Some aspects of Peat as a Substrate for Tree Growth

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Introduction.

EXPERIMENTAL work on the afforestation of peat in Britain, up to about 1952, showed that phosphatic fertilization and some form of ground preparation was essential or beneficial to most species on all but *Molinia caerulea* peats, though pines might grow without P on some *Calluna vulgaris* peats (Zehetmayr, 1954). Little response to other nutrients was recorded, probably because the trees were all very young and there were adequate supplies in the peat at that stage. As a result, foresters have tended to assume that nutrients other than P would be deficient only in exceptional cases, provided that the severe check that spruces often suffer on *Calluna* ground (presumed to be due largely to competition for nitrogen) is excluded. More recent work has shown that, in addition to deficiency of N and P, potassium deficiency has now been found in peat-grown trees in Britain (Wright, 1959).

On the other hand in agriculture, calcium, manganese, copper, boron, and molybdenum, in addition to N, P, and K, may be necessary for the establishment and growth of crops on deep blanket bog, although the nutrients which are deficient will vary from case to case. It would, therefore, be reasonable to anticipate that, as early plantations come into the pole stage and more difficult types of peat are ploughed and planted, deficiencies of other nutrients might be detected in trees.

In its most infertile form peat is little more than a rooting medium for trees, and it would seem wise to delimit, as soon as possible, those nutrients which will eventually have to be added to maintain satisfactory growth. The problem is thus to decide on a suitable way of investigating the potential fertility of peat for all the essential nutrients; this paper describes one approach and the work from which it has developed.

Investigations at Inchnacardoch Forest.

An investigation by Illingworth-Longbottom (1954), at Inchnacardoch Forest, suggested that basic slag applied to peat could still be detected 23 years afterwards where trees had failed, but not where they had grown well; he also observed that the acetic soluble P content of the peat was highest in the surface layers.

This work was followed up at the Lon Mor experimental area in Inchnacardoch Forest (cf Macdonald, 1945), where the changes in peat due to tree growth were examined in two experiments, 19 P.26 and 47 P.28, growing Scots pine (*Pinus silvestris* L.) and lodgepole pine (*Pinus contorta* Loudon) respectively, which had both been partially treated with basic slag or ground mineral phosphate (G.M.P.). Some figures for tree growth in these two experiments (Edwards, 1962) suggest that increment has fallen off appreciably in the last few years. The investigations on the peat showed that a number of physical and chemical changes had taken place (Binns, 1959). As regards chemical changes, total potassium and inorganic phosphorus contents in the upper layers of the peat were lower under lodgepole pine than in unplanted ground, while organic phosphorus, total nitrogen, calcium and magnesium contents were not significantly different; a similar, though less marked, relationship was found under Scots pine. These results suggest that the P readily available to trees is largely in inorganic form and, in view of decreasing increment, are suggestive of incipient if not actual P and K deficiency: the results of a PK trial on the lodgepole pine show however that only K was limiting growth at that stage (Binns, 1961).

It would, therefore, seem that, as removal of nutrients by the trees over a period of 30 years can be detected by relatively simple analytical techniques, the chemical composition of peat in other areas may be used to estimate site fertility for trees; the usefulness of this approach can then be judged by comparison with tree growth and responses to fertilizers.

Experimental.

Deep Peat Sites Selected for Sampling.

In addition to the Lon Mor, eleven sites from Cumberland to Caithness (Fig. 1) have been selected, and the top foot of the peat sampled in two-inch layers; samples of the natural vegetation have also been taken, except at Mounces. Sampling has been in rides and outside experiments or, in some cases, within young experiments. Details of the sites are given in Table I.

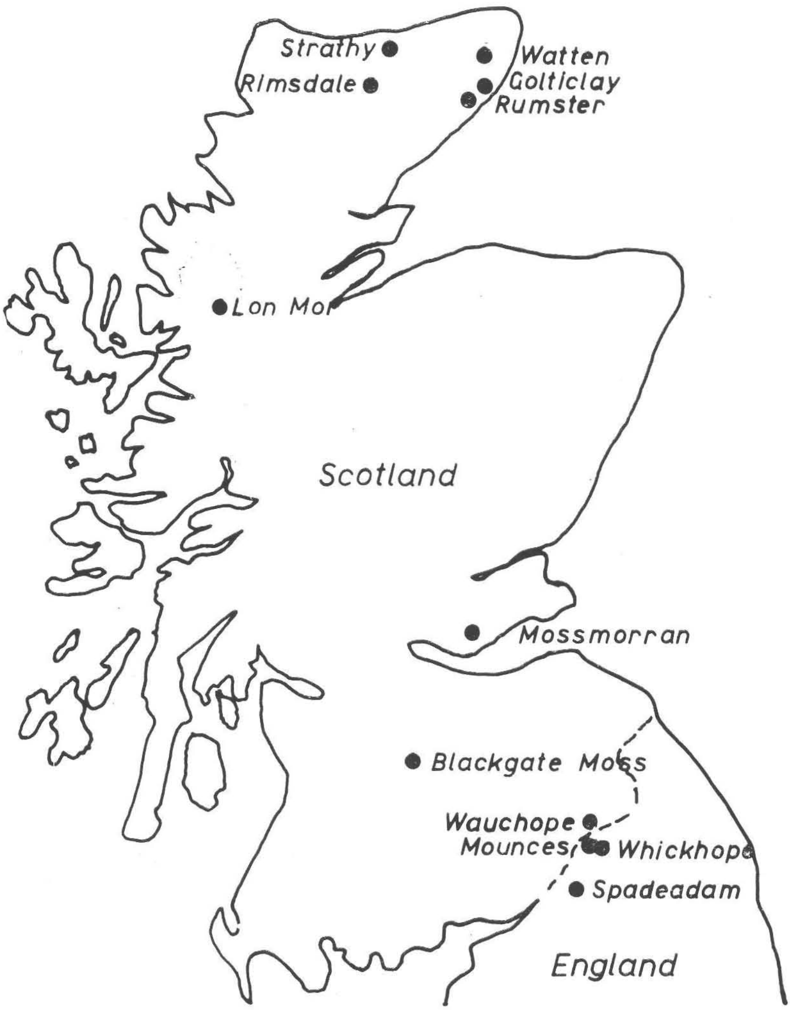

Fig. 1. Location of sites sampled.

TABLE I
Details of sites sampled

Site	Forest and use*	Type and depth of peat	Approx. area covered, acres	No. of profiles	Main plant species (excluding liverworts, and mosses other than *Sphagnum*)
Spadeadam, Cumberland.	Spadeadam, Experiments 1 and 2 P.56.	Raised bog, over 6 feet deep.	8	8	1. *Eriophorum vaginatum/Calluna*, some *Eriophorum angustifolium, Molinia* and *Sphagnum*. Now going to *Deschampsia flexuosa*. 2. *Trichophorum caespitosum/Calluna/Eriophorum/Sphagnum*, some *Erica tetralix* and *Narthecium ossifragum*. Now going to *Calluna*.
Whickhope, Northumberland	Kielder Forest, Compartments 158-160.	Flushed blanket bog, about 4 feet deep.	25	6	Pure *Molinia*.
Mounces, Northumberland	Kielder Forest, Experiment 73 P.54.	Blanket bog, 3½ to 5 feet deep.	1	4	*Calluna/Eriophorum, Trichophorum* and *Sphagnum* frequent.
Wauchope, Roxburghshire	Experiments 4 P.53, 5 P.55, 6 P.55.	Raised bog over 6 feet deep (4 P.53), or 3½ to 5 feet deep.	20	7	*Calluna/Trichophorum/Eriophorum*, some *Molinia* and *Erica*. *Deschampsia* in Expts. 5 and 6.
Blackgate Moss, Lanarkshire	Couthally Sect. Clydesdale Forest, Cpts. 1-10.	Raised bog, over 6 feet deep.	200	11	*Calluna/Eriophorum* with some *Juncus conglomeratus* and *Sphagnum*.
Mossmorran, Fifeshire	Blairadam Forest, Cullaloe No. 2, Cpts. 66-69.	Raised bog, over 6 feet deep.	150	9	*Calluna*, with *Eriophorum* and *Erica*.
Lon Mor, Inverness-shire	Inchnacardoch Forest, Experiments 19 P.26 and 47 P.28.	Basin and blanket bog, 1½ to 4 feet deep.	2	16	*Calluna/Molinia/Erica*; frequent *Sphagnum*, some *Eriophorum, Narthecium* and *Myrica gale*.
Rumster, Caithness	Rumster Forest, Cpts. 4 and 5.	Flushed blanket or basin bog, over 6 feet deep.	20	6	*Calluna* with *Molinia, Sphagnum* and some *Deschampsia* and *Erica*.
Golticlay, Caithness	Rumster Forest, proposed acquisition.	Blanket bog, mostly over 6 feet deep.	over 1000†	10	*Calluna/Eriophorum/Trichophurum/Sphagnum* with *Eriophorum angustifolium, Narthecium, Erica*.
Watten, Caithness	D.O.A.S. farm block, with Forestry Commission Experiments.	Blanket bog, over 6 feet deep.	60†	6	*Calluna* with *Trichophurum, Sphagnum, Molinia* and some *Erica*.
Rimsdale, Sutherland	Pilot plot in Naver Forest.	Blanket bog, 2 to 6 feet deep.	60	9	*Calluna*, with *Trichophorum, Molinia, Sphagnum, Eriophorum*, and about 10 other species.
Strathy, Sutherland	Strathy Forest, experimental. sections I and II.	Blanket bog, 1½ to 4 feet deep.	20	6	I. *Calluna/Trichophorum/Molinia* with *Erica tetralix* and *E. cinerea*. II. *Calluna/Molinia*, with *Erica tetralix, E. cinerea. Sphagnum*.

*All ground belongs to the Forestry Commission except Watten. †Part of the area on shallow peat has been omitted.

Of the six southern sites, four are very deep raised bogs, one, Mounces, is deep blanket bog, and one, Whickhope, a flushed *Molinia* peat. Of the six northern sites, two, Golticlay and Watten, are very deep blanket bog, three are deep blanket bog, and one, Rumster, is blanket or basin bog that has been extensively flushed. The terms "deep" and "very deep" are used here to differentiate between those sites where tree roots may reach the mineral soil in places, and those where they will probably never do so. At the time of acquisition all the sites except Whickhope and Mounces were considered poor, and either have been or will be given phosphate at time of planting; Sitka spruce [*Picea sitchensis* (Bong.) Carr.] would probably not now be planted pure on any of these ten sites, and its use in mixture with lodgepole pine is becoming less frequent. The sampling intensity varied in proportion to the area, being highest at the Lon Mor and lowest at Golticlay, and no attempt was made to get a constant intensity.

Although subjective estimates of the plant frequencies have been made at all sites except Mounces and Whickhope, the flora had apparently been altered by ploughing and application of phosphatic fertilizer in some cases, and by frequent burning and grazing in others, and it is therefore difficult to use the plant communities as indicators of site conditions. With draining, *Calluna* generally increases, and this has probably happened at most of the sites, except Golticlay, which is not yet drained or planted.

Analytical Methods.

(a) Peat Samples. All samples were oven-dried at 80° C., and, except for those from the Lon Mor (which were broken up and spread out to dry), were left during drying in the tins in which they were taken; this has probably resulted in loss of N. After drying and the determination of moisture content and dry weight per unit volume of wet peat, the samples were broken up and milled through a 2 mm. screen in a Christy-Norris Junior mill. Nitrogen was determined by the semi-micro Kjeldahl method. After ignition overnight at 470°-500° C., the ash was extracted with HCl and this extract was used for the following determinations: inorganic + organic P ($\approx$ total P except for peats with a high ash content) by the vanado-molybdate method (Hanson, 1950); total K, Ca and Na by the multichannel flame photometer (Ure, 1958) after removal of Al and P by complexing on an ion exchange resin in the citrate form (Riley, 1958; Binns, 1959); total Mg by the porous cup—spark method (Scott and Ure, 1958), and total Mn (six sites only) by a modified form of the tetrabase method (Nicholas and Fisher, 1950). Inorganic P was determined by the method of Saunders and Williams (1955) and organic P found by difference.

(b) Vegetation Samples. The methods used were the same as for the peat samples, except that only total P was determined, that P was

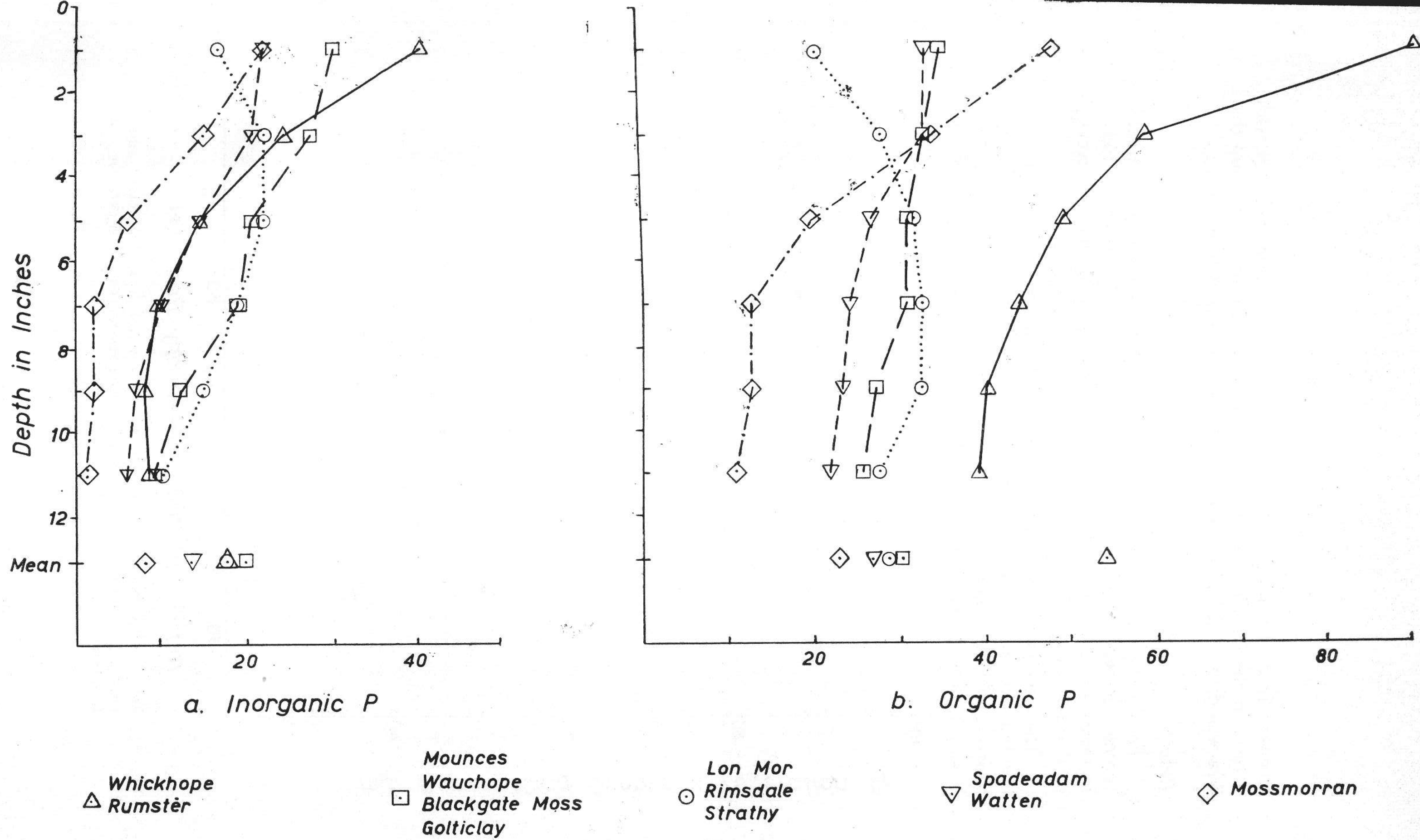

Fig. 2. Phosphorus content of peat (mg. P per 100g. oven dry peat).

removed from the solutions for flame photometry by ion exchange with a resin in the Cl form (Pinta and Bove, 1956; Binns, 1959), and that Mn was determined in the HCl extract by the periodate method.

Results.

Phosphorus. From the results in Figure 2 it is clear that the total P content decreases with depth at 9 out of the 12 sites, at three it increases and then decreases; the sites are grouped in order of average total P contents.

The sites in the first group have a high content of inorganic P in the top two inches, which then decreases rapidly; the second group shows moderate contents which fall fairly steadily, Blackgate Moss having a higher content than the others in this group, presumably due

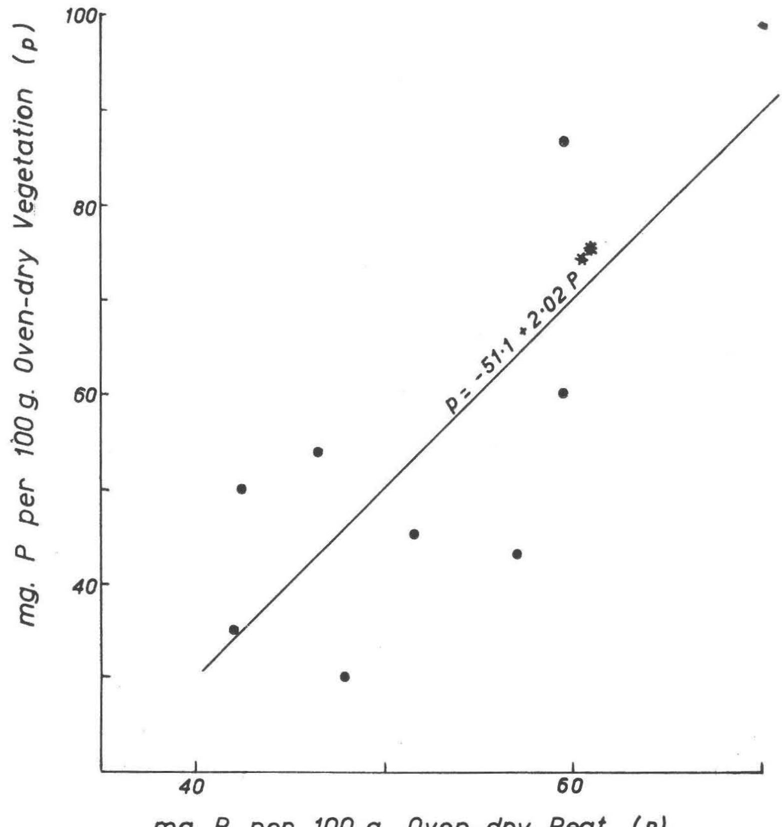

Fig. 3. Relationship between total phosphorus in 0-4 inch peat layer and in natural vegetation (9 sites, excluding Mounces, Whickthope, and Rumster).

to partial reclamation in the 1930's (Robertson, I. M., priv. comm.); the third group, the three northern deep blanket bogs, shows a slight rise followed by a fall; the fourth group shows still lower contents, which fall at about the same rate as the second group. The organic P contents follow the same trends as the inorganic P contents. However Mossmorran has a high content in the top two inches, and the first group maintains its superiority all the way down the profile, the reserves of slowly available P thus being substantially higher at the two sites in this group than at all the others.

The P content of the vegetation in general seems to be correlated with the inorganic and organic P content of the upper layers (though there were no vegetation samples from Mounces); eliminating the two flushed sites (Rumster and Whickhope) with high contents in the top layer, there is a fair correlation between the P in the 0-4″ layers and the total P in the vegetation (Figure 3). Though the regression is highly significant, the P content of the vegetation would only give a poor estimate of the content of the peat.

Potassium. For K contents the sites fall into four groups (Figure 4) but the arrangement is different from that for P contents. Three profiles at Golticlay have a very much higher K content than the rest, and are

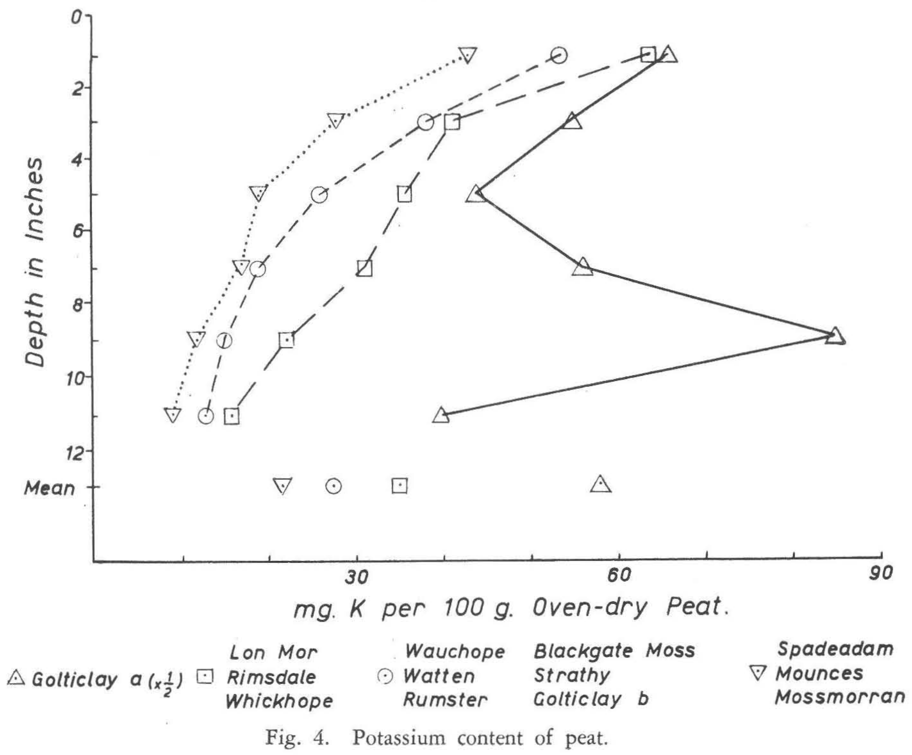

Fig. 4. Potassium content of peat.

shown separately; in all profiles other than these there is a rapid decrease in K content with depth. The Spadeadam samples represent two distinct sites (Table I), and the first has a higher K content in the peat and shows better tree growth than the second. The K content of the natural vegetation is two to five times that of the upper layers of the peat, but there seems to be no obvious correlation between the two.

Ash. The ash contents (Figure 5) fall into six groups, and if Figures 2 and 5 are compared it will be seen that, in general, ash and P contents have the same distribution at any one site, though there are large differences between sites; an exception is Whickhope, which has a high P content in the upper layers but only a moderate ash content.

Calcium, Magnesium and Manganese. Averaged values for all sites are shown in Table II. The Ca and Mg contents do not vary much down the profiles, and for most sites there is slightly more Ca in the vegetation than in the upper layers of the peat, while the Mg contents are about the same in the vegetation and the upper layers of the peat. Ca contents are higher at Blackgate Moss and lower at Wauchope and

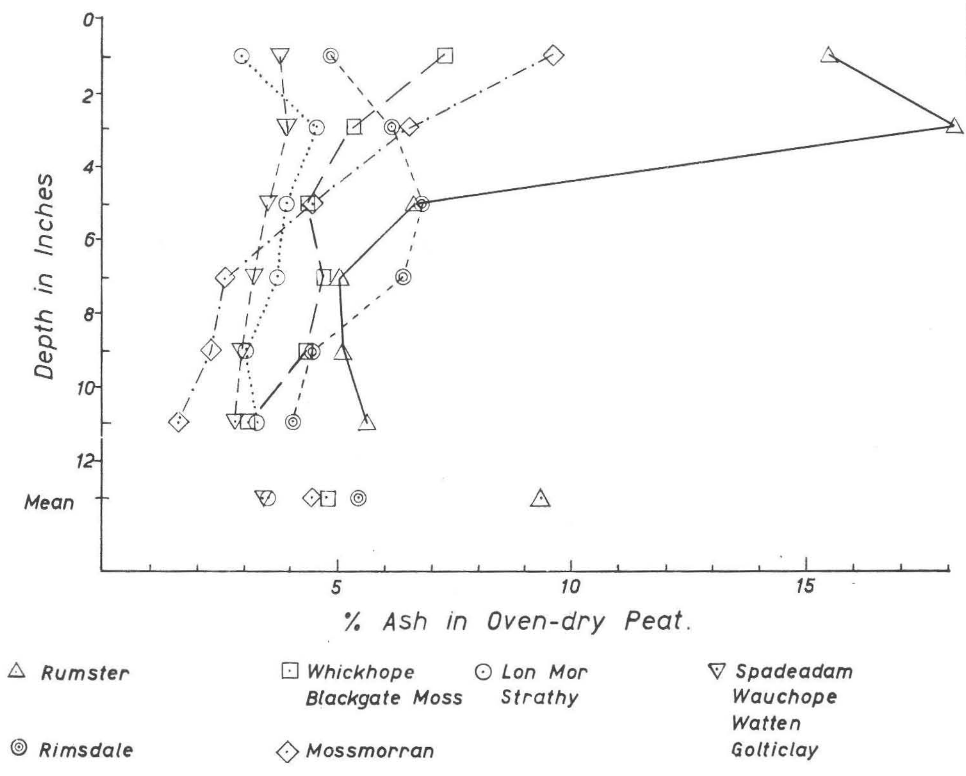

Fig. 5. Ash content of peat.

TABLE II

Amounts of Ca, Mg, and Mn in natural vegetation and peat, in mg./100g. dry matter, for the sites in Figure 1.

		Calcium		Magnesium		Manganese
		Blackgate Moss	All other sites	Watten and Strathy	All other sites	
Natural Vegetation*		265	200	125	90	27
Peat	0-2″	450	135	175	80	3.0†
	2-4″	405	130	150	80	1.8†
	4-6″	350	125	150	75	1.6†
	6-8″	310	135	160	75	1.4†
	8-10″	265	140	160	80	1.3†
	10-12″	220	145	160	80	1.2†
	Average	335	135	160	80	1.7†

* Values do not include Mounces.

† Values for Lon Mor, Watten, Strathy, Wauchope, Spadeadam, and Mounces only.

Mossmorran, and Mg contents lower at Mounces, Whickhope and Mossmorran, than at the other sites, but the Ca values at Blackgate Moss have presumably been affected by pre-war liming. Mn contents, where determined, show the same order of decrease with depth as K contents, and the content in the vegetation is about nine times that in the upper layers of the peat.

Nitrogen. The total N contents do not show much variation with depth, but there are considerable variations between sites. The average N content of the peat varies from 1.2 to 1.5% for the raised bogs, and from 1.6 to 2.4% for the other sites. At two of the four sites with average N contents of over 2% (Whickhope and Rumster) young Sitka spruce is, or until recently was, growing well, at another (Rimsdale) the experiments are still young, and at the Lon Mor the N values are probably not strictly comparable with the other sites because of the different method of drying the samples. At Mounces, where the N content of the peat averages 1.9%, the Sitka spruce have foliage N contents slightly over 1%, but are not in check. At Wauchope, however, where the average nitrogen content of the peat is 1.3%, the foliage nitrogen content of Sitka spruce has averaged between 1.0 and 1.5% over the last few years.

Thus, while high nitrogent contents in the peat may in some cases indicate a high nitrogen status, the converse may not be true, as most of the N in peat is in organic form, and largely unavailable: more important is the rate of mineralization, and although this is almost certainly related to the C/N ratio (e.g. Duchaufour and Mangenot, 1956) and therefore (in peat of low ash content) to the total N content itself, the method and intensity of ground preparation and the use of fertilizers seem to have an effect on this rate.

Nitrogen Mineralization.

The effect of ground preparation on nitrogen mineralization rates was seen in Experiment 4 P.53 at Wauchope, which was designed to test various ways of mixing several species of conifer with lodgepole pine. In this experiment alternate deep single mouldboard and shallow double mouldboard Cuthbertson ploughing were used, and in the second growing season trees on the deep ridges were growing up to 50% faster than trees on the shallow ridges; at first this was attributed to shelter. By 1957 however the trees were all well above the ridges, and as foliage N contents in the deep-ridge trees were higher than in the shallow-ridge trees in that autumn, samples of peat from the rooting zone (the "sandwich" layer) were taken at monthly intervals during 1958. Six pairs of samples were taken each month, three from among Sitka spruce and three from among lodgepole pine, each pair being on adjacent deep and shallow ridges. Seven adjacent sampling points along the ridges, midway between trees, were marked, and the pairs arranged in random order for monthly sampling. The ammonia- and nitrate-nitrogen contents were determined on the fresh samples, using the method of Bremner and Shaw (1955), and the moisture contents were also determined. The results are shown in Figure 6.

The values for NO_3-nitrogen were low and variable, being on average 1-2 mg. N/100g. dry peat. The NH_3-nitrogen content was significantly higher in the deep ridges in four out of the seven sets of samples, and the moisture content was higher in three sets of samples (the first set of samples for moisture determination was accidentally destroyed).

Foliage analysis and height measurements have been continued annually, and some of the results are shown in Figure 7. Each average is based on only three values, which gives a poor estimate of the variability, and statistical significance is not very meaningful. Differences between deep and shallow ridges for height increment and foliage N content have been decreasing year by year, while differences in foliage K content have been increasing, the deep-ridge trees containing *less*

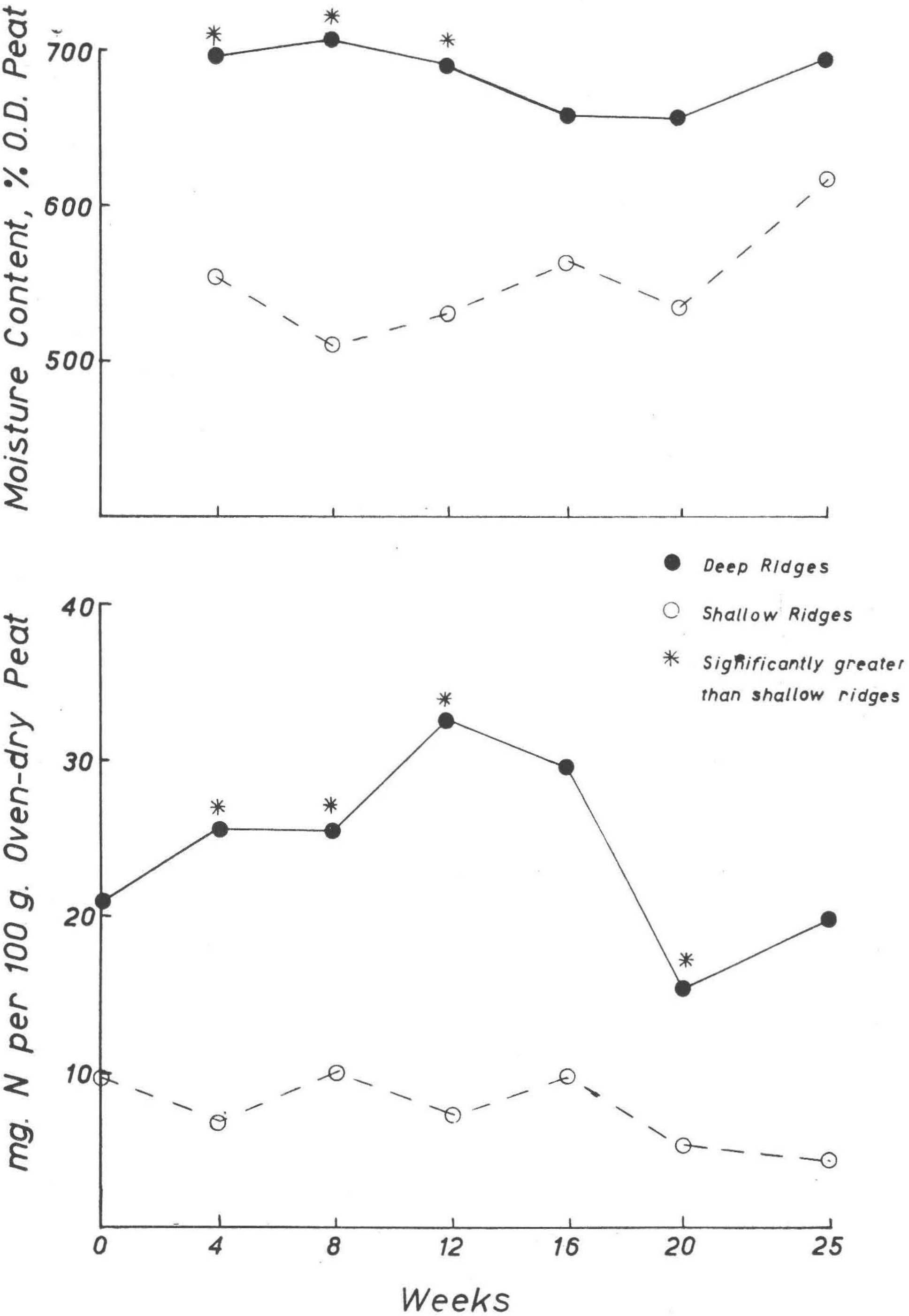

Fig. 6. Wauchope Experiment 4 P.53. Variation in moisture and ammonia-nitrogen content of peat between April 14th and October 6th, 1958.

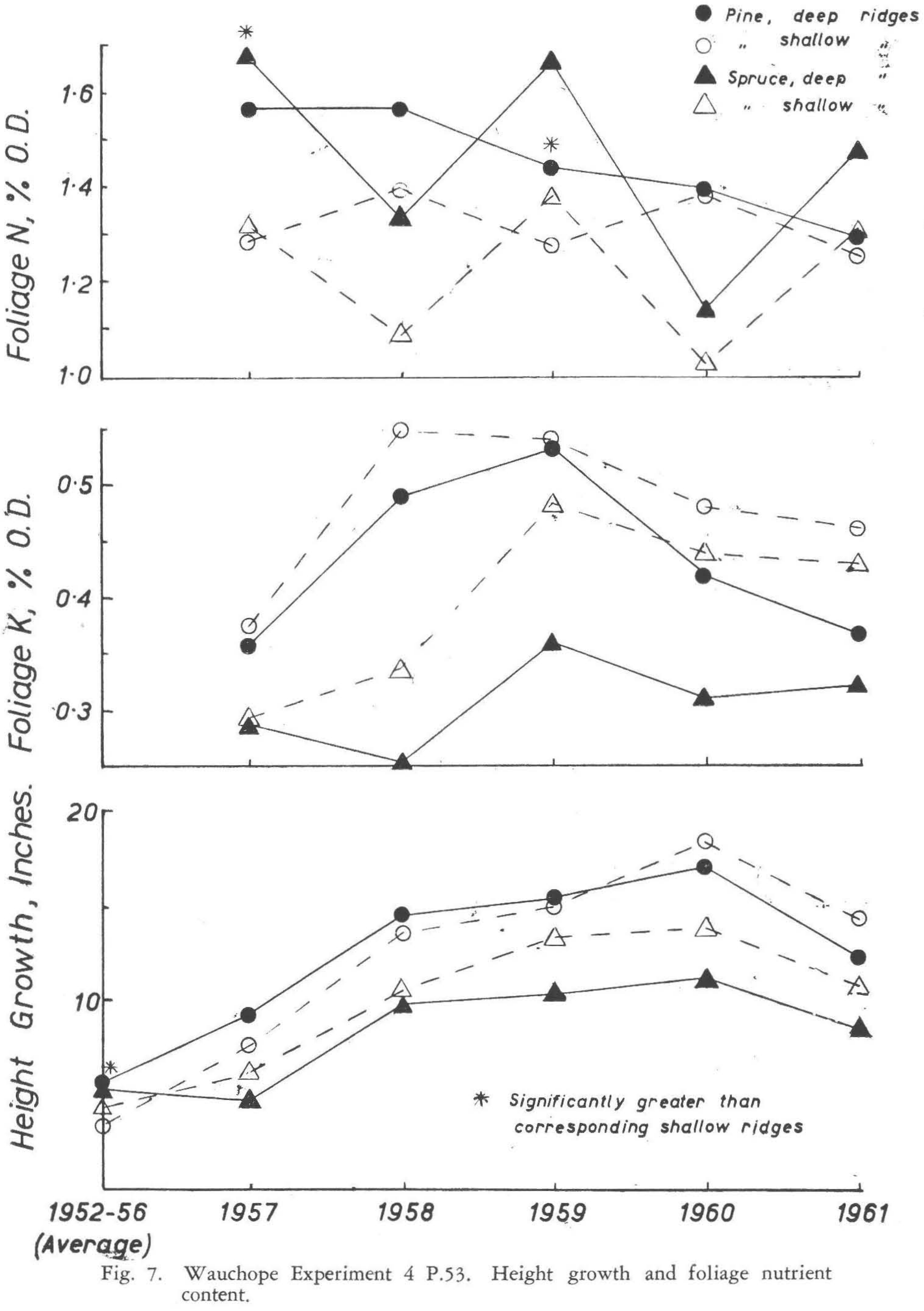

Fig. 7. Wauchope Experiment 4 P.53. Height growth and foliage nutrient content.

than the shallow-ridge trees. There is little doubt that all the trees are borderline for K deficiency, and that the Sika spruce on the deep ridges are definitely deficient. Figure 3 has already indicated that the peat at Wauchope contains less K than peat at the Lon Mor, so deficiency might be expected : the difference between deep and shallow ridge trees was, however, unexpected. The peat samples in 1958 were bulked and then analysed for nutrients as already described; the results show that the peat in the deep ridges contained significantly *more* inorganic P, total N, K and Mg than that in the shallow ridges, though all samples came from the same original peat layers (Binns, 1959). Leaching of nutrients down through the deep ridges possibly accounts for this, and may help to explain differences in growth and in N mineralization rates, but this would not account for lower K foliage values in the deep ridge trees. Although Gore and Allan (1956) and Kaila and Kivekäs (1956) have suggested that a large proportion of the K and Mg in peat is in exchangeable form, it seems that the total amounts of K and Mg present here are not directly related to uptake by the trees, and that temperature and moisture variation as well as the availability of nutrients may be affecting uptake; in 1957 the lodgepole pine on the deep ridges had much larger needles than the shallow ridge trees, but since 1958 for lodgepole pine, and 1959 for Sitka spruce, needle weights have been roughly the same on the two ridge types (needle weights for Sitka spruce were not determined before 1959).

An assessment for the whole experiment six years after planting showed Scots pine, lodgepole pine, and hybrid larch (*Larix eurolepis* Henry) to be significantly taller on deep ridges throughout the experiment and *Tsuga heterophylla* to be significantly taller in half the plots; Sitka spruce and *Picea omorika* show smaller differences between deep and shallow ridges, and these are significant in one or two plots (Edwards, unpublished).

This phenomenon of more rapid early growth on deep ridges has been reported from other Forestry Commission areas, and work at Glentrool, Kirkudbrightshire, now in progress, suggests that N mineralization there is more rapid in deep ridges than in shallow ridges, and that the difference is increased by adding P (Keay, J., unpublished). While the evidence is incomplete, the effect of P in mineralizing peat N under agricultural conditions has been known for some time (e.g. Kaila, 1958).

It is not clear whether this differential growth will be important as a long term effect: it might even be beneficial for lodgepole pine in reducing the incidence of wind-sway.

The Concentration Gradient in Peat.

One particular striking feature of the analytical results is the apparent accumulation of total K, Mn, and inorganic P in the surface layers of the peat, and the concentration of K and Mn by the vegetation vis-à-vis the amounts in the peat—which consist essentially of the dead plants of previous generations.

At the Lon Mor, where deeper samples have been taken, at 18 inches below the surface the inorganic P content falls to 2mg./100g. and the total K content to 5mg./100g. (Binns, 1959), and a similar decrease probably occurs at the other sites. Impeded drainage is a prerequisite for the formation of raised bog, and this is also true to some extent for blanket bog: though there may be lateral water movement, and fluctuations in the water table, there will usually be little leaching in a vertical direction. In some blanket bogs, nutrient-rich water may flow in from higher ground, but this is not possible in raised bogs.

The difference in P, K, and Mn content of the upper and lower peat layers has to be explained, and two theories have been advanced—either, that a recycling or "pumping" process by the vegetation maintains the nutrients at the surface (e.g. Kaila and Kivekäs, 1956; Binns, 1960), or that the nutrients are supplied by dust and rainfall (e.g. Mattson and Koutler-Andersson, 1955; Walsh and Barry, 1958). The recycling theory seems the more probable for the following reasons:

1. Although the nutrients supplied by rain are undoubtedly important for bog nutrition, rain water contains insufficient phosphate to account for the P gradient.

2. The Na/K ratio in rain water is of the order of 25/1 near the coast, and falls to 2/1 in some inland areas (Tamm, 1958) while the average Na/K ratio in the top foot of the peat at the 12 sites varies from 2/1 at Watten to 1/2 at Whickhope. Figure 8 shows the averages and the ranges for all sites. There is little change down the profiles for Na contents, and the change in ratio with depth is due almost entirely to the change in K content.

3. If leaching were responsible for the removal of P and K from the lower layers, one would expect replenishment by leaching from above; if there is no loss by leaching, the increase in concentration of the scarce nutrients at the surface can only be accounted for by recirculation of nutrients in the vegetation as the bog develops, which also explains loss of nutrients from the lower layers.

Mattson and Koulter-Andersson (1955) suggest that the higher concentration of nutrients and ash in the surface layers is due to increasing human activity during the historic period. However the main increase in K and inorganic P content at the Lon Mor occurs between 14 inches and the surface, while N increases between 24 and 10 inches, but is fairly constant in the top 10 inches (Binns, 1959). It may be that there are different causes for changes in P and K and for changes in N content, and the effect of human activity will of course vary greatly from place to place.

Apart from its fundamental interest, the practical importance of this

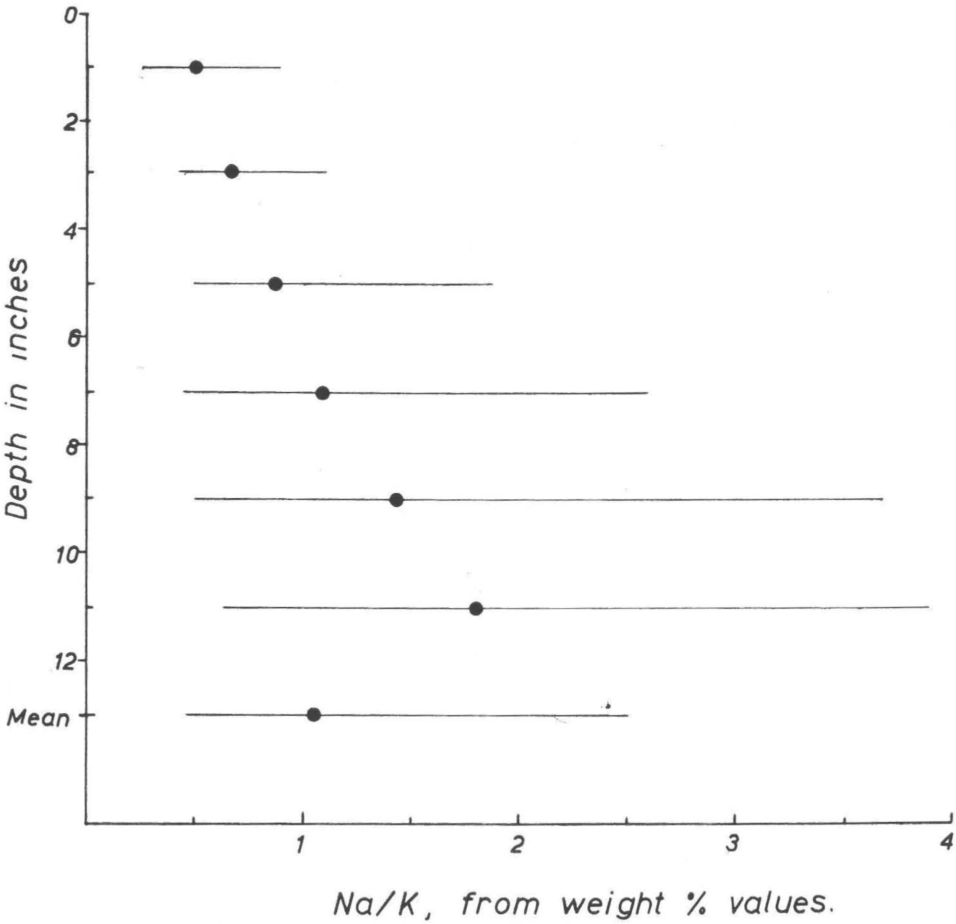

Fig. 8. Sodium-potassium ratios in peat; averaged values for all sites, and ranges.

phenomenon of a concentration gradient in peat is that while doubling the rooting depth may increase stability, it will only increase slightly the amounts of the scarce nutrients within reach of the trees.

Nutrient Requirements of a Whole Crop.

The data from the twelve sites studied may be used to calculate the amounts of nutrients in terms of lb. per acre, including the amounts in the vegetation, which can then be compared with the estimated demands of a tree crop. For the urgent short-term problem of growing the crop to maturity, the maximum immobilization of nutrients by a crop may be compared with the nutrients present in peat; for the long term problem of maintaining site fertility, the nutrients permanently removed in harvesting the tree crop may be calculated. While it is obvious that no tree can extract all the nutrients from peat, the total content of any nutrient may well, in the the present state of our knowldge, be a more useful measure of fertility than trying to determine the "available" fraction: not only is the latter difficult, but the peat is undergoing continual changes as a result of draining and tree growth, and the concept of availability is probably meaningless except for a single point in time.

Table III shows values for peat and natural vegetation at the sites studied, and the amounts immobilized by conifers, the latter calculated from data published by Rennie (1955), Meshechok (1957), and Wright and Will (1958). The weakness of both the comparison of Meshechok (1957) for Norwegian bogs and the present work is that since the data for the trees are not from peat grown trees, a large measure of luxury uptake may be involved. Although only the nutrients in the top foot of the peat are included in the table, the concentration gradient for scarce nutrients is such that for practical purposes the amounts in the top foot can be used as a basis for calculating the amounts per acre for these nutrients.

A direct comparison suggests that in relation to tree growth peat contains sufficient N, reasonable amounts of Ca and Mg, and apparently enough P, but is deficient in K. Though peat contains large reserves of

TABLE III

Nutrients in natural vegetation and the top foot (30 cm.) of peat at the sites studied, and immobilization by conifers, in lb./acre (x 1.12=Kg./ha.).

	N	P	K	Ca	Mg	Mn
Ground vegetation	130	7	22	30	10	3.7
Peat	5285	149	84	450	280	4.9
Total	5415	156	106	480	290	8.6
Immobilization by conifers	200-550†	20-80‡	120-300‡	180-500‡	30-90†	20-60*

* Data from Meshechok (1957).
† Data from Meshechok, and Wright and Will (1958).
‡ Data from Meshechok, and Wright, and Rennie (1955).

N, the rate at which it is mineralized will control its availability to trees, and it is possible that N may be lost with increased soil biological activity following drainage and afforestation. In peat, as in other soils, only a small part of the soil P needed to produce satisfactory growth is actually taken up by plants, and the comparison can only be used to show the probable drain of P over a rotation. Conifers tend to accumulate Ca in the heartwood, and the amounts lost to the site may be proportionately large, but this loss may be made up in practice as Ca is applied in all commonly used P fertilizers.

Figures for Mn are given for only six of the sites, and as plants may take up trace elements in much greater amounts than is needed for adequate growth, the comparison in Table III may be misleading. However older lodgepole pine at the Lon Mor, manured with G.M.P., show foliage Mn contents of under 1mg./100g., which is the approximate level recorded for Mn deficient spruce in Sweden (Ingestad, 1958); lodgepole pine manured with basic slag shows much higher foliage Mn contents.

Considered over a whole rotation, the amounts taken up by trees are not large, and Madgwick and Ovington (1959) have shown that the amounts of K, Ca, and Mg in trees in Kent, permanently lost to the site, are made up by the amounts in the rainfall, and Ebeling (1959), for example, shows that in South Sweden 1-3 lb. N per acre per annum may be expected in the rainfall : only P, of the major nutrients, shows a large deficit. Tamm (1958) has pointed out the importance of the nutrients in rainfall in bog economy.

Discussion.

Only two of the twelve sites, Whickhope and Mounces, were originally considered capable of growing a tree crop without added P. At Whickhope, with high peat N and P, and Rumster, with high peat N, P, and ash, Sitka spruce has made a good start, although a routine dressing of G.M.P. was given at Rumster. Growth disturbances at Rumster now reported may be due to competition for N by *Calluna*, or to K deficiency; the peat K contents at both sites are lower than at the Lon Mor, where older trees have already shown K deficiency.

The peat at Mounces contains more P on the average than at any site except Whickhope and Rumster, but in the experiment on the site (Kielder 73 P.54) Sitka spruce and lodgepole pine have both shown a small but significant response to G.M.P. (Edwards, 1959) though the trees have not failed in its absence; foliage P levels in the controls were by 1960 barely adequate at 100-120mg./100g. At Wauchope, in Experiment 5 P.55, Sitka spruce has not responded to G.M.P. (Edwards, *loc. cit.*) and growth is quite good, though variable; foliage P content of the controls in 1960 was adequate at about 150mg./100g. The P levels in the peat are higher for this experiment than for the rest of Wauchope, and inorganic P levels are slightly higher than at Mounces.

At the Lon Mor lodgepole pine grew for 11 years without added P, while at Rimsdale the same species was dying without it 3 years after planting. However the lodgepole pine site at the Lon Mor is richer in P than the Scots pine site there (Binns, 1959), and is also richer than Rimsdale, particularly for organic P, although these areas are grouped together in figure 2.

While it seems that the P available to trees is mainly within the inorganic fraction, an examination of the results suggests that the organic fraction also contributes to site fertility for P. Table IV shows

TABLE IV

Total P content of 0-6″ peat layer in mg./100g. dry weight, compared with responses to P.

Site, and Experiment or Compartment Number	P content	Response to phosphate
RIMSDALE, Naver Experiment 3 P.58	45	Lodgepole pine failing at 3 years without P, growing well with P.
LON MOR, Inchnacardoch Expt. 19 P.26	46	Scots pine slow early growth, eventual severe check without P, good response to P added in 1928.
LON MOR, Inchnacardoch Expt. 47 P.28	59	Lodgepole pine survived for 11 years without P, good response to P added in 1939. Some unmanured controls still surviving and growing (but probable root interaction).
MOUNCES, Kielder Expt. 73 P.54	71	Sitka spruce and lodgepole pine respond to P in the early years, pine more than spruce.
WAUCHOPE, Expt. 5 P.55	76	Sitka spruce has shown no early response to P, and growth is slightly better than at Mounces, though variable.
WHICKHOPE, Compartment 159	90	Sitka spruce growing well in youth without P.

how values for peat P may be tentatively related to response to P at those sites where there are controls. While the evidence is thus incomplete (and interpretation at some sites is complicated by K deficiency), it does suggest that the total P content in the top six inches of the peat may be used to indicate those areas where additional P is unnecessary, and those where application may safely be delayed for some years after planting if desired.

There have been colour and growth responses to added K at the Lon Mor (Binns, 1961); low foliage K levels of 0.3-0.5% have been found at Wauchope, Watten and Strathy, and very low levels of 0.2-0.4% at Mossmorran and Mounces, where there have also been marked colour responses to recently applied K. Thus the results of foliage analyses and fertilizer trials, when compared with figure 4, suggest that the time at which K deficiency first occurs is well correlated with the total K content of the top foot of the peat; if this proves to be generally true, peat analysis should be useful for forecasting K requirements.

The ash content of the peat is used elsewhere as an estimate of peat quality class for forestry (e.g. Vomperskij, 1958), but unless ash and P contents are well correlated (or unless other nutrients are correlated with ash content), the evidence suggests that ash content by itself is not likely to be an important parameter. For example, Mossmorran has a high ash content in the surface layers (due possibly to industrial pollution) but appears to be the most infertile of the sites studied, and Rimsdale has a high average ash content but appears to be rather deficient in P.

High peat N contents may indicate ground where Sitka spruce will grow well in youth, but the future of this species is problematical on all but the better, *Molinia,* peats.

The nutrient content of the natural vegetation gives only an approximate indication of site fertility for P, and virtually none for N and K, which is disappointing; there may however be several reasons for this. Thus, previous land use followed by fencing and ploughing has usually resulted in unstable communities. In addition, the mixture of species on each site has been alalysed, not individual species, and sampling has not been done at the same time of year for all sites, which have probably affected the results considerably. Moreover, work in Canada on forest plant communities by Gagnon *et al.* (1958) has suggested that the levels of cations in plant tissues are apparently governed, not by the available amounts in the humus layer, but by the inherent capacity of the species; useful differences between sites will therefore only appear when there is a clear deficiency of any nutrient, and species with higher requirements have been unable to compete on all these infertile sites.

It is clear that a detailed examination of tree foliage and tree growth at the sites studied is needed, together with further fertilizer trials, and it will also be necessary to see if the trace element contents of the peat, the trees, and the natural vegetation are in any way related, and if there are any responses to trace elements; preliminary studies on these problems are now in progress.

The phenomenon of more rapid early growth on deep compared with shallow plough ridges, though striking in the early years, seems to become less marked later on, but it is still not clear how important it will eventually be. It seems probable that ploughing regimes in the future are more likely to be designed on the basis of their effect on drainage intensity, crop stability, and extraction techniques, rather than their effect on early growth rate, provided the last reaches an acceptable minimum.

While peat analysis looks promising for estimating site fertility for P and K, and perhaps for N, foliage analysis is well established as a means of detecting major nutrient deficiencies in trees (e.g. Leyton, 1958), and may be better and easier than peat analysis. Analysis of newly acquired and unplanted peat may however help to prevent the planting of unsuitable species, as well as forecast probable nutrient deficiencies.

Foliage analysis for trace elements is another matter : though foliage levels for deficiencies of some nutrients have been reported, e.g. for Cu (Benzian, 1956), Mn (Ingestad, 1958), and Zn (Kessel, 1943), little is known of the best time of year and place in the crown to sample the foliage, and both of these may differ for major and minor nutrients. The trace element content of Scottish peats varies considerably, showing zones of accumulation in some cases (Mitchell, 1954), and the total amounts may be a poor guide to the availability of elements which are strongly bound by organic matter, e.g. Cu (Mitchell *et al.*, 1957). Nevertheless, in peats with a low ash content the relative amounts of the micronutrients in different areas may be a useful guide to the likelihood of deficiencies, and in conjunction with foliage analysis may simplify diagnosis and field trials considerably.

The calculation of nutrient turnover in peatland forests, by analysis of whole trees, natural vegetation, peat, rain water, and drainage water, would provide a better understanding of bog economy, and the effects which afforestation may have on this. Important as such a study would be from the long term aspect, it would probably not provide information quickly enough, or for sufficiently varied conditions, to answer the urgent questions concerning fertilizer requirements for trees on peat : this can probably be done more easily and rapidly by a comparison of the chemical composition of peat and by foliage analysis, followed by fertilizer trials. Studies of forest nutrient balance, though generally incomplete, suggest that if the working capital of deficient nutrients is increased sufficiently, only small additions may be necessary thereafter under good management.

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Summary.

Investigations at 12 deep peat sites in Scotland and N. England, have suggested that the needs of conifers for additional P and K may be estimated from the total P and K contents of the upper layers of the peat; concentration of these two nutrients in the surface layers, attributed to recycling by the natural vegetation, indicates that although deep rooting may improve stability it will probably not benefit trees much nutritionally. Mineralization of nitrogen, more rapid under deep than under shallow plough ridges, appears to be responsible for faster growth of young pine and larch on deep ridges. The deficiency of potassium at the sites studied is confirmed by a comparison of the maximum amounts of nutrients immobilized by conifers with the amounts present in the peat.

References.

Benzian, B., 1956. Copper deficiency in Sitka spruce seedlings. *Nature* **178,** 864-5.

Binns, W. O., 1959. The physical and chemical properties of deep peat in relation to afforestation. Ph.D. Thesis, University of Aberdeen.

——— 1960. Scottish soils in relation to afforestation. *J. Inst. Biol.* **7,** 18-20.

——— 1961. Forest soils research in Scotland. *Rep. For. Res.,* Lond. **1960,** 93-4.

Bremner, J. M., and Shaw, K., 1955. Determination of ammonia and nitrate in soils. *J. Agric. Sci.* **46,** 320-8.

Duchaufour, Ph., and Mangenot, F., 1956. Recherches sur l'évolution expérimentale de certains humus. *Ann. Agron* **A7,** 159-81.

Ebeling, F., 1959. Bonitering av Skogsmark—trolleri med tabeller eller tillämpad biologi? *Skogen* **46,** 472-5.

Edwards, M. V., 1959. Use of triple superphosphate for forest manuring. *Rep. For. Res.,* Lond. **1958,** 117-30.

——— 1962. The progress of peatland afforestation in Great Britain. *Irish Forestry* **19,** 102-109.

Gagnon, D., Lafond, A., Amiot, P., 1958. Mineral nutrient content of some forest plant leaves and of the humus layer as related to site quality. *Can. J. Bot.* **36,** 209-20.

Gore, A. J. P., and Allen, S. E., 1956. Measurement of exchangeable and total cation content for H^+, Na^+, K^+, Mg^{++}, Ca^{++} and iron, in high level blanket peat. *Oikos* **7,** 48-55.

Hanson, W. C., 1950. The photo electric determination of phosphorus using the phospho-vanado-molybdate complex. *J. Sci. Fd Agric.* **1,** 172-3.

Illingworth-Longbottom, K., 1954. A study of ground vegetation types and tree growth on a typical area of moorland in the north-west Highlands of Scotland. Unpubl. Thesis, University of Aberdeen.

Ingestad, T., 1958. Studies on manganese deficiency in a forest stand. *Medd. SkogsforsknInst.* Stockh. **48,** (4).

Kaila, A., 1958. Effect of superphosphate on the mobilization of nitrogen in a peat soil. *Maataloust. Aikakausk.,* **30,** 114-24.

Kaila, A., and Kivekäs, J., 1956. Distribution of extractable calcium, magnesium, potassium, and sodium in various depths of some virgin peat soils. *Ibid.* **28,** 237-47.

Kessel, S. L., 1943. The nutrition of the forest crop. *Australian Forestry* **8,** 5-21.

Leyton, L., 1958. The mineral requirements of forest plants. *Encyclopedia of plant physiology* IV, 1026.

Macdonald, J. A. B., 1945. The Lon Mor: twenty years' research into wasteland peat afforestation in Scotland. *Forestry* **19,** 67-73.

Madgwick, H. A. I., and Ovington, J. D., 1959. The chemical composition of precipitation in adjacent forest and open plots. *Forestry* **32,** 14-22.

Mattson, S., and Koutler-Anderson, E., 1955. Geochemistry of a raised bog. *Kungl. Lantbruks. Ann.* **21,** 321-66; **22,** 219-24.

Meshechok, B., 1957. Om myrgjodsling for skogproduksjon. *Tidsskr. Skogbruk* **64,** 119-48.

Mitchell, R. L., 1954. Trace elements in Scottish peats. Pap. Int. Peat Symposium, Dublin, Section B.3., pp.9.

——— Reith, J. W. S., and Johnston, I. M., 1957. Trace element uptake in relation to soil content. *J. Sci. Fd Agric.* **8,** Suppl. Issue 551-9.

Nicholas, D. J. D., and Fisher, D. J., 1950. A note on the use of tetramethyldiamino-diphenylmethane for determining small amounts of manganese in plants. *Long Ashton Ann. Rep.* **1950,** 115-20.

Pinta, M., and Bove, C., 1956. Application of flame photometry to the analysis of plant material (in French). *Mikrochim. Acta* **12,** 1788-817.

Rennie, P. J., 1955. The uptake of nutrients by mature forest growth. *Plant and Soil* **7,** 49-95.

Riley, J. P., 1958. Analysis of silicate rocks. *Analyt. Chim. Acta* **19,** 413-28.

Saunders, W. M. H., and Williams, E. G., 1955. Observations on the determination of total organic phosphorus in soils. *J. Soil Sci.* **6,** 254-67.

Scott, R. O., and Ure, A. M., 1958. The determination of magnesium in solution by direct photometry. *Analyst* **83,** 561-70.

Tamm, C. O., 1958. The content of plant nutrients in precipitation, dust and air. *Encyclopedia of plant physiology* IV, 233-42.

Ure, A. M., 1958. Spectrochemical applications of electronics in soil research. *Brit. Commun. Electronics* **5,** 846-9.

Vomperskij, S. E., 1958. Methods of assessing wet peatland in surveys with a view to forest site improvement. *Lesn. Hoz.* **11,** 76-7 (in Russian). *For. Abs.* 1960, **21,** 1346.

Walsh, T., and Barry, T. A., 1958. The chemical composition of some Irish peats. *Proc. roy. Irish Acad.* **59B,** 305-28.

Wright, T. W., 1959. Use of fertilizers in the afforestation of deep peat. *J. Sci. Fd Agric.* **10,** 645-50.

——— and Will, G. M., 1958. The nutrient content of Scots and Corsican pines growing on sand dunes. *Forestry* **31,** 13-25.

Zehetmayr, J. W. L., 1954. Experiments in tree planting on peat. *Bull. For. Comm.,* Lond. **22.**