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Long term response of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) to fertilisers on low level blanket peat in the west of Ireland

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Abstract
A nitrogen and phosphorus experiment on Sitka spruce (*Picea sitchensis* (Bong.) Carr.), which ran from 1967 to 1982, was reopened in 1992. Half of the original experimental plots were left untreated, and the other half received lime and further applications of nitrogen and phosphorus in factorial combination. Levels of foliar nitrogen and phosphorus have fallen since 1979, with nitrogen now deficient throughout. Despite this, the effect of applied nitrogen and phosphorus on their respective foliar concentrations is still in evidence. Foliar concentrations of other nutrients, except sulphur, are adequate. The decline in the foliar concentration of nitrogen and phosphorus, coupled with estimates of top height, suggests that the lime has failed to achieve its long term objective of stimulating growth.

Key words: peatland forests, Sitka spruce, fertilisers

Introduction
In the first decades of blanket peatland forestry, there was a great deal of uncertainty about the fertiliser requirements of the two species in general use, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Dougl.). Many experiments were established to investigate their response to various fertiliser materials, in particular, phosphorus and nitrogen (OCarroll, 1967, 1972; Dickson, 1965, 1969; O'Hare, 1967). The experiment reported here was installed in a 6-year old Sitka spruce stand at Glenamoy in 1967. It was continued until 1982 and involved, in addition to a straightforward fertiliser trial (Farrell and McAleese, 1972; Farrell, 1985a), a range of studies on water relations (Farrell and O'Hare, 1974; Farrell, 1985b), peat shrinkage (Farrell, 1985b) and nitrogen transformations (Farrell, 1985b). Following an inspection in Autumn 1992, it was decided to conduct some limited studies to determine whether the experiment, 25 years after its establishment, could yield useful information on long term effects. The results of these studies are reported here.

Experimental design
The experiment was located in a Sitka spruce crop on low level blanket peat at Glenamoy Forest, north-west Co. Mayo. The climate of the area is extreme maritime, with an annual rainfall averaging 1,400 mm and distributed over 270 days. Wind is very severe, with gales in almost every month (Farrell, 1985a). The natural flora is dominated by the

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Schoenus nigricans L. association (O'Hare, 1959). The top 50 cm of peat has an ash content of 2.5% and a humification of 5 to 6 on the Von Post scale (Walsh and Barry, 1958). Bulk density is approximately 0.09 g/cm^3 in the 0-5 cm layer, and 0.10 g/cm^3 at 5-10 cm. Saturated hydraulic conductivity is approximately 1 cm/day (Burke, 1967).

Establishment procedures described by Farrell and McAleese (1972) included a spot application of 85 g (3 oz) of ground rock phosphate.

The fertilisation experiment was established in 1967 (Farrell and McAleese, 1972), comprising 48 x 0.03 ha plots. A randomised block design was employed with three levels of sulphate of ammonia and four levels of ground rock phosphate in factorial combination replicated four times, i.e. four blocks of 12 plots each. All fertilisers were applied broadcast, without incorporation, in April 1967. Some plots received a further application of nitrogen in 1969 (Table 1). Measurements were initially made in the centre of each plot inside a buffer strip two rows in width. From 1972 onwards, assessment was confined to the 16 trees closest to the plot centres, due to concern regarding the spread of fertiliser effects between plots. In 1976, trenches were dug between plots to prevent the further spread of such effects.

The original experiment was divided in two in Spring 1977. Blocks 3 and 4 received no further treatments (Experiment 1). Blocks 1 and 2 (Experiment 2) received an application of 8 t/ha of ground limestone, in addition to further applications of nitrogen and phosphorus (Table 1).

Water table studies have also been carried out in the experiment. In August 1969, a 7.0 cm x 1.6 m slotted pipe was installed in the centre of each plot according to the method described by O'Hare (1972). Depth to water table was measured during two periods, at weekly intervals between October 1969 and October 1970, and at weekly intervals between May 1981 and June 1983.

Systematic thinning, involving the removal of one line in three, was carried out in early summer 1982. As a result, some of the 16 designated trees at the centre of each plot were removed.

Table 1. *Summary of treatments applied in Experiment 1 and Experiment 2 (kg nutrient/ha). All treatments were applied in springtime. From Farrell (1985a).*

Year	N_0	N_1	N_2	P_0	P_1	P_2	P_3
1967[1,2]	0	132	264	0	55	110	220
1969	0	132	0	0	0	0	0
				Experiment 1			
1977-79			No further treatments applied				
				Experiment 2			
1977[3,4]	0	75	75	0	35	70	105
1978	0	0	75	0	0	0	0
1979	0	0	75	0	0	0	0

[1]N applied as sulphate of ammonia; P as ground rock phosphate.
[2]Sulphate of potash (42% K) was applied to all plots at 125 kg/ha and copper sulphate (25% Cu) at 11 kg/ha.
[3]N applied as calcium ammonium nitrate; P as superphosphate.
[4]All plots limed at 8 t ground limestone/ha.

Methods

Foliar analysis

In November 1992, foliar samples were collected from the lower live crowns of six trees at the centre of each plot in Block 1 (Experiment 2) and Block 3 (Experiment 1). In the laboratory, 1-year old needles were removed from the lateral branches of the samples. Each sample was then oven dried at 70°C for 48 hours. Following this, they were ground and placed in airtight plastic bags.

Nitrogen content was determined by digesting 0.2 g of oven dry material in H_2SO_4 (conc.) and selenium, followed by standard distillation and titration with 0.01N HCl. Phosphorus, K, Ca, Mg, S, Mn and Cu were calculated by Inductively Coupled Plasma Emission Spectrometry (Varian, Liberty 200) following $HNO_3/HClO_3$ digestion of 1.0 g of oven dry material.

Top height

Tree height measurements were made in April 1993, using a Blume-Leiss hypsometer. The average height of the two trees of largest diameter at breast height in a circular plot of 5.0 m radius at the centre of each plot was taken as an estimate of top height (Edwards and Christie, 1981).

Results

Growth response to treatment

Experiment 1

Local waterlogging and windthrow within Block 4 gave rise to anomalies in height values. Results for individual treatments were inconsistent with those in the other three blocks. Consequently, data from this block were excluded from further consideration.

In the early years of the experiment, phosphorus had a large effect on height growth, increasing it by 67% over the control in the 1967-72 period (Farrell, 1985a). It was not appropriate to apply statistical analysis to the most recent data and the results must therefore be treated with caution. They do, however, suggest a residual influence of nitrogen and phosphorus on top height (Table 2). They also suggest that the effect of nitrogen is now more pronounced than in the early years of the experiment, whereas the effect of phosphorus is less than on previous occasions.

Table 2. *Mean top height (TH) and general yield class (GYC) in Experiment 1. General yield class is taken from top height age curves in Edwards and Christie (1981). Figures for 1972, 1975 and 1979 taken from Farrell (1985a).*

Year	*1972*		*1975*		*1979*		*1993*	
Age	*11*		*14*		*18*		*32*	
Main Effect	*TH (m)*	*GYC*	*TH (m)*	*GYC*	*TH (m)*	*GYC*	*TH (m)*	*GYC*
N_0	4.6	18	5.7	16	7.6	14	14.4	14
N_1	5.1	20	6.3	16	8.3	16	16.5	16
N_2	4.9	18	6.6	18	8.9	16	17.5	16
P_0	3.7	14	5.1	14	6.8	12	15.2	14
P_1	5.5	18	6.5	18	8.5	16	15.9	16
P_2	5.3	18	6.7	18	9.8	18	16.7	16
P_3	5.0	18	6.7	18	8.8	16	16.8	16

General yield class, which declined progressively from 1972 to 1979, has apparently stabilised at 16 over all levels of applied nitrogen and phosphorus (Table 3).

Table 3. *Mean top height (TH) and general yield class (GYC) for Experiment 1 and Experiment 2 in 1993.*

	Experiment 1		*Experiment 2*	
Main Effect	*TH (m)*	*GYC*	*TH (m)*	*GYC*
N_0	14.4	14	15.2	14
N_1	16.5	16	16.7	16
N_2	17.5	16	16.2	16
P_0	15.2	14	16.0	16
P_1	15.9	16	16.3	16
P_2	16.7	16	16.5	16
P_3	16.8	16	15.6	14

Experiment 2

Farrell (1985a) observed the following responses to fertilisation in Experiment 2. Height increment in the 1976-79 period was significantly increased by phosphate in conjunction with lime. A significant effect of nitrogen on basal area was also recorded. Basal area increment in the 1976-81 period showed a 63% increase in the phosphate-treated plots over the P_0 treatment. The effect of nitrogen was smaller, with a 28% increase in basal area over the 1976-81 period. There is some evidence that the response to phosphate was beginning to fall off as it was less in the 1980-81 period than in 1976-79. This is probably true as examination of top height for each main effect mean (Table 3) shows that height increment may be increased by nitrogen and is no longer increased by phosphate.

Comparison of Experiment 1 and Experiment 2

Despite the stimulation produced by the fertiliser treatments in Experiment 2, top height increment over all the plots in this experiment was significantly less than that in Experiment 1 in the 1976-79 seasons (Farrell, 1985a). It was hoped that the lime would have the ultimate effect of stimulating microbial activity, with a consequent increase in the mineralisation of nitrogen and phosphorus (Farrell, 1985a). Instead, it has probably caused a decrease in mineralisation. Comparisons of the top height and general yield class data for Experiment 1 and Experiment 2 in 1993 (Table 3) show no major differences. This indicates that the crop is no bigger as a result of the treatments applied in 1977, and that the lime has failed to stimulate growth.

Nutrient status

In the early years of the experiment, it was found that maximum or near maximum growth responses can be obtained on this site at relatively low concentrations of foliar nitrogen, with both fertilisers producing increases in foliar nitrogen and phosphorus (Farrell and McAleese, 1972). This response of foliar phosphorus to the fertiliser application in 1967 gradually declined, but in 1979, the response of foliar phosphorus and magnesium to applied phosphate was still in evidence (Farrell, 1985a).

In Experiment 2, both fertilisers produced an increase in foliar nitrogen and phosphorus. In Experiment 1, however, where no treatments were applied in 1977, levels of foliar nitrogen also increased in the period 1976-79 (Farrell, 1985a). Liming produced an

Table 4. *Mean nutrient concentration (% DM) for Block 1 (Experiment 2) and Block 3 (Experiment 1).*

	Nutrient Concentration (% DM)															
	N		*P*		*K*		*Ca*		*Mg*		*S*		*Mn*		*Cu*	
Main Effect	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*	*Block 1*	*Block 3*
N_0	0.874	0.706	0.173	0.110	0.983	0.755	0.819	0.279	0.128	0.108	0.108	0.086	0.006	0.004	0.0009	0.0009
N_1	0.935	0.962	0.189	0.155	0.995	0.878	0.340	0.337	0.099	0.138	0.095	0.075	0.004	0.021	0.0004	0.0003
N_2	0.934	0.956	0.148	0.150	0.608	0.857	0.362	0.351	0.114	0.131	0.085	0.093	0.007	0.006	0.0002	0.0003
P_0	1.010	0.944	0.105	0.103	0.806	0.793	0.942	0.353	0.104	0.122	0.100	0.087	0.009	0.010	0.0004	0.0003
P_1	0.812	0.858	0.189	0.145	0.893	0.904	0.391	0.260	0.120	0.138	0.085	0.101	0.005	0.007	0.0005	0.0009
P_2	0.898	0.795	0.200	0.149	0.999	0.828	0.300	0.303	0.115	0.129	0.091	0.081	0.004	0.005	0.0003	0.0004
P_3	0.936	0.902	0.187	0.155	0.750	0.795	0.395	0.373	0.116	0.114	0.107	0.069	0.006	0.020	0.0007	0.0005

increase in foliar calcium, with no other significant differences being recorded in foliar nutrients between experiments (Farrell, 1985a).

Foliar nitrogen levels have fallen considerably since 1979 (Farrell, 1985a) and are now below the level of 1.0% DM which is considered to be adequate for this site (Farrell and McAleese, 1972). Qualitative analysis of the main effect means shows that the effect of applied nitrogen on foliar nitrogen concentrations is still in evidence (Table 4).

Watts (1983) considered a foliar concentration 0.15% DM to be adequate for phosphorus in evergreen conifers. Following this, it can be seen that Experiment 2 has an adequate level of phosphorus and Experiment 1 a moderately deficient level (Table 5), although individual treatments may be deficient. Levels of phosphorus have not fallen as rapidly since 1979 as those of nitrogen (Farrell 1985a), but will probably continue to do so over time. Despite this, the effect of applied phosphorus on foliar phosphorus concentrations can still be seen (Table 5).

Further evidence of the failure of the lime to increase mineralisation is provided by the decline in the foliar concentration of nitrogen and phosphorus since 1979. Of the other nutrients (Table 5), potassium, calcium, magnesium, manganese and copper are adequate and sulphur is deficient when compared to the ranges given by Watts (1983).

Table 5. *Mean foliar nutrient concentrations for Block 1 (Experiment 2) and Block 3 (Experiment 1) (% DM).*

	N	*P*	*K*	*Ca*	*Mg*	*S*	*Mn*	*Cu*
Block 1	0.914	0.170	0.862	0.507	0.114	0.096	0.006	0.005
Block 3	0.875	0.138	0.830	0.322	0.126	0.084	0.011	0.005

Discussion and conclusions

Accelerated growth as a result of fertiliser application is usually explained in terms of nutrients accumulated in tree tissues immediately following fertilisation which are in excess of the requirements for growth. This improved growth generally continues in the years following treatment until the nutrient concentration in tissues fall to pre-treatment levels (Savill and Evans, 1986). This situation was illustrated in the early years of the experiment, where height growth responded vigorously to phosphorus and less so to nitrogen. These responses were reflected in the foliar concentrations of phosphorus and nitrogen. In keeping with the expectations of Savill and Evans (1986), latter years saw a fall in foliar concentrations with a consequent fall-off in growth rate. The declining general yield classes presented by Farrell (1985a) most readily illustrate this. By 1993, this decline had slowed considerably, although the decline in foliar nutrient concentrations has continued, with nitrogen deficient throughout and phosphorus moderately deficient to deficient. This ongoing decline in general yield class is probably due to continuing immobilisation of nitrogen in the forest floor, measurable levels of which were found by Farrell (1985a).

The failure of the lime to stimulate growth means that forest crops on peat will not benefit from the application of nitrogen and phosphorus in the presence of lime. Similar results have been found for nitrogen-poor soils in Sweden (Andersson and Persson, 1988), where the decreased growth was explained by a decrease in the net nitrogen mineralisation caused by liming.

It is useful to hypothesise whether fertilisers without lime would have improved the growth of the crop. At this stage, canopy closure was complete, with nutrient cycling within the ecosystem (as litterfall, crown leaching, root death and root exudation) and within the trees themselves becoming the dominant processes. Also, at this time, the capture and retention of nutrients from rainwater, aerosols, dust and gas is most efficient. Low immobilisation and enhanced inputs mean that for many elements, demands on the soil nutrient capital is low so that supplies are rarely inadequate and consequently responses to fertilisers unlikely (Miller, 1981).

At this stage, it is uncertain whether the crop will maintain the same general yield class until maturity. Levels of nitrogen are clearly inadequate and it has been hypothesised that on low nutrient capital sites, of which this is typical, litter which is low in nitrogen takes longer to decompose, resulting in the availability of nitrogen being reduced even further (Heilmann, 1966; Tamm *et al.*, 1960). Consequently, progressive nutrient deficiency can develop on marginal sites. Forest crops are capable of supplementing their nitrogen requirements by scavenging nitrogen from the atmosphere. In a study carried out in a Sitka spruce crop in Cloosh Valley, Connemara, Boyle *et al.* (1997) found evidence of nitrogen uptake by the canopy. It is unlikely, however, that these amounts would be sufficient to complete the nitrogen requirements of the crop.

It is pertinent to ask, given the limitations of the results, what are the lessons in this work for forest managers and the afforestation of peatlands. It is clear that, in order to achieve satisfactory levels of growth, the application of fertilisers is necessary. This would involve application at establishment and probably more following canopy closure. It is also clear that the magnitude of the growth response to these inputs decreases with time. Whether the decline in yield class will continue is uncertain.

This presents the question of the sustainability of peatland forestry. In recent years, interest has been focused at both policy and research level on the long term sustainability of the forest resource (Farrell, 1995, 1997; Anon., 1996; Mulloy, 1997). The principle of sustained yield is a cornerstone in the management of a forest resource. Over 40% of our plantations are on peatland and the processes which govern their sustainability are complex. The soil material in a peatland forest is organic, and drainage and forest establishment begin a process of subsidence and decomposition which threatens the sustainability of the peat soil. These losses may be offset by litter inputs from the forest crop. Whether such sites can continue to support forest crops beyond the first rotation, without artificial inputs, is unclear. Should yield class continue to decline with time, investigation of the measures necessary to arrest this decline would be warranted, as would the economics of such measures.

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