FORESTRY COMMISSION
BULLETIN No. 40

Rooting and Stability in Sitka Spruce

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LONDON: HER MAJESTY'S STATIONERY OFFICE
PRICE 8s. 6d. NET

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INTRODUCTION

Sitka spruce, *Picea sitchensis* (Bong.) Carr. is now the species of tree most extensively planted by the Forestry Commission in Great Britain, occupying in 1963 416,000 acres out of a total of 1,752,000 acres. One fifth of this has now reached the thinning stage. Private owners also plant it widely.

Some of the older plantations are being severely damaged by storms, and the prospects are that the problem will become greater as more plantations reach a susceptible size. The type of damage which most commonly occurs is uprooting, often of large numbers of trees, but occasionally large-scale stem-breakage can occur. The two types of damage are illustrated in Plates 2 and 3.

Day (1949, 1963 and elsewhere) drew attention to the effects of various forms of soil impedance on the root systems, health and stability of crops. The present investigations confirm his observations and provide new quantitative evidence on the effects of soil impedance and new factors on the stability of trees.

Investigations of the various factors rendering crops susceptible to wind-throw were initiated in 1960. A technique for pulling trees over was developed (Fraser 1962) which enabled studies to be made of the root systems, and of tree mechanics. Sites were selected around Britain on a range of soil types. A number of old silvicultural experiments were also used, in order to study as many of the factors as possible which might influence root development. These studies are incomplete, especially in that comparisons have not been made with other species of tree, but a considerable amount of useful results have been accumulated. Certain distinct patterns have become apparent which it is hoped will be helpful in making silvicultural and managerial decisions.

Chapter 1

TECHNIQUES USED IN THE STUDY

The primary object of these investigations has been to compare the tree's ability to withstand wind forces when grown under various conditions. The only part of the root system measured is the portion which comes out of the ground when the tree is pulled over. The very fine root tips, and long rope-like surface roots which break off during winching, were not weighed or measured. The function of these roots is considered to be primarily feeding.

A sample of at least eight trees was selected at random (excluding "whips" and "wolves") for each soil type or silvicultural treatment examined. The tree-pulling technique was developed so that an almost horizontal force would be applied to the test tree, at one-third of its height from the ground. This is achieved by attaching snatch blocks to a second tree, in the direction that it is desired to pull, and guying this tree to prevent it bending towards the sample tree. The wire rope used is passed over an upper snatch block, then down the tree to a lower one, from which it goes to a hand-operated winch, which is anchored, through a dynamometer. The two snatch blocks are supported by an adjustable spacer. The initial pull is slightly downward, to allow for the reduction in the height of the attachment point, as it moves round in an arc when the stem bends and the roots pivot. The technique is illustrated in Figure 1 and Plate 20.

A system was devised enabling the angle through which the tree has been deflected from its original position to be measured on the winch rope. The length of rope for 1° of deflection varies according to the height at which the pulling rope is attached to the tree. The appropriate length is marked on the rope with white paint, so that the force being applied can be noted as each mark reaches the winch. (See Fig. 1.)

Trees which would have obstructed the fall are normally cut before pulling the test tree, so that no more than light brushing of the crown occurs. The direction of the pull is varied according to the subject being studied, but it is normally away from the prevailing wind, i.e. towards the north-east.

Once the tree has been pulled over, the following measurements are made, as illustrated in Fig. 2:—

Stem

1. The total length (tree height) from ground level to tip.
2. The length (height) from ground level to the point where the stem reaches a diameter of 3 inches.
3. The girth at breast height, i.e. 4 ft. 3 ins. above ground level.
4. The girth 4 ft. 3 ins. below breast height, i.e. stump girth, at ground level.
5. The *weight* of that part of the stem that is *larger than* 3 inches in diameter.
6. Occasionally, discs were removed from the stem for specific gravity determination, but this line of investigation is not dealt with further herein.

Crown

7. The depth of live crown, measured as the length from the tip to the lowest live whorl of branches.
8. Two measurements of the maximum crown diameter, taken at right angles to each other, and averaged.
9. The *weight* of the live branches, and that part of the stem that was *less than* 3 inches in diameter.
10. The weight of the *dead* branches.

Roots

11. Two measurements of the width of the root-system, taken at right angles to each other, to give a mean value for maximum root diameter.
12. The width of the ball of soil or peat adhering to the roots, called the 'root ball diameter'.
13. The maximum depth of the root system. (This is the measurement used in the tables).
14. The depth of the ball of soil material adhering to the roots, called the 'depth of root ball'.
15. The *weight* of the root system after all soil material was cleaned off.
16. The root system is also photographed in plan, and also in elevation while suspended for weighing. The plates illustrate many examples.

The relationship between 'crown diameter' and 'root diameter' was found to vary on different soil types. This is illustrated in Figure 4.

In addition to these studies, observations have been made of the root systems of trees which have been blown over. However, since it is usually the trees with the poorest root systems which are uprooted by the wind, such observations are of limited value in determining rooting habits. Examination of the roots and soils in undamaged stands around windblown areas has often been more informative.

The turning moment at the base of each sample tree is calculated, for each degree of deflection from its original position, from the pull applied, the height of attachment of the pulling rope, and the tree's weight. This turning moment rises to a maximum, and then decreases, as the tree is pulled over. The maximum value is recorded as the tree's *maximum resistance*. (see Figure 3).

It was found that the stem weight of all trees was highly correlated to all the other dimensions of tree size measured, such as height, girth and crown weight. It has therefore been used as an indication of tree size.

Analysis of the relationship between the dimensions of the different components have frequently shown high correlation. These correlations vary with soil type, site condition and thinning treatment. One cannot draw definite conclusions at this stage as there are still insufficient data available.

The value of a tree's maximum resistance is dependent on its size, and on the soil type in which it is growing. Regressions of maximum resistance on stem weight for each sample of trees show variation in slope according to soil type, and rooting characteristics (see Figure 5). Comparison of the slopes of these regressions is useful in the study of susceptibility to windthrow, and is referred to later. (Chapter 6).

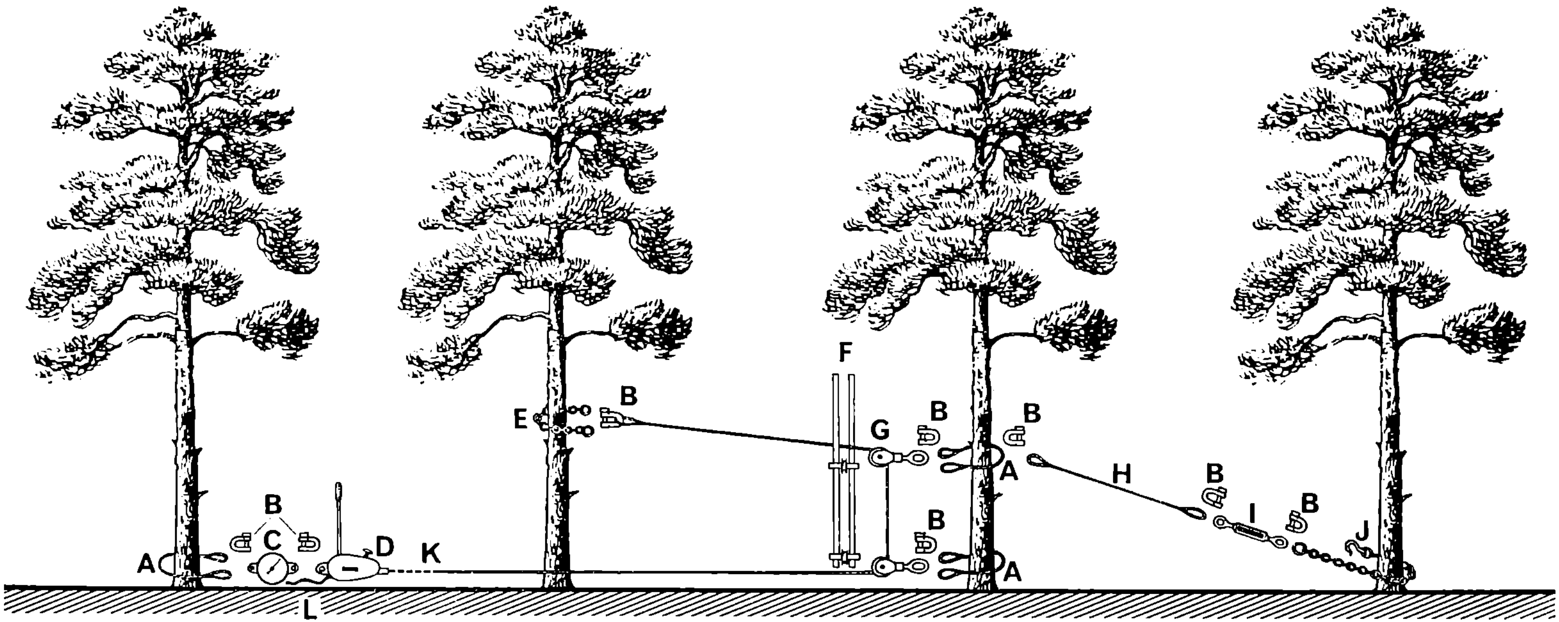

Figure 1. Tree Pulling Technique: Layout of Equipment.

A —Wire rope slings

B —Screw D shackles

C —Dynamometer

D —Tirfor hand winch

E —Chain sling with reevable egg links

F —Adjustable pulley block spacer, fabricated from alloy scaffold poles and coupler clips

G —Single sheave swivel snatch-blocks

H —Backstay wire rope

I —Rigging screw

J —Chain sling with shortener hook

K —White paint marks on rope

L —Free end of wire rope

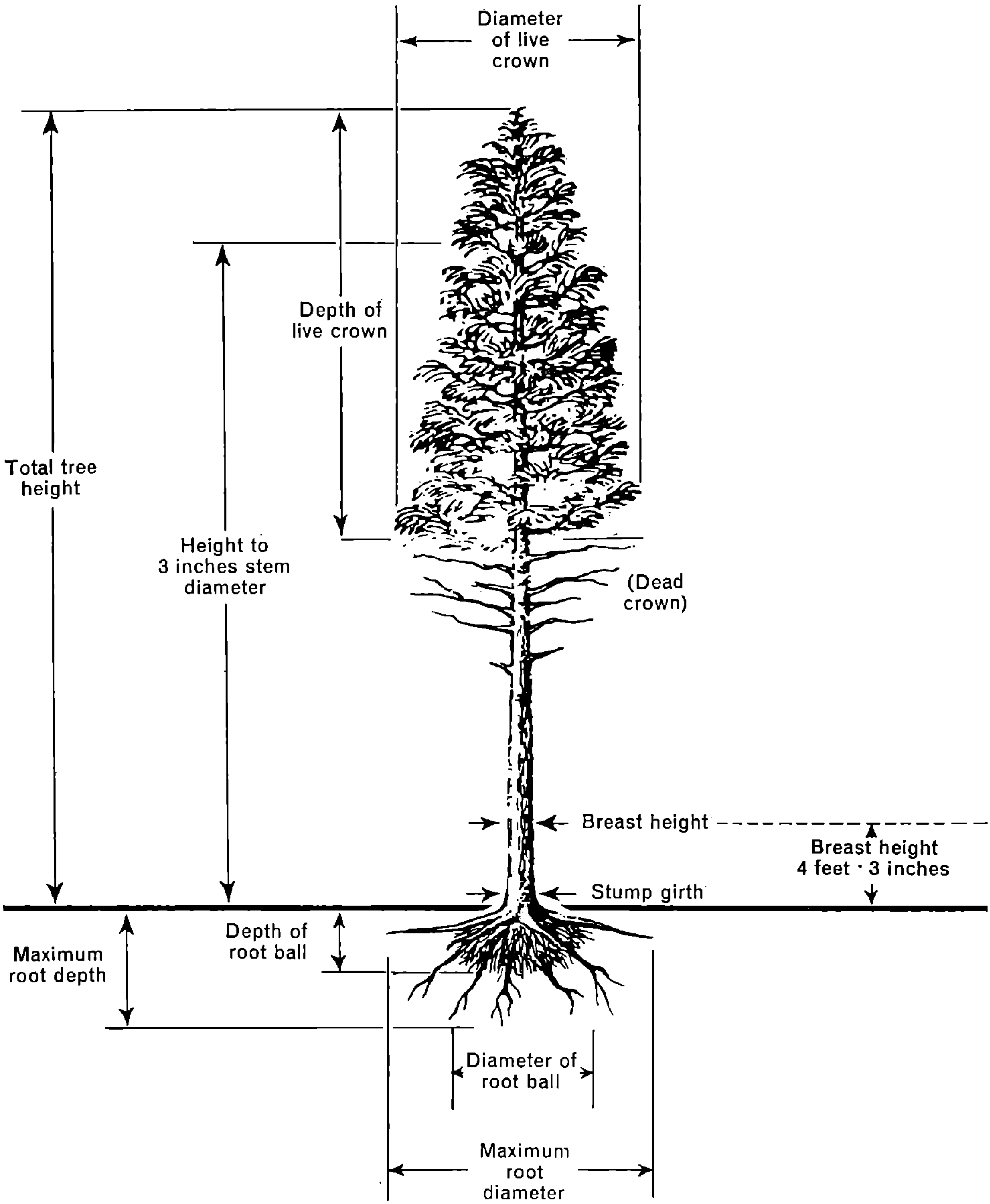

Figure 2. Diagram of tree showing points at which measurements were taken

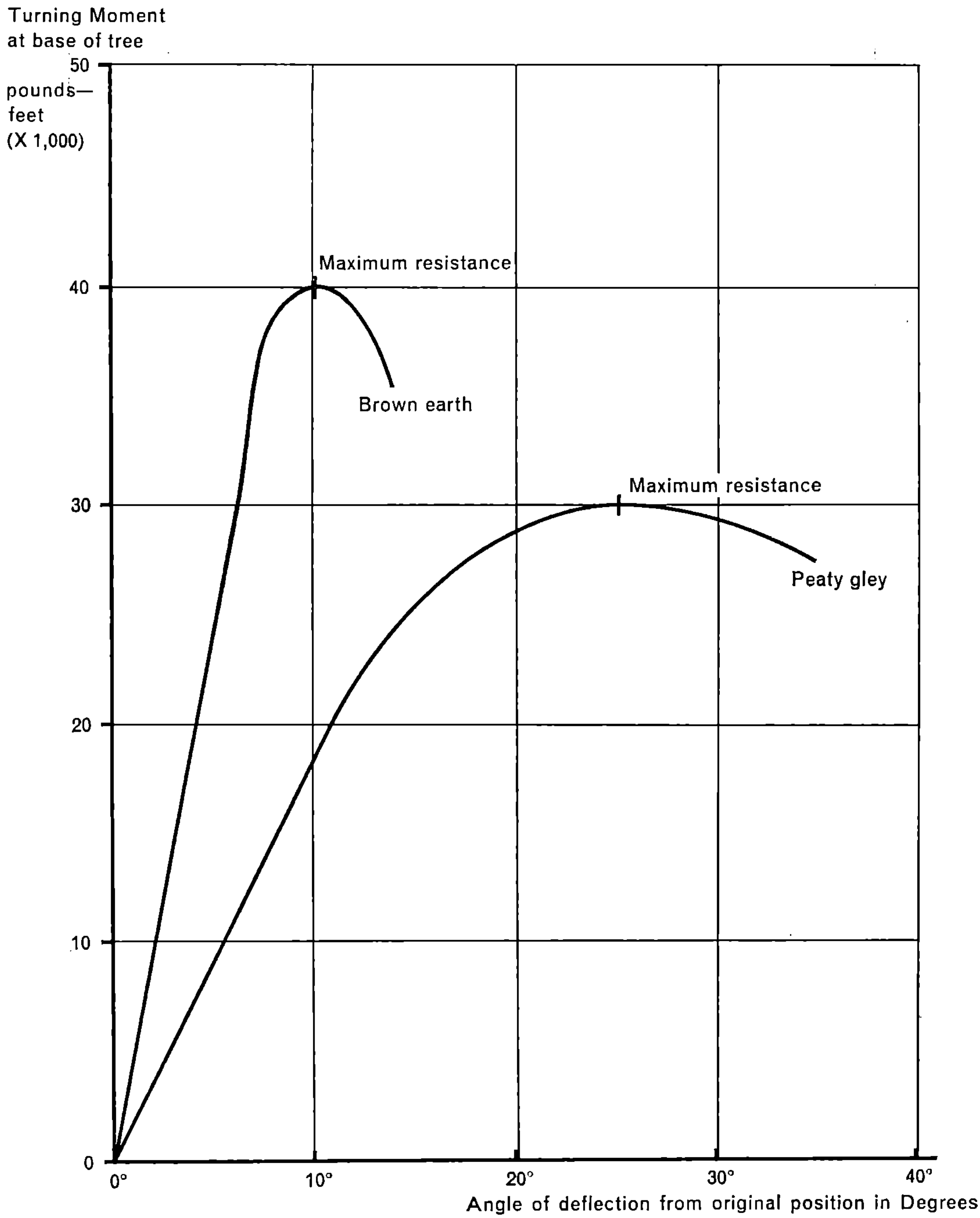

Figure 3. Typical curves showing the relationship between the turning moment at the base of a tree, and the angle through which it has been deflected from its original position, for brown earth and peaty gley soils.

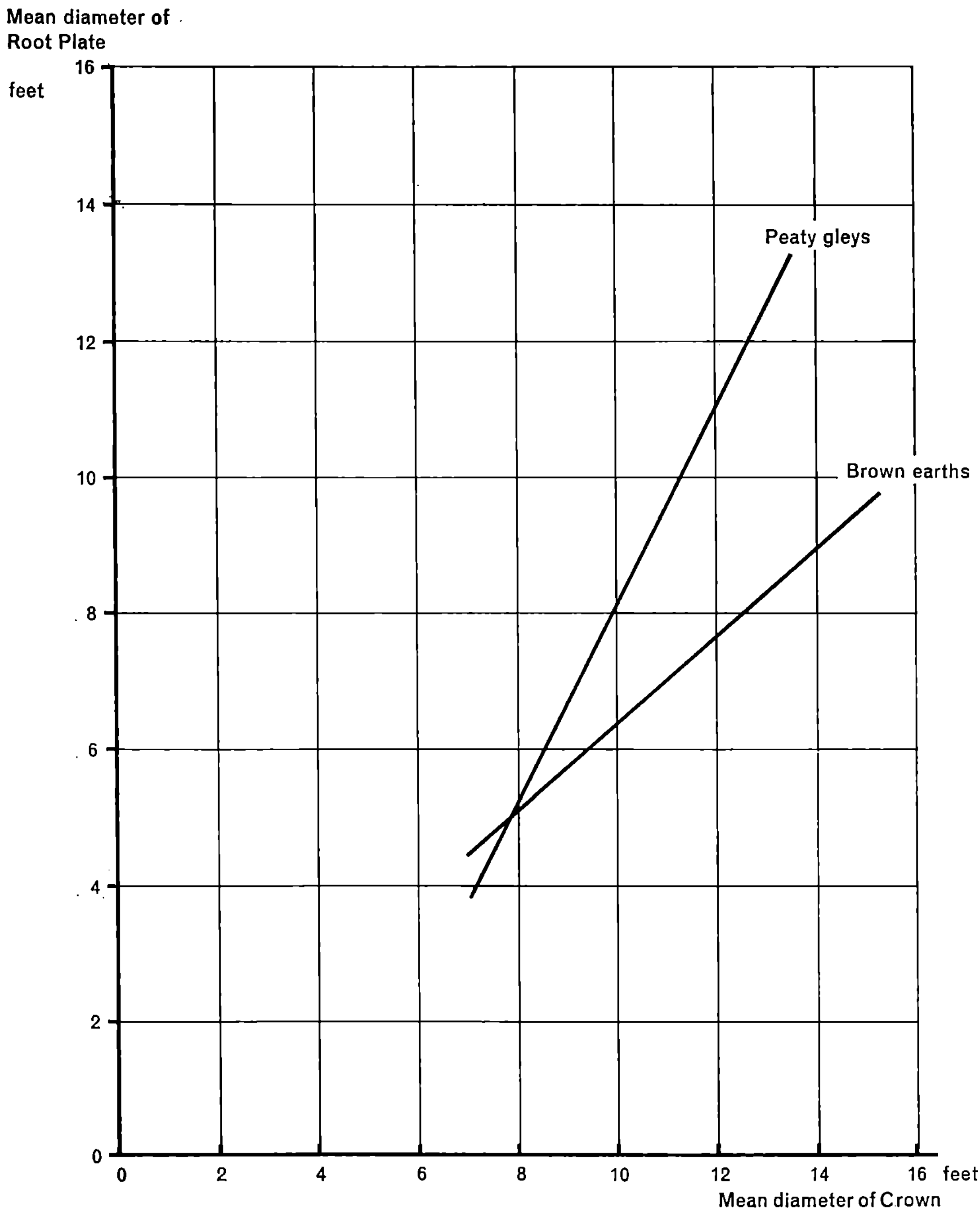

Figure 4. Regressions of mean root plate diameter on mean crown diameter for trees growing on brown earth and peaty gley soils. Crown diameter will tend to increase following thinning, and as crops get older, but for any given crown diameter, trees on a peaty gley soil will tend to have wider root plates than trees on a brown earth.

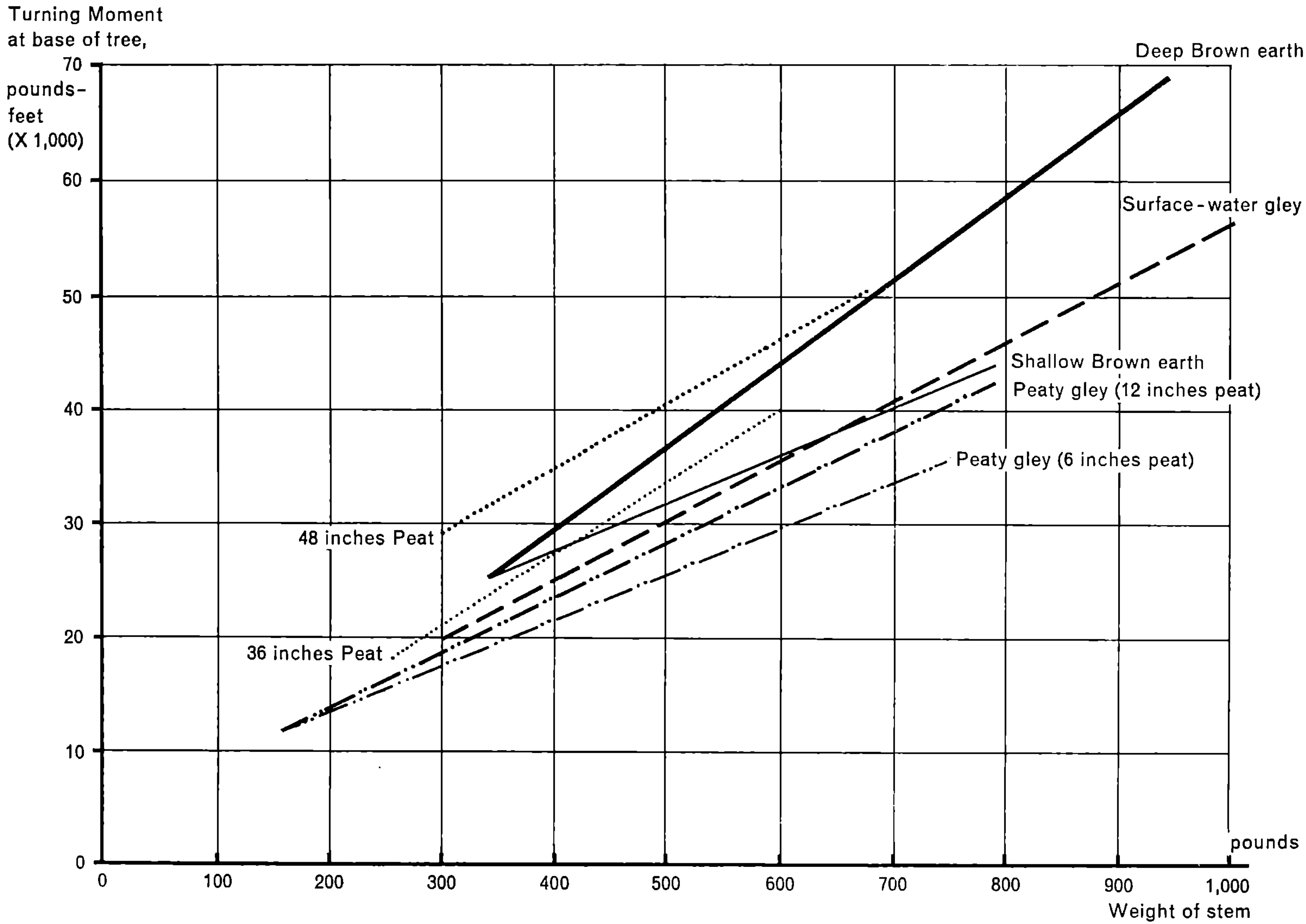

Figure 5. Mean regressions of turning moment on stem weight for several samples of trees pulled over on different soil types

Chapter 2

THE SITES AND SILVICULTURAL TREATMENTS STUDIED

Sitka spruce shows a well-marked preference for oceanic climatic conditions, and has been mainly planted in the wetter and more humid western and northern parts of Britain. Most of the tree pulling studies have been carried out in the important regions of North Wales and the English-Scottish Borders, since storm damage is most frequent in these regions.

The soils in these areas are largely developed from glacial drift, derived from the local solid rocks, which are predominantly fine-textured. Silurian and Ordovician Shales and Greywackes occur in both regions, while the softer shales and sandstones of the Lower Carboniferous measures form much of the Border region. Igneous rocks appear in the Beddgelert area of North Wales, and on a small scale in the Borders.

Soil conditions in the two regions are very similar; most of the drift is predominantly heavy textured, giving impeded drainage. Small areas of better-drained loamy drift appear on some lower rounded hill tops, and on steeper slopes.

On the impeded soils, peat deposits are common, usually not exceeding 24 inches, but in a few basins and upland saddles peat deposits exceeding three feet in depth may be found. On the loamy drift, limited peat accumulation (usually less than 12 inches) may occur, associated with the development of a thin iron pan in the mineral soil beneath. Very stony soils occur on scree slopes and river terraces, and Brown Earths are often deep at the foot of steep slopes, due to slip and wash. The areas of these stony soil types are small.

It is therefore possible to classify the soils studied into five basic types; these, including transitional types, account for a very large proportion of the soils that are found in forests in these regions. Rooting has been examined on some or all of these soil types in seven forests, as listed in Table 1. More detailed descriptions follow of the soils on which trees were pulled over.

TABLE 1. LOCATION OF INVESTIGATIONS CLASSIFIED BY SOIL TYPES, WITH THE NUMBERS OF TREES PULLED OVER

	FOREST							
Soil Type	*Ae Dumfries-shire*	*Beddgelert Caern-arvonshire*	*Clocaenog Denbigh-shire*	*Kielder North-umberland*	*New-castleton Roxburgh-shire*	*Radnor Radnor-shire*	*Redesdale North-umberland*	*Total*
Brown Earth	8	32	40	—	8	32	9	129
Peaty Podzol	30	—	—	—	8	—	14	52
Surface W. Gley	—	—	8	—	8	—	—	16
Peaty Gley	45	7	8	40	12	—	13	125
Deep Peat	5	9	8	16	8	—	—	46
Total	88	48	64	56	44	32	36	368

Investigations of a number of factors, which may influence trees' stability, have been made at the same time as the studies of rooting in relation to soil type. These are artificial drainage, intensity of thinning, initial plant spacing, direction of pull, and ground slope.

Chapter 3

GENERAL SOIL AND SITE DESCRIPTIONS

3.1 Mineral Soils with Free Natural Drainage

3.1.1. Boulders and Shattered Rock

Extremely stony soils are occasionally met with consisting of large stones, boulders, and shattered rock, with soil particles in between them. They were found in low hummocks and ridges, on, or at the foot of, steep slopes, in gullies and on hill tops near rock outcrops. Areas of rounded stones and boulders were found on level areas at the foot of steep slopes, and occasionally as terraces in valley bottoms. No complete study was made on this type as it is not common, but some samples were examined at the same time as a study of the brown earths.

3.1.2. Fine Scree

The soils of this type examined were composed of fine slate and shale fragments, mostly less than 1 inch in diameter, but with occasional larger pieces and some stones. There was some fine soil in the upper layers, frequently concentrated in bands. The main characteristic of this type is the unweathered nature of the rooting material. One sample of eight trees has been examined on this type, which is, however, quite rare.

3.1.3. Brown Earths and Podzolic Brown Earths

As indicated in Table 1, this was the soil type most extensively studied, not so much because of its importance, but because a large sample was required for the two spacing experiments studied at Radnor and at Clocaenog Forests.

The soils of this type studied were all well drained, but the depth of permeable soil varied greatly. Generally, the depth of soil over rock or compacted till *decreased* as the ground slopes increased, and also as elevation increased. In Clocaenog Forest in particular, increase in elevation was also associated with more pronounced podzolisation, and many transitional soils between a Podzolic Brown Earth and peaty podzol were encountered. However, unless a distinct pan had formed, the rooting appeared similar to that found in Brown Earth, and so these soils have been classed together.

The soils of this type have a yellow-brown or red-brown colour, and little or no raw humus on the surface. Stones are sometimes present, and the soils are predominantly light textured. Flame-like discolorations are frequently present in the upper layers of the soil. There are no abrupt colour changes down the profile. The colours become paler with depth, and small yellow-brown specks are often visible in this region. In podzolic Brown Earths the A horizon is usually darker brown than the B horizon beneath, due to a fairly high organic matter content, although individual sand grains may be bleached white. In normal Brown Earths there is usually less organic material in the A horizon, and it is less clearly defined from the underlying B horizon. The B horizon of the podzolic Brown Earth is a richer, more red-brown colour than that of the normal brown earth.

Such soils will be found on moderate slopes, and on the lower slopes of valley sides, and in areas where the drift is lighter textured, or where no drift occurs and the underlying rock is permeable. They are present in all the forests studied, though no Sitka spruce have been pulled over on these soils in Kielder Forest.

3.2 Peaty Podzols and Peaty Gleyed Podzols

These soils have been encountered in all the forests where studies were made, but detailed investigations were made in only three forests (see Table 1).

The soils have a peat layer on the surface which may be from 3 to 15 inches deep. Below this the A horizon is reached, but may also be mottled above the pan, which appears at the top of the B horizon. The pan may or may not be continuous, but the colour change between the A and B horizon is always abrupt and is usually marked by a dark line. The B horizon is well drained and typically is a bright yellow-brown or red-brown colour.

This soil type occurs most commonly at elevations above 1,000 feet, either on well-drained hummocks, or over permeable till or rock. The vegetation is usually dominated by heather, *Calluna vulgaris*, or *Nardus stricta* grass in North Wales, but more often by *Molinia caerulea* grass in the Border region.

3.3 Soils with Impeded Drainage and Heavy Textured Sub-soils

3.3.1. Surface Water Gleys

In both areas where this soil type was studied (see Table 1) the underlying material is heavy textured drift, largely impervious to water. The A horizon is usually loamy in texture and permeable, but the dull grey colour with rusty mottling indicates that water movement is inhibited by the relatively impervious subsoil. The uppermost layer is darkened with the high content of well-decomposed organic material; the subsequent loamy layer is lower in humus and very pale grey. The colour, texture and structure change to the subsoil (B horizon) is abrupt, this being a mottled yellow and grey. It becomes less wet with depth and the mottling decreases in intensity as the parent till is approached. The vegetation characteristically includes much *Deschampsia caespitosa* and *Juncus effusus*.

3.3.2. Peaty Gleys

A large proportion of the Sitka spruce plantations in the Borders and in North Wales are situated on soils of this type, and hence (as indicated in Table 1) it has been well represented in the root samples.

The term peaty gley is used for impeded surface water soils with a peat accumulation up to 24 inches. The trees sampled were found on a full range of peat depths from 6 inches to 24 inches; but in fact 75% of trees sampled were found on about 12 inches of peat. The peat is typically dark brown to black, well decomposed and relatively fertile. It is often referred to as "*Molinia* peat" due to the characteristic dominance of this species in the vegetation.

Under the peat, the upper A horizon with incorporated humus is usually only weakly developed, but the succeeding pale grey horizon is marked. The clayey B horizon is mottled yellow and grey. This sub-soil is frequently referred to as "clay" but it was found that while heavy textured soils predominated, some trees were growing on quite light textured and even stony soils. These lighter soils often appeared like clays when very wet.

3.4 Deep-peat Soils

The Soil Survey has defined accumulations of organic material deeper than 24 inches as *deep peat*. This soil type was studied in five different forests (see Table 1) and usually the depth of the peat appreciably exceeded this. Depths of 36 ins. were found at Forest of Ae and Clocaenog, and over 48 ins. at Beddgelert.

All the sites studied were basin peats, and usually at fairly high elevations. Both fibrous peats, usually associated with *Calluna*, and black amorphous peats, as found under *Molinia*, were studied.

The soils studied are considered to be fairly representative of basin peats and similar to the deep blanket peat that occurs in the wetter and upland parts of the two regions.

Chapter 4

DETAILS OF SILVICULTURAL EXPERIMENTS INVESTIGATED

4.1 Artificial Drainage

There is unfortunately only one drainage experiment with deep drains, old enough, and with a suitable crop for tree-pulling investigations. This experiment was laid down in 1949 at Kielder to study the effect of drain deepening on a thicket stage crop, on a peaty gley soil.

The experiment (Kielder No. 54) lies on the edge of a large basin, so that the whole area is covered with peat, varying in depth from 6 inches round the edges to about 24 inches in the basin.

The tree crop was originally planted on turfs cut from shallow (approximately 6-inch) "drains" at 15 ft. spacing, laid out in a herring-bone pattern. When it was 19 years old and 25–30 ft. tall, plots were marked out extending across three of these old drains (i.e. 45 ft.) and in every alternate plot the drains were deepened to 24 inches.

Since the drains are barely 2 ft. deep, and their angle to the contour is frequently as much as 40°, they would not be accepted as being fully efficient by present day standards. These defects are probably overcome to some extent by the close spacing of the drains (15 ft.).

Two plots with deepened drains, and two with just the original turf "drains", were chosen, so as to have one of each pair on deep peat (24 inches plus) and one on shallow peat (6 inches). Randomly selected samples of eight trees were then pulled over in each of these four plots.

4.2 Initial Planting Spacing

A large series of spacing experiments was laid down in forests scattered all over the country in 1935; most of them are still required for assessment of yield of timber, and therefore they are not available for tree-pulling experiments. Two experiments from this series were, however, available for tree pulling studies, but these are both on well drained soils. Unfortunately no experiments on wet soils are available at present.

The experiments had half-acre, or bigger, unreplicated plots, with trees planted at 3 by 3 ft., 4½ by 4½ ft., 6 by 6 ft., and 8 by 8 ft. One experiment at Radnor Forest had been thinned, two plots once, and two twice. The plots at Clocaenog Forest had not been thinned when the eight sample trees were pulled over in each plot.

The soils in both experiments are rather variable, mainly in the depth of rootable soil, but at Clocaenog there was also variation in the degree of podzolisation between plots, and up to 8 inches of peaty material was encountered locally.

4.3 Thinning

There are very few comparative thinning experiments where it is possible to study the effect of thinning on root development by distinctive assessments. However, at Kielder Forest there was a series of four sample plots, which had been laid down in 1948 to examine the effect of heavy early thinning on the stability of the crop when it reached pole stage.

Three of these plots were comparable and could be used for tree-pulling studies, but the fourth was not used because it was sited in a different place, and had suffered badly from wind-damage, so that sample trees with comparable rooting conditions were difficult to find. The soil type in the three plots actually used is a peaty gley.

The crop is Sitka spruce, planted in 1934, and the original prescription was to remove one-third of the number of trees at each thinning. The first plot was thinned in 1948 when 14 years old and 18 ft. top height. It was then given its second thinning, 3 years later, when the second plot received its first thinning, and both these plots were thinned again 3 years later, when the third plot received its first. This process was repeated on a 3-year cycle until 1960, when some wind damage occurred. The first plot to be thinned had by then had 5 thinnings. The top height of the plots when the pulling was done in 1964 was approximately 40 ft., and by this time wind-damage had become so severe that all the plots were abandoned. The most recently thinned plot was not used.

4.4 Directional Stability

It has often been suggested that trees build up resistance to the prevailing wind, and that in Britain trees should be more resistant to south-westerly storms than those from other directions. An experiment designed to examine this theory was carried out at Forest of Ae. It actually formed part of the basic assessment for the experiment Ae No. 32 established in 1962, which was being laid down to examine the effect of various sizes of clear-felled areas on the subsequent wind-damage in the surround. The plots used were circular, and ranged in area from 10 acres to 0·1 acres.

It was decided to investigate the relative stability of the margins of these plots before felling, in order to ascertain whether any parts of the margin were appreciably less stable than others. This was done by pulling over trees round the intended margins, parallel to the radii of the circular plots.

Working round the perimeter of the circles, alternate trees were pulled towards the centre and away from it so that the 64 trees were pulled over at all compass bearings with about 7° intervals. The soils varied appreciably round the circles from peaty podzols through peaty gleys to deep peat.

4.5 Ground Slope

Another aspect of directional stability is the ability of trees to withstand upslope or downslope winds, and it was considered that this could have a bearing on the incidence of wind-damage.

A small comparative trial was therefore carried out at Beddgelert in one of the Brown Earth sample areas, whereby a sample of eight trees was pulled over uphill, and another similar sample downhill.

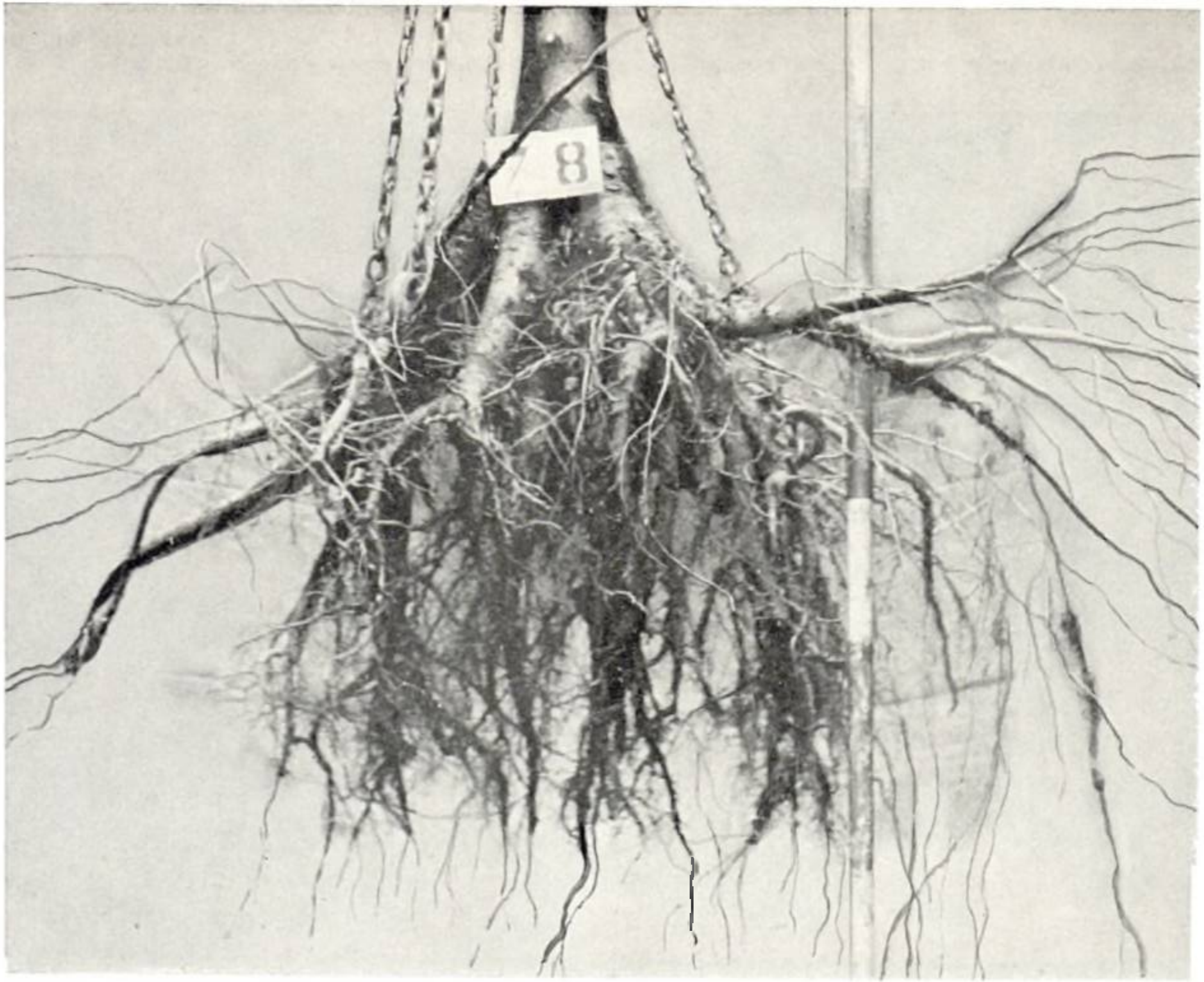

Plate 1. A typical example of a Sitka spruce root system on a deep unimpeded brown earth soil. The tree was 40 feet tall and growing at Newcastleton Forest, Roxburghshire. It shows the predominantly vertical root system extending to a depth of about 36 inches.

Plate 2. A typical example of a large block of wind-damage. The majority of the trees have been uprooted and the tangle on the ground presents a problem when extracting the timber.

Plate 3. Sitka spruce broken by the wind. Most of the stems have broken off between 4 feet and 10 feet, and the splitting and tearing of the stem seriously reduces the volume of produce which is usable.

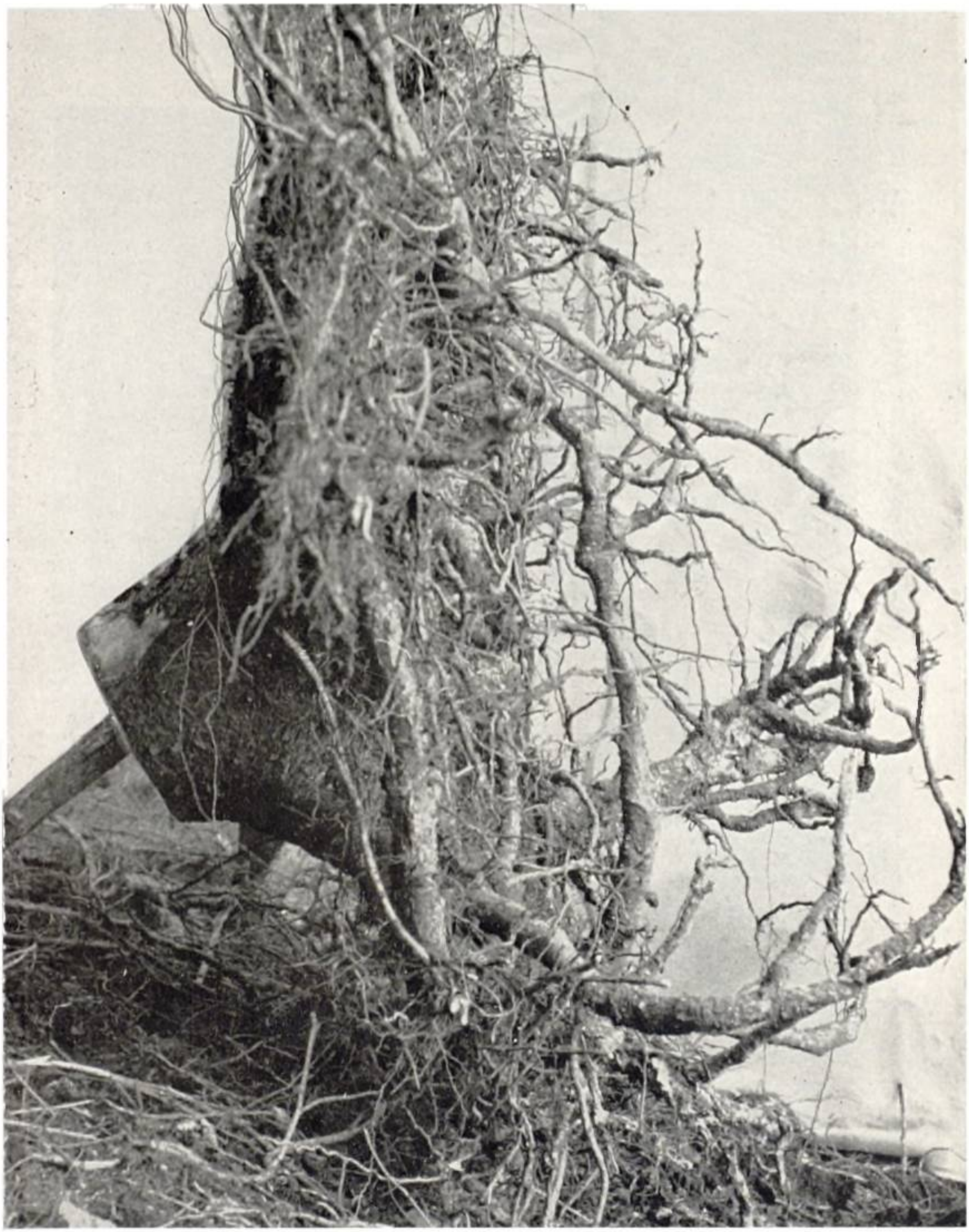

Plate 4. An example of a root system of Sitka spruce growing on a very dry stony soil at Beddgelert Forest, Caernarvonshire. Note the callouses and distortion of the roots, thought to be caused by abrasion on the sharp stones, and the almost complete absence of fine roots which have died back.

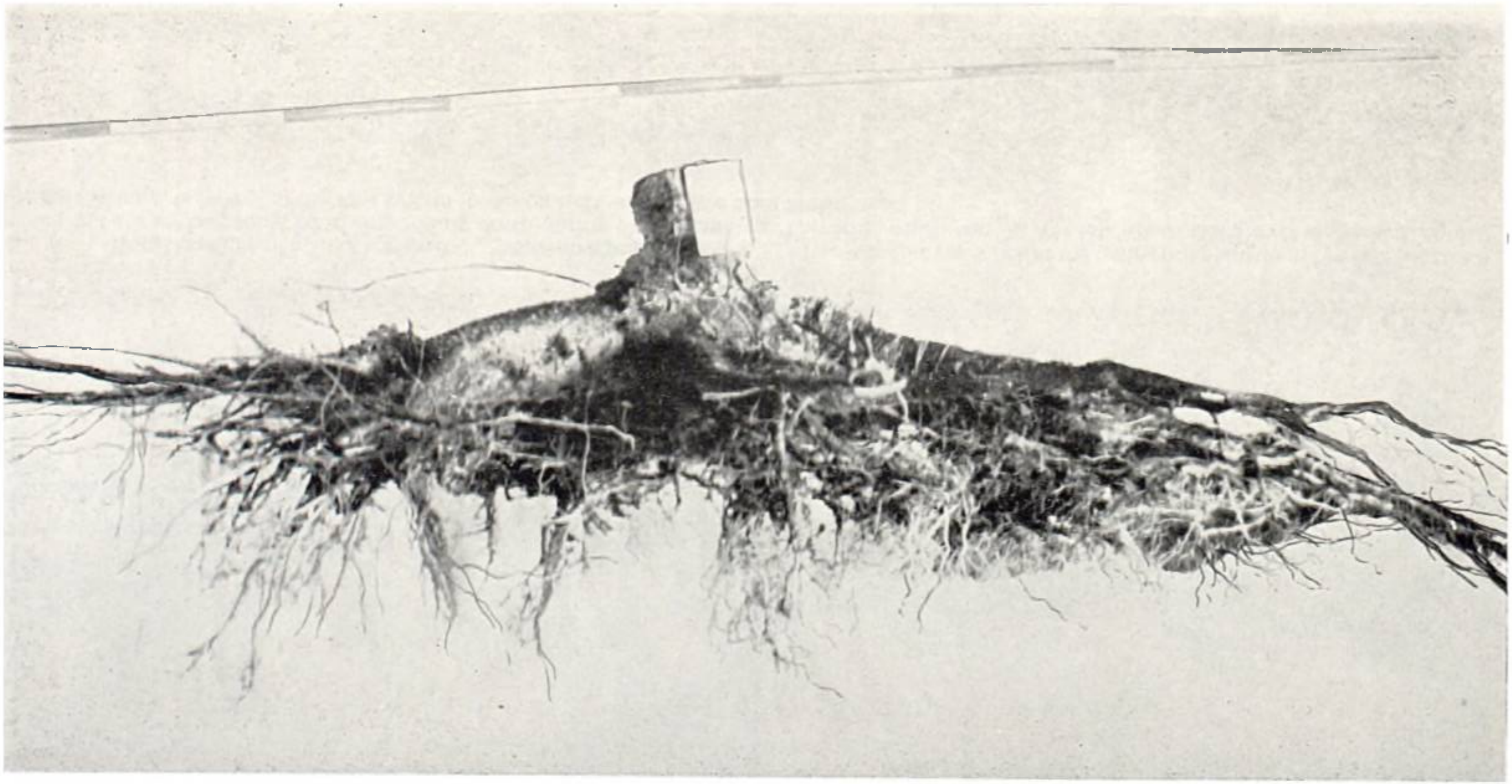

Plate 5. An example of a Sitka spruce root system on a peaty podzol at Clocaenog Forest, Denbighshire. Note the strong surface development of the roots, with some sinkers which have penetrated the pan.

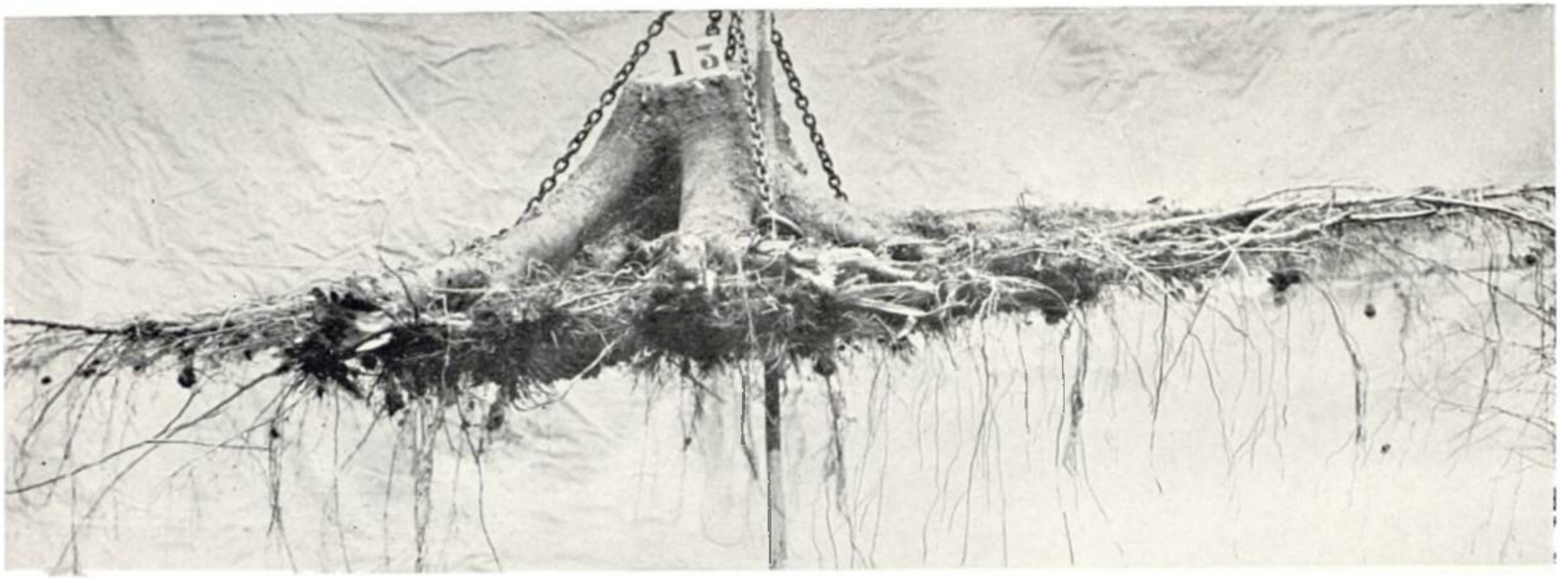

Plate 6. A typical example of a Sitka spruce root system on a peaty gley soil. The fine hair-like roots below the main root plate do not in fact penetrate the soil but are surface roots which have hung down during photographing. This tree, which was 40 feet tall when pulled over at Kielder Forest, Northumberland, is typical of the root system found on trees which have been blown over.

Plate 7. The root system of a Sitka spruce growing on deep peat at Beddgelert Forest, Caernarvonshire. The peat was very wet and rooting has been confined to the surface few inches. (c.f. Plate 8).

Plate 8. The root system of a Sitka spruce on deep peat also at Beddgelert Forest (see Plate 7), where the peat was drier due partly to topographic drainage and partly to artificial drainage. Note the downward and outward inclination of the roots.

Plate 9. The root system of a drainside Sitka spruce on deep peat at Beddegelert Forest (see Plates 7 and 8). The tree was growing above the drain, which therefore only had a limited effect as illustrated by the sinker roots in the aerated zone at the drain edge.

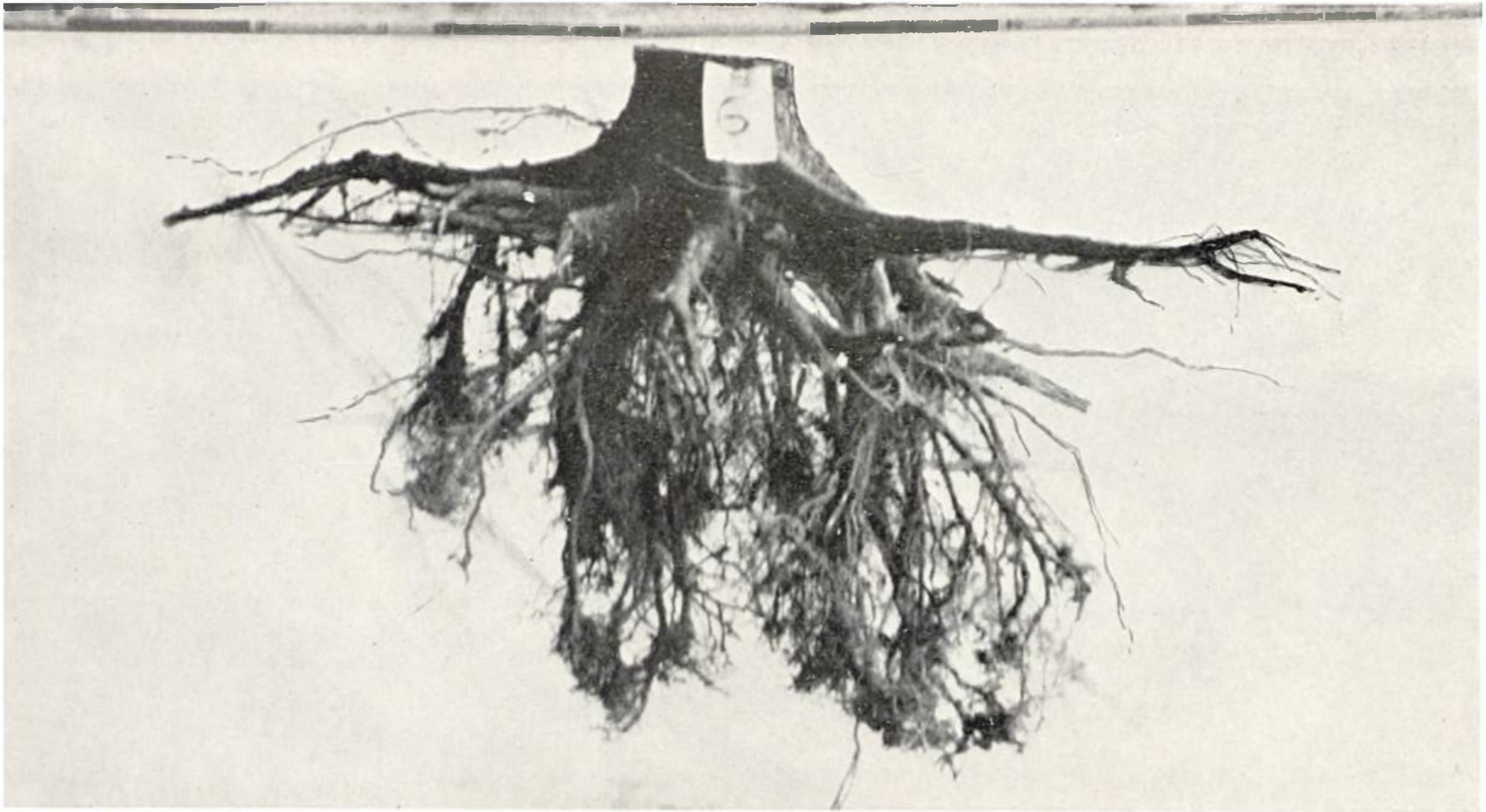

Plate 10. The root system of a Sitka spruce at Radnor Forest, Radnorshire, planted at 3-foot spacing. Note the strong development of sinker roots directly under the stump (*cf.* Plate 11).

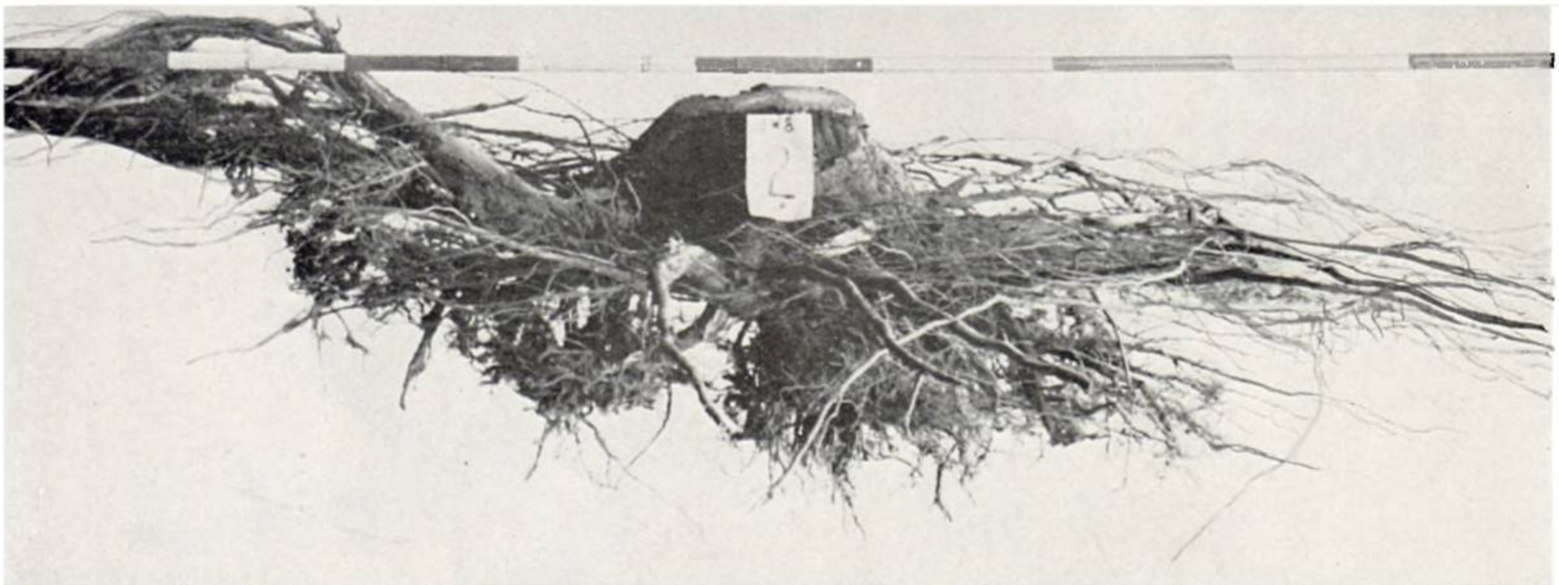

Plate 11. The root system of a Sitka spruce at Radnor Forest planted at 8-foot spacing. Note the strong development of lateral roots, with sinker roots growing down from them (*cf.* Plate 10).

Plate 12. The root system of a Sitka spruce on a brown earth at Beddgelert Forest on a 20° slope. Note the predominance of sinkers on the uphill side and laterals extending on the downhill side (right).

Plate 13. Root system, Type A, elevation (see Chapter 7.3). An example of the deep narrow type of root systems. (See also Plates 1 and 14). Note the strong downward inclination of the lateral roots.

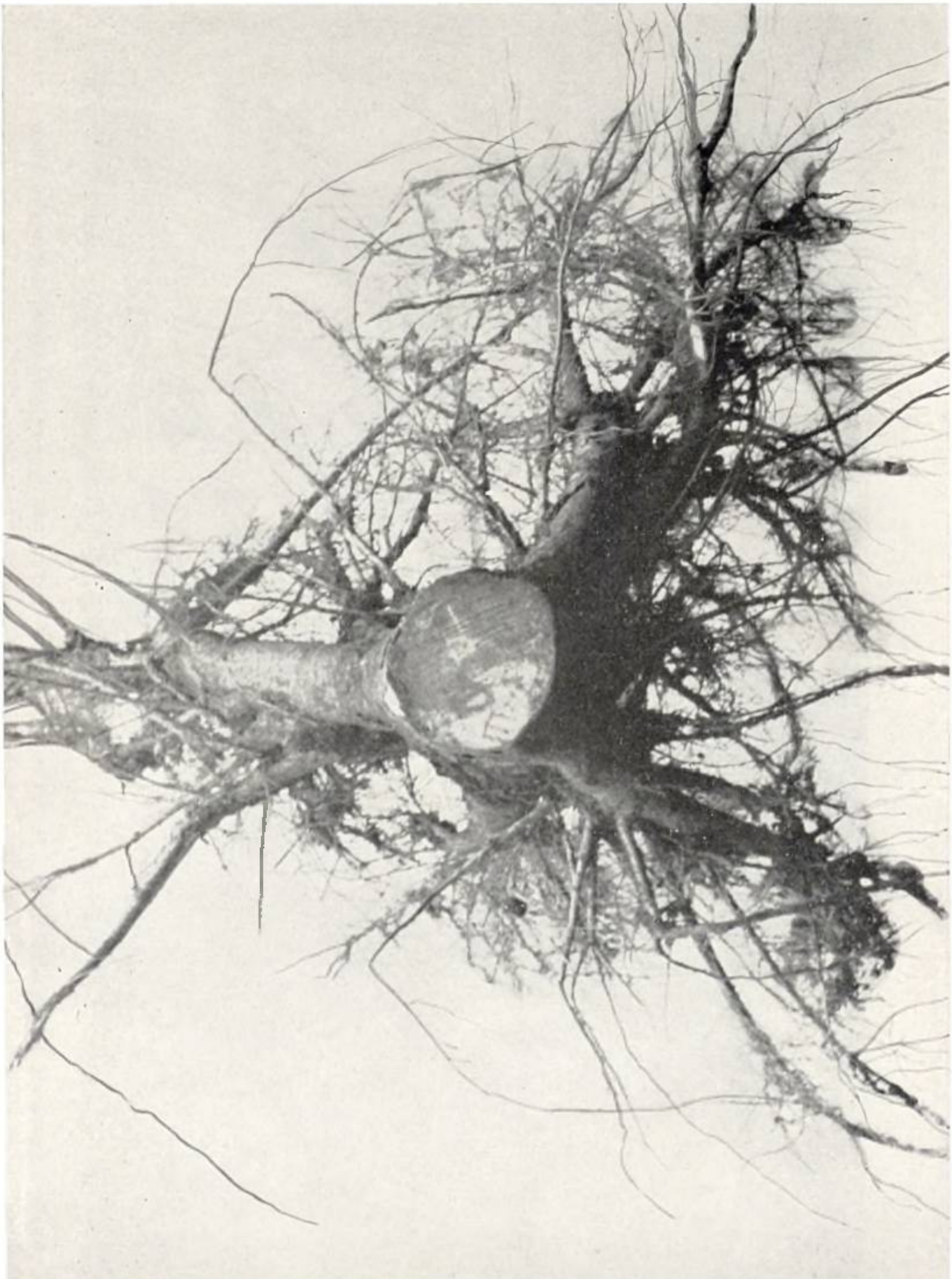

Plate 14. Root system, Type A, plan (see Plate 13). Note the small number of lateral roots and their rapid taper.

Plate 15. Root system, Type A. elevation. An example of a tree which has encountered an impenetrable layer at about 24 inches. The root system is narrow but not very deep and shows how a misleading impression of rooting can result if the surface roots are investigated without studying the soils (see Chapter 7).

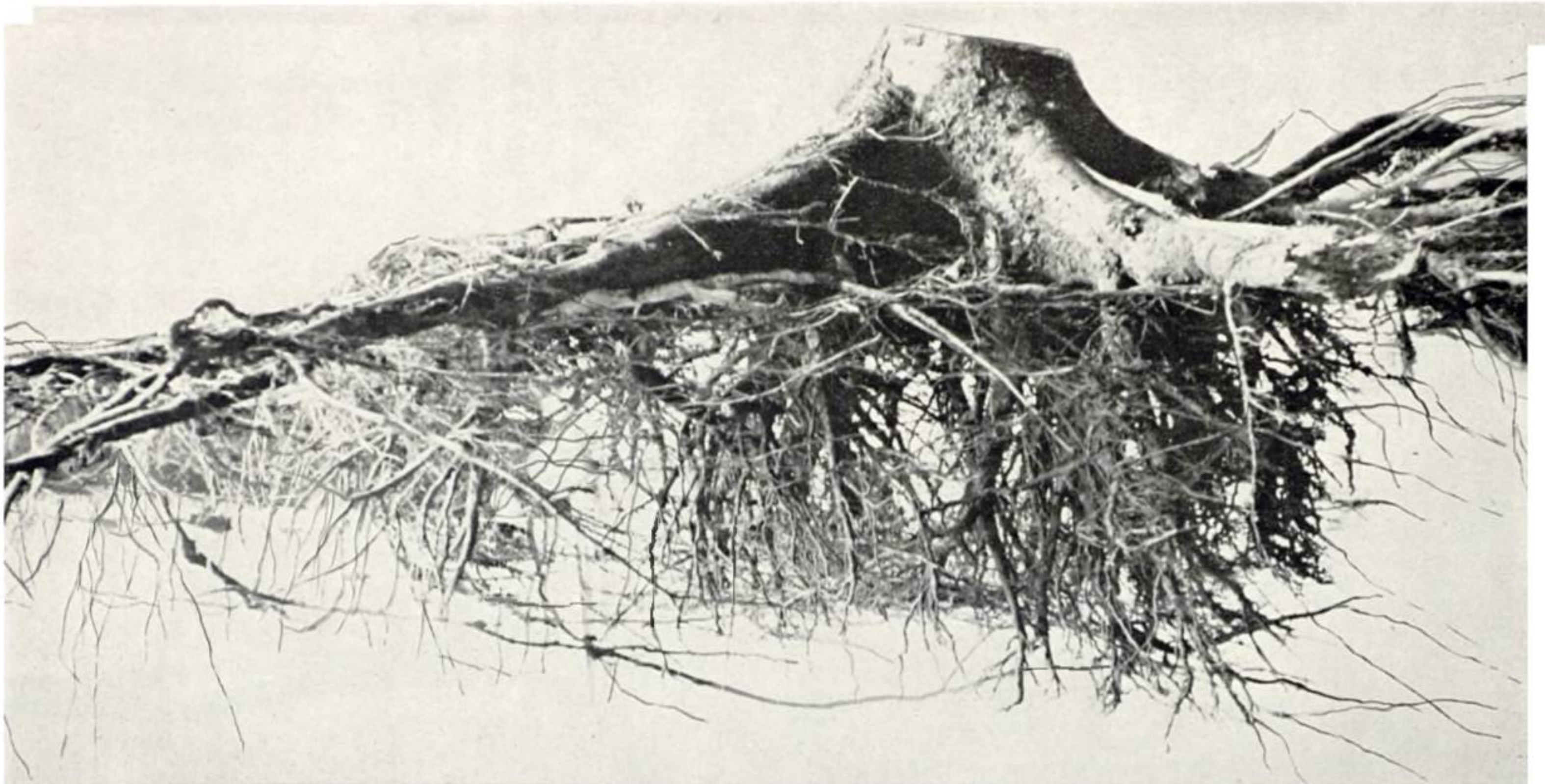

Plate 16. Root system, Type B, elevation. An example of a root system with intermediate depth and spread. Note how the vertical roots mainly originate from laterals rather than from under the stump.

Plate 17. Root system, Type B, plan. An example of an intermediate root system (see Plate 16). Note how the lateral roots are stepped where a sinker descends. The roots at 2, 4, 7 and 12 o'clock all illustrate these steps at about 2 to 3 feet from the stump.

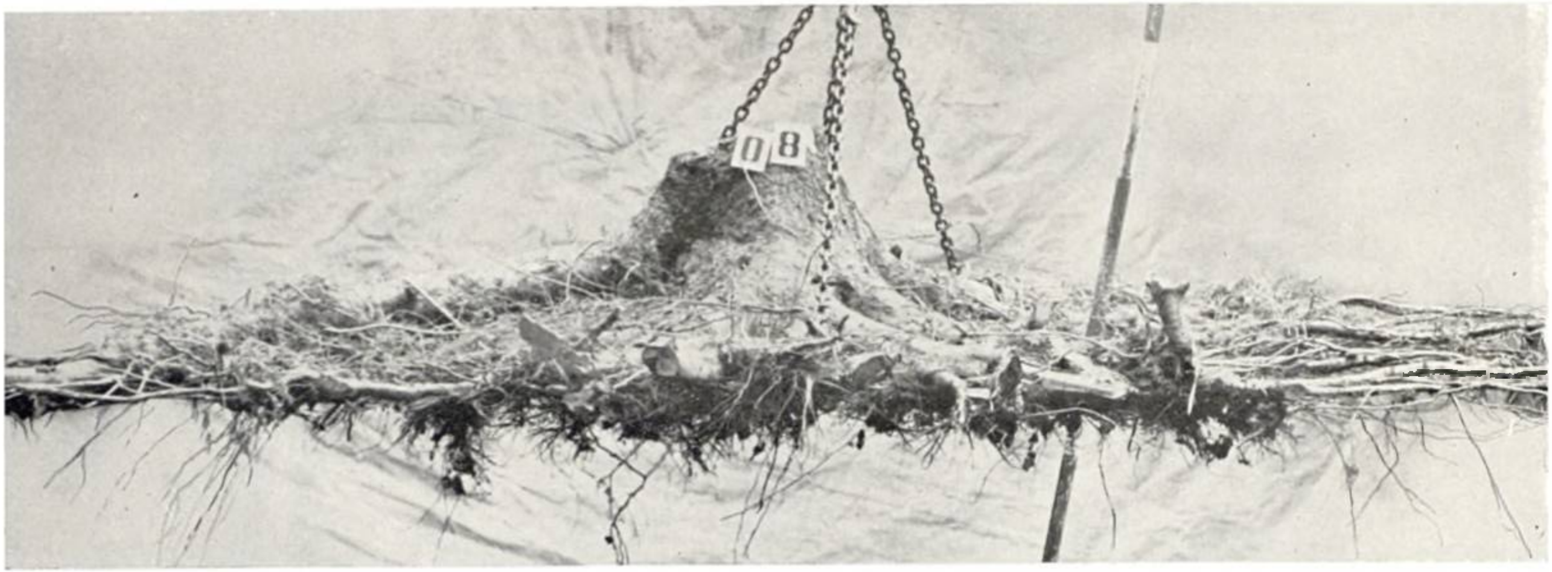

Plate 18. Root system, Type C, elevation. An example of a wide-shallow root system, found on ill-drained soils.

Plate 19. Root system, Type C, plan (see Plate 18) Note how the lateral roots extend 3 or more feet from the stump without appreciable taper.

Plate 20. The tree-pulling technique in operation. Note the dynamometer and winch near the man's feet; the spacer and two snatch blocks on the anchor tree in the background; and the tree being pulled over just visible in the top left hand corner of the photograph. In this instance a chain sling and holdfast were used (right).

Chapter 5

RESULTS OF THE ROOT STUDIES

5.1 The General Form of the Root System in Relation to Soil Type

5.1.1. Mineral Soils with Good Natural Drainage

The mean rooting depth for the trees pulled over on these soils types was 34·3 inches, ranging from a minimum of 12 inches at Radnor to 60 inches at Newcastleton, Beddgelert, and Redesdale. The shallowest mean root depth was 23·6 inches at Radnor where a combination of rock and attack by the Honey fungus, *Armillaria mellea*, had interfered with root penetration. The maximum site mean root depth was 44·9 inches at Beddgelert. Table 2 at the end of Chapter 5.1 shows fuller details of the rooting depths recorded.

Sinker roots formed the major part of the root system on these soils and on many trees the sinkers were clustered underneath the stump. Additional sinkers were frequently found under lateral roots, but usually near the stump (see Plate 1). At Clocaenog, where the soil was transitional between a podzolic brown earth and a peaty podzol, the sinkers were more widely distributed along the laterals, and began to resemble the rooting pattern on peaty podzols which is described later.

The only important factor on this type which limits the ultimate rooting depth is soil compaction or rock, which offer severe physical barriers to roots. Some roots had penetrated quite far into very stony ground, and down fissures in shattered rock. These roots were frequently distorted and had callouses, probably as a result of abrasion on sharp edged rocks (see Plate 4).

Usually the spread of the lateral roots increased as rooting depth increased, but the two spacing experiments showed that the proximity of neighbouring trees has a very strong influence on the extent of lateral rooting (see Chapter 5.3.1.).

Very little root grafting or root interlocking was observed on these soil types. Crops which had not been thinned or only slightly thinned, had very narrow root systems. This was particularly true of the samples at Forest of Ae and Newcastleton. The lateral roots showed a marked reduction in diameter at the point where sinkers descended, and the laterals tapered rapidly.

5.1.2. Peaty Podzols and Peaty Gleyed Podzols

The mean depth of rooting for trees growing on this soil type was 26·1 inches (see Table 2). The range of rooting depths, from 14 inches to 50 inches, was similar to that in the brown earths, but the majority of trees had root depths at the shallower end of the range.

Typically, the sinker roots were not clustered under the stump as they were on brown earths, but were spaced along the lateral roots. This is illustrated in Plate 5, showing a tree at Clocaenog.

The amount of sinker root penetration seems to be related to the state of development of the pan, and to some extent to the amount of gleying apparent in the A_2 horizon. Trees were frequently found with root systems having one or two sinkers which had made good downward growth where the pan was almost absent, but with the remainder of the root system confined to the peat layer above the pan. Examples of this partial penetration of the pan layer were observed in all forests where this soil type was studied.

Roots which penetrated the pan continued down freely, except where rock or a compacted C horizon restricted them.

5.1.3. Soils with Impeded Drainage (Surface-water Gleys and Peaty Gleys)

These two soil types can be considered together, since the forms of the root systems were similar and the mean rooting depth on both soil types was the same at 16·5 inches (see Table 2). The range of depths of rooting encountered was from 8–36 inches, but the most common depths were from 12 to 18 inches.

The main root system on these soils usually consists of large lateral roots forming a wide flat plate (see Plate 6). There are a large number of lateral roots (5 to 9) radiating from the stump, and it was observed that they did not taper much, frequently extending 4 or 5 ft. from the stump, before the diameter was reduced to about ½ inch.

Root interlocking and root grafting were found frequently on these soils, and in some cases two or three other trees were partially pulled over with the sample tree. Old thinning stumps were commonly found grafted into the root system. Root grafting appears to be particularly characteristic of peaty soils.

The rooting depth tended to decrease as the diameter of the root plate increased, unlike the root systems in brown earths. (see sections 5.1.1. and 5.3.2). In the Forest of Ae even the shallowest rooted trees had narrow root plates.

Sinker roots were found on these soils, but they were distributed along lateral roots rather than under the stump. In extremely waterlogged soils, no sinker roots appeared on the lateral roots at all, but some sinkers were found, where the soil was marginally drier, usually on slight slopes or knolls.

These frequently resembled "shaving brushes", being short stubby sinkers with a mass of dead and dying fine roots at the tip. Day (1963) records similar death of fine roots on waterlogged soils.

On peaty gley soils, root penetration into the mineral soil was variable, and appeared directly related to the wetness of the site. At Forest of Ae, for example, in one sample of eight trees, six had root systems less than 12 inches deep, but two had rooted to 20 and 24 inches respectively. These two trees were growing on rather steeper slopes where the soil was slightly drier. The "peaty gley" at Beddgelert overlaid a fine shale scree, which influenced the soil drainage.

Similar variations were found in both these soil types at all forests (see Table 2).

5.1.4 DEEP PEAT

The average depth of rooting of sampled trees growing on deep peat is 25·5 inches (see Table 2), but the range is considerable, as in all the other soil types except peaty gleys. The range of samples from all forests was from 12 to 50 inches. The shallowest rooting was found at Newcastleton Forest where the mean for the sample was only 19·7 inches. The deepest rooting was found at Beddgelert on a reddish-brown pseudo-fibrous peat, where some artificial drainage had been carried out.

The wetness of the soil determined the rooting depth, as in the peaty gleys. Many root systems penetrated to, and ceased at, a definite level, which corresponded to the depth at which water was found in small holes dug in the peat (see Plates 7 and 8).

Plate 9 shows improved depth of rooting close to a drain. The drain was situated below the trees and was therefore having only a limited effect. In very wet areas rooting was quite as shallow as on the peaty gleys, but on drier sites the typical form of the root system was both downwards and outwards. There were no large lateral roots but merely heavy buttress roots, which inclined downwards. These sinker roots terminated in a mass of fine roots, which spread downwards like a cone.

TABLE 2. MEAN ROOTING DEPTHS IN INCHES ON EACH SOIL TYPE FOR ALL SAMPLES IN EACH FOREST, WITH THE RANGE IN BRACKETS

Soil Type	FOREST							Overall Mean
	Forest of Ae	Beddgelert	Clocaenog	Kielder	New-castleton	Radnor	Redesdale	
Brown earth	33.7(24-42)	44·9(30-53) 40.5(33-57) 33·6(27-40) 37·5(30-60)	40·5(27-54) 34·1(24-42) 29·2(21-36) 35·2(27-48) 35·2(21-48)	—	38·1(24-60)	30·7(18-36) 28.1(12-39) 28·5(24-36) 23·6(18-30)	35·0(15-60)	
Forest Sample Mean	33·7	39·1	34·8	—	38·1	27·7	35·0	34·3
Peaty Podzol	27·7(18-36) 25·6(14-50)	—	—	—	25·6(17-31)	—	25·7(18-39)	
Forest Sample Mean	26·6	—	—	—	25·6	—	25·7	26·1
Surface Water Gley	—	—	17·1(12-30)	—	15·6(10-24)	—	—	16·3
Peaty Gley	19·2(12-36) 13·7(8-24) 12·3(8-21) 14·4(10-17)	29·0(14-42)	18·5(12-27)	9·75(8-11) 15·0(12-18) 14·5(9-18) 15·0(13-18) 20·9(16-24)	17·0(10-25)	—	15·7(10-33)	
Forest Sample Mean	14·9	29·0	18·5	15·0	17·0	—	15·7	16·5
Deep Peat	22·6(15-27)	32·6(12-50)	24·7(12-33)	24·5(17-34) 31·1(21-36)	19·7(15-22)	—	—	
Forest Sample Mean	22·6	32·6	24·7	27·8	19·7	—	—	25·5

5.2 The Effect of Drainage on the Root System

The anaerobic conditions which arise following prolonged waterlogging have a very harmful effect on tree roots, and are almost certainly the cause of death of most of the fine roots that penetrate into the soil, presumably during periods when the upper soil layers are dry. Day (1963) has recorded similar death of fine roots on waterlogged soils.

In the Kielder drainage experiment, already described, increased rooting depth was recorded in the drained plots. The difference in rooting depth corresponded closely to differences in water levels measured in boreholes in 1955. These borehole readings were unfortunately not continued until the time of the tree pulling, but Table 3 shows the available data. For details of the borehole investigation carried out see Stewart (1958).

TABLE 3. COMPARISON OF ROOTING DEPTH AND BOREHOLE WATER LEVELS IN KIELDER DRAINAGE EXPERIMENT 54/49.

Series	*Peat depth*	*Treatment*	*Mean depth of water level* 1955	*Mean root depth* 1961
I	24 in.	Drained	21·1 in.	31·1 in.
II	24 in.	Undrained	14·9 in.	24·5 in.
III	6 in.	Drained	18·9 in.	20·9 in.
IV	6 in.	Undrained	15·2 in.	15·0 in.

On peaty gley soils in other forests, deeper rooting occurred where the natural drainage was better, because of steeper ground slope or lighter soil texture. This gives considerable hope that trees will respond to artificial drainage, if it can be done intensively enough to eliminate surface waterlogging. See Table 2—range of rooting depths on peaty gleys.

5.3 The Effect of Initial Spacing and Thinning on Root Development

It is unfortunate that few sites are available to make detailed studies of the effects of spacing and thinning, since the work done to date suggests that the effects of these treatments alter according to soil type.

5.3.1. SPACING

The two spacing experiments started were on moderately freely draining soils, and rooting depth was between 2 and 3 ft. The depth would probably have been greater, but on both sites the rock was near the surface.

The Clocaenog experiment had not been thinned, and it was still at the original planting spacings of 3, 4½, 6 and 8 ft. The mean tree height of the plots was about 40 ft. The Radnor experiment, on the other hand, had been thinned, two plots once and two plots twice, to average spacings of 5½, 8½, 11 and 13 ft. The mean tree height of the plots was 46 ft. The soil conditions at Radnor were fairly uniform, but there was considerable variation in the form of the root systems. Ring counts were made of the sinker roots as an additional observation, to see whether the variation was due to differences in the age of roots.

In both experiments the mean diameter of the root plate pulled out varied according to the spacing. In the unthinned plots the rooting diameter was slightly greater than the spacing. In the thinned plots the diameter of the root plate was less than the spacing. (see Table 4).

TABLE 4. THE MEAN ROOT PLATE DIAMETER, STEM DIAMETER AND HEIGHT FOR THE SAMPLE OF EIGHT TREES PULLED OVER IN THE TWO SPACING EXPERIMENTS

CLOCAENOG					RADNOR					
Original Spacing	*Root Diam.*	*Root Dep.*	*Ht.*	*B.H. Diam.*	*Average Spacing*	*Root Diam.*	*Root Dep.*	*Ht.*	*B.H. Diam.*	*Years since 1st Thinning*
3 ft.	4·2 ft.	34·1 in.	42·0 ft.	6·6 in.	5½ ft.	5·2 ft.	30·7 in.	47·2 ft.	6·9 in.	8
4½ ft.	5·0 ft.	29·2 in.	40·0 ft.	6·7 in.	8½ ft.	6·6 ft.	28·1 in.	47·4 ft.	7·6 in.	8
6 ft.	6·2 ft.	35·2 in.	39·5 ft.	7·6 in.	11 ft.	6·2 ft.	28·5 in.	46·5 ft.	8·1 in.	4
8 ft.	7·6 ft.	35·2 in.	36·0 ft.	7·8 in.	13 ft.	8·7 ft.	23·6 in.	40·1 ft.	9·2 in.	4

In both experiments the sinker roots of trees in the closest spaced plots were located under the stumps, and the ring counts at Radnor suggest that these roots grew down very soon after planting. (see Plate 10 and Table 5). In contrast the trees in the wider-spaced plots did not have the same core of large sinker roots under the stem, but had smaller sinkers growing down from the lateral roots (see Plate 11). Ring counts suggest that these sinker roots did not start growing until the trees were 8–10 years old (see Table 5). The trees had 29 growing seasons before they were pulled over, and were 4 years old when planted.

Records of the experiment show that the time intervals between canopy closure in the four plots were very similar to the differences in age of the sinkers.

The differences in rooting depth between the four plots at Radnor can be attributed to variation in the depth of rootable soil over the rock, and is not likely to be an effect of spacing.

An analysis of variance showed that the differences were not significant statistically.

TABLE 5. SUMMARY OF SINKER ROOT RING COUNTS AT THE RADNOR SPACING EXPERIMENT. (THE COUNTS WERE MADE WHERE THE SINKER ORIGINATED FROM THE STUMP.)

	Original Spacing			
	3 *ft.* × 3 *ft.*	4½*ft.* × 4½*ft.*	6 *ft.* × 6 *ft.*	8 *ft.* × 8 *ft.*
Mean number of rings—all sinkers	25	23	20	17
Mean number of rings in oldest sinker	28	25	23	19
Mean diameter of sinkers	2·5 in.	2·8 in.	2·5 in.	2·6 in.
Mean rooting depth	30·7 in.	28·1 in.	28·5 in.	23·6 in.

5.3.2. THINNING

The results from the Kielder thinning experiment, which was on a *peaty gley* soil, showed a marked contrast to those of the spacing experiments described above.

The three plots examined had been thinned at 14, 17 and 20 years of age. The mean spacing between the trees, and the mean root diameter and depth are given in Table 6.

TABLE 6. THE MEAN ROOT PLATE DIAMETERS, ROOT DEPTHS, STEM DIAMETERS AND HEIGHTS FOR THE SAMPLE OF EIGHT TREES PULLED OVER IN EACH PLOT OF THE KIELDER THINNING EXPERIMENT

(Rt. depth: Diff. for Sig. at 1%=3·48 at 5%=2.45 in.)

Effective Spacing (ft.)	*Rooting Diameter (ft.)*	*Rooting Depth*	*Ht.*	*Breast-height Diam.*	*Years since first thinned*
8·5	8·2	15·0 in.	36·5 ft.	7·5 in.	10
10·0	9·2	13·2 in.	40·0 ft.	9·3 in.	13
12·0	13·2	9·8 in.	37·5 ft.	8·9 in.	16

The lateral spread of the root systems is very large, almost equalling the space between trees, but the depth of rooting diminishes as the spread increases. A 't' test shows the differences in rooting between the extreme treatment to be highly significant, and the middle treatment is significantly different from the most widely spaced. This supports the comments made in paragraph 6.1.3 about rooting on soils with impeded drainage; i.e. lateral spread increases as depth decreases. The causes for this are not known, but it may be related to the soil moisture, and the effect of the crop on interception and transpiration

In the early life of the crop, the greater canopy density at closer spacings may have a correspondingly greater drying effect on the site and therefore encourage greater depth of rooting.

It is interesting that such small differences in rooting depth on peaty gleys should be significant, since this indicates great uniformity of conditions within the plots, as opposed to the more variable samples on the brown earth, where relatively large. differences were not significant.

The relationship between the mean crown diameter and the mean root plate diameter was found to differ on Brown earths and Peaty gleys. On both soils crown diameter increases as crops get older, and as spacing between trees increases, but as Figure 4 shows, root plate diameter increases more rapidly on Peaty gleys than Brown earths.

5.4 The Directional Development of Roots in Relation to Prevailing Wind and Ground Slope

The 64 sample trees pulled over to study directional stability were growing on three soil types: peaty podzol, peaty gley, and deep peat. As there were only 5 trees on the deep peat, they were included with the peaty gleys. A study was made to determine whether resistance to overthrow varied with direction of pull, and whether any variation was associated with soil type.

The results showed that variation of the measured turning moments was large, but was independent of the direction of pull, and that soil type and rooting depth had a greater effect on the resistance. Observations on the root systems did not reveal any tendency for more or bigger roots to be developed on any side, even to the lee side of the prevailing south-west wind.

Studies at Beddgelert on the effect of slope revealed a similar lack of measurable difference in turning moment between trees pulled uphill and downhill. However, the general form of the root system had been more obviously affected by the slope. The slopes where the test was made exceeded 15°, and here there was a marked tendency for the lateral roots to be concentrated on the downhill side, and for well-buttressed sinkers to grow on the uphill side (see Plate 12).

Chapter 6

OTHER RESULTS OBTAINED DURING THE INVESTIGATION

6.1 Results of the Measurement of Turning Moment

The maximum turning moment at the base of the tree was calculated for each tree (as described in Chapter 1), and regressions of moment against stem weight may be plotted for each sample of trees.

The regressions do not differ significantly between samples on the same soil type, even when they are in different forests, and the regressions are significantly different between soil types.

The small amount of data has necessitated the use of straight line relationships, but it seems clear that curves would often fit the data better. There are also several other factors, which are highly correlated with each other, such as depth and spread of rooting, which need to be considered.

Figure 5 shows the mean regressions calculated for seven different sites. The brown earths have been shown as two lines, representing deep and shallow versions, and the peaty gleys and deep peat have been split according to peat depth.

It can be seen from these regression lines that the turning moment increases rapidly with tree size on deep brown earths, but that where rock makes the soil shallow the line is flatter. This indicates that big trees on shallow brown earths are apparently no more resistant than large trees on surface water gleys and the deeper peaty gleys. The lines also show that, in general, resistance to overthrow becomes greater as peat depth increases.

Regressions for peaty podzols have not been shown because the variation in turning moment was found to be considerable, and at Newcastleton the line had a negative slope. This was probably due to the greater variability in rooting depth dependent on whether trees had penetrated the pan.

It is possible to make estimates of susceptibility to windthrow from these regression lines, and this is dealt with in detail in the Appendix.

6.2 Measurements of Root Weight and its Relation to Stem Weight

At Newcastleton, where the most recent and comprehensive study has been made of rooting in relation to soil type, root systems were cleaned of soil and then weighed, and some interesting comparisons of root/shoot ratio were obtained.

By 'shoot' in this context is understood the total weight of stem and crown as defined in Chapter 1.

It was found that the ratio of the weight of root to the weight of shoot increased from a minimum on the well drained mineral soil to a maximum on the deep peat. The differences were not quite large enough to be significant between each group, but the ratio for "brown earth" soil was significantly different from those of the others. An analysis of variance also showed that the difference between soils accounts for a highly significant proportion of the variation.

TABLE 7. MEAN ROOT/SHOOT RATIOS FOR EACH SOIL TYPE AT NEWCASTLETON

Soil Type 1	*Rt. wt.* / *Stem wt.* 2	*Standard Error* 3	*Yield Class (Av.)* 4
Brown earth	·383	± ·034	180
Surface water gley	·488	± ·040	140—160
Peaty gley	·543	± ·041	140
Peaty podzol and peaty gley podzol	·580	± ·062	140
Deep peat	·612	± ·057	120—140
Difference for sig. 5%	·14		
1%	·18		

The peaty podzol figures are the most interesting in this series, having a high mean root/shoot ratio, with a high variance. This follows the pattern of variation in rooting generally found on this soil type.

The ratios are not directly related to any measurable rooting characteristic such as depth or spread. A subjective classification of the sites studied, indicates that the root/shoot ratio is lowest on the most productive site and highest on the least productive site (see Column 4, Table 7).

In the spacing experiments at Radnor and Clocaenog the root/shoot ratios were calculated in a similar way. The results showed that spacing has no significant effect on the ratio, although the ratios of crown weight and stem weight vary considerably (see Table 8). Both sites corresponded approximately to Yield Class 160.

The data in Table 7 suggest that the less fertile the site, the greater will be the proportion of the tree's total weight made up by roots, and therefore not exploitable. There is, however, no way of telling as yet whether artificial site improvements such as drainage and fertilising can reverse this trend.

TABLE 8. THE EFFECT OF SPACING ON MEAN ROOT/SHOOT RATIOS, AND MEAN CROWN WT./STEM WT. RATIOS FOR CLOCAENOG AND RADNOR.

Spacing and Forest	*Mean Stem wt. lb.*	*Mean Crown wt. lb.*	*Mean Root wt. lb.*	*Rt. wt. / Total shoot wt.*	*Crown wt. / Stem wt.*
3 ft. × 3 ft.					
Clocaenog	289	119	113	·27	·41
Radnor	378	113	140	·28	·30
4½ ft. × 4½ ft.					
Clocaenog	288	124	199	·29	·43
Radnor	446	150	160	·27	·34
6 ft. × 6 ft.					
Clocaenog	351	201	150	·27	·57
Radnor	499	167	210	·31	·33
8 ft. × 8 ft.					
Clocaenog	345	233	175	·30	·68
Radnor	566	301	276	·32	·53

Chapter 7

DISCUSSION

7.1 The Influence of Soils and Rooting on Silvicultural and Management Prescriptions

The results have shown that the soil type plays a major part in determining the form of the root system of Sitka spruce, and that through this it will affect the stability of trees. The soil condition is the basic factor which determines the susceptibility to being blown over. Given good rooting conditions, such as are found on a deep brown earth, Sitka spruce is most unlikely to suffer from up rooting. It appears, however, that there may be a risk of wind-break, if close-planting or light or delayed thinnings have depressed stem girth growth. The volume increment, on any site appears to be at least partly determined by the development of roots, relative to the stem.

The results suggest that for optimum stability on *brown earths* the crop should be widely spaced at planting and kept open by heavy thinning, in order to encourage the development of a good lateral root system to supplement the sinker roots, which Sitka spruce will develop naturally.

The evidence is clear that the pan, in *peaty podzols*, presents a definite barrier to downward rooting. Where the pan is well defined, root penetration will be prevented, but where the pan is less well formed, root penetration may be merely delayed. Therefore it is important that these soils be recognised where possible before planting, and that tine ploughing should be carried out, to rupture the pan and allow rooting into the permeable B horizon. These remarks only apply to the type of peaty podzol found in the regions studied, where the B horizon is permeable, and do not necessarily apply to the hard heaths in East Scotland, and the North East of England, where the B horizon may be unpenetrable to roots.

On *surface water gleys*, *peaty gleys* and *deep peat*, improved drainage is essential in order to allow full root development, and it seems most likely that greater volume production will also be achieved. The limited evidence available concerning the response to improved drainage suggests that Sitka spruce will root deeply in these soils if waterlogging is eliminated, and the soil conditions thereby improved.

The risk of wind-throw will be high on these three soil types, whenever shallow rooting is consequent upon poor drainage. Wide spacing or heavy thinning without drainage will stimulate lateral root development, but apparently at the expense of rooting depth (see Chapter 5.3.2). There is no suggestion that wide spacing or heavy thinning will *by themselves* improve the stability of crops on these soil types.

Cultivation, drainage, spacing and thinning prescriptions should therefore all be related closely to soil type, as well as to species, rainfall, slope etc.

7.2 Forecasting of Wind-damage

It is important that a forest manager should be able to forecast the likelihood of wind-damage with some precision, so that suitable allowances can be made when preparing management systems and production forecasts.

The frequency of occurrence, and the intensity of storms in different parts of the country, will of course influence the actual date when any stand is damaged.

Observations of the tree height at which crops on similar soil types are damaged, will enable some estimate to be made of the height which younger crops might attain, on the same soil type and with similar exposure.

Soil type and exposure are the most important factors affecting stability, poorer soils, especially peats, being frequently found in more exposed areas. It is therefore helpful to draw some arbitrary distinction between exposed and sheltered sites, since trees will grow taller before being damaged on susceptible soils when situated in sheltered areas.

In the preparation of a forecast of wind-damage susceptibility at Kielder, the forest was divided into three zones of exposure; *very exposed*, approximately above the 1,000 ft. contour; *moderately exposed*, between the 750 ft. and the 1,000 ft. contour; and *moderately sheltered*, below the 750 ft. contour.

Observations of existing wind-damage, and a knowledge of the distribution of soil types within such zones, will then allow estimates to be made of the feasible rotation length of younger crops, as yet undamaged.

The tree-pulling studies and field observations made to date suggest that on surface water gleys, peaty gleys and deep peats, tree crops are unlikely to exceed a height of about 50 ft. on exposed hill top sites, and 60 ft. on less exposed valley side sites, before suffering severe windblow.

Wind-damage is unlikely to occur on brown earths, deeper than about 24 inches, before the crop has reached an economically acceptable size, provided thinning is commenced in early pole-stage. On very exposed sites some wind-damage can be expected at an earlier stage.

The prospects are that Sitka spruce crops will be as stable on peaty podzols as on brown earths, but that crops may pass through a susceptible stage between 40 and 50 ft. in height.

7.3 Classification of Root Systems

The surface development of the root system gives a general indication of the depth and vigour of the sinker roots which cannot be seen unless the root system is exposed. Usually deep rooting is associated with a few short laterals, and shallow rooting with a large number of long laterals. Between these extremes an intermediate type can be recognised.

The following three types are therefore described briefly as a rough guide to the assessment of root conditions by superficial examination.

Type A. Narrow-spread; Deep root

This type is normally associated with deep well-drained mineral soil, or deep peat, and may be identified in the forest by the downward inclination and abrupt taper of the lateral roots. Plates 13 and 14 illustrate a typical example of this type of root. This should not be confused with the shape found in turf-planted trees, where the roots flatten out after an initial downward inclination. Removal of the litter will clearly expose the type of rooting.

It is not possible to estimate the depth to which roots have penetrated, without digging a soil pit to determine the depth of permeable soil. A variant of this type may be quite shallow rooted if there is no great depth of soil over rock, pan or compacted layer (see Plate 15).

Type B. Intermediate root

This type is normally associated with peaty podzols, and drier peaty gleys, and may be identified in the forest by a predominantly surface root system with several long laterals. The position of sinker roots may be identified by sudden reductions in diameter in the lateral roots.

If the peaty surface feels dry, and a soil pit shows a yellow-brown—or red-brown B horizon, it is quite likely that sinker roots will be well developed (see Plates 16 and 17).

Type C. Wide-spread; Shallow roots

This type is always found on wet surface water gleys, peaty gleys and deep peat. When leaf litter and debris has been brushed away, large gently tapering laterals may be observed radiating in all directions along the surface. These laterals will show no sudden reduction in diameter. Where this type of lateral is observed, shallow rooting is almost certain certain (see Plates 18 and 19).

Chapter 8

CONCLUSIONS

Investigations of the root-development and stability of Sitka spruce in North Wales and the English-Scottish Borders lead to the following general conclusions.

1. The form of the root system of Sitka spruce is determined very largely by the soil type on which it is planted (see Chapter 5, 1). This is closely in accord with the well-known observations of Day (1963 and elsewhere).

- **a.** On mineral soils with good natural drainage, the species will develop deep sinker roots. The depth of rooting is determined by the amount of permeable soil, over rock or compaction. The lateral root development is largely determined by the proximity of neighbouring trees, but root plate diameter tends to increase as rooting depth increases. (See Chapter 5.1.1).
- **b.** On peaty podzols, the depth of rooting achieved will be very variable, depending entirely on the degree of development of the pan. Downward rooting may be delayed until the tree crop has dried the surface. Lateral roots are generally more strongly developed than on brown earths. (See Chapter 5.1.2).
- **c.** On surface-water gleys, peaty gleys and deep peat, the depth of rooting is determined by the depth of aerated soil. (See Chapter 5.1.3. and 5.1.4).

2. Artificial drainage of peaty gleys, and almost certainly the surface-water gleys and deep peats, will result in deeper rooting. A pole-stage crop was shown to have responded to intensive drain deepening. (See Chapter 5.2).

3. The influence of spacing and thinning is different on dry and wet soils. Response of lateral roots to thinning is slow on dry soils, but more rapid on wet soils. Close spacing (3 ft.) results in early initiation of sinker roots on dry soils, though the effect in comparison with widely spaced (8 ft.) crops disappears by pole-stage. Wide spacing results in a reduction of rooting depth on wet soils. (See Chapter 5.3. and 1*c* above.)

It is thought that the density of young (pre-canopy stage) crops has a marked influence on the wetness of the surface layers of the soil. The soil under denser crops is drier than under more open ones, and the rooting deeper. Hence in crops of different initial espacements, there is a well marked inverse relationship between lateral spread and depth of rooting.

4. No difference in form, or increase in resistance to overthrow, was measured in relation to compass direction. On slopes greater than 15°, the lateral roots were concentrated on the downhill side of the tree, but no measurable difference in resistance to overthrow was detected when trees were pulled upslope and downslope. (See Chapter 5.4).

5. The resistance to overthrow is related to tree size and soil type. Trees on the same soil type in different forests showed similar resistances to being pulled over. Resistances were significantly different between soil types. Trees on deep brown earths are appreciably more stable than other soil types. Large trees on shallow brown earths (30 in.) were appreciably less stable than those on deep brown earths. Peaty podzols showed considerable variation, related to root penetration of the pan. In general, resistance to overthrow increased as peat depth increased. (See Chapter 6.1).

6. The ratio of total root weight: total shoot weight varied with the fertility of the site. The higher yield class had a lower ratio. (See Chapter 6.2).

7. Cultivation, draining, spacing and thinning treatments must be varied according to soil type in order to obtain the optimum development of the root system.

Each soil type requires certain special treatments, in order to reduce the risk of wind-damage.

- **a.** Brown earths—wide spacing, and heavy early thinning.
- **b.** Peaty podzols (with permeable B_2 Horizon)—Tine ploughing to rupture the pan.
- **c.** Surface water gleys, peaty gleys and deep peat—Deep drainage, and light thinning in older crops which cannot now be drained. (See Chapter 7.1).

8. A knowledge of the distribution of soil types, combined with estimates of exposure for a forest, will enable a useful forecast of wind-damage to be prepared. (See Chapter 7.2).

ACKNOWLEDGEMENTS

The authors would like to record their appreciation of help and advice given by Mr. D. G. Pyatt (Soil Survey Officer) in connection with many of the site selections. Also to Messrs. R. M. G. Semple, R. Lines, S. A. Neustein and D. W. Henman for suggestions and helpful criticism: also to Messrs. G. S. Forbes, R. Ure, I. Blackmore, T. Wilkinson, J. Busby, A. C. Hansford and J. White, who all at one time or another contributed towards the improvement of the tree-pulling technique. Thanks also to Mr. P. Gregory who carried out the root-sectioning studies at Radnor. Finally to the many field foresters, in charge of the plantations where our researches were carried out, for readily providing labour and assistance.

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APPENDIX

THE UNCERTAINTIES OF WIND-DAMAGE IN FOREST MANAGEMENT

by A. I. FRASER

(Paper delivered to the Annual General Meeting of the Society of Irish Foresters, March 20th, 1965, and reprinted in *Irish Forestry*, Vol. 22, No. 1, 1965, pp. 23–30.)

Introduction

It is most undesirable to have the uncertainty of large scale wind-damage when preparing long-term forest management plans. Looking ahead, I do not think that wind-damage will necessarily be inevitable within acceptable economic rotations in Britain, but there are many areas where, in the first rotation at least, wind will be the deciding factor. As a first step, therefore, it is necessary to be able to recognise those sites where wind-damage will occur, so that account can be taken of them in forecasting production, and decisions can be taken on whether or not to try preventive measures.

The occurrence of storms of sufficient strength, and with a high frequency, is of course the basic requirement for wind damage, but there seems little doubt that this condition will be fulfilled in most upland parts of Britain, and probably Ireland. Wind-damage takes two forms, stem-break and uprooting, so that it will occur anywhere where conditions are such that the trees are unable to develop their stems or roots fully.

There are numerous ways in which the silviculturist can affect the development of both the roots and the stems of trees, so that a better understanding of the response of trees to different treatments will help in deciding on the most effective preventive measures.

Many factors are involved in the problem of wind-damage, but studies over the past few years have indicated that the main concern is uprooting of the spruces on poorly drained soils, and stem breakage of a range of species on freely draining soils. My own investigations have therefore been directed towards these two aspects, though exceptions have been noted when they occurred.

This division between freely draining and poorly drained soils is a convenient one, and it will, I hope, become apparent that it is most important to be able to recognise these soil types and treat them differently.

Poorly Drained Soils

This category includes surface water gleys, peaty gleys (peat up to 24 inches deep) and frequently deep peats. Other soil types may be included, but these three account for the major proportion.

It is not really known at what stage excess soil moisture becomes harmful to tree roots, but if the soil remains saturated for prolonged periods, at any depth, rooting will be restricted.

There is some difference between species in their ability to tolerate water-logging, but Sitka spruce seems to be as vigorous as any under these conditions.

In the most severe conditions the roots will be restricted to the familiar flat plates seen on uprooted trees, but under slightly better conditions short sinkers may develop under the lateral roots. Rooting depth may vary from as little as 10 inches on the wettest sites to about 20–24 inches on some of the better deep peats. Uprooting will therefore be the predominant kind of damage, and it can be expected to start with small groups of trees blowing over, any time after the crop has exceeded about 35 feet in height.

Once wind-damage has started it is likely to continue at an accelerating rate until most of the crop has been affected. Changes in soil type, crop size or species will frequently form a boundary at which the damage stops.

The onset of wind-damage in these sites may also be associated with a slowing down in height growth in the remaining crop; probably due to a combination of damage to roots, and to increased exposure.

Here then is one situation where some uncertainty can be removed. A fairly quick reconnaissance with a spade, in a crop which has just started to show signs of wind-throw, will reveal how far it is likely to extend. Observations of the rate of extension for a season or two will soon indicate the time when action should be taken to clear the crop. A number of factors can initiate the wind-throw; perhaps the most common are thinning and drain maintenance, which respectively expose the remaining trees, and result in roots being severed.

However, while delayed or heavy thinning may make matters worse, early thinning does not appear to have any advantage, and only the complete avoidance of thinning would seem to help prolong the life of the crop slightly. Where rooting is bad, however, wind-throw is inevitable.

Freely Drained Soils

This category includes brown earths of a range of depths, and a complex of podzolic soils, which may or may not have a pan, or a peat layer.

Under these conditions most species, especially

Sitka spruce, will develop deep sinker roots, often almost tap roots under the stem of the tree, and rooting depths from 2 to 7 feet are common. Except where rock or an indurated layer physically restricts the rooting, the predominant type of damage will be breakage of the stem. In Britain this type of damage is most often found on fertile sites where height growth is rapid and delayed thinnings depress girth growth of the stems.

The first thinning suddenly exposes the trees, and small groups can be snapped off. It may or may not then extend, depending on the growth of the remaining trees, and the nature of the soil. Uprooting may also occur on these soils where depth is physically restricted by rock or induration.

RESULTS

These then are the two main problems that the forest manager must face, but before discussing ways and means of overcoming the problems it is, I think, worth having a look at recent research results which will provide some evidence to support recommendations.

We have for the past few years been studying the root development of various species, but mainly Sitka spruce, on a range of soil types, and have some measure of trees' resistance to break or uprooting from the tree-pulling investigation. We also have some data on the forces which will be applied to trees, as measured in wind tunnels, and although the research is nowhere near complete, the available results from the two lines of investigation have been linked up. The results, while being far from decisive, are, I think, still worthy of close inspection because they do fit in remarkably well with field observations.

If the turning moment at the base of the tree, that will be applied by any wind velocity, is calculated and the result equated with the turning moment that trees on a given site are known to resist from tree-pulling studies, it is possible to find the critical wind velocity for any size of tree. This critical velocity can then be plotted against size of tree for a range of sites, so that a family of curves as shown in Figure 6 are produced.

All that is now required to predict the size that a crop will reach before being blown over, is a knowledge of the frequency of gales of any velocity. It seems from still fairly limited observations that on upland sites a mean hourly wind speed of 40 knots can be expected quite frequently; probably in 2 out of 3 years. It can be seen then that trees on peaty gleys and surface water gleys would be blown at 50 feet, deep peat at 60 feet, and brown earths at 70 feet by such a wind. This accords well with observations. In sheltered valley sites the maximum wind velocity may only be 30–35 knots, allowing correspondingly taller trees.

This now gives us a base line against which we can judge the likely benefit from silvicultural treatments such as spacing, ploughing, draining, and thinning. It also gives us a better idea of the relative susceptibility of different soil types, and something on which to base estimates of rotation length. It should, however, be made clear that the curves shown are the average of several sites in different forests, and that there is quite an amount of variation about each line. Thus some deep peats may be as poor as peaty gleys, and others nearer brown earths.

As already mentioned, Sitka spruce and, as far as can be seen, most other species will develop deep sinker roots, given a free draining soil. On these sites, however, lateral root development is very much affected by the proximity of neighbouring trees.

This is clearly illustrated by the measurements of root-spread of trees pulled over in two spacing experiments, in Radnor and Clocaenog forests in North Wales. Both sets of plots were planted in the same year, but one which grew more rapidly had been given thinnings, while the other was still unthinned when pulled. Both plots were 28 years old when pulled over, and the thinned plots averaged 45 feet tall, while the unthinned ones were 39 feet tall.

Rooting depth varied from 2–3 feet, according to the depth of soil. It can also be seen from these figures that the response after thinning is quite slow, and in the closest spaced plots the root spread is still less than the spacing after eight years.

TABLE 9. ROOT SPREAD DEVELOPMENT RELATED TO SPACING ON THINNED AND UNTHINNED SITKA SPRUCE AT RADNOR AND CLOCAENOG FORESTS

Unthinned		*Thinned*		*Years since First Thinning*
Spacing	*Root Spread Diameter*	*Average Spacing*	*Root Spread Diameter*	
3 ft. × 3 ft.	4·2 ft.	5½ ft. × 5½ ft.	5·2 ft.	8
4½ ft. × 4½ ft.	5·0 ft.	8½ ft. × 8½ ft.	6·6 ft.	8
6 ft. × 6 ft.	6·2 ft.	11 ft. × 11 ft.	6·2 ft.	4
8 ft. × 8 ft.	7·6 ft.	13 ft. × 13 ft.	8·7 ft.	4

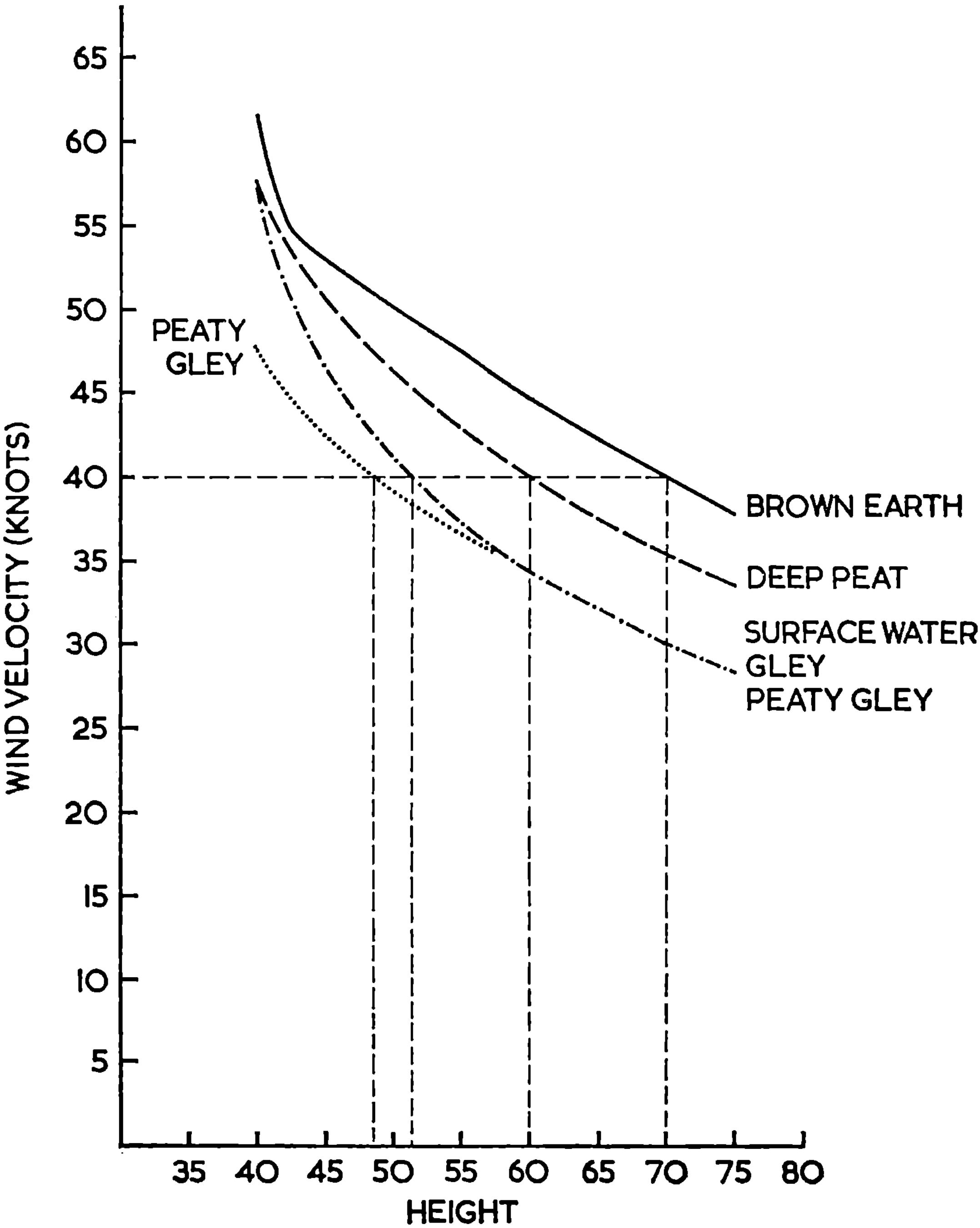

Figure 6. Curves showing the relationship between critical velocity and tree size, for trees on different soil types.

On poorly drained soils the situation is quite different; directly comparable figures are not available, but two other experiments are of interest.

One of these was an experiment at Forest of Ae in South Scotland where pairs of dominant Norway spruce were selected when the crop was 11 years old, and one tree of each pair randomly chosen for isolation. These trees have been maintained as isolated dominants while the other one of the pair has been left in the unthinned crop. The trees were pulled over when 25 years old.

The second experiment was a thinning experiment at Kielder in North England in Sitka spruce, where four plots were marked out in a 14-year-old crop. The plots were then heavily thinned in turn (one third of the stocking removed at each thinning) on a three-year cycle, so that the first thinnings were given at the age of 14, 17, 20 and 23 years respectively.

Although the plots were not replicated and one was eliminated because of a difference in soil type, it is interesting to study the relationship between rooting diameter and depth for these two experiments, as seen in Table 2. The trees were 30 years old when pulled over.

Compared with the freely draining soils, the root systems of these trees have responded much more to opening up in terms of lateral root spread. On the other hand there has been a detrimental effect on rooting depth which was not nearly so apparent on the freely drained soils.

TABLE 10. EFFECT OF SPACING ON ROOTING DIAMETER AND ROOTING DEPTH IN TWO EXPERIMENTS (SEE TEXT)

Species	Effective spacing	Rooting diameter		Rooting depth		Years since thinned
NS Isolated dominants experiment	5·7 ft.	6·6 ft.	±0·5	21·0 in.	±1·72	—
	12·7 ft.	10·1 ft.		14·6 in.		14
SS Thinning experiment	8·5 ft.	8·2 ft.	±0·6	15·0 in.	±0·7	10
	10·0 ft.	9·2 ft.		13·2 in.		13
	12·0 ft.	13·2 ft.		9·8 in.		16

The resistance to pulling over, comparing similar sized trees on the various treatments, is the same, but of course the wind forces applied to the trees in the open plots will be much greater.

One possible explanation of these results is provided by considering the effect of the crop on the moisture regime of the soil. In the close spread crops, the interception of rainfall and removal by transpiration will be greater than in the widely spaced crops, because of the denser cover and the greater crown surface area. This could result in an appreciable drying out of the site and improved rooting conditions. Is this an argument in favour of "no thinning" on badly drained soils which are susceptible to wind-damage?

Little work has been done yet on studying the effects of initial ploughing treatment on the development of the root systems in the thinning stage. However, observations definitely indicate that on freely draining soils lateral root development takes place under the plough furrows, and the tree stability is unlikely to be affected. On badly drained soils, especially if the depth of the plough furrow is almost the same as the depth of the permeable top soil, lateral root development is restricted, and in the absence of sinker roots the trees are quite unstable.

A much more important form of ground preparation is of course drainage, which not only is the main requirement to prevent wind-throw, but will also go a long way towards increasing the productivity of the site.

Unfortunately there is very little experimental evidence available at present to provide information on the response of tree crops to drainage, either as improved root or shoot growth. One experiment described in an earlier paper (Fraser 1962 a), has shown that a thicket-stage crop will respond to drain deepening, but the experiment did not have drains up to present-day recommendations. The prospects of major improvements in rooting are high if drainage is carried out at planting, or in the first few years of growth; but it becomes a more uncertain operation when trying to save crops which have already reached thicket stage. The response seems unlikely to be enough to postpone wind-throw sufficiently to recover the high cost of the operation.

Economic calculations tend to confirm the view that drainage at planting is in all respects the most desirable, but that up to early thicket stage (say 10 years) it is still a profitable operation.

So far we have dealt with the soil and roots, and silvicultural treatments which can improve these and hence a tree's ability to withstand wind forces. The silviculturist can also influence the forces which are applied to the trees, by giving attention to crop structure and layout.

Wind tunnel tests, which have been described in detail elsewhere (Fraser 1962 b and 1964), have demonstrated the adverse effects of roads and thinning on the problem. Both of these factors result in very appreciable increases in the forces applied to the trees and, as has been discussed earlier, on the most susceptible soils trees are unable to resist these by developing better roots.

These same studies and field observations on forests growing in exposed sites, strongly suggest that the most effective method of reducing the forces on the trees in a crop is to achieve a smooth surface to the canopy. By doing this, the amount of energy which can be transmitted to the trees is reduced to a minimum, and it is confined to the tip of the tree, where the cross-sectional area is least. If a rough surface is developed, either by thinning or by felling small groups, turbulent flow is created, and much greater forces are applied to the main crown lower down the trees. On well rooted soils, the trees are likely to be able to withstand these high forces, and will probably develop roots in response, but on badly drained soils this is not possible and wind-throw will occur. Any kind of thinning tends to make the surface of the canopy rougher. Experiments are now in hand to throw more light on this topic.

Conclusions

With the results discussed so far, it becomes possible to rationalise any given situation and make plans with some prospect of adhering to them.

The first obvious step is to obtain some detailed knowledge of the soils in a forest, so that the likely extent of the problem can be assessed, and also so that treatments can be adjusted accordingly. A soil map is perhaps a luxury, but notes kept in compartment records can go a long way towards indicating soil type.

The second step must be to obtain a break-down by age classes of crops on the susceptible soils, so that decisions can be made on the allocation of work. It has been found convenient in some cases to recognise three age-class groups, on susceptible soils.

1. Crops which are more than about 25 feet tall; probably over 20 years of age. These will be in imminent danger of blowing over, and will almost certainly have passed the stage where drainage could be effective. Thinning in such crops will probably initiate some wind-throw.

   Such crops are almost certainly past saving, and consideration of anticipatory fellings seems eminently worthwhile; this avoids the fluctuations in work and output of produce which are inevitable if wind-throw is accepted as it comes.
2. Crops which are between 10 and 25 feet tall; probably 10–20 years of age. These crops will be expensive to drain, but have a reasonable chance of responding. The resources available will decide whether drainage can be attempted, but they will be of low priority because of the uncertainty of success. On the other hand, thinning and even brashing could be avoided with reasonable prospects of prolonging the life of the crop. (Avoidance of brashing reduces costs rather than increases stability).
3. Crops less than 10 feet tall; younger than 10 years. These crops can readily be drained, and with improved techniques, at an acceptable cost. The response is likely to be large, and so wind-throw may well be eliminated or at least delayed long enough to make a decent income from the crop.

A fourth category of course are crops on non-susceptible soils, which, apart from being thinned early and regularly, need not be subject to other constraints.

Much useful information can also be obtained by studying any wind-damage that occurs in some detail. The frequency of damage, the soils on which it occurs, and the height of the trees that are blown over, are all useful guides as to how long younger crops will stand. This is invaluable if deciding on anticipatory fellings, which ideally should be the day before the trees would have blown over!

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Printed in England for Her Majesty's Stationery Office
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(B20316) 106921/Dd.126936 K30 7/67 Gp.466

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