

Summary and Conclusions about Vertical Rooting in White Spruce

The 114 white spruce trees which were examined in detail in this study represent age classes from three-year-old seedlings to several trees more than 150 years old. Thirteen different upland site conditions were studied in natural stands and 17 different plantation sites were considered. These 30 sites represent a wide variety of upland sites where white spruce grows in the Lake Superior region. The most conclusive statement which can be made about the vertical rooting habit in white spruce is that the species appears to express a distinct tendency to produce prominent vertical roots in most site conditions. This was evident on nearly all of the trees examined.

Prominent tap roots were found on trees growing in most site conditions examined. Sinker roots, although not usually as large in diameter as tap roots, were frequently longer and were always present. The average depth attained by tap roots measured in natural stands was 33.5 inches, and several of these roots descended deeper than four feet. On plantation trees, tap roots averaged 20 inches in depth, and several were much deeper. Sinker roots averaged 36 inches deep in natural stands and 20 inches in plantations. More than 30 percent of all sinker roots examined in both natural stands and plantations descended deeper than three feet, and

more than 22 percent of the tap roots exceeded that depth.

Seedlings produced recognizable vertical roots in whatever soil environment they grew. No particular soil environment inhibited vertical penetration completely, although a compacted layer in the soil did impede growth significantly.

Vertical rooting of all trees was most pronounced in sandy soils which are exceptionally well drained and thus well aerated. Root growth seemed best under such conditions.

Vertical root growth in natural stands was less pronounced in the loamy sand and sandy loam soils than it was in the coarse sands and the finer textured silt loams. In plantations, vertical growth was also less in the loamy soils than in sands; but it was not quite as shallow as in clay where penetration was definitely restricted, probably by poor aeration.

The main conclusion about white spruce exhibiting a prominent vertical rooting habit has important implications when it is considered from a silvicultural viewpoint. This is discussed in Chapter VI.

CHAPTER V

BALSAM FIR ROOT EXCAVATIONS

The vertical rooting habit in balsam fir was found to be even more pronounced than in white spruce. Thirty-six balsam fir trees were examined in natural stands, and 16 three-year-old seedlings were studied at the termination of the greenhouse study. Mortality was high in that study and only those which grew in the sandy soil survived in numbers sufficiently high to be of diagnostic value.

Balsam Fir Trees in Natural Stands

The 36 balsam fir trees were examined at 18 different sites in the Lake Superior region. Eight were exposed by the hydraulic method, three were excavated by hand-and-shovel techniques, and the other 25 were examined at road construction and logging sites. Two of these were uprooted by a local logger who fastened a chain to the bole of each tree and pulled them out of the sandy soil with his bulldozer. (These trees were examined at Site No. N-13 and one of them is illustrated in Figures 42 and 43.) Data pertaining to these 36 trees are presented in Table 17 and Appendix Table 9.

TABLE 17

SOIL CHARACTERISTICS AND VERTICAL ROOT PENETRATION OF BALSAM FIR TREES IN NATURAL STANDS

Site No.[a]	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-13	Sand	Sand	1	59	6.2	40(41)1.68	41(43)1.68	43(45)1.68	46(50)1.64	35(37)1.68
			2	64	6.4	29(31)1.56	93(95)1.64	31(43)1.68	51(66)1.64	34(37)1.68
N-17	Loamy sand	Loamy sand	1	57	2.8	22(25)1.78	20(23)1.53	25(27)1.78		
			2	60	4.3	31(35)1.78	30(33)1.78	24(27)1.78		
N-18	Loamy sand	Loamy sand	1	14	0.5	22(24)1.68	18(22)1.68			
N-19	Loamy sand	Loamy sand	1	62	5.7	116(118)1.89	106(110)1.89	89(94)1.89	94(96)1.89	84(88)1.89
			2	57	1.8	30(33)2.02	19(22)1.58	24(26)2.02		

[a]A more complete site description is given in Appendix Table 1. Data presented in this table are arranged by soil texture classes and range from the coarsest to the finest textures.

[b]Numbers listed first are the depths of roots below ground either at the point of breakage or the unbroken terminus; numbers in parentheses are the estimated total vertical depths reached when calculated by the method of Dittmer (1959); and the final numbers are the bulk density at greatest root depth attained.

TABLE 17--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-21	Loamy sand	Loamy sand	1	4	c	4(4)1.22				
			2	4	c	4(4)1.22	2(2)1.30			
			3	25	4.8	16(18)1.45	25(28)1.55	18(21)1.45	26(27)1.55	13(15)1.45
N-1	Sandy loam	Loamy sand	1	21	1.2	9(12)1.28	5(10)1.28	21(24)1.54		
			2	30	4.1	22(22)1.54	21(21)1.54	19(19)1.54	23(23)1.54	21(23)1.54
			3	26	3.3	18(18)1.54	16(21)1.54	15(17)1.54	22(22)1.54	16(18)1.54
			4	32	5.7	19(29)1.64	48(53)1.48	31(41)1.48	44(48)1.48	38(38)1.48
			5	21	1.4	16(17)1.54	26(28)1.64	18(22)1.54		
N-20	Sandy loam	Loamy sand	1	19	2.1	19(21)1.76	22(23)1.76			
			2	31	3.0	24(27)1.76	24(25)1.76	26(27)1.76		

[c]Tree was a seedling less than two feet in height.

TABLE 17--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-22	Sandy loam	Loamy sand	1	38	3.1	23(25)1.66	24(27)1.66			
N-2	Sandy loam	Sandy loam	1	34	6.0	16(18)1.51	21(22)1.51	20(22)1.51		
N-4	Sandy loam	Sandy loam	1	26	3.3	30(32)1.47	33(34)1.47	35(38)1.59		
			2	28	5.1	29(32)1.47	32(33)1.47	30(31)1.47		
N-5	Sandy loam	Sandy loam	1	87	7.2	30(33)1.67	29(31)1.67	30(31)1.67	30(31)1.67	30(31)1.67
N-7	Sandy loam	Sandy loam	1	58	8.8	34(35)1.67	35(38)1.77	29(30)1.67		
N-8	Sandy loam	Sandy loam	1	52	10.6	43(49)1.41	51(52)1.41	48(50)1.41	41(43)1.41	48(49)1.41
			2	49	6.1	21(33)1.41	36(43)1.41	31(31)1.41	26(28)1.41	26(30)1.41
N-10	Sandy loam	Sandy loam	1	25	1.7	29(30)1.41	36(37)1.41	24(27)1.41		

TABLE 17--Continued

Site[a] No.	Soil Texture		Tree No.	Tree Age	Tree DBH	Depths Reached by Principal Vertical Roots and Soil Bulk Density				
	0-6 in.	6-24 in.		(yr.)	(in.)	Main Vertical Root	Other Roots (inches below ground and grams/cc)[b]			
N-3	Loam	Sandy loam	1	25	4.0	37(42)1.70	24(28)1.70	37(41)1.70	26(26)1.70	21(27)1.70
			2	17	2.2	22(29)1.70	19(22)1.34	29(33)1.70	25(36)1.70	21(32)1.70
			3	38	10.3	32(32)1.70	48(51)1.70	49(59)1.70	50(56)1.70	35(36)1.70
N-25	Silt loam	Sand	1	56	5.0	29(33)1.82	31(34)1.82	31(32)1.82	28(31)1.82	
			2	48	4.7	36(39)1.89	40(42)1.89	27(29)1.82		
			3	43	3.0	24(27)1.82	24(25)1.82	20(25)1.82	18(20)1.86	
			4	51	5.0	26(27)1.82	19(21)1.86			
			5	45	7.0	32(34)1.82	34(37)1.89	30(31)1.82		
N-27	Silt loam	Loam	1	76	6.7	38(40)1.94	32(33)1.94	36(39)1.94	31(34)1.94	33(35)1.94
N-24	Silty clay loam	Silt loam	1	48	5.2	52(55)1.94	42(46)1.94	50(51)1.94	38(41)1.94	

Every balsam fir tree examined in this phase of the study, including the two seedlings at Site No. N-21, exhibited a distinct tap root and many sinker roots. Most of these vertical roots were more pronounced than any found in either white spruce or black spruce, and some were very large. Only one of the 34 older trees examined had a tap root which did not descend below 12 inches; and, furthermore, one 57-year-old tree had a tap root which was excavated to a depth of nearly 10 feet. Many sinker roots exceeded four feet in depth and several had penetrated from six to nine feet into the soil. Examples of several of the balsam fir central root masses which were examined are shown in Figures 42 through 50. A summary of vertical root penetration by balsam fir trees is given in Table 18.

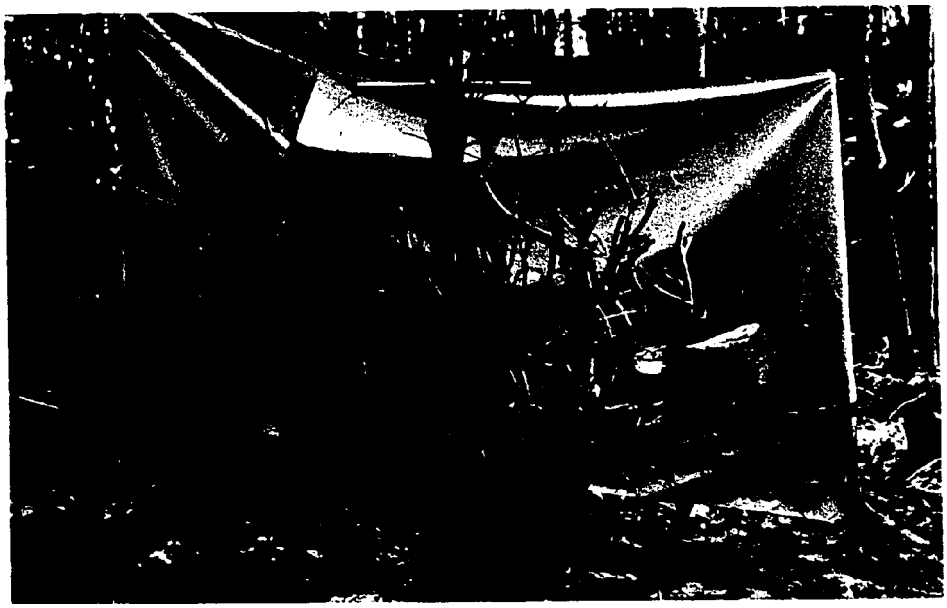


Fig. 42.--Abundant sinker roots on stump of a 64-year-old balsam fir which grew in a pure sandy soil. Site No. N-13, Schoolcraft County, Michigan.



Fig. 43.--Large sinker root found descending to a depth of 93 inches below stump of tree shown in Figure 42. Root diameter was 1.5 inches at 30 inches below ground and 0.25 inch at 72 inches depth.



Fig. 44.--Prominent tap root on 57-year-old balsam fir tree growing in a loamy sand. Bulk density was 2.02 at root terminus 30 inches below soil surface. Site No. N-19, Iron County, Michigan.



Fig. 45.--Mass of sinker roots beneath stump of a 25-year-old balsam fir growing in a loamy sand above a hardpan with bulk density of 1.55. Site No. N-21, Gogebic County, Michigan.



Fig. 46.--Central root mass of a 62-year-old balsam fir tree excavated to a depth of 10 feet in a sandy soil. Site No. N-19, Iron County, Michigan.

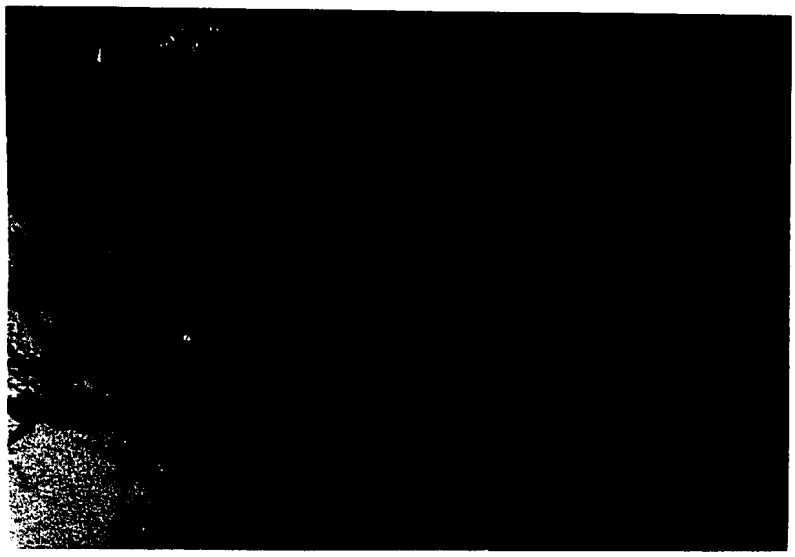


Fig. 47.--Distinct tap root and prominent descending lateral root on 38-year-old balsam fir tree growing in a sandy soil. High water table probably impeded vertical root growth below 24 inches. Site No. N-22, Gogebic County, Michigan.

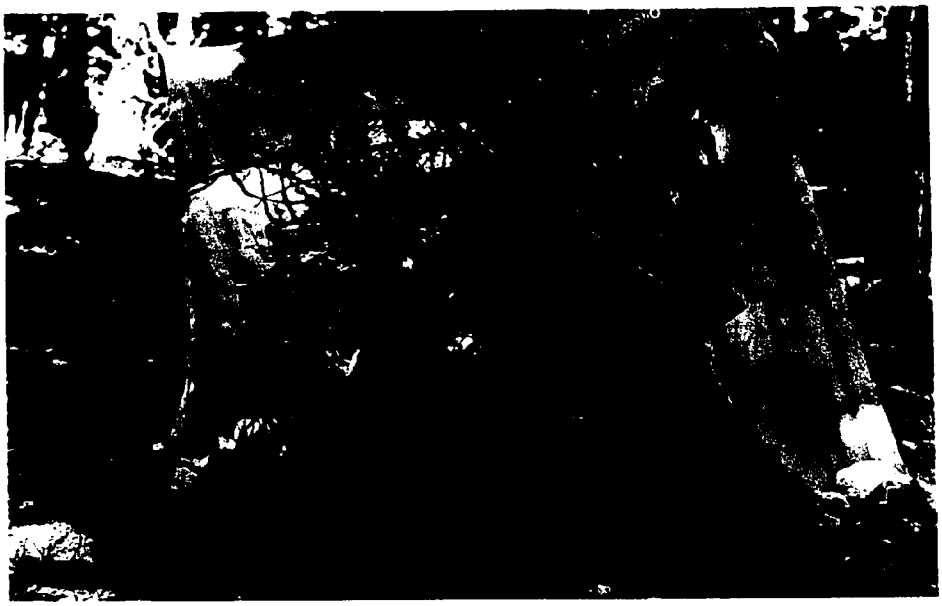


Fig. 48.--Massive central root mass on an 86-year-old balsam fir which grew in a sandy loam soil. Most roots terminated about 30 inches below ground level where bulk density of soil was 1.67. Site No. N-5, Gogebic County, Michigan.



Fig. 49.--Distinct tap root and sinkers on a 25-year-old balsam fir growing in a sandy loam. Roots descended from two to three feet. Site No. N-10, Baraga County, Michigan.

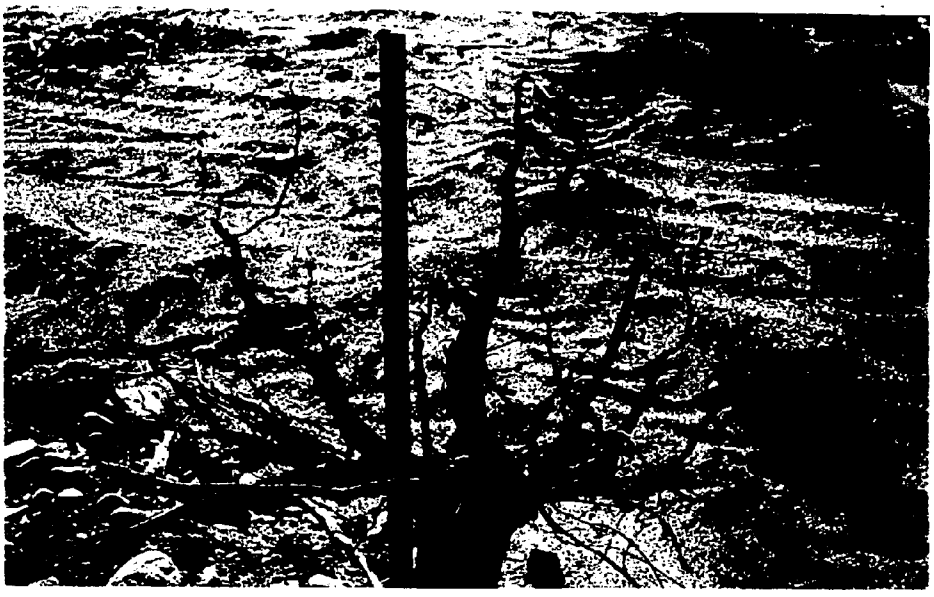


Fig. 50.--Prominent vertical roots on stump of a 43-year-old balsam fir tree growing in a sand with bulk density of 1.89. Site No. N-25, Ontario.

TABLE 18

SUMMARY OF VERTICAL PENETRATION BY ROOTS OF THIRTY-SIX BALSAM FIR TREES GROWING IN NATURAL STANDS

Maximum Depth of Penetration	Number of Roots Observed[a]		Number of Trees[b]
	Tap Roots	Sinker Roots	
0 - 12 inches	3	2	2[c]
12 - 24 inches	7	21	6
24 - 36 inches	19	39	13
36 - 48 inches	4	19	8
48 - 60 inches	2	9	5
60 - 72 inches	---	1	---
72 - 84 inches	---	---	---
84 - 96 inches	---	4	1
96 - 108 inches	---	---	---
108 - 120 inches	1	1	1
Total	36	96	36

[a]Same as footnote a in Tables 4 and 9.

[b]This is the number of trees for which the greatest depth of root penetration was in the depth class shown.

[c]These two trees were four years old.

More than a third of the sinker roots observed (34 out of 96) on these balsam fir trees were found at least three feet below the soil surface, and 99 out of all 132 vertical roots examined (75 percent) were deeper than two feet below

the surface where they terminated. The percentage figures are somewhat lower than was the case with white spruce but they are significantly higher than black spruce.

The same linear regression analyses as were made for white spruce were made for balsam fir root penetration data in relation to bulk density of the soil at the ends of the roots. Four of the six regression analyses yielded correlation coefficients which were significant at either the 95 or 99 percent levels of probability. The variables which were tested are indicated below, and the regression equations and correlation coefficients are presented in Table 19. All of the relationships indicated that a positive relationship exists between depth of rooting and bulk density. The two seedlings which were only four years old were not included in these analyses because of the great differences in ages and stage of development.

A large number of the roots examined on the balsam firs which grew in natural stands grew in sandy loam soils. In fact, 97 percent of all vertical roots examined were growing in soils classed as sand, loamy sand, or sandy loam. No strong differences were apparent in the depths attained by vertical roots in any of these soils. This would account somewhat for the rather low "r^2" values in Table 19. None of those values were as great as any found in the analysis of

Relationship Reference No.	Variables Tested (Y)		(X)
1	Depths of all 34 tap roots	vs.	Bulk density at end of each tap root
2	Depths of all 95 sinker roots	vs.	Bulk density at end of each sinker root
3	Depths of all 129 vertical roots examined	vs.	Bulk density at end of each vertical root
4	Depths of the one deepest tap root at each of the 18 different sites	vs.	Bulk density at end of deepest tap root at each site
5	Depths of the one deepest sinker root at each site	vs.	Bulk density at end of deepest sinker root at each site
6	Depths of the one deepest vertical root at each site	vs.	Bulk density at end of deepest vertical root at each site

white spruce rooting depth. This is helpful to know, however, because it leads to the conclusion that vertical rooting of balsam fir may not be as strongly influenced by soil as in the case of white spruce. It is clear from measurements taken and from visual observations of the root systems that balsam fir does produce prominent vertical roots. Mean depths of the vertical roots examined on the 34 older balsam fir trees are presented in Table 20 according to the soil texture class at the root terminus.

TABLE 19

REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS OF ROOT PENETRATION BY BALSAM FIR TREES IN NATURAL STANDS VERSUS SOIL BULK DENSITY AT ROOT TERMINUS

Relationship Reference No.[a]	Regression Equation[b]	r^2	Significance[c]
1	$\hat{Y} = 39.8\ X - 36.5$	0.166	*
2	$\hat{Y} = 27.8\ X - 13.1$	0.076	**
3	$\hat{Y} = 30.8\ X - 19.0$	0.094	**
4	$\hat{Y} = 59.4\ X - 63.7$	0.223	*
5	$\hat{Y} = 27.1\ X - 3.7$	0.039	NS
6	$\hat{Y} = 33.7\ X - 13.7$	0.053	NS

[a]Reference numbers pertain to the variables listed on the previous page.

[b]$\hat{Y}$ is the estimated depth of root penetration, in inches; and X is the soil bulk density at the root terminus, in grams per cc.

[c]A single asterisk indicates that the correlation coefficient, r, is significant at the 95 percent level of probability; and two asterisks indicate significance at the 99 percent level. NS indicates that the coefficient is not significant.

Because too few observations were obtained in the silt loam soil, it is hazardous to compare the rooting depths measured there with the depths attained in the more sandy soils. Although the difference is not great, the mean rooting depth of sinker roots consistently exceeds that of tap roots in the sandy soils. In this respect, balsam fir trees exhibit the same trait as white spruces.

TABLE 20

MEAN DEPTH OF BALSAM FIR ROOTS IN RELATION TO SOIL TEXTURE AT ROOT TERMINUS, NATURAL STANDS

Soil Texture at Root Terminus	Mean Depths and Numbers of Roots Examined[a]		
	Tap Roots	Sinker Roots	All Vertical Roots
	(inches and numbers of roots)		
Sand	28.0 (11)	33.5 (23)	31.5 (34)
Loamy sand	29.5 (10)	32.0 (31)	31.5 (41)
Sandy loam	30.0 (12)	32.5 (38)	32.0 (50)
Silt loam	52.0 (1)	43.3 (3)	45.5 (4)
Grand Mean	30.0 (34)	33.0 (95)	32.0 (129)

[a]Means are to the nearest one-half inch; numbers in parentheses represent the numbers of roots measured in each category.

No balsam fir trees were examined in plantation environments because it has not been common forestry practice to plant this species in the Lake States region. Natural regeneration is usually exceptionally good, even to the point of being excessive, so that foresters have not made efforts to cultivate it as they have the two spruces. Where balsam fir has been planted, failure of the plantings has been a common occurrence. The same difficulty was experienced in the greenhouse experiment with balsam fir seedlings.

Balsam Fir Seedlings in Greenhouse Experiment

Only 16 balsam fir seedlings survived in the soil boxes which represented different rooting environments. None survived in the four compartments which contained sandy clay loam soil with a bulk density of 1.24 (treatment 4), and only one survived in each of treatments 2 and 3. The compartments containing sand provided the only satisfactory surviving environment. All trees were received and planted at the same time, so it is probable that the soils other than sand were unfavorable for balsam fir seedlings to grow and survive. Results of vertical root growth for the trees which did live are presented in Table 21, and several representative seedlings are illustrated in Figures 51, 52, and 53. Comparing the two trees which survived in treatments 2 and 3 with those which lived in the sandy soil gives a fair idea of the differences in the amount of roots produced in the different soils. Clearly, the sandy soil with its conditions of excessive drainage and aeration was a satisfactory environment for growth of balsam fir roots.

Since comparisons among the four soil conditions are not possible with respect to root growth, the only conclusion possible is that balsam fir trees do have the capacity to grow distinct vertical roots in sandy soils and that soils which are not well drained may not be favorable environments

TABLE 21

INITIAL AND FINAL VERTICAL ROOT PENETRATION BY BALSAM FIR SEEDLINGS GROWN IN GREENHOUSE EXPERIMENT

Tree No.	Vertical Root Penetration in Different Soil Treatments[a]							
	1		2		3		4	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	(inches)							
1	3.8	8.5	3.3	6.0	3.4	6.0	No Trees Survived	
2	4.9	9.0						
3	4.3	7.0						
4	5.3	6.0						
5	4.1	9.0						
6	3.8	8.0						
7	3.0	11.0						
8	5.0	11.0						
9	6.5	11.0						
10	3.3	11.0						
11	3.8	11.0						
12	3.5	9.0						
13	4.0	11.0						
14	4.0	10.0						
Means	4.2	9.5	3.3	6.0	3.4	6.0	---	---

[a]Treatment 1 is a sand with average bulk density of 1.70; 2 is a sandy clay loam with bulk density of 0.88; 3 is a sandy loam with bulk density of 1.07 over a packed loam with bulk density of 1.65; and 4 is a sandy clay loam with bulk density of 1.24.

for seedlings. The mean rooting depth of the surviving seedlings is slightly less than that found for white spruce and this will be considered in the next chapter where comparisons are made among the three species.

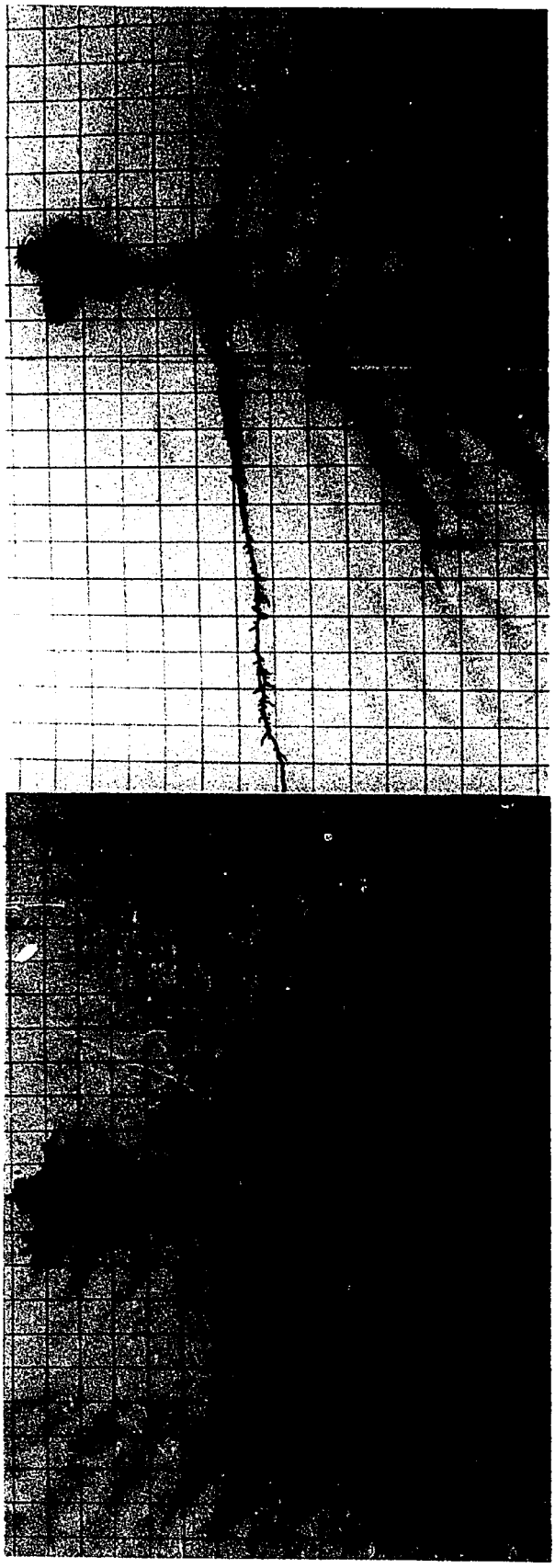


Fig. 51.--Selected typical balsam fir seedlings which grew in soil treatment 1--sand (bulk density 1.70).

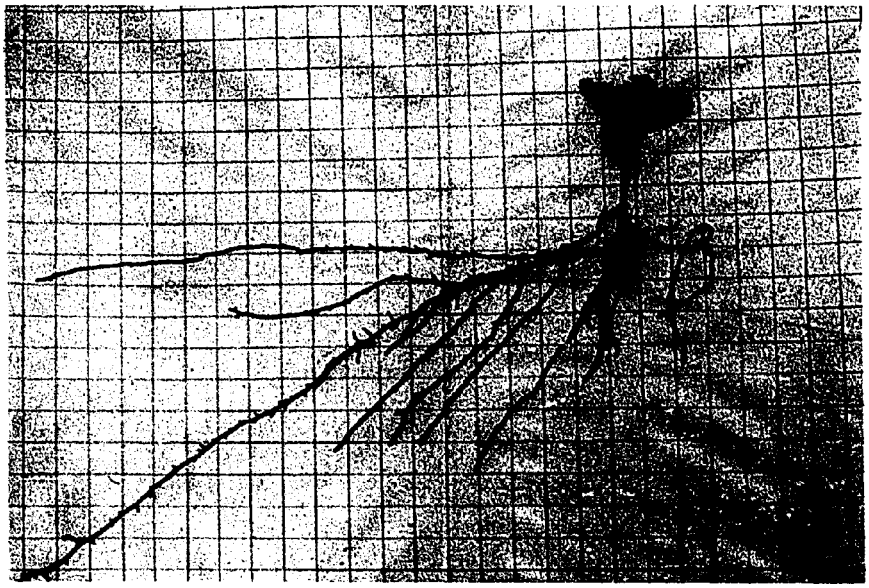


Fig. 52.--The only balsam fir seedling which survived growth in soil treatment 2--sandy clay loam (bulk density 0.88).

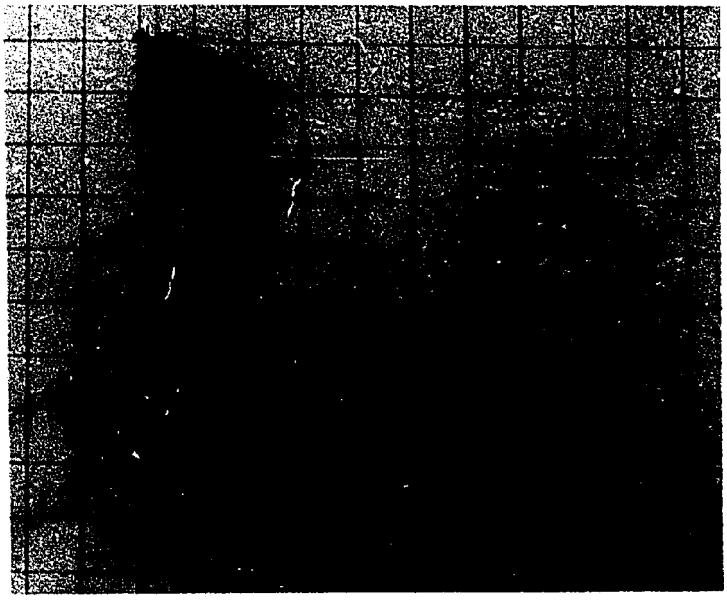


Fig. 53.--The only balsam fir seedling which survived growth in soil treatment 3--sandy loam (bulk density 1.07) over compacted loam (bulk density 1.65).

Summary and Conclusions about Vertical Rooting in Balsam Fir

The rooting habits of 34 balsam fir trees ranging in age from 14 to 87 years were examined in this study, and 18 seedlings were also examined. The 34 trees in natural stands grew on 18 different sites which ranged from pure sandy soils to a silt loam soil. Most trees grew in sand, loamy sand, or sandy loam conditions. Balsam fir is found on a wider variety of sites in the Lake Superior region but no others were sampled.

It is clear from the field observations made in this study that balsam fir trees produce distinct tap roots and sinker roots. The average depth attained by these roots was somewhat short of three feet, but many trees had roots which penetrated significantly deeper.

No strong differences in vertical rooting depth appeared among the trees which grew in sands, loamy sands, or sandy loams; but the roots of one tree growing in a silt loam were deeper than in the other soil texture conditions. A comparison between the mean vertical depth attained by tap roots and that reached by sinker roots showed little difference. The tap roots averaged 30 inches deep and the sinkers 33.

More than 76 percent of the sinker roots descended deeper than two feet, and over 35 percent of them were deeper than three feet. Tap roots were somewhat more confined, but

over 72 percent of them were deeper than two feet and almost 20 percent exceeded three feet.

Seedlings exhibited distinct vertical rooting habits, but not enough of them were examined in finer textured soils to make conclusive statements regarding the effect of soil environment on this habit. Balsam fir seedlings are evidently sensitive to some trait of non-sand soils and do not survive sufficiently long to establish any modifying influence of the soil on vertical root development.

Because balsam fir and white spruce seem to possess about the same type of vertical rooting habit, and because both of them occupy many of the same sites throughout their natural ranges, it is appropriate that they be discussed together in the silvicultural sense. This is done in Chapter VI.

CHAPTER VI

COMPARISONS OF VERTICAL ROOTING AMONG SPECIES

It is clear, from the foregoing results, that rooting habits of the three species studied are different. Between white spruce and black spruce and between balsam fir and black spruce there is little doubt that distinct differences exist. The differences between white spruce and balsam fir, however, are merely ones of degree. Both of these species seem to produce distinct vertical roots in most upland site conditions. Black spruce produces vertical roots but they are not nearly as prominent as those of the other species.

Data presented in the previous chapters in separate tables, by species, have been pooled in Table 22 to provide a comparison of rooting depths among species. Here it can be seen just how much white spruce and balsam fir differ from black spruce in rooting depth in each of the various soil texture conditions. Data were not collected in such a way that it would be appropriate to test for statistical differences among the rooting depth means, but this is not necessary because of the wide differences between black spruce rooting depths and those of the other two species. It seems

TABLE 22

COMPARATIVE MEAN MAXIMUM DEPTHS OF VERTICAL ROOTS OF BLACK SPRUCE, WHITE SPRUCE, AND BALSAM FIR EXAMINED IN NATURAL FOREST STANDS IN THE LAKE SUPERIOR REGION

Soil Texture at Root Terminus	Mean Maximum Rooting Depth and Numbers of Roots Examined[a]								
	Tap Roots			Sinker Roots			All Vertical Roots		
	BS	WS	BF	BS	WS	BF	BS	WS	BF
Sand	20.5(3)	45.5(8)	28.0(11)	18.0(23)	35.5(18)	33.5(23)	18.5(26)	40.5(26)	31.5(34)
Loamy sand	12.0(5)	22.0(5)	29.5(10)	11.5(18)	34.0(11)	32.0(31)	11.5(23)	30.5(16)	31.5(41)
Sandy loam	18.5(7)	29.5(10)	30.0(12)	20.0(27)	33.5(22)	32.5(38)	19.5(34)	32.0(32)	32.0(50)
Loam	26.0(1)	---	---	20.5(10)	---	---	21.0(11)	---	---
Silt loam	24.0(1)	33.5(6)	52.0(1)	14.0(4)	39.5(11)	43.5(3)	16.0(5)	37.5(17)	45.5(4)
Clay	---	---	---	29.0(1)	---	---	29.0(1)	---	---
Grand Mean	17.5(17)	33.5(29)	30.0(34)	17.5(83)	36.0(62)	33.0(95)	17.5(100)	35.0(91)	32.0(129)

[a]Means are to nearest one-half inch; data are derived from Tables 3, 8, and 17.

safe to conclude that black spruce normally produces mostly shallow, lateral roots in most soil environments where it grows and that both white spruce and balsam fir may be considered to be shallow rooted species which almost invariably produce distinct tap roots and sinker roots in upland soil conditions. While black spruce frequently produces roots that are classed as vertical roots, most of these are small and remain close to the soil surface.

The vertical growth of white spruce roots in Kimberly-Clark plantations was markedly better than that of black spruce. Comparative mean penetration data are presented for the two species in Table 23.

Not only were prominent vertical roots lacking in black spruce trees, but the depths attained by any roots which did descend were not deep. White spruce trees, on the other hand, produced distinct tap roots and sinker roots which grew downward into the soil to considerably greater depths than any similar roots on black spruce trees.

It has already been shown that the seedlings which were grown in different soil environments in the greenhouse experiment were affected by the compacted soil layer of treatment 3. A summary of the means of rooting depths attained by each species is provided in Table 24. Within each of the four treatments, each difference between means

TABLE 23

COMPARATIVE MEAN MAXIMUM DEPTHS OF VERTICAL ROOTS OF BLACK SPRUCE AND WHITE SPRUCE EXAMINED IN PLANTATIONS OF THE KIMBERLY-CLARK CORPORATION IN THE LAKE STATES

Soil Texture at Root Terminus	Mean Maximum Depths and Numbers of Roots Examined[a]					
	Tap Roots		Sinker Roots		All Vertical Roots	
	BS	WS	BS	WS	BS	WS
Sand	8.5(5)	32.5(12)	10.0(10)	31.0(24)	9.5(15)	31.5(36)
Loamy sand	5.0(1)	12.0(4)	5.0(1)	10.5(6)	5.0(2)	11.0(10)
Sandy loam	9.0(5)	8.5(5)	8.5(13)	12.0(11)	8.5(18)	11.0(16)
Loam	---	---	13.0(2)	---	13.0(2)	---
Silt loam	---	18.0(4)	---	15.5(10)	---	16.0(14)
Clay	---	10.5(6)	---	8.0(7)	---	9.0(13)
Grand Mean	8.5(11)	20.0(31)	9.5(26)	20.0(58)	9.0(37)	20.0(89)

[a]Means are to the nearest one-half inch; numbers in parentheses represent the numbers of roots measured in each category. Data are derived from Tables 5 and 12.

is statistically significant at the 99 percent level when analyzed by the "t" test. One exception to this is that the difference between white spruce and balsam fir in treatment 1 is significant only between the 90 and 95 percent levels.

This completes the presentation of results for individual tree species and for comparisons among the three species. It is now fitting to discuss why the attainment of an understanding about the nature of vertical rooting in these trees

TABLE 24

MEAN DEPTHS ATTAINED BY THE MOST PROMINENT VERTICAL ROOTS OF BLACK SPRUCE, WHITE SPRUCE, AND BALSAM FIR SEEDLINGS GROWN IN DIFFERENT SOIL ENVIRONMENTS

Soil Treatment Number	Mean Vertical Root Penetration		
	BS	WS	BF
	(inches)		
1	6.5	10.4	9.5
2	6.6	9.8	6.0[a]
3	5.1	7.0	6.0[a]
4	6.7	9.4	---

[a]Only one tree survived in this treatment.

is important.

Implications of Vertical Rooting Habits

With the information obtained in this study it now seems possible to broaden the understanding of these root systems. Clearly, it must be concluded that balsam fir and white spruce do not produce only shallow, lateral roots on many of the upland sites where they grow. This necessitates a reconsideration of the management and silviculture of these trees on such sites.

All three species of this study are considered to be relatively tolerant, or highly competitive, in the forests where they grow. The normal type of harvest cutting that

would be used for tolerant species, if the management objective were to perpetuate them in succeeding generations of trees, is the selection method or partial cutting. In fact, the shelterwood system is frequently used in spruce and fir forests. Clearcutting, from the silvical viewpoint, is the least satisfactory type of logging practice in tolerant tree species.

Spruce-fir forest management practices, however, do not always follow the partial cutting schemes because of the general experience of windthrow of residual trees when partial cutting is done. This has been true in the past, particularly in swamp situations where shallow rooting is prevalent. Because the largest extensive commercial stands of spruce and fir have been located in wetland environments, the use of clearcutting has been prescribed, wisely, for many years.

On upland sites spruce and fir have been clearcut--not because research has shown clearcutting to be best--but, rather, because this kind of harvesting has been successful on wet-site practices. Perhaps windthrow could be a serious problem on some upland sites, such as loose sand, if anything other than clearcutting were practiced. But, on other sites, such as rocky, finer soils, clearcutting might well not be necessary.

Balsam fir and white spruce do produce strong vertical

roots in addition to well developed surface lateral roots on most upland sites. If vertical rooting does not provide adequate mechanical support it is probably because the depths attained are not great enough in relation to the lateral spread of roots. In fine textured soils, including some of the glacial tills which are well endowed with included rock material, the vertical rooting habit may be quite adequate to allow these species to withstand the effects of wind movement through a partially opened stand. Roots were observed in this study to be tightly wound around large stones and rocks wherever these occurred in the soil. Such a feature certainly would aid in anchoring the tree in the ground, particularly if the anchorage were moderately deep in the soil. In sandy or other coarse textured soils, on the other hand, even very deep sinker roots and tap roots may not provide adequate anchorage unless rocks are in the soil.

Future research may determine that certain upland site conditions are satisfactory for the practice of a genuine selection method of silviculture for balsam fir and white spruce. It may be established that these trees cannot be managed in this way on some upland sites. Both balsam fir and white spruce require an abundant source of moisture to make best growth, but poorly drained lowland sites are not necessarily the most favorable sites on which to achieve the

objective of good growth for these trees. Best growth is attained in loamy soils which have good moisture supplies. Upland sites of this kind do occur commonly throughout the spruce-fir region, so it would seem that silvicultural research could determine the most successful system of management--selection, shelterwood, or clearcutting--for these species on upland sites.

It has not been the purpose of this investigation to determine what silvicultural practices may be best for spruce and fir, but the conclusion that vertical rooting predominates in white spruce and balsam fir in upland conditions should not be overlooked by forest managers.

Black spruce does not produce large or abundant vertical roots in any of the sites where it grows naturally--uplands or lowlands. Thus, its root system is probably more correctly classed as predominantly shallow than is true for white spruce and balsam fir. Although some vertical roots are produced, most do not descend very far into the soil on any site. The silviculture of black spruce, therefore, must continually take into account the importance of shallow rooting. Whether black spruce could persist on some upland sites with white spruce and balsam fir if selective logging were desirable for the latter two species is another aspect of the problem which might be studied.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

Black spruce, white spruce, and balsam fir--all dominant species of the Boreal Forest Formation and the adjoining region which is in transition to the Eastern Deciduous Forest Formation--are known to be shallow rooted. This knowledge has dominated forestry and botanical thought about these species. It has also affected silvicultural decisions regarding cutting practices.

In moist habitats the three species do produce a root system which must be characterized as distinctly shallow. The trees, however, occupy much land area that is considered upland or non-swamp habitat. On such areas the management and, indeed, the ecology of the trees may differ. Preliminary field work and a search of literature revealed some evidence that the trees possess a vertical rooting habit. The purpose of the present study has been to examine the nature of vertical rooting by these species and to describe the conditions under which this habit occurs.

Spruce and fir trees were investigated on a wide variety of upland sites. In 28 different natural stands, 108 trees were examined. Some trees were excavated by hydraulic means and by hand, and many were examined at sites of road construction and logging activities where they had been uprooted by heavy machinery. In spruce plantations established between 1944 and 1956 by the Kimberly-Clark Corporation, 45 black and white spruce trees were excavated by hand. To complete the study of root development, an experiment was conducted in which spruce and fir seedlings were grown in a greenhouse in four different soil environments for nearly a year before being excavated.

Forty black spruce trees ranging in age from four-year-old seedlings to trees from 30 years to 154 years old were studied in 19 different natural stands. In 11 different plantations, 14 black spruces were excavated; and 44 seedlings were examined at the end of the greenhouse experiment.

Thirty-two white spruce trees were examined in 13 different natural stands. The trees ranged in age from four-year-old seedlings to trees from 25 to 181 years old. Thirty-one plantation trees were examined at 18 different locations. In the greenhouse experiment, 51 three-year-old seedlings survived and their root systems were examined.

Thirty-six balsam firs were examined in 18 natural

stands, and these trees ranged in age from a few young seedlings to trees from 14 to 87 years old. Only 16 of the greenhouse seedlings survived the experiment to be examined.

Vertical rooting does not seem to be a prominent habit of black spruce trees of any age or on any site. Only a few of the 98 trees examined produced prominent vertical roots. The tap roots which were found were poorly developed, dead, or rotten. Only four vertical roots, out of 108 examined, descended into the fourth foot below the soil surface in the natural stand conditions which were studied. None were below that level, and almost 80 percent of all vertical roots examined on these trees were confined to the upper two feet of soil. The 14 plantation trees had no roots below 18 inches in the soil, and 75 percent of the vertical roots studied were confined to the upper foot of soil. In the greenhouse study, a soil with a compacted layer impeded vertical root growth significantly in comparison with other soils which did not have such a feature.

Soil texture and bulk density did not seem to influence the development of vertical roots by black spruce because this feature is expressed to such a limited degree by this species in any soil condition. No significant correlations between rooting depth and texture or bulk density were established for black spruce.

Contrasted with black spruce, white spruce does exhibit a distinct vertical rooting habit. Nearly all of the 114 trees examined produced prominent vertical roots. Most trees had a well defined tap root and one or more sinker roots. In general, the sinker roots descended slightly deeper into the soil than the tap roots. Of the 95 vertical roots examined on trees in natural stands, 39 grew below three feet deep into the soil. Whereas nearly 80 percent of black spruce vertical roots were confined above two feet in the soil, the same percentage of white spruce roots studied were below that depth. Possibly because of the youth of the trees, vertical penetration by roots of the white spruces in plantations was much less than in the natural stands. Of the 31 trees examined, 22 had their deepest vertical roots confined to the upper two feet of soil; but roots of several of the trees penetrated below four feet. Vertical penetration in the greenhouse study was significantly greater for white spruce than for black spruce seedlings in all of the soil conditions studied, and the compact soil layer again impeded vertical penetration significantly. Roots of white spruce were able to penetrate into it to some degree, however.

Soil texture appeared to affect the vertical rooting habit of white spruce in that greater penetration nearly always occurred in sandy soils than in any other texture class.

A definite positive correlation between soil bulk density and vertical rooting depth was found. The greatest root depths were attained in sandy soils which are porous and have high bulk density.

Balsam fir trees have a vertical rooting habit at least as pronounced as that of white spruce, and the results obtained in this study were very similar for both species. The depth of rooting in balsam fir was somewhat greater for the sinker roots than for the tap roots. Soil bulk density was also positively correlated with vertical rooting depth. Since most trees studied were in relatively sandy soil conditions, no distinct differences in the influence of texture were noted. Two differences between balsam fir and white spruce were apparent in this study. Balsam fir tap roots were notably larger in diameter, and considerably more sinker roots were found on balsam fir trees than on white spruces.

Conclusions

No comprehensive studies of the vertical rooting habits of black and white spruce and balsam fir have ever been conducted. Consequently, little has really been known about the extent of development of vertical roots by these species or under what conditions such roots are produced. Some evidence has accumulated but the general paucity of information has

led to an inadequate understanding of this morphological feature of the trees.

All three species are known to be predominantly shallow rooted wherever they grow. In addition to this, however, it must now be concluded that both white spruce and balsam fir produce prominent tap roots and sinker roots on most upland sites. The average depth attained by such roots examined in natural stands was more than 30 inches for both white spruce and balsam fir. Black spruce does exhibit feeble vertical rooting, but the average depth of vertical roots of this species was less than 18 inches on upland sites.

Vertical rooting of balsam fir was about equal in sand, loamy sand, and sandy loam. It was about a foot deeper in a silt loam, but too few roots were examined in that texture class to draw a conclusion about differences among textures.

White spruce trees consistently produced deepest vertical roots in sand, averaging over 40 inches depth. Roots in silt loam were next deepest, at 37.5 inches; and they averaged somewhat over 30 inches in sandy loam and loamy sand.

Vertical roots of black spruce were mostly confined to the upper two feet of soil and no apparent differences were observed due to texture of the soil.

While all three species must continue to be regarded as shallow rooted, it should now be recognized that white

spruce and balsam fir, on non-swamp sites, exhibit distinct vertical rooting habits.

APPENDIX TABLES

APPENDIX TABLE 1

GENERAL GEOGRAPHIC LOCATIONS AND MISCELLANEOUS NOTES ABOUT AREAS IN THE LAKE SUPERIOR REGION WHERE SPRUCE AND FIR ROOTING HABITS WERE EXAMINED IN NATURAL STANDS

Site No.	Approximate Geographic Location	Miscellaneous Notes
N-1	Sec. 23, T42N, R30W, Dickinson County, Michigan.	Gravelly ridge between two low, swampy areas. Pole-sized aspen stand with mixed saplings of spruce and fir, mostly fir.
N-2	Sec. 3, T38N, R28W, Menominee County, Michigan.	Sandy ridge between swamps. Pole-sized balsam fir with scattered black and white spruce poles.
N-3	Sec. 26, T42N, R30W, Dickinson County, Michigan.	Sandy till with many rocks and boulders on gentle slope between upland and swamp.
N-4	Sec. 23, T43N, R27W, Dickinson County, Michigan.	Sandy moraine above swamp. Aspen poles with spruce-fir poles and some sugar maple.
N-5	Sec. 13, T47N, R42W, Gogebic County, Michigan.	Till plain with compact layer at 14-inch depth and rock at 36 inches. Stand mainly large hemlock, yellow birch, and sugar maple.
N-6	Sec. 13, T47N, R42W, Gogebic County, Michigan.	Till plain with hardpan at 23-inch depth. Stand mainly large hemlock, yellow birch, and sugar maple.
N-7	Sec. 24, T47N, R42W, Gogebic County, Michigan.	Till plain. Large hemlock, yellow birch, sugar maple; scattered large white spruces and old balsam firs.
N-8	Sec. 14, T48N, R32W, Baraga County, Michigan.	Sandy outwash plain. Large balsam firs and spruces plus smaller aspen and paper birch. Some white pine small sawtimber.
N-9	Sec. 14, T48N, R32W, Baraga County, Michigan.	Same as Site N-8.
N-10	Sec. 14, T48N, R32W, Baraga County, Michigan.	Same as Site N-8.

APPENDIX TABLE 1--Continued

Site No.	Approximate Geographic Location	Miscellaneous Notes
N-11	Sec. 14, T49N, R34W, Baraga County, Michigan.	Sandy outwash plain, very flat. Jack pine poles and saplings with black spruce saplings. High water table at 30-inch depth.
N-12	Sec. 33, T49N, R33W, Baraga County, Michigan.	Thin glacial drift over rock outcroppings. Black spruce and aspen poles; some aspen and balsam fir reproduction.
N-13	Sec. 7, T44N, R18W, Schoolcraft County, Michigan.	Sandy, well-developed podzol with scattered blocks of hardpan. Maple, beech, hemlock stand with scattering of balsam poles and sawtimber.
N-14	Sec. 20, T49N, R15W, Alger County, Michigan.	Sandy former lake bed. Dense pole stand of jack pine with scattered black spruce and red pine.
N-15	Sec. 22, T47N, R9W, Luce County, Michigan.	Sandy ridge surrounded by swamp. Pure sand, no rock. Red and white pine, black spruce, balsam, and tamarack on ridges.
N-16	Sec. 30, T46N, R36W, Iron County, Michigan.	Ice-contact ridge between two bog lakes. Red pine, black and white spruce, balsam, paper birch and aspen.
N-17	Sec. 30, T46N, R36W, Iron County, Michigan.	Same as Site N-16.
N-18	Sec. 30, T46N, R36W, Iron County, Michigan.	Same as Site N-16.
N-19	Sec. 30, T46N, R36W, Iron County, Michigan.	Same as Site N-16.
N-20	Sec. 1, T44N, R37W, Iron County, Michigan.	Stony and gravelly slope above creek. Aspen, balsam, and white spruce stand.
N-21	Sec. 3, T44N, R38W, Gogebic County, Michigan.	Morainic ridge dipping sharply into stream-cut valley. Sandy soil with indurated hardpan beginning 6 inches down and about 6 inches thick. Balsam, white spruce, and some black spruce on ridge above stream.

APPENDIX TABLE 1--Continued

Site No.	Approximate Geographic Location	Miscellaneous Notes
N-22	Sec. 24, T44N, R38W, Gogebic County, Michigan.	Sandy transition area between till plain and seepage swamp. Good mixture of both spruces and balsam.
N-23	Sec. 12, T67N, R19W, St. Louis County, Minn.	Former lake bed. Clay below top few inches. Large aspen with some white pine and cedar, much black spruce.
N-24	Approx. 49 miles east of town of Longlac, Ontario, along paved highway.	Former lake bed. Very large white spruce trees.
N-25	Approx. 16 miles south of Longlac, Ontario, near McLeod Lake.	Till plain. Spruce, fir, jack pine.
N-26	Approx. 48 miles southwest of Longlac, Ontario, near Chorus Lake.	Till plain. Spruce, fir, jack pine.
N-27	Approx. 37 miles southwest of Longlac, Ontario, between Wintering Lake and Rogers Lake.	Till plain.
N-28	Sec. 30, T46N, R36W, Iron County, Michigan.	Sandy transition between ice-contact ridge and bog lake. Mixture of red and white pines, aspen, and spruce-fir.

APPENDIX TABLE 2

SOIL TEXTURE, BULK DENSITY, AND GRAVEL CONTENT DATA AT STUDY SITES IN NATURAL STANDS

Site No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
N-1	0-3	73.5	22.0	4.5	SaLo	1.41	0.1
	3-6	74.0	20.5	5.5	SaLo	1.22	0.0
	6-12	77.0	21.5	1.5	LoSa	1.28	0.1
	12-24	81.5	16.5	2.0	LoSa	1.54	2.1
	24-36	91.5	6.5	2.0	Sand	1.64	0.0
	36-48	85.5	12.0	2.5	LoSa	1.48	0.0
N-2	0-3	66.0	26.5	7.5	SaLo	1.34	10.8
	3-6	67.0	26.5	6.5	SaLo	1.54	6.7
	6-12	73.5	17.5	9.0	SaLo	1.63	7.0
	12-24	67.0	15.0	18.0	SaLo	1.51	4.9
N-3	0-3	45.0	48.0	7.0	Loam	1.33	1.9
	3-6	50.5	42.5	7.0	SaLo	1.10	4.4
	6-12	67.0	29.5	3.5	SaLo	1.04	4.9
	12-24	70.0	27.0	3.0	SaLo	1.34	12.4
	24-36	71.5	22.5	6.0	SaLo	1.70[d]	14.4
	36-48	70.5	23.0	6.5	SaLo	1.70	11.0
	48-60	71.0	22.0	7.0	SaLo	1.70	13.8
N-4	0-3	55.5	29.5	15.0	SaLo	1.10	0.4
	3-6	59.0	28.0	13.0	SaLo	1.22	1.0
	6-12	64.5	24.0	11.5	SaLo	1.28	1.2
	12-24	69.0	22.0	9.0	SaLo	1.35	1.1
	24-36	67.0	23.0	10.0	SaLo	1.47	0.8
	36-48	66.0	20.5	13.5	SaLo	1.59	0.4

[a]Percentages of sand, silt, and clay were determined by means of the Bouyoucos hydrometer method. The analyses were made only on the soil fraction which passed through a 2.0 mm sieve.

[b]Combination letters refer to the soil texture class and are based on the first two letters of each word, e.g., SaLo refers to sandy loam, and LoSa refers to loamy sand.

[c]Gravel percentage is determined on a weight basis and is based on the portion of the sample which would not pass through a 2.0 mm sieve.

[d]No bulk density samples were obtained below this depth, so the values for the next lower depths are assumed to be the same as this one.

APPENDIX TABLE 2--Continued

Site No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
N-5	0-3	57.0	33.0	10.0	SaLo	0.74	15.7
	3-6	63.5	27.0	9.5	SaLo	1.10	7.8
	6-12	64.0	26.5	9.5	SaLo	1.67	7.8
	12-24	66.0	22.5	11.5	SaLo	1.60	6.4
	24-36	70.5	20.5	9.0	SaLo	1.67	6.0
N-6	0-3	59.0	34.0	7.0	SaLo	1.32	2.8
	3-6	61.0	34.0	5.0	SaLo	0.82	3.8
	6-12	58.0	38.0	4.0	SaLo	1.03	2.4
	12-24	58.5	32.5	9.0	SaLo	1.43[d]	10.1
	24-36	57.0	31.5	11.5	SaLo	1.43	7.2
N-7	0-3	55.0	25.5	19.5	SaLo	1.20	4.9
	3-6	64.0	21.5	14.5	SaLo	1.16	6.2
	6-12	65.5	24.0	10.5	SaLo	1.31	7.4
	12-24	63.5	27.0	9.5	SaLo	1.42	11.8
	24-36	68.0	26.5	5.5	SaLo	1.67	10.7
	36-48	70.5	24.0	5.5	SaLo	1.77	11.4
N-8	0-3	55.0	37.0	8.0	SaLo	1.01	2.0
	3-6	60.5	36.0	3.5	SaLo	1.06	4.3
	6-12	53.0	42.0	5.0	SaLo	1.15	4.0
	12-24	76.5	21.0	2.5	LoSa	1.51	22.3
	24-36	61.0	35.5	3.5	SaLo	1.41[d]	17.2
	36-48	64.5	28.5	7.0	SaLo	1.41	15.8
	48-60	60.5	30.5	9.0	SaLo	1.41	16.4
N-9	0-3	53.0	43.0	4.0	SaLo	1.08	1.8
	3-6	59.5	37.0	3.5	SaLo	1.14	2.7
	6-12	64.5	33.5	2.0	SaLo	1.25	0.4
	12-24	61.0	27.5	11.5	SaLo	1.38	6.8
	24-36	65.5	20.0	14.5	SaLo	1.41[d]	12.4
	36-48	64.0	23.5	12.5	SaLo	1.41	11.7
N-10	0-3	58.5	39.0	2.5	SaLo	0.99	0.4
	3-6	62.0	34.5	3.5	SaLo	1.17	1.7
	6-12	63.5	32.5	4.0	SaLo	1.32	0.4
	12-24	66.0	28.0	6.0	SaLo	1.51	12.3
	24-36	69.5	20.5	10.0	SaLo	1.41	10.8
	36-48	67.0	21.5	11.5	SaLo	1.60	10.9

APPENDIX TABLE 2--Continued

Site No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
N-11	0-3	89.5	7.0	3.5	Sand	1.37	0.1
	3-6	93.0	4.5	2.5	Sand	1.26	3.0
	6-12	96.5	2.0	1.5	Sand	1.59	0.1
	12-24	98.5	0.0	1.5	Sand	1.70	8.5
N-12	0-3	46.0	47.0	7.0	Loam	1.14	4.0
	3-6	49.5	40.5	10.0	Loam	1.20	5.2
	6-12	75.5	21.5	3.0	LoSa	0.99	14.3
	12-24	72.0	24.0	4.0	SaLo	1.58	18.8
	24-36	98.5	0.0	1.5	Sand	1.65	1.0
N-13	0-3	93.0	4.5	2.5	Sand	1.30	0.0
	3-6	91.5	4.5	4.0	Sand	1.42	0.0
	6-12	94.5	2.0	3.5	Sand	1.29	0.1
	12-24	96.0	2.0	2.0	Sand	1.41	0.0
	24-36	96.0	2.5	1.5	Sand	1.56	0.0
	36-48	98.5	0.5	1.0	Sand	1.68	0.0
	48-60	97.5	1.0	1.5	Sand	1.64	0.0
	60-72	97.0	1.5	1.5	Sand	1.70	0.0
	72-84	96.0	2.5	1.5	Sand	1.62	0.0
	84-96	98.0	1.0	1.0	Sand	1.64	0.0
N-14	0-3	93.5	5.0	1.5	Sand	1.25	0.4
	3-6	94.5	3.5	2.0	Sand	1.51	3.5
	6-12	93.5	3.0	3.5	Sand	1.45	4.0
	12-24	97.5	1.0	1.5	Sand	1.49	0.1
	24-36	98.5	0.0	1.5	Sand	1.56	0.6
N-15	0-3	92.5	5.0	2.5	Sand	1.41	0.0
	3-6	95.5	3.0	1.5	Sand	1.32	0.0
	6-12	96.0	2.5	1.5	Sand	1.35	0.0
	12-24	97.0	1.0	2.0	Sand	1.48	0.0
	24-36	98.0	1.0	1.0	Sand	1.54	0.0
	36-48	96.5	2.0	1.5	Sand	1.55	0.0
N-16	0-3	74.0	21.0	5.0	SaLo	1.54	9.1
	3-6	75.5	18.5	6.0	SaLo	1.46	3.0
	6-12	82.5	14.0	3.5	LoSa	1.35	1.5
	12-24	71.5	20.5	8.0	SaLo	1.52	0.9
N-17	0-3	78.5	18.0	3.5	LoSa	1.53	1.0
	3-6	76.5	19.0	4.5	LoSa	1.61	1.4
	6-12	84.0	13.5	2.5	LoSa	1.16	5.6
	12-24	81.0	15.5	3.5	LoSa	1.53	5.2
	24-36	81.5	13.5	5.0	LoSa	1.78	7.7

APPENDIX TABLE 2--Continued

Site No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
N-18	0-3	75.5	19.5	5.0	LoSa	1.27	8.8
	3-6	77.5	18.5	4.0	LoSa	1.39	17.5
	6-12	80.0	16.5	3.5	LoSa	1.48	6.8
	12-24	79.5	16.5	4.0	LoSa	1.68	11.3
N-19	0-3	82.5	14.0	3.5	LoSa	1.55	10.7
	3-6	82.5	13.5	4.0	LoSa	1.64	8.2
	6-12	85.0	11.5	3.5	LoSa	1.67	11.5
	12-24	85.0	11.5	3.5	LoSa	1.58	18.2
	24-36	93.5	4.0	2.5	Sand	2.02	39.4
	36-48	84.5	12.0	3.5	LoSa	1.86	3.2
	48-60	83.0	13.0	4.0	LoSa	1.89[d]	6.2
	60-72	82.0	13.0	5.0	LoSa	1.89	11.4
	72-84	76.5	20.5	3.0	LoSa	1.89	12.7
	84-96	78.0	16.0	6.0	LoSa	1.89	8.6
	96-108	82.0	8.0	10.0	LoSa	1.89	14.2
	108-120	85.5	7.0	7.5	LoSa	1.89	4.1
N-20	0-3	73.0	21.0	6.0	SaLo	1.47	6.4
	3-6	73.5	19.5	7.0	SaLo	1.17	4.9
	6-12	73.5	18.5	8.0	SaLo	1.43	14.3
	12-24	90.0	7.5	2.5	Sand	1.76[d]	33.6
	24-36	82.0	14.0	4.0	LoSa	1.76	55.1
N-21	0-3	78.5	16.0	5.5	LoSa	1.30	0.2
	3-6	82.0	13.5	4.5	LoSa	1.22	0.1
	6-12	82.5	15.5	2.0	LoSa	1.38	0.1
	12-24	80.0	18.0	2.0	LoSa	1.45	0.1
	24-36	81.5	17.0	1.5	LoSa	1.55	0.0
N-22	0-3	74.0	21.5	4.5	SaLo	1.38	0.0
	3-6	73.5	20.5	6.0	SaLo	1.24	0.1
	6-12	81.0	16.5	2.5	LoSa	1.14	0.4
	12-24	82.5	14.0	3.5	LoSa	1.62	0.1
	24-36	96.5	2.0	1.5	Sand	1.66	0.0
N-23	0-3	50.0	27.0	23.0	SaClLo	1.51	3.7
	3-6	32.0	25.0	43.0	Clay	1.52	3.0
	6-12	28.5	23.5	48.0	Clay	1.49	6.6
	12-24	34.5	20.0	45.5	Clay	1.54	2.8
	24-36	31.5	22.5	46.0	Clay	1.49	1.1

APPENDIX TABLE 2--Continued

Site No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
N-24	0-3	13.0	58.0	29.0	SiClLo	1.63	0.3
	3-6	12.5	60.0	27.5	SiClLo	1.78	0.2
	6-12	13.5	62.0	24.5	SiLo	1.94[d]	0.4
	12-24	17.0	63.0	20.0	SiLo	1.94	0.1
	24-36	24.5	56.0	19.5	SiLo	1.94	0.0
	36-48	20.0	55.0	25.0	SiLo	1.94	0.0
	48-60	12.0	65.0	23.0	SiLo	1.94	0.0
N-25	0-3	33.5	54.0	12.5	SiLo	1.57	3.9
	3-6	40.5	47.0	12.5	Loam	1.38	0.8
	6-12	91.0	5.5	3.5	Sand	1.59	3.6
	12-24	91.0	4.5	4.5	Sand	1.86	53.9
	24-36	95.0	1.5	3.5	Sand	1.82[d]	32.3
	36-48	88.5	11.0	0.5	Sand	1.82	27.2
	48-60	90.5	5.0	4.5	Sand	1.82	19.4
	60-72	91.0	4.5	4.5	Sand	1.82	26.1
N-26	0-3	54.0	33.5	12.5	SaLo	2.10	9.9
	3-6	49.5	35.0	15.5	Loam	2.15	10.6
	6-12	49.5	34.0	16.5	Loam	2.14	12.2
	12-24	48.5	34.0	17.5	Loam	2.24	16.8
N-27	0-3	27.5	59.0	13.5	SiLo	1.47	6.7
	3-6	32.0	54.5	13.5	SiLo	1.45	11.2
	6-12	37.0	53.5	9.5	SiLo	1.50	8.5
	12-24	54.0	31.5	14.5	SaLo	1.65	12.4
	24-36	56.0	29.5	14.5	SaLo	1.94[d]	8.6
	36-48	60.0	27.5	12.5	SaLo	1.94	14.8
	48-60	61.5	28.0	10.5	SaLo	1.94	15.0
	60-72	59.0	27.5	13.5	SaLo	1.94	7.2
N-28	0-3	78.0	17.0	5.0	LoSa	1.47	11.4
	3-6	81.0	14.5	4.5	LoSa	1.51	14.6
	6-12	82.5	10.0	7.5	LoSa	1.67	10.2
	12-24	80.0	12.0	8.0	LoSa	1.58	19.7

APPENDIX TABLE 3

GEOGRAPHIC LOCATIONS OF KIMBERLY-CLARK SPRUCE PLANTATIONS WHERE ROOTING HABITS OF BLACK AND WHITE SPRUCE WERE EXAMINED

Plantation[a] No.	Geographic Location
44-S-1 Michigan	W½NW¼, Sec. 32, T46N, R39W, Ontonagon County, Michigan
45-S-1 Wisconsin	SESE, Sec. 25, T45N, R2W, Ashland County, Wisconsin
52-S-1 Michigan	E½NE¼, Sec. 30, T48N, R41W, Ontonagon County, Michigan
52-S-1 Minnesota	NWSW, Sec. 21, T57N, R10W, Lake County, Minnesota
52-S-2 Minnesota	Lot 1, Sec. 31, T57N, R10W, Lake County, Minnesota
52-F-14 Michigan	NESW, Sec. 29, T44N, R11W, Mackinaw County, Michigan
52-F-16 Michigan	SWSE, Sec. 18, T45N, R12W, Luce County, Michigan
52-F-18 Michigan	NENE, Sec. 22, T42N, R2E, Chippewa County, Michigan
53-S-4 Michigan	NESW and NWSE, Sec. 1, T42N, R30W, Dickinson County, Michigan
53-S-5 Michigan	E½NW¼ and NESW, Sec. 16, T45N, R33W, Iron County, Michigan
53-S-6 Michigan	W½, Sec. 6, T45N, R29W, Marquette County, Michigan
53-S-10 Michigan	NESW, Sec. 19, T45N, R12W, Luce County, Michigan

[a]Plantation numbers are those assigned by the Kimberly-Clark Corporation. The first two digits refer to the year of planting, the letter indicates whether the trees where planted in the spring (S) or fall (F), and the final number indicates which of the plantations it was among those planted in a particular state for that year.

APPENDIX TABLE 3--Continued

Plantation[a] No.	Geographic Location
53-S-11 Michigan	NWNW, Sec. 12, T43N, R2E, Chippewa County, Michigan
53-F-5 Minnesota	SE¼, Sec. 9, T62N, R19W, St. Louis County, Minnesota
54-S-3 Michigan	W½NW¼, Sec. 32, T46N, R39W, Ontonagon County, Michigan
54-S-4 Minnesota	S½NE¼, Sec. 13, T56N, R11W, Lake County, Minnesota
54-S-10 Michigan	SENW and SWSE, Sec. 9, T42N, R24W, Marquette County, Michigan
54-F-8 Minnesota	W½NW¼, Sec. 28 and E½NE¼ and SWNE, Sec. 29, T56N, R11W, Lake County, Minnesota
54-F-19 Michigan	SESW, Sec. 16, T45N, R9W, Luce County, Michigan
54-F-20 Michigan	SESW, Sec. 22, T43N, R2E, Chippewa County, Michigan
54-F-21 Michigan	SWNE, Sec. 27, T43N, R2E, Chippewa County, Michigan
56-S-2 Michigan	W½, Sec. 16, T45N, R29W, Marquette County, Michigan

APPENDIX TABLE 4

SOIL TEXTURE, BULK DENSITY, AND GRAVEL CONTENT DATA AT STUDY SITES IN SPRUCE PLANTATIONS

Plantation No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
44-S-1 Michigan	0-3	73.0	23.5	3.5	SaLo	1.08	0.2
	3-6	73.0	23.0	4.0	SaLo	1.34	0.1
	6-12	74.5	21.5	4.0	LoSa	1.09	0.4
	12-24	77.0	21.0	2.0	LoSa	1.30	1.4
	24-36	76.5	20.0	3.5	LoSa	1.46	6.6
Tree[d] 1	36-48	98.0	0.5	1.5	Sand	1.72	3.1
	48-60	98.5	0.0	1.5	Sand	1.69	0.4
	60-72	98.0	0.0	2.0	Sand	1.65	0.2
	72-84	98.5	0.0	1.5	Sand	1.61	1.4
	84-96	97.5	0.5	2.0	Sand	1.70	0.8
	96-108	98.0	0.0	2.0	Sand	1.70	1.0
	0-3	73.0	22.0	5.0	SaLo	1.28	0.2
	3-6	80.0	17.0	3.0	LoSa	1.06	1.0
	6-12	77.5	19.5	3.0	LoSa	1.13	0.6
Tree 2	12-24	74.0	21.5	4.5	SaLo	1.41	0.2
	24-36	88.0	7.5	4.5	Sand	1.53	16.4
	36-48	98.0	0.0	2.0	Sand	1.65	2.1
	48-60	96.5	0.5	3.0	Sand	1.72	7.4
	60-72	97.0	1.0	2.0	Sand	1.65	4.8
45-S-1 Wisconsin	0-3	59.5	35.5	5.0	SaLo	0.69	2.9
	3-6	64.0	32.0	4.0	SaLo	1.08	12.9
	6-12	66.5	28.0	5.5	SaLo	1.26	13.5

[a] Percentages of sand, silt, and clay were determined by means of the Bouyoucos hydrometer method. The analyses were made only on the soil fraction which passed through a 2.0 mm sieve.

[b] Combinations of letters refer to the soil texture class and are based on the first two letters of each word, e.g., SaLo refers to sandy loam, and LoSa refers to loamy sand.

[c] Gravel percentage is determined on a weight basis and is based on the portion of the sample which would not pass through a 2.0 mm sieve.

[d] Two different soil pits were dug in this plantation and data for each are presented.

APPENDIX TABLE 4--Continued

Plantation No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
52-S-1 Michigan	0-3	39.5	32.0	28.5	ClLo	1.17	0.9
	3-6	28.0	29.0	43.0	Clay	1.27	1.4
	6-12	9.5	19.0	71.5	Clay	1.48	0.2
52-S-1 Minnesota	0-3	74.0	23.0	3.0	LoSa	1.07	6.3
	3-6	79.5	18.5	2.0	LoSa	1.02	6.4
	6-12	72.5	24.5	3.0	SaLo	1.44	23.2
	12-24	68.5	29.0	2.5	SaLo	1.61	12.4
	24-36	66.5	31.0	2.5	SaLo	1.81	14.9
52-S-2 Minnesota	0-3	73.5	19.0	7.5	SaLo	0.79	2.9
	3-6	72.0	22.0	6.0	SaLo	1.11	3.9
	6-12	68.5	24.5	7.0	SaLo	1.22	26.6
	12-24	74.5	20.5	5.0	SaLo	1.69	26.2
	24-36	73.0	21.0	6.0	SaLo	2.10	31.4
52-F-14 Michigan	0-3	94.0	3.5	2.5	Sand	1.61	0.0
	3-6	94.5	2.0	3.5	Sand	1.65	0.0
	6-12	92.5	2.5	5.0	Sand	1.58	0.2
Tree[d] 1	12-24	96.5	0.5	3.0	Sand	1.60	0.2
	24-36	97.5	0.0	2.5	Sand	1.64	0.7
	36-48	97.5	0.0	2.5	Sand	1.63	0.1
	48-60	96.5	1.0	2.5	Sand	1.76	0.0
	0-3	90.5	7.0	2.5	Sand	1.55	0.7
	3-6	92.0	5.0	3.0	Sand	1.52	0.0
Tree	6-12	93.5	3.0	3.5	Sand	1.46	0.1
2	12-24	96.0	1.5	2.5	Sand	1.53	0.8
	24-36	97.5	0.5	2.0	Sand	1.56	0.1
	36-48	97.5	0.5	2.0	Sand	1.67	0.1
52-F-16 Michigan	0-3	26.0	70.0	4.0	SiLo	1.24	0.1
	3-6	25.0	71.5	3.5	SiLo	1.26	0.0
	6-12	22.5	71.0	6.5	SiLo	1.25	0.0
	12-24	24.0	72.0	4.0	SiLo	1.43	0.1
	24-36	29.0	65.0	6.0	SiLo	1.54	0.0
	36-48	44.0	51.5	4.5	SiLo	1.66	0.0
52-F-18 Michigan	0-3	81.0	11.5	7.5	LoSa	1.51	4.7
	3-6	91.5	6.0	2.5	Sand	1.33	13.6
	6-12	88.0	9.5	2.5	Sand	1.79	51.3
	12-24	96.0	1.0	3.0	Sand	1.91	15.5
	24-36	97.0	1.0	2.0	Sand	1.82	1.9
	36-48	98.0	0.0	2.0	Sand	1.84	0.0

APPENDIX TABLE 4--Continued

Plantation No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
53-S-4	0-3	50.0	44.5	5.5	SaLo	1.30	0.1
Michigan	3-6	51.0	44.5	4.5	SaLo	1.31	0.1
	6-12	76.0	21.5	2.5	LoSa	1.43	0.1
	12-24	82.0	16.0	2.0	LoSa	1.62	0.0
53-S-5	0-3	59.0	36.5	4.5	SaLo	1.37	9.0
Michigan	3-6	56.5	38.5	5.0	SaLo	1.41	6.9
	6-12	55.0	41.5	3.5	SaLo	1.26	2.2
	12-24	39.5	52.0	8.5	SiLo	1.47	6.6
	24-36	66.0	27.0	7.0	SaLo	1.93	11.5
53-S-6	0-3	67.0	29.0	4.0	SaLo	1.16	1.7
Michigan	3-6	67.0	29.5	3.5	SaLo	1.16	2.0
	6-12	74.0	23.5	2.5	LoSa	1.26	1.9
Tree[d]	12-24	92.0	6.0	2.0	Sand	1.64	1.6
1	24-36	89.0	8.5	2.5	Sand	1.58	1.6
	0-3	42.0	50.0	8.0	SiLo	0.81	0.5
	3-6	30.0	63.0	7.0	SiLo	1.10	0.1
Trees	6-12	31.5	60.5	8.0	SiLo	1.23	0.1
2,3	12-24	15.5	67.5	17.0	SiLo	1.36	0.0
	24-36	38.5	54.5	7.0	SiLo	1.56	1.3
	36-48	97.0	0.5	2.5	Sand	1.71	2.6
53-S-10	0-3	19.0	73.5	7.5	SiLo	1.39	0.0
Michigan	3-6	26.5	67.5	6.0	SiLo	0.98	0.0
	6-12	29.0	65.0	6.0	SiLo	1.29	0.0
	12-24	42.5	25.5	32.0	ClLo	1.55	8.1
53-S-11	0-3	38.5	29.5	32.0	ClLo	1.41	0.1
Michigan	3-6	87.5	5.5	7.0	LoSa	1.70	0.2
	6-12	93.5	3.0	3.5	Sand	1.73	0.1
	12-24	74.0	12.5	13.5	SaLo	2.04	0.0
	24-36	8.0	53.0	39.0	SiClLo	1.71	0.0
53-F-5	0-3	21.0	34.0	45.0	Clay	1.22	0.0
Minnesota	3-6	8.5	26.5	65.0	Clay	1.36	0.0
	6-12	3.5	19.0	77.5	Clay	1.48	0.0
54-S-3	0-3	82.5	13.5	4.0	LoSa	1.32	0.0
Michigan	3-6	87.0	10.5	2.5	LoSa	1.30	2.0
	6-12	87.0	10.5	3.0	LoSa	1.57	6.3
	12-24	96.0	2.5	1.5	Sand	1.63	0.8
	24-36	98.0	0.5	1.5	Sand	1.79	0.3

APPENDIX TABLE 4--Continued

Plantation No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
54-S-4	0-3	47.5	46.0	6.5	SaLo	1.17	6.1
Minnesota	3-6	64.0	31.5	4.5	SaLo	1.22	17.3
	6-12	59.5	35.0	5.5	SaLo	1.49	14.9
	12-24	81.5	14.5	4.0	LoSa	2.43	48.7
54-S-10	0-3	54.5	39.0	6.5	SaLo	1.51	1.8
Michigan	3-6	55.5	35.0	9.5	SaLo	1.52	3.0
	6-12	59.5	30.0	10.5	SaLo	1.63	2.3
	12-24	46.0	30.5	23.5	Loam	1.75	1.5
54-F-8	0-3	81.5	16.0	2.5	LoSa	1.41	7.2
Minnesota	3-6	73.0	23.5	3.5	SaLo	1.44	6.0
	6-12	74.0	20.5	5.5	SaLo	1.68	16.2
	12-24	64.0	27.0	9.0	SaLo	1.80	9.2
54-F-19	0-3	88.5	8.5	3.0	Sand	1.35	0.1
Michigan	3-6	89.5	7.5	3.0	Sand	1.49	0.3
	6-12	90.0	7.0	3.0	Sand	1.38	0.9
	12-24	96.0	1.0	3.0	Sand	1.59	0.7
	24-36	97.0	0.5	2.5	Sand	1.64	0.4
	36-48	97.0	0.5	2.5	Sand	1.68	2.7
	48-60	96.5	0.5	3.0	Sand	1.70	0.6
54-F-20	0-3	83.5	14.5	2.0	LoSa	1.48	0.2
Michigan	3-6	88.0	10.0	2.0	Sand	1.20	0.6
	6-12	88.0	10.5	1.5	Sand	1.42	1.5
	12-24	84.5	14.0	1.5	LoSa	1.56	0.0
	24-36	71.0	25.5	3.5	SaLo	1.69	0.0
54-F-21	0-3	89.5	8.5	2.0	Sand	1.60	2.1
Michigan	3-6	89.0	7.0	4.0	Sand	1.52	0.9
	6-12	96.5	1.5	2.0	Sand	1.45	0.5
	12-24	97.5	1.0	1.5	Sand	1.77	0.1
	24-36	97.0	1.0	2.0	Sand	1.76	0.3
56-S-2	0-3	89.5	8.0	2.5	Sand	1.43	0.1
Michigan	3-6	89.5	8.0	2.5	Sand	1.40	0.2
	6-12	92.0	7.0	1.0	Sand	1.31	0.5
Tree	12-24	92.5	6.5	1.0	Sand	1.57	0.2
1	24-36	96.5	2.5	1.0	Sand	1.64	0.1

APPENDIX TABLE 4--Continued

Plantation No.	Soil Depth	Soil Texture Analysis[a]				Bulk Density	Gravel Content[c]
		Sand	Silt	Clay	Class[b]		
	(inches)	(percentages)				(g/cc)	(percentage)
56-S-2	0-3	83.0	13.5	3.5	LoSa	1.41	1.2
Michigan	3-6	83.0	12.5	4.5	LoSa	1.31	1.4
	6-12	85.5	9.0	5.5	LoSa	1.37	1.2
Tree	12-24	89.5	7.0	3.5	Sand	1.54	5.8
2	24-36	97.5	0.5	2.0	Sand	1.59	0.1

APPENDIX TABLE 5

DIAMETERS OF VERTICAL ROOTS FOUND ON BLACK SPRUCE TREES IN NATURAL STANDS

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-11	1	(10)0.40[b] (16)0.06	(6)0.36 (10)0.12			
	2	(6)1.13 (18)0.12 (19)0.06	(6)0.56 (11)0.12	(5)0.41 (11)0.06	(7)0.48 (11)0.06	
N-14	1	c	(13)2.32 (25)0.25 (26)0.06	(7)1.52 (18)0.12	(6)0.97 (18)0.12 (20)0.06	(8)0.44 (20)0.06
N-15	1	c	(3)0.87 (15)0.06 (27)0.06 (32)0.03	(3)0.24 (14)0.06	(3)0.22 (15)0.03	(3)0.14 (15)0.06 (27)0.06 (33)0.03
	2	(3)1.09 (15)0.20 (27)0.06 (33)0.03	(3)0.66 (15)0.25 (20)0.06	(3)0.34 (15)0.06 (17)0.03	(2)0.22 (14)0.12 (26)0.06 (39)0.03	(2)0.12 (14)0.06 (18)0.06
N-17	1	c	(10)0.98 (16)0.04	(7)0.64 (12)0.11		
N-18	1	(7)0.82 (11)0.16	(7)0.49 (13)0.07	(6)0.38 (12)0.05		
	2	c	(6)0.74 (12)0.10	(6)0.68 (10)0.14		

[a]Data correspond with the same trees and roots for which information is given in Table 3, Chapter III. The first entry for each root represents data taken at the point on the root where it became distinctly separated from the main root mass. Subsequent diameters were measured at 12-inch intervals below that point, and the final measurement was at the end of the root.

[b]Decimal figures are the averages of two diameters measured with calipers at the depths indicated in parentheses.

[c]No distinct main vertical root was found on this tree.

APPENDIX TABLE 5--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-19	1	(8)2.43 (15)1.84	(6)1.83 (11)0.30	(6)1.02 (9)0.25		
N-21	1	(1)0.06 (3)0.03	(1)0.06 (2)0.03	(1)0.06 (2)0.03		
	2	(2)0.06 (5)0.03	(1)0.06 (4)0.03			
	3	(1)0.06 (2)0.03				
	4	(1)0.06 (2)0.03	(1)0.06 (2)0.03			
N-28	1	(5)1.74 (13)0.35	(6)0.94 (12)0.13	(6)0.75 (14)0.08		
	2	(5)1.04 (12)0.23	(6)1.17 (11)0.33	(6)1.00 (15)0.10		
	3	c	(7)1.01 (10)0.25	(6)0.89 (11)0.15		
	4	(6)1.22 (9)0.49	(7)0.80 (11)0.27			
N-22	1	c	(6)0.95 (9)0.38	(7)0.75 (10)0.30	(5)0.90 (11)0.22	
N-2	1	(7)1.05 (13)0.15	(6)0.82 (18)0.20	(5)1.10 (16)0.10	(6)0.75 (18)0.11	(6)0.70 (14)0.14
	2	c	(6)1.02 (10)0.21			
	3	(8)0.90 (14)0.13	(7)0.78 (12)0.13			
	4	c	(9)1.14 (14)0.19	(7)0.70 (11)0.14		

APPENDIX TABLE 5--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-9	1	(16)0.83 (28)0.06	(11)2.33 (23)0.52 (33)0.06	(17)0.99 (27)0.12	(8)0.89 (20)0.06 (24)0.06	(15)0.86 (27)0.35 (39)0.25 (40)0.12
	2	(15)2.61 (27)0.36 (30)0.06	(15)3.74 (27)1.52 (39)0.95 (44)0.50	(14)1.69 (26)0.06		
N-16	1	(9)1.59 (18)0.12	(7)1.49 (19)0.06	(6)1.40 (16)0.06	(8)0.96 (20)0.03	(6)0.48 (19)0.03
N-3	1	c	(14)1.03 (24)0.06	(11)0.85 (19)0.12	(12)0.48 (16)0.06	
	2	(8)0.74 (14)0.06	(8)1.08 (20)0.62 (23)0.25	(9)0.40 (16)0.06		
N-12	1	c	(8)0.93 (13)0.06	(9)0.90 (21)0.12 (24)0.06	(4)0.35 (14)0.06	(9)0.34 (14)0.06
	2	(10)1.16 (13)0.03	(11)1.04 (13)0.03			
N-26	1	c	(9)1.94 (12)0.78	(10)0.82 (13)0.33		
	2	c	(11)1.99 (16)0.57	(10)2.04 (18)0.56		
	3	c	(12)1.86 (18)0.46	(11)1.43 (16)0.54		
N-25	1	c	(I1)1.10 (18)0.40	(9)0.87 (16)0.32		
	2	c	(8)0.90 (10)0.45	(8)1.04 (11)0.42		
	3	c	(9)1.25 (11)0.62	(8)0.87 (12)0.29		

APPENDIX TABLE 5--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]		
		Main Vertical Root	Other Vertical Roots	
		(inches below ground and root diameter in inches)		
N-27	1	(11)1.03 (23)0.55 (26)0.22	(10)1.14 (22)0.16	(11)0.87 (23)0.30 (25)0.18
	2	c	(13)1.98 (25)0.90 (37)0.43 (44)0.13	(11)1.02 (22)0.27
N-24	1	(10)2.04 (22)1.30 (24)0.65	(10)1.01 (15)0.69	(9)0.90 (16)0.20
	2	c	(7)1.03 (12)0.29	(6)0.75 (13)0.09
N-23	1	c	(11)1.90 (23)1.10 (29)0.16	

APPENDIX TABLE 6

DIAMETERS OF VERTICAL ROOTS FOUND ON BLACK SPRUCE TREES IN PLANTATIONS

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
54-F-19 Mich.	1	b	(3)0.30[c] (15)0.03			
54-F-20 Mich.	1	(3)0.50 (6)0.12	(3)0.38 (6)0.06	(3)0.24 (5)0.06		
54-F-21 Mich.	1	b	(6)0.61 (8)0.38	(6)0.48 (8)0.25	(6)0.29 (8)0.25	(5)0.34 (8)0.25
56-S-2 Mich.	1	(3)0.23 (15)0.06 (16)0.03	(2)0.10 (11)0 03			
54-S-3 Mich.	1	(2)0.76 (9)0.12	(5)0.06 (15)0.03			
	2	(4)0.33 (6)0.20	(4)0.22 (7)0.03	(2)0.27 (15)0.03		
56-S-2 Mich.	1	(2)0.61 (5)0.06	(2)0.33 (5)0.06			
52-S-1 Minn.	1	(3)0.28 (7)0.18	(4)0.08 (14)0.03	(5)0.05 (14)0.02	(3)0.20 (11)0.03	(3)0.10 (11)0.02
54-F-8 Minn.	1	b	(2)0.11 (5)0.02			
45-S-1 Wis.	1	b	(6)0.51 (11)0.06	(5)0.24 (10)0.03		

[a]Data correspond with the same trees and roots for which information is given in Table 5, Chapter III. The first entry for each root represents data taken at the point on the root where it became distinctly separated from the main root mass. Subsequent data are from 12-inch intervals below that point, and the last measurement is from the root terminus.

[b]No distinct main vertical root was found on this tree.

[c]Decimal figures are the averages of two diameters measured with calipers at the depths indicated in parentheses.

APPENDIX TABLE 6--Continued

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
52-S-2 Minn.	1	(6)0.38[c]	(4)0.25		
		(14)0.06	(8)0.06		
53-S-5 Mich.	1	(3)0.62	(3)0.51	(3)0.13	
		(7)0.43	(6)0.39	(6)0.06	
	2	(2)0.31	(2)0.20	(2)0.23	(2)0.17
		(8)0.06	(7)0.06	(7)0.03	(8)0.06
54-S-10 Mich.	1	(2)0.29	(2)0.17	(2)0.08	(2)0.07
		(8)0.02	(13)0.03	(13)0.03	(6)0.03

APPENDIX TABLE 7

DIAMETERS OF VERTICAL ROOTS FOUND ON WHITE SPRUCE TREES IN NATURAL STANDS

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-19	1	(14)2.12[b] (18)1.55	(13)1.94 (25)1.26 (37)1.07 (49)0.84 (61)0.42 (72)0.06	(14)1.44 (26)1.01 (38)0.72 (50)0.22 (60)0.06		
N-21	1	(1)0.06 (6)0.02				
	2	(1)0.06 (4)0.02				
	3	(1)0.06 (3)0.02	(1)0.06 (2)0.02			
N-1	1	(19)2.18 (31)0.28 (35)0.06	(18)0.66 (30)0.22 (38)0.06			
	2	(11)2.31 (20)0.77	(12)1.33 (24)0.70 (32)0.50	(12)2.04 (22)0.90		
	3	(6)0.57 (15)0.25	(4)0.41 (16)0.06 (19)0.03	(4)0.37 (16)0.06 (22)0.03		
	4	(13)1.53 (25)0.27 (30)0.06	(14)1.02 (26)0.20 (32)0.06	(8)1.29 (20)0.32 (28)0.03	(9)0.91 (21)0.15 (24)0.06	(6)0.67 (18)0.13 (21)0.06

[a]Data correspond with the same trees and roots for which information is given in Table 8, Chapter IV. The first entry for each root represents data taken at the point on the root where it became distinctly separated from the main root mass. Subsequent data are from 12-inch intervals below that point, and the last measurement is from the root terminus.

[b]Decimal figures are the averages of two diameters measured with calipers at the depths indicated in parentheses.

APPENDIX TABLE 7--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-20	1	(13)1.44[b]	(14)1.07	(11)1.12		
		(25)0.74	(26)0.47	(19)0.31		
		(27)0.44	(38)0.07			
	2	(14)1.72	(13)1.90	(11)0.97		
		(26)0.89	(25)0.48	(20)0.10		
		(30)0.30	(34)0.05			
	3	(9)1.02	(8)0.88			
		(16)0.49	(18)0.20			
		(19)0.24				
N-2	1	(5)0.42	(8)1.04			
		(7)0.25	(19)0.22			
N-4	1	(9)1.17	(10)1.27			
		(18)0.21	(20)0.29			
	2	(4)0.77	(12)1.94	(11)1.08	(10)1.87	
		(7)0.38	(24)0.76	(23)0.68	(22)0.44	
			(31)0.17	(27)0.14	(24)0.15	
N-6	1	(18)1.98	(17)1.84	(17)1.56	(19)1.99	(14)1.06
		(30)0.49	(29)0.99	(29)1.00	(31)0.78	(26)0.43
			(33)0.42	(32)0.25	(35)0.26	(33)0.10
N-7	1	(15)1.09	(16)1.98			
		(27)0.45	(28)1.01			
		(28)0.30	(31)0.40			
N-8	1	(12)2.94	(11)2.69	(13)2.45	(22)1.21	(12)1.18
		(24)0.94	(23)1.73	(25)1.12	(32)0.12	(24)0.25
		(29)0.16	(35)0.25	(35)0.12		(27)0.12
	2	(12)2.57	(11)0.37			
		(24)0.81	(23)0.06			
		(35)0.12	(35)0.06			
N-10	1	(9)2.08	(7)2.18	(8)1.35	(11)0.80	(9)0.61
		(21)0.98	(19)1.49	(20)0.51	(21)0.06	(21)0.25
		(33)0.57	(31)0.25	(27)0.12		(27)0.12
		(34)0.12				

APPENDIX TABLE 7--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
N-25	1	(15)2.94[b]	(13)1.97	(11)1.56	
		(27)2.08	(25)0.88	(23)0.77	
		(39)1.44	(32)0.26	(27)0.33	
		(51)0.43			
		(58)0.18			
	2	(18)2.45	(17)2.01	(13)1.87	
		(30)1.87	(29)1.65	(25)1.12	
		(42)1.12	(41)1.19	(37)0.46	
		(54)0.68	(53)0.34	(48)0.12	
		(56)0.51	(62)0.14		
	3	(16)2.15	(15)1.86	(18)2.18	(13)1.73
		(28)1.87	(27)1.03	(30)1.57	(25)1.05
		(40)0.56	(39)0.57	(42)1.04	(37)0.44
		(44)0.34	(40)0.50	(53)0.22	(39)0.29
	4	(16)2.87	(13)1.97	(16)1.84	(14)1.65
		(28)2.03	(25)1.09	(28)1.03	(26)0.95
		(40)1.23	(37)0.56	(40)0.33	(38)0.25
		(52)0.45	(49)0.14	(46)0.08	(45)0.09
		(60)0.17			
	5	(16)2.87	(14)1.99	(13)1.74	
		(28)2.01	(26)1.23	(25)1.02	
		(40)1.67	(38)0.57	(37)0.58	
		(52)0.88	(50)0.22	(48)0.58	
		(61)0.35	(54)0.12		
N-27	1	(14)1.86	(16)1.99	(15)1.87	
		(26)1.04	(28)1.14	(27)0.86	
		(38)0.55	(40)0.44	(39)0.23	
		(42)0.31	(51)0.09	(49)0.04	
	2	(13)2.83	(14)1.76	(15)1.82	
		(25)2.04	(26)0.85	(27)1.10	
		(37)1.35	(38)0.44	(39)0.58	
		(49)0.65	(48)0.10	(51)0.21	
		(61)0.37		(53)0.15	
		(65)0.21			

APPENDIX TABLE 7--Continued

Site No.	Tree No.	Average Root Daimeters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
N-24	1	(9)1.18[b]	(9)1.28	(8)1.04	
		(21)0.61	(21)0.44	(20)0.35	
		(27)0.20	(29)0.12	(27)0.08	
	2	(10)1.13	(13)1.65	(11)1.22	
		(22)0.49	(25)1.00	(23)0.57	
		(28)0.20	(37)0.42	(33)0.09	
			(39)0.28		
	3	(11)1.33	(10)1.01		
		(23)0.49	(22)0.23		
		(28)0.14	(24)0.14		
	4	(15)1.87	(13)1.87	(11)1.65	
		(27)1.01	(25)0.84	(23)0.83	
		(39)0.55	(37)0.52	(35)0.17	
		(41)0.41	(45)0.17	(42)0.04	
	5	(12)1.54	(16)2.04	(14)1.85	(14)1.97
		(24)0.97	(28)1.23	(26)1.03	(26)1.44
		(36)0.22	(40)0.58	(38)0.59	(38)0.58
		(37)0.16	(50)0.26	(50)0.20	(48)0.13
	6	(11)1.75	(15)1.95		
		(23)0.73	(27)1.04		
		(35)0.44	(39)0.43		
		(39)0.15	(49)0.12		

APPENDIX TABLE 8

DIAMETERS OF VERTICAL ROOTS FOUND ON WHITE SPRUCE TREES IN PLANTATIONS

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
52-F-14 Mich.	1	(6)0.65[b]	(5)0.39	(5)0.29	(5)0.56
		(18)0.39	(17)0.12	(17)0.03	(17)0.12
		(30)0.12	(29)0.06	(29)0.03	
		(42)0.12	(41)0.03	(37)0.02	
		(54)0.06	(45)0.02		
		(59)0.03			
	2	(5)0.44	(2)0.35	(4)0.32	(5)0.46
		(17)0.03	(14)0.12	(16)0.06	(16)0.06
		(21)0.02	(26)0.06	(28)0.03	
			(30)0.03	(36)0.02	
54-F-19 Mich.	1	(4)0.61	(6)0.18	(5)0.28	(7)0.20
		(10)0.25	(18)0.03	(17)0.12	(19)0.06
			(30)0.03	(29)0.06	(31)0.06
			(42)0.03	(41)0.03	(37)0.03
			(54)0.03	(50)0.02	
			(60)0.02		
54-F-20 Mich.	1	(3)0.50	(3)0.41	(4)0.10	
		(6)0.25	(14)0.03	(14)0.03	
54-F-21 Mich.	1	(2)1.26	(7)0.10		
		(14)0.26	(19)0.06		
		(26)0.19	(28)0.06		
		(34)0.06			
52-F-18 Mich.	1	(3)0.87	(4)0.15	(4)0.48	
		(11)0.25	(16)0.03	(8)0.06	
			(29)0.03		

[a]Data correspond with the same trees and roots for which information is given in Table 12, Chapter IV. The first entry for each root represents data taken at the point on the root where it became distinctly separated from the main root mass. Subsequent data are from 12-inch intervals below that point, and the last measurement is from the root terminus.

[b]Decimal figures are the averages of two diameters measured with calipers at the depths indicated in parentheses.

APPENDIX TABLE 8--Continued

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
54-S-3 Mich.	1	(5)0.62[b] (11)0.06	(5)0.25 (15)0.03	(5)0.22 (13)0.03	
	2	(3)0.11 (15)0.06 (22)0.03	(2)0.18 (14)0.06 (22)0.03	(4)0.06 (16)0.03 (19)0.03	(2)0.19 (14)0.06 (17)0.03
44-S-1 Mich.	1	(9)2.40 (21)0.65 (33)0.13 (45)0.06 (57)0.03 (65)0.02	(8)0.69 (19)0.25	(8)0.39 (20)0.12 (23)0.03	(7)0.35 (15)0.06
54-F-8 Minn.	1	(3)0.25 (10)0.06	(3)0.21 (7)0.02	(2)0.19 (11)0.02	
	2	(2)0.12 (5)0.03			
44-S-1 Mich.	1	(10)2.84 (22)2.03 (34)1.12 (46)0.43 (58)0.22 (70)0.14 (82)0.08 (94)0.06 (105)0.02	(10)1.13 (22)0.84 (34)0.48 (46)0.32 (58)0.13 (70)0.06 (82)0.03 (94)0.03 (96)0.02	(11)1.11 (23)0.39 (35)0.30 (47)0.17 (59)0.06 (70)0.03	
53-S-4 Mich.	1	(4)0.38 (9)0.16	(3)0.16 (8)0.06	(3)0.22 (8)0.10	(4)0.18 (8)0.03
	2	(5)0.24 (9)0.06	(5)0.29 (11)0.03		
	3	(2)0.69 (5)0.25	(2)0.32 (5)0.12		
53-S-6 Mich.	1	(2)1.02 (11)0.06	(4)0.39 (16)0.03 (18)0.02	(6)0.13 (13)0.03	

APPENDIX TABLE 8--Continued

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]			
		Main Vertical Root	Other Vertical Roots		
		(inches below ground and root diameter in inches)			
53-S-11 Mich.	1	(4)0.44[b] (8)0.25	(3)0.35 (9)0.06	(3)0.27 (10)0.03	
54-S-4 Minn.	1	(3)0.28 (15)0.06 (18)0.03	(3)0.17 (8)0.03		
52-S-2 Minn.	1	(3)0.33 (14)0.03	(3)0.21 (14)0.02	(5)0.11 (14)0.03	(2)0.34 (9)0.02
53-S-5 Mich.	1	(1)0.65 (9)0.03			
	2	(3)0.72 (15)0.06 (24)0.03	(5)0.17 (15)0.03	(3)0.28 (13)0.06	(3)0.59 (6)0.25
53-S-10 Mich.	1	(3)0.39 (6)0.16	(3)0.12 (7)0.03	(3)0.44 (5)0.25	
52-F-16 Mich.	1	(4)0.15 (16)0.03 (28)0.03 (32)0.02	(4)0.14 (16)0.03 (26)0.02	(4)0.17 (16)0.03 (23)0.02	(3)0.15 (15)0.03 (21)0.02
53-S-6 Mich.	1	(2)0.80 (10)0.25	(2)0.20 (14)0.06	(3)0.30 (10)0.06	
	2	(2)1.51 (14)0.24 (26)0.15 (37)0.06	(8)0.32 (20)0.17 (32)0.06 (44)0.03 (49)0.02	(2)0.33 (14)0.12 (21)0.06	
52-S-1 Mich.	1	(1)1.26 (9)0.03	(1)0.15 (5)0.06		
	2	(1)0.82 (7)0.06	(2)0.20 (8)0.03		
	3	(2)0.51 (8)0.06	(1)0.45 (6)0.06		

APPENDIX TABLE 8--Continued

Plantation No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]		
		Main Vertical Root	Other Vertical Roots	
		(inches below ground and root diameter in inches)		
52-S-1 Mich.	4	(2)0.61 (10)0.06	(3)0.32 (8)0.03	
53-F-5 Minn.	1	(5)0.41 (14)0.03	(3)0.38 (14)0.03	
	2	(3)0.36 (14)0.02	(3)0.49 (11)0.06	(2)0.31 (5)0.12

APPENDIX TABLE 9

DIAMETERS OF VERTICAL ROOTS FOUND ON BALSAM FIR TREES IN NATURAL STANDS

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-13	1	(13)3.04[b] (25)1.00 (37)0.12 (40)0.12	(10)2.35 (22)0.33 (34)0.20 (41)0.12	(14)1.91 (26)0.47 (38)0.24 (43)0.12	(10)1.28 (22)0.80 (34)0.32 (46)0.12	(7)1.18 (19)0.52 (31)0.06 (35)0.06
	2	(9)2.59 (21)0.53 (29)0.38	(9)2.78 (21)1.85 (33)1.48 (45)0.60 (57)0.45 (69)0.30 (81)0.12 (93)0.06	(11)1.67 (23)0.86 (31)0.63	(12)1.35 (24)0.58 (36)0.47 (48)0.38 (51)0.38	(9)1.23 (21)0.53 (33)0.12 (34)0.12
N-17	1	(10)1.94 (22)0.39	(8)1.42 (20)0.28	(9)1.21 (21)0.44 (25)0.15		
	2	(11)2.12 (23)1.59 (31)0.53	(9)1.74 (21)0.61 (30)0.15	(10)1.27 (22)0.42 (24)0.25		
N-18	1	(7)1.92 (19)0.27 (22)0.11	(6)1.01 (18)0.25			

[a]Data correspond with the same trees and roots for which information is given in Table 17, Chapter V. The first entry for each root represents data taken at the point on the root where it became distinctly separated from the main root mass. Subsequent data are from 12-inch intervals below that point, and the last measurement is from the root terminus.

[b]Decimal figures are the averages of two diameters measured with calipers at the depths indicated in parentheses.

APPENDIX TABLE 9--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-19	1	(14)2.17[b] (26)1.83 (38)1.42 (50)1.01 (62)0.74 (74)0.53 (86)0.21 (98)0.11 (110)0.06 (116)0.02	(15)1.90 (27)1.40 (39)1.02 (51)0.46 (63)0.21 (75)0.16 (87)0.08 (99)0.06 (106)0.02	(13)1.74 (25)1.03 (37)0.70 (49)0.22 (61)0.16 (73)0.10 (85)0.06 (89)0.03	(15)1.60 (27)0.71 (39)0.63 (51)0.41 (63)0.16 (75)0.12 (87)0.06 (94)0.02	(14)1.72 (26)1.00 (38)0.55 (50)0.31 (62)0.16 (74)0.08 (84)0.02
	2	(8)2.07 (20)0.72 (30)0.17	(7)0.84 (19)0.17	(8)1.01 (20)0.40 (24)0.13		
N-21	1	(1)0.06 (4)0.02				
	2	(1)0.06 (4)0.02				
	3	(11)1.14 (16)0.33	(10)0.82 (22)0.31 (25)0.15	(11)0.74 (18)0.22	(11)0.91 (23)0.22 (26)0.05	(10)0.68 (13)0.27
N-1	1	(3)1.56 (9)0.52	(2)1.00 (5)0.70	(4)0.75 (16)0.25 (21)0.09		
	2	(7)1.96 (19)0.29 (22)0.02	(6)1.06 (18)0.12 (21)0.02	(7)0.89 (19)0.03	(9)0.74 (21)0.12 (22)0.03	(7)0.49 (19)0.12 (21)0.06
	3	(6)0.91 (18)0.03	(5)0.42 (16)0.12	(5)0.38 (15)0.06	(4)0.38 (16)0.06 (22)0.03	(5)0.35 (16)0.06
	4	(8)2.53 (19)1.18	(9)0.93 (21)0.61 (33)0.47 (45)0.16 (48)0.10	(10)0.76 (22)0.63 (31)0.25	(9)0.62 (21)0.25 (33)0.13 (44)0.06	(10)0.52 (22)0.23 (34)0.06 (38)0.02

APPENDIX TABLE 9--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-1	5	(7)1.14[b] (16)0.11	(10)1.04 (22)0.38 (26)0.13	(8)0.91 (18)0.26		
N-20	1	(8)1.47 (19)0.30	(10)0.84 (22)0.06			
	2	(11)1.93 (23)0.47 (24)0.35	(9)0.82 (21)0.22 (24)0.05	(11)1.02 (23)0.41 (26)0.10		
N-22	1	(7)2.37 (19)1.04 (23)0.35	(8)1.00 (20)0.27 (24)0.12			
N-2	1	(10)1.42 (16)0.35	(9)0.87 (21)0.07	(8)0.70 (20)0.10		
N-4	1	(12)2.04 (24)1.01 (30)0.25	(13)1.97 (25)0.73 (33)0.08	(12)1.70 (24)0.22 (35)0.05		
	2	(13)1.74 (25)0.87 (29)0.37	(11)1.04 (23)0.42 (32)0.04	(10)0.70 (22)0.40 (30)0.04		
N-5	1	(10)2.65 (22)0.25 (30)0.06	(10)3.37 (22)0.96 (29)0.25	(14)1.83 (26)0.42 (30)0.06	(13)3.13 (25)0.71 (30)0.06	(15)1.30 (27)0.12 (30)0.06
N-7	1	(14)2.07 (26)0.74 (34)0.08	(15)2.94 (27)1.01 (35)0.28	(12)1.07 (24)0.46 (29)0.08		
N-8	1	(16)2.47 (28)1.01 (40)0.66 (43)0.48	(15)2.13 (27)0.22 (39)0.12 (51)0.06	(13)1.90 (25)0.83 (37)0.57 (48)0.12	(11)1.76 (23)1.45 (35)0.54 (41)0.12	(15)1.75 (27)0.67 (39)0.25 (48)0.06
	2	(10)2.33 (21)1.20	(13)2.34 (25)0.87 (36)0.54	(10)1.07 (22)0.40 (31)0.02	(9)0.98 (21)0.42 (26)0.12	(7)0.67 (19)0.27 (26)0.12

APPENDIX TABLE 9--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-10	1	(4)1.54[b]	(4)1.53	(3)0.89		
		(16)0.49	(16)0.71	(15)0.25		
		(28)0.06	(28)0.25	(24)0.12		
		(29)0.03	(36)0.03			
N-3	1	(14)0.35	(4)0.82	(17)0.40	(6)0.28	(5)0.24
		(26)0.13	(16)0.24	(29)0.25	(18)0.05	(17)0.17
		(37)0.06	(24)0.12	(37)0.18	(26)0.02	(27)0.06
	2	(10)1.29	(11)0.70	(9)0.71	(9)0.62	(7)0.23
		(22)0.49	(19)0.18	(21)0.29	(21)0.27	(19)0.12
				(29)0.12	(25)0.25	(21)0.10
	3	(19)3.65	(16)2.82	(12)2.35	(20)2.16	(16)2.01
		(31)0.92	(28)1.84	(24)1.54	(32)1.21	(28)1.16
		(32)0.06	(40)0.66	(36)0.77	(44)0.68	(35)0.12
			(48)0.25	(48)0.50	(50)0.38	
				(49)0.45		
N-25	1	(12)1.94	(16)2.07	(14)1.04	(10)1.47	
		(24)0.88	(28)0.72	(26)0.46	(22)0.55	
		(29)0.39	(31)0.36	(31)0.08	(28)0.18	
	2	(15)2.74	(11)1.92	(10)1.04		
		(27)1.01	(23)0.84	(22)0.71		
		(36)0.25	(35)0.31	(27)0.20		
			(40)0.09			
	3	(11)1.97	(10)1.48	(11)1.62	(10)1.04	
		(23)0.81	(22)0.72	(20)0.58	(18)0.21	
		(24)0.61	(24)0.24			
	4	(11)2.46	(10)1.81			
		(23)0.90	(19)0.33			
		(26)0.22				
	5	(14)2.07	(12)1.91	(13)1.46		
		(26)0.90	(26)0.47	(25)0.52		
		(32)0.22	(34)0.13	(30)0.09		

APPENDIX TABLE 9--Continued

Site No.	Tree No.	Average Root Diameters at Particular Soil Depths[a]				
		Main Vertical Root	Other Vertical Roots			
		(inches below ground and root diameter in inches)				
N-27	1	(18)2.97[b]	(17)2.46	(20)1.81	(16)1.67	(18)1.94
		(30)1.04	(29)1.22	(32)0.72	(28)0.91	(30)0.46
		(38)0.21	(32)0.30	(36)0.31	(31)0.45	(33)0.18
N-24	1	(16)1.98	(14)1.63	(17)1.90	(15)1.27	
		(28)0.82	(26)1.01	(29)0.92	(27)0.68	
		(40)0.37	(38)0.38	(41)0.28	(38)0.15	
		(52)0.07	(42)0.19	(50)0.03		

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