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Reference Experiments on Young Conifers at Woburn Experimental Farm, 1961–69

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In 1961, a year after the Reference experiments on farm crops and soft fruit had been started at Woburn Experimental Farm, Bedfordshire (Widdowson & Penny, 1972; Williams, 1973), we laid down on an adjoining site 25 small plots sown annually with Sitka spruce—a Western American conifer widely planted in this country by the Forestry Commission. The techniques we used were similar to those we had developed over many years (jointly with the Commission) in a large experimental programme on problems of nutrition in forest nurseries, where—with the aid of factorial experiments—we tested interactions between nutrients, forms and rates of soluble and slow-release fertilisers, bulky organic manures and partial sterilants (Benzian, 1965). As part of this programme, we had started at five nurseries in 1955 some simple Nutrient Reference plots, which omitted in turn N, P, K, Mg, to observe nutrient deficiency symptoms and obtain colour records for different soils and seasons.

The two main aims of our conifer reference experiments were to compare the growth and nutrient uptake of Sitka spruce seedlings grown on a soil about which much was known from agricultural experiments (1) with the performance of arable crops grown under comparable conditions and (2) with the growth of Sitka spruce in our forest nursery experiments.

Our first set of Woburn Reference plots, Experiment 1, begun in 1961 were started on soil that had been under mixed arable cropping since 1876. The design was similar to that used in research nurseries but included some additional treatments: compost—with and without NPKMg fertiliser, Norway spruce litter with fertiliser, and formalin (drench) with fertiliser. Tests on added organic matter were thought important on a soil of poor structure that contained very little (Table 1). The effect of a partial sterilant was of special interest on a soil which was known not to have carried conifers for at least 100 years and was unlikely therefore to have built up pathogens specific to that crop. The 25 plots sown with Sitka spruce seed were arranged in two blocks of 12, with a central plot (with full NPKMg manuring) separating the blocks.

In 1965, a set of 12 plots, Experiment 2, was started on a parallel bed, comparing slow-release with soluble fertiliser on two ages of crop—seedlings and transplants—each in two blocks of three plots. All 12 plots were split to compare Sitka spruce with other conifer species (first Norway spruce, then Grand fir) which have proved more susceptible to damage from fertiliser salts at the transplant stage (Benzian, 1966a; Aldhous, 1972). The cropping of both experiments is shown below and Appendix Table 1 (page 171) gives details of the species tested.

	Species	Age of crop	Duration
Experiment 1	Sitka spruce	Seedlings	1961–69
Experiment 2	Sitka spruce	Seedlings, Transplants	1965–69
	Norway spruce	Seedlings, Transplants	1965–67
	Grand fir	Seedlings, Transplants	1968–69

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TABLE 1

Some soil properties of experimental sites

Per cent size distribution of mineral particles in oven-dry soil (Sample TE/A11870)

Coarse sand	2 –0·2 mm	44·5
Fine sand	0·2 –0·02 mm	35·7
Silt	0·02–0·002 mm	6·2
Clay	<0·002 mm	10·5

	Sample TE/A No.	pH in		In air-dry soil									In solution		In air-dry soil			
					Total elements							NaHCO$_3$-soluble	CaCl$_2$-soluble		Exchangeable			
		H$_2$O	0·01*M* CaCl$_2$	% org. C*	% N	ppm P	ppm K	ppm Mg	ppm Ca	ppm Mn		ppm P	ppm P	ppm K	ppm K	ppm Mg	ppm Ca	CEC me/ 100 g
Experiment 1																		
Block I	14328	5·35	4·73	0·83	0·088	798	5120	1270	938	322		32	0·09	7·8	76	21	870	7·1
II	14329	5·03	4·59	0·78	0·087	768	5620	1380	850	315		29	0·09	7·6	76	20	820	5·7
Experiment 2																		
Block I	11102	4·91	4·21	0·72	0·085	735	5380	1230	775	435		32	0·08	4·5	48	17	652	6·2
II	11105	4·94	4·37	0·85	0·087	835	6000	1470	1000	425		33	0·08	4·2	48	19	800	5·9

* Measured by the Walkley (1947) method using 1·3 for the correction factor

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During March the seedbed plots, on slightly raised beds 107 cm wide, were sown broadcast over 0·84 m^2 (3 ft × 3 ft) and then covered with a lime-free grit (10–12 kg/m^2) from St. Austell, Cornwall. The transplant plots were lined out with 108 one-year seedlings, 54 per species, at 5 × 18 cm spacing. The plots within each experiment were separated by undug buffer strips 38 cm wide, rather than by the impervious partitions found necessary with the agricultural crops. The plots were not limed, as the initial soil reaction was close to that which experimental evidence had shown to be the optimum for growth of Sitka spruce, i.e. around pH 4·5 in 0·01*M* $CaCl_2$.

Tree heights were measured and numbers counted *in situ* during October or November, and plant samples taken to determine dry-matter yields (for tops and roots separately) and N, P, K, Mg, Ca and Mn concentrations in the whole crop (tops + roots). Methods of analysis were described by Benzian, Freeman and Patterson, 1972. The remaining seedlings and transplants were then lifted, and some seedlings (grown with soluble NPKMg fertiliser) were bedded out on an adjacent unmanured site for lining out the transplant plots during the following spring. Thus, results for *seedlings* in this paper refer to trees after one growing season in the seedbed and results for *transplants* after one season in the seedbed and one in the transplant lines.

Soil samples, to a depth of about 15 cm, were taken from both blocks of Experiment 1 during the autumn of 1960 (before cropping began) and from the untreated transplant plots of Experiment 2 in the autumn of 1965 (the end of the first growing season); size distribution of mineral particles was determined on a sample taken from the fallow part of the bed adjoining Experiment 2. Analytical results for both experiments are given in Table 1 and methods of analysis in Appendix A. After the experiments had been concluded, soil samples were taken from individual plots (Table 13 and 14).

Experiment 1, 1961–69, treatments and results

The treatments, applied to the same plots annually (unless otherwise stated), were:

*None
Fertiliser (1961–69)
  PKMg = no N
  NKMg = no P
  NPMg = no K
  NPK = no Mg
  *NPKMg
Compost (1961–67)
  alone
  +NPKMg fertiliser
Litter (1961–63)
  +NPKMg fertiliser
Formalin (not in 1966)
  +NPKMg fertiliser
* duplicates per block

Rates of fertiliser application are shown in Table 2, composition of composts and litter in Table 3, and the nutrients they supplied in Table 4.

On fertiliser plots, N was given as 'Nitro-Chalk' (15·5% N 1961–64, 21% N 1965–69), P as single superphosphate, K as potassium chloride, Mg as kieserite. P, K and Mg were dug in 8–10 cm deep shortly before sowing, 'Nitro-Chalk' applied during the summer either in three equal top-dressings (before 1966), or, in later years, in four, to attempt to maintain a more steady supply of N to the plants.

Composts (prepared at Kennington Forest Nursery during mid-summer of the previous year) were made from 75% (by volume) chaffed green bracken (*Pteridium aquilinum*)

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and 25% fresh hopwaste. Both ingredients could easily be obtained and were complementary: bracken was rich in K, hops in N and P. Composts of similar composition had been tested for many years in nursery experiments (Benzian, Freeman & Patterson, 1972). As Sitka seedlings had given large responses to P in 1961 and 1962, and the compost had provided less than three-quarters of the amounts of P supplied by fertiliser, the application rate of compost was increased in 1963. None was applied in 1968 and 1969.

TABLE 2

Average amounts of nutrients supplied annually by fertilisers

			g element per m²						
			N			K			
	Fertiliser	Crop	before 1966	1966–69	P	before 1967	1967–69	Mg	Ca*
Experiment 1	Soluble	Seedlings	16	22	11	11	11	4	41
Experiment 2	Soluble	Seedlings	16	22	11	11	11	4	37
		Transplants	11	14	11	11	11	4	32
	Slow-release	Seedlings	19	23	11	7	10	4	16
		Transplants	13	16	11	7	10	4	10

* Approximate amounts supplied by 'Nitro-Chalk' + superphosphate or potassic superphosphate

TABLE 3

Average composition of compost and litter

			% in dry matter (DM)								ppm in DM
	No. of samples	% in fresh moisture	Org. matter	Ash	N total	N inorg.	P	K	Mg	Ca	Mn
Compost	7	79	76	23	3·7	0·33	0·67	1·91	0·31	1·69	430
Litter	3	64	69	31	1·4	n.d.	0·13	0·15	0·07	0·50	2382

TABLE 4

Average amounts of nutrients supplied annually during the periods shown

	kg/m² of fresh product		g element per m² in fresh product						
	Total	Org. matter	N total	N inorg.	P	K	Mg	Ca	Mn
Compost applied									
1961–62	5·4	0·78	40·8	4·0	7·8	22·7	3·6	19·7	0·44
1963–67	7·9	1·30	61·3	5·7	10·6	31·0	5·0	27·1	0·73
Litter applied									
1961–63	10·0	2·50	51·9	n.d.	4·8	5·4	2·5	18·2	8·65

The litter was collected under a mature stand of Norway spruce (Bloxworth Estate, Dorset). It was chosen as a source of organic matter with physical properties thought to be beneficial for small-seeded crops on a soil liable to 'cap'. However, after it had been applied for only three years, the plots became so 'fluffy' that they could no longer be consolidated sufficiently to give the firm seedbed needed for Sitka spruce, and the treatment had to be discontinued. The litter dressings supplied, annually, as much total N as the compost, substantial quantities of P, Mg and Ca, more than ten times as much Mn but less than a quarter of K. Compost and litter were applied at the same time as P, K, Mg fertilisers and incorporated to the same depth.

Formalin (containing approximately 40% formaldehyde) was applied at the rate of 300 ml/m² as a drench in 4–5 litre water during the preceding winter, using a method

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which had proved beneficial when growing Sitka spruce on high-pH soils previously under arable cropping or on land infested with eelworm (Benzian, 1965).

There were large differences between the amounts of nutrients applied to the conifer seedbeds of Experiment 1 and to the arable rotation crops in the Woburn Reference experiments on the adjoining site. The fertiliser regime of the forestry plots was based on nursery experiments which had as their aim the consistent annual production of green healthy conifer seedlings—a high-value crop for which fertilisers and their application constituted less than 5% of the production costs. Nominal annual application rates for forestry and arable crops are compared in Table 5. (The amounts of nutrients supplied

TABLE 5

Nominal amounts of nutrients added annually (kg/ha)

	N	P	K
Agricultural			
Rotation crops[a], 1960–69			
Fertiliser[b]	132	27	177
Farmyard manure[c]	132	44	176
Both	264	71	353
Conifer seedlings			
Experiment 1, 1961–69			
Fertiliser	187	110	110
Compost	431	77	222
Both	618	187	332

(a) From Widdowson *et al.* (1967) Appendix Table 2; Widdowson and Penny (1972) Appendix Table 5
(b) N_2PK fertiliser (N_1PK fertiliser supplied half the quantity of N, but similar amounts of P and K)
(c) Confined to two of the five rotation crops: sugar beet and potatoes

by materials not applied every year, i.e. FYM and compost were calculated by dividing the quantities given during the cropping period by the number of years cropped; this ignores differences between residues and fresh applications.) The table shows that on the fertiliser-treated plots the conifers received four times as much P as the arable crops, but less than two-thirds of the K. The value of 132 kg N/ha (level 2) for the fertiliser-treated agricultural crops represent the average of dressings given to different crops ranging from 56 kg/ha for the rotation ley to 188 kg/ha for sugar beet, the latter amount being similar to that given to Sitka spruce seedlings. Compost supplied between three and four times more total N than FYM, 75% more P and 25% more K.

Seedling height. For conifer seedlings, height is the most important index of plant performance; trees of less than 3·8 cm (1·5 in.) are too small to transplant. Table 6 shows heights for two periods: 1961–64 and 1965–69. This division corresponds to a change in seed origin—Queen Charlotte Island during the early period, Washington State later. It also happens to coincide with a change in summer rainfall; the first four seasons were very dry (all had less than 250 mm rain from June to September), whilst the later period had only two dry summers in five. Thus, without other supporting evidence, differences between the periods not caused by experimental treatments may be attributable to seed origin, to weather, or to progressive chemical, physical or biological changes in the soil associated with continued cultivation or cropping, or by the addition of annual dressings of seedcover grit.

Comparing height growth of seedlings which had one of the four nutrients omitted with those given the full NPKMg treatment, increases from N and P were between 40 and 50% during both periods; the small decreases from K and Mg during the early

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TABLE 6

Field measurements of Sitka spruce seedlings grown in Experiment 1

Treatments	Height (cm) 1961–64	1965–69	Mean	Number of plants per m² 1961–69
None	1·88	4·34	3·25	1278
PKMg (no N)	2·59	4·37	3·58	1253
NKMg (no P)	2·44	4·19	3·40	1248
NPMg (no K)	3·94	5·41	4·75	1243
NPK (no Mg)	3·76	5·66	4·83	1241
NPKMg	3·71	6·20	5·10	1184
Compost	2·95	6·17	4·72	1144
Compost + NPKMg	4·47	7·67	6·25	1268
Litter + NPKMg	4·70	7·19	6·07	1113
Formalin + NPKMg	4·55	6·91	5·87	1286
S.E. ±	0·231	0·170	0·137	39·3
c.v. %	9·7	4·2	4·2	4·6

period changed to increases of between 10 and 15% later. Results for both periods are shown below:

Mean percentage increases from	Height 1961–64	1965–69
N	43	42
P	52	48
K	−6	15
Mg	−1	10

Between 1961 and 1964, when growth was generally poor, seedlings without N or P failed to reach the critical height for transplanting of 3·8 cm.

Seedlings responded better to N in wet (>250 mm rain June–September) than in dry summers as is shown below.

PKMg present	Height (cm) Dry summers (6)	Wet summers (3)
no N	3·4	3·9
N	4·2	6·9

The compost treatment by itself resulted in poorer growth than fertiliser during the early period but equalled it later, even though no compost was applied in 1968 and 1969. Throughout, compost plus fertiliser increased height more than either material alone, the joint treatment exceeding the fertiliser treatment by between 20 and 25%. During the 1961–64 period, litter plus fertiliser was as beneficial as compost plus fertiliser; even during the later period residues from the three litter dressings applied between 1961 and 1963 give substantial benefits. The improved growth from compost and litter (in the presence of fertiliser) may stem from the larger amounts of nutrients supplied and, especially, of N earlier in the season than that given in fertilisers. However, as the organic-matter content increased, soil structure may have improved, for Williams and Cooke (1961) have shown this to be a soil with low permeability and liable to 'cap'.

The benefit from formalin of between 11 and 23% was comparable with that obtained in the better Forestry Commission nurseries; it did not approach the very large increases in nurseries where 'stunted growth' was a problem (Benzian, 1970; see also this paper, Appendix B by G. A. Salt).

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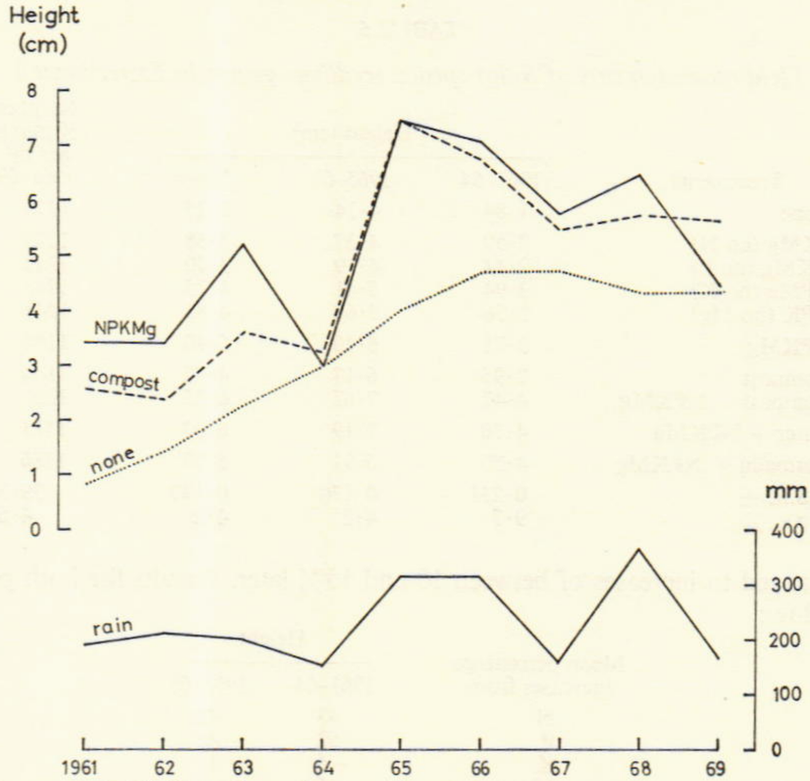

FIG. 1. Summer rainfall (June–September totals) and heights of Sitka spruce seedlings for three treatments in Experiment 1: none, NPKMg soluble fertiliser applied annually, compost applied 1961–67.

Fig. 1 shows summer rainfall and annual heights of seedlings grown with three treatments: without added nutrients, with the full fertiliser treatment, and with compost (applied 1961–67 only). There is a clear relationship, especially in the later period, between rainfall and growth on the manured plots. By contrast, seedling height on the untreated plots increased steadily from year to year until 1966, irrespective of rainfall. The curves for treatments omitting single nutrients (not shown) tended to resemble those with the full fertiliser treatment; only the 'no-N' plots followed more closely the trend of the untreated plots. The spread of mycorrhizal infection was considered a possible explanation for the puzzling phenomenon of the steady improvement of growth on the unmanured plots, although if this explanation is correct, one might have expected a similar trend on the 'no-P' plots. Mycological examination of the seedlings during the winter 1965–66 lent support to this possibility. (See G. A. Salt, Appendix B.) No similar progressive improvement on unmanured plots was ever observed in our forest nursery experiments where the pattern of mycorrhizal infection was studied by Levisohn (1965).

Plant number (Table 6). The different treatments hardly affected plant numbers.

Deficiency symptoms. Sitka spruce seedlings develop distinctive nutrient deficiency symptoms. The discolorations corresponding to shortage of N, P, K and Mg at Woburn were similar to those described and shown for forest nurseries by Benzian (1965).

Other observations

Fungi. G. A. Salt took samples for mycological examination and found only fungi which can be regarded as normal root surface microflora for Sitka spruce. His report is given in Appendix B.

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Eelworms. S. R. Gowen (1971) studied, during 1968 and 1969, the occurrence of *Tylenchus emarginatus* and *Tylenchorynchus dubius* around the roots of Sitka spruce in Experiment 1; both species were more abundant than in nearby land under other crops. Experiments in tubes showed that Sitka spruce was a good host and that these nematodes were able to stunt root growth; there was however no clear evidence that they had done so in the field, where numbers per unit weight of root were much smaller than in the tube experiments.

Needle necrosis. It happened repeatedly that seedlings developed brown needle tips. On at least one occasion there was strong circumstantial evidence that fumes from the nearby brickworks were responsible. On the morning of 3 September 1964 it was foggy and a temperature of 0°C was recorded, but no frost injury was observed on frost-sensitive plants such as dahlias. The Sitka seedlings, which had been healthy up to that date (and are much less frost-sensitive than dahlias) developed brown needle tips. On the same day, similar sudden damage on Scots pine seedlings was reported by the forester in charge of Millbrook Nursery—about 4 miles from our Woburn plots. (It is under conditions similar to those described above that the characteristic smell from the brickwork chimneys is most noticeable.) During October of the same year, symptoms resembling the earlier ones were specially severe on our 'no-K' plots.

The symptoms observed on Sitka spruce seedlings at Woburn resemble closely those seen by one of the authors (B.B.) on mature trees growing near aluminium works in Norway, where they are thought to be caused by emission of fluorine, and where according to Robak (1969) damaged trees occur at distances up to 32 km from the works. Similar damage has been observed on agricultural crops at Woburn, and investigations on this problem have recently been started (Hoskin & Dawson, 1973).

Dry weight, nutrient concentrations and removals. Dry weight of tops plus roots, top/root ratios, and nutrient concentrations in the whole crop are shown in Table 7. (Standard errors cannot be given, as replicates were bulked.) The treatment effects measured as dry weights followed the same trends as those of seedling heights but percentage increases were considerably larger. These percentage increases (from N, P and K supplied by fertiliser) are compared in Table 8 with those for arable crops. Whereas responses to N

TABLE 7

Nine-year means of dry matter weights and nutrient concentrations of seedlings grown in Experiment 1, 1961–69

	Dry matter mg/plant		In dry matter of tops + roots					
Treatments	Tops (T) + roots (R)	T/R ratio	% N	% P	% K	% Mg	% Ca	ppm Mn*
None	113	2·4	1·81	0·28	1·06	0·106	0·58	518
PKMg (no N)	131	2·2	1·72	0·32	1·42	0·121	0·53	941
NKMg (no P)	131	2·6	2·13	0·22	1·28	0·110	0·46	918
NPMg (no K)	207	2·6	2·03	0·28	0·65	0·131	0·61	838
NPK (no Mg)	206	2·7	1·97	0·27	1·33	0·060	0·60	945
NPKMg (full)	230	2·5	1·99	0·27	1·25	0·101	0·53	850
Compost	239	2·6	2·00	0·27	1·55	0·112	0·54	485
Compost + NPKMg	290	2·9	2·11	0·27	1·50	0·107	0·54	909
Litter + NPKMg	282	2·7	2·06	0·26	1·33	0·100	0·55	1385
Formalin + NPKMg	300	2·8	2·14	0·25	1·34	0·099	0·50	1309

* Derived from seven years only

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TABLE 8

Comparison of relative responsiveness of five arable crops to each nutrient tested in the presence of the other two nutrients (1960–69) with that of Sitka spruce seedlings, Experiment 1(1961–69)

	Percentage increase in dry matter produced			
	from N_1	from N_2 over N_1	from P	from K
Arable crops*				
Barley				
grain	110	12	6	44
straw	160	28	8	67
Oats				
grain	75	22	−2	−3
straw	117	32	9	21
Potato tubers	46	26	6	142
Sugar beet				
tops	70	23	5	18
roots	54	6	8	79
Rotation ley	14	1	4	48
Conifers				
Sitka spruce seedlings	76	—	76	11

* From Widdowson & Penny (1972), Table 2

Note: For amounts of N, P and K supplied see Table 5

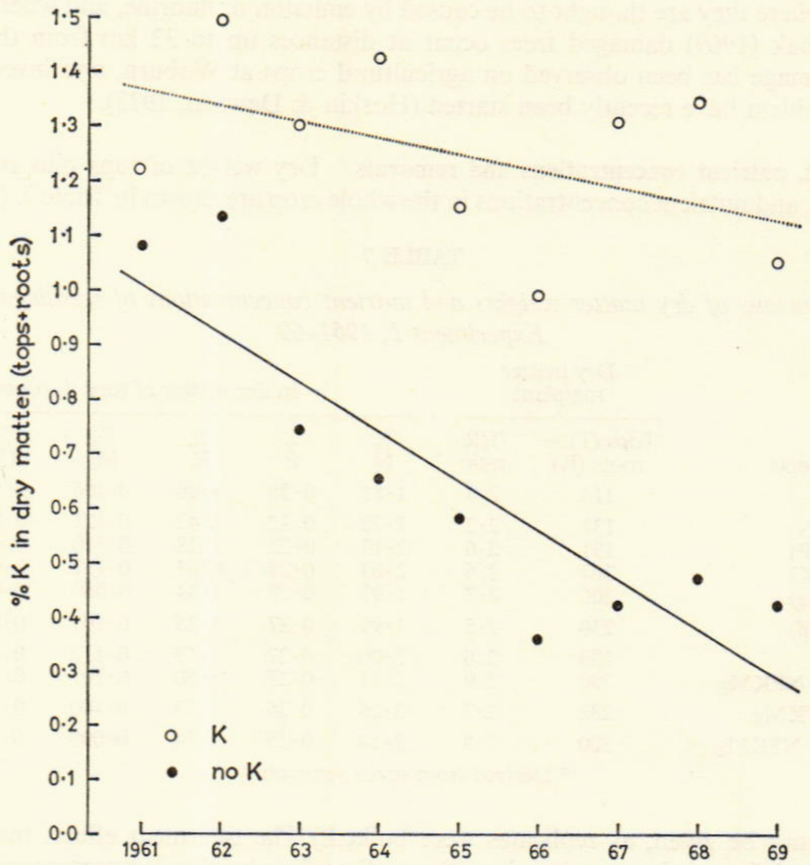

FIG. 2. Annual potassium concentrations in Sitka spruce seedlings (%K in dry matter of tops + roots) from plots with and without added K in Experiment 1, 1961–69. Mean annual change is indicated by fitted regression lines: 'no K' line significant at 0·05 level, 'K'-line not significant.

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fall within the same range, and those to K are smaller in Sitka than in most of the arable crops, those to P are much larger, possibly because seedlings of Sitka spruce require higher concentrations of P in the soil solution than arable crops to compensate for their slow rate of root growth. Comparisons of Mg responses in the arable-rotation Reference Experiments and Sitka spruce experiments are not possible because the former had too few tests on magnesium. However, in an eight-year study (1960–67) on a nearby site on successive crops of ryegrass, clover, sugar beet, potatoes, kale and barley, Bolton and Penny (1968) reported that dry-matter yield increases ranged from 3% for ryegrass to 11% for potatoes—compared with 12% for Sitka spruce seedlings.

Concentrations of N, P, K and Mg in spruce seedlings were less where the respective nutrient had been omitted, but otherwise treatment differences were small, except that plants grown with compost had—as is usual—larger K concentrations than those with fertiliser. For plants given either full fertiliser or compost, all nutrient values (including Ca and Mn) came within the sufficiency range (Benzian & Smith, 1973); the large increases in Mn caused by litter and formalin accord well with those observed elsewhere (authors' unpublished data).

Between 1961 and 1969, K and Mg concentrations in seedlings (Figs. 2 and 3) declined slightly, if at all, on plots with the full fertiliser treatment, and seedlings did not lose

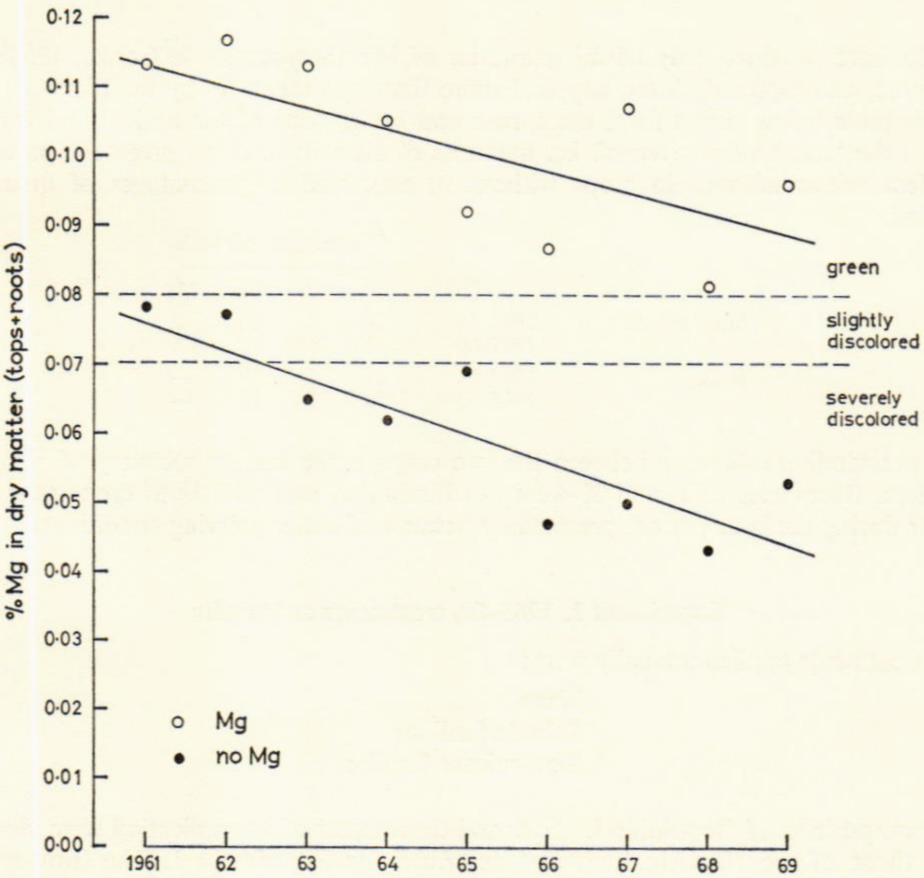

FIG. 3. Annual magnesium concentrations in Sitka spruce seedlings (%Mg in dry matter of tops + roots) from plots with and without added Mg in Experiment 1, 1961–69. Mean annual change is indicated by fitted regression lines, both significant at 0·05 level.

their healthy green colour. However, on plots without K or Mg, the respective nutrient concentrations decreased greatly, and seedlings developed typical discolorations.

The amounts of major nutrients added in fertiliser, compost, compost plus fertiliser and in litter plus fertiliser (Table 9) were far in excess of those removed by crops. Fertiliser

TABLE 9

Total nutrients (g/m^2) *added in manures and removed in Sitka spruce seedlings* (*tops + roots*) *during whole cropping period of Experiment 1, 1961–69*

	N		P		K	
Treatments	added	removed	added	removed	added	removed
Fertiliser (NPKMg)	168	48	99	6·9	99	30
Compost	388	47	69	6·7	200	37
Compost + fertiliser	556	56	168	9·1	299	49
Litter + fertiliser	324	56	113	7·6	115	37
	Ca		**Mg**		**Mn**	
	added	removed	added	removed	added	removed
Fertiliser (NPKMg)	367	13	36	2·5	trivial	2·1
Compost	175	12	32	2·7	4·5	1·1
Compost + fertiliser	542	17	68	3·5	4 to 5	2·7
Litter + fertiliser	422	15	44	2·8	26·0	3·8

would have provided only trivial quantities of Mn (Stojkovska & Cooke, 1958), but compost, and especially litter, supplied more than was taken up by the plants.

The table below shows for Sitka spruce and barley (one of the agricultural rotation crops) the 'apparent recoveries', i.e. amounts of element in crops given the particular nutrient minus amount in crops without it, expressed as percentages of quantities applied.

		% apparent recoveries			
		N	P	K	Mg
Sitka spruce	1961–64	16	2	10	2
	1965–69	13	4	22	4
Barley	1960–64	42	4	9	—
	1965–69	50	7	16	—

The outstanding difference between the two crops is the smaller recovery of N by the conifers. Recoveries of P and K were not dissimilar, and with both crops they were better during the later period, presumably because of better growing conditions.

Experiment 2, 1965–69, treatments and results

The treatments applied annually were:

None
Soluble fertiliser
Slow-release fertiliser

The composition of the soluble fertiliser and the manner of its application were identical with those of the NPKMg treatment described for Experiment 1. The 'slow-release fertiliser' consisted of an application of magnesium ammonium phosphate $MgNH_4PO_4.H_2O$ (8% N, 17·5% P, 14% Mg) and potassium metaphosphate KPO_3 (25·3% P, 32·2% K); it was dug in at the same time and to the same depth as the soluble

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PKMg fertiliser. 'Nitro-Chalk' top-dressings, given to *all* manured plots, were similar to those in Experiment 1, except that the transplants received smaller amounts. The quantities of all nutrients supplied are shown in Table 2; only the slow-release fertiliser provided a 'starter' dose of N. (In 1967 the relative proportions of magnesium ammonium phosphate and potassium metaphosphate were changed to make the amounts of N and K more closely comparable with those supplied by the soluble fertiliser.)

Both slow-release fertilisers had been tested previously in forest nurseries (Benzian, 1966b), because (1) many were located on light soils where soluble salts are easily lost by leaching, and (2) because transplants of some conifer species may be severely damaged by soluble salts. Good results, especially from potassium metaphosphate, had been obtained on the very light sandy soil of Wareham Nursery, Dorset (Benzian, Bolton & Mattingly, 1969; Benzian, 1972).

Height, dry-matter weights and nutrient concentrations

Seedlings. Results for the three species are shown in Table 10; those for Sitka spruce are given separately for the 1965–67 and 1968–69 periods to match those for Norway spruce and Grand fir. Responses to both soluble and slow-release fertilisers were large in all three species (whether measured as height or dry-matter weight). However, the slow-release fertilisers were consistently the better of the two, and it is likely that more than one factor was responsible for these differences. According to results from Experiment 1, conifer seedlings at Woburn respond to N and P and, after some years of cropping, also to K and Mg; it is therefore possible that the rate of release of one or more of these nutrients might have been involved.

Concentrations of N, P and K in the crops were not affected by fertiliser source, but Mg values were larger and Ca values smaller in seedlings grown with the slow-release

TABLE 10

Field measurements, dry-matter weights and nutrient concentrations of seedlings grown in Experiment 2

Species and years	Fertiliser applied	Height cm	Number of plants/ m^2	Dry matter mg/plant: Tops (T) + roots (R)	T/R ratio	In dry matter of tops + roots: % N	% P	% K	% Mg	% Ca	ppm Mn
1965–67											
Sitka spruce	None	2·82	1577	99	1·9	1·28	0·24	0·89	0·066	0·45	532
	Soluble	6·73	1462	314	3·1	1·70	0·26	1·10	0·079	0·41	789
	Slow-release	8·00	1546	375	3·5	1·71	0·25	1·02	0·092	0·39	776
Norway spruce	None	3·07	1356	142	1·6	1·58	0·31	0·77	0·085	0·60	641
	Soluble	5·59	1385	343	2·3	2·02	0·28	0·79	0·089	0·56	857
	Slow-release	6·35	1440	376	2·3	1·89	0·29	0·76	0·097	0·49	773
1968–69											
Sitka spruce	None	3·38	1174	110	2·8	1·76	0·31	0·81	0·070	0·53	533
	Soluble	6·25	1170	242	3·9	1·95	0·24	1·32	0·076	0·47	1012
	Slow-release	6·83	1321	294	4·0	2·05	0·24	1·31	0·094	0·41	1042
Grand fir	None	3·05	677	126	1·4	1·86	0·29	0·74	0·096	0·55	436
	Soluble	4·88	742	286	1·9	2·26	0·29	1·50	0·096	0·43	870
	Slow-release	5·13	698	312	1·8	2·24	0·29	1·46	0·105	0·38	918

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TABLE 11

Field measurements, dry-matter weights and nutrient concentrations of transplants grown in Experiment 2

Species and years	Fertiliser applied	Height cm	Dry matter mg/plant: Tops (T) + roots (R)	T/R ratio	In dry matter of tops + roots: % N	% P	% K	% Mg	% Ca	ppm Mn
1965–67										
Sitka spruce	None	19·9	3542	2·8	1·14	0·23	0·79	0·078	0·56	389
	Soluble	25·0	5842	2·9	1·31	0·22	0·92	0·080	0·53	440
	Slow-release	27·5	7230	3·0	1·34	0·20	0·77	0·094	0·55	308
Norway spruce	None	15·8	2646	2·5	1·42	0·26	0·72	0·087	0·76	467
	Soluble	19·0	3741	2·7	1·62	0·25	0·72	0·084	0·66	526
	Slow-release	20·3	5699	2·6	1·56	0·23	0·66	0·089	0·64	346
1968–69										
Sitka spruce	None	22·9	3638	3·0	1·17	0·22	0·61	0·069	0·58	434
	Soluble	34·3	7426	3·3	1·30	0·19	0·94	0·090	0·58	696
	Slow-release	35·3	8600	3·5	1·29	0·18	0·82	0·096	0·55	526
Grand fir	None	18·3	3644	2·0	1·38	0·23	0·54	0·092	0·68	493
	Soluble	21·3	5644	2·4	1·50	0·20	0·96	0·105	0·62	620
	Slow-release	23·4	6562	2·6	1·53	0·19	0·82	0·111	0·60	451

TABLE 12

Total nutrients (g/m²) added in fertilisers and removed in Sitka spruce seedlings and transplants (tops + roots) during whole cropping period of Experiment 2, 1965–69

Fertiliser applied	N added	N removed	P added	P removed	K added	K removed	Ca added*	Ca removed	Mg added	Mg removed	Mn added	Mn removed
Seedlings												
None	0	11	0	2·0	0	6	0	3·4	0	0·5	0	0·4
Soluble	104	34	55	4·9	55	22	170	8·3	20	1·5	tr.	1·6
Slow-release	112	44	55	6·0	44	27	80	9·7	17	2·3	tr.	2·1
Transplants												
None	0	26	0	5·2	0	16	0	13	0	1·7	0	1·0
Soluble	67	55	55	8·0	55	39	160	23	20	3·6	tr.	2·4
Slow-release	78	67	55	9·8	44	40	65	28	17	4·8	tr.	2·1

* Approximate quantities supplied in fertiliser

fertiliser. Norway spruce seedlings tended to have larger N, P and Ca but smaller K concentrations than Sitka spruce; this accords well with results from other experiments (authors' unpublished data). Grand fir had larger concentrations of all nutrients, except Ca and Mn, which were slightly less.

***Transplants* (*Table 11*).** As with seedlings, slow-release fertiliser produced larger plants, but at no time was there any sign of visible damage caused by fertiliser salts to the foliage of the two susceptible species—Norway spruce and Grand fir. Plants grown with slow-release fertiliser had slightly less % K, but otherwise nutrient concentrations differed hardly at all between trees grown with the two forms; the differences between species resembled those described for seedlings.

Transplants removed considerably more nutrients than did seedlings (Table 12)—about 50% more N, P and K, and between two and three times as much Ca and Mg. The magnitude of the amounts of N and K removed in transplants approached that of the additions, but the excess of additions over removal was larger than might appear, because the table does not show the extra nutrients introduced in seedlings at the time of lining out.

Soil analyses, Experiments 1 and 2

Results of analyses for soil samples taken from each plot at the end of the cropping period are given in Tables 13 and 14. All show clear-cut differences between treatments.

Experiment 1 (Table 13)

pH values (measured in $CaCl_2$) were a little below 4·5, the optimum for Sitka spruce.

TABLE 13

Carbon, nitrogen, phosphorus and cations in soil samples of Experiment 1 taken at end of nine-year cropping period (1961–69)

			In air-dry soil				In solution		In air-dry soil		
	pH in			Total			$CaCl_2$-soluble		Exchangeable		
Treatments applied	H_2O	0·01*M* $CaCl_2$	% Org. C	% N	ppm P	$NaHCO_3$-soluble ppm P	ppm P	ppm K	ppm K	ppm Mg	ppm Ca
None	4·98	4·19	0·53	0·060	576	17·6	0·05	2·9	31	13	420
PKMg (no N)	5·03	4·30	0·44	0·056	742	86·0	0·98	10·2	84	41	487
NKMg (no P)	4·72	3·90	0·48	0·061	565	18·1	0·04	9·4	75	31	262
NPMg (no K)	4·85	4·18	0·54	0·063	790	84·7	0·97	2·6	26	31	554
NPK (no Mg)	4·90	4·18	0·57	0·066	792	86·0	0·91	8·1	78	8	546
NPKMg (full)	4·86	4·16	0·49	0·064	764	87·8	0·98	8·2	76	27	508
Compost	5·16	4·27	1·29	0·118	798	49·6	0·47	10·6	96	42	557
Compost + NPKMg	4·74	4·11	1·08	0·114	1002	106·4	1·96	11·0	102	33	728
Litter + NPKMg	4·80	4·10	0·84	0·080	828	83·5	1·06	7·9	67	26	526
Formalin + NPKMg	4·98	4·27	0·54	0·066	852	84·9	0·95	7·9	70	31	516
S.E. ±	0·095	0·073	0·074	0·0018	45·8	2·60	0·086	0·43	3·7	1·4	48·2
c.v. %	2·7	2·5	16·1	3·6	8·6	4·4	11·8	8·1	7·8	13·6	7·3

Note: Between 1961 and 1969 a total of about 100 kg/m² of St. Austell seedcover grit was applied and mixed with the top 10 cm of soil. Part of this material (particles less than 2 mm) dilutes the soil taken for analysis.

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Organic carbon values, measured by the Walkley (1947) method using 1·3 for the correction factor, averaged about 0·5% on plots without added organic matter; the three early litter additions increased this value by 50% and compost more than doubled it. However, both compost and litter will have decreased bulk densities (not measured) of the soil, and treatment differences would have been smaller, had the analytical values been expressed on a volume instead of a weight basis.

Total N values showed similar trends but the percentage increases caused by additions of organic matter were slightly smaller. C/N ratios ranged from about 8–9 on plots without compost or litter to about 10–11 on plots with these additions.

Fertiliser P increased *total P* in the soil from about 570 ppm to between 740 and 800 ppm and so did compost, despite the fact that compost supplied less P than fertiliser. (This discrepancy may be a reflection of the decrease in bulk density on the compost-treated soil.)

Soluble P, both bicarbonate-soluble P and P in equilibrium with 0·01*M* $CaCl_2$ solution were greatly increased by fertiliser-P, but increases were much less when P was added in compost.

Total cations were not determined on seedbed plots because of the annual additions of St. Austell seedcover grit consisting of quartz, kaolinised felspar, mica and other minerals; it contains 0·6% K, with little if any available to plants.

Exchangeable cations showed the expected differences between plots with and without the respective nutrient, except for an unexplained low Ca value (smaller than on the untreated plots) for the no-P plots.

Experiment 2 (Table 14). Soil treated with slow-release fertiliser had slightly more soluble P and considerably more exchangeable Mg than that with soluble fertiliser. No such effects were obtained with K given as potassium metaphosphate; this contrasts with results on the sandy soil of Wareham Nursery where considerably more exchangeable K was retained on plots treated with KPO_3 than with potassic superphosphate.

TABLE 14

Carbon, nitrogen, phosphorus and cations in soil samples of Experiment 2 taken at end of five-year cropping period, 1965–69

	In air-dry soil							In solution		In air-dry soil		
	pH in		%	Total			NaHCO₃-soluble	CaCl₂-soluble		Exchangeable		
Fertiliser applied	H_2O	0·01*M* $CaCl_2$	Org. C	% N	ppm P	ppm K	ppm P	ppm P	ppm K	ppm K	ppm Mg	ppm Ca
Seedbeds												
None	4·97	4·12	0·54	0·067	678	n.d.	19·7	0·06	3·5	32	15	494
Soluble	4·79	4·05	0·60	0·069	838	n.d.	65·9	0·70	8·5	72	37	494
Slow-release	4·77	3·98	0·59	0·066	890	n.d.	70·8	0·72	8·2	70	48	412
Transplants												
None	4·97	4·24	0·69	0·082	758	5335	20·8	0·05	3·0	32	16	647
Soluble	5·17	4·26	0·87	0·086	1055	6175	55·6	0·54	6·4	66	44	719
Slow-release	5·09	4·31	0·81	0·085	1032	5485	56·6	0·60	5·6	60	60	692

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Discussion and conclusions

The comparison between the young conifers and the arable crops grown on an adjoining site, produced similarities but also some spectacular differences in the effects of nutrient additions on crop yields. Whereas nitrogen responses of Sitka spruce seedlings came within the wide range of dry-matter weights found with arable crops, those to K tended to be much smaller in the conifers. The outstanding difference was with responses to P: those for arable crops ranged from −2 to 9%, whilst dry-matter weights of Sitka spruce seedlings were increased by nearly 80%. In the instances of P and K, it would not have been possible to predict the responsiveness of one type of crop from tests done on the other. By contrast, the magnesium deficiency symptoms reported for Sitka spruce as early as 1963 might have served as a useful pointer to the need for magnesium dressings on the arable crops.

Sitka spruce seedlings manured with NPKMg fertiliser in Experiment 1 were considerably smaller than those grown during the same nine-year period in parallel experiments at the two main English forest research nurseries—Kennington near Oxford and Wareham, Dorset (Table 15). The reason for the poor performance at Woburn is more likely to be associated mainly with physical than with chemical or biological factors, since not only were responses to nutrients smaller at Woburn than at Wareham, but the fully manured Woburn seedlings had nutrient concentrations in the sufficiency range. The lack of a spectacular response to formalin (except in the first year) makes it unlikely that damage from serious pathogens or nematodes occurred. Differences in rainfall between nurseries were too small to account for the discrepancy. A contributory cause may be the poor physical condition of Woburn soil with small pore space and low permeability. As mentioned above, the benefit from compost and litter might be associated with structural improvement.

TABLE 15

Comparison of heights of Sitka spruce grown at Woburn with those at the two main English forest research nurseries

	Height (cm)		
	Kennington	Wareham	Woburn
Seedlings			
After one growing season	7·6	6·3	5·1
Transplants			
After one season in the seedbed and one in the transplant lines	28·7	24·6	28·7

The transplants, less sensitive to adverse soil conditions, grew as well at Woburn as at Kennington—the better of the two nursery soils.

Summary

Seedlings of Sitka spruce *Picea sitchensis*, a species widely planted by the Forestry Commission in Britain, were tested for nine years in reference experiments on land previously under agricultural cropping. Their growth and nutrient uptake were compared with those of (1) arable rotation crops grown on an adjoining site and (2) conifer crops grown in the Forestry Commission's main research nurseries. Sitka spruce seedlings responded to N mainly in wet seasons, to P consistently, but to K and Mg only during later years. The P effects were much larger with conifers than with arable crops. Compost and spruce litter (with fertiliser given) benefited the spruce seedlings on a soil of poor structure with low permeability and liable to cap, though a better nutrient supply may also have

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been involved. A partial sterilant—formalin—increased growth, but not enough to indicate the presence of serious pests or pathogens. The progressive improvement of seedling growth on the unmanured plots (not previously observed) could not be explained.

In a second experiment, lasting five years, seedlings and transplants of Sitka spruce were compared with those of firstly, Norway spruce *Picea abies* and subsequently Grand fir *Abies grandis*—two species susceptible (at the transplant stage) to damage from fertiliser salts. NPKMg fertilisers in slow-release form were slightly more effective than soluble salts, although the latter caused no visible damage.

The seedlings of Sitka spruce grew less well than those in similar experiments at the research nurseries of Wareham and Kennington, whereas the transplants reached the same size as those at the better of the two nurseries.

Nutrient concentrations of N, P, K, Mg, Ca and Mn in whole-plant samples of fully manured seedlings and transplants were in the 'sufficiency range'. Results of soil analyses were well related to treatments.

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APPENDIX A

Methods used for soil analysis

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Air-dried samples of soil were prepared for analysis by passing them through a 2 mm mesh sieve. These sieved samples were used for all analyses except total P, total cations and organic carbon. For these analyses the soils were further ground to pass a 100 mesh sieve.

Organic C. Determined by the method of Walkley (1947). All values have been corrected to total carbon by multiplying them by 1·3.

Total N. Kjeldahl digestion with $CuSO_4$ + Se catalyst (Bremner, 1960). Ammonia in digest determined by distillation with alkali.

Total P. Fusion of soil with anhydrous sodium carbonate (Mattingly, 1970). P determined by the method of Murphy and Riley (1962).

Total K, Mg, Ca, Mn. Soil extracted with hydrofluoric acid (Jackson, 1958). K, Ca measured by flame photometry and Mg, Mn by atomic absorption spectrophotometry.

Sodium bicarbonate-soluble P. Extraction with 0·5*M* $NaHCO_3$ (pH 8·5), Olsen *et al.* (1954). P determined by the method of Murphy and Riley (1962).

Calcium chloride soluble P, K. Extraction with 0·01*M* $CaCl_2$ Schofield (1955). P determined by the method of Murphy and Riley (1962), K measured by flame photometry.

Exchangeable cations. Soil leached with *N* ammonium acetate (pH 7·0) (Metson, 1956). K, Ca measured by flame photometry, Mg by atomic absorption spectrophotometry.

Cation exchange capacity. Soil leached with *N* ammonium acetate (pH 7·0) and excess removed by washing with 95% ethanol. Ammonia in soil determined by distillation with magnesium oxide (Metson, 1956).

pH. Measured by glass electrode in soil suspensions in water and in 0·01*M* $CaCl_2$ (10 g soil to 25 ml water or $CaCl_2$ solution).

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APPENDIX B

Incidence of root–surface fungi on Sitka spruce seedlings

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Appendix B Table 1 shows the most common genera of fungi (recorded in October 1964) on roots washed in tap water, cut into 1 cm lengths and plated on water agar at 20°C. *Pythium* is a primary pathogen and will kill seedlings before or just after emergence (damping-off). Damping-off is a problem in many forest nurseries, especially where the soil pH is 5·0 or more, but has not been troublesome at Woburn, and this is reflected in the small numbers of *Pythium* spp. isolated from roots. The other fungi isolated can be regarded as normal components of the root surface of Sitka spruce, or are soil saprophytes and are unlikely to damage roots directly. *Cylindrocarpon radicicola* is usually the most prevalent fungus on Sitka roots from soils of widely different types and pHs, and is rarely found in soil away from roots. It was not decreased by formalin treatments but was less prevalent in unmanured plots. This fungus quickly invades roots damaged physically or by a primary pathogen such as *Pythium*. Of the *Fusarium* species, *F. solani* was the most prevalent. *F. oxysporum* and *F. sambucinum* are more usual in forest nursery soils and *F. solani* on arable soils, but *F. solani* was sometimes locally abundant on conifer roots of Old Kennington (Ram Reddy, 1962). There were fewer *Fusarium* isolates from formalin-treated plots.

APPENDIX B TABLE 1

	Per cent root pieces[1] yielding cultures of:							
Treatment	*Cylindrocarpon*	*Fusarium*	*Penicillium*	*Aspergillus*	*Gliocladium roseum*	*Phoma*	*Trichoderma*	*Pythium*
None	12	18	25	28[2]	6	2	0	0
NPKMg	45	39	19	6	5	4	1	2
Compost + NPKMg	38	52	10	0	8	5	5	5
Litter + NPKMg	38	15	20	8	5	2	0	0
Formalin + NPKMg	62	2	5	0	0	5	8	0

[1] 20 pieces, each 1 cm long, from each replicate
[2] Includes 100% infection in one plot

There is therefore no evidence for any serious pathogen problems on Sitka spruce in Woburn arable soil, and this is also indicated by the lack of a spectacular response to formalin applied annually for several years. Fumigants have been applied for arable crops at Woburn either because of a known disease or a history of poor growth, and in these situations striking improvements in growth and yield have usually followed (Salt, 1971; Williams & Salt, 1970).

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In January 1966 roots of seedlings from unfertilised plots in Experiment 1, that had grown several crops of Sitka spruce, were compared with those from Experiment 2, where there had been no previous spruce seedlings and where seedling growth was much poorer. Roots from Experiment 1 were darker, appeared less healthy as there was some sloughing of cortex, and were covered with large amounts of septate fungus mycelium, whereas those from Experiment 2 were lighter in colour and had little or no mycelium attached to them. It seemed likely that this mycelium was forming a mycorrhizal association with the roots, but it was not possible to confirm this by microscopic examination. When roots were surface sterilised lightly in sodium hypochlorite and plated on acid potato dextrose agar (pH 4·0) to suppress bacteria, colonies of dark brown septate sterile mycelium were obtained from those from Experiment 1 but not from those from Experiment 2. Whether or not this was the same mycelium as observed covering the roots could not be determined with any confidence, and as it produced no reproductive spores it was not possible to identify it.

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APPENDIX TABLE 1

Common name	Botanical name	Number of viable seeds/m²	Origin	Identity number
Sitka spruce	*Picea sitchensis* (Bongard) Carrière			
	1961–64	2200	Queen Charlotte Island, B.C., Canada	60(7111)
	1965–66	2200	South Coastal Washington State, USA	61(7972)
	1967	1700		
	1968–69	1400		
Norway spruce	*Picea abies* (Linnaeus) Karsten			
	1965–66	1800	Carinthia, Austria	61(4362)
	1967	1800	St. Viet/Pongau, Austria	63(4362)3
Grand fir	*Abies grandis* Lindley	960	Pe Ell, Washington State, USA	64(7975)7

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