FORESTRY COMMISSION

BULLETIN No. 21

TREE ROOT DEVELOPMENT ON UPLAND HEATHS

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By

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1955

FOREWORD

THIS bulletin presents the results of an investigation on the rooting of coniferous trees on upland heaths, carried out between November, 1951, and April, 1953, by Mr. C. W. Yeatman. This work was done on experimental areas in the Commission's forests, where one of the objects under investigation is the value of various methods of soil preparation on the establishment and subsequent growth of tree crops. In view of the considerable areas of upland heaths available for afforestation in Great Britain, and the difficulties that commonly attend the early growth of trees thereon, the subject is of great importance to forest development.

FORESTRY COMMISSION,
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London, W.1.

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INTRODUCTION

This bulletin presents the findings of an investigation carried out between November, 1951 and October, 1952, at five selected forests in north-east England and Scotland, namely, Allerston Forest and Langdale Forest, Yorkshire; Teindland Forest, Morayshire; Clashindarroch Forest, Aberdeenshire; and Dornoch Forest, Ross and Cromarty.

The investigation was initiated by the Forestry Commission as part of the programme of research into the afforestation of heathlands, of which there are great areas potentially available for afforestation in Britain.

The object of this investigation was to study the root development of coniferous forest crops on upland heaths to determine:—

(i) The relationships existing between the development of the root systems, the soils, and the types and intensities of cultivation prior to planting.

(ii) The effects of the application of fertilisers on the vigour of the root systems.

(iii) Differences occurring in the root systems of the species studied.

(iv) The comparative ability of the root systems of these species to exploit the soils, both in their natural state and when cultivated.

In the light of this information, and with reference to relevant studies and practice in Britain and elsewhere, desirable methods of cultivation and the selection of species for the afforestation of upland heaths are considered.

Chapter 1

THE UPLAND HEATHS

I. DESCRIPTION AND DISTRIBUTION OF UPLAND HEATHS

Tansley (1939) in *The British Islands and their Vegetation* describes "the heath formation of western Europe, of which the chief consociation is characteristically dominated by the common heather or ling, *Calluna vulgaris* Salisb." This he divides into Lowland heath (Callunetum-Arenicolum) and Upland Heaths (Callunetum).

The upland heaths include both the callunetum or heather moor and the vaccinietum or bilberry moor. In the past, heath and heather moor have often been separated both by German, English and Scottish authors and Tansley quotes Adamson as distinguishing "upland heaths" on shallow peat in which the roots of the vascular plants penetrate into the sub-peat layer, from "heather moors" on deep peat in which they are confined to the peat itself. Owing to the lack of floristic distinction Tansley rejects this differentiation and classes all communities dominated by *Calluna* as "Upland heaths". He classifies the plant communities formed on the constantly wet acid peats and characterised by Sphagnetum, Eriophoretum, Scirpetum and Molinietum under the moss or bog formation, although they may sometimes bear heather and may be referred to as heather moors. Fraser (1933) uses the term "climatic *Calluna* moor" to denote the upland heath formation, in contradistinction to *Scirpus* moor and *Molinia* moor.

Definition

In the practice of afforestation the practical viewpoint of Adamson has been accepted and for the purpose of this investigation the upland heath is defined as: *A callunetum on shallow peat in which the roots of the vascular plants penetrate into the sub-peat layer. The peat is commonly two to four and never greater than twelve inches thick.*

Status of the Heath Formation

In dealing with the 'Status of the heath formation' Tansley (1939) states: "Primarily it is a west European formation, interdigitating so to speak with bog and forest, replacing the former on the better drained soil, and the latter on the lighter and poorer soil, where pasturing or burning prevents the colonisation of trees. It can only be counted as a climatic formation on exposed coasts and on exposed mountain slopes between 300 and 600 metres (higher than this in Scotland and north-east Ireland) that is in situations where the wind factor is definitely inimical to tree growth and where this is combined with good drainage and acid soil, either derived from acid rocks or where the climate favours rapid leaching and peat formation. In these situations heath is certainly a climax, for, although the upland heaths of northern England and Scotland are practically always used as "grouse moors" and are fired periodically, there is no evidence that such heath, where it lies above the forest limit, would be superseded by any other type of vegetation were it left entirely untouched". Tansley considers that the heath formation may in some cases be the result of the degeneration of former forests and in others may never have borne forest.

Distribution in the British Isles

Tansley (1939) gives the distribution of upland heaths as follows: "On the eastern side of Ireland and Wales, for example on the Wicklow Mountains, the Mourne Mountains, and on the Welsh Marches; and of Great Britain, as in the eastern Highlands and on the Cleveland Moors, upland heath dominated by *Calluna* is far more extensive, both on steep and gentle slopes and even on plateaux where the soil is permeable. These calluneta are the typical grouse moors."

Adamson also classed the heather moors of the Southern Pennines as upland heaths which are "very closely allied to the heaths of the lowlands and the South."

Afforestation Problems

Great areas of upland heath are available for afforestation in Great Britain, particularly in the north-east, provided that an economic means of establishing successful tree growth on them is available. On much of the better type of heath successful plantations are attained by direct planting. In the last two decades great advances have been made in the establishment of trees by cultivation and the application of fertilisers on the poorer types of heath. It is with experiments established on these latter heaths between 1928 and 1943 that this report is mainly concerned. Direct planting of trees into the poor heaths frequently results in an initial high mortality and lack of vigour, resulting in complete or partial check, or else very slow growth. The degree of success of such a plantation depends on the quality of the heath, the fertility of the soil, the severity of the climate and the species planted; once established, the crop may be liable to windthrow or early senescence owing to shallow restricted root systems.

Methods must be devised to ensure the successful establishment of forests on heathlands which, as far as can be foreseen, will ensure their continued growth to provide useful timber.

II. THE CLIMATE, VEGETATION AND SOILS OF THE UPLAND HEATHS

Climate

The development of the heath formation is primarily determined by climate. Other factors such as soil, drainage, exposure, fires and grazing also play their part in determining the extent of the heaths. Tansley (1939) states 'The general European distribution of heath follows the cool temperate oceanic and sub-oceanic climatic regions pretty closely.'

The essential features of such a climate are: a fairly even rainfall distribution, a generally high relative humidity and the absence of prolonged periods of high temperatures, i.e. a low rate of evaporation, for most of the year. Fraser (1933) in describing the distribution and climate of climatic *Calluna* moors (upland heaths) of eastern Scotland, and comparing them with the climatic *Scirpus* moor of the west, states: "This type of moorland vegetation occurs . . . . where the rainfall is lower and less evenly distributed throughout the year, and where the relative humidity is also lower and the number of days of bright sunshine is greater". The mean rainfall over the upland heaths lies generally between twenty-three and forty inches a year.

With reference to frost, Day and Peace (1946) in *Spring Frosts* make the following relevant observations. ". . . largely because of loss of heat by evaporation, wet soil surfaces also tend to be cold frosty ones . . . during the day time loss of heat by evaporation is so much greater from wet soil that it will start the night too cold for its greater specific heat to give it any advantage". When discussing low shrubs (in particular normal *Calluna* cover) as shelter for trees they say "Observations showed that shelter of this type was not often effective. The reason is that interplanted trees are left too open to the sky and thus receive little or no shelter during radiation frosts". The writer has noticed that during a spell of frosty weather even in a mildly peaty surface, at Devilla Forest, Fife, frost was held in the surface to three or four inches over brief periods of thaw, when exposed ploughed mineral soils were free of frost. Where the surface was covered with unburned birch litter the soil was frosted only for an inch or so while that under heather, burned or unburned, was solid for several inches. On the other hand bare, mineral surfaces, and particularly tilth, were more affected by mild frosts of short duration than were peaty surfaces.

In conclusion Day and Peace state: "Frequently serious frost damage occurs in places where the soil conditions are to some extent unfavourable to tree growth. When such conditions exist the trees recover (from frost damage) more slowly and take longer to get above the usual level of cold air than would otherwise be the case".

Thus upland heaths accentuate the severity of frosts and their various effects rather than the reverse.

Wind and severe exposure are inseparable from upland heaths and their effects on trees become more pronounced on the poorer sites supporting unhealthy plantations.

Vegetation

The species and proportion of plants associated with the dominant *Calluna* of a callunetum vary with the nature and quality of the heath, and locally with the incidence of heath burning. The poorest heaths on the wetter sites support a degraded form of *Calluna* with a high proportion of *Erica tetralix*, lichens and algae which may form an intermittent surface scum over the peat surface. The best heaths on the drier sites support a vigorous form of *Calluna* predominant over *Erica cinerea* and other plants indicative of the better sites. More detailed descriptions of the vegetation types are given below for each area under consideration.

The age and origin of the upland heaths vary and often remain obscure. Some have supported forest vegetation in ancient (inter-glacial and post-glacial) periods and others have supported trees to within comparatively recent times (within the century). Many reasons are advanced for the deterioration of the forests, any or all of which may apply to a particular area. Major changes in the climate have occurred during the period following the last glacial period. The soils have deteriorated owing to the process of podsolisation which occurs naturally under the climate and vegetation prevailing on the upland heaths, especially where, as frequently happens, the parent soils materials are sandy. Man has aided these processes by timber felling, repeated burning, and intensive grazing. *Calluna* is thus able to invade the forest and by its nature assists this deterioration of the vegetation and soil until finally a stable callunetum becomes firmly established. When protected from fire and grazing the better heathlands may in time become recolonised with forest species. Many of the extreme examples of upland heath at the higher elevations have in all probability, never borne trees.

Soils

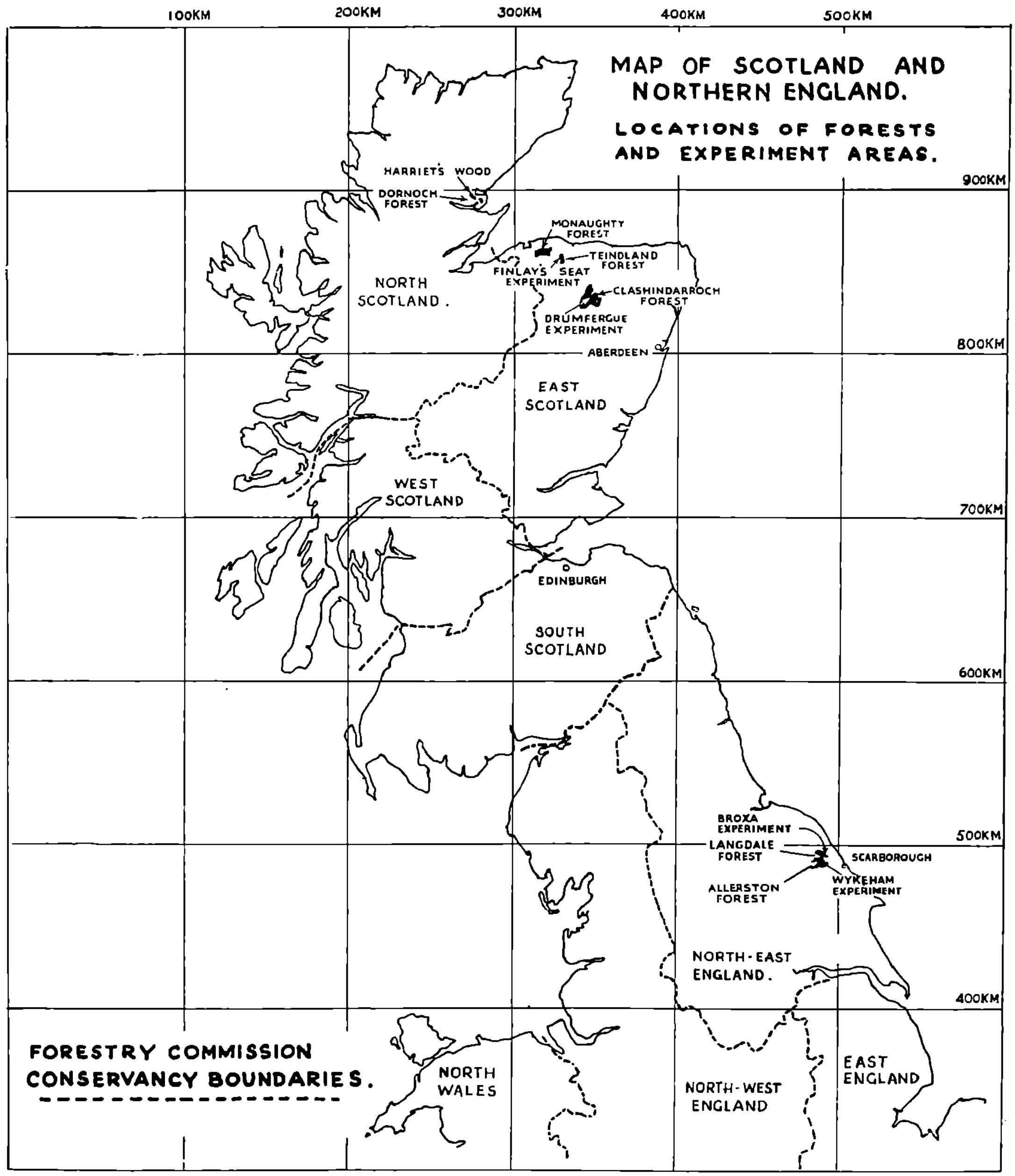
The establishment of *Calluna* transforms the strongly mineralised topsoil into a poorly mineralised soil or thin peat. This develops into a continuous soil cover of fibrous *Calluna* peat which retains a large amount of water, thus excluding air and preventing the aerobic decomposition of the organic matter. Once this process has begun the peat continues to accumulate and air is unable to penetrate through it to the underlying soil during the greater part of the year.

At most sites encountered in this investigation the subsoil underlying the weathered profile was compact in nature and impeded the vertical drainage of moisture, as well as providing a definite limit to the depth of soil available to the roots of any vegetation, shrub or tree. It is the view of the writer that it is largely the nature and intensity of compaction of this subsurface barrier that has greatly aided the formation of the soil and vegetation type of the extreme forms of upland heath. The compact subsoil is by no means a complete barrier to drainage as the frequent formation of a mature podzol profile evidences but it is capable of slowing down considerably the rate of the vertical movement of water. An iron pan frequently forms in later stages of podzolisation and prevents vertical drainage almost completely, with the consequent formation of a gley horizon above it.

The anaerobic nature of these undisturbed peat soils has been demonstrated by many workers in this field. Rennie (1953) states that "*Calluna* peat overlying all geological types at Allerston remains waterlogged for considerable periods of the year, the aeration only increasing for prolonged dry periods. Peat supporting *Eriophorum* and to a lesser extent *Erica tetralix* is only slightly aerated during dry summer periods".

Fraser (1933: p. 40-1) bases his determinations of the degree of aeration of peat on its oxygen requirement, determined by the ability of the peat to reduce a ferric iron solution to the ferrous condition, and expressed as the number of grams of oxygen required for the oxidation of the iron reduced by the action of 100 grams of air-dry peat. The following statement is worthy of note. 'In peat soils, in which iron is accumulating either throughout the general mass, or in layers, the oxygen requirement figures are abnormally high'.

Upland heath soils are invariably acid in reaction, both in the peat and the weathered mineral soil (the profile). Fraser (1933: Table II) quotes figures for the pH of *Calluna* moor in eastern Scotland ranging from 3.0 to 4.2 with an average of 3.3. Muir and Fraser (1939-40: p. 272) in their survey of soils in Aberdeenshire state that in the peaty podzol group "the surface peaty layer is always strongly acid, in some cases reaching a pH of 4.0. The acidity decreases as usual with depth, but in no case does the pH exceed 5.5." Their data indicate that in certain profiles the acidity increases somewhat from the surface to a maximum somewhere about the peat-soil interface, and then decreases downwards towards the parent material. Muir (1934) shows a similar range of pH values for normal podzols and peaty gley podzols at Teindland forest.


MAP OF SCOTLAND AND NORTHERN ENGLAND.
LOCATIONS OF FORESTS AND EXPERIMENT AREAS.
100KM
200KM
300KM
400KM
500KM
900KM
800KM
700KM
600KM
500KM
400KM
HARRIETS WOOD
DORNOCH FOREST
MONAUGHTY FOREST
TEINDLAND FOREST
FINLAY'S SEAT EXPERIMENT
CLASHINDARROCH FOREST
DRUMFERGUE EXPERIMENT
ABERDEEN
NORTH SCOTLAND.
EAST SCOTLAND
WEST SCOTLAND
EDINBURGH
SOUTH SCOTLAND
BROXA EXPERIMENT
LANGDALE FOREST
SCARBOROUGH
ALLERSTON FOREST
WYKEHAM EXPERIMENT
NORTH-EAST ENGLAND.
NORTH WALES
NORTH-WEST ENGLAND
EAST ENGLAND
FORESTRY COMMISSION CONSERVANCY BOUNDARIES.

The nutrient status of upland heaths varies with the degree of podzolisation of the soil profile and the nature of the parent material. The physical characteristics of these soils in their natural state, noticeably their anaerobic nature and degree of compaction, generally limit the growth of trees. It is only after these limitations have been overcome by cultivation that the level of fertility of the mineral soils becomes apparent. Thus each soil type must be treated individually. For instance, in the Teindland experiments there is a proven necessity for artificial fertilisers in order to obtain reasonable tree growth, while no such limitation is apparent at Clashindarroch. Generally, however, the soils are poor in available nutrients, particularly phosphorus and nitrogen.

III. LOCALITIES CHOSEN FOR INVESTIGATION

1. ALLERSTON AND LANGDALE FORESTS

Locality

Allerston Forest lies on the southern and eastern slopes of the North Yorkshire moors, a few miles west of Scarborough on the north side of the Vale of Pickering. Wykeham moor forms the south-east section of Allerston forest. The Broxa outlier, which forms part of Langdale Forest, is two to three miles north of Wykeham moor.

Site

Geology. The area lies on Jurassic limestones and sandstone covered for the most part by the lower Calcareous Grits of the middle oolite series. The bulk of the planted area is between the 500 foot and 750 foot contours. (Zehetmayr 1951.)

Climate. Mean annual rainfall of the forest is twenty-five to thirty inches per annum, the moors are totally exposed to winds from all directions, the prevailing winds are from south-west to west.

Vegetation. The predominant vegetation is callunetum with small localised areas of *Eriophorum* in shallow depressions.

Soils. *Historical.* Dimbleby (1950 and 1952a) has shown that the present-day soil and vegetation of these moors belong to the post-glacial period. The discovery of ancient frost wedges now filled with boulder clay prove that the areas were at one time ice covered. Further studies of the occurrence, identity and distribution of charcoal fragments and plant pollen within the soil profile show complex phases of disturbance in the upper soil horizons during the glacial period. These involved deposition and mixing *in situ* of boulder clay and local material transported by mud-flow (solifluction). Post-glacial flora developed during the Atlantic period as mixed broadleaved forest which included *Corylus*, *Ulmus*, *Quercus*, and *Tilia*. Destruction of the broadleaved forest and its replacement by heath coincided with the first occupation of these plateaux by man with a culture (Bronze Age) which enabled him to clear the forest. Continued burning, grazing, and fuel collection, together with some deterioration in climate have prevented re-colonisation of the moorland by trees, and has encouraged the growth of heather with the consequent formation of a podzol. Podzolisation probably commenced approximately 2,500 years ago and extended as the tree cover deterioriated, with the subsequent formation of an iron-aluminium hard pan.

Present day soils. Over the greater part of the plateaux the surface level of mineral soil has remained virtually unchanged since the end of the last glacial period. The soil today is a strongly developed podzol: one to three inches of raw humus (peat) above the leached sandy (A) horizon, under which is an indurated hard pan one-eighth to half an inch thick at depths ranging from six to twenty-four inches, typically eight to ten inches. deep. The pan at the shallower levels (six to twelve inches) appears to divide the sandy eluvial (A) horizon from the silt or clay sand illuvial (B) horizon. The deeper pan (sixteen to twenty-four inches) appears to form the base of the illuvial horizon, dividing it from the unweathered compact sand and stone parent material (C) horizon below. A further less compact region, referred to as the "loose region" sometimes occurs at depths ranging from three to six feet. (Photo 4)

2. TEINDLAND FOREST

Locality

Teindland Forest is situated about seven miles from Elgin, Morayshire, north-east Scotland, on the Orton road, and overlooks the Moray Firth.

The experimental area in which the work of this investigation was carried out is located at the south-west corner of Teindland Forest on high ground, rising gently to Findlay's Seat. The aspect is north-east and the altitude about 700 feet.

Site

Geology: A description of the forest area is found in *The Soils of Teindland State Forest*, Muir (1934): "Findlay's Seat rises very gently from the surrounding undulating plain and has all the characteristics of a well-glaciated hill. According to Bremner three great ice movements have taken place in north-east Scotland, and to the last of these the present surface form of the country is largely due. That part of the hill occupied by the forest can be divided into three distinct geomorphological elements with which are associated very closely both soils and vegetation.

The three elements are:—

(i) The upper slopes (above 700 feet) which do not seem to have suffered any fluvio-glacial action.

(ii) The fluvio-glacial channel margins which are found on the northern face of the hill, and run almost parallel to the Red Burn.

(iii) The overflow channels which are found up to a height of about 700 feet.

The main drift in this area is a purplish-red boulder till, the colour indicating its origin from the Old Red Sandstone rocks which it presumably overlies; this till is of considerable depth.

The till is extremely stony, and many of the stones are pebbles from the Old Red Conglomerate rocks. This red till is found over the whole of the upper part of the hill and at the bottom of the overflow channels."

Climate. Teindland is located between the thirty and thirty-five inch isohyets. The elevated plateau rising to Findlay's Seat is totally exposed to winds from all directions, and in particular to those from the north and north-east coming from the North Sea.

Vegetation. The natural vegetation of the experimental area may be described as a degraded callunetum. *Scirpus caespitosas* is commonly the co-dominant with *Calluna* and becomes dominant locally. *Erica tetralix*, *Sphagnum*, other mosses and the lichens *Cladonia* spp., occur throughout the area. Until recently scrubby Scots pine planted ninety to one hundred years ago occupied the area but had little influence on the ground flora.

Soils. Muir (1934) describes three main soil types of the great group of podzol soils which occur at Teindland.

(i) Normal podzols on fluvio-glacial sands and gravels.

(ii) Peaty gley podzols with hard pan on boulder till.

(iii) Peat gley soils on boulder till.

The soils of the area covered in this report belong to type (ii).

The surface of this soil type presents a continuous cover of peat three to four inches thick supporting the poor vegetation type described above. This peat remains in a water saturated condition for the greater part of the year, and may be frozen for much of the winter. In his description of the soils Muir states, "The main characteristic of these soils (as distinct from (i) and (iii)) is the presence of an extremely hard and almost continuous iron pan. The formation of this pan has led to an impedance in the drainage of the layers above it, with the result that the eluvial layer is no longer of the customary grey tint but tends more to an olive grey tone (gley) and the ground has been invaded by a very inferior type of vegetation. The hard pan is remarkable for its continuity and compactness . . . . and seems to be quite impermeable to water. It invariably has a thin matting of fine roots on its upper surface, ... and in none of the profiles in which it was continuous were live roots found below it. It fluctuates remarkably in depth from the surface, variations of fifteen to twenty centimetres (six to eight inches) over a distance of one metre (thirty-nine inches) being quite common . . . probably connected in some way with slight textural differences in the boulder clay."

The mean depth of pan for all profiles examined in this investigation was sixteen and a half inches, ranging in depth from eight and a half inches to more than twenty-eight inches, with differences in depth of more than twelve inches within a few feet.

Muir offers a choice of two explanations for the development of this soil.

(i) The soil developed as a normal podzol with the formation of an increasingly impervious hard pan underlying the layer of humus accumulation. Thus surface water-logging was made possible and peat formation set in.

(ii) Due to the layer of heather remains (peat) which has a high absorption capacity for water, the surface layers of the mineral soils would be kept in a wet (anaerobic) condition for fairly long periods. Under these conditions iron compounds would be reduced to the ferrous state, and as such leached out into the lower layers. These would be in a drier state and the iron would then be reoxidised and precipitated, eventually forming the hard pan.

The writer considers that a modification of both (i) and (ii) above offers a more reasonable explanation for the formation of this soil. The soil became podzolised before the formation of a surface cover of raw humus set in, that is when the area supported a higher vegetation type. As the profile developed through the natural processes of podzolisation, aided by fire and grazing, the fertility level of the soil decreased and the pH dropped, particularly in the surface horizons. Poorer vegetation types invaded the area, raw humus accumulated within the mineral surface horizon and on the surface, thus hastening the process of podzolisation. The intensely fibrous shallow rooted type of vegetation (callunetum) further accentuated the anaerobic state of the mineral horizons. Iron complexes remaining in the soil horizons were reduced and leached from the upper soil horizons to be re-precipitated lower down as a pan.

Dimbleby (private communication) has demonstrated that flocculating ferric hydroxide may be filtered from a slowly percolating suspension at the interfaces between horizons of different textures.

This suggests that the formation of a pan does not necessarily take place in the same horizon as the chemical flocculation of the iron colloids. Since textural differences occur naturally in these soils due to the manner of their deposition, they may determine the position of the (B) horizon in the subsequent podzol profile.

The impervious layer so formed causes water to accumulate for long periods of the year, causing the typical gleying immediately above the pan. The duration and depth of waterlogging of the soil depend on the depth and intensity of the pan formation, the degree of free surface run off, and the depth and permeability of the peat.

3. CLASHINDARROCH FOREST

Locality

Clashindarroch Forest lies thirty-five miles to the north-west of Aberdeen near Huntly. The forest stretches from the Rhynie-Cabrach road to Strath Bogie and the Hill of Foudland.

The Drumfergue experimental area is located about the 1,000 foot contour. The aspect is north and the slope gentle.

Site

Muir and Fraser (1939-40) in *The Soils and Vegetation of the Bin and Clashindarroch Forests* give a detailed description of the forest area, from which much of the following information is extracted.

Geology. The experiments overlie slates (Macduff group) belonging to the Highland schists which form the oldest rocks of the area.

Climate. The mean annual rainfall is thirty-five inches per annum.

The long ridge of high ground to the west and north-west of Clashindarroch Forest offers a barrier to the prevailing south-west winds. Winds from the north and north-west can be very severe in this area.

Moderately deep snow lies for many weeks of the winter (December-March) and may cause damage to young plantations.

Vegetation. According to the classification by Muir and Fraser, the vegetation of the area falls into the moist *Calluna-Vaccinium* heath type, described as *Calluna* dominant, with suppressed or poor growth of *Vaccinium myrtillus* and much *V. vitis-idaea*. Turf exposed and showing growth of crustaceous lichens.

Soils. The soil is a podzolised silty loam developed from the slate parent material beneath. The surface is covered with thin peat two to three inches thick. The first four to eight inches of mineral soil is a dark organic silty loam. This is followed by a reddish yellow silt with a crumb structure and contains small fragments of soft slate. Below is a moderately compact olive grey silt, mixed with broken slate parent material; it is sharply defined from the weathered soil above at depths ranging from twelve to twenty-four inches, occasionally exceeding that depth. Muir and Fraser classify this soil as a concealed podzol which occurs at higher elevations on flat to undulating sites and sometimes on steepish sites. The podzolised nature of these soils was brought out in chemical analyses which showed that there had been considerable leaching of the sesquioxides of iron and aluminium.

An appreciable amount of oak (*Quercus* spp) charcoal was found in one profile between six and fifteen inches below the surface. Its age and origin can only be guessed, but it is probable that it is quite old and would seem to indicate a previous oak wood vegetation on the area.

4. DORNOCH FOREST

Locality

Harriet's Wood, in which this investigation was conducted, is a section of Dornoch forest which lies three miles north-west of Dornoch, between Dornoch Firth and Loch Fleet, Sutherland. The main physical feature of the forest area is a broad ridge running north-west to south-east rising from four hundred feet to about five hundred feet above sea level.

Site

Geology. The surface geological formation is mixed Old Red Sandstone glacial drift which probably overlies Old Red Sandstone. The smooth rounded form of the ridge is typical of a well glaciated hill.

Climate. The average annual rainfall at Harriet's Wood is about thirty inches.

Vegetation. The natural vegetation is a poor *Calluna-Scirpus* association similar to that described at Teindland. *Juncus squarrosus* and *Erica tetralix* are fairly common.

Soils. The soils of the ridge top closely resemble the peaty gley podzol described at Teindland. The glacial drift parent material has a smaller proportion of Old Red Sandstone and a greater number of rounded unweathered boulders than that at Teindland. A two to three inch layer of water-saturated peat covers the mineral surface of the soil. The top of the mineral soil is a leached sand with varying degrees and depths of included organic matter. This horizon merges with a silty gley illuvial horizon above the pan. The pan is well developed at depths ranging from ten to twenty-four inches on top of very compact sandy subsoil which varies in colour from light yellow to pinkish.

Frequently a thin mat of dead heather roots occurs above the pan. At one site well off the ridge top, the profile contained a great many water worn boulders, no pan had formed and there was altogether less definition of the horizons within the profile.

Chapter 2

METHODS AND PROCEDURE OF TREE ROOT INVESTIGATION

I. PAST RESEARCH

Most root investigations which have been carried out in the past have consisted of detailed studies in the field of individual trees, tracing root systems root by root, recording root sizes, distribution and relation to the soil profile. A great deal of work was done to cover a limited range of conditions. Much information has been gained in this way, but it has necessarily been of limited application for the following reasons:—

(i) Relatively few trees can be studied.
(ii) Individual trees differ widely within the same stand.
(iii) However careful and exact measurements of an individual may be, without considerable replication the conclusions cannot be said to represent the stand as a whole except along certain broad lines.
(iv) The method is very time consuming and, in consequence, the number of sets of conditions it is possible to study is limited.

In view of the proven importance by field experiments of soil type and degree of cultivation for establishment of trees on the upland heaths, it was felt that the direct result of these factors on the tree root systems of established stands should be known. Taking into account the variations of site, the large number of cultivation treatments and number of species involved, the task would be impracticable using the detailed methods of the past.

II. PRESENT RESEARCH

A method of excavation and recording had to be evolved which would supply the information required as quickly and as economically as possible.

Diagrams of the root system of the stand were required to show:—

(i) Vertical distribution of the roots in relation to the cultivation and soil horizons.
(ii) Size distribution of the roots within the rooting zone.
(iii) Plan diagrams of the surface or near surface root system in conjunction with the vertical distribution of roots.
(iv) Measurements of height and girth at breast-height, over-bark of the standing trees surrounding the site of excavation.

III. FIELD METHODS OF SOIL AND ROOT EXPOSURE

Choice of Site

The species and cultivations to be studied and the number of replications to be made were decided after referring to the individual experiment working plans. Trenches, ten to fifteen feet long (or as long as was practicable), about two feet wide, and deep enough to expose the deepest roots were dug at sites located by field examination. Such sites were chosen bearing in mind the following points:—

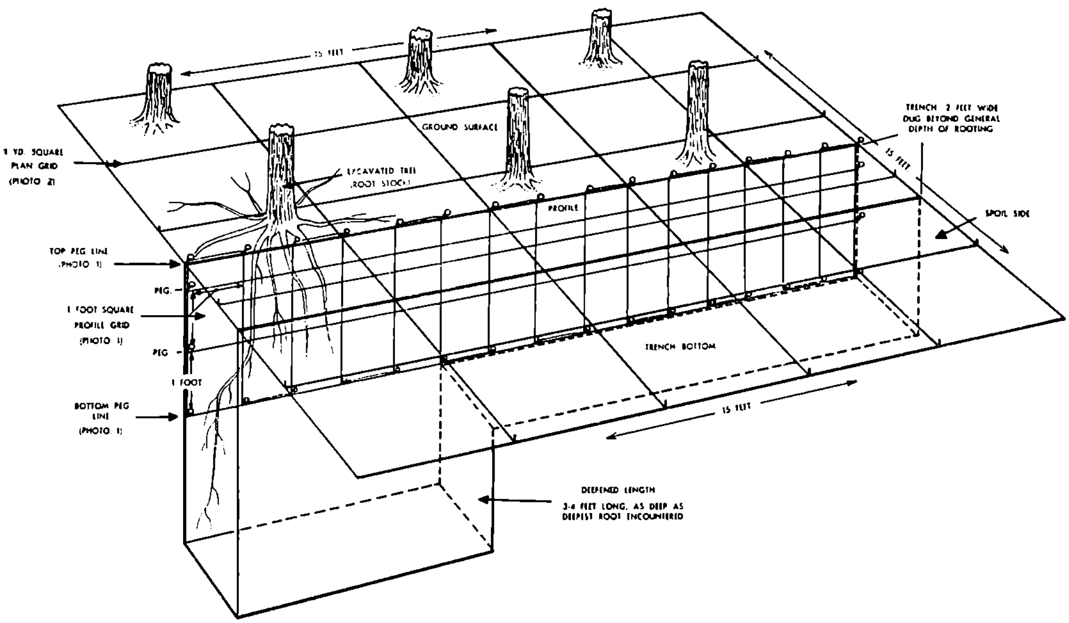
(i) Select a representative sample of the *stand* being studied;
(ii) Include at least one dominant tree adjacent to the section;
(iii) Avoid any side effect such as open rides or change in cultivation;
(iv) Place the section at right angles to the line of cultivation where applicable.

It was not possible to lay out the side of the trench (i.e. the section) at a constant distance from the individual trees because of irregularities in tree position and stocking. Generally, however, the section was located six to twelve inches from the bases of the nearest trees, taking in as many trees as the sample ((i) above) allowed. Fig. 1 shows diagramatically the field method of profile and plan exposure.

Trench Digging Procedure. (For a fifteen foot section)

(i) The line of section was laid out by a sixteen foot cord between two pegs.
(ii) An area sixteen foot square, with the line of section as a central axis, was cleared of debris, i.e. branches, tops, etc.
(iii) The surface litter on the side indicated for throwing the spoil was cleared to the edge of the square.
(iv) Digging commenced using the cord to keep the section straight. When removing the

FIG. 1. DIAGRAM OF FIELD METHOD OF PROFILE AND PLAN EXPOSURE



topsoil care was taken to throw it well to the back, on top of the removed litter. Beginning at one end, a hole two to three feet long and as deep as required was dug. The soil at the top was loosened with a strong gardening fork, and stony compact subsoil broken with a crowbar. All roots one half inch or over in diameter and any others crossing the trench from one side to the other, were kept *in situ*, hence unrestricted use of the spade was not possible as it easily cut the smaller roots. After the initial hole was completed, it was a relatively simple matter to proceed along the trench freeing the soil with fork or crowbar into the hole and throwing out with a spade. Thus the trench was taken down in stages to an overall depth of six to twelve inches below the general rooting level; usually about three and a half feet. If some roots descended beyond this level a suitable length of four to five feet was selected for further deepening and was dug to the extreme depth of rooting.

Profile

The major roots one half inch diameter and over and those passing from one side of the trench to the other lay exposed. In addition the remainder of the root system, the smaller roots and fine roots, extended into the trench by varying degrees or had been cut off at the trench side. The section was clarified by the following procedure:

(i) All small roots and fine roots were cut off with pruning shears or a sharp knife close to the trench side thus leaving only the major roots exposed.

(ii) A slice of soil two inches thick, the length of the trench and as deep as the soil compaction and stones would allow, was eased from the trench side (subsequently referred to as the *profile*) with a gardening fork. Care was taken to expose all the small and fine roots with the minimum of damage. This was done by gentle agitation of the fork, crumbling the soil away from the roots rather than pushing it away as a sod. The resulting loose earth was thrown from the trench bottom to the spoil heap.

(iii) The profile clearly showed the major zones of rooting, the size distribution and intensity, but finer details of soil and roots tended to be marred by loose soil and fork marks. It was therefore necessary to clarify the profile further. This was done by the recorder with a thin long-bladed knife using a flicking probing action. At the same time a careful examination was made of the profile, exploring all the detailed characteristics which were not very clear at first sight, such as colour and texture boundaries, degree of compaction, air spaces, vertical channels, and lines of fine rooting in the lower horizons.

Root Stock

In the majority of sites one individual dominant tree was chosen for excavation and the exposure of its root stock. This operation followed the recording of the profile. The tree was felled a few inches above ground level and the height and girth breast-height over-bark recorded. The trench was deepened beneath the selected tree, and the roots were excavated in a similar way to the profile exposure, doing as little damage as possible to the fine roots by gently easing away the soil into the trench with fork and crowbar.

Plan

Needle litter was raked clear of an area surrounding a dominant tree adjacent to the profile. Primary and secondary surface roots were exposed to a depth of two or three inches with hands and knife. In two instances, where the root plan was considered especially important, all trees within the plan area had their surface roots exposed.

IV. METHODS OF RECORDING

The Trench Profile

As a preliminary and to facilitate accurate sketching of each profile a one foot grid of cord was built up over the face of the profile as follows: a fifteen foot length of flexible insulated telephone wire, carrying nine inch wire pegs spaced at one foot intervals, was set out a few inches behind the exposed profile and the pegs driven firmly into the soil, with the wire between each peg in tension. A similar line carrying six inch steel pegs (nails) was aligned horizontally in the bottom of the trench, with the aid of a plumb bob hanging from the pegs already fixed in position above. After adjustment the pegs in this second line were driven into the face of the profile. The advantages of such peg lines were: speed in setting out combined with accuracy of spacing position; support was given by the line as a whole to any individual pegs which were not firmly located. As the lines were repeatedly used, it was important that they should not stretch or contract, hence flexible wire was used in preference to cord. A horizontal base line was selected at about pan level or at a convenient number of feet plus two inches from the trench bottom, and was fixed in position with a peg at each end, using a cord and spirit level for guidance. At each end of the trench, pegs, at one foot intervals above and below this line, were driven into the face of the trench. By threading cord between opposite sets of pegs a one foot grid was built up over the profile.

Millimeter graph paper (scale 1 cm.=1 ft.) was used as a field form to record details of the profile. A small pair of callipers measured the individual root diameters greater than one-eighth inch. A one-foot length of wooden lath divided into tenths was used to check distances within the foot square of the grid. Further descriptive notes were made as necessary.

The field profile and plan diagrams were converted to large scale in the office. Profile and root stock diagrams were enlarged to a scale of one inch to one foot, plan diagrams were redrawn at a scale of half an inch to one foot.

The profile diagram consisted of the soil profile drawn on squared paper. The features and horizons were distinguished by symbols and colours. A semi-transparent tracing sheet was laid over this, and the root profile superimposed on the soil profile. Finally, the two were fixed together along the top edge. This technique reduced the confusion of the drawing and it was useful to separate clearly the soil and root profiles.

For the purposes of this publication, selected profiles have been redrawn to combine both the soil and root profiles and the following colour code has been used:

Black: Main soil profile.

Red: Features of the soil profile caused by cultivation.

Green: Root profile.

The Root Stock

The exposure of the root system of individual trees was most helpful in the better interpretation and understanding of the exposed profiles. The root stocks were photographed from three sides, i.e. front, left and right side, so that a three dimensional view could be built up from the photographs.

The Horizontal Plan

A yard grid was erected over the fifteen foot square, the profile forming the centre line or axis. The following data were recorded on squared paper.

(i) Position, height, and girth breast-height over-bark of standing trees.
(ii) Position and diameter of stumps of trees removed in previous thinnings.
(iii) Plan of surface roots exposed.
(iv) Lines of furrows, ridge and subsoiler work.

The plan of the exposed root system indicated the nature of the lateral roots (e.g. long and ropelike surface roots, or short dividing and descending roots) and the orientation of the root system in relation to the cultivation. The plan may be directly compared with the profile diagrams to get a three dimensional picture of the root system of the stand, by tracing corresponding roots in plan and profile.

V. THE DIAGRAMS AND ATTACHED NOTES

The soil and root profile diagrams provided a pictorial record to scale of the observations made. These were amplified by notes on the outstanding features exhibited and a summary of the data collected.

Methods of Measurement

With regard to the data it should be noted that all depths were measured from the mean present soil surface level (not the litter surface). When comparing depths of the same feature in different profiles it must be borne in mind that ploughed soil occupies a greater space than the same mass of unploughed soil. Thus, for the same depth of a feature beneath the original peat surface, the present measured depth under complete ploughing will be greater than that under partial ploughing, which in turn will be greater than on unploughed treatments, e.g. prepared patches. There was not sufficient of the original peat surface in all profiles to make its mean level the constant reference line for depths. Certain profile features, which occurred to a greater or less extent in any one profile, were recorded on a comparative scale of percentage occurrence. The profile was divided into thirty half-foot vertical strips, each of which was considered a sample of the profile. The number of strips in which a certain feature was found was counted and converted to a percentage of the whole.

The occurrence of vertical channels was stated simply as the number of channels found within the fifteen feet of the profile.

The mean depths, maxima and minima of soil and root horizons were determined for each profile. The figures were combined in Tables, (e.g. Table 3), in which ranges of depths are given in place of maxima and minima, i.e. in any given case the range is the difference between the maximum and the minimum depths at which the horizons occurred.

Roots—Occurrence and Size Distribution

The rooting exposed by the profile was divided into two groups:—

(i) Fine rooting (less than one-eighth inch diameter);
(ii) Major rooting (one-eighth inch diameter and over).

The fine rooting was indicated on the diagrams as a rooting zone by dotted lines. The area between the surface and the first continuous dotted line was called the "zone of free fibrous rooting." Non-continuous dotted lines indicated isolated lines and spots of fine roots which extended below the zone of free rooting. Comparison between depths and distribution of rooting zones in different profiles was possible since the fine roots exploited suitable soil conditions regardless of the distance from the tree. It was difficult to measure and record varying intensities of fine rooting within a zone, but where great differences occurred the position was described.

The major roots were classified in diameter classes, indicated on the diagrams by a series of symbols:—
$\frac{1}{8}$ to $\frac{1}{4}$ inch, $\frac{1}{4}$ to $\frac{1}{2}$ inch, $\frac{1}{2}$ to $\frac{3}{4}$ inch, $\frac{3}{4}$ to 1 inch, 1 to $1\frac{1}{2}$ inch, over $1\frac{1}{2}$ inches.

Their position does indicate to some extent any preferred rooting medium within the rooting zone. Comparison of root size distribution between profiles was not warranted since size and position vary greatly with the distance from the bases of the trees.

Chapter 3

THE PILOT STUDY

INFLUENCE OF CULTIVATION OF AN UPLAND HEATH ON THE FOREST ROOT SYSTEM, AS INDICATED BY JAPANESE LARCH IN THE ALLERSTON DISTRICT, YORKSHIRE

I. OBJECT OF RESEARCH

The object of this investigation was to study the development of the root system of a forest crop on upland heath soils in relation to the initial methods of ground preparation prior to planting.

Wykeham and Broxa experimental areas were chosen for the work in view of the wide variety of cultivation methods and replications of same over apparently uniform heathland soil conditions. Wykeham lies in Allerston Forest and Broxa in Langdale Forest; both are on the North Yorkshire moors, a few miles west of Scarborough. The experiments dealt with at Wykeham were established between the years 1928 and 1933, while those at Broxa were established in 1943.

TABLE 1

ALLERSTON DISTRICT: WYKEHAM, 1951-2. PROFILES 1-14

Experiment and Establishment Details, Japanese larch

Ground Preparation			Profile No.	Expt. No.	P. year	Species	Planting Stock	Basic Slag	Beating up	Thinning
Hand prepared patches			1	6	P.28	Jap larch	1+1	—	1929 and 1930	Nil
Hand prepared patches			2	2	P.28	Jap. Larch + *Sitka spruce	1+1 2+2	—	1929 and 1930 1939 C.P.+slag	Dec. 1949 S.S. liberated in S.S./J.L. units.
Shallow ploughing	Single furrow		3	6	P.28	Jap. larch	1+1	—	1929 and 1930	Nil
Shallow ploughing	Three furrow		4	6	P.28	Jap. larch	1+1	—	1929 and 1930	1946
Shallow ploughing	Three furrow		5	9	P.29	Jap. larch + *Sitka spruce + *Sycamore	1+1 2+1 1+2	—	1930 1942 C.P. and 1 oz. slag/tree	Nil
Shallow ploughing	Complete	No. 1	6	6	P.28	Jap. larch	1+1	—	1929 and 1930	1946
Shallow ploughing	Complete	No. 2	7	6	P.28	Jap. larch	1+1	—	1929 and 1930	1946
Mod. deep ploughing	Two furrows		8	14	P.31	Jap. larch	2+0	—	Early losses 25% 1932 28/57 Japan Large plants	Aug. 1942 Aug. 1944
Mod. deep ploughing	Two furrows		9	78	P.32	Jap. larch	1+0 2+1	+ 1oz./tree	Nil	Thinning grades: heavy to med. 1942 and 1946
Mod. deep ploughing	Two f'rows No. 1		10	11	P.31	Jap. larch	2+1	—	1932 28/57 Japan	1944
Mod. deep ploughing	Sub soil No. 2		11	11	P.31	Jap. larch	2+1	—	1932 28/57 Japan	1944
Mod. deep ploughing	Complete		12	14	P.31	Jap. larch	2+0	—	Early losses 25% 1932 28/57 2+1 Large plants	1942 and 1944
Mod. deep ploughing	Complete		13	11	P.31	Jap. larch	2+1	—	1932 28/57 Japan 2+1	1944
Mod. deep ploughing	Complete		14	26	P.33	Jap. larch	1+1	—	Nil	1945

Note.—*Owing to the virtual failure of Sitka spruce and sycamore, these species are not discussed further.

ALLERSTON DISTRICT: BROXA, 1951-2. PROFILES 15-17

Experiment and Establishment Details, Japanese larch (with Sitka spruce in two row mixture)

TABLE 2

Ground Preparation		Profile No.	Expt. No.	P. Year	Species	Planting Stock	Slag
Deep (R.L.R.) ploughing	Single Furrow	15	9	P.43	Jap. larch + Sitka spruce	1+1 2+1	1 oz./tree
	Complete	16	9	P.43	Jap. larch + Sitka spruce	ditto	ditto
Shallow single furrow ploughing plus sub-soiling		17	9	P.43	Jap. larch + Sitka spruce	ditto	ditto

Note.—See Appendix 6, page 71, for abbreviations used in Tables.

Japanese larch was chosen as a representative species for the following reasons:—

(i) It appeared to show significant response to the intensity of cultivation.
(ii) It occurred through the experiments over the whole range of cultivation types.
(iii) Different planting stocks were likely to be genetically similar.
(iv) It showed promise of being an important species in any extensive planting programme on heathland.

II. CULTIVATIONS STUDIED

There are five main groups into which the methods of cultivation fall. They are:

1. Hand preparation. Wykeham.
2. Shallow ploughing. Wykeham.
3. Moderately deep ploughing. Wykeham.
4. Deep ploughing. Broxa.
5. Shallow ploughing with subsoiling. Broxa.

Tables 1 and 2 list the sites chosen for study and details of establishment. It may be noted that the shallower methods of ploughing and hand preparation were compared in the older experiments at Wykeham whereas the deeper methods were only used at Broxa. In the early days no equipment for deep ploughing had been devised and suitable ploughs were only developed later when the Broxa heaths were being planted. As a result, the differences in tree growth caused by different methods of ground preparation are confounded with the two different sites, but in view of the uniformity of the two localities any errors thus introduced are believed to be small and unimportant.

1. HAND PREPARATION. WYKEHAM
(Profile No. 1 (Diagrams 1, 3 and 5, Photo 3) and Profile No. 2)

This involved the preparation of individual tree sites for planting with no major disturbance of the surface beyond the small area necessary to plant the tree. The example chosen for study was the prepared patch planting method in which patches of approximately one square foot spaced at three and a half foot intervals north/south and five foot intervals east/west, were stirred up with pick and mattock, breaking the pan beneath when possible.

2. SHALLOW PLOUGHING. WYKEHAM

This was carried out with a heavy agricultural plough built to carry two mouldboards but only one was used and all wheels removed. (Records 1928). There were three intensities of shallow ploughing all of which were sectioned. They were:—

(i) Single furrow. Profile No. 3. This method did not rupture the pan, and the furrow was not always completely turned out, hence a poor planting site was obtained. (Records August, 1928). Furrows were spaced five feet apart, trees planted at three and a half foot intervals, the ploughing depth was four to five inches.
(ii) Three furrow ploughing. Profile Nos. 4 and 5. Ploughed strips five feet centre to centre, pan to be broken in the centre furrow by the plough or by hand, planting in the middle furrow. (Working plan 1928). The pan was ruptured and turned over in large patches but not continuously, largely owing to the difficulty of keeping the plough down. (Records August, 1928). Ploughing depth was four to five inches for the first furrow, seven to eight inches for subsequent furrows, maximum nine inches.
(iii) Complete ploughing. Profile No. 6 (Diagram 6) and Profile No. 7. Ploughed completely once with similar pan disturbance and depth of ploughing to (ii) above.

3. MODERATELY DEEP PLOUGHING. WYKEHAM

This cultivation was carried out with an Oliver plough drawn by a powerful crawler tractor. The moor was burnt prior to planting; where the burning was satisfactory the furrows lay well showing the yellowish subsoil (and pan) in places. (Records 1931). This investigation covers the following intensities of cultivation:

(i) Two furrow ploughing. Profile No. 8 (Diagram 8, Photos 2 and 29) and Profile No. 9. The strip was ploughed in double furrows at five foot intervals as deeply as the tackle will allow. (Working Plan 1930)
(ii) Two furrow ploughing and subsoiling. Profile No. 10 (Diagram 9, Photos 6 and 30) and Profile No. 11. Subsoiling was done with a special subsoiling plough with a two foot deep blade having a wedge-pointed shoe about three inches wide by twelve inches long at its base. When this was drawn through the subsoil at a depth of fifteen to eighteen inches it caused the ground to loosen and heave making it easier for subsequent ploughing. (Records 1931)
(iii) Complete Ploughing. Profile No. 12 (Diagrams 2 and 4) and Profile Nos. 13, 14. The whole surface of the strip was completely ploughed as deeply as the tackle would allow. (Working plan experiment 1930). No figures are available for estimates of ploughing depth made at the time of ploughing but the ploughing of experiment 26 was considered unsatisfactory as the area was not burnt before ploughing.

4. DEEP PLOUGHING. BROXA

A Forestry Commission R.L.R. plough had been used, designed to plough a single furrow at twelve to fourteen inches depth throwing the soil well on to the surface, leaving a clean deep furrow and a high ridge. (Photo 31). The heather was not burnt before ploughing. Two intensities of ploughing were sectioned:

(i) Single furrow. Profile No. 15 (Diagram 10). Ploughed at four and a half foot intervals.

(ii) Complete ploughing. Profile No. 16.

5. SHALLOW PLOUGHING WITH SUB-SOILING. BROXA. (Profile No. 17)

Subsoiling had been carried out at four and a half foot intervals to the maximum depth possible. Subsequently a single furrow was ploughed along the line of the subsoiler to about five inches deep.

III. THE SOIL PROFILE

Ploughing

The outlines of the plough furrows remain clear in the profile, and are distinguished by the overturned surface peat. In most cases the peat lost the capacity to remain waterlogged, but maintained its identity within the profile.

The depths of ploughing are estimated as closely as possible but, owing to the settling and falling in of open furrows, the boundary between ploughed and unploughed soil is now rarely distinct.

Where sufficient undisturbed surface remains *in situ* an estimate is made of the increase in volume of the soil as the result of ploughing. However, it is not possible to measure any drop in the old level due to decomposition of the peat or compaction by spoil above. Certainly some increase in volume of the disturbed soil remains, and the estimated percentage increase in volume of the disturbed depths of soil reflects the degree of disturbance.

The direction of throw of the spoil in most ploughing treatments is clear. In some cases the profile covers the forward and return direction of the plough, thus a throw to the left and right may be found in the same profile, e.g. Profile No. 8, Diagram 8.

The efficiency of any ploughing method is greatly increased when the heather is burnt shortly before ploughing. The poor result obtained when the area was not burned before ploughing is typified by Profile No. 14, Oliver complete ploughing. The ploughing is shallow and uneven and not comparable with the remainder of the moderately deep ploughed examples.

Soils

Parent Material. There are two types of parent material of different origin, which occur either pure or mixed in varying proportions. They are:—

(i) Lower calcareous grit sandstone. This is the cap rock of the plateaux, and within the reach of tree roots it occurs as broken stone and sand, compacted to greater or less degree. (Photo 4)

(ii) Glacial boulder clay, which is found as pure pinkish fine sandy clay and ferruginised rubble in frost wedges and other smaller pockets (e.g. Profile 6, Diagram 6). No erratics were found in this material at Wykeham, where the rubble was of calcareous grit or sandstone; some erratics, notably quartzite were found at the Broxa excavations. Clay occurs, in varying depths, over the surface of the plateaux, mixed by solifluction with the calcareous grit material ((i) above) to a greater or less degree. (Dimbleby 1950). Refer to the profile discussions (Appendices 1 and 2) for occurrence.

Soil Horizons. The *litter* provides a continuous soil cover of an average depth of one and a half inches under established stands of Japanese larch.

The *eluvial horizon* (A horizon) is typical of a mature podzol, varying in depth from six to twelve inches. The raw humus (peat) A_0 horizon maintains a fairly constant depth of two to three inches. The A_1 horizon of sand and organic matter is confined to two or three inches of the surface mineral soil. The leached sandy A_2 horizon varies in depth and intensity of leaching with the depth of the eluvial horizon and the nature of the parent material. Where the pan is deep, i.e. below twelve inches, the leached horizon merges into a horizon with increased clay fraction, frequently containing soft, orange-centred stones of calcareous grit.

The *illuvial horizon* (B horizon) is sharply defined above or below by a continuous humus iron aluminium hard pan, varying in intensity with depth. The proportion of humus deposit above the hard pan decreases with depth, the pan colour varies from dark reddish-brown to bright red accordingly. The pan frequently appears to have formed at an interface between two soil materials of different texture. Where shallow pan divides the sandy eluvial horizon from the silt or clay sand illuvial horizon below; the latter merges into the compact sandy subsoil (calcareous grit) or into the fine sandy clay and rubble of the boulder clay. Where deeper the pan, frequently markedly convoluted, varying in actual depth as much as eighteen inches, divides the illuvial horizon from the compact sand and stone unweathered parent material below.

The *loose region* (Photo 4). The loose region is a remarkable phenomenon found in the subsoil at depths varying from three to five feet, usually at about four feet. Typically it is composed of horizontally aligned, flat calcareous grit stones and sand, and frequently there is also a deposit of clay which is apparently illuvial. The undersides of the stones may be stained brown or black. The degree of looseness varies from being a little less compact than the highly compacted soil above, to having considerable air space, enabling stones to be pulled from the profile by hand. The thickness of the region varies, but usually it extends beyond the limit of the digging, although frequently becoming more compacted again with depth. Its origin is obscure. One theory is that it formed at the time of the frost wedge formation when the upper soil was subjected to enormous side pressure, putting the surface in compression and leaving the region beneath in relative tension. The boundary between the compact subsoil and the loose region below is usually distinct.

Horizontal and vertical channels. Small horizontal channels, empty or containing loose organic loam (this frequently has the appearance of the excrement of wood borer insects, hence it is sometimes described as frass holes) frequently occur beneath the pan, especially in association with a relatively high proportion of clay in all upper horizons. These are apparently the result of the decomposition of roots of woody plants which occupied the site in the past. They provide air space and relief from compaction beneath the pan, and so assist in the development of the root system in this horizon of any new crop of trees. The mature pan appears to have formed *after* the destruction of the trees whose roots formed these frass holes.

Larger vertical channels penetrating the compact subsoil are evident in every profile exposed. In a few cases charcoal was found within them notably in profile No. 8 which was identified as oak (*Quercus* sp.). These channels were undoubtedly originally provided by descending tree roots which have long since disappeared. Their nature, as seen today, varies according to the texture of the surrounding soil and that above, the time elapsed since the death of the root and general pan formation (i.e. advanced podzolisation), and their size and chance position in the soil in relation to the soil forming processes. The channels may be divided into the following types:—

- (i) Those with a pale leached core of fine sand with red ironstaining at the edges in the compact calcareous grit matrix;
- (ii) Those which were half empty with a loose dark loamy filling, with little evidence of leaching; and
- (iii) Dark or leached channels with diffused staining and leaching beyond the boundaries of the channel, which may be seen in less compact clay sand or in very stony soil.

Instances were found of a concentrated black amorphous deposit towards the bottom of some of the vertical channels, and in each case the pan form was of the convoluted type leading by funnels into vertical channels. Rennie and Handley of the Imperial Forestry Institute, Oxford, showed that this material was probably raw humus mixed in a ferruginous complex, not charcoal as was first thought. The following are the results of tests they carried out on the material supplied by the writer, using powdered charcoal for comparison.

Total Nitrogen—

Sample A (Charcoal) 9.35 mg. N per gm. sample.

Sample B (Black deposit) 18.79 mg. N per gm. sample.

Microscopal examination (Handley). After cleaning with hypochlorite:

A. Many elements of wood cell structure

B. No sign of cell structure.

The origin of the humus is uncertain. It may be colloidal humus in suspension from the surface horizons precipitated due to a partial constriction at the point of accumulation in the channel, or it may be the result of accumulation of generations of dead *Calluna* roots. Instances were seen where either explanation seemed likely.

Intermediate types occur, or one channel may be of two or three types, e.g. intensely leached at the top, but with dark brown humus plus clay deposition further down. The more intensely leached channels invariably lead to the loose region where they diffuse, depositing clay and mud. This region appears to act as a sink from which drainage is quite free.

Drainage.

No profile showed any signs of lack of drainage to the extent of waterlogging, although the deeper pans exhibited some temporary vertical impedance to free drainage, causing localised mottled gleying in pockets of clay or clay loam soil.

IV. THE ROOT SYSTEM IN RELATION TO THE SOIL ENVIRONMENT

Zone of Free Fibrous Rooting

This term is used to describe the zone of the profile (referred to on page 11) which is freely exploited by fibrous rootlets and constitutes the major feeding medium of the stand. The extent of this zone is wholly governed by conditions of aeration found in the soil provided artificially tby cultivation) or occurring naturally. The in(ensity of rooting within the zone appears to depend on the local conditions with regard to fertility, soil/water relationships and minor variations in degree of compaction, all of which are to some extent inter-dependent.

The evidence suggests that the horizons in which rooting is most profuse, given cultivation or some other form of aeration, are the A_0 peat, the A_1 humus/mineral layer, and the regions immediately above and below the pan. The leached sandy A_2 horizon is not explored as extensively as other horizons by fibrous rootlets, and is positively avoided when left undisturbed, forming a partial barrier which reduces the opportunities for exploration of more favourable conditions below. (See profile No. 15 Appendix 1 and Diagram 10).

Similarly, undisturbed peat prevents the free penetration by roots, probably due to its high capacity for retaining water and preventing free drainage from the surface (see Profile No. 1 Appendix 1, Diagrams 1, 3 and 5, Photo 3).

Unbroken well developed hard pan may form a positive barrier to descending roots, but in such cases it is associated with a very compact subsoil immediately below it. (Profile No. 10 Appendix 1, Diagram 9). When the pan occurs some distance above the very compact subsoil, the pan may form the limit of "free rooting" but numerous fine roots will explore the soil below the pan to the level of the compact subsoil.

The Descending Root System

Moderately Deep Rooting. This level of rooting is beyond the reach of the plough, within the region of the subsoil. Root distribution within this region depends entirely on local relief from compaction provided naturally by weathering, horizontal and vertical root channels, or planes of weakness, or artificially by subsoiling. The extent to which these avenues for deeper rooting are made available for exploration by the root system is controlled primarily by the area of cultivation of the surface given a normal ploughing depth of, say, eight to nine inches. The effect of the subsoiler is seen in the three examples examined where it had broken the moderately deep pan and stirred the compact subsoil a little (Profile Nos. 10, 11 and 17, Appendix 1, Diagram 9, Photo 6).

Deep Rooting. The presence of the loose region beneath the compact subsoil enables roots exploring vertical channels to develop and branch freely. All roots found at these depths appeared healthy with an extensive system of feeding roots.

This deep rooting should have an important effect on the long-term health of the stand by maintaining the fertility of the upper soil horizons where the main rooting system will remain. It would not be true at the moment, however, to say that as rooting occurs below pan in these channels and in the loose region, that the subsoil as a whole is being readily exploited by the forest root system. Apart from the channels, there is only a limited penetration of the compact subsoil by fine roots branching from the major descending roots, though it is to be hoped that this form of rooting will increase with the age of the stand. Taking the long-term view, successive generations of tree roots will readily exploit the soil channels opened by the previous crops and there will be deeper and more complete penetration of the soil.

V. PLOUGHING AND THE ROOT SYSTEM

The accompanying histograms (Fig. 2) represent the development of the root system within the profile in relation to the degree of pre-planting cultivation. The depths shown are the mean measurements of features from the profile diagrams (see Table 3). The profiles illustrated have been selected in order to give a gradation of cultivation intensity within as near comparable soil profiles and stand conditions as possible. Further reference may be made to the Japanese larch profile diagrams (1 to 10) and to the detailed discussions of the profiles in Appendix 1, page 51.

On close examination of the summary of the profile data, and, more particularly of the profiles themselves, it will be seen that there are important differences between profiles which affect the root development and consequently the growth of the stand, apart from the intensity of cultivation. For instance, the pan depth, its variation, and the nature of the subsoil differ, but the outstanding examples of such differences have been omitted from Fig. 2. Also, treatments which ensured a better survival and subsequent growth have been thinned to a greater or less degree (see Table 1, page 12, for thinning details) which may lead to doubt concerning the absolute value of the figures given for the mean annual height increments. It is considered that these values give a fair indication for general growth comparisons.

In early experiments at Wykeham, Japanese larch was planted directly into the heath. This resulted in virtual failure; the few surviving trees have grown very slowly. Little better results were obtained by shallow single furrow ploughing. Both better growth and survival accompanied more intensive ploughing methods. Thus it is evident that the natural environmental growth factors of these heathland soils derived from lower calcareous grit are close to the limiting point for Japanese larch.

Any one factor showing an adverse variation from the mean will restrict the tree growth of the site. The improvement of another limiting factor

FIG. 2. WYKEHAM EXPERIMENTAL AREA. 1951-52

HISTOGRAMS ILLUSTRATING RELATIONSHIPS OF ROOT AND SHOOT DEVELOPMENT OF JAPANESE LARCH TO SOIL CULTIVATION.

(THE DEPTHS SHOWN ARE THE MEAN MEASUREMENTS OF FEATURES FROM THE PROFILE DIAGRAMS)

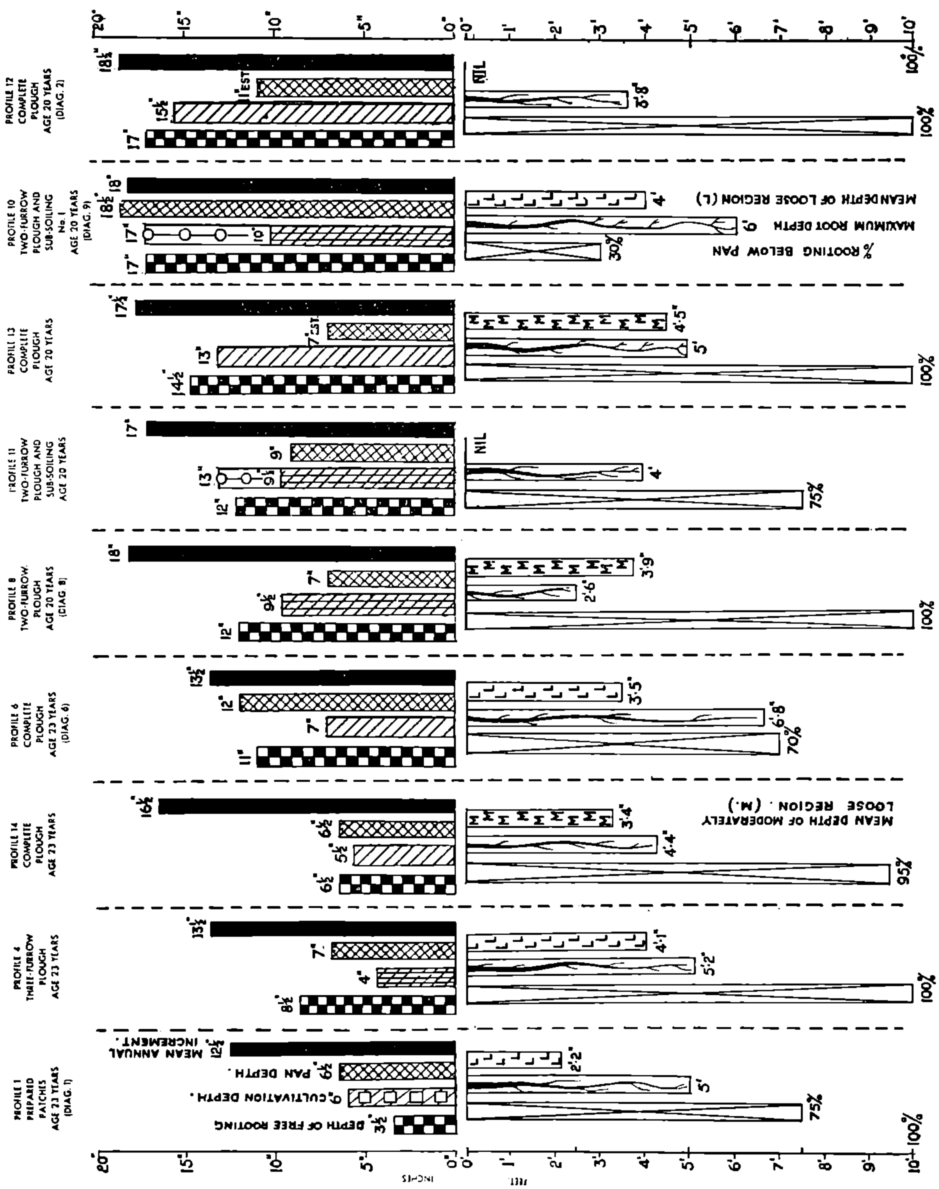


TABLE 3

ALLERSTON DISTRICT: WYKEHAM AND BROXA, 1951-2. PROFILES 1-17

Summary of Profile and Stand Data, Japanese Larch

		WYKEHAM														BROXA		
	Cultivation: Depth	Hand Preparation		Shallow Ploughing					Medium Depth (Oliver) Ploughing							Deep Ploughing R.L.R.		Shallow Ploughing
	Cultivation: Intensity			Single furrow	Three furrows		Complete		Two furrow		Two furrows + subsoiling		Complete			Single furrow	C'plete	Single furrow + subsoiling
	Profile Feature: Profile No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Age (Years)	23	23	23	23	22	23	23	20	19	20	20	20	20	18	8	8	8
Free Rooting Zone	Free Rooting Zone Mean Depth (in.) Range	3½ (2½)	13 (8½)	6½ (19)	8½ (12)	12 (12)	11 (12)	11½ (7)	12 (18)	10 (12)	17 (15½)	12 (12)	17 (13)	14½ (8½)	6½ (7)	6 (8½)	14 (7)	3½ (14)
Free Rooting Zone	Cultivation Mean Depth (in.) Range	6 Patch	6 Patch	5 (2½)	4 (4)	6½ (3½)	7 (3½)	9½ (3½)	9½ (1)	8½ (3½)	10 (3)	9½ (2½)	15½ (6)	13 (12)	5½ (5)	11 (2½)	12½ (8½)	5 (2½)
Free Rooting Zone	Volume Increase of Ploughed Horizon	—	—	—	15%	9%	30%	—	20%	18%	13%	14%	30%	—	—	12%	—	25%
Free Rooting Zone	Subsoiling Mean Depth (in.) Range	—			—		—		—		17 (3½)	13 (3½)	—	—	—	—	—	9½ (2)
Free Rooting Zone	Pan Mean Depth (in.) Range	6½ (3)	6½ (3½)	8 (8½)	7 (3½)	8 (1)	12 (24)	7 Est.	7 (2½)	9 (9½)	18½ (24)	9 (7)	11 Est.	7 Est.	6½ (12)	12 (8½)	10½ Est.	21½ (18½)
Free Rooting Zone	Clay-Rubble Occurrence Pure (P) or Mixed (M)	30% P	100% P	0	100% M	100% P	30% P	40% P	100% M	0	0	15% P	0	30% P & M	5% P	0	35% 75% P M	0
Free Rooting Zone	Horizontal Channels: Occurrence	0%	60%	30%	20%	35%	55%	15%	100%	55%	5%	0	10%	0	45%	30%	20%	0
Free Rooting Zone	Rooting Below Pan Level Occurrence	75%	100%	35%	100%	100%	70%	90%	100%	100%	30%	75%	100%	100%	95%	55%	95%	0
Deep Rooting	Vertical Channels: No. per Profile	3	4	2	3	7	3	6	2	5	7	6	2	6	2	4	6	0
Deep Rooting	Maximum Root Depth (inches)	60	39	51	62	55	80	66	30	48	72	48	44	60	52	36	56	12
Deep Rooting	Loose Region Mean Depth (ins.) Loose (L) Medium (M) Absent (A)	26 L	52 M	37 L	49 L	50 L & M	41 L	41 L	45 M	48 M	45 L	— A	— A	53 M	40 M	41 M	— A	— A
	Height (Feet) Mean Range	24 (9.0)	23.5 (4.5)	15.5 (7)	6.5 (5)	26.0 (1.5)	26.0 (4.0)	25.0 (9)	30 (3.5)	30 (6)	30.5 (2.5)	28.5 (4.5)	31 (4.5)	29 (3.5)	24.5 (9)	8.5 (4.5)	10 (2)	9.7 (5)
	Girth B.H.O.B. (inches) Mean Range	12.4 (6.75)	14 (8)	7.6 (7.2)	15.5 (8)	14.25 (3.25)	13.5 (7.75)	13.6 (12.5)	13.5 (6.25)	15 (3)	17 (3.25)	14 (5.5)	15 (3)	15 (6)	11 (9)	—	—	—

Est. = Estimated

by treatment may have a beneficial effect, but one which is not fully realised owing to the remaining repressive factor(s). Similarly, if one factor is more favourable than the mean, and another limiting factor is improved by treatment, then the response will appear to be comparably greater. An example of the former case might be a comparison of profile No. 8, Diagram 8, two-furrow ploughing, and profile No. 11, two-furrow ploughing and subsoiling, which appear by measurement to have produced similar results (Fig. 2). One might reasonably expect the subsoiling to produce the better growth, whereas in fact it is a little the poorer. This profile, however, has a very compact subsoil with no horizontal channels, no loose region and only a small pocket of pure clay and rubble. Profile No. 8 is shown to have a well aerated illuvial horizon, and moderately loose region at four feet, while the whole topsoil is clay and rubble mixed with the lighter sand and stone. An example of the latter case might be a comparison of Profile No. 1, Prepared Patches, Diagram 1, and Profile No. 2, Prepared Patches. The presence of the clayey topsoil and horizontal channels in Profile No. 2 have induced a much deeper and more variable zone of free rooting and deeper rooting beyond. Such variations are beyond the control of the investigation. Justified useful conclusions may be drawn from the profiles, but it is important that the complicating factors should be realised and no false conclusions drawn from a limited set of comparative measurements.

The following conclusions are drawn from the histograms (Fig. 2). Root and Shoot development are improved by:

(i) Increase in depth of cultivation. At least partial breaking of a shallow pan (say nine inches or less) is advantageous.

(ii) Increase in intensity (area) of cultivation. The greater the proportion of the area cultivated, the greater is the opportunity provided for the roots to explore every favourable circumstance of topsoil and subsoil.

(iii) Subsoiling beneath the planting position. This gives the descending root system a better chance to develop within the compact subsoil to the depth of disturbance, and increases the accessibility of the channels penetrating the subsoil.

The lower set of histograms of the deeper rooting levels and subsoil apparently bear no direct interrelation with growth and cultivation. On closer inspection, the modifying effects of the subsoil, favourable or unfavourable, may be detected as explained above.

Apart from the histograms, the following points in relation to ploughing are noted:

(i) Strip ploughing, with one or two furrows, tends to confine the major rooting system to the ploughed soil of the ridge and to the furrow side and bottom, leaving the undisturbed soil to be only partially exploited. The stand is therefore not able to make use of the full site potential, at least up to the age of the oldest stand examined, twenty-five years. Such root orientation may endanger the stability of the stand as height increases.

(ii) The presence of pan below the ploughing depth of eight to ten inches is of little practical significance, subject to its being broken beneath each planting point if within fifteen inches of the surface.

Complete medium depth ploughing, say eight to ten inches, should provide adequate depth and volume of suitable soil for the establishment of a balanced root system both in the horizontal and vertical planes. This cultivation would turn over the peat, leached A horizon and the pan, if shallow, and provide an opportunity for descending roots to explore any favourable conditions which occur below the ploughing depth. The lateral part of the root system is the most important in the growth of the tree, for the food supply and for mechanical support, and its encouragement towards normal development is the primary concern.

The descending part of the root system is of less immediate value, but its long term significance in supplementing the main surface nutrient supply, exploiting the more even soil water and temperature conditions of the subsoil in times of climatic extremes and for providing mechanical support, may be considerable. Subsoiling, particularly beneath the planting position, encourages the descending part of the root system; by breaking the pan and compact subsoil within the depth of the treatment, it facilitates the penetration of these horizons which otherwise may form significant barriers to descending roots.

Subject to complete surface cultivation of the soil, Japanese larch in the Allerston district is able to exploit the full depth of the weathered profile, irrespective of the depth of the pan in relation to that profile. Thus, a sound method of cultivation for the establishment of forests on this land would be complete ploughing to a depth of eight to ten inches. Subsoiling to depths of eighteen to twenty-four inches beneath the planting position would be an additional advantage, but not essential to the healthy establishment of the stand.

Chapter 4

THE ROOT DEVELOPMENT OF CONIFEROUS SPECIES IN THE ALLERSTON DISTRICT, YORKSHIRE

Figures 3, 4 and 5 illustrate by histograms the species investigated and methods of ground preparation at Wykeham and Broxa respectively. The general comparisons and relationships are clear, but reference should be made to the discussions below to avoid any possible false impressions. Table 4 lists the sites, experiments and establishment details for the other species at Wykeham and Broxa. Table 5 sets out the data from the profile and stand measurements. Further reference may be made to the detailed discussions of the profiles in Appendices 1 and 2, pages 51 and 56.

I. JAPANESE LARCH

Larix leptolepis Gord.

(Profile Numbers 1 to 17, Tables 1, 2, 3, Diagrams 1-6, 8-10, Photos. 2, 3, 6, Figs. 2, 3, 4, 5)

The root system of Japanese larch is typically intermediate between the horizontal plate type and the single tap root. The root system may be considered to consist of two parts, the lateral and the descending. Under good soil conditions providing a suitable rooting medium for several feet around, both parts develop to form a well balanced feeding and supporting mechanism fully utilising the site.

Japanese larch is able to adapt the form of its root system to suit the prevailing soil conditions, and will survive and continue to grow when the ideal balance of the root system described above is made impossible.

In the absence of mechanical cultivation but with suitable conditions for establishment provided by prepared patches, the root system develops primarily on the surface, and lateral roots develop in a rope-like manner. (Diagrams 1 and 3) They extend to lengths greater than the height of the tree, branching but seldom, and lying on top of the old *Calluna* peat surface covered only by such litter as is present. Sinkers descend through the peat from these surface roots as the opportunity occurs; such as a local disturbance, e.g. a planting site; down the edge of a large surface stone; or by means of the core of a dead *Calluna* bush. The descending roots under these conditions must make such progress as the condition of the subsoil allows. Since it is only the larger surviving trees that have been examined, and all these have a restricted descending root system, it seems probable that the failures were not able to develop descending roots early in life.

The root system under these conditions is therefore frequently two storied, Diagram 5, the surface storey, and the lower storey which exploits the more favourable nutrient and moisture status of the illuvial horizons, restricted from further descension by the hard pan or the very highly compacted subsoil, or by both.

On deep complete ploughing (say to a depth of fifteen inches of ploughed soil) the root system may freely exploit the available soil, at least to the depth of ploughing, and will normally develop a balanced lateral/descending root stock (Diagrams 2 and 4). The lateral roots extend in all directions some inches below the surface, individual roots branching freely and tapering rapidly, creating a mass of fine roots evenly throughout the profile, with a spread little beyond the diameter of the crown. Sinkers descend from the lateral roots to augment the exploitation of the subsoil by the major descending roots. The two parts of the root system are not distinct but merge one into the other. The true descending root system may be considered a multiple tap root, and such roots will continue to descend and divide so long as conditions are favourable for them.

Up to the age of the trees examined (twenty-five years) the roots of Japanese larch are not able to penetrate and exploit far into the extremely compact subsoil found in this area. In all cases of deep rooting (the maximum depth observed was six feet) access below the surface, or below the level of cultivation, was provided by distinct regions of loose soil, by old vertical root channels and by the deeper loose rocky region. In a case of cultivation over a compact subsoil lacking vertical channels, the descending roots exploit freely to the depth of cultivation, and below it as conditions permit, but on reaching the undisturbed compact region the roots divide rapidly producing a mass of short fine roots above the compact soil. Alternatively, the root on striking the compacted horizon may turn and run horizontally.

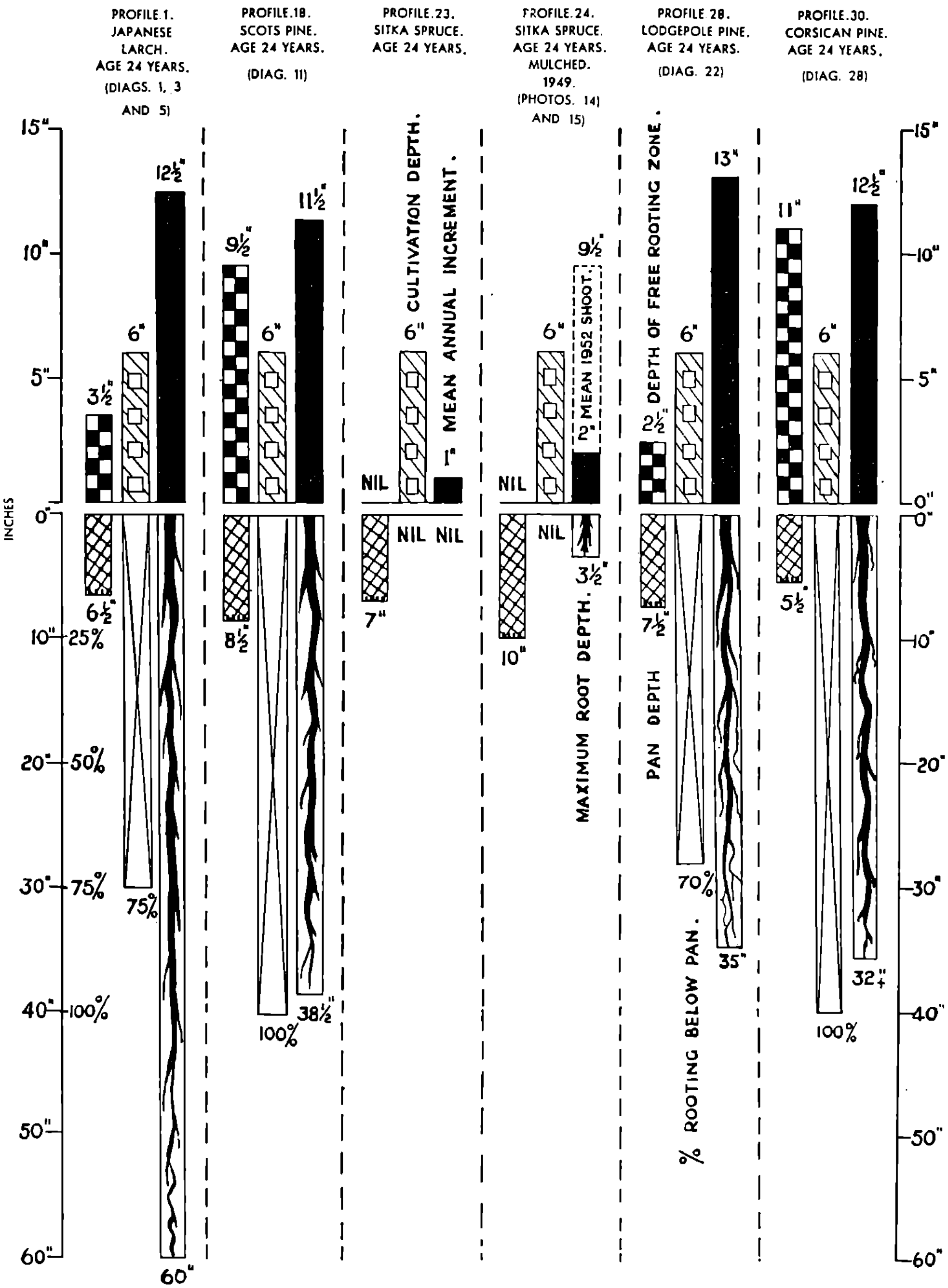
Between the two extremes of root form, intermediate forms may be found depending on the nature of the soil profile and whether suitable conditions are induced by treatment, or occur naturally. Partial ploughing, for example single or double furrow, produces a lateral root system aligned with the ridge and furrow. In an extremely compact soil the depth of free rooting increases with the depth of ploughing and subsoiling. (Photo 6.)

FIG. 3

WYKEHAM EXPERIMENTAL

HISTOGRAMS COMPARING RESPONSE OF THE SPECIES

PREPARED PATCHES.



AREA 1951-52

INVESTIGATED TO SIMILAR METHODS OF CULTIVATION.

DOUBLE-FURROW PLOUGHING.

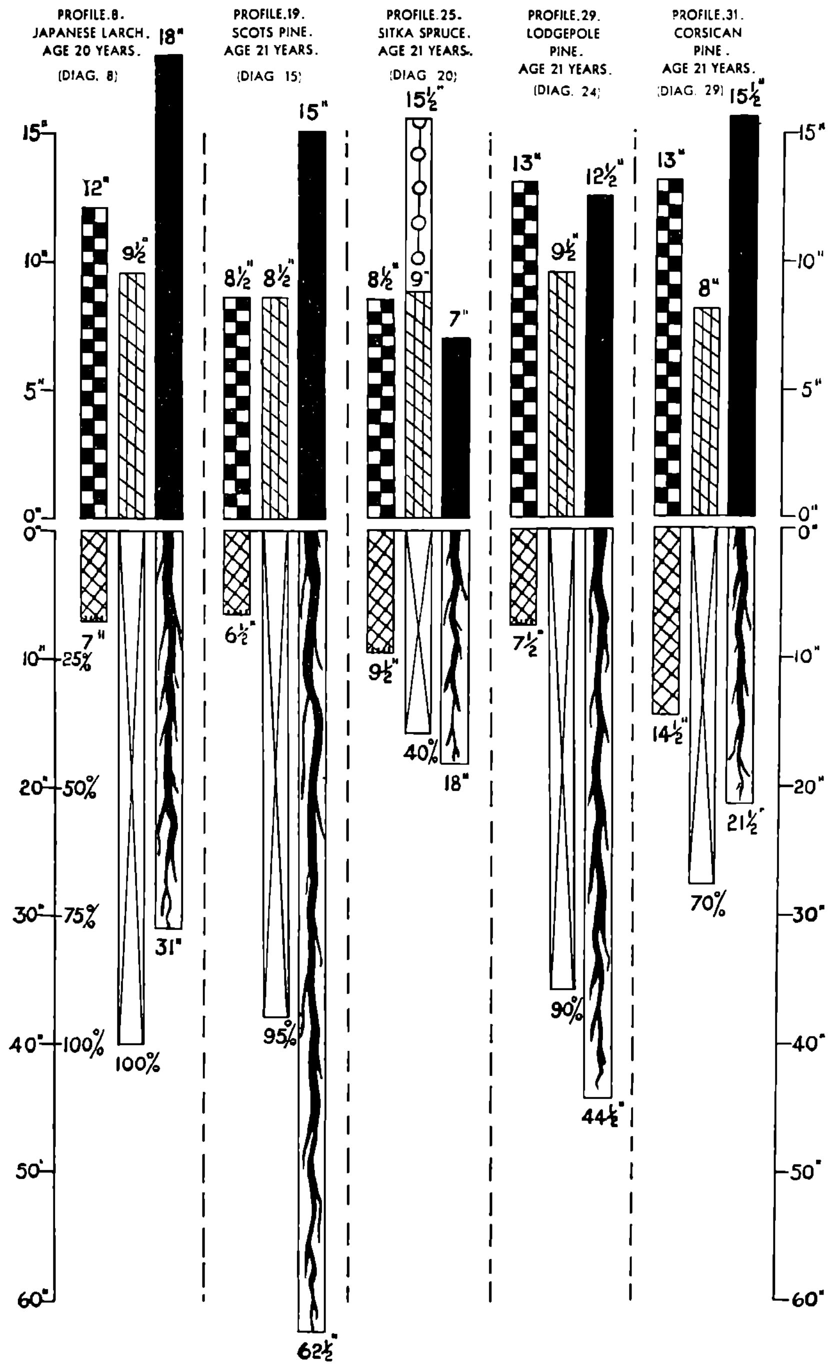


FIG. 4. BROXA EXPERIMENTAL AREA, 1951-52.

HISTOGRAM COMPARING RESPONSE OF SPECIES INVESTIGATED AND METHODS OF CULTIVATION.

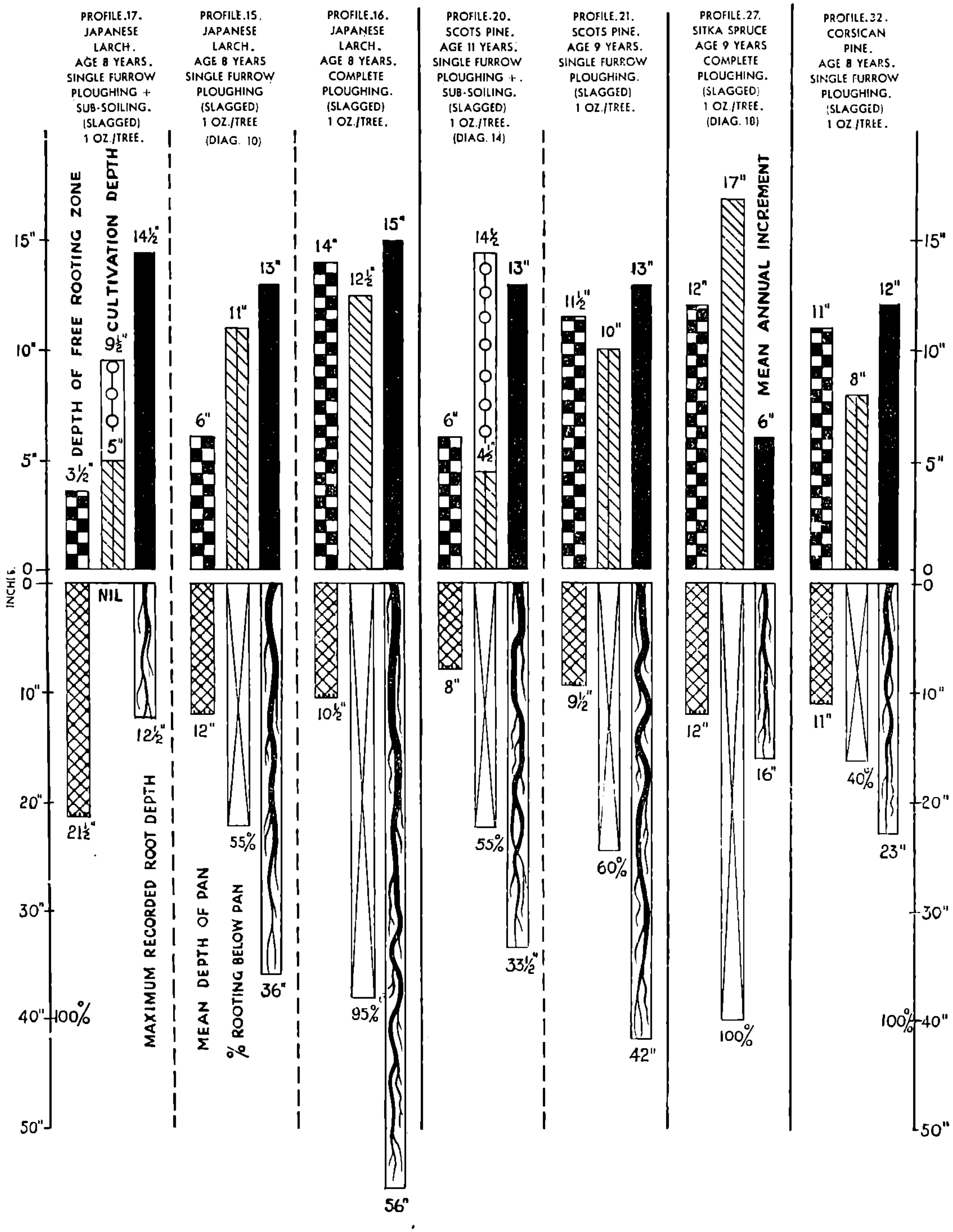
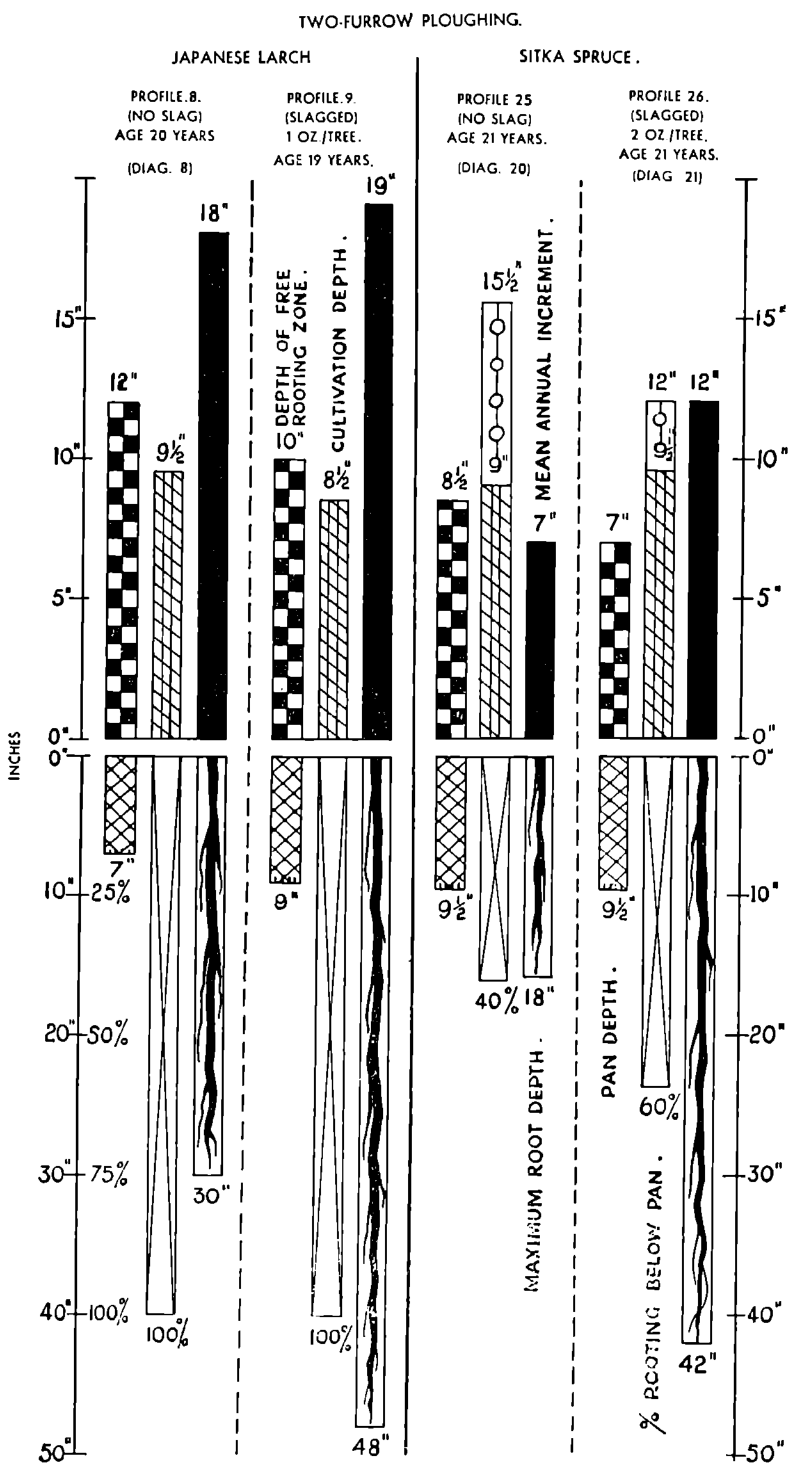


FIG. 5 WYKEHAM EXPERIMENTAL AREA.
1951-52.

HISTOGRAMS ILLUSTRATING RESPONSE TO BASIC SLAG

(SEE ALSO FIG. 6)



ALLERSTON DISTRICT: WYKEHAM AND BROXA, 1952. PROFILES 18-32

Experimental and Establishment Details. Scots pine, Lodgepole pine, and Corsican pine

TABLE 4

Species	Profile No.	Area	Expt. No.	P. year	Ground Preparation	Planting Stock	Basic Slag
Scots pine	18	Wykeham	6	P.28	Prepared Patches	2+1	nil
	19	,,	13	P.31	Moderately deep two furrow ploughing	1+0	nil
	20	Broxa	4	P.41	Single furrow shallow ploughing and subsoiling	1+1	1 oz./tree
	21	,,	8	P.43	Single furrow deep R.L.R. ploughing	1+1	1 oz./tree
	22	Turkey Carpet	Private Woodland	(1872)	None	—	nil
Sitka spruce	23	Wykeham	60	P.28	Hand preparation. No mulch.	2+2	—
	24	,,	60	P.28	Hand preparation Mulch in 1940	2+2	—
	25	,,	11	P.31	Moderately deep 2 furrow ploughing and subsoiling.	2+2	nil
	26	,,	11	P.31	,,	2+2	2 ozs./tree
	27	Broxa	9	P.43	Complete deep R.L.R. ploughing	2+3 2+2+1	1 oz./tree
Lodgepole pine	28	Wykeham	2	P.28	Hand preparation	2+1	nil
	29	,,	13	P.31	Moderately deep two furrow ploughing	1+0	—
Corsican pine	30	Wykeham	6	P.28	Prepared Patches	2+1 or 1+1	—
	31	,,	16	P.31	Moderately deep two furrow ploughing	1+0	—
	32	Broxa	12	P.44	Single furrow deep R.L.R. ploughing	1+0	1 oz./plant

TABLE 5

ALLERSTON DISTRICT: WYKEHAM AND BROXA, 1952. PROFILES 18-32

Summary of Profile and Stand Data of Scots pine, Sitka spruce, Lodgepole pine and Corsican pine

	Scots Pine					Sitka Spruce					Lodgepole Pine		Corsican Pine		
	Wykeham		Broxa		Turkey Carpet	Wykeham				Broxa	Wykeham		Wykeham		Broxa
	Prepared Patches 1 sq. ft.	Two Furrow Ploughing	Shallow Single Furrow Ploughing Subsoiled	Single Furrow R.L.R. Ploughing	Unknown	Prepared Patches 1 sq. ft.	Prepared Patches Mulched	Two Furrow Ploughing Subsoiled Noslag	Two Furrow Ploughing Subsoiled Slag	Complete R.L.R. Ploughing	Prepared Patches 1 sq. ft.	Two Furrow Ploughing	Prepared Patches 1 sq. ft.	Two Furrow Oliver Ploughing	Single Furrow R.L.R. Ploughing
Profile No.	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Cult. depth	6″	8½″	4½″	10″	—	6″	6″	9″	9½″	17″	6″	9½″	6″	8″	8″
Subsoil ,,	—	—	14½″	—	—	—	—	15½″	12″	—	—	—	—	—	—
Pan ,, Range in ,,	8½″ (2½″)	6½″ (3½″)	8″ (4″)	9½″ (7″)	9½″ 18″ (12) —	7″ (1″)	10″ (4″)	9½″ (12″)	9½″ (11″)	±12″ Est.	7½″ (1½″)	7½″ (8½″)	5½″ (1″)	14½″ (6″)	11″ (10″)
Depth to compact horizon	17″	19″	8″	not defined	24″	17½″	15½″	—	not defined	not defined	not defined	25″	15½″	not defined	18″
Depth of loose region					33½″				23″						34″
Age in years	24	21	11	9	±80	24	24	21	21	9	24	21	24	21	8
Mean depth Free Rooting Range	9½″ (11″)	8½″ (14″)	6″ (22″)	11½″ (26″)	18″		2½″ (3″)	8⅓″ (21″)	7″ (18″)	12″ (13″)	2½″ (12″)	13″ (24″)	11″ (11″)	13″ (7″)	11″ (11″)
% Rooting below pan	100%	95%	55%	60%	100%	Nil	Nil	40%	60%	100%	70%	90%	100%	70%	40%
Max. Rooting Depth	38½″	62½″	33½″	42″	+48″	—	3½″	18″	42″	16″	35″	44½″	32″	21½″	23″
Mean GBH	11.1″	13.4″	—	—	32″	—	—	—	11½″	—	13.3″	10.7″	13.7″	16.5″	—
,, Ht.	23′	24′ 7″	10′	10′ 3½″	—	2′ 1″	4′ 0″	12′ 7″	21′ 6″	4′ 6″	25′ 9″	22′ 2½″	25′ 1″	27′	7′ 1″
M.A.I.	11½″	15″	11″	13½″	—	1″	2″	7″	12″	6″	13″	12½″	12½″	15½″	12″
Slag	—	—	1 oz./tree	1 oz./tree	—	—	—		2 oz./tree	1 oz./tree	—	—	—	—	1 oz./tree

II. SCOTS PINE

Pinus sylvestris L.

(Profile Numbers 18-22, Diagrams 11, 14, 15, Photos. 7, 10, 12, Figs. 3 and 4)

Under suitable conditions of climate and soil Scots pine is typically deep rooted, with a pronounced tap root and numerous sinkers arising close to the butt from the lateral roots. The lateral roots are well developed within the top soil, branch freely, and taper rapidly.

Under the minimum soil preparation investigated in the Wykeham experiments, prepared patches, Scots pine is well established and has grown steadily but slowly. (Diagram 11). There is considerable variation in tree height, girth and form within the stand. The free rooting zone extends from the surface to the shallow pan, but the intensity of rooting, both of large roots and fibrous roots, is greatest at the surface and immediately above the pan. Few fibrous roots are to be found in the leached sandy A_2 horizon. Some descending roots penetrate the pan and exploit the favourable illuvial horizon beneath, but are prevented from further descent by the compact parent material. (Photo 7). Thus the excavated root stock has a three-storied appearance—surface, pan, and parent material coinciding with the horizons.

Any form of cultivation, ploughing or subsoiling, induces the roots to exploit vigorously all disturbed soil and other favourable soil horizons exposed by the cultivation. This root activity is reflected by an increased height and girth increment and a greater uniformity of individual trees within the stand. When the soil is partially cultivated in strips, the rooting is concentrated in the disturbed soil, and the intermediate undisturbed top soil is exploited only to a minor degree. Thus single furrow ploughing induces a marked degree of alignment of the major lateral roots with the line of ploughing. (Profile 20, Photo 12).

Advantage is taken by the descending roots of any rupture of an obstruction to deeper rooting such as pan or compact subsoil. Any naturally occurring relief within the compact subsoil, such as an old root channel, is explored. The descending roots exhibit a considerable ability to penetrate adverse soil conditions in order to exploit and develop in more suitable rooting media beyond.

Subject to a complete cultivation of the surface to a depth of eight to ten inches there would appear to be little necessity for subsoiling of this soil for the successful establishment and continued growth of Scots pine.

III. SITKA SPRUCE

Picea sitchensis Carr.

(Profile Numbers 23 to 27, Tables 4, 5, Diagrams 18, 20, 21, Photos. 14, 15, 18, 19, 20, Figs. 3, 4, 5)

The Allerston district upland heaths do not naturally provide suitable conditions for the growth of Sitka spruce. If the edaphic and micro-climatic conditions and the vegetation of the site are sufficiently altered by treatment, the spruce may be established and brought into canopy. Both the lateral and descending parts of the root system of such a stand are well developed. The lateral roots tend to be shallow within the profile but do not appear on the surface. They branch freely and taper rapidly, and produce numerous sinkers. The descending roots form a significant proportion of the root system and arise both as sinkers and directly from the bases of the trees. The depths which these roots explore is determined by the depth of soil providing a suitable medium for root development. This is normally the weathered profile.

When Sitka spruce is planted into prepared patches the initial survival is good. By the second year after planting the trees go into check, and subsequently remain in that condition. With the passing years the initial stocking steadily decreases as individuals die. Root systems of the survivors are confined to adventitious roots which arise from the stem at the soil collar and extend stringlike over the surface of the *Calluna* peat. The original nursery root systems in most cases fail to develop further after planting and are smothered in fine *Calluna* roots. Any extension of the nursery roots is towards the surface, and thereafter on the surface.

If a cut *Calluna* mulch is applied to the surface in sufficient quantity the living *Calluna* is suppressed. Further effects are the amelioration of extremes of temperature and moisture at the peat surface and direct manuring of the area by decomposing plant material. The response of the superficial root system described above is to extend over the surface and to maintain a greater mass of fibrous rootlets exploiting the decomposing *Calluna* litter above the peat. New adventitious roots may arise from the stem at the mulch collar. No new descending roots develop, at least within a period of three years after the complete suppression of the *Calluna*. The existing foliage changes from a sickly yellow green to a healthy dark green, and pronounced leading shoots develop, which produce normal healthy needles. (Photos. 14 and 15).

In the period following the mulch application, the trees come temporarily out of check and in order to maintain this growth, re-invasion of the *Calluna* must be prevented. Also the nature of the surface peat must be modified to allow sufficient vertical aeration and drainage, which in turn permit descending roots to exploit the mineral soil underneath. This is necessary to maintain the supply of nutrients and to provide the necessary mechanical support for the growing trees. The first requirement can be fulfilled by further applications of mulch as necessary. Possibly both requirements may be satisfied if the stand closes canopy.

The response of Sitka spruce to any form of light cultivation is quickly nullified by the rejuvenation and re-invasion of *Calluna* which is followed by a check in the growth of the spruce. Circumstances which modify this state of affairs are discussed below in dealing with the nursing effect of adjacent stands. The response to deeper and more complete cultivation may be maintained, at least in part, up to the formation of canopy, as is demonstrated by double furrow ploughing and subsoiling at Wykeham. (Profile No. 25, Diagram 20). The nursery root system developed in the disturbed mineral soil, together with fresh adventitious roots from the soil collar. The greatest development was by the lateral roots, but a few roots descended in the region of the subsoiling and beneath the plough furrows. Undisturbed topsoil remained practically free of spruce roots. Half the area had been turned over by ploughing to a depth of nine inches and the remaining unploughed land was covered to some few inches by spoil. In addition the subsoiler had caused further and deeper disturbance within or beside the unploughed land. Thus the initial suppression of the *Calluna* was good. Its subsequent establishment was slow, and took place by seedling regeneration rather than by rejuvenation of old *Calluna* stools. The spruce were able to maintain a constant, though slow, increment until canopy closed and once more completely suppressed the *Calluna;* this was followed by a dramatic increase in the annual height increment.

Half of this plot had been treated with two ounces of basic slag per tree at the time of planting and was the site of profile 26. (Diagram 21). Fig. 5 illustrates by histograms the responses of Japanese larch and Sitka spruce to the application of basic slag (phosphatic fertiliser).

The form of the root profile was similar to that in profile 25, but the vigour of the roots, reflected by their size and number, is very much greater.

Along the ploughed ridges and furrows there is a marked degree of orientation of the lateral roots, parallel to the direction of cultivation. (Photo 18). A vigorous descending root system developed to the pan, and beyond it where the pan had been ruptured by the plough or subsoiler. The descending roots cease abruptly at the level of compact parent material. (Photo 19). A very few roots extend to the loose region further below by way of vertical channels.

The vigour and extent of the root system is reflected in the growth of the trees above ground. Height increment was steadily maintained and canopy closed many years before that of the unslagged plot.

The effect of the slag was to initiate and maintain an early vigour in root and shoot development. This minimised the effects of the late return of *Calluna* competition, both by the suppressing effect on the *Calluna* of the larger crowns; and secondly because the slag induced the spruce roots to exploit rapidly a considerable depth of soil made available by the cultivation, before the re-invasion of the *Calluna.*

An assessment made of the ten tallest trees in each plot in Wykeham Experiment 11 in 1948 showed somewhat better growth for pure Sitka spruce on complete ploughing plus slag than on two furrow ploughing and subsoiling plus slag.

Any attempt to analyse the results of assessments of Sitka spruce in Experiment 11 at Wykeham must take into account important factors which relate especially to this species. The plots are small, $1\frac{1}{3}$ chains long and half a chain wide, and this area is halved for the slag application trials. The nursing effect of adjacent stands, both in regard to the root system of the spruce and to the wind protection afforded the stand, cannot be discounted for any treatment and have had a major effect on all but the most intensive treatments. Care must therefore be taken when interpreting the results in terms of large areas of pure Sitka spruce plantations on similar soils. The mean dominant height growth of the less intense cultivation and treatments without slag is greater by reason of the nursing effect than it would be for large areas similarly treated. This is also true of the intense cultivation and treatment with slag, but to a less extent.

Profile 27 was exposed at Broxa in a nine-year-old plantation of pure Sitka spruce established on ground completely ploughed to a depth of seventeen inches with an R.L.R. plough. (Diagram 18). There had been relatively slight disturbance within the ploughed spoils, which remained intact when turned over by the plough. As a result there was little mixing of the soil horizons and large air pockets remained between the spoils. In 1946, three years after planting, it was reported that *Calluna* regeneration covered ten per cent of the area, in terms of foliage cover of the soil. In 1951 there was a complete cover of vigorous *Calluna,* the trees were a yellowish-green colour and were in a state of check or semi-check. The heights of the trees ranged from three to seven feet. The ploughed depth of soil was explored freely by spruce roots originating from the nursery root systems, and from adventitious roots. (Photo 20). They were sparsely scattered throughout the soil, were of small diameter and tended to be long and stringlike. A profusion of fine *Calluna* roots was present in the same ploughed soil as the spruce roots. In spite of the deep cultivation and one ounce of basic slag per tree at the time of planting, the spruce was not able to gain control of the site sufficiently to compete with the re-invasion of *Calluna*. Sitka spruce in mixture with broom (*Sarothamnus scoparius* (L.) Wimmer), which received a 2½ cwt. per acre dressing of basic slag (i.e. more than two and a half ounces per tree), shows healthy development in an adjacent plot on the same cultivation.

In the Wykeham experiment the response in growth of pure Sitka spruce plantations to the formation of adjacent coniferous stands is a common phenomenon referred to as a nursing effect. Individual Sitka spruce trees adjacent to the nurse crop develop long ropelike lateral roots bearing, near the extremities, fibrous rootlets within the litter beneath the nurse species. As a result of this root extension the spruce trees concerned regain a healthy colour and rapidly increase their annual shoot growth. Subsequent to the suppression of *Calluna* beneath these nursed edge trees, their neighbours obtain some benefit and the nursing effect spreads slowly into the Sitka spruce. The nursed spruce when in canopy does not nurse the neighbouring spruce trees as rapidly as the initial nurse crop in the adjacent plantation.

The nursing effect is least where minimum cultivation had been done, assuming that the nurse crop has formed canopy. It is most noticeable under the more intensive types of cultivation where no slag has been applied to the spruce crop. More cultivation, which ensures the initial suppression of the *Calluna* together with a thorough disturbance of the surface peat and mineral soil, and the application of a sufficient quantity of basic slag allows the spruce to become well established and to form canopy without check, at least in a small sheltered stand. In this case any possible nursing effect is masked.

Bearing in mind the foregoing discussions on the types of root systems developed under varying types and intensities of cultivation, it is apparent that the suppression of *Calluna* is of prime importance for the establishment of a stand of Sitka spruce on these heaths. Adequate opportunity for the spruce roots to exploit the mineral soil provided by cultivation is of equal, though of secondary importance. Finally, the level of fertility of the soil, directly or indirectly related to the amount of available phosphates, may be limiting especially in the early years of establishment.

IV. LODGEPOLE PINE

Pinus contorta var. *latifolia* Engelm.

(Profile Numbers 28 and 29, Diagrams 22, 24, Photo 22, Fig. 3)

The root system of lodgepole pine is similar to that of Scots pine, but exhibits greater ability to overcome adverse soil conditions by both lateral and descending roots. This ability is reflected by the stand which forms an even quality crop under the minimum of soil preparation provided at Wykeham, i.e. prepared patches. Under these planting conditions the lateral roots exploit the surface organic horizons. Numerous sinkers descend from these roots and together with descending roots arising directly from the butt, penetrate the sterile sandy eluvial horizon to exploit the soil immediately above the pan. On reaching the pan, such roots are deflected by it, but not arrested. Many continue to run along the pan surface, others penetrate the pan to exploit the illuvial horizon below. Any access into the compact parent material provided by channels is readily made use of by descending roots. The fine roots of lodgepole pine tend to have a fine wirelike appearance.

The response of this species to cultivation is least of any investigated. The ploughed soil is more freely used by the lateral roots than the undisturbed soil and this leads to some degree of alignment of these roots with the direction of ploughing. The descending roots take advantage of any shattering of the pan to extend freely as far as the compact parent material will allow. At least in the examples excavated there is no increase in height growth as a result of cultivation although it would appear reasonable to suppose that the well distributed root system of the stand grown on cultivated soil would serve the forest better in the long run.

Intense cultivation is not essential for the satisfactory establishment of lodgepole pine at Allerston, but a surface cultivation is advisable for the uniform development of the root system throughout the soil profile.

V. CORSICAN PINE

Pinus nigra var. *calabrica* Schneid.

(Profiles 30 to 32, Diagrams 28, 29, Photos. 27, 28, Figs. 3, 4)

The root system of Corsican pine is very similar to that of Scots pine, both in its normal character and development and in its reaction to varying soil conditions.

The stand of Corsican pine planted into prepared patches was more uniform than a comparable stand of Scots pine and the form of the trees was good. Beneath the planting position the free rooting zone extended freely beyond the shallow pan and further descending roots explored channels in the compact parent material. The excavated root stock is decidedly three storied, the lateral roots follow the near surface soil and the descending roots extended laterally at the pan level and compact parent material. (Profile 30, Diag. 28 and Photo 27.)

There was a marked response by the root system to cultivation (Profiles 31 and 32). All horizons above the relatively deep pan (11 to 14½ inches) were freely used by roots with some preference for the sandwich layer. The lateral roots were well developed and the descending roots were numerous, sinkers as well as many large roots arising from below the butt.

Although not essential for the formation of a stand complete cultivation is advisable for the full utilisation of these soils by Corsican pine. Partial cultivation would lead to a degree of alignment of the major lateral roots with the direction of ploughing which may endanger the stability of the stand.

Chapter 5

THE STUDY IN NORTH-EAST SCOTLAND

This chapter discusses the observations made at three field experiment sites on the upland heaths and two other areas, in north-east Scotland in the autumn of 1952. This is an extension of the study in the Allerston district to compare the root development of conifers in relation to the site factors and ground preparation.

TEINDLAND FOREST. FINDLAY'S SEAT EXPERIMENT

I. GROUND PREPARATION AND THE STAND ROOT SYSTEMS

In view of the semi-permanent waterlogged state of this heath, accompanied by a very poor vegetation association, the early experiments at Findlay's Seat were drainage trials. That is to say, it was thought necessary to carry excess water off the area, clear of the land to be planted. Scots pine was used for these experiments. (Profile numbers 2, 3 and 4). Two years later in 1928 a series of experiments were established to test the effects of ploughing without drains, together with the application of basic slag, on a number of species including Scots pine and Sitka spruce (Profile numbers 5 and 6). In 1929 an experiment was established to test the suitability of lodgepole pine over a series of ground treatments, with and without basic slag (Profile numbers 7, 8 and 9). Many more experimental plots were established on the area but, unfortunately, most of them were burned in 1942. Profile number 1 in Japanese larch was located in a remnant of a drainage and Semsol (phosphate) application experiment.

Table 6 sets out the species and treatments dealt with in this investigation and these are elaborated below in the detailed discussions of the profiles and sites. Table 7 lists a summary of the root and soil profile data of the excavations made at Teindland.

Fig. 6 illustrates by histograms the profiles exposed at Findlay's Seat, showing the effects of ground preparation and the application of basic slag on root and shoot. Detailed discussions of the profiles are to be found in Appendix 3, page 61.

Direct planting by notching on this heath results in complete failure or severe check. The permanently water saturated anaerobic character of the surface peat prevents the development of roots in the mineral soil beneath the peat with the result that such roots as do develop are confined to the peat surface.

Any rupture of the peat by drains, mounds or ploughing relieves the saturation of the peat in the vicinity of the disturbance and provides direct local aeration of the mineral soil. Scots pine and lodgepole pine are able to take advantage of these altered conditions to develop, within the weathered profile, root systems which are capable of supporting the slow but continued growth of the trees. As the root systems develop and the canopy forms, the duration and degree of waterlogging of the surface and mineral soil above the unbroken pan/compact subsoil are reduced, and finally eliminated.

Thus when trees are planted on land drained at intervals, the trees on the drainsides benefit immediately from deeper rooting in the drain spoil and in the aerated soil beside and below the drains. Deeper drains provide both more spoil and expose a greater depth of soil which encourages correspondingly better growth in root and shoot of the

TEINDLAND FOREST: FINDLAY'S SEAT EXPERIMENTS, 1952. PROFILES 1-9

Experiment and Establishment Details. Japanese larch, Scots pine, Sitka spruce and Lodgepole pine

TABLE 6

Species	Profile No.	Expt. No.	P. Year	Ground Preparation	Seed-ling	Fertilizer
Jap. larch	1	56	P.35	Drained—Turf planting	1+1	3 oz. Semsol/tree 2 yrs. after planting
Scots pine	2	13	P.26	Control—no preparation, notch planting	2+1	—
„	3	13	P.26	Shallow plough drains notch planting	2+1	—
„	4	13	P.26	Shallow plough drains and hand deepened. Notch planting	2+1	—
„	5	23	P.28	Complete shallow ploughing	2+1	1929 Slag ½ ton/ac.
Sitka spruce	6	23	P.28 P.35 extn.	Complete shallow ploughing	3+2	1929 Slag ½ ton/ac. 1935 in strips
Lodgepole pine	7	41	P.29	Mound planting	2+1	Slag 2 oz./tree
Lodgepole pine	8	41	P.29	Three furrow ploughing	2+1	—
Lodgepole pine	9	41	P.29	Three furrow ploughing	2+1	Slag 2 oz./tree

drainside trees. In the early years of the plantation the drains also provide some relief from excess surface water between the drains by carrying away surface run-off at times of heavy precipitation. As the drainside trees grow into canopy, the root systems of the trees between the drains benefit from longer periods of relief from water saturation of the peat, and extend within the mineral soil beneath.

The physical limitations of the undisturbed surface horizons (the ability of the *Calluna* peat to hold moisture and the compactness of the sterile sand) remain in between the drains to limit the full utilisation of the site by the stand root system. When canopy is complete between the drains, the supporting root systems of the inter-drain trees are mainly confined to lateral roots on or near the surface. Alleviation of the soil water relationship at the surface makes little difference to the established superficial support of these trees, as further root extension below the surface occurs well away from the bases of the trees from which the roots arise. A further factor which limits the growth of the root system and stand is the low fertility level of this soil, and this is discussed below in dealing with the application of basic slag.

Mound planting was done by digging a patch of ground to some inches and piling the spoil beside the patch, the tree was then planted in the spoil. Thus the conditions for growth of all the trees are similar to those for the trees planted beside shallow drains as described above.

Ploughing disrupts the surface peat and mineral soil to the depth and extent of the cultivation, thus eliminating the limiting physical surface phenomena. Excessive water, falling as rain or snow, is not carried away as by open drains, but percolates below the surface and may form a temporary perched water table above the pan/compact subsoil if this has not been ruptured. The healthy development of a stand root system in the disturbed soil reduces this water accumulation within a short period after planting. By the time the stand has formed canopy, there is no sign of waterlogging above the pan/compact subsoil and the roots within the cultivated soil extend to exploit the full depth of the weathered profile.

The soils in the Teindland experimental area are chemically as well as physically infertile. This is demonstrated by the better growth of all species on cultivated ground when basic slag is applied to them at planting (see Fig. 6). The effect of basic slag on the root system of a stand is to induce a vigorous development throughout the weathered profile. In particular, it encourages root exploration within soil horizons which normally deter root

TABLE 7

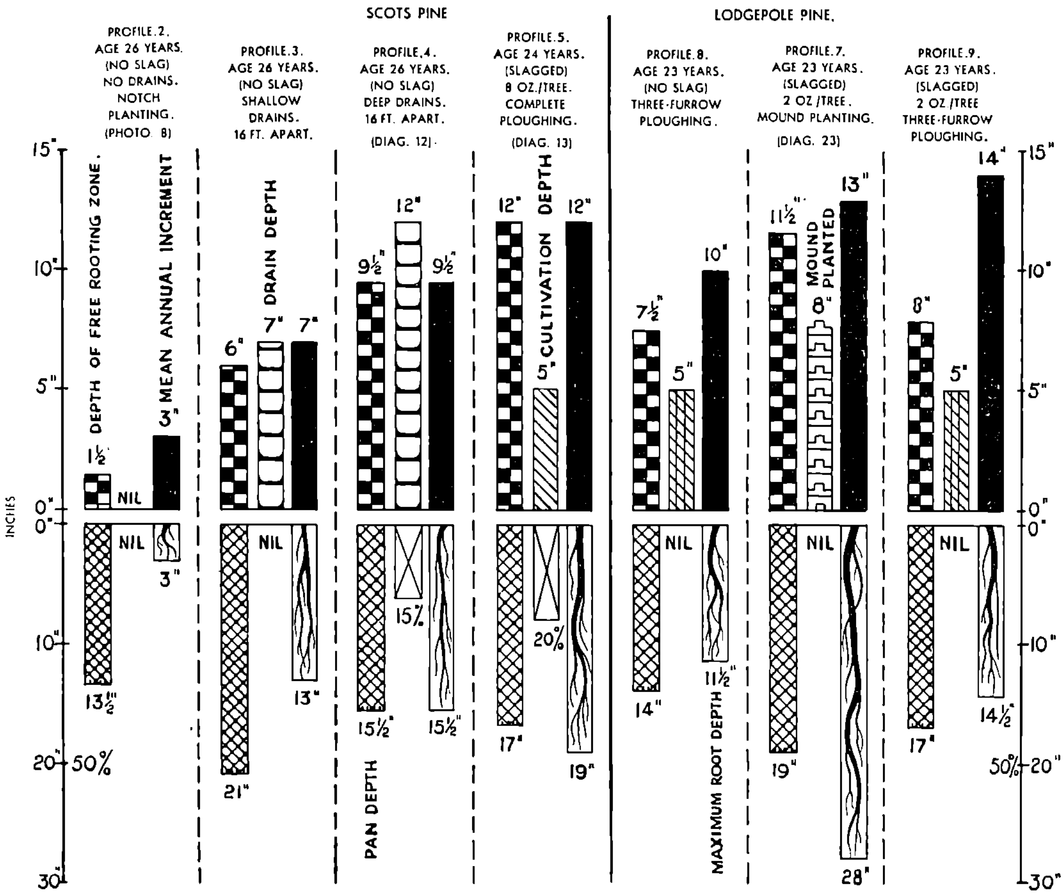
TEINDLAND FOREST: FINDLAY'S SEAT EXPERIMENTS, 1952. PROFILES 1-9

Summary of Profile and Stand Data of Japanese larch, Scots pine, Sitka spruce and Lodgepole pine

	Japanese Larch	Scots pine				Sitka Spruce	Lodgepole Pine		
Profile No.	1	2	3	4	5	6	7	8	9
Ground Preparation	Drains 6′ apart	Nil	Drains 16′ apart	Drains 16′ apart	Complete ploughing	Complete ploughing	Mound planting	Three furrow Ploughing	
Depth of ploughing	—	—	—	—	5″	5″	—	4″—6″	4″—6″
Depth of drains	6″—9″	—	6″—8″	12″	—	—	—	—	—
Mean pan depth Range in pan depth	12½″ (7″)	±13½″	21″ (4½″)	15½″ 6½″	17″ (13″)	17½″ (10″)	±19″	±14″	17″ (11″)
Age in years	19	26	26	26	24	24	23	23	23
Mean free rooting depth Range in free rooting depth	3″ (8½″)	1½″ (2½″)	6″ (10″)	9½″ (12″)	12″ (12″)	7″ (3½″)	11½″ (23″)	7½″ (12½″)	8″ (12″)
% Rooting below pan	Nil	Nil	Nil	15%	20%	Nil	Nil	Nil	Nil
Max Rooting depth	6½″	3″	13″	15½″	19″	8½″	28″	11½″	14½″
Mean Girth B.H.	7.5″	—	12.8″	10.9″	13.4″	10.5″	11.9″	9.9″	11.6″
Mean Height	15′ 7″	6′ 2″	16′ 6″	20′ 3½″	23′ 11″	18′ 6½″	23′ 8″	19′ 5″	25′ 7″
Mean Annual Increment	10″	3″	7″	9½″	12″	9″	13″	10″	14″
Slag	Semsol 3 oz. /tree	—	—	—	8 oz./tree	8 oz./tree	2 oz./tree	—	2 oz./tree

FIG. 6 TEINDLAND FOREST FINDLAY'S SEAT EXPERIMENT 1952

HISTOGRAMS OF SCOTS PINE AND LODGEPOLE PINE IN RELATION TO GROUND PREPARATIONS AND THE APPLICATION OF BASIC SLAG.



penetration, e.g. undisturbed or semi-permanently waterlogged horizons. This may in part be a secondary effect as the result of an improvement of soil, air and water relationships within the cultivated soil readily available to roots and which is initially vigorously exploited. The minimum amount of phosphatic fertiliser necessary to ensure satisfactory tree growth is not clear from the experiments. Lodgepole pine grew satisfactorily with only two ounces of basic slag per tree. It is certain that a greater application is required to establish a stand of pure Sitka spruce than is necessary for the pines. The requirement of Sitka spruce is closely related to the presence or re-invasion of *Calluna*.

II. THE SPECIES ROOT SYSTEMS

A clear comparison of the root systems of the species is complicated by the lack of uniformity of ground preparation for each species. The basic characteristics are the same as those found at Allerston, but there is a greater response to both cultivation and basic slag by all species at Teindland.

One example of *Japanese larch* was examined, established in an experiment with drains six to nine inches deep and six feet apart. Three ounces of Semsol (phosphatic fertiliser) were applied to each tree at planting. The root system is mainly confined to shallow lateral roots extending within the surface horizon and along the drainsides and bottom. A few small descending roots extend from beneath the butt for ten or twelve inches and are confined by the waterlogged soil above the pan at about fourteen inches. Without the addition of Semsol even this limited development would not have been attained.

Scots pine notch planted into this heath goes into early permanent check and senescence with-

PHOTO 1. DRUMFERGUE. Profile 2. Japanese larch, 20 years. View of profile and plotting grid. (1 foot squares) (Fig. 7).

PHOTO 2. WYKEHAM. Profile 8. Japanese larch, 20 years. View of profile and plan grid. (3 foot squares) (Diag. 8, Figs. 2, 3 and 5).

PHOTO 3. WYKEHAM. Profile 1. Japanese larch, 23 years. Planted in prepared patches. Note surface habit of lateral roots. (Diags. 1, 3, 5, Figs. 2 and 3.)

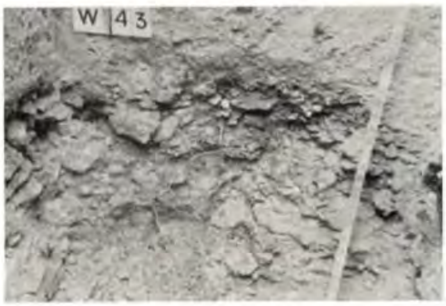


PHOTO 4. WYKEHAM. Near Profile 10. "Loose Region" at 4 to 4½ feet below the surface and beneath the compact subsoil. Note lodgepole pine roots.

PHOTO 5. DRUMFERGUE. Profile 1. Japanese larch, 18 years. Notch planted. (Diag. 7, Fig. 7.)

PHOTO 6. WYKEHAM. Profile 10. Japanese larch, 20 years. Two furrow medium depth ploughing plus subsoiling (below planting position). (Diag. 9, Fig. 2.)

PHOTO 7. WYKEHAM. Profile 18. Scots pine, 24 years. Planted in prepared patches. Note storied character. (Diag. 11, Fig. 3.)

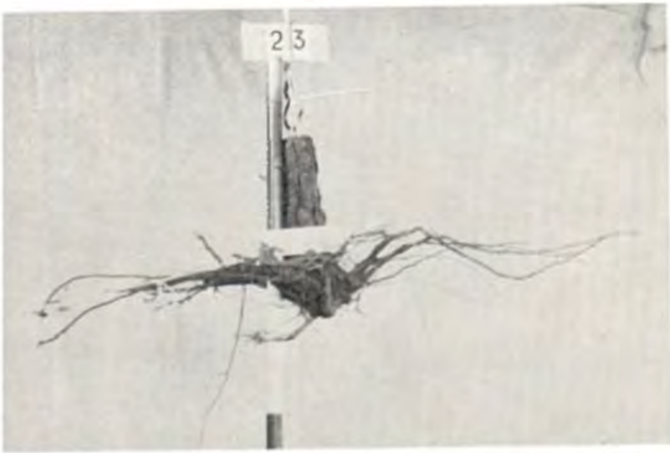


PHOTO 8. TEINDLAND. Profile 2. Scots pine, 26 years. Notch planted. Note lateral roots confined to peat surface. (Fig. 6.)

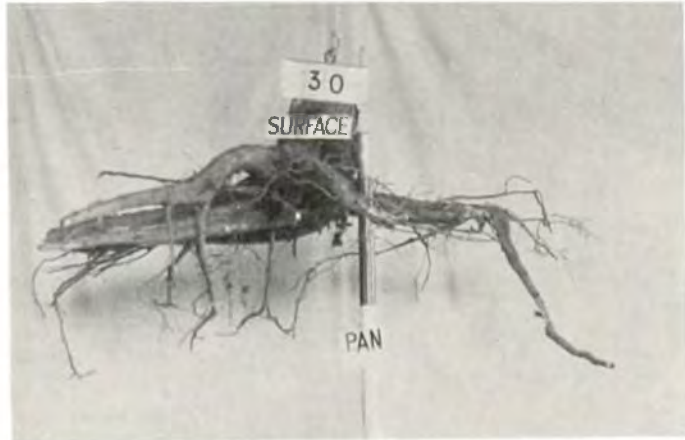


PHOTO 9. TEINDLAND. Profile 4. Scots pine, 26 years. Planted beside 12 inch drain. Note major roots, shallow laterals in line with the drain. (Diag. 12, Fig. 6.)

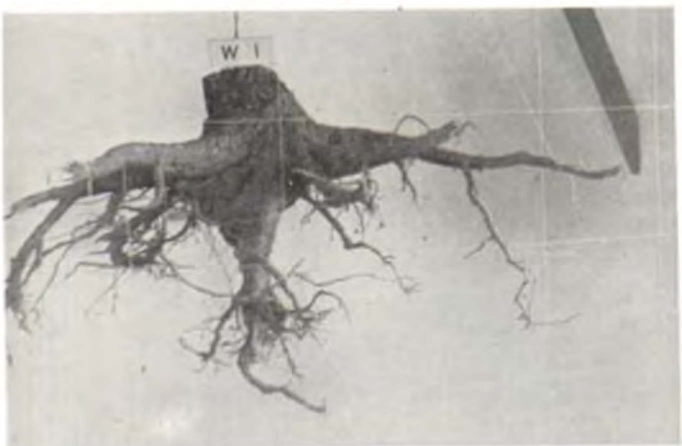


PHOTO 10. WYKEHAM. Profile 19. Scots pine, 20 years. Two furrow medium depth ploughing. Note tap root. (Furrow left, ridge right.) (Diag. 15, Fig. 3.)

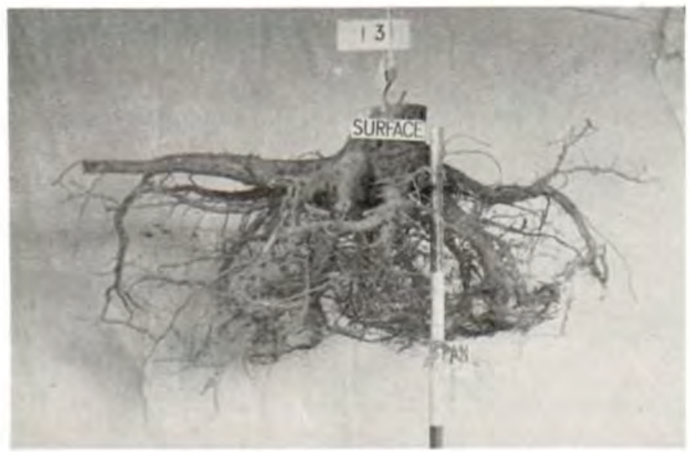


PHOTO 11. TEINDLAND. Profile 5. Scots pine, 24 years. Complete shallow ploughing plus basic slag. Note extensive root system throughout rooting depth. (Diag. 13, Fig. 6.)

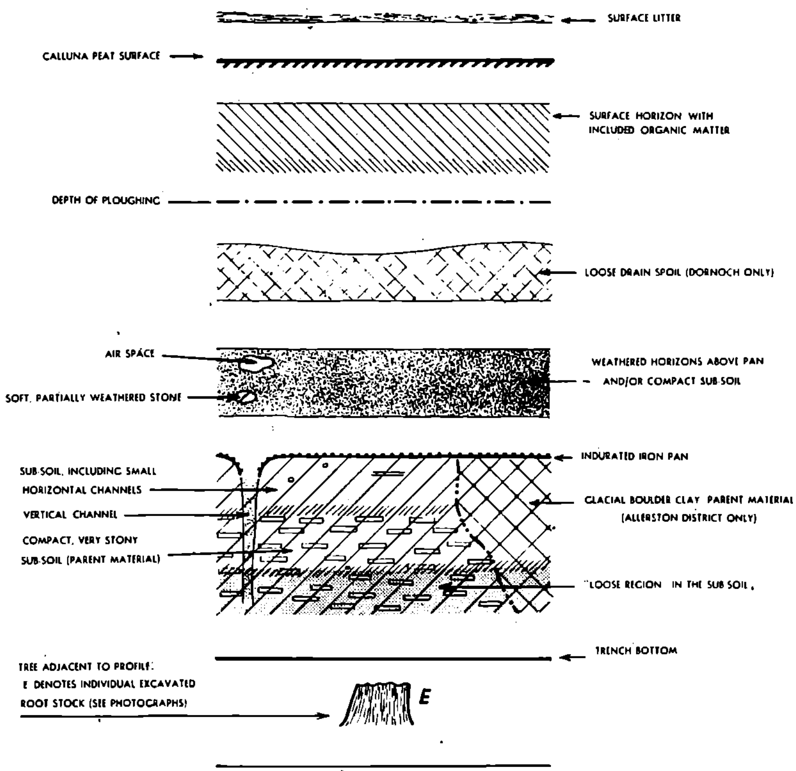
PHOTO 12. BROXA. Profile 20. Scots pine, 11 years. Single furrow shallow ploughing plus subsoiling. Note major laterals follow furrow, deep roots spread beneath shallow pan. (Diag. 14, Fig. 4.)

PHOTO 13. DRUMFERGUE. Profile 5. Sitka spruce, 21 years. Turf planted. Note ropelike roots on peat surface. (Fig. 7.)

PHOTO 14 and PHOTO 15. WYKEHAM. Profile 24. Sitka spruce, 24 years. Planted in prepared patches. Heavily mulched 4 years. Note (i) Great length of superficial lateral roots, and response of the shoot to the mulch, and (ii) Restriction of basal nursery root system and development of adventitious roots from the collar. (Fig. 3.)

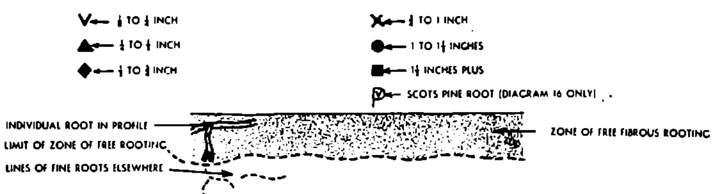
KEY TO SYMBOLS USED IN THE PROFILE DIAGRAMS

SOIL PROFILE



ROOT PROFILE

MEASURED ROOT DIAMETERS



EXPERIMENT AND ESTABLISHMENT DETAILS AND PROFILE AND STAND DATA ARE LISTED IN THE APPROPRIATE TABLES FOR EACH AREA.

FOR INDIVIDUAL SOIL DESCRIPTIONS REFERENCE SHOULD BE MADE TO THE DETAILED DISCUSSIONS IN THE APPENDICES

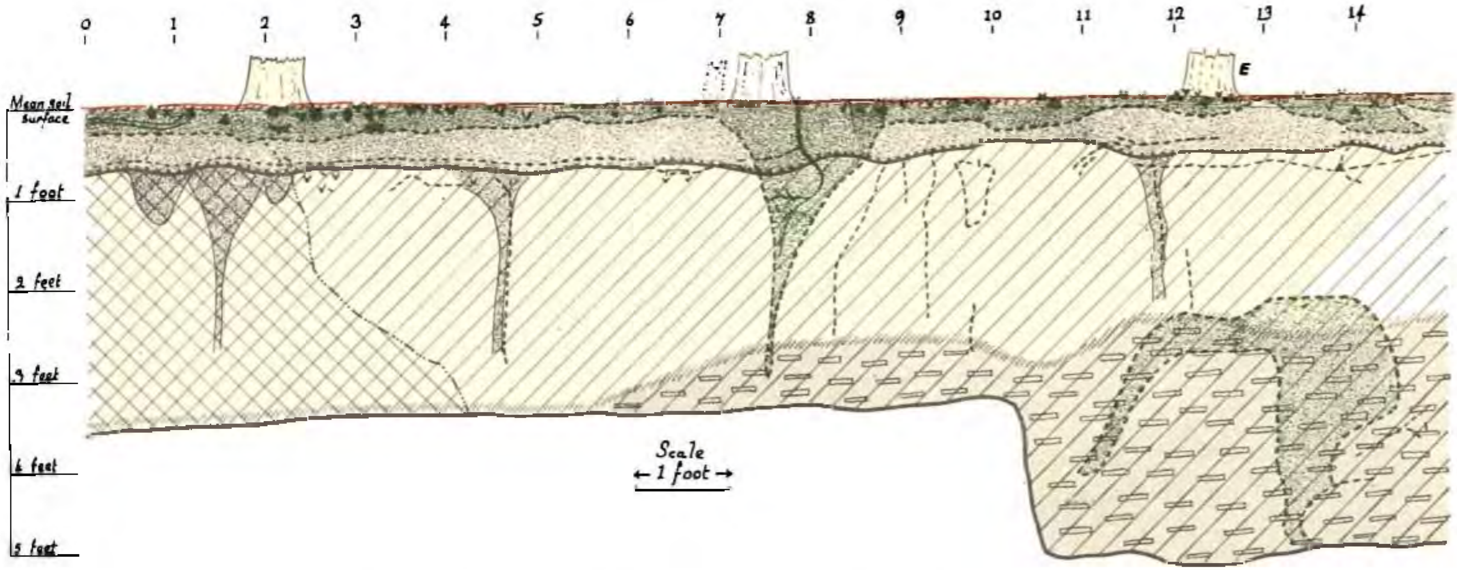
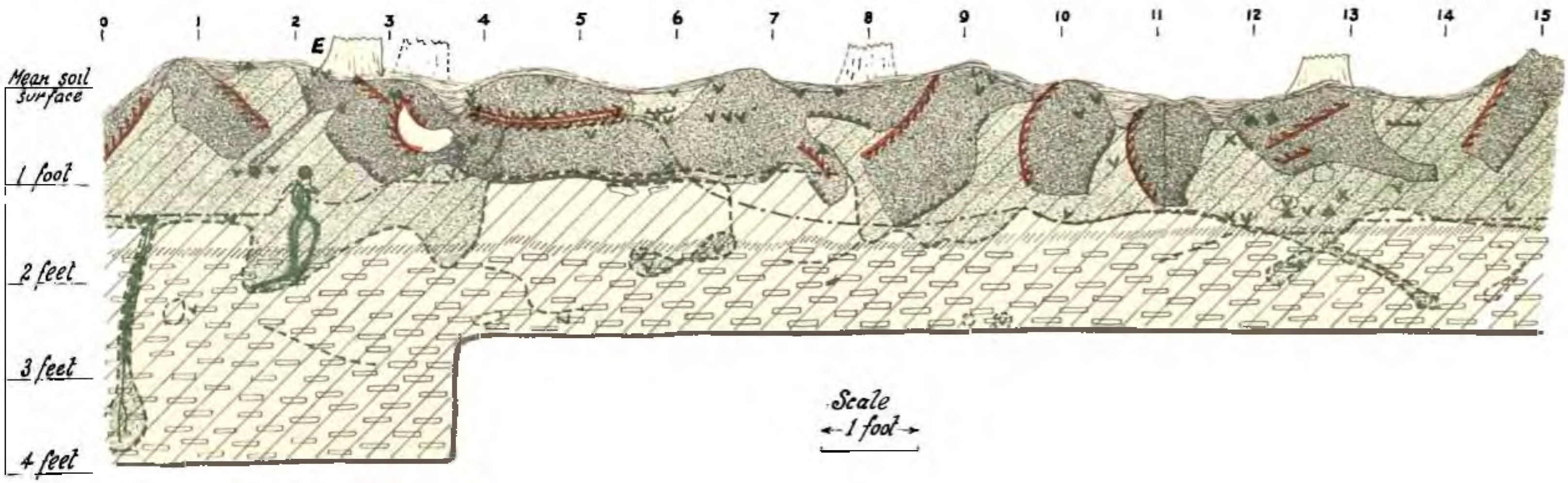


DIAGRAM 1.—WYKEHAM Profile 1. Japanese larch (23 years). Planted in prepared patches.
(See also Photo 3.)



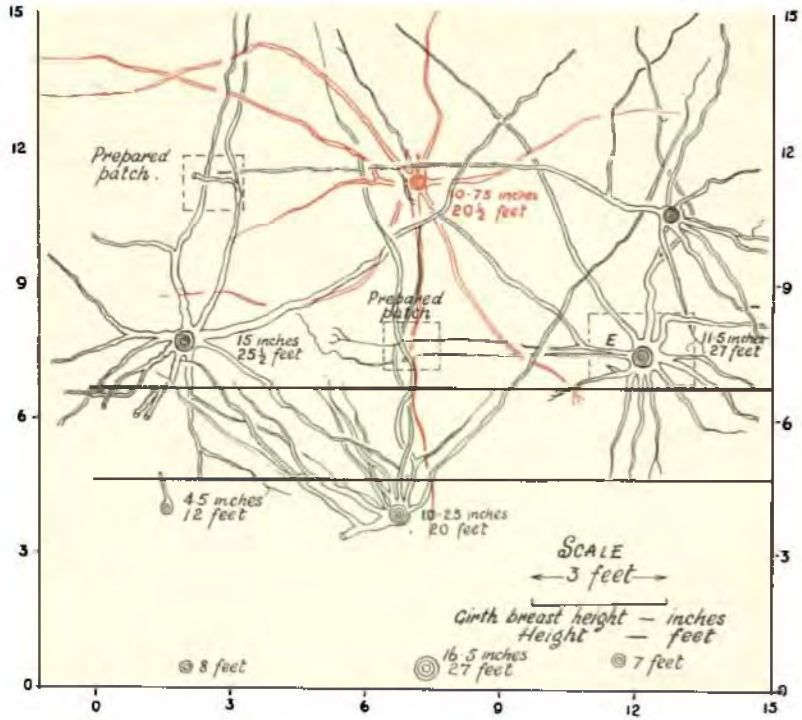


DIAGRAM 3.—PLAN AREA WYKEHAM Profile 1. Japanese larch (23 years). Exposed surface root system. (See also Diagram 1.)

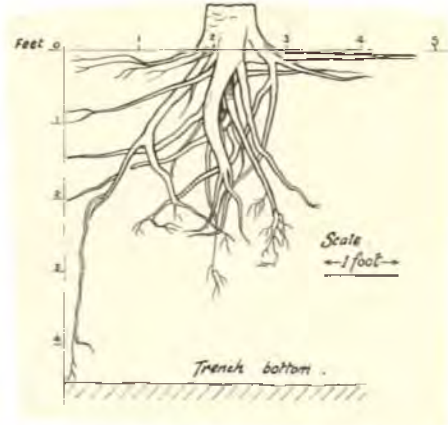


DIAGRAM 4.—ROOT STOCK WYKEHAM Profile 12. Japanese larch (20 years). Excavated root stock. (See also Diagram 2.)

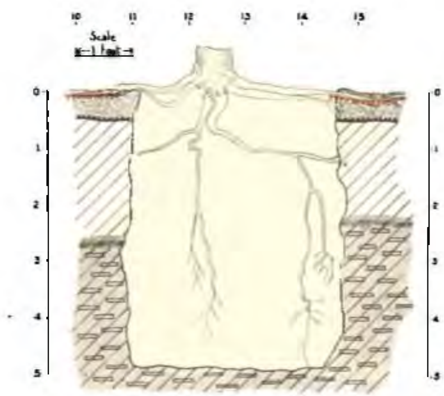


DIAGRAM 5.—ROOT STOCK WYKEHAM Profile 1. Japanese larch (23 years). Excavated root stock in relation to profile. (See also Diagram 1.)

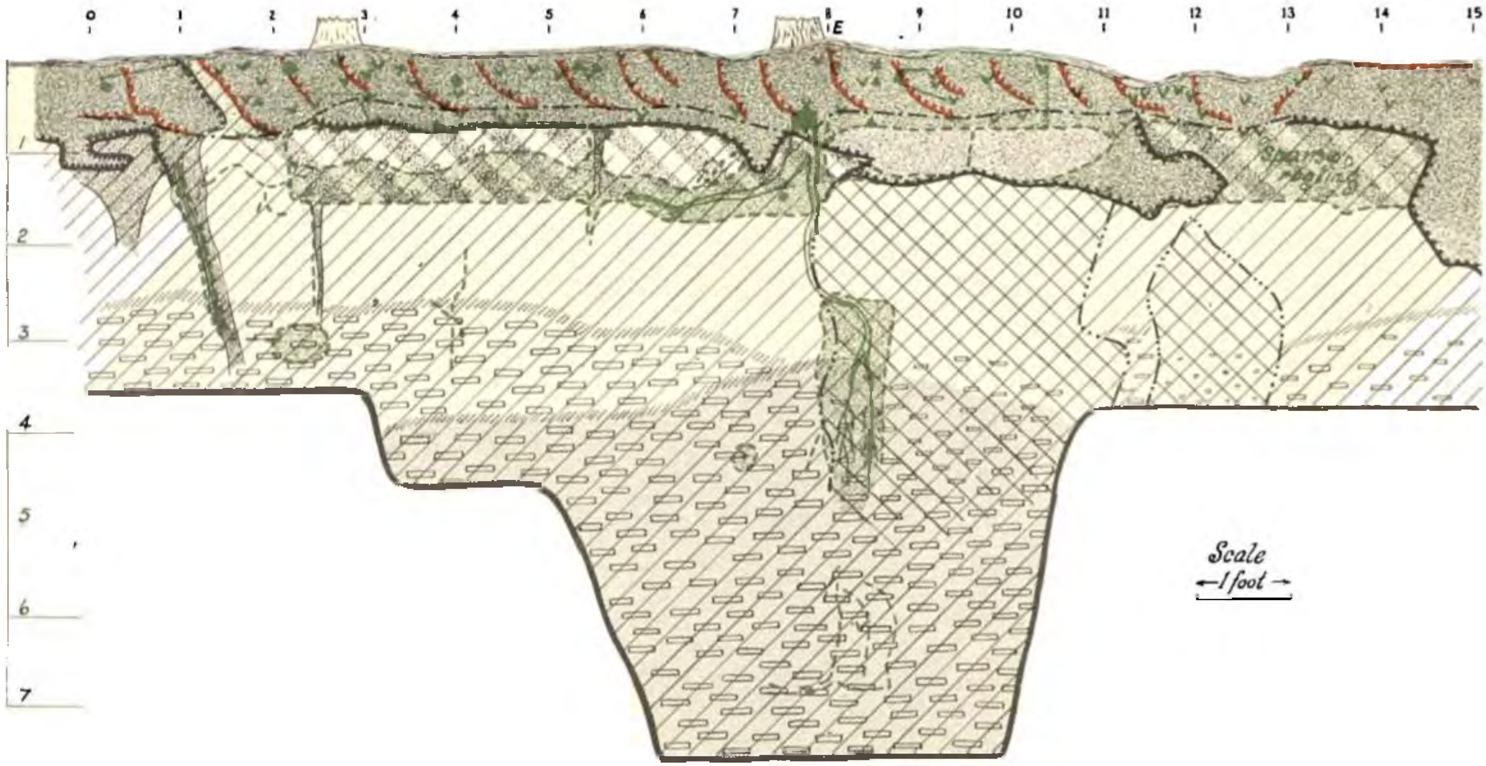


DIAGRAM 6.—WYKEHAM Profile 6. Japanese larch (23 years). Complete shallow ploughing.

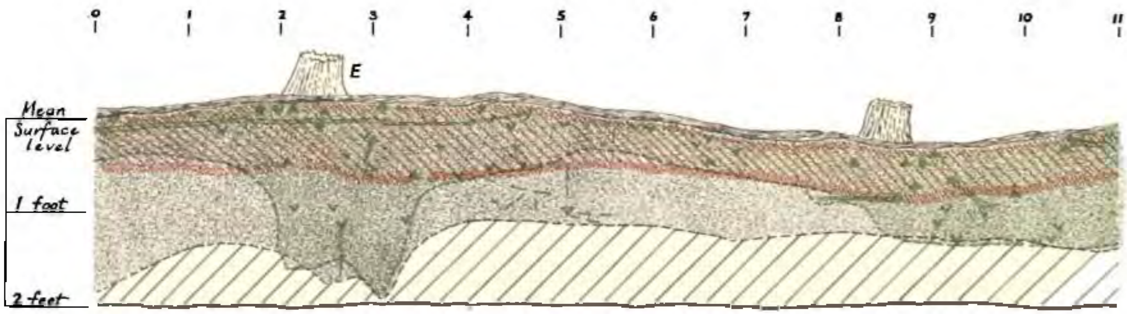


DIAGRAM 7.—DRUMFERGUE Profile 1. Japanese (Hybrid ?) larch (18 years). Direct notch planting. (See also Photo 5.)

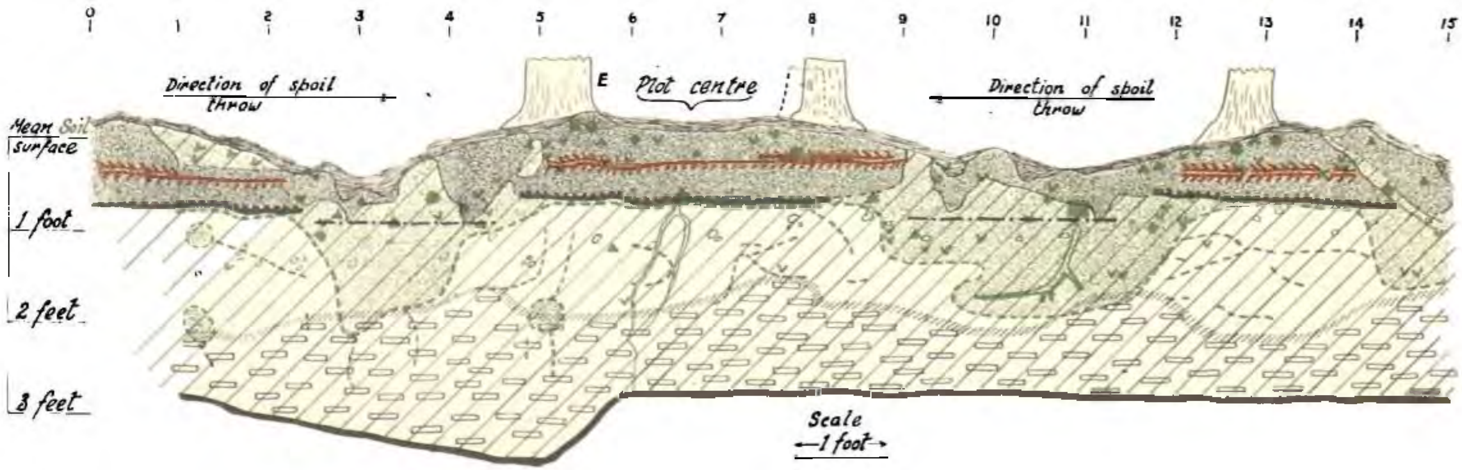


DIAGRAM 8.—WYKEHAM Profile 8. Japanese larch (20 years). Two furrow medium depth ploughing. (See also Photo 2.)

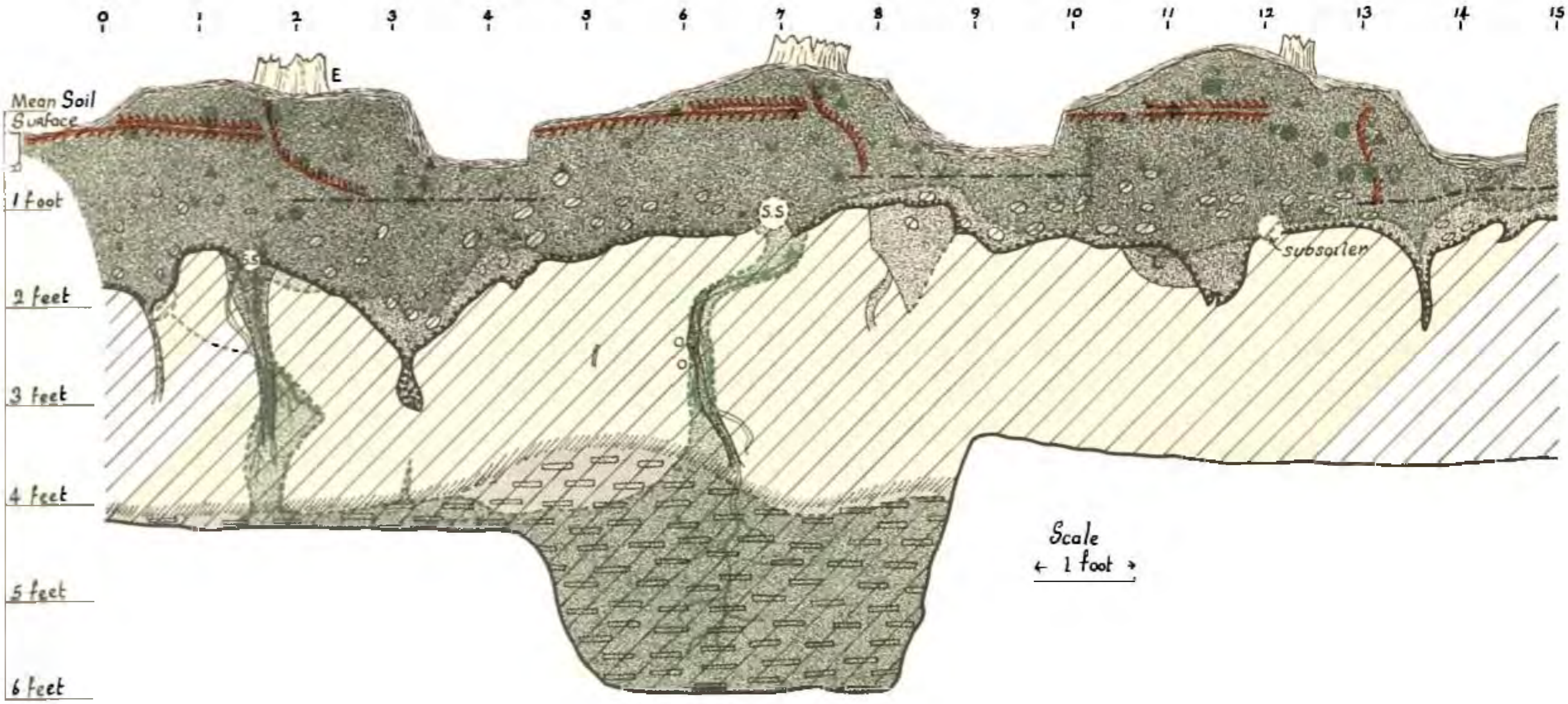


DIAGRAM 9.—WYKEHAM Profile 10. Japanese larch (20 years). Two furrow medium depth ploughing plus subsoiling. (See also Photo 6.)

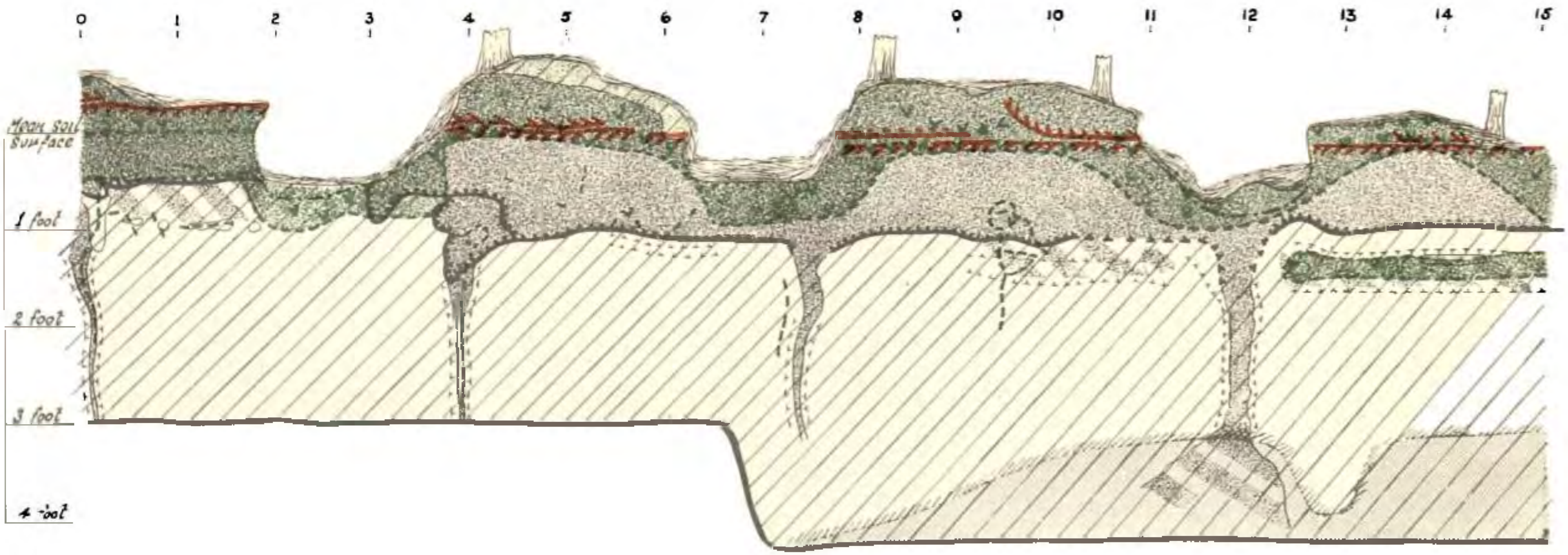


DIAGRAM 10.—BROXA Profile 15. Japanese larch (8 years). Single furrow deep ploughing.

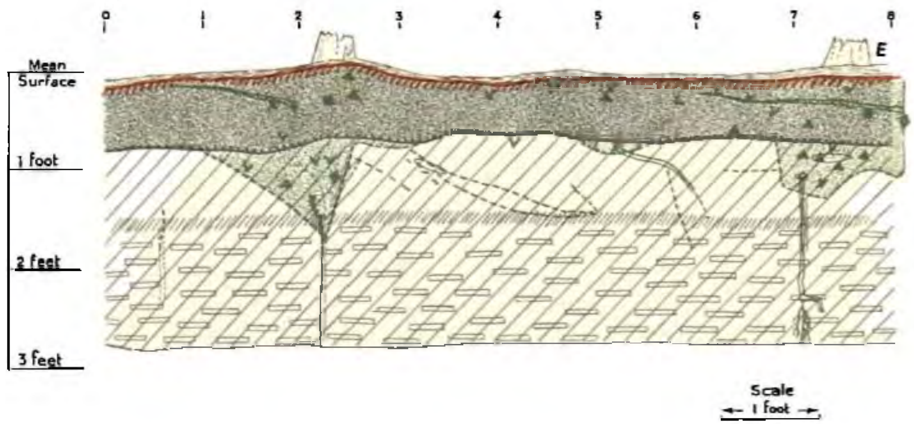


DIAGRAM 11.—WYKEHAM Profile 18. Scots pine (24 years). Planted in prepared patches. (See also Photo 7.)

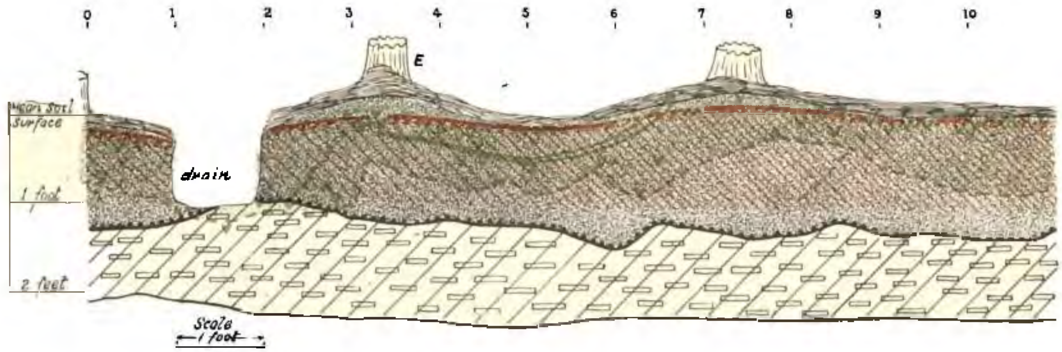


DIAGRAM 12.—TEINDLAND Profile 4. Scots pine (26 years). Notch planted between drains 16 feet apart and 12 inches deep. (See also Photo 9.)

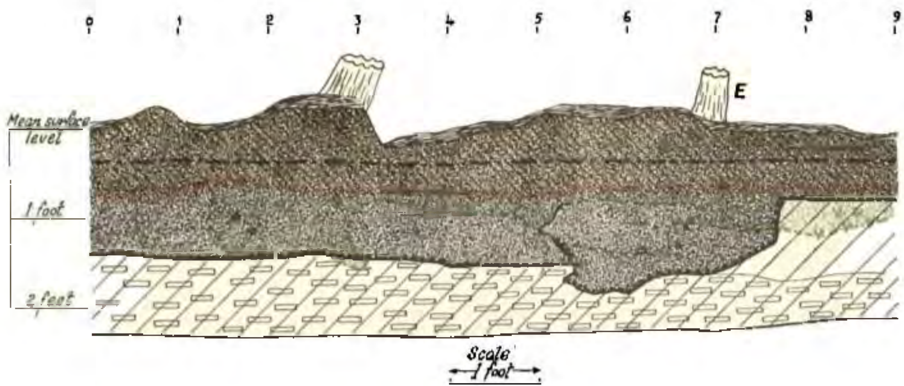


DIAGRAM 13.—TEINDLAND Profile 5. Scots pine (24 years). Complete shallow ploughing plus basic slag. (See also Photo 11.)

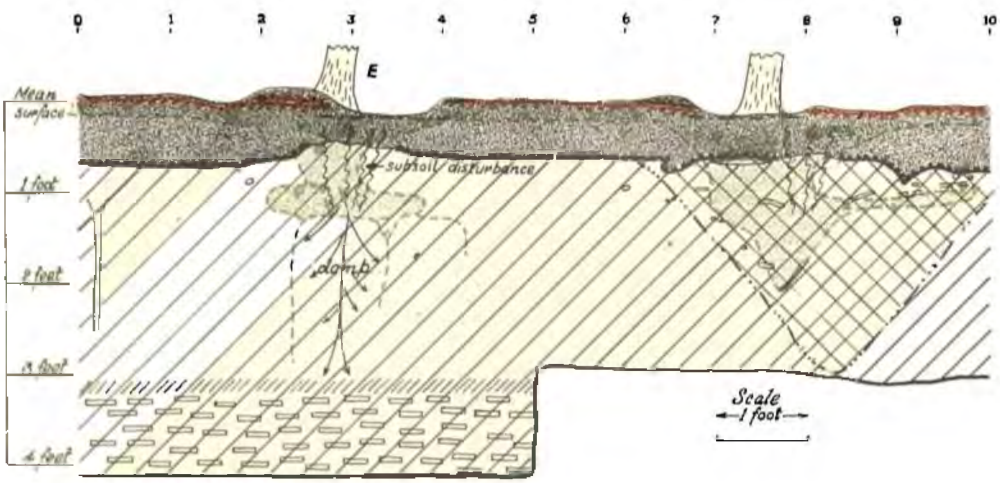


DIAGRAM 14.—BROXA Profile 20. Scots pine (11 years). Single furrow shallow ploughing plus subsoiling. (See also Photo 12.)

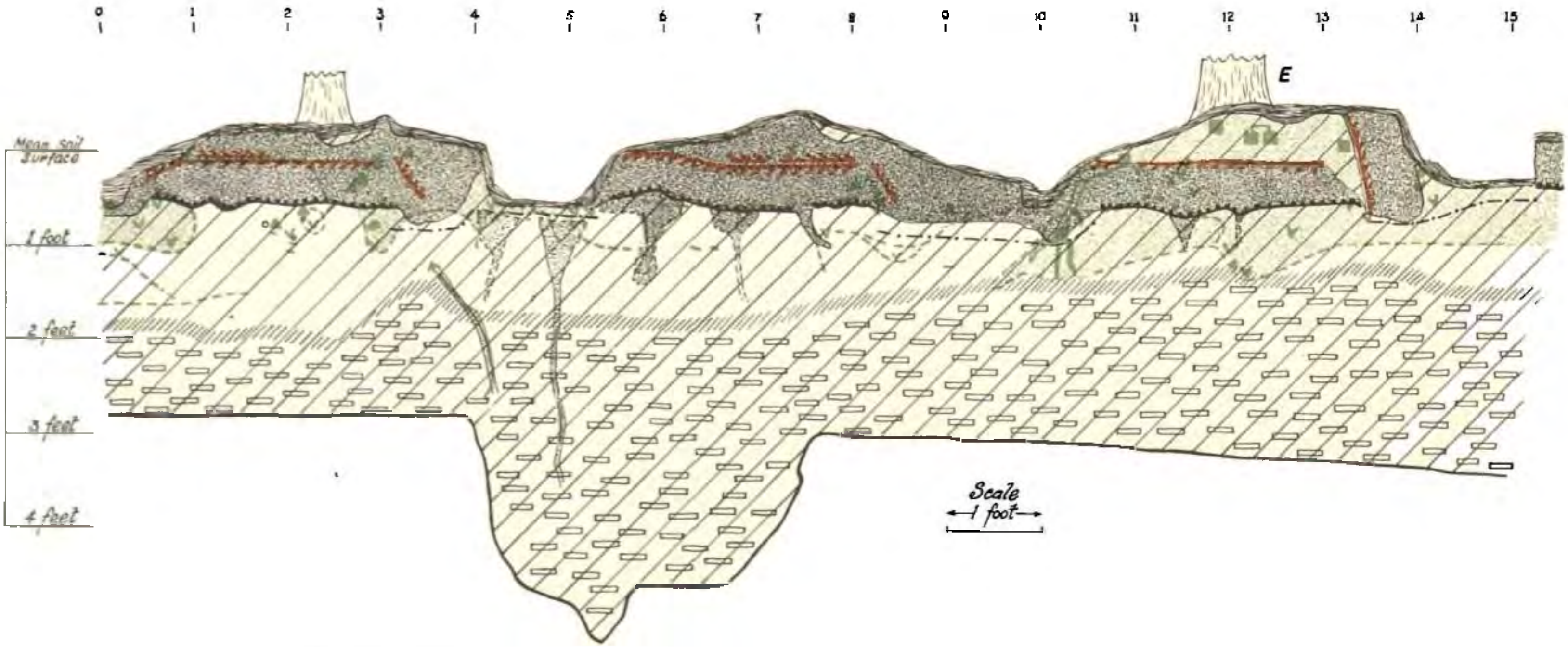


DIAGRAM 15.—WYKEHAM Profile 19. Scots pine (20 years). Two furrow medium depth ploughing. (See also Photo 10.)

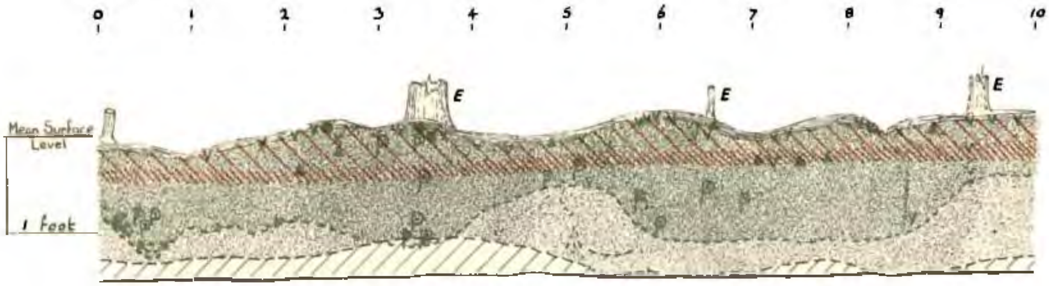


DIAGRAM 16.—DRUMFERGUE Profile 4. Sitka spruce (21 years). Complete shallow ploughing (Nursed). (See also Diagram 19 and Photos 16 and 17).

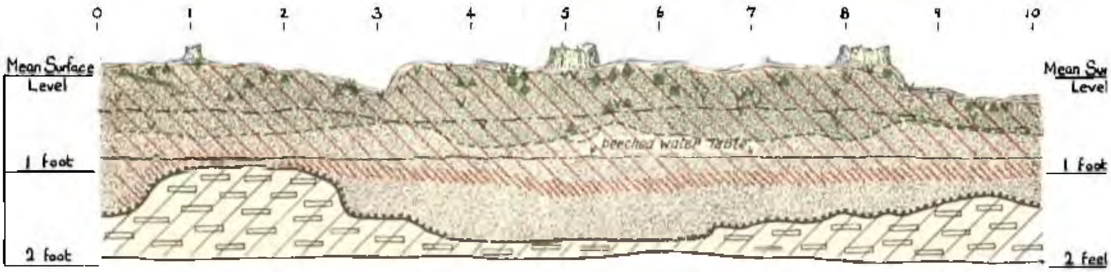


DIAGRAM 17.—TEINDLAND Profile 6. Sitka spruce (24 years). Complete shallow ploughing plus basic slag.

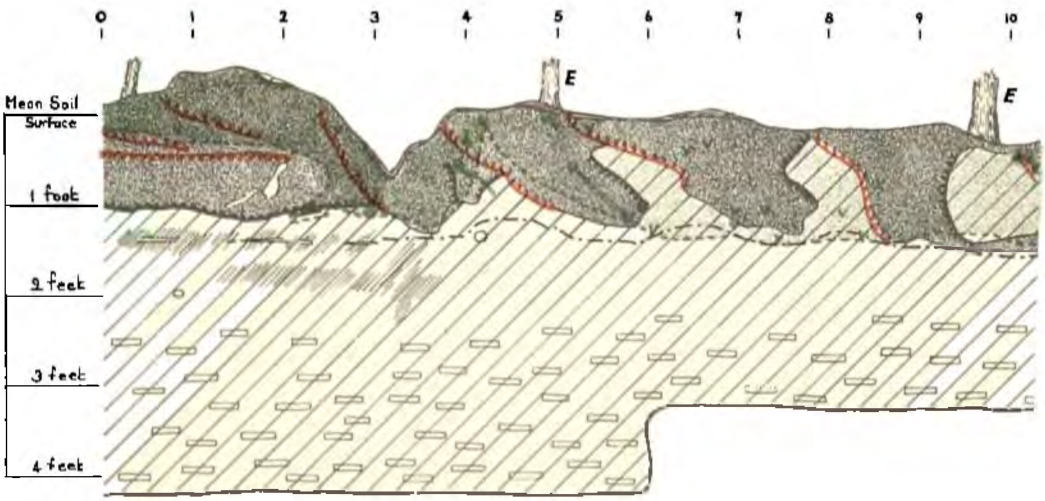


DIAGRAM 18.—BROXA Profile 27. Sitka spruce (9 years). Complete deep ploughing. (See also Photo 20.)

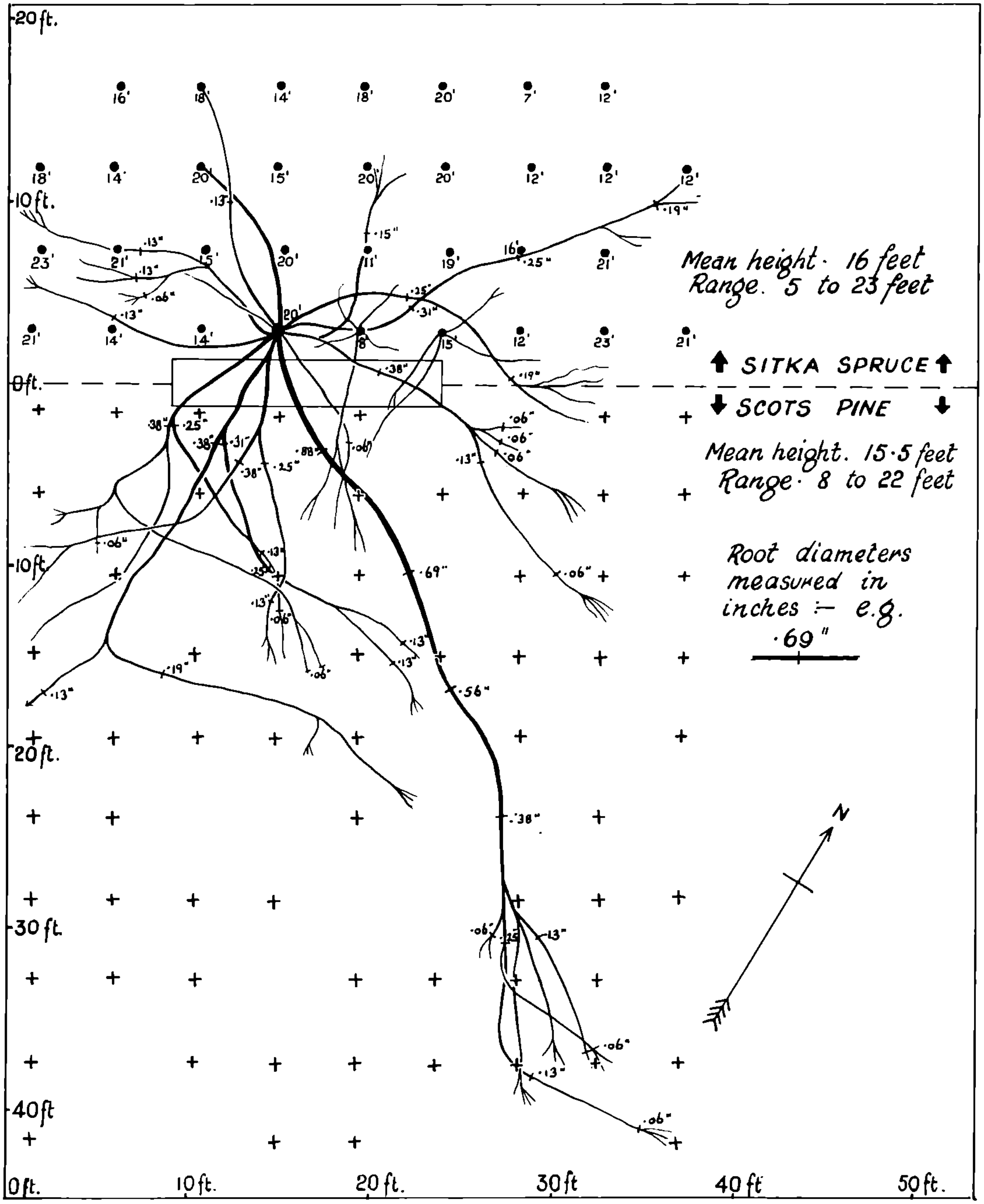


DIAGRAM 19.—PLAN AREA DRUMFERGUE Profile 4. (21 years). Exposed surface roots nursed by Scots pine. (See also Diagram 16 and Photos 16 and 17.)

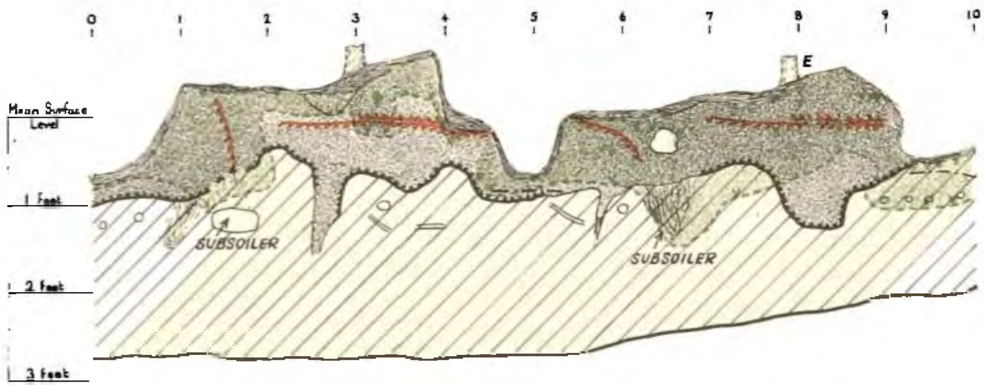


Diagram 20.—WYKEHAM Profile 25. Sitka spruce. Two furrow medium depth ploughing plus subsoiling. (21 years). No basic slag.

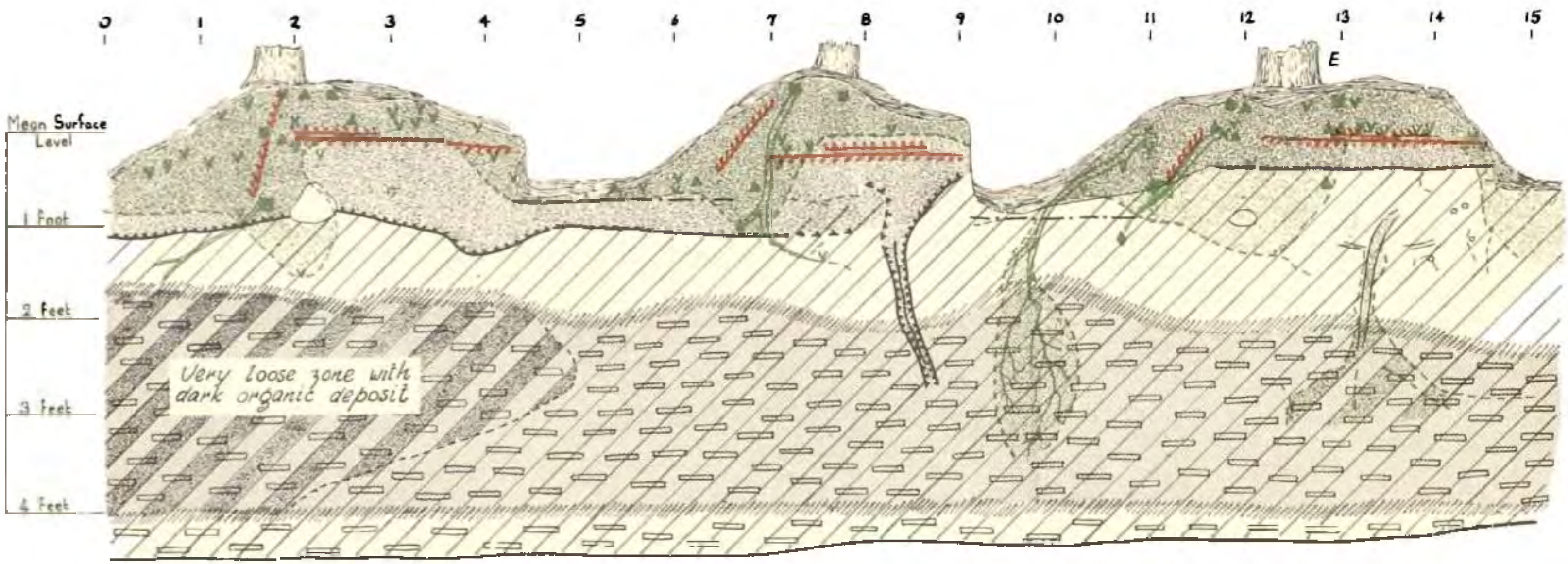


Diagram 21.—WYKEHAM Profile 26. Sitka spruce (21 years). Two furrow ploughing plus subsoiling plus basic slag. (See also Photos 18 and 19.)

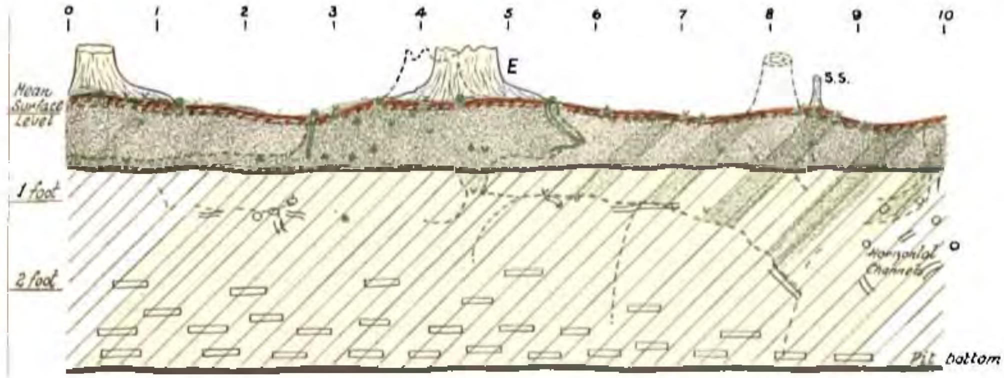


DIAGRAM 22.—WYKEHAM Profile 28. Lodgepole pine (24 years). Planted in prepared patches. (See also Photo 22.)

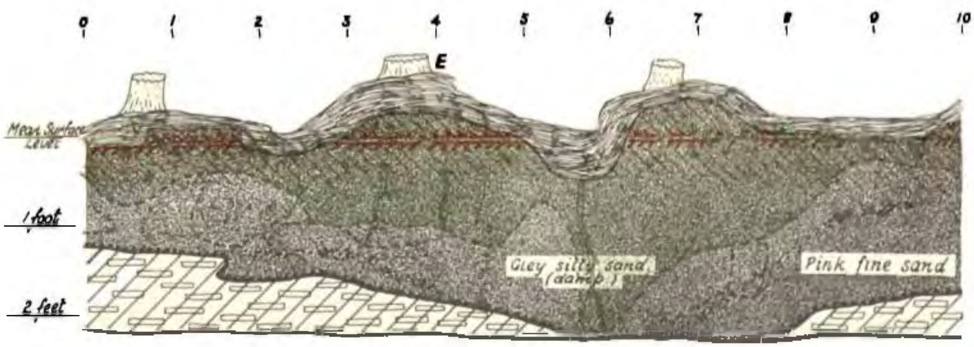


DIAGRAM 23.—TEINDLAND Profile 7. Lodgepole pine (23 years). Mound planting plus slag. (See also Photo 23.)

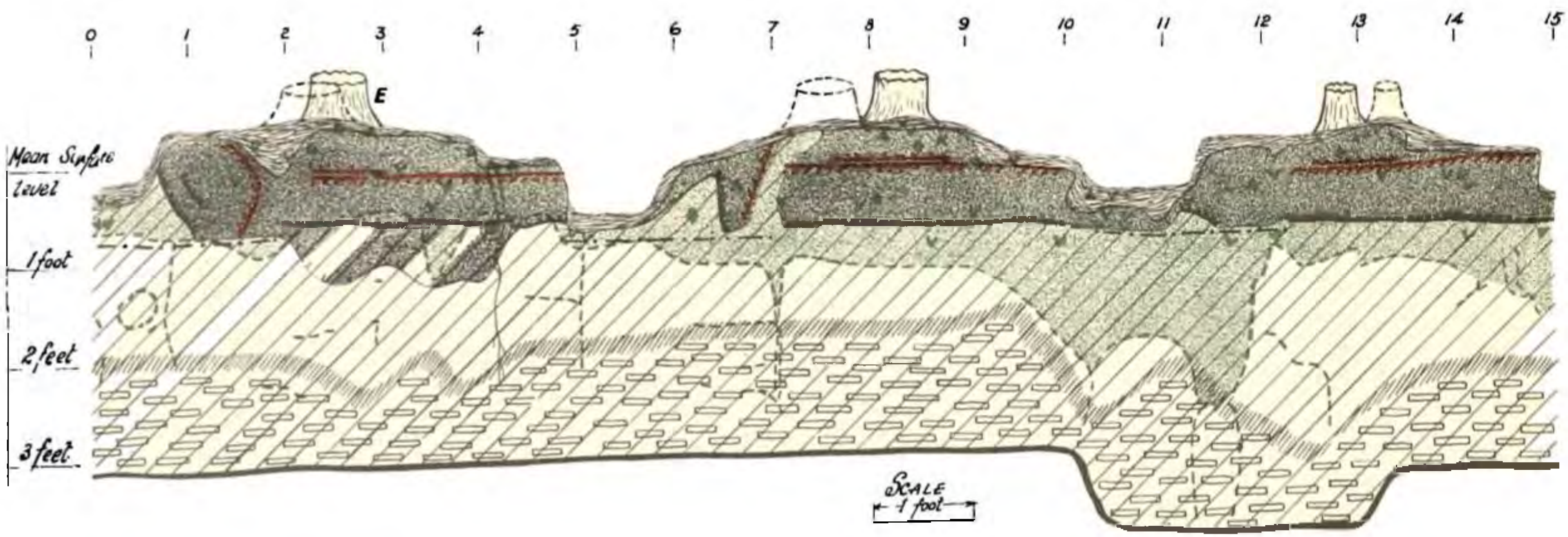


DIAGRAM 24.—WYKEHAM Profile 29. Lodgepole pine (21 years). Two furrow medium depth ploughing.

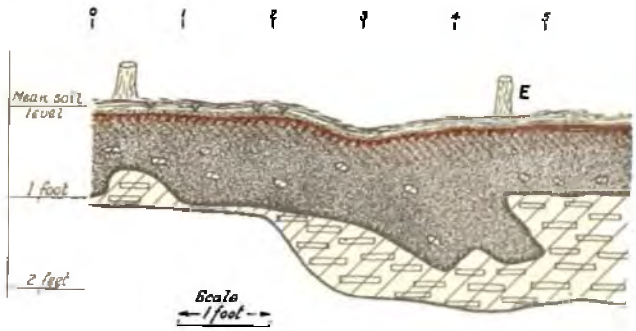


Diagram 25.—DORNOCH Profile 6. Lodgepole pine (20 years). Direct notch planting. (See also Photo 24.)

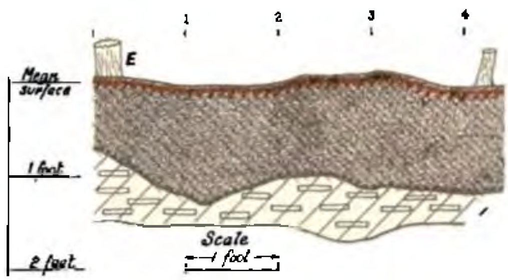


Diagram 26.—DORNOCH Profile 8. Lodgepole pine (20 years). Planted between drains 19 feet apart, 18 inches deep. No spoil spread. (See also Photo 26.)

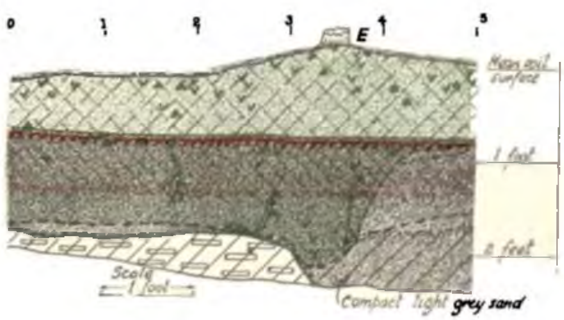


Diagram 27.—DORNOCH Profile 5. Lodgepole pine (16 years). Planted between drains 16 feet apart, 24 inches deep. Spoil spread between drains. (See also Photo 25.)

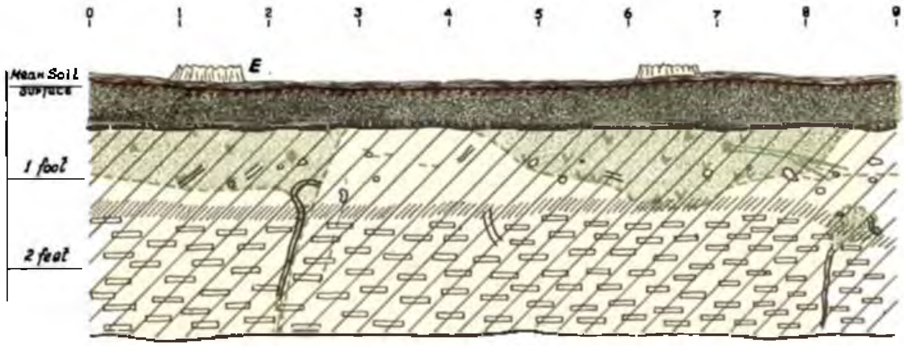


DIAGRAM 28.—WYKEHAM Profile 30. Corsican pine (24 years). Planted in prepared patches. (See also Photo 27.)

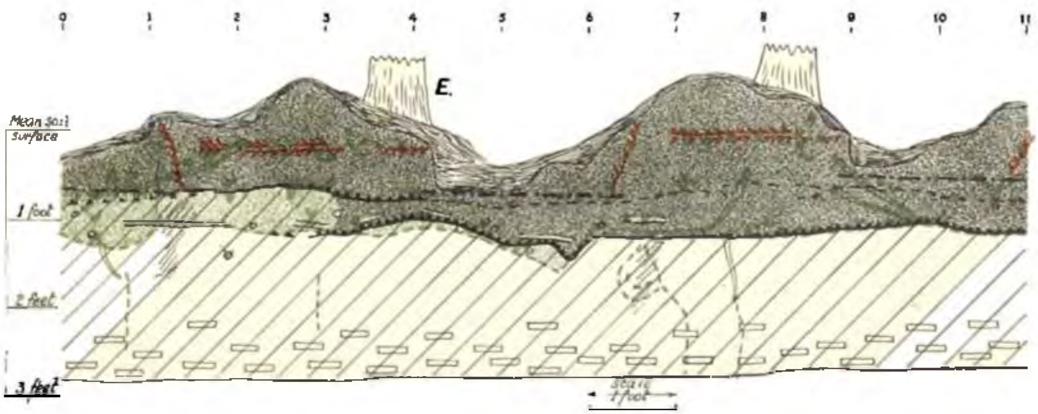


DIAGRAM 29.—WYKEHAM Profile 31. Corsican pine (21 years). Two furrow medium depth ploughing. (See also Photo 28.)

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PHOTO 16. DRUMFERGUE. Profile 4. Sitka spruce, 21 years. Complete shallow ploughing, nursed by Scots pine. Note extensive fibrous descending root system of vigorous tree. (See also Photo 17, Diags. 16, 19 and Fig. 7.)

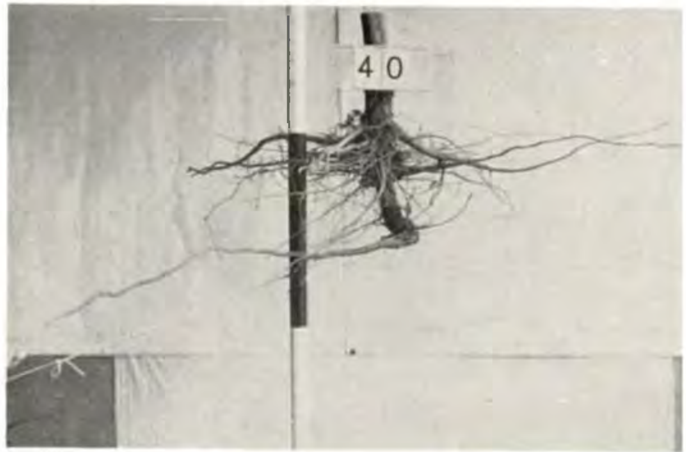


PHOTO 17. As Photo 16, but showing restricted root system of a suppressed tree.

PHOTO 18. WYKEHAM. Profile 26. Sitka spruce, 21 years. Two furrow medium depth ploughing plus basic slag. Note view of profile—lateral roots following spoil ridges: (See also Photo 19, Diag. 21 and Fig. 5.)

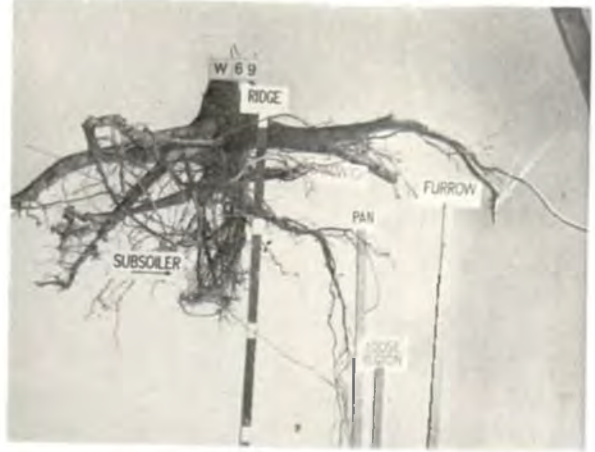


PHOTO 19. Root-stock excavated from site shown in Photo 18. Note extensive descending root system.

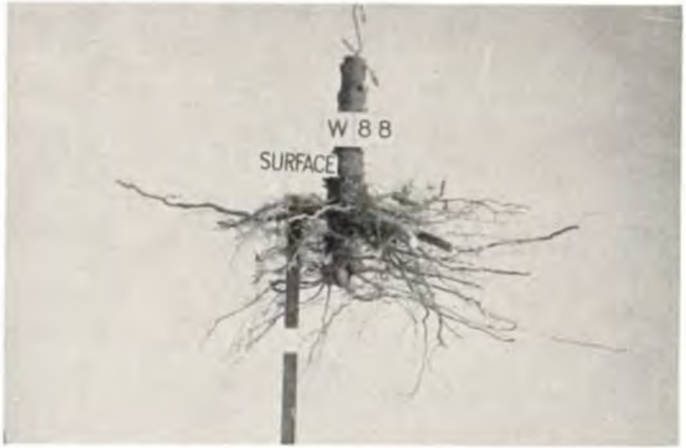


PHOTO 20. BROXA. Profile 27. Sitka spruce, 9 years. Complete deep ploughing. Note even distribution of the root system throughout ploughed soil. (Diag. 18, Fig. 4.)

PHOTO 21. MONAUGHTY. Sitka spruce, 23 years. Notch planted. Note balance of lateral and descending roots.

PHOTO 22. WYKEHAM. Profile 28. Lodgepole pine, 24 years. Planted in prepared patches. Note vigour of the root system and restriction by shallow pan. (Diag. 22, Fig. 3.)

PHOTO 23. TEINDLAND. Profile 7. Lodgepole pine, 23 years. Mound planted plus basic slag. Note vigour and extent of the root system. (Diag. 23, Fig. 6.)

PHOTO 24. DORNOCH. Profile 6. Lodgepole pine, 20 years. Notch planted. Note restricted surface root system of checked tree. (Diag. 25, Fig. 8.)

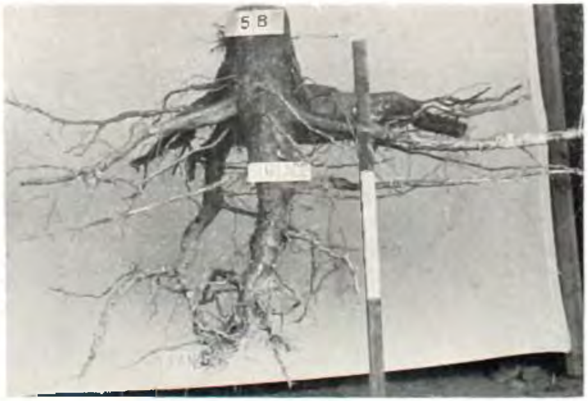


PHOTO 25. DORNOCH. Profile 5. Lodgepole pine, 16 years. Deep drains and spoil spread. Note deep well distributed root system. (Diag. 27, Fig. 8.)

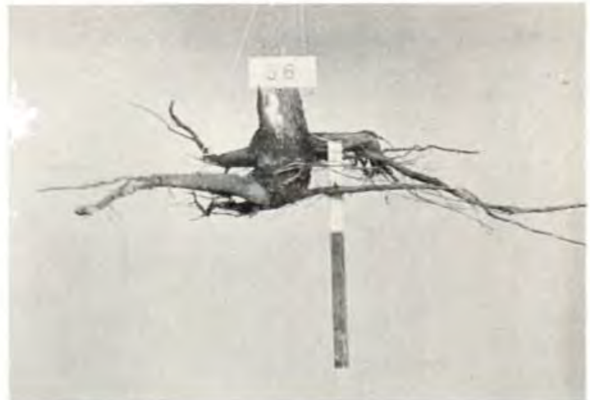


PHOTO 26. DORNOCH. Profile 8. Lodgepole pine, 20 years. Deep drains—no spoil spread. Note restricted superficial root system. (Diag. 26, Fig. 8.)

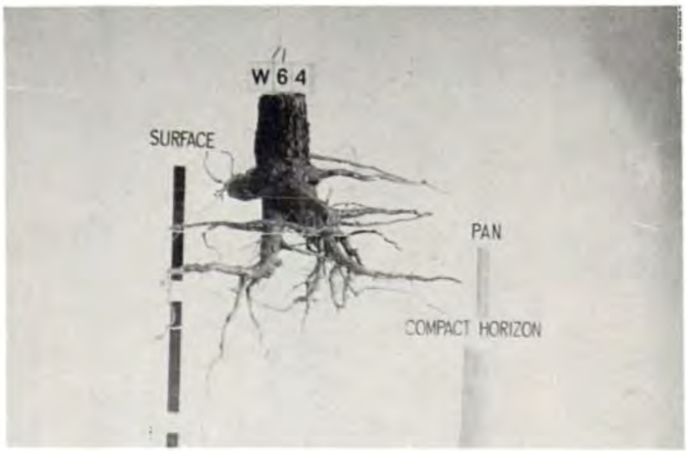


PHOTO 27. WYKEHAM. Profile 30. Corsican pine, 24 years. Planted in prepared patches. Note strong descending roots. (Diag. 28, Fig. 3.)

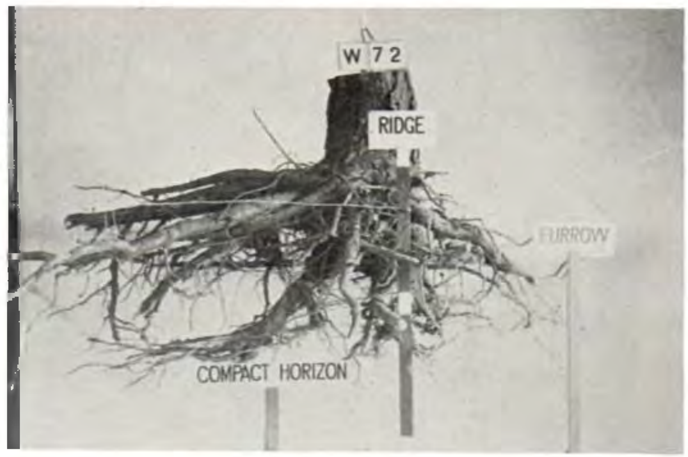


PHOTO 28. WYKEHAM. Profile 31. Corsican pine, 21 years. Two furrow medium depth ploughing. Note furrow right, spoil ridge above undisturbed profile left. (Diag. 29, Fig. 3.)

PHOTO 29. Oliver two furrow (Medium depth) plough drawn by a Caterpillar D.2. tractor. WYKEHAM, 1931.

PHOTO 30. Subsoiler in operation at Wykeham 1931.

PHOTO 31. New type Forestry Commission plough (R.L.R.) in its original form, as used for the deep ploughing experiments at Broxa, September, 1942.

PHOTO 32. Wind-blown 20-year-old Japanese larch, Allerston Forest, Feb., 1953. Planted on the spoil between deep (approx. 12 inch) single furrows running cross wind.

out forming canopy. The root systems of such trees are confined to ropelike lateral roots on the peat surface. (Photo 8). The species grows slowly and forms canopy if sufficient relief of the waterlogged surface conditions and aeration of the mineral soil are provided by drains or cultivation. The reaction of the roots is described in Section 1 above. It is clear that the shallow complete cultivation ensures a more even development, laterally and vertically, of the stand root system (Diagram 13, Photo. 11) than do intermittent drains. These cause an irregular depth distribution of the root system, and a marked degree of alignment with the drains of the lateral roots of the drainside trees (Diagram 12, Photo 9). The addition of basic slag at the time of planting increases the vigour of the root system which ensures the even development of the stand into early canopy and sustained growth.

Under any conditions of planting without adequate dressings of basic slag *Sitka spruce* fails or checks beyond recovery as the *Calluna* becomes re-established. The small stand in canopy examined in this investigation was planted on complete shallow ploughing together with a heavy dressing of basic slag ($\frac{1}{2}$ ton/acre or more than 8 oz./tree). This was followed by a further partial cultivation and dressing of slag some seven years after planting. Some shelter was provided for the spruce by the surrounding pine plots. The root system (Diagram 17) developed as strong lateral roots ramifying within the ploughed surface soil, and an inch or two below it, but no descending roots exploit the wet gleyed horizon immediately above the pan. The presence of the intense root system in the surface horizons does not, in this case, prevent the accumulation of water above the pan/compact subsoil, probably because the stand is small and surrounded on three sides by open ground which maintains a soil water table. The spruce roots do not appear to have the same ability to enter and tap this fluctuating perched water table as do the healthy pine roots. (Profile 6.)

Lodgepole pine is best able of the species examined to develop a vigorous root system in these soils, but some additional phosphatic fertiliser (basic slag) is necessary for satisfactory growth. When grown on shallow ploughing without basic slag (Profile 8) the primary roots are, in the main, large laterals within the surface soil which support secondary sinkers at some distance from the butt. Some excessive accumulation of water still occurs above the pan/compact subsoil. In both examples to which basic slag was applied (mound planting, profile 7 and shallow ploughing, profile 9) the primary roots are both lateral and descending with a profusion of large sinkers arising close to the butt (Photo 23). The descending roots extend freely to the pan/compact subsoil ramifying freely, and there is no sign of waterlogging within the profile. The method of mound planting (Diagram 23) proved remarkably successful for this species, but was a more intense treatment than either notching or simple turf planting. There is little difference in the stand root systems developed by mound planting and on shallow ploughing. Early assessments indicated smaller initial losses by mound planting, although losses on the ploughing were less than ten per cent. Subsequent assessment figures indicate a slight advantage in height growth for the trees on the ploughing.

III. NOTES ON SCOTS PINE ROOTSTOCKS UPROOTED IN HEATHLAND NURSERY AT TEINDLAND DURING 1952

Several acres of twenty-five-year-old Scots pine notch-planted into heathland, were cleared in 1952 at Teindland to provide ground for heathland nurseries. The trees were felled and the root stocks pulled up with a tractor, reasonable care was taken so that the subsoil was not brought to the surface. There were thus some thousands of tree root systems available for examination. All details of relative position in the stand and micro-site soil conditions had been lost, and any information gained from examination of the root stocks could only be of a general character.

The soil was a podzol derived from a mixed Old Red Sandstone drift overlying a compact subsoil of the same material. In a cutting adjacent to the cleared area there was no continuous iron pan formation, but there was some evidence of iron staining above the compact subsoil. The depth of weathered soil varied from twelve inches to two or three feet, but was generally on the shallow side.

Five root stocks were selected at random with basal trunk diameters ranging from eight to two-and-a-half inches. They all came from the same two-acre clearing, and probably grew within a more limited area. It can reasonably be assumed that the site conditions were the same in all cases, and that the stand was of uniform quality. Further, it may be assumed that the relative stump diameters represent the place of the trees within the stand, the largest was a dominant and the smallest suppressed. Thus looking at the root systems in order, from the largest to the smallest, the following points may be noted:—

(i) The descending root system was best developed in extent and intensity in the largest tree, and included both tap root and sinkers. The descending root system of the smallest tree was confined to two small sinkers, limited in development.

(ii) The amount of root fibre, i.e. fine roots capable of producing feeding rootlets, was much greater in the two largest root stocks and the smallest pair were virtually devoid of fibre.

(iii) There was some gradation in the maximum depth attained by the descending roots, but it was noted that the smallest root stock had one sinker longer than any in the preceding two root stocks.

(iv) The number and size of lateral roots varied with the size of the tree. The lateral roots of the larger root stocks tapered rapidly and divided freely, horizontally and vertically (sinkers) whereas the lateral roots of the smaller root stocks tended to be ropelike.

(v) The lateral roots of the larger trees appeared to operate in the top four to six inches of soil whereas in the smaller trees the root system was flatter in profile and confined to the top inch or two of soil.

Thus it may be seen that the character as well as size of the root stock of the healthy dominant tree was quite different to that of the suppressed tree. The position of a tree within the stand must have been determined by the nature of its root system before canopy formation and later crown suppression. The question arises whether the difference in the root systems, and thus the growth and position of trees within the stand, were due to inherent vigour, micro-site conditions, care in planting or on the size of plant at the time of planting. In the writer's view the inherent vigour of the individual was the dominant factor within such apparently uniform site conditions, and such differences in vigour express themselves under any conditions but become more apparent on relatively poor sites. The primary concern is to raise the potential of the site as a whole, to enable all the trees within the stand to develop to the best of their ability.

It would appear that the extensive and relatively deep character of the root system of the dominant is necessary for successful growth under these site conditions. When considering a means of improving site conditions it would be desirable to encourage this type of root system to the exclusion of the suppressed shallow root system, thus raising the quality of the stand as a whole.

MONAUGHTY FOREST

The Root System of Sitka spruce

The root development of Sitka spruce on the heaths is dealt with at some length in this investigation. It was considered desirable to study the type of root system developed by this species in a similar climate to that of the heaths, but on an apparently favourable site where notch-planted spruce grew satisfactorily without check. Such a stand, twenty-three years old, was located in Monaughty forest which is near Elgin, Morayshire. The stand was located on a small flat on the lower eastern slope of the ridge which forms the backbone of the forest.

The soil is a well-drained, brown silty loam with a high proportion of angular stones and boulders, which make digging difficult, but there is no sign of compaction of the soil matrix. Soil horizons are not distinguished apart from some darkening of the surface horizon due to organic material.

The stand was thinned in 1951 and a large stump was chosen for excavation (Photo 21). The root system is well developed both laterally and vertically. Lateral roots, thick and asymmetrical near the base, taper rapidly as sinkers branch down to exploit the lower soil horizons. The distinction between the surface lateral roots and the descending sinkers is clear, but together they provide a root system which exploits the soil to considerable depth (more than three feet).

Under suitable soil conditions of adequate fertility and internal drainage Sitka spruce grows vigorously under these climatic conditions. The root system exploits the soil to a considerable depth by means of descending roots about the base of the tree which appear no less important for the sustenance of the tree than the large lateral roots, which also provide the major mechanical support against wind sway. On the upland heaths the prevailing soil conditions must be made to permit Sitka spruce to develop this type of root system if growth is to be satisfactory.

CLASHINDARROCH FOREST, DRUMFERGUE EXPERIMENTAL AREA

I. GROUND PREPARATION AND THE STAND ROOT SYSTEMS

The soil of this area is manifestly different to those dealt with on the other three main areas in this investigation. It is developed on slates with no apparent surface covering of a glacial origin. The soil is a slightly podzolised loam with no clear horizon divisions of texture in the profile. A further significant difference is the complete absence of an indurated iron pan, or even incipient iron staining, within the profile. Drainage within the mineral soil is free so that periods of excessive accumulation of water below the surface do not occur. The one factor in common with the other soils dealt with is the thin surface cover of *Calluna* peat which remains in a wet condition for the greater part of the year. Compared with the other examples, this peat is thinner, is not sharply defined from the organic/mineral soil beneath, and does not retain its character for long when cultivated.

These soil conditions are reflected by the superior type of moist callunetum plant association characterised by a moderately dense cover of healthy *Calluna* together with *Vaccinium* and some *Sphagnum*.

In profile 5 a pocket of soil mixed with fragmentary oak charcoal was disclosed between six and sixteen inches below the surface, beneath which was a bleached soil "hearth". From its position and nature in the profile and from past records, it seems probable that this area supported oak forest at one time, some hundreds of years ago. There is no natural oak to be found within the environs of Clashindarroch forest today. The experiments established on this area were designed to test a number of species under different methods of planting including notch planting, turf planting, light cultivation, pure species plots and mixtures. Table 8 sets out the species and treatments dealt with in this investigation. Table 9 lists a summary of the root and soil profile data, and figure 7 illustrates selected profile and ground data by histograms for comparison. Detailed discussions of the profiles are to be found in Appendix 4, page 65.

All species except Sitka spruce survive and grow into canopy when directly notched into this heath. The notch planted Japanese larch (Profile 1, Diagram 7, Photo 5) chosen for investigation had grown remarkably well, in fact better than the pines in the same experiment. From the records of seed origin it is thought that this seed, collected at Blervie in Scotland, probably contained hybrids. The large lateral roots are confined within the surface organic/mineral horizon (formerly the thin peat) and many secondary sinkers arise from them to produce a dense ramification of fibrous roots (the free rooting zone) throughout the mineral/organic horizon (six to ten inches), and beyond to the parent material beneath the planting site (fourteen to twenty-four inches). The full depth of weathered soil between the planting sites is partially utilised by exploring roots. The effect of shallow complete ploughing which turns over the raw humus surface is to induce the primary lateral roots to exploit a greater depth of surface soil. The free rooting zone extends to the depth of the parent material beneath most of the stand. (Profile 2, Photo 1). The full depth of the weathered profile is equally exploited by fibrous roots and there is little tendency for the root system to appear two storied except for some concentration of fine roots above the compact parent material.

CLASHINDARROCH FOREST: DRUMFERGUE EXPERIMENTS, 1952. PROFILES 1-6

Experiment and Establishment Details. Japanese larch, Scots pine, Sitka spruce and Lodgepole pine

TABLE 8

Species	Profile No.	Expt. No.	P. Year	Ground Preparation	Planting Stock	Fertiliser
Japanese larch	1	16	P.34	Notch planting	1+1	—
	2	5	P.31	Calluna burned before complete shallow ploughing	2+0	
Scots pine	3	5	P.31	Calluna burned before complete shallow ploughing	2+1	—
Sitka spruce	4	5	P.31	Calluna burned before complete shallow ploughing	2+2	
	5	13	P.33	Turf planting		2ozs. Semsol/tree
Lodgepole pine	6	5	P.31	Calluna burned before complete shallow ploughing	2+1	—

TABLE 9

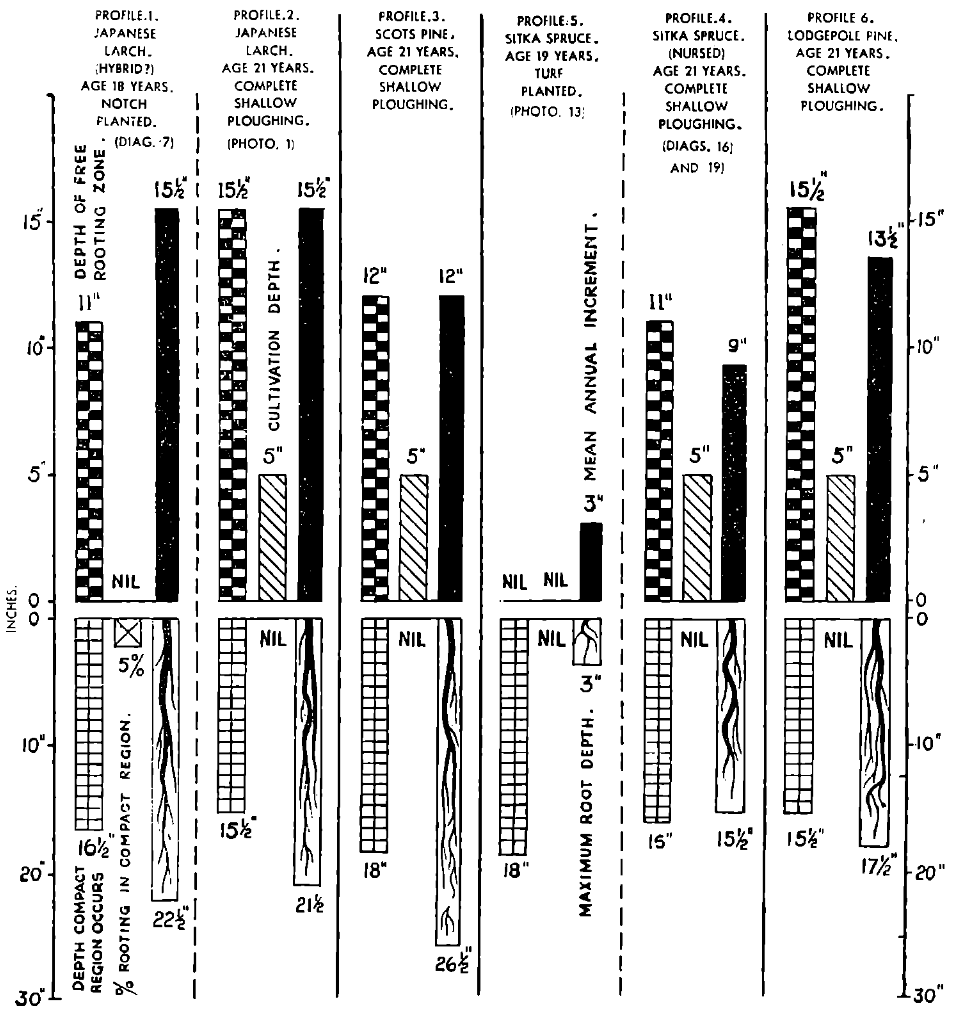
CLASHINDARROCH FOREST: DRUMFERGUE EXPERIMENTS, 1952. PROFILES 1-6

Summary of Profile and Stand Data of Japanese larch, Scots pine, Sitka spruce and Lodgepole pine

	Japanese Larch		Scots Pine	Sitka Spruce		Lodgepole Pine
Profile No.	1	2	3	4	5	6
Ground Preparation	Nil	Complete Ploughing	Complete Ploughing	Complete Ploughing	Nil	Complete Ploughing
Depth of ploughing	—	4″—6″	4″—6″	4″—6″	—	4″—6″
Depth of compact horizon	16½″	15½″	18″	16″	18″	15½″
Age in years	18	21	21	21	19	21
Mean free rooting depth Range in rooting depth	11″ (18½″)	15½″ (9″)	12″ (24″)	11″ (10½″)	Less than 3″ —	15½″ (5″)
% Rooting in compact horizon	5%	Nil	Nil	Nil	Nil	Nil
Max. rooting depth	22½″	21½″	26½″	15½″	3″	17½″
Mean Girth, B.H.	11.2″	12.8″	11.9″	6.4″	—	12.6″
Mean Height	23′ 3″	28′ 0″	21′ 5″	15′ 6″	4′ 10″	23′ 9″
Mean Annual Increment	15½″	15½″	12″	9″	3″	13½″
Semsol	—	—	—	—	2 oz./tree	—

FIG. 7 CLASHINDARROCH FOREST: DRUMFERGUE EXPERIMENT

HISTOGRAMS OF JAPANESE LARCH, SCOTS PINE, SITKA SPRUCE AND LODGEPOLE PINE IN RELATION TO GROUND PREPARATION.



Although cultivation is not essential for the establishment of a stand on this relatively fertile heathland soil, a complete cultivation of the surface is a decided advantage as it ensures the rapid establishment of the stand and increases the mechanical support given the tree by the deeper lateral roots. Subsoiling in addition to ploughing would provide no advantage.

II. THE SPECIES ROOT SYSTEMS

Japanese larch, Scots pine and lodgepole pine root systems provide no exceptions to their general differences in character under good soil conditions at Allerston forest. The form of the individual root stocks from the ploughed experiment was influenced by the snow damage in 1941 which flattened some pines and severely bent some larch. The general result was an increase in the size of the lateral roots in the direction of the lean of the trees and a disruption of the arrangement of the lateral roots about the butt. The root development of Scots pine and lodgepole pine within the profile is essentially the same as that described for Japanese larch above.

Sitka spruce remains the outstanding example of failure on this site when planted in pure formation. Two examples were chosen for investigation, the first turf-planted with two ounces of Semsol (phosphatic fertiliser) applied to each tree (Profile 5, Photo 13); the second planted on complete shallow ploughing surrounded on three sides by plots of Japanese larch, Scots pine and lodgepole pine respectively (Profile 4, Diagrams 16 and 19, Photos. 16 and 17).

The turf-planted spruce remain in a typically heather-checked condition, many trees are in complete check, while some maintain a small annual shoot growth. The principal root system in both cases is confined to the surface of the raw humus (Photo. 13), the roots are typically long and stringlike. In addition, the trees with a small annual shoot growth have a pronounced descending root system which extends to the compact parent material, but which lacks the fibrous character associated with healthy roots.

The trees established on shallow ploughing have reacted strongly to the nursing effect of the surrounding larch and pine stands on three sides of the chain-square plot. The trees in the centre near the fourth open side are in a semi-checked condition, gradually being brought out of check as the formation of canopy and consequent elimination of the *Calluna* converges from the other three sides. An excavation was made between Sitka spruce and Scots pine plots in an attempt to elucidate the nursing phenomenon. The lateral root systems of the spruce trees adjacent to the profile were exposed and plotted on a chart (Diagram 19) together with the positions of the spruce and Scots pine and the heights and girths of the spruce within the area covered by the exposed roots. This area did not extend far enough on the spruce side to show a downward gradation in height from the Scots pine border, but the trend is apparent in the northern corner, furthest from both larch (south-west) and Scots pine (south-east). The major factor which enables the spruce to prosper is the elimination of *Calluna* from about the young trees.

The largest tree (Photo 16) adjacent to the section (Diagram 16) extended lateral roots as much as forty feet over the surface beneath the litter under the Scots pine. In addition, it had a pronounced descending root system beneath and close to the butt with a vigorous spread of fibrous roots as far as the parent material. The smallest tree (Photo. 17) was limited to a few straggling lateral roots near the surface and one root arising from beneath the butt which extended back to the surface beneath the Scots pine. The coincident development of both lateral and descending roots is necessary if the tree is to take full advantage of the absence of the *Calluna*. The condition of the soil must be such that descending roots are encouraged both before and after the suppression of the *Calluna*. The tree which fails to have a sound nucleus of descending roots is slow to take advantage of an improvement in the surface conditions, and remains suppressed when the stand forms canopy. This confirms the reaction noted at Allerston where the nursing effect was more pronounced on the more intensely cultivated sites, which not only induced the more rapid development of the stand concerned, but also enabled the spruce to develop descending roots from the time of planting. Subject to the maintained elimination of *Calluna* this soil is sufficiently fertile for the successful growth of Sitka spruce.

DORNOCH FOREST, HARRIET'S WOOD

Ground Preparation and the Root Development of the Species

The site conditions found at Harriet's Wood closely resemble those at Teindland. The experiments and Conservancy trials investigated are located towards the top of a broad glaciated ridge rising on the north side of the Dornoch Firth and the detailed observations below refer only to this, the poorest, section of Harriet's Wood.

The parent material is mixed Old Red Sandstone and erratic boulders of glacial origin, very compact in nature beneath the weathered soil horizon. An indurated continuous iron pan divides the weathered podzol profile above from the compact subsoil below, which together form an effective barrier to the downward percolation of moisture beyond the pan. Thus the soil above the pan tends to be a semi-permanently wet gley. The natural vegetation is a poor *Scirpus* type of callunetum growing on a thin peat (three to four inches) which remains waterlogged for most of the year. The experiments and trials were designed to test the effectiveness of a series of depths and intensities of drains for a number of species. The principal species dealt with here is lodgepole pine (*Pinus contorta* var. *latifolia*) together with two examples of Japanese larch. Shore pine (*P. contorta*), Scots pine, Sitka spruce and Oregon alder (*Alnus rubra* (*oregona*)) are mentioned below but were not sectioned. The treatments and data are set out in Tables 10 and 11. Fig. 8 compares the treatments by histograms of the relevant data. Detailed discussions of the profile are to be found in Appendix 5, page 67.

The only species to survive direct notch planting into this heath are lodgepole pine and Scots pine, both of which check and become senescent with no indication that they will ever make canopy. The Scots pine is poorer than the lodegpole pine and is not dealt with in detail as no drainage trials were made with it.

Notch-planted lodgepole pine. The root system is typical of that of a severely checked tree on a

DORNOCH FOREST: HARRIET'S WOOD, 1952. PROFILES 1-10

Experiment and Establishment Details. Japanese larch, Lodgepole pine and Shore pine

TABLE 10

Species	Profile No.	Expt. No. and P. year	Ground Preparation	Planting Stock
Japanese larch +Sitka spruce	1	1.P.36	Deep drains—Spoil spread	1+1+1
,,	2	,,	Ordinary drains—Turf planting	1+1+1
Lodgepole pine +Sitka spruce	3	,,	Control—no drains Notch planting	2+1
,,	4	,,	Shallow "plough" drains Turf planting	2+1
,,	5	,,	Deep drains—Spoil spread	2+1
Lodgepole pine	6	Conservancy P.32	No treatment	2+1
,,	7	,, ,,	Shallow drains	2+1
,,	8	,, ,,	Deep drains (no spoil spread)	2+1
,,	9	,, ,,	Deep drains dug after planting —spoil spread	2+1
Shore pine	10	,, ,,	Shallow drains	2+1

When not otherwise stated spoil from drains was spread.

poor untreated upland heath (Profiles 3 and 6, Diagram 25, Photo. 24). The roots are entirely superficial, confined to the surface of the peat, are ropelike and lacking in fibre. No roots descend below the water-logged peat into the mineral soil.

Shallow drains eight feet apart provide some relief to the surface by running off free surface water, but the peat between the drains retains water to the point of saturation for much of the year. Lodgepole pine is able to take advantage of this relief by developing long lateral roots within the peat, the drain spoil and drainsides and bottom (Profile 4). When planted close to the drains, the trees develop a restricted descending root system in addition to the shallow lateral roots, maintaining a slow rate of growth to form canopy in twenty years.

Japanese larch under these conditions (Profile 2) fails to develop the necessary descending roots, many trees die and the remainder are in various stages of severe check. The Conservancy shallow drain trial (Profile 7) with drains twenty-one feet apart is on a slightly better soil than the other examples investigated; there is no pan and no gley soil above the parent material, which suggests a better internal soil drainage. In this example the lodgepole pine developed a strong fibrous descending root system to the depth of the parent material (about 10½ inches) beneath the bases of the trees. The lateral roots and sinkers there-

DORNOCH FOREST: HARRIET'S WOOD, 1952. PROFILES 1 AND 3-9

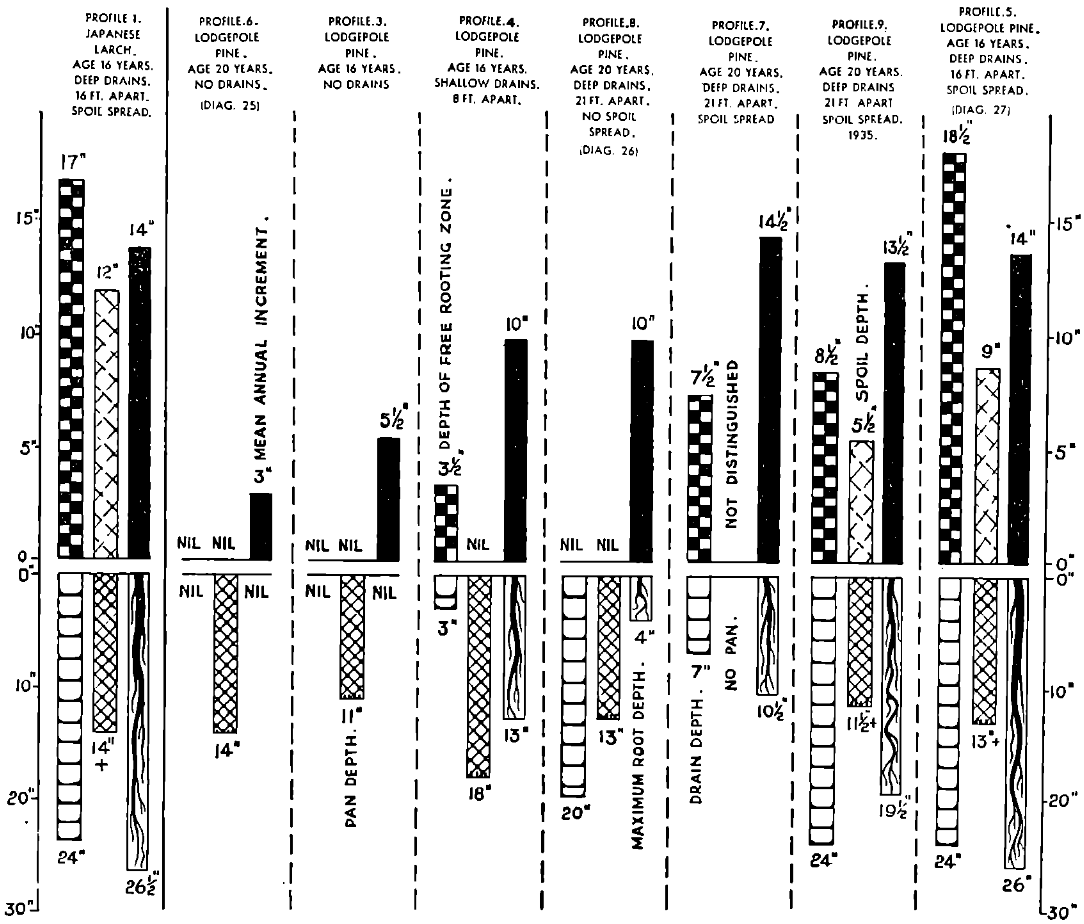
Summary of Profile and Stand Data of Japanese larch and Lodgepole pine

TABLE 11

	Japanese larch	Lodgepole Pine						
Profile No.	1	3	4	5	6	7	8	9
Expt. No. and P. year	1.P.36	1.P.36	1.P.36	1.P.36	Conservancy P.32	Conservancy P.32	Conservancy P.32	Conservancy P.32
Ground Preparation	Deep drains 16′ apart Spoil spread	Nil	Shallow drains 8′ apart	Deep drains 16′ apart Spoil spread	Nil	Shallow drains 21′ apart Spoil spread	Deep drains 21′ apart	Deep drains 21′ apart Spoil spread
Mean depth drain	±24″	—	3″	±24″	—	6—9″	18—24″	18—24″
Mean depth spoil	12″	—	—	9″	—	Not disting-uished	—	5½″
Mean depth of pan Range in depth of pan		11″ (5″)	±18″	13″+	14″ (13″)	No true pan —	13″ (7″)	11½″
Age in years	16	16	16	16	20	20	20	20
Mean depth of free rooting Range in depth of free rooting	17″	—	3½″	18½″ (16″)	—	7½″ (5½″)	—	8½″ (3″)
Rooting below pan	Nil	Nil	Nil	Nil	Nil	—	Nil	Nil
Max. rooting depth	26½″	—	13″	26″	—	10½″	4″	19½″
Mean Girth, B.H.	9″	—	6.4″	10.9″	—	11.6″	8″	11.5″
Mean Height	19′	9′	13′ 1″	18′ 6″	5′	24′ 2″	16′ 9″	22′ 2″
Mean Annual Increment	14″	5½″	10″	14″	3″	14½″	10″	13½″

FIG. 8 DORNOCH FOREST: HARRIET'S WOOD 1952

HISTOGRAMS OF JAPANESE LARCH AND LODGEPOLE PINE IN RELATION TO GROUND PREPARATION.



from freely exploit the organic surface soil for seven to eight inches, and some fine roots extend into the horizon below. The trees grew steadily from the time of planting (mean annual increment in 20 years, 14½ inches per annum) and formed a uniform stand in canopy.

Shore pine (Profile No. 10) planted on poor ground at a higher elevation near the ridge top was accorded a similar treatment to profile 4 above and despite a poorer site than profile 7, developed in a similar manner though in a somewhat coarse form. It is therefore concluded that this race is the more vigorous under these site conditions.

An excavation was made in a small stand of lodgepole pine between two drains eighteen inches deep and about eighteen feet apart (Profile 8, Diagram 26, Photo. 26). The trench was dug centrally between the drains to avoid the direct influence of the open drains and spoil beside the drains. The trees are not in check but have grown slowly and have not formed canopy in twenty years. The root system is confined to lateral roots barely within the peat-organic surface horizons. The trees developed no descending roots of consequence and some have been windblown.

The most intensive treatment in both the experiments and the Conservancy trials was the creation of drains, eighteen to twenty-four inches deep, with the spoil spread evenly over the surface between the drains. The spoil provided several inches of mixed, aerated and drained mineral soil for the extending roots. It further acted as a mulch over the original peat surface, protecting it from sudden flushes of moisture. The character of the peat is so altered that sixteen years after the treatment the horizon is a mixture of humus and mineral soil, open in texture, having lost the capacity to remain saturated with water as does the exposed peat.

In the Conservancy trials the treatment followed three years after planting. In the experiment, a smaller area and more intensely drained, the trees were planted in the spoil after the drains were dug. This difference in timing remains apparent in the forms of the stand root profiles and in the individual root stocks. In the former treatment the zone of free rooting extends from the spoil into the original organic surface horizon. The form of the root stock is similar to that amid the deep drains without spoil spread but the roots are larger, and only scattered descending roots exploit the soil to the depth of the pan/compact subsoil. The free rooting zone in the latter treatment of lodgepole pine (Profile 5, Diagram 27, Photo 25) extends the full depth of the profile to the pan/compact subsoil. The root stock has vigorous primary roots descending to the pan/compact subsoil and large lateral roots within the spoil and original organic surface. It appears that the primary root form initiated in the early years of growth in the Conservancy trial was incapable of change when conditions for root growth improved with the addition of the spoil. The juvenile roots capable of taking advantage of the improved conditions were well clear of the bases of the trees owing to the lack of division of the primary roots close to the butt, and subsequent development served only to increase the size of the primary roots, and not to alter their form or induce the creation of adventitious roots in the region of the bases of the trees.

The Japanese larch planted into the spoil in the experiment (Profile 1) developed lateral and descending roots freely in the spoil. The descending roots however appear to break at the old surface level (peat) and continue into the undisturbed profile as a number of smaller roots, some of which extend to the level of the pan/compact subsoil some thirty inches below the spoil surface. It seems probable that there was a time lag of some years before the waterlogged anaerobic nature of the undisturbed soil profile was sufficiently altered, by the spoil and development of the stand root system within it, to encourage the healthy extension of the larch roots. This is probably a further reason for the early maintenance of the character of the rootstock of lodgepole pine in the Conservancy trial.

It was observed that both Sitka spruce (in mixture with pine and larch) and Oregon alder were growing successfully on this deep drainage trial, and that they had failed on all less intense treatments. This is especially remarkable for Oregon alder which has seldom been observed by the writer to flourish for more than a few years on any upland heath.

It is clear that the soil of these sites is not too infertile for the growth of these tree species if sufficient volume of it can be made readily available to the free exploitation by roots. In the intense treatment above, deep drains in themselves do not appear to play an important part by direct drainage, the main effect is, in fact, the cultivation and 'mulch' provided by the spoil covering of the natural heath surface. It may be argued that a similar effect would be produced by a thorough cultivation together with deep subsoiling at intervals in order to lower, and perhaps prevent, the accumulation of water above the pan/compact subsoil.

Chapter 6

CONCLUSIONS

The previous chapters have dealt in some detail with the root development of the selected species on a series of sites and over a range of methods of ground preparation. The main conclusions arising from these observations are summarised below. Methods for the sound establishment of coniferous plantations on upland heaths are also proposed.

I. MORPHOLOGY OF THE ROOT SYSTEMS

There are certain inherent differences in the morphology of the root systems of the species which predispose the distribution of the larger roots in any given soil conditions.

Sitka spruce develops near-surface lateral roots, which form the principal support of the tree, irrespective of the condition of the soil. In addition descending roots, sinkers, form a significant proportion of the root system of healthy unchecked spruce on these relatively dry and infertile heathland sites. These descending roots extend from the laterals to exploit the deeper soil horizons and provide anchorage for the lateral roots, but they fail to develop, or remain very restricted, in the natural heathland conditions in which spruce checks severely.

Japanese larch has a somewhat similar root system to spruce, but tends to form a short central carrot-like tap root which divides into a number of descending roots. The lateral roots are not confined to the near surface horizon (A_0-A_1) if the soil conditions are equable to some depth; they readily divide laterally and vertically and may themselves descend instead of maintaining their horizontal character. The support of the weight of the tree and resistance to wind sway is shared by all the large roots of a normally well dispersed root system, which appears very fibrous owing to the profusion of fine roots typical of this species. The ability of the larch roots to penetrate difficult soil conditions is considerably greater than that of spruce. Both larch and spruce are capable of producing adventitious roots from the region of the soil collar in young trees.

The pines (Scots, Corsican and lodgepole) typically have pronounced carrot-like tap roots which may retain their identity to some depth, though commonly they divide into two or more descending roots. The lateral roots are seldom confined to the surface, but normally extend within several inches of the surface horizons. They divide freely, supporting sinkers which exploit the lower horizons, and the laterals themselves may descend. The weight and anchorage of the tree are shared by all the larger roots of the system. The roots of the pines have a considerable capacity to exploit adverse soil conditions. Lodgepole pine frequently forms within the litter a profusion of fine red rootlets which appear capable of developing rapidly when growth conditions are suitable, dying back when conditions become limiting once again.

II. NUTRITIVE DEMANDS OF THE SPECIES

Besides the morphology, or form, of the root systems of the species, the physiology, as expressed by the minimum nutritive demands, differ. The two aspects are in fact closely related in any given soil conditions. Tolerance to a low level of fertility on the upland heath, including physical infertility such as waterlogging, lack of aeration and lack of pore space, is in the following descending order; shore pine, lodgepole pine, Scots pine, Corsican pine, Japanese larch, and finally Sitka spruce.

The growth of a forest root system is capable of reducing the moisture status of a soil and in this way converts naturally limiting waterlogged horizons into soils suitable for further root exploitation. Rennie (1953) reports the capacity of tree species to reduce the high moisture status of moorland in the following descending order; Japanese larch, lodgepole pine, Sitka spruce.

III. SOILS AND FERTILITY

The total fertility of a given site is directly related to the volume of soil readily available to tree roots, and to the amount and nature of the available nutrients within this soil. The primary concern in the afforestation of the upland heaths is to increase the volume of this soil to the greatest advantage of the forest for growth and stability.

It is clear that the most important single factor, limiting the availability of the mineral soil to root exploitation, is the surface peat which seals the profile beneath from adequate aeration and the percolation of fresh water from the surface. Rennie (1953) has shown that *Calluna* peat overlying all geological types remains waterlogged for a considerable part of the year, the aeration only increasing for prolonged dry periods. The peat formation is a direct result of the persistent Callunetum vegetation complex which forms the peat and maintains a dense mat of living roots within the peat and mineral soil surface horizon.

The second limiting factor is the relatively compact and infertile eluvial horizon below the peat. It has been shown that the porosity of highly podzolised soils supporting a shallow rooted plant association is relatively low. (Kissin 1940).

The third factor is the depth of the weathered profile and the nature of the parent material beyond. This includes the depth, relative position in the profile and intensity of a pan, if present. Prolonged impedence of vertical drainage by this latter formation may cause semi-permanent waterlogging of the soil above it, further reducing the volume of soil freely available to roots.

A continuous indurated pan forms a physical barrier to root penetration which is a complete obstruction when it coincides with the top of the compact subsoil. The subsoil (parent material) is frequently a very compact glacial drift which impedes drainage and prevents penetration by exploring tree roots. Ancient root channels, where they occur, may provide some access for descending roots through the pan/compact subsoil. If the pan forms above the illuvial horizon it presents only a partial barrier to the roots of larch and the pines, which exploit the relatively rich, and frequently more porous, horizon below.

Finally, the soil may be inherently infertile, lacking sufficient of the necessary nutrients even when the physical soil factors are no longer limiting. The nutrient level of the horizons of any podzol differ, being greatest at the surface and in the illuvial horizons, and least in the leached eluvial horizon. This, together with attendant physical drawbacks in the undisturbed profile, induces the stand root system to develop zones of more intense rooting accordingly. It may be noted that all these factors tending to confine root development to definite layers result in the wind stress on the crown of the tree being transferred to certain layers of the soil. Under extreme conditions they become cleavage planes or zones of weakness along which the tree may be uprooted.

The presence of *Calluna* about young trees on an infertile site has a marked influence on the rate of tree growth, especially of Sitka spruce which checks in the presence of *Calluna* even on a moderately fertile site.

IV. COMPARISON OF HEATHS STUDIED

The sites dealt with in this investigation may be compared on the basis of the above factors. Findlay's Seat, Teindland and Harriet's Wood, Dornoch, are the poorest sites encountered. The surface conditions are naturally bad in the extreme; the soils are mature podzols developed from poor sandy parent materials; the subsoil (parent material) is very compact, for the most part capped with an impervious indurated iron pan which prevents subsoil drainage and causes waterlogging of the soil above it. The soils of Findlay's Seat are inherently less fertile than those at Harriet's Wood.

At Wykeham and Broxa in the Allerston district the heaths are not suitable for direct planting owing to the bad surface conditions in the peat and eluvial horizon. Waterlogging directly above the pan does not generally occur for any significant period of the year. The presence of vertical (root) channels and the peculiar loose region aid subsoil drainage and add to the depth available to descending roots, although the intervening subsoil is compact and impenetrable by roots.

The Drumfergue area of Clashindarroch forest provides suitable growth conditions for direct-planted trees, except Sitka spruce, although the raw humus (peat) surface restricts the vertical dispersion of the primary lateral roots. The horizons are not distinct and below the surface the weathered soil is a yellowish brown loam with a marked crumb structure. The distribution of fine roots is even throughout the profile. There is no pan formation, and subsoil drainage is sufficient to cope with requirements; the subsoil is compact and restricts rooting beyond the weathered profile. No direct nutritional deficiency is apparent.

V. GROUND PREPARATION

In a consideration of the type of cultivation which is to be of greatest benefit for the development of a healthy root system, and therefore the tree, two aspects should be borne in mind. Firstly, the response in the growth of a tree to the preparation of the soil before planting on an upland heath depends on the additional volume of soil made available to the roots by the treatment, as compared to direct planting, and on the level of fertility of that soil. Secondly, the healthy vigorous root system which develops in suitable soil conditions is able to exploit further relatively infertile or obstructive horizons which may deter the development of less vigorous root systems. In particular, the depth attained and the intensity of rooting at depth are greater for an initially vigorous root system. It is therefore more effective to release a given volume of a potentially fertile soil horizon which is readily available to early root development, than the same volume of a relatively infertile soil horizon in the same profile, or a horizon which may gain little value from *direct* disturbance.

Similarly, the effect on the root system of the application of suitable fertilisers on infertile soils is to increase the total length and root density within the rootable soil, especially in the early years of establishment. Rennie (1953) reports that basic slag applied to Sitka spruce at Wykeham appears to increase the root density twofold in the 0-12 inch zone, but fivefold in the 16-20 inch zone. Thus the addition of fertilisers enables the tree root systems to take full advantage of the soils improved by physical preparation, but which remain chemically infertile.

The response in tree growth to ground preparation is most noticeable at Findlay's Seat, first to physical preparation (drains and ploughing) and secondly to the application of basic slag. At Wykeham there is a clear increase in growth rate with intensity of cultivation but only Sitka spruce shows a marked response to basic slag. The Drumfergue experiments show some increase in the rate of growth of trees on shallow ploughed land to those notch planted.

When considering the formation of useful forests on the upland heaths, it is not enough to ensure that the trees will grow satsifactorily in early life; they must continue to flourish and remain stable in the face of frequent gales which may be expected in these exposed places. Such tests may not become critical until canopy has formed and the forest is fully utilising the available potential of the site. The factor of stability becomes increasingly important as stand height increases and thinnings are made.

E. K. Kalela (1950) in Finland, describes the root distribution in terms of root weight per unit volume of soil (root density) of spruce and pine stands ranging in age from ten to 135 years. He found that eighty-seven per cent of the roots of both species were in the top eight inches of soil. Rennie (1953) bears out this trend in his root density function curves. It was also apparent throughout the course of this investigation.

Kalela further found that the roots of both spruce and pine were found within ten to twenty years at all soil levels at which they are found in older stands. The writer considers that this will prove to be also true of the heaths, subject to modification in the examples where the formation of canopy modifies the soil root relationships. This points to the fact that the first (primary) root system extending from the base of the tree is also the last, excepting the possible production of adventitious roots by spruce and larch (e.g. Wykeham hand planting methods and mulching). The stability of the individual tree will depend on the form of the root system laid down in the first ten years or so of growth when the primary roots extend from the base of the young tree. Sitka spruce and Japanese larch may subsequently form adventitious roots close to the butt, but in no instance were the pines observed to have this ability. Thus any ground treatment, or lack of it, which tends to confine the root system to the surface, to prevent the free division of the primary roots, to induce a shallow storied character in the root system, or to align the major roots in any one direction, must risk growing a forest more liable to windblow and/or possible early senescence. An inspection of gale damage at Wykeham moor in February, 1953 emphasised that it was these factors which were the primary cause of tree instability. Japanese larch stood firm on the moor *except* for extensive windblow where the trees were planted in 1931 on the spoil of deep single furrow ploughing of a sandy soil, and where the line of ploughing was cross wind. (Photo 32). Only a few individual trees of the same age suffered windblow on the same ploughing in the direction of the wind.

VI. RECOMMENDED TREATMENT

(i) **Heath Burning.** The heath should be effectively burned shortly before cultivation to increase the efficiency of the cultivator, to aid the even lie of the soil, to prevent the formation of large and persistent air pockets and to retard the re-growth and re-invasion of *Calluna*.

(ii) **Cultivation.** The object of any ground preparation must be to ensure the early development of a sound evenly-distributed root system which will maintain the vigour and stability of the trees. For this purpose the most effective preparation of an upland heath prior to tree planting is a complete moderately deep cultivation of the surface. This should thoroughly disrupt the peat and turn over several inches of the eluvial horizon to a total average depth of eight inches, plus or minus two inches. The better soils, e.g. Drumfergue experiment brown loam, require only a shallow cultivation sufficient to break up the raw humus surface.

(iii) **Subsoiling:** The poorest soils, e.g. Findlay's Seat and Harriet's Wood mature podzols, require a deep disturbance in addition to the surface cultivation. Subsoiling at regular intervals of the planting distance to a depth of eighteen to twenty-four inches breaks the deep pan seal and disrupts a small volume of the compact subsoil, thus allowing any water above the pan to drain slowly into the subsoil, and relieving subsurface waterlogging. The additional volume of soil made available to root exploration by the subsoiling is not of great significance early in the life of a stand unless the subsoil is relatively free, thus making available a still greater volume of soil for rooting, or should the depth of the compact subsoil be shallow, say within twelve inches of the surface. Subsoiling must be regarded as an additional treatment to surface cultivation, not a substitute, for the latter is increasingly important as the quality of the heath decreases.

The soils in the Allerston district require a thorough surface cultivation to the maximum practicable depth (eight to ten inches) but subsoiling has little additional advantage for root development except as a long term stability insurance.

(iv) **Fertilisers.** The addition of a phosphatic fertiliser is frequently necessary on heathland soils; the necessity depends on the local soil fertility level and generally decreases as the degree of cultivation increases. Other nutrients may or may not be desirable, but past experience suggests that they are far less important than phosphates.

VII. SELECTION OF SPECIES

The choice of species for heathland afforestation must depend on many factors besides the essential one that it will form a forest and produce useable timber. It must depend on the initial quality of the heath and the degree of preparation which may be possible economically or physically. As a pioneer species lodgepole pine appears to be the most vigorous and its root development most readily overcomes poor soil conditions, although its use as an economic crop is still in doubt. The root system of Sitka spruce is very sensitive to low soil fertility, and competition with *Calluna* in any peaty soil induces check, but it appears to go ahead if it forms canopy. On the best sites it is possible to grow spruce successfully in mixture with other species, but the climate of the upland heaths is thought to be marginal for Sitka spruce, at least of the provenances normally used, so that its long term development remains in doubt. Given reasonable soil disturbance the root system of Japanese larch develops well on all but the poorest soils and will then respond to suitable fertilisers (phosphate). Scots pine develops a satisfactory root system over a wide range of site conditions and with moderate surface cultivation forms a stable forest. Corsican pine is growing successfully at Allerston but is of doubtful value generally for the upland heaths of northern Britain.

In an inspection of wind damage at Wykeham Moor in February, 1953, the outstanding inherent characteristic determining wind stability, after the depth and form of the root system, was the crown size and density of the species. In this respect, Japanese larch (deciduous) was considerably more stable than the evergreen conifers, which, under similar soil and stand conditions, were liable to wind throw in ascending order of crown density, viz. Scots pine, Corsican pine, lodgepole pine. Stem breakage occurred more commonly in lodgepole pine, with a few instances in Scots pine.

SUMMARY

This paper described the methods used, the findings and the conclusions of an investigation into the root development of the principal conifers (Japanese larch, Scots pine, Sitka spruce, lodgepole pine and Corsican pine) used extensively in the plantations established on the upland heaths of north-east England and Scotland. The study covered a series of intensities of ground preparation over five forest experiment sites from the North Riding of Yorkshire to Dornoch Firth, Scotland. The ages of most of the plantations studied ranged from nineteen to twenty-five years. Those of the Broxa experiments in Yorkshire were nine to ten years old.

1. An Upland Heath has been defined as: A Callunetum on shallow peat in which the roots of the vascular plants penetrate into the sub-peat layer. The peat is commonly two to four inches thick.

The status, distribution in Britain and the problems of afforestation of the upland heaths are described.

2. The climate of the upland heaths is cool temperate oceanic, with an even distribution of annual rainfall of between twenty-three and forty inches. The vegetation is a callunetum developed on thin peat, the density of the *Calluna* and the type and density of associated species varies with the quality of the heath. The soils are commonly mature shallow podzols developed on sandy parent materials, with the attendant formation in the poorer heaths of a hard impervious iron pan at depths ranging from six to twenty-four inches. The better heaths however overlie a wide range of soil types, some of which may show little evidence of podzolisation.

3. Detailed descriptions are given of the locality, geology, climate, vegetation and soil of each of the sites chosen for investigation.

4. The methods used in some earlier root development studies are discussed. The information required in this study, and the field methods of root excavation and recording are described. In order to determine the manner in which the root systems of stands of trees, rather than those of individual trees, exploited the soil in which they were planted, an extensive method of root exposure was adopted. A soil and root profile was exposed on one side of a trench ten to fifteen feet long, and was plotted to scale. A scale plan diagram of the position of the trees surrounding the profile was made, including the position of exposed surface roots. One dominant tree adjacent to the profile was selected for the complete excavation of the root stock which was set up and photographed for record. Additional field notes were made as necessary. From these records relevant data were obtained and the significant points fully discussed for each profile (appendices).

5. The initial study covered the development of the forest stand root system over a range of cultivation intensities at Allerston Forest, Yorkshire, using Japanese larch as the test species. This was later extended to cover the remainder of the species dealt with. Further root excavations were made at four sites in north-east Scotland.

6. The general reactions in root development to the soil conditions, ground preparations and application of phosphatic fertilisers are described and discussed for each site. The root development of the species as it occurred at each site is discussed. The outstanding fact which emerges from the study is that roots will only exploit freely soil which is sufficiently porous and well aerated. In the natural upland heath the thin surface peat (A_0) prevents adequate aeration of the soil beneath it, remaining waterlogged for much of the year. The mature podzol soil profiles are markedly layered

in horizons differing in texture, compaction and level of fertility. Notably, the eluvial horizon (A_2) is commonly a sterile compact leached sand. Any disturbance of the surface horizons alleviates the limiting physical conditions and encourages free root development within the disturbed soil and illuvial horizons beyond. Thus partial line cultivation induces a high degree of orientation of the primary roots with the direction of ploughing, which endangers the long term stability of the stand.

7. Undisturbed hard pan, between six and ten inches in depth, which occurs between the eluvial (A) and illuvial (B) horizons, forms a significant barrier to descending roots. This lends a shallow storied character to the root system. Undisturbed hard pan, between fourteen and twenty-four inches depth, which coincides with the top of a very compact subsoil (parent material) forms a complete barrier to root penetration, as does the subsoil itself. Such a pan/compact subsoil induces a deeper storied character in the form of the root system, with no roots beyond the horizontal flattening at the impenetrable horizon.

8. The response in vigour of the tree root system to the application of phosphatic fertiliser varies inversely with the degree of cultivation; and also inversely with the inherent level of fertility of the site in question.

9. The response of the root systems, and consequently the growth of Japanese larch to the degree of cultivation was significant. In all cases healthy well-grown trees had root systems penetrating to some depth by primary descending roots and by sinkers from the lateral roots, which themselves were not necessarily shallow in the soil. A significant response to fertilisers was observed only on the poorest site.

10. On all sites and soil conditions Sitka spruce checked severely when growing in competition with *Calluna* (heather). The response of this species to phosphate application was noticeably greater than for the other species dealt with. The root system of healthy Sitka spruce extended to some depth by sinkers from lateral roots shallow within the soil.

11. The pines proved the best colonisers of poor heathland conditions; lodgepole pine proved more vigorous in root development than either Scots pine or Corsican pine. The healthy root system was characterised by a pronounced tap root, together with vigorous lateral and sinker roots. A significant response to phosphate was observed only on the poorest site. The greatest response to the intensity of cultivation of moderately poor site was reflected in the forms of root systems. They lost the shallow storied character in the more complete and deeper cultivations, which proved to be the more wind firm.

12. As a result of this detailed study of the tree root development on upland heaths, desirable methods of cultivation are proposed. A prerequisite of any method of cultivation is an adequate burn of the natural callunetum. The first essential for all upland heaths is a complete cultivation of the surface in order to destroy the continuity of the surface peat and to mix and disturb the mineral soil and peat to some depth. A total cultivation depth of at least eight inches on the normally poor sites is recommended. This will also disrupt a large proportion of shallow pan formation. The poorest sites have a relatively shallow (10-16 inches) pan/compact subsoil, and attendant poor drainage from above the pan, may require, in addition, frequent subsoiling to about eighteen inches. For preference, the trees should be planted as nearly above the lines of subsoiling as possible.

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APPENDIX 1

Details of Profile and Site, Allerston District, Yorkshire, January, 1952

Japanese Larch

Profile No. 1. Wykeham Experiment 6.P.28. Prepared Patches. (Diagrams 1, 3, 5. Photo. 3. Figs. 2, 3.)

Soil and Root System. The most significant feature of this profile was the shallow surface rooting system of the stand, the region of major rooting and free fine rooting was confined to the top three-and-a-half inches, including the litter. A few roots penetrated the undisturbed leached A_2 horizon above the pan but did not explore it freely. The pan generally offered a barrier to further penetration, fine roots were content to form a thin mat above it with little further development. Rooting below pan level was associated with vertical channels, only a few of which were exposed in the profile. The fine roots which were seen below the pan were associated with major descending roots such as were found in the root stock of the excavated tree. Horizontal channels were scarce, comparative occurrence of ten per cent. The loose rocky sandy region at three feet was clearly defined and associated with freely branching fine rooting developed from descending roots. The excavated tree showed the major root system to be on the surface with a divided central descending root system. The tap root had penetrated the pan and flattened out on encountering the highly compacted region of lower illuvial horizon parent material. Odd roots descended to the loose region by exploring the better conditions found in vertical channels, and divided again freely on reaching this region.

Plan. The plan showed the surface root system of the stand, exposed to a depth of two to three inches, but for the most part the roots lay on top of the old peat surface and under the litter. There was a marked tendency for the root system as a whole to orientate itself about the disturbed patches of soil, including two in which the transplants did not survive. (Diagram 3). It appeared that the exploring root system, creeping over the surface of the peat, found these patches and prospered. Individual roots, having been encouraged, pushed on to discover further sources of nutriment, leaving secondary descending roots to exploit the patch. It was common to find a root with very small taper for some feet before encountering a patch, it rapidly lost diameter as secondary roots branched off into the patch, and carried on the far side once again with little taper. These long even diameter sections on the peat surface may be described as ropelike. In a few instances the primary root descended into the patch.

It therefore appeared that the process of breaking up the peaty surface and aerating the mineral soil made it an attractive medium for root growth. The shading effect under the living trees may have had some contributory effect on the orientation of the surface roots, but this would not have operated in the patches where the seedling did not survive.

Profile No. 2. Wykeham Experiment 2.P.28—Prepared Patches.

Soil and Root System. The topsoil was all of the pinkish sandy clay material, no normal calcareous grit parent material appeared at the surface. The pan was well defined but softer and darker than usual and proved no serious deterrent to descending roots. Discoloration due to leaching below the pan was common. Soil colours generally were not clear or well defined. Horizontal channels, empty and partially filled, were very numerous. Vertical channels, leached to a greater or less degree, were common. A mass of soil mixed with charcoal was found at one point within the profile, ten to fifteen inches below the surface. The charcoal was identified by Mr. Orr of the Royal Botanic Garden, Edinburgh, as Ericaceous. From its position in the profile it was unlikely that the charcoal was associated with the present Callunetum of the heath, but was rather a relic of burned Ericaceous shrubs belonging to a former woody plant association. A further occurrence of fragmentary charcoal in a matrix of bleached clay, was located at one to two feet depth. The major root system of the stand was found at or near the surface but the fine root distribution was unusually extensive and directly associated with the presence of horizontal channels. The area above the line of free rooting was by no means completely explored by the roots, as may be the case in ploughed ground. No roots were found beyond three-and-a-half feet below the surface, although a region of moderately loose sand and stone was present.

Plan. The surface root system, exposed to a maximum depth of two inches, indicated the mainly superficial nature of the rooting. The points where roots descended frequently occurred at points of disturbance of the peat surface, either on an original prepared patch or where *P. Contorta* had subsequently been turf planted. The remainder of the points of descent were investigated, and in most cases the roots followed the edge of a stone or the dead rooting system of a *Calluna* group. At one point there appeared a group of roots descending for which no such explanation could be found. Reference to the profile indicated that this was associated with the presence of charcoal below.

Stand. Originally planted as a mixture of Japanese larch and Sitka spruce in one-fifth acre plot, many of the original plants failed leaving scattered specimens of larch and checked Sitka. The area was beaten up with *P. contorta* in 1939. The trench was located in a small group of surviving larch with only scattered specimens beyond the trees within the plan area.

Profile No. 3. Wykeham Experiment. 6.P.28 Shallow Ploughing. Single Furrow

Soil and Root System. The notable feature of this profile was the large area of disturbance below the pan due to horizontal channels, mostly empty, and some as large as one inch in diameter. The soil was stained dark and of a crumbly, loam nature. This area extended to both sides of the trench and it was here that the only two larch of moderate size on the plot occurred. The remainder of the original planting had failed or consisted of checked spindly specimens. The pan was shallow and well defined except in the region of disturbance by channels, where it was darker and soft. Secondary leaching beneath the pan was evident. Owing to the poor stocking and growth the pan had not had any influence on the root distribution. Vertical channels were present but owing to the generally rocky nature of the subsoil the leaching action had become diffused beyond the original boundaries of the channels, except in one channel which showed the typically bleached character due to leaching. The loose rocky region was well defined but confined to a narrow band, considerably discoloured by deposition from above. The ploughing had little effect on the tree growth. Of the nine replications of Japanese larch on this ploughing type, this plot showed the best survival and growth. The root system was superficial except in the region of deep disturbance. The excavated root stock illustrated the manner in which finely branched rooting had freely exploited this region, which had also made the way for further descent of roots to the loose region.

Plan. The plan emphasised the surface nature of the rooting system, and showed a general orientation along the ploughed ridge and furrow.

Small secondary roots branched from the primary roots in the ridge and furrow, but over the undisturbed surface the primary roots maintained an even diameter ropelike nature. It was noted that the undisturbed peat here was waterlogged and that the roots did not penetrate to any degree, but lay covered by a thin layer of heather litter.

The major influence on the growth of the trees was the deeply disturbed region which is wholly independent of the ploughing, which was quite ineffective by itself.

Profile No. 4. Wykeham Experiment 6.P.28. Shallow Ploughing. Three Furrow

Soil and Root System. The overall clay content was high, especially at one to two feet depth. The profile was stony throughout, less so in the top horizons. There appeared to have been considerable original mixing of the upper two to three feet of soil. The pan was shallow and thin, soft in places of secondary leaching below it. It offered partial restriction to roots, which did penetrate in places to exploit the less compacted parts of the subsoil, which occurred in conjunction with horizontal and vertical channels. The latter were somewhat indistinct and tended to be diffused, with a concentration of alluvial clay towards the bottom. The loose region was distinct, its illuvial nature borne out by the presence of pinkish muddy clay and dark staining beneath the flat stones. The ploughing was very shallow, a mean depth of four inches, a maximum depth of five-and-a-half inches in the furrow bottom. The major concentration of roots was confined to the ploughed soil, but by no means to the surface. The loose region was vigorously exploited by fine roots.

Plan. The direction of ploughing had little influence on the orientation of the tree root system. The taper of the primary roots with distance from the root stock was rapid as secondary roots branched and descended.

Due to early losses the plot was poorly stocked, the remaining trees had made fair growth: mean height twenty-six-and-a-half feet.

Profile No. 5. Wykeham Experiment 9.P.29. Shallow Ploughing. Three Furrows

Soil and Root System. The top one to two feet of soil was mainly of the pinkish sandy clay and ferruginised rubble type, and appeared to be little mixed with the calcareous grit, sand and stones, below. The pan was shallow, soft and in places somewhat indistinct. Horizontal channels were very numerous and had a major influence on the distribution of rooting below the ploughing. Vertical channels were common but their outline was clearly defined only in the compacted calcareous grit horizon showing a central leached core of fine sand with iron-stained edges. The loose rocky region was restricted to one end of the deepened trench. Vertical channels, leached centres and stained sides, lead directly into this region giving it a characteristically darkened muddy appearance. The root system was scattered and not confined to the ploughed soil. Most of the primary roots were, however, in the top foot of soil, the secondary roots and fine rooting explored the subsoil, mainly by means of the horizontal and vertical channels. Roots extended through the vertical channels to the loose region where they branched freely.

Plan. The lateral root system was moderately extensive and the direction of rooting was influenced to some degree by the direction of ploughing.

Ploughing. The ploughing was deep enough to turn up the shallow pan and appeared to have been made use of by the roots. It had not, however, had the major influence on the distribution of the root system owing to the clay nature of the upper soil horizon.

Stands. Originally planted Japanese larch—Sitka spruce mixture on a one-quarter acre plot, only scattered specimens of larch remain except for the group in the plan area which extended to the nearby side. Height growth within this group was fair (mean twenty-six feet) but may reflect the soil rather than the ploughing intensity.

Profile No. 6. Wykeham Experiment 6.P.28. Shallow Ploughing Complete. (Diagram 6. Fig. 2.)

Soil and Root System. A wedge of pinkish sandy clay and ferruginised rubble was clearly defined within the profile and strongly suggested that it was an ancient frost crack filled with glacial material. It extended directly into a deep region of loose rock, sand and muddy clay. The rubble above and the rocks within the region were considerably discoloured, the latter stained black on the underside. The pan level was deep over this wedge, with marked convolutions at the edges; the remaining pan level was shallow. The ploughing was shallow but even, the small unploughed piece at the right-hand end of the profile was the centre of the plot dividing the forward and return ploughing. The pan was broken only in three places, once where it was less than six inches from the surface and twice where the plough went over seven inches deep. In both the latter cases direct access was given for roots to descend below pan level; in one case down a vertical channel, in the other both vertical and horizontal channels were explored. Distinct vertical channels leading from the pan level of the wedge were found when excavating the root stock. Near to the pan the channels contained dark sand, and iron-staining at the edges, followed by six to nine inches of broken charcoal, the remainder contained grey leached fine sand leading to the loose region below. These channels were explored by roots which branched freely on finding the loose level. Empty and frass-filled channels occurred beneath the pan over the remainder of the profile and were freely explored by fine roots. The distinction between the higher clay content B horizon and the normal firm calcareous grit parent material was marked by the lower limit of fine rooting. The root system was well distributed throughout the ploughed soil, the pan and undisturbed soil generally provided barriers to further free rooting. Some roots descended to divide freely in the region of horizontal channels. The root stock had a deep root system, the major roots were directed down and towards the channelled region left of the clay wedge, one storey was immediately above the pan, the lower storey penetrated the pan and explored the channelled region.

Plan. The plan emphasised the deep nature of the rooting by the scarcity of surface roots of any size. The two prominent shallow roots were relatively small in diameter, ropelike and tapering gradually and extended to the surface litter of the adjacent stand of Corsican pine. The direction of rooting was independent of ploughing. Most lateral and descending roots tapered rapidly, producing many secondary roots as they did so.

Stand. The stocking of the plot was fair, the fifteen-foot square of the plan area was surrounded by standing trees. Survival and height growth were good in comparison with less intense treatments, mean height growth was twenty-six feet.

Profile No. 7. Wykeham Experiment. 6.P.28. Shallow Ploughing, Complete.

Soil and Root System. The ploughing depth (mean nine-and-a-half inches) was deeper than found in the other examples of shallow ploughing and approached the standard of ploughing found in medium depth ploughing. The pan was completely turned up except for a short length of one foot which had the effect of impeding the depth of rooting at this point. There was no clearly differentiated firm rocky level, the whole upper profile being compact, with increasing stoniness with depth. This restricted root exploration to the region of the vertical channels. Pinkish sandy clay and rubble wedges occurred at each end of the trench, but had no direct bearing on the root distribution. The clay content of the soil immediately below the ploughing (old pan level) was moderately high. A large number of vertical channels of all types were present, many associated with horizontal channels and fan type fine rooting at the top, narrowing to a normal channel at the bottom. The loose region was sharply defined. At one spot a cavity the size of a pudding basin occurred, shalelike rubble and loamy sand partially filled it. The fine rooting in this region was particularly vigorous, spreading and branching freely in all directions. The major root system was well distributed throughout the ploughed soil.

Plan. The exposed surface roots tapered rapidly and showed little tendency to follow the line of ploughing.

Stand. The plot was well stocked but had not been thinned. Height growth was good (mean twenty-five feet) for the species compared with the remainder of the unslagged experiment.

Profile No. 8. Wykeham Experiment 14.P.31. Moderately Deep Ploughing. Two Furrow. (Diagram 8, Photo. 2, Figs. 2, 3 and 5.)

Soil and Root System. The pan was clearly defined and had marked influence on the distribution of fine roots. Where it was broken with the plough, the zone of free rooting descended below the pan level. The subsoil beneath the pan had only a moderate to small clay content, increasing in compactness, stones and sand towards the compact rock and sand region. A slightly less compact region was found at a depth of five feet. Vertical channels in this profile were few, one was found leading to the less compact rock and sand below. Some scraps of charcoal were found in this channel at two-and-a-half feet depth. Exposure of the opposite face of the trench after a thaw showed two or three well developed half-empty vertical channels containing a considerable quantity of charcoal, some pieces one half-inch cube, identified as oak (*Quercus* spp). Horizontal channels were common about one foot depth and were used extensively by the deeper fine root system. The root system of the stand was well distributed within the defined fine root zone, the more intense rooting was found in the ploughed soil. Advantage was taken of the breaking of the pan for the roots to explore the subsoil freely.

Plan. The excavated tree had a well distributed root system, branching freely and tapering rapidly in the ploughed soil, but generally avoiding the compacted subsoil. The exposed lateral roots (Diagram 8) illustrate the manner in which the roots followed the ploughed turf, descending and developing vigorously on the furrow side, developing well but with less inclination to descend on the side of the spoil.

Stand. The stand showed a good even quality with relatively good height growth (mean height thirty feet at twenty years). The stand had been thinned three times, 1942, 1944 and 1951.

Profile No. 9. Wykeham Experiment 78 (22) P.32. Moderately Deep Ploughing. Two Furrow. (Fig. 5.)

Soil and Root System. The pan depth varies considerably, from five inches to fourteen-and-a-half inches with a mean of nine inches. The convolutions were directly associated with the vertical channels, in the form of a series of connected funnels leading into the channels. The plough furrows disrupted the pan when the pan was within reach of the plough. Advantage was taken of this breaking of the pan by the root system to explore the subsoil where conditions of aeration and compaction were favourable. The ploughing was sufficient to give a good surface cover of soil to smother the original heather ground cover. The main root system of the stand was well distributed throughout the ploughed soil. The fine rooting was less prolific in the undisturbed step, i.e. the soil between adjacent ploughed strips, in two instances the fine rooting level was raised to the original peat-heather surface of the step. Vertical and horizontal channels were numerous and well explored by living roots, especially when free access was given them by the rupture of the pan by the plough. Some vertical channels led to the moderately loose region below, providing a way for descending roots. A vertical channel within the trench was excavated in a monolith and found to contain charcoal fragments at a depth of two-and-a-half to three feet. The stony loose region was not sharply defined, it merged above into the firm stony parent material, the stoniness decreasing towards the pan.

Plan. The direction of root spread was strongly influenced by the direction of ploughing, the roots preferring to exploit the turned-over soil and the furrow bottom. Most lateral roots tapered rapidly and divided freely, descending well below surface level. Two surface ropelike roots followed the furrows for several feet.

The survival of the original planting was good and there had been no beating up. Height growth was good, with a mean thirty feet at nineteen years. As part of a thinning trial the stand was thinned to medium intensity in 1942 and again in 1946. One oz. high grade basic slag per tree was applied at planting.

Profile No. 10. Wykeham Experiment 11.P.31. Moderately Deep Ploughing. Two Furrow with Subsoiling. (Diagram 9, Photo 6, Fig. 1.)

Soil and Root System. The pan was deep and convoluted, the convolutions were directly associated with a series of vertical drainage channels so that the contour of the pan would appear as a number of upright funnels joined by their margin. The pan formed a definite limit to the zone of free rooting. The subsoiling channels were still distinct and in each case broke the pan, allowing roots to explore the subsoil for a few inches at these points. The mean depth of the subsoiler was seventeen inches, seven inches more than the mean ploughing depth. The ploughing had not touched the pan owing to the depth of the latter, but had provided a soil freely used by the root system. The lower levels of the A horizon above the pan tended to have a gley character, especially towards the neck of the funnels. Soft rotten stones of bright orange sand were imbedded in this clay-sand material. The vertical channels were prominent, frequently forming the spout of a pan funnel, leading to the well defined loose rocky region below. The pan did not extend right to the loose region, but stopped at two to two-and-a-half feet, forming across the channel but apparently not making it impervious. These and other vertical channels were used by descending roots when the opportunity occurred. Horizontal channels below the pan were scarce and of no consequence. The subsoil beneath the pan and above the loose region consisted of very compact sand and stone, there was very little rooting in it beyond the vertical channels. The loose rocky region was clearly defined, stained dark with muddy clay, the flat stones were stained black on the underside. Such roots as reached this region branched freely and exploited it vigorously. The root system of the stand was well distributed throughout the disturbed soil. The unbroken pan and compact subsoil offered great resistance to penetration by roots. The excavated root stock (Photo. 6) illustrated in a striking manner the use of the disturbed soil by the roots, the furrow to the right, the spoil to the left and the subsoiler vertically in the middle. The manner in which the disturbance caused by the subsoiler gave access below the pan to descending roots was clear.

Plan. The plan emphasised the deep nature of the root system and the manner in which roots divided frequently, exploring freely.

Stand. The stand had made very good progress, with a mean height of thirty-and-a-half feet, mean girth seventeen inches, in twenty years. It was thinned in 1944 and in 1951.

Profile No. 11. Wykeham Experiment 11.P.31. Moderately Deep Ploughing. Two Furrow and Subsoiling. (Fig. 2.)

Soil and Root System. The pan level was moderately deep and even, turned up by the furrow in two cases and disrupted by the subsoiler. The pan formed a definite barrier to root exploration and each break in its continuity was taken advantage of by the roots. The subsoil was generally compact, a higher clay content was found at each end, with attendant pink and brown discolourations. In centre was a small wedge of pure boulder clay which may have been associated with a frost crack. Vertical channels were common and independent of the pan. Charcoal was found in quantity in one of these at one to two feet depth. This was identified as oak (*Quercus* sp.) and possibly root charcoal. By its position in the profile, this supposition seemed likely. There were few horizontal channels and they did not play any part in the lower root distribution. The major root distribution closely followed the disturbed and turned-over soil. Although the trees had not been planted over the subsoiler channel, this still encouraged fine rooting in the subsoil in the region of disturbance. The root stock of the excavated tree showed that the roots had not used the channel as in Profiles 8 and 10. Such deep rooting as there was on the side of the subsoiler was due to the presence of the subsoiler disturbance.

Plan. There was little inclination for the lateral roots to be confined to the surface and root division was frequent. There was some tendency towards orientation of the roots with the ploughing, especially along the plough furrows.

Stand. Quite heavy thinning had taken place. Height and girth development were only fair, compared with Profile No. 10, but the planting position in relation to the channel was slightly different, i.e. to one side of the channel instead of above it.

Profile No. 12. Wykeham Experiment 14.P.31. Moderately Deep Ploughing. Complete. (Diagrams 2 and 4, Fig. 2.)

Soil and Root System. The ploughing depth was greater than any other moderately deep ploughing encountered, consequently the zone of free rooting was conspicuously deep and even, mainly confined to the ploughed soil. The inhibiting effect on rooting of the pan was clear where the pan and surface remained unploughed between the forward and return ploughing in the centre of the plots. The subsoil above the firm rock and sand was a firm clay sand with very few avenues for root penetration. Both vertical and horizontal channels were infrequent. The deep nature of the root system was emphasised by the excavated root stock (Diagram 4). The level of flattening out and intense branching of the descending roots was at the region of compact stone and sand. The one root which descended beyond this level followed a leached vertical channel.

Plan. The lateral root system was well distributed, with a doubtful bias in the direction of ploughing. Taper was rapid as secondary roots descended below the surface.

Stand. The stand quality was even and good, the mean height growth was thirty-one feet in twenty years.

Profile No. 13. Wykeham Experiment 11.P.31. Moderately Deep Ploughing. Complete. (Fig. 2.)

Soil and Root System. The ploughing was comparatively deep, mean thirteen inches from present surface, estimated ten to eleven inches from original surface. The pan apparently of the shallow level type, had been completely turned over by the plough. The subsoil beneath the pan was clayey, a pocket of pinkish sandy clay and rubble occurred over three feet of the profile. The soil beneath the ploughing was compact and there were no horizontal channels. The vertical channels were well developed, a few had leached clay-sand cores with red iron-stained edges, the remainder had dark loamy cores. Charcoal fragments were found in the turned over subsoil of the ploughing embedded in a pale clay loam soil matrix, but owing to the disturbance its origin must be obscure. The lower very stony region was not loose but only less compact than that above it, but it did afford an opportunity for the spreading of fine roots at depth. The root system was well distributed throughout the ploughed soil and almost confined to it by the compact nature of the soil below. The descending roots beyond the ploughing were of little consequence.

Plan. The root system showed no tendency to follow the line of ploughing, most primary roots tapered rapidly as sinkers branched off.

Stand. The quality of the stand was good and it had been thinned in 1944 and 1951. The mean height growth was twenty-nine feet in twenty years.

Profile No. 14. Wykeham Experiment 26.P.32. Moderately Deep Ploughing. Complete. (Fig. 2.)

Soil and Root System. The ploughing was very shallow, mean depth of five-and-a-half inches, and irregular, and may be compared with shallow ploughing. The pan was shallow, mean depth six-and-a-half inches, but had only been broken by the ploughing in two places. The subsoil below the pan was stony throughout, somewhat less so at the top where the soil is a clay-sand. Vertical channels were scarce, those present showed signs of diffused leaching and were exploited by roots. Horizontal channels were numerous and explored by fine roots. One empty channel, showing no signs of leaching, led directly to the less compact region below, affording access to exploring roots. The rocky region at the bottom was only moderately loose but was used by descending roots. The root system was mainly confined to the shallow depth of ploughed soil, the pan offered a partial barrier to penetration, but there was considerable rooting below it in the region of the horizontal channels. There were few deeper roots.

Plan. The somewhat superficial nature of the root system was illustrated; the exposed roots did not lie on top of the surface, but just under it.

Stand. The stand quality was comparatively poor; a mean height of only twenty-four-and-a-half feet in eighteen years. One light thinning was made in 1945.

Profile No. 15. Broxa Experiment 9.P.43. Deep Ploughing-R.L.R.-Single Furrow. (Diagram 10, Fig. 4.)

Soil and Root System. The ploughing depth was not great for this type of plough. The spoil covered the greater part of the unploughed surface, giving a furrow bottom to ridge top difference of up to eighteen inches. The furrows had been partially filled with loose spoil from frost, etc. since the time of ploughing. On the left of the profile the spoil was thrown right, and on the right it was thrown left, the two spoils meeting in the middle where the forward and return furrow adjoined. The pan was deep and somewhat convoluted, the convolutions were concentric about the vertical drainage channels. In places the pan was somewhat diffused, extending by a type of horizontal banding a few inches below the main line of deposition. The plough broke the pan once only. The intact pan restricted rooting; the undisturbed top soil or leached sandy A horizon proved equally a barrier to the free exploration by roots. Horizontal channels were prominent and individuals quite large, making cavities up to one inch diameter. The vertical channels were well developed, with brown and/or bleached core with iron stained edges. At the top of one channel, within the enclosed pan, was an amorphous mass of black organic matter, probably the accumulated remains of old *Calluna* roots, together with precipitated colloidal humus. The subsoil below the pan was a clay sand, compact in the absence of horizontal channels, and merged into a compact sand with increasing stoniness with depth. The loose region at three feet was only moderately free, with the least compaction at the base of a large vertical channel where organic staining and clay discolouration were greatest. The root system was mainly confined to the ploughed earth, selecting the sandwich* and furrow bottom for preference. The undisturbed leached A_2 horizon was avoided by fine roots. Channels beneath the pan were being utilised to a limited extent. The fine rooting which penetrated the pan occurred where the pan was soft and diffused with evidence of weathering below it.

Plan. The heights of the adjacent trees were recorded including one line of Sitka spruce, part of the four line mixture. The average height of the Japanese larch was eight-and-a-half feet, the spruce six feet. It is not considered that spruce roots were a significant proportion in the profile, if present at all.

The heather regrowth had been suppressed beneath the larch, but remained vigorous about the Sitka spruce.

Profile No. 16. Broxa Experiment 9.P.43. Deep Ploughing—R.L.R.—Complete. (Fig. 4.)

Soil and Root System. The ploughing was deep and uniform, mean depth twelve-and-a-half inches from the present surface, estimated ten inches from the original peat surface. Maximum depth was seventeen inches, estimated fourteen inches from the original peat surface. Small air pockets remained within the ploughed soil. The pan, which must have been of medium depth, had been turned over wherever the ploughing exceeded ten inches, or about nine inches from old surface. A pinkish sandy clay also ocurred but was mixed with the calcareous grit material *in situ*. The subsoil was very stony and compact with little clay apart from that described above. Vertical channels were common and the drainage through them appeared to be diffused beyond their original limits, especially at the top and in the clay soils. Horizontal channels occurred but were of little significance. There was no loose region within the depth of the trench, the lower subsoil was particularly rocky and compact. Vertical channels extended beyond the maximum depth excavated, five feet. The root system was well distributed throughout the ploughed soil, the distribution of the larger roots suggested an early preference for disturbed peat and disturbed pan and subsoil. Fine roots explored vertical channels but did not appear to be very vigorous. Distinction between larch and Sitka spruce roots (trees in line mixture) was not possible but it is doubtful if any spruce roots extended to the profile.

Plan. The mean height of the larch was ten feet, somewhat better than single furrow ploughing, but the stand was too young to draw any real conclusions in this respect. The mean height of the spruce in mixture was about six feet.

Heather regrowth had largely been suppressed beneath the larch but was flourishing about the spruce.

Profile No. 17. Broxa Experiment 9.P.43. Shallow Ploughing. Single Furrow and Subsoiling. (Fig. 4.)

Soil and Root System. The pan was exceptionally deep, mean twenty-one-and-a-half inches, and consequently had not been broken by plough or subsoiler. The depth was too great to have had any effect on root development. The subsoiler channel below the furrow was clearly defined, the apparent uplifting of the old peat surface at the edges of the furrow was the result of the lifting and loosening action of the subsoiler. The ploughing was quite shallow, five inches, following directly over the subsoiling and the trees were planted on the spoil side of the furrow. No distinct vertical channels were found, a line of diffused drainage occurred. Some accumulation of water was evident above the pan and varying degrees of gley soil occurred in this

* Sandwich = the layer of decomposing organic matter between the inverted plough slice and the undisturbed ground surface.

region. No horizontal channels were found but a friable area occurred between twelve and twenty-four inches depth for a width of thirty inches above the deepest and least distinct pan at twenty-eight to thirty inches depth. The calcareous grit subsoil beneath the pan was particularly compact and stony with very little sand between the broken rocks. The boundary, marked by the pan, between the moderate clay-sand horizon and the very hard subsoil was quite distinct. The root system clearly made use of the disturbed soil of plough and subsoiler, with little exploration beyond this. The old humus sandwich and furrow bottom were preferred. The undisturbed leached sandy A_2 horizon had not been penetrated, in contrast to the same soil thrown up on the ridge.

Stand. The height growth was good in comparison with the deeper ploughing of the other Broxa examples, the maximum height, twelve feet, was greater than that for complete deep ploughing, ten feet. The depths of the soil profile were, however, quite different and may account for the better growth. The spruce in mixture showed similar progress, mean height seven feet.

APPENDIX 2

Details of Profile and Site, Allerston District, Yorkshire September, 1952

Scots pine

Profile No. 18. Wykeham Experiment 6.P.28. Prepared Patches. (Diagram 11, Photo. 7, Fig. 3.)

Ground Preparation. The trees were planted in undisturbed ground in patches one foot square prepared with a mattock.

Soil. The profile is an example of the simple pure calcareous grit type exhibiting a shallow, even depth, well developed pan above a zone of deposition in which were found a few horizontal channels. Below this was the region of very compact calcareous grit stone and sand, occasionally penetrated by vertical channels showing signs of leaching.

Root System. The major root system was confined to the topsoil, but *not* the surface (cf. Japanese larch). Further roots were found on and below the pan, the latter apparently forming only a temporary, though significant barrier to the descending roots. The real barrier to further descent was provided by the region of compacted stone and sand at about seventeen inches. Vertical channels into this region provided some access for deeper roots.

The system was generally not as fibrous as Japanese larch and the boundaries of the free rooting zone were not as distinct. The root stock of the excavated tree confirmed the three-layered nature of the root system, although the whole sandy eluvial topsoil had been used pretty freely near the base of the root stock. Note that this tree was a co-dominant within the stand and, presumably, the root system was not as well developed as that of the dominants.

Stand. The stand was of fair quality, but the growth of individuals was uneven (range of nine feet in height) with many blanks, runts and suppressed trees in the stand. Mean annual increment was relatively low at eleven-and-a-half inches. The form of the trees is generally poor but varied greatly.

Species Comments. (1) Moderately fibrous root system. (2) A balance between the lateral and descending parts of the root system (3) Ability to exploit undisturbed heathland soil. (4) Rooting as deep as the physical conditions, in the compacted calcareous grit sand and stone, would allow. (5) The root stock had no single tap root but a few divided roots descended directly from the base of the tree.

Profile No. 19. Wykeham 13.P.31. Two Furrow Ploughing. (Diagram 15, Photo. 10, Fig. 3.)

Ground Preparation. The area was ploughed in strips five feet apart by a two-furrow Oliver plough drawn by a powerful crawler tractor. The mean depth of ploughing was measured as eight-and-a-half inches, estimated as seven-and-a-half inches below the level of the original peat surface. The experiment file records the ploughing as satisfactory where the burn prior to ploughing was successful. The estimated increase in the volume of the ploughed depth of soil is seventeen per cent. The pan (mean depth six-and-a-half inches) was well within reach of the furrow bottom (mean depth eight-and-a-half inches).

Soil. The soil profile exemplified the normal calcareous grit podzol profile. The pan was at an even shallow depth (six-and-a-half inches) beneath a leached fine sandy horizon capped by the surface peat. Beneath the pan was a residual zone of deposition which quickly merged to a very compact subsoil of irregular stones and sand (mean depth nineteen inches). There were very few horizontal channels beneath the pan, but there were a number of dark stained drainage areas due, apparently, to the differential permeability of the pan. In addition, two examples were seen of vertical channels which were well developed and showed signs of leaching as drainage channels.

Root System. The major lateral root system was confined almost entirely to the ploughed soil, with subsidiary roots partially exploring the less attractive undisturbed horizons.

The illuvial horizon was partially explored beneath the pan and undisturbed top soil and freely beneath the plough furrows. The very stony compact subsoil was an almost impenetrable obstruction to further descent of roots except where vertical (ancient root) channels provided access.

The excavated tree had a pronounced tap root which penetrated the pan without difficulty but broke and petered out at the compact region. The undisturbed pan provided partial and complete obstruction of descending sinker roots with no such obstruction beneath the plough furrows. The lateral roots freely exploited the ploughed soil and consequently tended to be orientated with the direction of ploughing.

Stand Quality. The average quality of the stand was good with a good stocking of dominant and sub-dominant trees. A silvicultural thinning was carried out in 1945.

Profile No. 20. Broxa Experiment 4.P.41. Single Furrow Shallow Ploughing and Subsoiling. (Diagram 14, Photo. 12, Fig. 4.)

Ground Preparation. No record could be found of the instruments used. The ploughing was indeed shallow, merely scraping a twelve to fourteen inch strip of surface peat to a depth of about four-and-a-half inches. The subsoiler ran to a depth of fourteen inches, but no distinct open subsoiler channel was observed. However, the traces of the subsoiler were quite distinct, the pan had been broken by it and pushed up at the broken edges. The increased moisture status of the subsoil beneath the subsoiler disturbance was quite marked, following moderate falls of rain prior to examination. In a report dated July 1941 it is noted—'This area became very wet during the winter months. Following ploughing and subsoiling this feature was completely changed.'

Soil. The A horizon above the pan was quite dark with organic matter, with no signs of deposition beneath the thick impermeable pan which coincided with the compact stony calcareous grit subsoil. The pan was at an even depth of about eight inches with only small variations above the silty subsoil on the right of the profile. Only one vertical channel occurred, sealed at the top by the pan and in the silt and rubble subsoil. The normal calcareous grit subsoil, sand and stones, was compact between the pan and the loose region at three feet.

Root System. Exhibited a direct response to the cultivation, penetrating to depth only beneath the line of cultivation. On the right of the profile this gave access for roots to a loose area of horizontal channels extending beneath the unbroken pan. The remainder of the root system was confined to the surface or near surface, and positively avoided any exploration of the undisturbed sand of the eluvial horizon.

The distribution of the roots of larger diameters indicated that the system was aligned with the plough furrow. This was borne out by the excavated tree (Photo. 12). This also showed the remarkable use which the tree had made of the subsoiling disturbance to develop a vigorous root system below the pan level in the previously compacted and sealed subsoil. Few roots extended into the eluvial horizon above the pan except where this was churned up by the subsoiler.

Stand Quality. The stand was of fair quality and healthy appearance. Canopy had not yet been closed and the heather between the spread of the crowns was still vigorous. Note that 1 oz. of slag per tree had been applied at planting.

Species Comments. (1) Ability to explore disturbed and opened subsoil. (2) Lack of precise definition of zone of free rooting (cf. larch). (3) Has definite descending woody base but no single tap root.

Profile No. 21. Broxa Experiment 8.P.43. Single Furrow R.L.R. Ploughing. (Fig. 4.)

Ground Preparation. The profile was typical of this method of ploughing which produced a high, relatively unbroken, ridge of soil and a deep furrow. The greatest depth of ploughing shown in the profile was twelve inches, yet the corresponding difference in level between ridge top and furrow bottom was twenty inches within a width of three feet. One ounce of slag was applied to each plant soon after planting.

Soil. The important characteristic in this profile was the silt and rubble nature of the subsoil beneath most of the section, and the correspondingly large number of old channels which remain evidence of previous root colonisation. Fragmentary charcoal embedded in a pipe of grey silty material was found at a depth of three feet.

The pure calcareous grit subsoil on the left showed evidence of ancient vertical channels, now sealed by pan at the top and not functioning as drainage channels. The subsoil was compact from the pan downwards and no small horizontal channels were found within it.

Root System. It was apparent that the furrow bottom and sides proved most attractive for the root development to date. Little use had been made of the high ridges. The effect of subsoil difference was well illustrated, showing the encouragement given to the root system by the more friable and finer textured silt and rubble type.

Limited use was made of the humus sandwich between the ridge and old surface. The undisturbed eluvial A horizon remained relatively unexplored. The trees were planted on the spoil side of the furrow bottom. The above remarks were borne out by examination of the excavated tree. Descending fibrous roots extended freely to a depth of fourteen inches immediately below the tree, the deepest root reached three feet below the furrow. This was due to the silt rubble type subsoil in conjunction with horizontal and vertical channels, below and to the right of the planting position. It was clear that the lateral root system was markedly orientated in the direction of the plough furrow.

Stand Quality. The trees were healthy and vigorous. The mean annual height increment was thirteen inches. The mean height of the Scots pine of ten feet three-and-a-half inches compared favourably with about four-and-a-half feet for adjacent Sitka spruce planted in mixture with Scots pine. Canopy had not joined but adjacent branches were overlapping each other.

Species Comments. (1) The free fibrous nature of the root stock. (2) The tendency for deep rooting when given the chance.

Profile No. 22. Private Woodland. Direct Planting. Silpho Moor (Turkey Carpet Plantation)

Direct comparison with the other profiles is not possible owing to the great difference in age of the trees and the possible differences in original soil profile. Erratics of quartz and flint were found in the topsoil horizons indicating the glacial nature of this material. A double pan was evident over most of the length of the profile, the topmost (Pan 1) at nine-and-a-half inches was continuous for the full length. Pan 1 was dark red-brown, thick and frequently soft, as if in a state of decay rather than formation. Below it was an illuvial horizon with a discontinuous bright red pan or iron staining (Pan 2) marking the lower boundary at about eighteen inches. The stony calcareous grit subsoil was compact for about twelve inches, then became moderately loose with much dark muddy staining on the large flat stones.

The root system was not well defined into free rooting zone and otherwise, but there were places of concentration of rooting, notably the surface, above each pan and in the loose region. The compact subsoil was indeed free of any roots except vertical sinkers, these apparently following and extending old vertical channels. At the bottom of the trench, five feet deep, a large root two to three inches in diameter was uncovered.

Species Comments. The soil appeared to be essentially the same as other parts of the moor; it may be argued, a little better. The Scots pine had grown slowly with a mean annual girth increment of about four-tenths of an inch per annum. Height growth was not great and the crowns were flat topped and spreading. The species appeared to be capable, in time, of developing a significantly deep root system along with a primarily lateral system although large volumes of soil, particularly within a foot of the surface, remained relatively unexploited. The age of the crop was about 80 years.

Sitka spruce

Profile No. 23. Wykeham Experiment 60 P.28. Prepared Patches. No mulch. (Fig. 3.)

Ground Preparation. One foot square patches turned over by mattock to a depth of about six inches.

Soil. Normal Wykeham profile of shallow even depth pan type. The surface had a vegetation covering of vigorous *Calluna.*

Root System. No Sitka spruce roots were identified in the profile. The long roots of the excavated tree were exposed by simply following from the tree, clearing away the surface litter by hand. The original nursery root system failed to develop except for one meagre root which returned to the surface. The base of the root stock was noticed to be smothered in fine *Calluna* roots. The remainder of the root system was adventitious arising from the region of the collar. The development of these roots was ropelike within the decomposing heather litter above the peat surface. It was noticed that the roots passed around and between the heather clumps, and did not normally pass into or through such clumps. The long thin roots seldom branched and there were few fibrous feeding roots. The roots associated with a white fluffy aphid or scale insect ended frequently in a mass of short rootlets and fibrous roots. For further discussion see the description of the mulched plot profile (No. 24) below.

Stand Quality. The surviving trees were without exception in extreme check, being a poor yellowish colour, stunted and frequently without leaders. The mean annual height increment of the measured trees was one inch. Recent shoot growth observed ranged from one-and-a-half inches to two-and-a-half inches. There was no indication that the state of the trees would improve but rather the reverse, and that year by year further individuals will die.

Species Comments. The growth was typical of a seriously checked Sitka spruce plantation on poor peaty heathland. The development of long ropelike roots, many arising adventitiously, and the failure to develop a descending root system is characteristic of the species under these site conditions.

Profile No. 24. Wykeham Experiment 60 P.28. Prepared Patches, Mulched. (Photos. 14 and 15, Fig. 3.)

Ground Preparation. None beyond one foot square patches turned over by mattock.

1938 *Calluna* cut by autoscythe and heaped around the plants.

1942 More mulch applied but not enough to effectively cover and suppress the *Calluna.*

1949 Screefings used to re-mulch. Sufficient to suppress all heather growth to date.

Soil. Normal Wykeham profile of the shallow even depth pan type. The surface was covered with a mulch of dead *Calluna* to a depth of about three inches.

Root System. This was completely superficial, working on top of the peat surface within the decomposing litter. The excavated tree (Photo. 14) had long ropelike roots sparsely branched and with masses of feeding fibrous roots at the extremities. The roots were exposed without digging, merely by following the individual roots from the tree, gently pulling the roots upwards and cleaning away the litter and mulch by hand. However, these roots showed a greater length, more tendency to branch, and more fibre than the unmulched section. The root stock of the excavated tree (Photo. 15) showed that the original seedling root system had been suppressed at the bottom, a few roots had extended back to the surface, but that the main system was adventitious in origin. It is apparent from records and the current shoot growth that the greatest response to mulching followed the 1949 mulch application. A few new fibrous roots arose from the region of the root collar. The response in the root system to mulching had been to extend and multiply the already existing surface root system (cf. root system without mulch) without any encouragement for the roots to descend through the surface peat into the undisturbed mineral soil below. The following are probable causes for this reaction:—

1. Elimination of heather root competition.
2. Physical protection of the surface by the mulch inducing more even conditions of moisture and temperature in the rooting medium. Extremes of both drought and frost must have an inhibiting effect on an unprotected superficial root system and may be one reason for the roots developing in the characteristic ropelike manner by killing off the delicate feeding roots at critical periods of the year. Such ropelike roots however are also found beneath stands of other species in examples of the nursing of Sitka spruce.

Stand Quality. Most of the original plants were still alive and were a healthy colour and producing relatively vigorous current shoots. Mean annual height increment for the measured trees was two inches, current shoot nine-and-a-half inches. However, many plants had been so badly checked for a long period that it seemed doubtful if they would ever grow into normal trees. The stand was a long way from forming canopy. It remains to be seen how permanent is the effect of the mulching. Without the development of some form of descending root system it seems doubtful if the present growth will continue unabated.

Profile No. 25. Wykeham Experiment 11.P.31. Two Furrow Ploughing with Subsoiling. No Slag. (Diagram 20, Figs. 3, 5.)

Ground Preparation. See description below for adjacent Sitka spruce with slag. (Profile 26). No slag was applied to this plot.

Soil. The pan was convoluted and not well defined in places. Raw humus accumulation occurred in folds of the pan and at the top of vertical channels. Horizontal channels occurred in conjunction with a silty stained illuvial B horizon beneath the pan. The subsoil was the normal compact stones and sand. No loose region was found within the depth of the trench, two-and-three-quarter feet (cf. adjacent plot+slag).

Root System. Most of the root system was near the surface, the sandwich was another favourite region, but any open soil was well utilised. Undisturbed top soil (eluvial horizon) was avoided (Diagram 20). The subsoiler induced fine roots to descend to exploit the disturbed subsoil. The excavated tree had only two roots of consequence which descended, the one in response to the pocket of accumulated humus, the other probably associated with the subsoiling. Note that the descending roots were a minor part of the root system as a whole.

Stand Quality. Canopy recently completed and the heather suppressed, though dead bushes still covered the surface. The mean annual height increment was seven inches and the current mean shoot was twenty-four inches. Thus it would appear that vigorous growth had accompanied the formation of canopy and consequent heather suppression. Mean height of the tallest ten trees in each replicated plot of this treatment in the experiment was eleven feet in 1948.

Species Comments. (1) The fibrous nature of the healthy lateral system. (2) The paucity of descending roots and avoidance of undisturbed mineral soil.

Profile No. 26. Wykeham Experiment 11.P.31. Two Furrow Ploughing and Subsoiling, plus Slag. (Diagram 21, Photos. 18 and 19, Fig. 5.)

Ground Preparation. The subsoiling was not very deep—possibly due to the proximity of the old tramline ride. In the two observed examples it had broken the pan and stirred up the subsoil below; this allowed a greater vertical diffusion of moisture at the point of subsoiling.

The mean ploughing depth was nine and-a-half inches deep, enough to turn up the pan in some cases. Fifty per cent of the surface area was ploughed, the remainder was covered by the spoil.

There are no records of heather burning before it was ploughed in November, 1930; it was probably last burned in 1920.

Two ounces of slag were applied to each tree at planting.

Soil. The outstanding feature of the soil profile was the presence of a very pronounced loose, stony region less than two feet below the surface. Accumulation of mud and humus-staining within this zone indicated that it was probably a sink for moisture draining from the top soil. This staining was particularly intense near the lower extremities of vertical drainage channels.

The profile above the pan showed the normal fine sand eluvial A horizon and peaty surface. The horizon below the pan and above the loose region was compact fine sand, some stones and a few small horizontal channels near the pan.

Root System. The root system was remarkable for its vigour and extent, considering both the area and species. The fine roots were active in all horizons where the soil had been disturbed and made use of large and small channels in the subsoil where the opportunity occurred. The undisturbed pan appeared to have been a deterrent to deeper exploration by descending roots.

An outstanding feature was the virtual absence of free rooting within the undisturbed topsoil. Photo. 19 of the excavated root stock shows this clearly. Vigorous roots explored freely the spoil and furrow to the left and subsoiled region below. On the right—unploughed area—the roots were confined to the spoil on the surface, a few in the sandwich layer, and one on the pan which penetrated by a channel to the loose region below.

Note that the lateral roots were thick and asymmetrical near the base, tapered rapidly and branched freely. A vigorous descending root system had developed to the depth of the pan, and below where the pan had been ruptured. Some roots extended further to the loose region by way of vertical channels.

The shallow loose region had no significant direct effect on the development of the root system or the stand. However, such a region usually appeared to be associated with a slightly more favourable type of topsoil on this moor.

Stand Quality. The plot was carefully chosen as being free of any obvious nursing effect by adjacent stands, which is a common feature of Sitka spruce, more especially the unslagged plots, in this experiment. The plot, combined with the adjacent unslagged half, had rides on three sides and birch along the fourth side, with no sign there of nursing. Replications of the plot within the experiment, and Sitka spruce with slag on complete ploughing, were visually inspected for comparison and apart from blanks due to failures in early years all showed similar successful growth. The last recorded assessment in 1948, recording the tallest ten trees per plot, gave a mean height for this treatment over the whole experiment as sixteen-and-a-half feet, compared with eleven feet for the unslagged and seventeen-and-a-half feet for complete ploughing with slag. The mean for the measured (1952) trees about the profile was twenty-one-and-a-half feet or a mean annual increment of twelve inches. Mean current shoot for the same trees was eighteen inches.

Ground vegetation beneath the stand had long been suppressed and given way to a thick needle litter. Live canopy level had risen to between six and eight feet.

Species Comments. (1) The root system was not superficial, both lateral and descending parts of the root system were well developed. (2) The undisturbed eluvial horizon and compacted subsoil were not freely exploited by roots.

Profile No. 27. Broxa Experiment 9.P.43. Complete Deep (R.L.R. Ploughing). (Diagram 18, Photo. 20, Fig. 4.)

Ground Preparation. The ploughing was comparatively deep, seventeen inches from the present mean surface, or about twelve inches from the original peat surface. The area was not burned prior to ploughing. However, the sods of turned-over spoil tended to remain intact and large air pockets were left between the sods. Thus the surface peat and underyling soil were not broken and mixed. The pan, originally about nine inches below the surface, had been completely turned over by the ploughing. The increase in volume of the ploughed depth of soil was forty per cent. The surface was recolonised with vigorous *Calluna* vegetation. One ounce of slag per tree was applied at planting.

Soil. Typical Broxa profile in the top soil. A curious accumulation of black raw organic matter occurred beneath the pan and in conjunction with horizontal channels at the left-hand end of the profile (Diagram 18) No vertical channels were seen but proably occurred in the near vicinity. No loose region was observed within the depth of the trench (four feet).

Root System. The root system was distributed throughout the depth of the ploughed soil, but in keeping with the general condition of check of the trees the size of the roots was limited. Some preference was shown for the turned-over peat and generally the unbroken original eluvial A horizon was avoided. *Calluna* roots exploited vigorously the same horizons as the spruce and must have been in active competition with them for available moisture and nutrient. Two trees were excavated; Tree No. 1 was definitely in check whereas Tree No. 2 (Photo. 20) was growing slowly with a definite leading shoot. The root system of Tree No. 1 was best developed in the lateral phase, the roots arising from the base were alive, but restricted. The root system of Tree No. 2 was relatively vigorous in both lateral and vertical parts with greatly increased root fibre throughout the depth of rooting. The lateral roots were apparently aligned with the direction of ploughing, following the favoured turfs, etc. The following influences causing the poor development of the spruce may be advanced.

1. Rapid and vigorous recolonising by heather and consequent root competition.
2. Minimal nutrient requirements for the species.
3. Minimal micro-disturbance of the turned-over furrow spoils.

Stand Quality. Generally suppressed or growing very slowly. No likelihood of early canopy formation.

Species Comment. (1) Root system of the most suppressed tree (No. 1) poorly developed and superficial, though not on the surface. (2) The healthier tree (No. 2) had a fibrous system throughout the profile but the lateral roots remained the dominant factor and the taper of the primary roots was not rapid.

Lodgepole pine

Profile No. 28. Wykeham Experiment 2.P.28. Prepared Patches. (Diagram 22, Photo. 22, Fig. 3.)

Ground Preparation. One foot square patches turned over with a mattock to a depth of about six inches.

Soil. A typical undisturbed Wykeham profile as previously described for other sites. The pan was even depth at seven-and-a-half inches, below a grey leached fine sandy eluvial horizon (A_2) topped by the surface heather peat and raw humus (A_0 and A_1). A few horizontal channels occurred in a relatively compact illuvial horizon, which rapidly merged to the very compact calcareous grit sand and stone parent material. No sign of pronounced vertical channels was seen although fine rooting was found to the depth of the trench, three feet.

Root System. The root system was well developed though mainly limited to the top soil by the pan and the compact soil immediately below it. The regions of most proilfic rooting occurred in the organic surface soil and just above the pan. There appeared, however, to be no hesitation for the descending roots to pass through the sandy eluvial horizon to the pan. One or two large roots and numerous fine roots penetrated the pan and exploited a foot or so of the subsoil.

The lateral system was strongly developed but primarily confined to the surface organic horizons, working just within the soil, not on top of it.

Stand Quality. Originally mixed with Sitka spruce which were completely suppressed. The *Pinus contorta* had formed canopy and was healthy. Mean annual increment was thirteen inches.

Species Comment. (1) Ability to exploit undisturbed top soil. (2) Capacity for limited penetration of a well-developed pan. (3) Typically wiry appearance of the smaller roots.

Profile No. 29. Wykeham Experiment 13.P.31. Double Furrow Ploughing. (Diagram 24, Fig. 3.)

Ground Preparation. The mean depth of ploughing was nine-and-a-half inches below the present mean surface, i.e. about eight inches below the original peat surface. Over half the area had been ploughed, the remaining unploughed surface being for the most part covered by spoil. The estimated increase in volume of the ploughed depth of soil was ten per cent. The pan was well within the depth of ploughing and completely turned over for the breadth of the furrows. The area was ploughed with an Oliver two-furrow plough in 1930, and it had probably been burned in 1920.

Soil. The profile was typical of the Wykeham area, a peat surface (A_0) above leached fine sand (A_2) above a pan at seven-and-a-half inches. Below this was the illuvial horizon (B) merging into the very compact stony subsoil (C) at about two feet. No loose region was found within the depth of the trench, four feet.

Root System. The trees were planted in the spoil of the first furrow, above the unploughed ground. This did not appear to have had an adverse effect on the root development of this species. The whole topsoil was well populated with roots but there was a tendency for the larger roots to be found in the ploughed soil which gave a degree of orientation of the lateral roots with the direction of ploughing. The remaining pan appeared to have diverted and temporarily held up the descending roots. Some of the lateral roots were very long and slow to taper although they were well equipped with secondary branches, especially sinkers. It was noticed that the decomposing litter in the surface was mixed with a mass of loose fine red feeding rootlets of the pine, most of which had ceased to function and were dead. Live fine stringlike roots infested the near surface soil. It suggested that in favourable periods for growth the surface rooting bursts into activity to make the most of suitable moisture, temperature and aeration conditions of the surface, subsiding once more with surface drought or low temperatures.

Stand Quality. The stand was well established and had been lightly thinned in 1946. Growth of twelve-and-a-half inches mean height per annum is satisfactory.

Species Comments. (1) The roots had a characteristic wirelike appearance. (2) The lateral root spread was far beyond the crown diameter. The descending roots were well developed though subject to deflection by the physical obstruction of the pan and other barriers.

Corsican Pine

Profile No. 30. Wykeham Experiment 6.P.28. Prepared Patches. (Diagram 28, Photo. 27, Fig. 3.)

Ground Preparation. The trees were planted in foot-square patches turned over and broken up with a mattock to a depth of about six inches.

Soil. The pan was of the shallow uniform depth type with an illuvial horizon beneath it containing numerous horizontal channels. The vertical channels had not developed as drainage channels. The change to the very compact fine sand and calcareous grit stony subsoil was abrupt.

Root System. The shallow pan offered little resistance to root exploration of the horizon beneath it where the open channelled nature provided favourable conditions for root development. The excavated tree showed that the pan had induced a partially three-layered system in the root stock: surface-pan-subsoil. (Photo. 27). In contrast to Japanese larch planted in the same conditions, the lateral root system did not confine itself to the peat surface. It appeared that the eluvial horizon of leached sand between the peat and the pan was sterile in its undisturbed state.

Stand Quality. Canopy had been joined and growth was satisfactory, a mean annual increment of one foot. The stand had not been thinned.

Species Comments. (1) The ability of the root system to exploit this undisturbed heathland soil. (2) The even rate of growth throughout the plot with remarkably few failures or intensely suppressed trees.

Profile No. 31. Wykeham Experiment 16.P.31. Two-Furrow Plough. (Diagram 29, Photo. 28, Fig. 3.)

Ground Preparation. The cultivation was normal moderately deep two-furrow ploughing leaving a good spoil of disturbed soil, ploughing fifty to sixty per cent of the ground area. The mean depth of eight inches appeared adequate but had not broken the pan, which was relatively deep. The estimated increase in volume of the ploughed depth of soil was thirty per cent.

Soil. The outstanding feature of the soil profile was the change in level and nature of the pan. To the right of the profile the pan was quite distinct, relatively deep on top of compact calcareous grit parent material, and formed a definite barrier to deeper root exploration. On the central left of the profile this pan became weaker and petered out, its place being taken by a weak pan forming two to six inches above it. This changeover was co-incident with a large number of horizontal channels between the two levels. There were no vertical channels described but a few probably occurred giving access for the deeper fine roots. Two drainage stains were observed.

Root System. The trees were planted in the spoil over the step position of the ploughing, i.e. between the ridge and the next furrow. This had induced the rooting to explore the undisturbed soil beneath the tree as well as the ploughed soil. The profile showed a few fine roots making their way into the compact subsoil, but the excavated tree indicated that these had little significance. The root system was well distributed above the compact region, irrespective of the higher pan. The sandwich layer between the first furrow spoil and the original surface was freely exploited in earlier years but its importance diminished. The organic channelled zone between the two pans was well exploited.

The turned-over soil of the ridges was freely used by fine roots. The lateral roots tended to be orientated with the direction of ploughing, notably along the furrow side.

Stand Quality. The stand was well in canopy and of heatlhy vigorous appearance. No slag was applied at planting. Mean annual height increment had been fifteen-and-a-half inches.

Species Comments. (1) Vigorous exploitation of all soil above the compact region. (2) Well balanced lateral/vertical root systems.

Profile No. 32. Broxa Experiment 12.P.44. Single Deep (R.L.R.) ploughing. (Fig. 4.)

Ground Preparation. Intended to be a deep cultivation, the mean depth in this profile was only eight inches.

Soil. The undisturbed surface was the normal peat-raw humus merging in a few inches to the sandy eluvial horizon.

The pan was variable in depth and nature; at each end it divided the illuvial horizon from the compact calcareous grit subsoil, and in the centre divided the eluvial A horizon from the illuvial B horizon. Numerous horizontal channels were found in this centre illuvial horizon below the pan. A degree of weathering was noticeable below the deeper pan on the left where also a trace of vertical channel leaching was evident. These conditions were reflected in the deep root system of the excavated tree.

A moderately loose region showing signs of deposition staining occurred between from two-and-a-half to three feet depth, and a small area of very loose material was exposed at about four feet. These regions had not been exploited by the descending roots, but there was no doubt that they would be in time.

Root System. The roots confined themselves to the furrow sides and bottom and had ventured little into the undisturbed soil below the unbroken peat surface. A strong descending root seen in the excavated tree was no doubt the result of suitable conditions for rooting which happened to be beneath the planting site. The ploughing had, however, made these conditions available to the tree. The remainder of the root system reflected a reaction to the ploughing and suitable conditions in the illuvial horizons above and below the pan, especially where horizontal channels occurred. The major roots and much of the fine rooting were aligned with the direction of ploughing.

Stand Quality. The colour was healthy and growth fair, mean annual increment in eight years of twelve inches, current increment (1952) of fourteen to eighteen inches. One ounce of slag was applied to each tree at planting.

Species Comments. (1) Similar ability and nature of development as Scots pine. (2) Fine roots divided readily in suitable soil conditions but larger roots clearly maintained their identity.

APPENDIX 3

Details of Profile and Site, Teindland Forest, Morayshire October, 1952

Japanese Larch

Profile No. 1. Experiment No. 56.P.35. Turf Planting between Six-Foot Drains, Semsol Treated

Ground Preparation. The plot was originally part of a Semsol application trial on ground shallow drained at twelve-foot intervals. At the time of this investigation the drains were six feet apart and six to nine inches deep with the spoil thrown up on the sides. This effectively provided surface drainage together with a degree of cultivation.

Soil. Undisturbed peat between the drains was sparsely covered with spoil. The horizon immediately above the pan at about one foot was saturated to drain level. The lower boundary of the organic mineral soil apppeared to occur at about the mean level of the periodic perched water table. Surface vegetation was healthy *Calluna*.

Three ounces of Semsol per tree were applied two years after planting.

Root System. Away from the drains, the free rooting zone (mean depth three inches) was limited to the surface organic horizons except for the few struggling roots shown beneath the excavated tree which descended to the pan. Fibrous roots made particular use of the spoil beside the drain, the drainsides and bottom. It was impossible to determine any effect directly attributable to the Semsol application, but it is probable the trees would hardly have survived without it.

Stand. This was only a small unit of a larger experiment most of which was burnt in the 1942 fire. The plot was completely exposed on three sides, the south side was sheltered by the adjacent experiment. Stocking was very poor and, in effect, the profile was of two trees only, and did not represent a stand. The height growth was fair, the mean height of the measured trees fifteen and a half feet, the mean annual increment ten inches. The canopy of adjacent trees within the original planting distance of one another had joined.

Species Comments. (1) Japanese larch appeared to grow when the surface conditions were alleviated by drains. (2) Some descending root system developed in spite of undisturbed soil beneath the planting position.

Note.—Too much weight should not be given to this site when considering the root habits of the species or of the reaction of the root system to drainage owing to the degraded conditions of the experiment.

Scots pine

Profile No. 2. Experiment 13.P.26. Control. No Drains. Notch Planting. (Photo. 8, Fig. 6.)

Ground Preparation. Nil.

Soil. Surface peat in a saturated condition merged into the drier organic mineral horizon. A damp gleyed silty sand overlaid the pan (thirteen inches) and there was little moisture difference apparent above and below the pan. The pan descended below the depth of the trench (twenty-two inches) in the mid-left of the profile, and seemed to indicate the position of a sink. No water accumulated in the trench within twenty-four hours following the digging. Drainage of the exposed subsoil proved adequate for the continuous seepage of water from the peat surface. No fertilisers were applied. The surface had a vegetation cover of poor heather, lichens and *Sphagnum*.

Root System. This was very restricted in form, working on and in the surface peat only. No descending root system of any importance occurred; the roots developed from the original nursery root system had risen to the surface and developed just within it. One small root of the excavated tree (Photo. 8) developed from the base of the rootstock but appeared to be in a moribund state. The roots were not fibrous in nature and seldom branched. There was no true free rooting zone within the profile. The detailed characteristics of the mineral soil profile (i.e. pan depth, gley horizon, etc.) had no bearing on the development of the root system in the peat surface above.

Stands. All the trees within the plot were in a complete state of check or degeneration and would never form canopy. Mean height of the measured trees was six feet, the mean annual increment three inches. The mature development of this method of planting was illustrated on the moor beyond the experimental area where Scots pine planted about 100 years ago had not formed canopy nor produced any useful timber.

Species Comments. (1) Scots pine was unable to contend with the undisturbed undrained soil conditions of this mature peaty podzol. (2) The poor form of the root system was the direct result of the nature of the continuous peat surface which remains in a saturated, anaerobic condition for long periods of the year.

Profile No. 3. Experiment 13.P.26. Shallow Plough Drains. Notch Planting.

Ground Preparation. The plot was originally part of a drainage experiment designed for a cost analysis of mechanical and hand draining methods, followed by a long term study of the results of draining. This site was described as follows ". . . . use of a heavy plough turned out a series of regular shallow drains (at sixteen foot intervals) to a depth of ten to twelve inches . . . scoured by hand to permit water movement." Specific instructions were given to pile the spoil on the drainsides and not to scatter it between the drains. It seems doubtful if the drains were, in fact, made as deep as proposed and were probably six to eight inches deep. (Records 1927).

Soil. The profile was of the deep pan type of this area, but the mineral organic horizon was deeper than usual. The surface remained undisturbed peat except for the spoil next to the drains. Accumulation of moisture was apparent for about three to five inches above the pan. The drains within the plot operated as such only rarely. The surface vegetation was healthy *Calluna*, little suppressed by the stand.

Root System. The root system had an essentially surface character. Drainsides were freely exploited and the free rooting zone deepened close to the drain. This may have been the result of the exposure of the soil by the drain allowing additional aeration and/or supply of fresh water from the drain, or it may be due to sinkers from the healthy vigorous drainside roots. The excavated root stock exhibited a well developed, shallow lateral root system. The descending system chiefly originated from the tap root, but in addition there were a few poorly developed sinkers from the lateral roots. Few descending roots extended beyond about twelve inches below the surface, probably due to the periodic waterlogging above the pan (compact subsoil). The major part of the root system of the stand was within six feet of the drains and this was reflected in the tree heights, the smallest trees were in the centre between the drains, the tallest on the drainsides. The main effects of the drains have been to drain excess surface run-off and to alleviate the waterlogged condition of the peat immediately beside the drain. The spoil providing the roots with broken and aerated mineral soil to exploit.

Stand. The stand was poor, very uneven, and best growth was on the drainsides. Even the best trees had grown slowly, the mean annual increment of the three taller trees measured was seven inches. Canopy had not been completed nor had the vegetation been suppressed.

Species Comments. The lateral root system was predominant, the descending root system was developed only to a limited extent.

Profile No. 4. Experiment 13.P.26. Shallow Plough Drains—Hand Deepened. (Diagram 12, Photo. 9, Fig. 6.)

Ground Preparation. The prescribed treatment for this plot (Treatment 6) was as follows " . . . plough to turn out upper ten to twelve inches of the drainage system and the completion to a depth of about twenty inches, i.e. through the pan, by hand." This treatment was never carried out, in fact, and the drains are today about twelve inches deep and generally not below the pan. The drains sectioned at this site just broke the pan, which probably occurred in subsequent drain clearing which was last carried out in 1951.

Soil. The profile was normal for Teindland. Some gleying occurred just above the pan, but there appeared to be little waterlogging. Note that the spoil from the drain was piled on the drainsides and was not spread over the surface between the drains.

Root System. (Diagram 12). The root system was essentially shallow. There appeared a gradation in the depth of the larger roots from the drainside, as deep as the drain, to the right extremity of the trench where the roots were on the surface, five to six feet from the drainside. However, the free rooting zone was moderately deep on the right of the profile and was probably the result of the control and amelioration of the inter drain soil-water relationships by the stand subsequent to canopy formation. There had been a little penetration by roots of the undisturbed subsoil (below pan) beneath and to the side of the drain. There had been no penetration elsewhere. A free rooting zone beside the drain has deepened to the depth of the drain within the weathered soil profile as in the shallow drain example, and no doubt for the same reasons. The ridge of spoil alongside the drains had a marked effect on the development of the lateral roots within it, and this was borne out by the degree of orientation of the lateral roots of the excavated tree (Photo. 9). Many laterals were long and ropelike, especially away from the drainsides where they appeared on or just within the surface peat. The descending root system was very poorly developed, there was no tap root as such, and the few descending roots present were sinkers from the large lateral roots and were prevented from further descent by the pan (compact horizon). The similarity of this ground treatment to deep single furrow ploughing may be noted.

Stand. The plantation had formed canopy and suppressed surface vegetation yet it was of only moderate quality, the mean height of the measured trees was 20.3 feet, the mean annual increment had been nine and-a-half inches. There was, generally, a marked decrease in height of the trees from the drainsides to those in the centre between the drains.

Species Comments. (1) There was remarkably poor development of the descending root system. (2) The lateral roots beyond the drainside spoil were long and ropelike on the peat surface.

Profile No. 5. Experiment 23.P.28. Complete Shallow Ploughing, plus Slag. (Diagram 13, Photo. 11, Fig. 6.)

Ground Preparation. Cultivation was quite shallow at a mean depth of five inches, i.e. about four-and-a-half inches when ploughed. Heather was burnt in 1926, one year before ploughing in 1927 with a Grant's "Standfast" three-horse experimental plough.

Soil. Profile was normal for Teindland, pan varying in depth from ten inches to twenty inches, depending on whether it was above or below the illuvial horizon. No signs of excessive water accumulation were found at any point within the profile. Some small horizontal channels were noticed which may indicate that the mineral soil conditions were inherently slightly better than the normal for this area. Basic slag was applied in 1929, i.e. one year after planting, broadcast at the rate of half a ton/acre (i.e. about eight ounces per tree), which was a comparatively heavy dressing. Surface cover was needle litter.

Root System. This was well distributed throughout the ploughed soil and below it. The rootstock (Photo. 11) exhibited a very vigorous root system extending right to the pan beneath the tree, and with little evidence of layering of the fibrous roots. Undoubtedly this vigour was a reflection of the heavy manurial treatment combined with the alleviation of the surface conditions by complete shallow ploughing. The lateral roots were large at the base, tapered rapidly and branched freely, producing many large sinkers. Much of the descending root system consisted of these sinkers, but there was a central core below the tree which was not a single tap root, but a number of roots performing the same function. All roots were prevented from further descent by the pan/compact subsoil. The shallow pan at the right of the profile was only a partial deterrent to descending roots.

Stand. The stand was healthy and growing steadily and had long been in canopy, suppressing any ground vegetation which may have recolonised the area after ploughing. The mean annual height growth of the measured trees was twelve inches, the tallest tree measured twenty-seven feet.

Species Comments. (1) The growth and development of the tree and the root system in this experiment were much better than the controls. The plantation was in forest formation and capable of producing pit-props. (2) Both lateral and descending root systems developed vigorously throughout the profile above the impenetrable pan/compact subsoil.

Sitka spruce

Profile No. 6. Experiment 23.P.28. Complete Shallow Ploughing plus Slag. (Diagram 17)

Ground Preparation. The mean depth of ploughing was about five inches, i.e. about four inches from the original surface.

Soil. The profile was normal for Teindland with the exception of an accumulation of organic matter at the base of the mineral organic zone (A_1). It was thought to have been the lower limit of rooting of the previous vegetation. There appeared to be a perched water table above the pan, saturating the illuvial horizon to within seven inches of the surface. (There had been consistent heavy rains for some days before the excavation.) Note that the small plot was surrounded on two sides by open rides, and on a third by partial cover of Sitka spruce and mountain pine. The plot was slagged at the rate of half a ton per acre in 1929. Further strip applications of slag together with a light hand cultivation were made in 1935 at the rate of two ounces per five foot of strip, the strips between every alternate row of trees.

Root System. (Diagram 17). The shallow lateral root system was vigorous and confined to ploughed soil and two or three inches below it. The undisturbed waterlogged soil above the pan was avoided by any descending roots. No individual tree was excavated. There was no sign in the profile of any vertical root system extending to the pan, and, in particular, no deepening of the free rooting zone close to the base of the trees adjacent to the trench. The large lateral roots were not confined to the surface and were well distributed throughout the upper half of the free rooting zone. The vigour of the trees in root and shoot may be attributed to the heavy dressing of slag, and to the ploughing, which enabled the root system to develop in the mineral soil.

Stand. The stand was healthy and the canopy had joined. Growth rate had been only moderate in the past—the present mean height of the trees was eighteen-and-a-half feet, mean annual increment was nine inches—but the current shoot growth estimated was between twelve and eighteen inches. It was noted that the adjacent unslagged trees were in check.

Species Comments. (1) The marked response to the heavy application of slag. (2) The advantage taken by the root system of the ploughed soil. (3) The absence of roots in the undisturbed waterlogged soil above the pan.

Lodgepole Pine

Profile No. 7. Experiment 41.P.29. Mound Planting, plus Slag. (Diagram 23, Photo. 23, Fig. 6.)

Ground Preparation. Mounds were made at planting distances of three feet by five feet. The operation was apparently carefully and well done as the mounds are still quite distinct.

Soil. Generally profile is normal for Teindland. The pan and weathered profile deepened beyond the depth of the trench (two-and-one-quarter feet) in the right centre and appeared to have the function of a sink. In places the pan formation and boundary of the gleyed silty sand were independent. A few horizontal channels in the profile were evidence of past root activity. Slag was applied in 1930 at the rate of two ounces per tree.

Root System. The root system was remarkable for the extent and vigour of the descending roots. There was a good distribution of the lateral roots throughout the upper mineral-organic horizon (A_1) with no tendency for surface rooting alone. Descending roots of the excavated tree (Photo. 23) consisted of the branched tap root in addition to many sinkers and descending lateral roots with consistent root fibre throughout the depth of rooting. Further descent of the roots ceased abruptly at the pan/compact subsoil. The development of the deep roots following the dip in the pan, may indicate that the moisture there was actively percolating downwards and not, as was usual, held up for long periods. The extraordinary development (for this area) of the root system was reflected in the shoot growth and was, apparently, the result of the application of slag together with careful planting. It would appear that a healthy well nourished tree was better able to contend with the natural physical limitations of the soils and was able to exploit them to greater advantage. It should be noted, however, that the excavated tree was dominant within the stand and that the weathered profile beneath it was unusually deep.

Stand. The canopy had been joined for some time and the surface vegetation was suppressed. The mean height of the measured trees was twenty-three-and-a-half feet and the mean annual increment was thirteen inches, which may be compared with the figures for three-furrow ploughing, plus slag in the same experiment which were twenty-five and one half feet, and fourteen inches per annum respectively. (Profile 9).

Species Comments. (1) The descending and branched character of the vigorous rootstock. (2) Ability of the healthy tree of this species to deal with adverse physical conditions.

Profile No. 8. Experiment 41.P.29. Three-furrow shallow ploughing. No slag.

Ground Preparation. Three-furrow ploughing and the depth reported at the time was four to six inches.

Soil. Profile was normal for Teindland area. Some waterlogging occurred above the pan (twelve to twenty inches depth) which deepened at the left beneath a mottled pink-grey silty sand (distinct from the gleyed horizon above the shallower pan). The surface had been turned over by the ploughing or covered by the spoil—no slag had been applied.

Root System. Root system was moderately shallow; mean depth of the free rooting zone was seven and one half inches. Lateral roots were well distributed through the ploughed soil and branched freely, tapered rapidly and there was little tendency to form long ropelike roots. The descending root system was poorly developed and further descent ceased at the shallow pan level. The rootstock of the excavated tree showed no sign of a tap root. and the few descending roots originated as sinkers from the lateral roots. This would seem to indicate that the descending roots developed some time after the establishment of the tree and the development of the lateral roots.

Stand. The canopy had hardly formed and heather was still alive. The development of the stand was irregular and the individual tree growth varied considerably. Mean height of the trees measured was nineteen-and-a-half feet, ten inches was the mean annual increment.

Species Comments. Of particular interest was the lack of vigour of the descending roots which may be compared with the vigorous descending roots of the slagged examples in this experiment.

Profile No. 9. Experiment. 41.P29. Three-furrow shallow ploughing, plus slag.

Ground Preparation. Three-furrow ploughing and the depth reported at the time was four to six inches

Soil. Soil was normal for the Teindland area. Some water accumulation was apparent immediately above the deeper pan (eighteen inches). Two ounces of slag per tree were applied in 1930.

Root System. The root system was moderately deep with good distribution of the larger roots throughout the rooting depth. There was a shallow free rooting zone on the surface at the left of the trench, but there were a number of lines of roots shown below indicating active root exploration to about the pan depth. The lateral roots had developed strongly within the ploughed soil on the surface and within the organic mineral soil (A_1) beneath it. The descending roots of the excavated tree developed in part from the divided tap root and the greater part from a number of sinkers. These roots descended to the pan where they broke to produce a mat of fine roots giving the rootstock a two-storied appearance. There was, however, considerable fibre between the surface and the pan. As in the mound-planting+slag example, the vigour of the root system may be attributed to the application of slag. In this example the ploughing appeared to have had little advantage over the mound planting adjacent. There was a difference in the average stand height in favour of the ploughing and this has been reported consistently since the early days of the experiment. The effect of such a shallow cultivation would no doubt be most noticeable in the early establishment years of the stand up to canopy formation.

Stand. The stand was well in canopy and the surface vegetation suppressed giving way to a needle litter floor. Quality was even and good, mean height of the measured trees was twenty-five-and-a-half feet, mean annual increment was fourteen inches.

Species Comments. (1) A healthy vigorous tree had strongly developed descending roots. (2) A mat of fine roots formed above the pan. (3) The whole of the weathered soil profile was vigorously exploited by fibrous roots.

APPENDIX 4

Details of Profile and Site, Clashindarroch Forest, Aberdeenshire (Drumfergue), October, 1952

Japanese larch

Profile No. 1. Experiment 16.P.34. Notch Planting. (Diagram 7, Photo. 5, Fig. 7.)

Ground Preparation. Originally the experiment was designed to test notch planting methods, but there was no positive result.

Soil. The profile was normal for Drumfergue area and may be taken as a type example. It was a podzolised loam with a very pronounced organic surface horizon (thin peat when under open *Calluna*), but little colour or texture differentiation in the remainder of the weathered profile. Some tendency for an increase of the finer fraction towards the bottom of the profile may occur. The following is a detailed description of the profile:—

0-6/8 inches —Dark highly organic silty loam—porous.

6/8 inches-12/24 inches —Reddish clay silt, crumb structure, small soft fragments of slate.

12/24 inches + —Olive grey silt and broken slate parent material, compact.

There was no sign of excessive moisture or of pan formation. There did appear to be some accumulation of humus at the bottom of the organic horizon. No fertilisers were applied to the experiment.

Root System. The root profile showed that there was a marked preference for the organic top soil where the finer roots were evenly distributed. The depth of free rooting was considerably deeper beneath the planting position. Elsewhere above the compact parent material, beneath the free rooting zone, a few fine roots were found. The excavated tree showed a good balance of the lateral and descending parts of the root system and emphasised the intensely fibrous nature of the root system of this genus. Most of the descending roots were sinkers from the lateral roots and it was difficult to distinguish a true tap root. The root system responded directly to favourable soil conditions which must be suitable chemically and physically, at least to the depth of the weathered profile, for which the subsoil provided adequate drainage.

Stand. Over the whole experiment, which was last assessed in 1947, the larch had grown nearly twice as fast as the best of the other species, lodgepole pine. Comparable figures for mean height were as follows:—

1947 Assessment	
Japanese larch	13½ feet
Lodgepole pine	7 feet
Scots pine	4 feet
Sitka spruce	1½ feet

It is thought very probable that the larch stock ((32/505 Blervie) was in fact not pure Japanese larch but a hybrid strain which would account for its extraordinary vigour. The stand was thinned in 1951. The mean height of the measured trees was twenty-three feet three inches, and the mean annual increment fifteen-and-a-half inches.

Species Comments. (1) It is probable that the strain was a hybrid. (2) The dense fibrous nature of the rootstock. (3) The balance between the vertical and horizontal parts of the root system. (4) The ability of this vigorous strain to grow satisfactorily on a comparatively good heathland soil, initially in competition with heather and with no cultivation prior to planting.

Profile No. 2. Experiment 5.P.31. Complete Shallow Ploughing. (Photo. 1, Fig. 7.)

Soil. Profile was normal for the experiment. The most notable feature was the variation in depth of the compact parent material from thirty-two inches on the left to eleven inches right centre of the profile.

Root System. The root system freely exploited the weathered soil above the parent material and a few roots penetrated the top of the compact slate and silt. The lateral roots were found mostly in the ploughed soil and mineral organic surface horizon. The vertical root system was healthy and well developed to the compact zone and there was little tendency towards a storied character, fibrous rooting being evenly distributed throughout the depth of free rooting. The lateral system of the excavated tree developed large roots in the direction of the lean of the tree thus providing the necessary additional mechanical support on that side.

Stand. Snow damage was suffered in 1941, but the stand recovered remarkably well. The majority of the trees had a sweep in the butt for the first three or four feet giving them a permanent lean towards the east. The stand was healthy and growing vigorously. The mean height of the measured trees was twenty-eight feet and the mean annual increment fifteen-and-a-half inches.

Species Comments. (1) The dense fibrous rootstock. (2) The balance of the lateral and descending parts of the root system. (3) The even depth of the free rooting zone as the result of the ploughing on the surface. (4) The reaction of root and shoot to the upset in the balance of the crown.

Scots pine

Profile No. 3. Experiment 5.P.31. Complete Shallow Ploughing. (Fig. 7.)

Ground Preparation. The experimental area was burnt in March, 1930, and shallow complete ploughed in October, 1930, the depth reported at the time was six to seven inches and the furrow breadth sixteen to eighteen inches. It was reported that as the result of burning the turnover was good and the furrows lay evenly throughout the ploughing. However, it appeared that the reported ploughing depth was an over-estimate, at least in the sites investigated.

Soil. The unusual feature of this profile was the occurrence of a pocket of reddish chocolate-coloured slate rubble and silt on the left of the profile which extended from the surface to beyond the depth of the trench (two-and-a-half feet). The remainder of the profile was normal for the experiment, i.e. a mineral organic silt horizon on the surface (ploughed) above weathered

red clay silt above the compact olive grey silt and slate parent material at twelve to twenty-four inches.

Root System. The primary development of the root system was in the ploughed surface soil and the mineral organic horizon (A_1). The free rooting zone extended to the compact parent material in the normal profile, but avoided the unusual pocket of loose rubble on the left. There was no apparent cause for this diversion. The lateral roots were strongly developed in the direction of the lean of the trees as the result of the snow damage suffered in the winter of 1941. The descending roots were only moderately well developed, but in the example excavated the divided tap root appeared to have grown in such a way as to produce the maximum anchorage for the tree.

Stand. Owing to the very severe snow damage to this stand suffered in 1941 and the consequent permanent lean of the trees, special conditions altered the normal development of the individual rootstock. However, the root zones seen in the profile represented the ability of the species to explore this soil. Although malformed the trees were healthy and growth was satisfactory as the following figures indicate:—mean tree length (normally height) twenty-one-and-a-half feet; mean annual increment twelve inches. A sparse grass cover (*Deschampsia flexuosa*) mixed with the needle litter remained on the floor of the stand and its fine roots were seen throughout the profile.

Species Comments. It was interesting to note the reaction and recovery of root and shoot to the severe snow damage in 1941.

Sitka spruce

Profile No. 4. Experiment 5.P.31. Complete Shallow Ploughing. (Diagrams 16, 19, Photos. 16, 17, Fig. 7.)

Ground Preparation. See Scots pine experiment 5.P.31, Profile No. 3.

Soil. Soil profile was normal for Drumfergue and had no unusual characteristics.

Root System. The trench was located on the boundary between Sitka spruce and Scots pine plots. The Sitka spruce had obviously responded to nursing by the adjacent Scots pine and the purpose of this trench was to study that phenomenon. In the profile it was seen that the spruce roots were found mostly in the ploughed top soil and that the adjacent Scots pine extended the free rooting zone, ten to fourteen inches below the surface, beneath the Sitka spruce roots. The three excavated rootstocks showed clearly the differences of the root systems of trees of variable vigour within the same stand. Tree No. 1 (Photo. 16)—the largest—had a vigorous lateral root system, developed more strongly towards the stands of Scots pine and larch (to the left of the profile) and had a pronounced, fibrous, descending root system about the base of the tree, including a definite tap root. Tree No. 2 (Photo. 17) the smallest, had a limited root system, wiry in appearance with relatively little fibre. The lateral roots did not appear to have developed more on one side than another, and the descending root system was limited to a tap root which extended back to the surface on the side of the Scots pine and there developed to a considerable length. Tree No. 3 was intermediate between Nos. 1 and 2 in stature and root development though the root system resembled No. 3 rather than No. 1 in view of the lack of sinkers and fibre. A small scale plan of the trench and the extent of the Sitka spruce surface root system was drawn. (Diagram 19). This emphasised the extraordinary lengths to which the large, ropelike surface roots of spruce developed when exploiting the apparently favourable conditions of Scots pine or Japanese larch forest floor. This exploitation, however, was probably active only for certain periods of the year and it may be that extremes of climate, frost or drought, regularly killed off the delicate feeding roots from the primary roots thus maintaining its character. Note, however, that the extension of the surface roots away from the tree was accompanied by a sound descending root system which would appear to be essential for the satisfactory development of the tree. It seemed that there must have been a sound nucleus of descending roots for the tree to have taken advantage of the nursing effect (compared with tree No. 3) but it is rather like the argument of the chicken and the egg—whichever came first you cannot have one without the other.

Stand. The stand was uneven and showed on three sides the nursing effect of Japanese larch, Scots pine and *Pinus contorta;* the fourth side was open and faced northwest. Competition from *Calluna* appeared to be the limiting factor to the normal growth of the spruce. This was brought out by a comparison of current shoot lengths which ranged from thirty inches on large trees adjacent to the nursing species where *Calluna* had been suppressed for a number of years, to less than three inches in the centre of the plot where *Calluna* was still vigorous.

Species Comments. (1) The elimination of root competition from *Calluna* allowed Sitka spruce to flourish on this site. (2) A balanced development of the lateral and descending parts of the root system was essential to the successful growth of the species on this soil.

Profile No. 5. Experiment 13.P.33. Turf Planting—Semsol applied. (Photo. 13)

Ground Preparation. Shallow turfs eighteen inches square.

Soil. The surface had remained undisturbed except for shallow turfs taken from the cover of peat. The surface vegetation was vigorous *Calluna* and supported a soil cover of moss and decomposing litter (Photo. 13). Below this, a layer of peat two to three inches thick (A_0) formed a continuous cover over the surface and merged with a silty mineral soil mixed with raw humus (A_1). At the time of inspection there had been no rain for two days, yet the peaty horizon remained saturated with water, shown by pushing with the thumb when free water appeared about the point of pressure. At four to six inches depth the organic horizon merged with a rusty yellow clay silt (B) which had an open crumb structure and included small soft pieces of decomposing slate. Darker streaks and patches occurred in this horizon and appeared to be the result of accumulations of dead *Calluna* roots. A pocket of fragmentary charcoal mixed with soft clay silt over a band of bleached soil (hearth) was discovered at one point in this horizon. The charcoal was identified by Mr. Anthony of the Royal Botanic Garden, Edinburgh, as *Quercus* species. The presence of a bleached hearth beneath indicated that it was still *in situ*. The general depth below the surface, the fragmentary nature of the charcoal (much had decomposed to a black paste) and the initimate mixture with the soil material all pointed to a great age. There is no natural oak to be found in the forest today. Muir and Fraser (1939/40) in *The Soils and Vegetation of the Bin and Clashindarroch Forests*, reported: "In the Statistical Account for Scotland (1845) the hills around Gartly are said by tradition to have been covered by oak," and concluded a note on the former extent of the woodland with: "it may be assumed that, with the exceptions noted above (persistence of birch, alder, willow and Scots pine in a few sheltered places) the present vegetation represents the climax cover under which the soils of these areas have existed for a period of two centuries or more."

Root System. All the roots in the profile occurred within the decaying heather litter on top of the peat or just within the peat, and were long, thin and ropelike. The spruce roots were exposed by pulling the heather and brushing away the loose litter by hand; scratching of the peat was necessary only adjacent to the turf which may be clearly seen beneath the number in the photograph. Most of the roots of tree No. 2 emerged from beneath the turf (the sandwich), but a few worked within it. The root system of excavated tree No. 1 on the left of the profile was confined to the surface and a few adventitious roots had arisen within the turf. The tree was in a permanent state of check. Tree No. 2 had a comparatively well developed descending root system extending to the compact parent material at about sixteen inches. This tree was not in complete check and had an annual shoot growth of four to six inches. These descending roots did not look healthy, they were wiry in appearance and lacked fibre (compare with Sitka spruce tree No. 1, profile No. 4).

Stand. The trees were growing very slowly, many were in complete check and the remainder had annual shots varying from two to six inches.

Species Comments. (1) The surface habit of the lateral roots above the undisturbed peat cover. (2) Absent or restricted descending root system. (3) The *Calluna* continues to occupy the site unchecked.

Lodgepole Pine

Profile No. 6. Experiment 5.P.31. Complete Shallow Ploughing. (Fig. 7.)

Ground Preparation. Shallow complete ploughing, depth reported at the time was six to eight inches.

Soil. Normal for the area. The surface organic loam had been disturbed to a depth of about six inches, and was very porous in nature. This overlaid a mid-brown silty loam with marked crumb structure containing many soft slate fragments, bounded below by a sharp line marked by a thin mat of dead *Calluna* roots, which included some living fine exploring pine roots. Below this was the parent material of compact olive-yellow slate and silt. The slate pieces in the parent material were both large (six to eight inches diameter) and small (one-quarter inch diameter and less).

Root System. The root system was well developed throughout the weathered soil horizon. The free rooting zone was bounded below by the horizon of the parent material. The lateral roots were especially well developed to the direction of the lean of the trees, producing roots thick and asymmetrical (greater vertical axis) near the butt. The lateral roots were found mostly within the organic top soil, but were by no means confined to the surface. Generally these roots divided freely and tapered rapidly. The excavated rootstock provided some exceptions to this generalisation. The descending roots of this tree were limited to a few roots beneath the butt and one or two sinkers. The relatively few large lateral roots occurred some inches below the surface, and most of the feeding root system must have been well beyond the excavated root stock.

Stand. Much snow damage occurred in 1941 which resulted in a stand of malformed trees, all with sweeps in the butt. However, current shoot growth was satisfactory and the mean height of the measured trees was twenty-four feet, mean annual increment thirteen-and-a-half inches. The stand was thinned in 1951.

Species Comments. (1) The even distribution of the root system throughout the profile. (2) The root stock showed a normal lack of fibre for this species, and the free rooting zone did not contain the profusion of fine roots as, for instance, were found for Japanese larch.

APPENDIX 5

Details of Profile and Site, Dornoch Forest, Sutherland October, 1952

Japanese larch
(Sitka spruce in mixture)

Profile No. 1. Experiment 1.P.36. Deep Drains. Spoil Spread. (Fig. 8.)

Ground Preparation. Drains were dug two to two-and-a-half feet deep at sixteen-foot intervals, and the resulting spoil was spread over the surface of the plot between the drains to an average depth of twelve inches. The trees were planted into the spoil.

Soil. The profile *in situ* beneath the spoil was moderately compact sand with an organic surface horizon and some accumulation of clay in the lower horizon. All horizons included stones which varied in size from large boulders to pebbles. The stoniness increased with depth.

The most significant factor was the loose drain spoil covering the original surface. This was a loose mixture of all the soil horizons including the pan, which was below the depth of the trench, but within the depth of the drains surrounding the plot. The nature of the original surface peat beneath the spoil had changed. It was no longer a pure peat, but had mixed with the mineral soil, was not saturated with water and had become porous in nature. At no point within the exposed profile did the soil moisture status approach saturation. No fertilisers had been applied to the experiment.

Root System. The spoil was exploited freely and vigorously and offered no resistance to the natural development of the root system. The original undisturbed organic horizon encouraged free fibrous rooting. The character of this material had significantly altered as described above. The undisturbed mineral horizon was moderately compact but was explored by descending roots.

The lateral roots of the excavated tree were well developed and worked in the spoil throughout its depth. The descending part of the root system was equally vigorous. It appeared to break at the level of the original surface, descending into the undisturbed soil below by many smaller roots. It may be that the original peat maintained a tendency to absorb and hold moisture to the point of saturation for a number of years after draining and planting. This would temporarily limit the further descent of early primary descending roots. As the stand developed in root and shoot, the moisture status and drainage within the spoil was controlled. The spoil-surface interface became less distinct due to natural causes of duff decomposition and vertical moisture and soil particle movement, i.e. the spoil and peat surface married and the way was open for free root exploitation of undisturbed horizons below without any marked limitation by the peat.

The lateral roots which originiated from the Sitka spruce, located two to three feet behind the profile, worked near the surface of the spoil, but no doubt the root system as a whole exploited the full depth of spoil.

Stand. The small stand within the plot was well in canopy and had grown satisfactorily and may be compared with the failure of this species in the adjacent controls. Although this plot was completely exposed on the north-east and south-west sides there had been no windblow. Mean height of the trees measured was nineteen feet and the mean annual increment fourteen inches. *Calluna* had been suppressed beneath the stand. The development of the Sitka spruce was variable, some individuals were well within the canopy of the Japanese larch and growing vigorously, others were below it and suppressed—but not checked.

Species Comments. (1) Free exploitation of the soil by the fibrous root system. (2) A satisfactory balance was obtained of the lateral and descending parts of the root system, which were not distinct in boundaries.

Profile No. 2. Experiment 1.P.36. Ordinary Forest Drains, Turf Planting.

Ground Preparation. Described in the working plan of the experiment as "ordinary forest drains (six to nine inches deep) at sixteen foot intervals." The trees were turf planted, presumably in shallow turfs. At the present time these drains are only three inches deep, having either filled in with debris, or, as suspected, were not made as deep as proposed in the working plan. The evidence in the field suggested that they had been inoperative as drains for many years. The treatment left the surface peat undisturbed and uncovered and the *Calluna* vegetation unchecked. Some free water had been drained from the surface, but there had been little drainage of the peat itself.

Root System. No profile was dug in this instance; two root stocks of the few surviving trees in the plot were directly excavated. The height of one tree was about seven feet, that of the other about twenty inches. Both were in typically checked condition and showed no promise of improvement or development of root or shoot. The lateral roots were long and ropelike, lacking in fibre and confined to the surface. The descending roots failed to develop and appeared moribund.

Stand. The Sitka spruce failed completely and no specimens remained alive. Only a few specimens of Japanese larch survived varying in height from fifteen inches to eight feet, but even the best of them were poor.

Species Comments. Japanese larch was unable to develop a healthy root system in this undisturbed poor heathland soil. This example may be compared with the growth of Japanese (hybrid?) larch notch planted at Drumfergue, Clashindarroch Forest (Profile No. 1).

Lodgepole pine
(*Pinus contorta* var. *latifolia*)

Profile No. 3. Experiment 1.P.36. Control—No Drains —Notch Planting. (Fig. 8.)

Ground Preparation. None. Trees were directly notch-planted into the untouched peat surface.

Soil. Dornoch podzol. There had been no alleviation of the natural soil conditions by drains or other disturbance of the surface peat. The pan was relatively shallow (eleven inches) for this soil. The surface peat was saturated and moisture accumulated in places above the pan. Water accumulated in the trench overnight, during which there was no rain, as the result of seepage from the peat and to a lesser extent from above the pan. Drainage by the exposed compact subsoil below the pan was slow.

Root System. The excavated tree was the best of a few remaining survivors on this plot. The profile indicated that the root system was entirely superficial and that the roots were on the peat surface. This was borne out by the root stock of the excavated tree. The descending roots were limited to the organic horizon immediately below the tree, and the only roots which had developed from these had found their way to the surface away from the tree.

Stand. Only a few surviving trees remained and these were growing slowly. The height of the excavated tree was nine feet.

Species Comments. Lodgepole pine was not able to contend successfully with the undisturbed saturated thin heathland peat. Survival was better than other species tested, Scots pine, Japanese larch, and Oregon alder, all of which failed on the controls.

Profile No. 4. Experiment 1.P.36. Shallow plough drains, eight inches apart. (Fig. 8.)

Ground Preparation. Drains were hand-turfed along the contour to imitate shallow plough furrows not wider than ten inches and not deeper than six inches at eight foot spacings. The depth of the drains was seldom more than four inches.

Soil. Dornoch podzol. One to two inches of thin saturated peat on the surface; followed by four to ten inches of dark organic soil changing to a fawn sand merging to a clay sand just above the pan at about eighteen inches depth. Dead heather roots formed dark streaks in the profile and a thin mat of organic matter above the pan. A pocket of accumulated raw humus formed in a depression of the pan and was saturated with water. Water to a depth of one-and-a-half inches accumulated in the trench overnight, during which there was no rain, draining from the surface organic horizon beside and below the drain and from the organic pocket above the pan. The parent material beneath the pan was compact pale fawn (biscuit) coloured fine sand and stone with a limited capacity for drainage.

Root System. The profile indicated that the stand root system was confined primarily to the ridge and furrow, was shallow and a few fine roots extended below the free rooting zone, but not as far as the pan. The excavated tree and the plan emphasised the use made of ridge and furrow by the lateral roots. The descending root system of the excavated tree was well developed and was a pronounced carrotlike taproot ending in a brush of fine roots at a depth of thirteen inches. Only a few fine roots reached the pan. There were no sinkers originating from the lateral roots. The lateral roots extended within the surface beyond the drain and drainside, and the roots within the undisturbed ground were ropelike in character.

The development of the root system, and consequently the stand, compared to the controls, was fair and may be attributed to the following factors: 1. A partial break was created in the continuous surface peat permitting some degree of aeration and vertical percolation of fresh water from the surface in the region of the drains. 2. An excess surface run-off was rapidly drained in periods of heavy or continuous precipitation, reducing the period of extreme water saturation within the surface peat. 3. A small ridge of well-drained material was provided for root exploration.

Stand. The individual tree crowns were touching and canopy was forming. The live canopy had risen three or four feet. Heather was still living on the surface, but suppressed. The height growth was moderate; mean height of the measured trees was thirteen feet and the mean annual increment ten inches.

Species Comments. Lodgepole pine survived and continued to grow in the conditions of this treatment where other species tested in the experiment failed or checked.

Profile No. 5. Experiment 1.P.36.(c) Deep Drains—Spoil Spread. (Diagram 27, Photo. 25, Fig. 8.)

Ground Preparation. See Japanese larch, Dornoch 1, P.36, deep drains. Profile 1.

Soil. Dornoch podzol. The most important feature of the exposed soil profile was the nine to twelve inches of loose spoil above the original surface. The character of the original peat beneath the spoil had been modified to a porous mixture of organic matter and mineral soil, and showed no signs of waterlogging. Beneath this was a typical organic sandy zone followed by the illuvial mottled silty sand and stones above the pan which was twelve to fourteen inches below the original surface. At the right centre of the profile the pan dipped suddenly below the depth of the trench (eighteen inches below original surface), but the horizontal line of the pan was carried on at about the same level by a dark line of dead *Calluna* roots above a very compact weathered soil horizon. Ground vegetation had been suppressed and given way to a needle litter.

Root System. Free rooting zone originating from the lateral and vertical parts of the root system had a mean depth of eighteen-and-a-half inches and had extended the full depth of the profile to the pan/compact subsoil. There was a tendency for the larger lateral roots to be concentrated in the top four or five inches of spoil and in the organic soil of the original surface, a point confirmed by the root stock of the excavated tree (Diagram 27, Photo. 25). The remainder of the soil was used freely by fibrous roots. The descending roots of the excavated tree consisted of a strongly developed tap root which had numerous secondary side roots throughout the depth of the profile. Generally the root system showed no sign of inhibition above the pan/compact horizon. It took advantage of the moderated conditions of moisture and aeration provided by the mulch effect of the spoil above and, to an indeterminate degree, the drains at the side. A noteworthy point was the ability of a healthy vigorous root system to exploit the undisturbed original soil profile in which the moisture status had been controlled by the spoil cover and the development of the stand root system.

Stand. Stand was healthy and had been in canopy for many years. The mean height of the measured trees was eighteen-and-a-half feet and the mean annual increment fourteen inches. Sitka spruce in mixture had not checked; one specimen, height twenty-one-and-a-half feet had kept its crown within the canopy and appeared to be going ahead of the pine. The other example measured, twelve feet high, was suppressed.

Species Comments. When suitable physical conditions for growth were provided the nutritional level of these soils did not limit the successful growth of the pine. The root system did not confine itself to the very favourable spoil on the surface and developed pronounced descending roots into the undisturbed soil horizons below.

Profile No. 6. Conservancy P.32 (near Experiment 1.P.36.) No Treatment. (Diagram 25, Photo. 24, Fig. 8.)

Ground Preparation. None. The site was located in the Conservancy plantation beside the experiment and beyond the influence of drains.

Soil. Dornoch podzol. Surface vegetation consisted of poor *Calluna* and lichens. The following is a detailed description of the profile:—

0-1 inches	—Litter and decaying organic matter ("duff")
1 inch-3½ inches	—Peat
3½ inches-5½ inches	—Pinkish grey bleached sand.
5/8½ inches-8½/20½ inches	—Gley clay sand with included soft orange stones.
¼/½ inch thick	—Continuous iron pan with iron staining extending below for an inch or two.
9/21 inches plus	—Salmon pink sand and stones extremely compact.

The peat was in a saturated condition and water accumulated above folds in the pan. The gleyed nature of the illuvial horizon above the pan indicated lack of aeration and semi-permanent waterlogging of the horizon. The compact parent material beneath the pan was barely damp.

Root System. The few roots observed in the profile occurred in the surface litter above the peat and were ropelike and lacked fibre. The two excavated root stocks, tree No. 1, height seven feet, (Photo. 24), and tree No. 2, height two-and-a-half feet were both typically restricted in form with almost a complete lack of descending roots. Tree No. 2 had three small descending roots which had no apparent effect on the development of the tree. The remainder of the roots of both trees were confined to the peat and litter above it.

Stand. Growth had been very slow since planting, 1932, and many had failed. The surivors were in virtual check, the best measured trees had grown only seven feet.

Species Comments. Lodgepole pine was not able to contend with the natural conditions found in this heathland due to the semi-permanent condition of saturation of the surface peat which prevented healthy root development in the mineral soil beneath.

Profile No. 7. Conservancy P.32. Shallow Drains. (Fig. 8.)

Ground Preparation. Shallow drains were dug six to nine inches deep at twenty-one foot intervals and the spoil spread between the drains. The spread was not sufficient to determine a spoil depth at the time of this investigation. but some of the surface boulders and stones obviously came from the drains.

Soil. The profile of this site differs from the previously described sites (Dornoch podzol) in two primary respects: (1) The number and size of large unweathered water-worn boulders throughout the weathered profile and (2) The absence of a definite iron pan.

The following is a profile description of this podzolised soil:

0-6/11 inches	—light textured porous organic sand full of dead *Calluna* roots.
6/11 inches-20/24 inches	—compact rusty-brown silty sand.
20/24 inches plus	—very compact light yellow brown sand and stone.

There was no sign of gleying or of serious impedance in the vertical drainage and no horizons were waterlogged. Horizon boundaries were variable and indistinct. The drains had not operated as such for some time.

Root System. The mean depth of the free rooting zone was seven-and-a-half inches over the full length of the profile with the majority of the larger roots throughout the upper half of the zone. Fine roots extended beyond the free rooting zone into the compact illuvial horizon below to a maximum depth of eleven-and-a-half inches. There was evidence to suggest that roots descended more readily down the edges of the large boulders. The excavated root stock illustrated a strongly developed descending part of the root system breaking into a mass of fibrous roots above the compact horizon giving a two-storied appearance. It provided a firm anchorage to the tree and an extensive feeding system below the surface. Most descending roots originated close to the base of the tree as sinkers from the lateral roots. The lateral part of the root system was well developed and maintained a balance with the vertical part. The decomposing needle litter on the surface was found to be a mass of fine red feeding rootlets, now dead, and fungal mycelia. It would appear that the main effect of the drains had been to carry away excessive surface run-off in the early years of the establishment. The stand in canopy had gained control over the moisture status of the site. Some advantage was probably taken of the spreading of the drain spoil.

Stand. Canopy had been joined for some years. Mean height of the measured trees was twenty-three feet and the mean annual increment was fourteen inches.

Species Comments. Lodgepole pine demonstrated its ability to flourish in this heathland if conditions for establishment were made suitable by alleviation of the surface from periods of excessive moisture.

Profile No. 8. Conservancy P.32. Deep Drains—No spoil spread—Notch planting. (Diagram 26, Photo. 26, Fig. 8.)

Ground Preparation. The site of the profile was adjacent to a Conservancy deep drainage trial between two drains eighteen to twenty-four inches deep and about nineteen feet apart. The drain to the left of the profile formed the edge of the Conservancy trial in which the spoil was spread over the trial area. The drain to the right of the profile appeared to be older in origin, and the spoil was heaped in a ridge on the drainside. Thus the drainage effect was as great as that within the trial but there had been no mulching effect from any spread of the spoil.

Soil. Dornoch podzol. Surface was covered with one to two inches of saturated peat under which were a sandy eluvial horizon and a silty sandy illuvial horizon, both dark grey in colour to the pan at about thirteen inches. The pan was hard and impervious above the compact light yellow sandy subsoil. There was no excessive moisture below the peat. The profile was stony throughout its depth, with many large water-worn stones. The surface vegetation was a cover of healthy *Calluna*.

Root System. The profile showed that the lateral roots were confined to the peat surface (Diagram 26). This is borne out by the root stock of the excavated tree (Photo. 26) which exhibited no descending roots and the lateral roots were superficial, lacking in fibre and tended to be long and ropelike.

Stand. The stand was somewhat open due to initial failures and the trees remaining were relatively poor. The crowns were thin, touching each other in places, but had not yet formed a canopy. Mean height of the measured trees was seventeen feet and the mean annual increment ten inches. There had been little suppression of the surface heather.

Species Comments. The waterlogged conditions of the surface peat had undoubtedly been alleviated to some degree by the drains, but lodgepole pine was still unable to overcome the anaerobic conditions existing below the peat. The drains could not directly have drained the mineral soil at the trench site, particularly in the region of the pan, but would have helped indirectly by surface drainage as mentioned above. Neither the form of the root system nor the growth rate of trees were satisfactory. It was noticed that individual trees had suffered from windblow.

Profile No. 9. Conservancy P.32. Deep Drained after Planting—Spoil Spread. (Fig. 8.)

Ground Preparation. The trees were planted in 1932, probably by the simple notch method, and in the same year shallow drains were dug at twenty-one foot spacing. In 1935 the drains were deepened to about two feet and the spoil spread over the surface between the drains. No fertilisers were applied at any stage.

Soil. Dornoch podzol. The layer of spoil (five to seven inches deep) above the original peat surface was a loose mixture of all horizons, including the parent material below the pan. Beneath this, the nature of the peat had changed from the normal saturated condition and was porous, damp, and mixed to some extent with the mineral soil above. This was followed by the normal grey humus-sand mixture and the illuvial horizon above the pan which sharply defined the very compact light-coloured sand and stone parent material below. The pan depth ranged from nine-and-a-half inches to fourteen-and-a-half inches below the original surface and was moderately convoluted and well developed. The profile as a whole was damp but there were no signs of excessive moisture accumulation either in the original peat or above the pan.

Root System. The profile showed that the free rooting zone was confined to the spoil, the old peat surface, and a few inches of the dark grey eluvial horizon, and that the larger roots occurred in the spoil or in and on the original peat surface. Fine roots were sparsely scattered throughout the moderately compact, illuvial, silty sand above the pan, which prevented further penetration by the roots.

The form of the root stock of the excavated tree may be correlated with the stand root system described above, and compared with the root stock of the pine planted directly into the spoil in the equivalent experimental treatment (Profile No. 5). The form of the root stock was similar to that found in the controls, very shallow drains, and deep drains with no spoil spread, but was greater in bulk, i.e. the size of the individual roots was greater. The descending system was restricted to one sinker which, though restricted in form, bore healthy tertiary roots. The lateral system was shallow within the original profile (peat) and the largest of the roots extended from the side of the root stock nearest the drain. It would appear that the pattern of the root stock was set in the first three years growth prior to deep draining and spoil spread, during which time the extending roots grew in the superficial manner typical of the growth in the uncultivated health. It probably took some years for the spoil to alter appreciably the character of the peat surface, as was suggested also in the example of the Japanese larch on deep drains in experiment 1 (Profile No. 1). The established root extremities took advantage of the suitable conditions for growth prevailing in the spoil and freely developed in that medium, but were by this time well away from the bases of the trees. Later the peat was modified by the spoil above and fresh roots exploited the lower horizons *in situ*. No adventitious roots formed from the soil collar about the base of the tree. This meant that most of the large supporting roots were to be found on the original peat and in the spoil. Thus, the early character of the root stock was maintained. Roots from the drainside trees freely exploited the few inches of soil from the drainsides and bottom, which provided suitable conditions of drainage and aeration.

Stand. The stand was well in canopy and all surface vegetation had been suppressed giving way to a needle litter floor. The mean height of the measured trees was twenty-two feet two inches and the mean girth eleven-and-a-half inches. The mean annual height growth from 1932 was thirteen-and-a-half inches which was very satisfactory considering the relatively poor start given the trees. This increment was the same as that for lodgepole pine deep drains in Profile 5, which, in view of the remarks above, one may have expected to have had the greater increment. The experiment block, however, was very small, was located at a higher elevation near the crown of the ridge and was exposed to the elements on three sides.

Species Comments. (1) The early restriction of the root system was followed by extension when more suitable conditions prevailed in the rooting medium. (2) No adventitious roots arose from the soil collar. (3) The principle effect of the ground treatment on the root system of the stand has been a mulching or cultivation of the surface. Apart from initial surface drainage, the deep drains have not functioned as such for many years.

Shore pine
(*Pinus contorta*)

Profile No. 10. Conservancy P.32. Shallow Drains

Discussion. A full investigation was not made on this site. A trench was dug and two root stocks excavated. The heights and girths of the trees surrounding the trench were measured. The site of the trench was in a narrow block of shore pine located on the ridge top north of the experiment. The area was shallow drained soon after planting. The soil was a normal Dornoch podzol. The drains had not functioned as such for many years and there were no signs of water saturation in the profile.

Of the two excavated trees, one was dominant in the canopy with a height of twenty-five feet, girth breast-height over-bark fifteen-and-a-half inches, the other co-dominant with a height of twenty-and-a-half feet, girth breast-height over-bark nine inches. In both, the lateral systems were strongly developed though somewhat asymmetrical about the base owing to early lean caused by the exposed situation. The descending systems were composed of sinkers which arose from the lateral roots close to the base of the tree and branched profusely, terminating in a horizon of fine roots at a depth of about fifteen inches. The co-dominant tree had only a small number of such roots which did not form a great part of the root stock. In contrast, the root stock of the dominant tree supported a mass of descending roots and correspondingly larger lateral roots. Generally the root systems of this strain of *Pinus contorta*, in comparison with the inland lodgepole pine strain, reflected the comparative vigour and coarseness of the features of the shoot.

The mean height of the measured trees of the shore pine, twenty-four feet was nearly the same as that for lodgepole pine on the shallow drains (Profile No. 7) twenty-four feet, two-and-a-half inches, but the mean girth, fourteen inches, is noticeably greater than the eleven-and-a-half inches for the latter example. In view of the undoubtedly greater exposure and probably poorer soil of the site of the shore pine it may be said that this strain grows more vigorously at Dornoch.

APPENDIX 6

Abbreviations used in Tables, Profile Descriptions and Histograms

Tables

Profile No. Reference number for profiles examined; one series of Profile Numbers is used for each forest concerned.

Expt. No. Reference number in Forestry Commission Research Branch records for the Experiment in which the profile was prepared. A separate set of Experiment Numbers is used for each Forest.

P. Year. The Forest Year in which the plantation examined was planted; e.g. P.28—Forest Year, 1928, the year ending on 30th September, 1928.

Origin. Reference numbers are the Identity Numbers of seed lots used for raising planting stock.

Planting Stock. This column gives the age of plants used, abbreviated in the standard fashion. Thus 1+1 signifies a one-year, one-year transplant; and 2+0 stands for a two-year-old seedling.

Species Names. S.P.—Scots pine
C.P.—Corsican pine
J.L.—Japanese larch
N.S.—Norway spruce
S.S.—Sitka spruce

G.B.H.—Girth at breast height.
M.A.I.—Mean annual height increment.

Histograms (Figs. 2-8)

The purport of each upward or downward column is shown by the descriptions written vertically on each Figure—owing to limitations of space these descriptions are not always set against the first group of columns.

Note.—The description "Percentage rooting below pan" indicates the percentage of earth below the pan expressed on the area of the vertical face of the profile and down to the depth examined, which was found to hold tree roots. See Chap. 2, V.

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