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The Use of Foliage and Soil Information for Managing the Nutrition of Sitka and Norway Spruce on Cutaway Peatlands

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This investigation focuses on the development and nutrient status of the first Sitka spruce and Norway spruce stands established on milled cutaway peatlands in Ireland in the late 1980s and early 1990s. Phosphatic fertilization at planting is critical for the establishment of trees on cutaway peatlands but may not be sufficient to see the stands close canopy. Results from this study indicate the likely demand for P and N fertilizer during the rotation of these plantations. During the ten-year-study period (1994–2004), the nutrient status of both Norway and Sitka spruce stands deteriorated with the passage of time. Twenty-seven out of the twenty-eight examined stands became P deficient before 10 years old and half of the plots were N deficient within 13 to 15 years. Sitka spruce stands became N and P deficient earlier than Norway spruce. Regardless of species, tree stands growing on *Sphagnum* peat entered the critical N deficiency threshold sooner and were all severely deficient by 2004 compared to 22% of the trees growing on *Phragmites* peat. The effects of aerial re-fertilization were also site specific and although P deficiency was cured, the trees were likely to suffer from nutrient imbalance (N and Cu especially). These results demand a change of standard fertilization practices, which should be related more specifically to peat type and species requirements. Peat type identification and foliar analysis monitoring should become standard management tools while the long-term continuous monitoring of these new forests would be very valuable throughout their first rotation.

Keywords foliar analysis, long-term trend, *Picea sitchensis*, *Picea abies*, cutaway peatland, fertilization
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1 Introduction

Following the cessation of peat harvesting for fuel and horticultural production in Ireland, over 80 000 ha of industrial cutaway peatlands will be available over the next 15–30 years for other uses, such as forestry (Renou and Farrell 2005). Tree plantation is also expected to be a predominant after-use of cutaway peatlands in Finland, Estonia and Sweden (Vasander et al. 2003) and is an option considered in eastern Canada when restoration is not feasible (Bussières 2005, Caisse et al. 2006). In order to successfully grow commercial stands on these sites, effective silvicultural treatments must be prescribed which rely on an understanding of the relationship between tree growth and site characteristics. One important aspect of this relationship is tree nutrition.

Nutrient availability is one of the primary factors limiting growth on peat soils (Taylor and Worrell 1991). It is difficult to estimate the nutritional suitability of cutaway peatlands for growing trees because chemical properties are often quite complex. For example, phosphorus (P) contents are much lower in peat than in any mineral soil, requiring an application of phosphatic fertilizer at planting (Carey et al. 1985, Kaunisto and Aro 1996). However, P concentrations typically vary within the peat profile (Kaunisto 1997), so that variation in peat depth can cause variation in P nutrient regime of the peat. In addition, peat has a low P sorption capacity (Cuttle 1983, Nieminen and Jarva 1996) so that most of the applied P will end up in the solution and be available for up-take or will be leached.

No studies have yet shown that a standard initial phosphatic fertilization is sufficient to see tree stands develop to canopy closure on cutaway peatlands in Ireland. Several authors have reported that plantations on Finnish cutaway peatlands frequently experience P, K and also N deficiencies before canopy closure (Paavilainen and Päivänen 1995, Kaunisto and Aro 1996, Aro 2003). Nutritional requirements are greatest between about 5 and 15 years of age, when all nutrients are employed in the development of a tree crown and root system (Miller 1981). At this stage of the rotation (pre-canopy closure), plantations are dependent on the availability of soil nutrients in order to build a canopy and this is the period when nutrient deficiencies are most likely to occur.

Good nutritional status is critical for an optimum wood production but also increases resistance against stress from both biotic and abiotic agents. Miller (1995) argues that if deficiencies are rectified prior to canopy closure there is then unlikely to be any further nutritional problems later in the rotation, provided that nothing occurs to disrupt one or more of the nutrient cycles. However, standard initial and re-fertilization practices may not allow severely deficient cutaway peatland plantations to complete crown development. Whether it is necessary to plan for a second or even third fertilization prior to canopy closure is important for the economics of cutaway peatland plantations.

This investigation focuses on the development and nutrient status of the first Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Norway spruce (*Picea abies* (L.) Karst.) stands established on milled cutaway peatlands in Ireland in the late 1980s and early 1990s. The monitoring over the first fifteen years produced a chronosequence that can be used to examine the duration of initial fertilization and the variation of the nutrient concentrations with time. Growth and nutritional status varied greatly among these plantations and this study examined whether foliar nutrient concentrations reflected underlying variation in soil nutrient content. Furthermore, the short-term effects of re-fertilisation were examined in three Sitka spruce stands displaying variable site quality. By creating the first base-line information on the long-term foliar mineral changes in cutaway peatland plantations, this study examines whether fertilizing practices on such sites should be related more specifically to site type and species requirements.

2 Material and Methods

2.1 Sites

The investigation was based on twelve Norway spruce stands and sixteen Sitka spruce stands located across eleven forest sites in the Irish midlands (mild temperate climate and elevation between 40 and 70 m a.s.l.). These sites were planted between 1988 and 1990 at a density of 2500 stems/ha, without any site preparation, and 600 kg/ha of 0-10-20 (NPK) was manually broadcast soon after planting. Three Sitka spruce stands were also examined, namely Clongawney, Clonsast and Noggus; these stands were planted in 1989 with seedlings of identical provenance and received the same silvicultural treatments as described above. In 2001, they received a second application of fertilizer by helicopter: 350 kg/ha of rock phosphate (12% P) and 250 kg/ha of urea (46% N).

2.2 Sampling and Analyses

Sampling protocols and analyses were similar for all sampling campaigns carried out between 1994 (when the trees were between 5–7 years old) and 2004. A permanently marked circular plot (8 m diameter) was used in each stand with the plot centre chosen for site uniformity and away from drainage ditches. Total height, leader growth and diameter at breast height (DBH) were measured on all trees within the plot. Each tree was also assessed visually for foliar nutrient deficiency symptoms. Foliar sampling was carried out during the dormant season (November–January). Twenty trees per plot were chosen for randomly foliar sampling among the dominant and co-dominant trees. Current year needles from the top third of the crown (lateral branches) were chosen and the twenty samples pooled by plot. Samples were oven-dried to a constant weight at 70°C. Twigs were removed and needles were ground with a Glen Creston grinder to < 2 mm size. Total nutrient concentrations (phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), sulphur (S), boron (B), copper (Cu) and zinc (Zn) were extracted by wet digestion with nitric and perchloric acids (Zasoski and Burau 1977) and the extracts were analysed by Inductive Coupled Plasma Optical Emission Spectrometry (Varian, Liberty 200). Total nitrogen (N) was measured using a Kjeldahl distillation and digestion unit after a sulphuric acid digestion. The same chemical analyses were carried out on peat samples collected from each site in 2001 and again in 2004 for the three re-fertilised Sitka spruce stands. One peat sample was analysed per plot and comprised five sub-samples, systematically taken from the 0–20 cm peat layer using a 25 mm gauge auger. The pH of the peat was determined in distilled water (peat/water V/V=1/2). Percentage loss on ignition (% organic matter) was calculated as the percentage difference in weight of soil lost in combustion at 400ºC relative to the weight of soil dried at 105ºC.

Table 1. Deficient and optimum foliar nutrient concentrations for young stand of Sitka and Norway spruce during the dormant season, as unit oven-dry weight. Modified from Everard (1973), Leaf (1973), Binns et al. (1980), Taylor (1991) and Savill et al. (1997).

Element	Unit	Deficient	Marginal	Satisfactory
N	g/kg	<12	12–15	>15
P	g/kg	<1.2	1.2–1.8	>1.8
K	g/kg	3–5	5–7	>7
Ca	g/kg	<0.5	0.7–1	1–2
Mg	g/kg	<0.3	0.3–0.7	>0.7
S	g/kg	<0.9	0.9–1.5	>1.5
Fe	mg/kg	<20	20–50	>50
Cu	mg/kg	<2.5	2.5–4	>4
Zn	mg/kg	<9	9–15	>15
Mn	mg/kg	<4	4–25	>25
B	mg/kg	<5	5–20	>20

The foliar concentration ranges against which results should be compared are a function of different factors such as species, age, sampling material, time of sampling and geographical location (Van den Driessche 1974, Raitio 1995). In the absence of such standards for spruce growing in Ireland, the values used for this study have been compiled from a number of works published in Britain (Everard 1973, Leaf 1973, Binns et al. 1980, Taylor 1991, Savill et al. 1997) and are presented in Table 1. Nutrient concentration ratios may reveal nutritional imbalance, even when element concentrations are in the normal range. These ratios were calculated as the percentage of a nutrient relative to the needle N concentration.

All analyses were carried out using the SAS statistical software package (SAS Institute Inc. 2002). Proportions were transformed using arcsine square-root transformation. Relationships

Table 2a. Summary of soil properties of the 28 spruce stands grouped according to peat type. Soil properties refer to 0–20 cm soil depth sampled in 2001. Figures are means and standard deviations in brackets. Significant differences ($p < 0.5$) between means are indicated with a different letter.

	Peat type			
	All	*Phragmites* peat	*Sphagnum* peat	Woody fen
n	28	14	9	5
Depth (cm)	85 (27)	86 (25)	≥100 (0)	30 (25)
Aeration (%)	62 (24)	58 (22)	55 (22)	93 (12)
pH	4.8	5.1	3.6	5.8
OM (%)	93 (4)	93.5 (3)	96.2 (2)	87 (7)
N (g/kg)	14.2 (5.6)	17 (4.8)a	10.7 (5.6)b	15.2 (5.2)ab
P (g/kg)	0.27 (0.08)	0.29 (0.09)a	0.22 (0.07)a	0.29 (0.10)a
K (g/kg)	0.13 (0.13)	0.12 (0.09)a	0.07 (0.02)a	0.32 (0.23)b
Ca (g/kg)	14.6 (10.6)	15 (8.3)a	8.8 (4.8)a	27.9 (17)b
Mg (g/kg)	0.9 (0.5)	0.8 (0.5)a	1.09 (0.6)a	0.7 (0.3)a
S (g/kg)	4.4 (1.6)	4.9 (1.4)a	3.3 (1.6)b	4.9 (1.5)ab
Fe (mg/kg)	8.3 (6.5)	11.4 (7.3)a	4.2 (4.2)b	9.5 (2.4)ab

Table 2b. Pearson coefficients of correlation between peat properties. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

	Depth	Aeration	OM	N	P	K	Ca	Fe	S
Depth	1								
Aeration	–0.6***	1							
OM	0.32	–0.36	1						
N	–0.25	–0.05	–0.33	1					
P	–0.23	0.2	–0.55**	0.46*	1				
K	–0.68***	0.63***	–0.65***	0.14	0.47*	1			
Ca	–0.13	0.35	–0.56**	0.37	0.15	0.13	1		
Fe	–0.33	0.22	–0.41*	0.57**	0.45*	0.06	0.48*	1	
S	–0.12	–0.01	–0.55**	0.61***	0.36	0.009	0.61***	0.75***	1

between foliar and soil nutrient concentrations were studied by Pearson correlation analysis. The effects of peat types on soil variables were tested by analysis of variance and means were further compared using a pairwise *t*-test (α = 0.05). The degree of association between soil parameters and foliar nutrient concentrations as well as morphological attributes of the trees was evaluated using the simple linear correlation procedure (Pearson).

3 Results

3.1 Peat Nutrient Concentrations

P concentrations were very low (Table 2a) (average across all sites 0.27 g/kg), but did not vary significantly between the different peat types encountered. Apart from Mg, all other edaphic properties varied between the peat types. The nitrogen content in *Phragmites* peat was significantly higher than in *Sphagnum* peat. The same comparison was valid for iron and sulphur. Woody fen peat contained much higher concentrations of cations such as potassium and calcium than the two other peat types which was probably due to their relatively shallow depth and proximity to calcareous mineral sub-soil. Compared to *Phragmites* and woody fen peat, *Sphagnum* peat was strongly acidic with a higher organic matter content. Sites where *Sphagnum* peat was present at the surface were much deeper and had a shallower layer of aerated peat. Regardless of peat type, peat depth was negatively correlated with K and with aeration (Table 2b). P was positively correlated with K (Pearson coeff. = 0.47, p = 0.013) and with Fe (Pearson coeff. = 0.46, $p = 0.016$). Higher N concentrations were also associated with higher Fe and S concentrations. P, K, Ca, Fe and S were all negatively correlated with percentage of organic matter. *Phragmites* peat was found on 58% of the Norway spruce stands and 44% of the Sitka spruce stands while *Sphagnum* peat was found on 25% of the Norway spruce stand and 37% of the Sitka spruce stands.

3.2 Foliar Nutrient Concentrations between 1994 and 2004

The concentrations of all foliar nutrients studied were above the deficiency threshold in 1994. Foliar N and P decreased during the following 10 years to reach values below the deficiency threshold by 2004. While foliar Fe also decreased, it did not fall below the critical threshold value (Fig. 1). On the other hand, Mg and Ca concen-

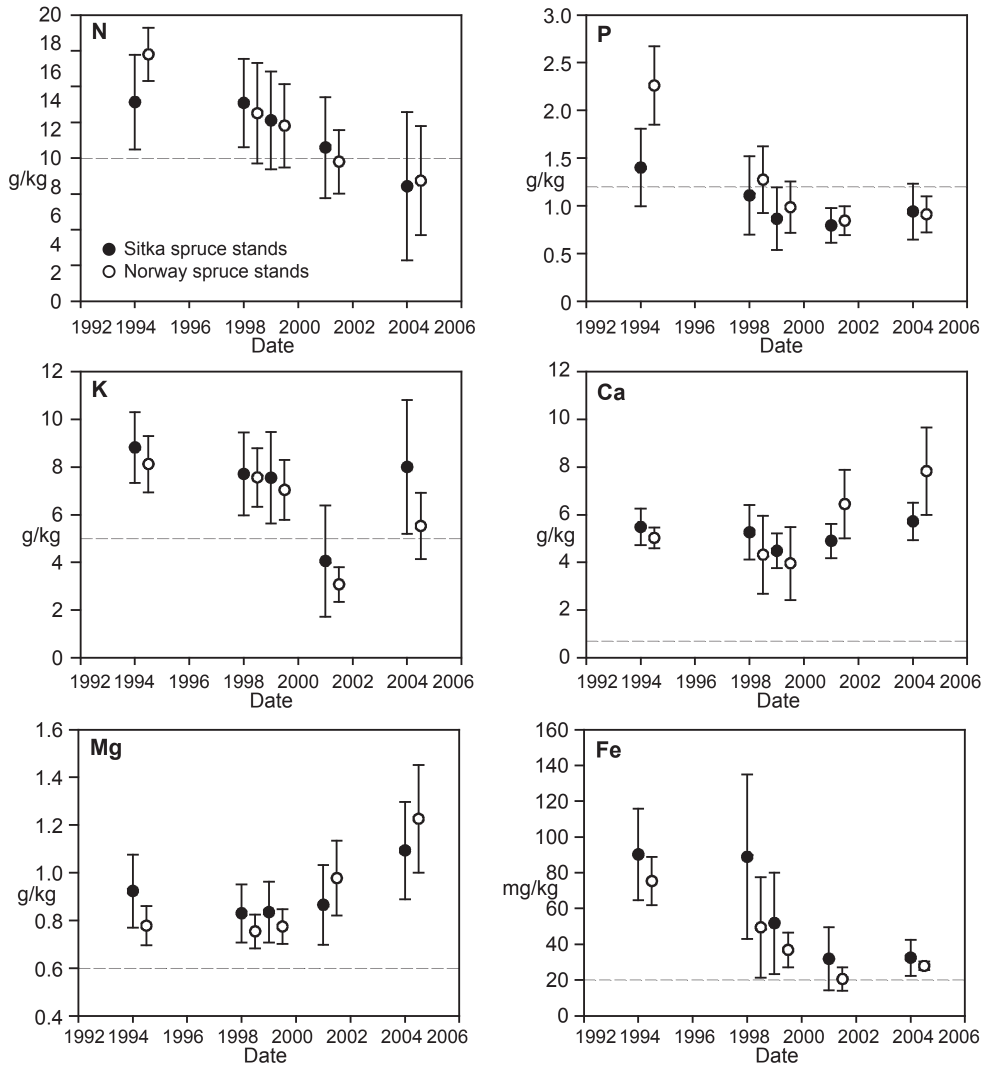

Fig. 1. Foliar concentrations (N,P, K, Ca, Mg and Fe) measured in 1994, 1999, 2001 and 2004. Means of 16 Sitka spruce stands and 12 Norway spruce stands. Error bars denote ± standard deviation and dashed line denotes deficiency threshold.

Table 3. Foliar element concentrations for 1994 and 2004: ranges, means, coefficients of variation, percentage changes relative to 1994 values and paired *t*-test values.
* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$ and ns = not significant.

Foliar nutrient Macro (g Kg^{-1})	1994 Range	1994 Mean	1994 CV	2004 Range	2004 Mean	2004 CV	Relative difference (% of initial value)	*t*-test value
a) BY SPECIES								
Norway spruce (N = 12)								
N (g/kg)	15.1–19.6	17.8	0.08	4.3–15.4	10.7	0.28	–40	5.83***
P (g/kg)	1.8–3.1	2.3	0.18	0.7–1.3	0.9	0.21	–60	12.35***
K (g/kg)	6.8–10.47	8.1	0.15	3.7–8.5	5.5	0.25	–32	5.13**
Ca (g/kg)	4.5–6.0	5.0	0.09	5.3–10.9	7.8	0.23	55	–3.32*
Mg (g/kg)	0.6–0.9	0.8	0.11	0.9–1.5	1.2	0.18	58	–7.41***
S (g/kg)	1.1–1.6	1.3	0.10	0.7–1.2	0.9	0.16	–31	6.31***
Fe (mg/kg)	53–100	75.3	0.18	24.1–31.2	27.8	0.09	–63	8.97***
Cu (mg/kg)	1.8–4.8	3.3	0.30	2.2–6.6	4.1	0.36	24	–1.92ns
B (mg/kg)	16.6–27.3	21.5	0.17	9.9–35.6	20.0	0.52	–7	2.07ns
Zn (mg/kg)	24.6–37.2	29.5	0.13	14.2–50.0	30.1	0.37	2	–0.8ns
Sitka spruce (N = 16)								
N (g/kg)	11.8–20.3	15.3	0.17	2.1–16.2	10.4	0.40	–32	3.06*
P (g/kg)	0.9–2.0	1.4	0.29	0.6–1.7	0.9	0.31	–36	3.93**
K (g/kg)	6.0–10.8	8.8	0.17	2.3–10.7	8.0	0.35	–9	0.69ns
Ca (g/kg)	4.1–7.1	5.4	0.14	4.4–7.0	5.7	0.14	6	–0.48ns
Mg (g/kg)	0.7–1.2	0.9	0.17	0.7–1.3	1.1	0.19	21	–2.5*
S (g/kg)	1.2–1.8	1.5	0.12	0.8–1.5	1.2	0.14	–17	3.05*
Fe (mg/kg)	53.0–146.7	90.2	0.28	19.5–55.1	32.4	0.31	–64	11.06***
Cu (mg/kg)	2.4–4.9	3.5	0.18	1.7–6.9	4.4	0.38	27	–1.65ns
B (mg/kg)	18.5–26	22.9	0.12	22.4–57.7	37.2	0.27	62	–5.9***
Zn (mg/kg)	22.2–44.65	28.7	0.23	19.3–50.1	29.4	0.29	2	–0.11ns
b) BY PEAT TYPE								
Phragmites peat								
N (g/kg)	11.8–19.4	16.3	0.15	7.9–16.2	12.5	0.19	–23	3.7**
P (g/kg)	0.9–2.4	1.7	0.28	0.6–2.6	1.02	0.49	–40	4.2**
K (g/kg)	6.8–8.9	7.8	0.08	2.4–9.5	6.5	0.35	–17	1.98ns
Ca (g/kg)	4.1–6.5	5.1	0.13	3–8.4	5.9	0.21	16	–2.31*
Mg (g/kg)	0.7–0.9	0.8	0.11	0.7–1.5	1.1	0.21	40	–4.7**
Sphagnum peat								
N (g/kg)	12.7–19.6	16.5	0.13	4.06–12	9.04	0.32	–45	5.3**
P (g/kg)	1.1–2.6	1.7	0.30	0.6–1.7	0.9	0.33	–47	4.84**
K (g/kg)	6.02–10.8	8.8	0.21	2.3–10.7	7.2	0.41	–18	1.07ns
Ca (g/kg)	4.9–7.1	5.5	0.14	4.5–10.5	6.4	0.27	16	–0.13ns
Mg (g/kg)	0.7–1.1	0.9	0.15	1–1.4	1.2	0.13	33	–1.8ns

trations increased with the passage of time while K remained steady except in 2001 when it fell temporarily below deficiency threshold. Overall, foliar nutrient concentrations showed significant changes between 1994 and 2004 (Table 3). N, P and K decreased significantly with decreases being more pronounced in Norway spruce than in Sitka spruce (Table 3a). Concentrations of foliar cations (Ca and Mg) increased for all plots but increases were higher in the Norway spruce plots. Among the micro-elements, there were large changes in Fe concentrations with a decrease of 63% for Norway spruce and 64% for Sitka spruce. Levels remained however above deficiency thresholds. No other micro-elements varied in the Norway spruce, while a significant increase was recorded for boron concentrations in Sitka spruce (62%). Analysing the data by peat type showed that

Table 4. Percentage of plots within each foliar nutrient category over time for major nutrients.

a) By species

		Norway spruce			Sitka spruce		
		Deficient	Marginal	Satisfactory	Deficient	Marginal	Satisfactory
N	1994	0	0	100	0	34	66
	1999	8	59	34	13	44	44
	2004	50	42	8	50	25	25
P	1994	0	0	100	19	25	56
	1999	83	17	0	88	13	0
	2004	92	8	0	100	0	0
K	1994	0	8	92	0	6	94
	1999	0	50	50	13	19	69
	2004	25	42	33	13	6	81

b) By peat type

		Phragmites			*Sphagnum*		
		Deficient	Marginal	Satisfactory	Deficient	Marginal	Satisfactory
N	1994	9	18	73	0	14	86
	1999	9	62	29	33	56	11
	2004	22	67	11	100	0	0
P	1994	20	20	60	14	29	57
	1999	100	0	0	89	11	0
	2004	100	0	0	78	22	0
K	1994	0	10	90	0	14	86
	1999	8	46	46	11	22	67
	2004	27	27	46	22	22	56

decreases in N and P concentrations were significant in both peat types but greater for trees growing in *Sphagnum* peat compared to *Phragmites* peat (Table 3b). The increase of foliar cations (Mg and Ca) was significant in *Phragmites* peat plot but not in *Sphagnum* peat plots.

When examining the percentage of plots within each foliar nutrient category over time (Table 4a), it was observed that all Norway spruce plots had satisfactory foliar N concentrations in 1994 in comparison to only 66% of the Sitka spruce plots. However, by 2004, Sitka and Norway spruce plots suffered from N deficiency in the same proportion (50%). Norway spruce plots had also satisfactory P concentrations, while almost 20% of the Sitka spruce plots already showed critical P deficiency. In 1999, that is 8–10 years after planting, all the stands suffered from either marginal or severe P deficiency. While no plots of either species showed strong N:P imbalance in 1994, about 20% of all plots showed critically high N:P ratio (>16) by 2004. K deficiencies were experienced sooner in the Sitka spruce plots but in 2004, the number of marginal or deficient K levels were ~ 3 times more frequent in Norway spruce and Sitka spruce. 45% of Norway spruce plots showed N:K imbalance (< 2) compared to 25% in Sitka spruce.

When analysing the data by peat type, trees growing on *Sphagnum* peat entered the critical N deficiency threshold sooner and were all severely deficient by 2004 compared to only 22% of the trees growing on *Phragmites* peat (Table 4b). However, trees growing on *Phragmites* peat were all severely P deficient by 1999. While there was no severe K deficiency recorded in any of the plots in 1994, 27% of the *Phragmites* plots were severely K deficient compared to 22% of the *Sphagnum* plots in 2004.

3.3 Relationships between Foliar Nutrients, Soil Nutrients and Stand Characteristics

Foliar N concentrations were positively correlated to the soil nitrogen content (Pearson coeff. = 0.63, p = 0.007, Fig. 2). This was true for both *Sphagnum* and *Phragmites* peat and both species. Foliar N was also positively correlated to soil calcium content (Pearson coeff. = 0.45, p = 0.0263). Foliar and soil levels of P were poorly correlated, although the lowest foliar concentrations coincided with low levels of available P in acid *Sphagnum* peat plots. There was no relationship between foliar K and its availability in the soil. No relationships were found amongst foliar nutrient concentrations.

Stand growth characteristics did not correlate with any nutrient variables (foliar or soil). Height and diameter growths were very variable among the studied plots, especially as the trees grew older. Norway and Sitka spruce's growth patterns are similar enough to allow a direct comparison. In 1994 (5–7 years after planting), mean heights of Norway and Sitka spruce were similar: 154 cm (CV = 0.14) and 156 cm (CV = 0.16) respectively. In 2004, mean height of Norway spruce plots averaged 614 cm (CV = 0.22; range: 267 to 793 cm) while mean height of Sitka spruce plots averaged 515 cm (CV = 0.40; range: 240 to 954 cm). Between 1994 and 2004, average annual leader growth dropped by 50% for both Sitka and Norway spruce.

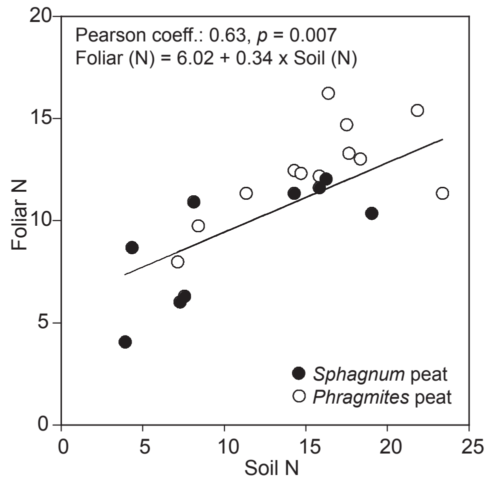

Fig. 2. Relationship between foliar N and soil N concentrations, measured in 2001 in different peat types, *Sphagnum* peat and *Phragmites* peat.

3.4 Effects of Re-fertilization in Three Sitka Spruce Stands

As with the other Sitka spruce stands monitored in this study, foliar P and N concentrations changed with time at Clongawney, Clonsast and Noggus (Fig. 3). Prior to re-fertilization in July 2001, the three stands suffered from severe P nutrient deficiency, and either severe or critical N deficiency. In the winter following aerial fertilization (2001), trees growing in Clonsast and Noggus showed immediate positive response in terms of foliar P, reversing the trend observed over the previous three years (Fig. 3). In Clongawney, on the other hand, there was no immediate response and P concentrations first continued to decline and increased only during the second year. Clongawney experienced a more rapid response in P levels than the other two plots. Re-fertilization increased foliar N content immediately at Clongawney and Noggus but not in Clonsast where foliar N concentration was not in the critical range prior to re-fertilization (Fig. 3). Foliar N dropped subsequently at all sites to reach values below the critical level after four years. The foliar N:P ratio was excessively high in Clongawney the first winter following re-fertilization but dropped subsequently for the following 3 years, in the same fashion as in the other two sites (Fig. 3). Foliar K levels also increased except at the superior site in Noggus where K concentrations consistently decreased following re-fertilization and fell below critical level after four years (Fig. 3). The foliar N:K ratio increased at all sites following re-fertilization and decreased subsequently to reach just above 1 (Fig. 3). Other elements measured remained above critical threshold following re-fertilization. Boron remained in the critical range during two years following re-fertilization and increased to optimum level after that (data not shown).

Foliar nutrients did not correlate with tree growth characteristics prior to re-fertilization and the stands displayed a growth gradient from very poor, mediocre to superior for Clongawney, Clonsast and Noggus respectively. In 2001, the trees in

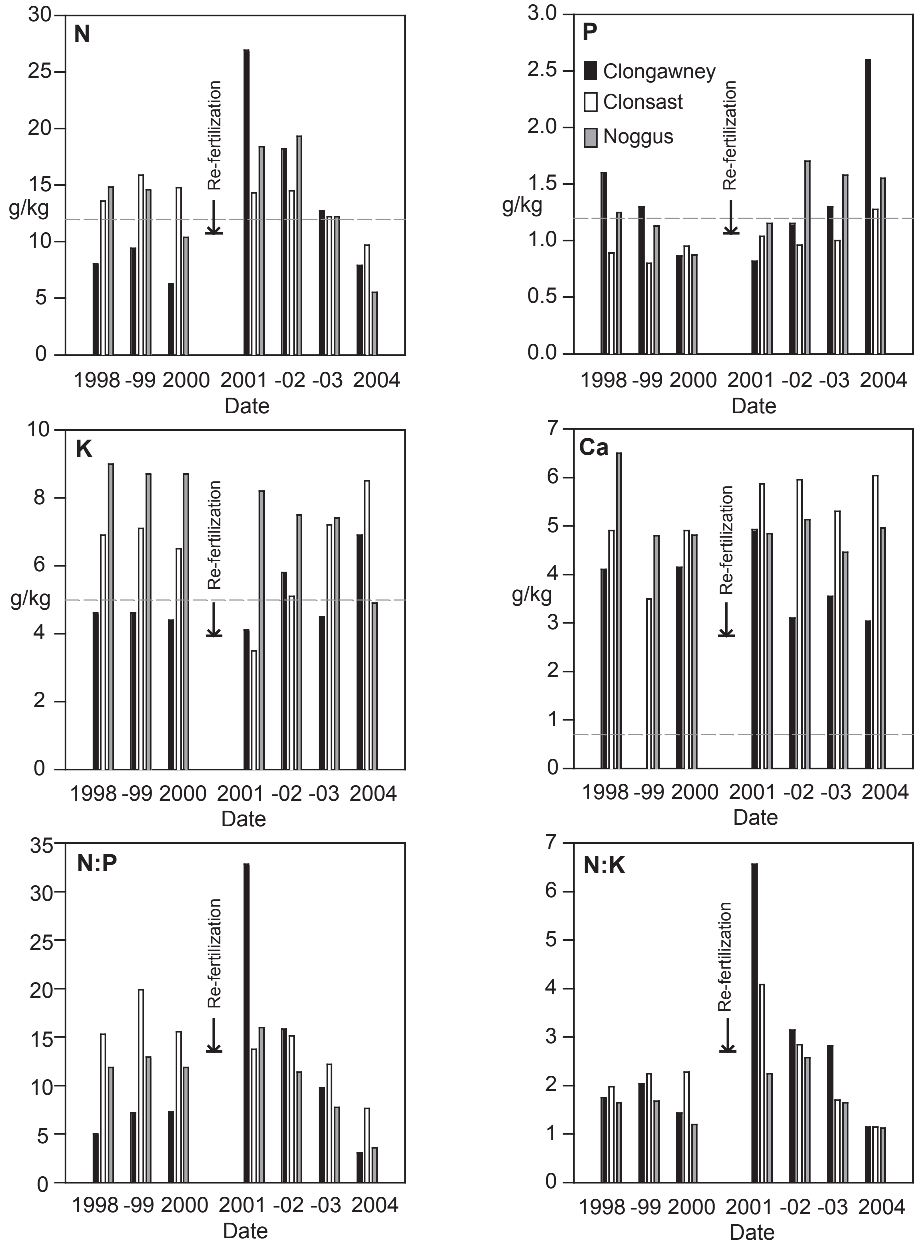

Fig. 3. Foliar concentrations (N, P, K, Ca) and ratios (N:P and N:K) measured in three Sitka spruce stands re-fertilized in July 2001 with P and N. Dashed line denotes deficiency thresholds.

Noggus were on average 261% taller and 264% larger in diameter than the trees in Clongawney (Table 5). Differences between the three stands were even more pronounced for average basal area with Noggus showing its superiority. Following re-fertilization, annual height increment increased at all three sites for three consecutive years (Fig. 4). It slightly increased at Clonsast during the fourth growing season but decreased at the two other sites. The highest annual height increment was recorded in Noggus, for the first two years but Clongawney, the poor site, had the

Table 5. Site characteristics comparison between the three re-fertilized Sitka spruce stands measured in 2001.

	Clongawney *Phragmites*	Clonsast *Phragmites*	Noggus *Phragmites*
Peat characteristics			
Average depth (cm)	100	100	80
Aerated layer (%)	55	50	75
pH	4.9	3.6	5.8
OM (%)	98.0	97.6	92.3
Soil nutrients			
N (g/kg)	6.40	10.70	16.30
P (g/kg)	0.16	0.19	0.41
K (g/kg)	0.10	0.09	0.10
Ca (g/kg)	2.15	5.70	16.10
Mg (g/kg)	2.06	0.95	0.56
S (g/kg)	2.5	2.2	3.8
Fe (mg/kg)	0.32	2.40	6.68
Stand characteristics			
Height (m)	2.22 (0.55)	3.15 (0.82)	5.80 (1.2)
DBH (cm)	2.76 (0.9)	4.22 (0.39)	7.28 (2.3)
Basal area (m^2/ha)	1.26	2.73	8.53
Growth characteristics	Very poor	Mediocre	Superior

highest height increment for the following two years. On average over the four years following re-fertilization, the poorest site (Clongawney) had the highest annual height increment with 0.50 m/yr compared to 0.42 m/yr for Noggus and 0.31 m/yr for Clonsast (Table 5). The basal area increment was the greatest at the superior site in Noggus with 2.31 m^2/ha/yr, compared to 1.05 m^2/ha/yr at Clongawney and 0.22 m^2/ha/yr at Clonsast. However, Clongawney was the only site to show steady increased basal area increment for four years after re-fertilization (Fig. 4). In effect, re-fertilization trebled the basal area increment at Clongawney, doubled at Noggus while increase was limited in Clonsast.

N, P, Ca and Fe concentrations measured in the peat at the three sites mirrored the growth gradient: in the increasing order Clongawney < Clonsast < Noggus (Table 5). Clongawney and Clonsast were very nitrogen-poor sites. On the other hand, Noggus, the superior site, contained a healthy 16.3 g/kg. P concentrations at Noggus were also twice those found in Clongawney and Clonsast. Peat nutrient concentrations measured in 2004 were not significantly different to that of 2001 (data not shown).

4 Discussion

4.1 Pattern of Nutritional Status over Time

The nutrient status of both Norway and Sitka spruce stands established in the late 1980s has deteriorated with the passage of time. It is clear from the data presented here that the factor most critically affecting the nutrient status and early development of spruce is the availability of phosphorus and nitrogen. During the 10-year study period, P and N foliar concentrations decreased almost linearly reaching levels well below deficiency levels, especially for P. While foliar nutrient concentrations are generally higher in newly-planted seedlings than in young and mature trees (Bonneau 1988), such low-level nutrient status engendered growth stagnation and retarded canopy closure. Despite an initial PK fertilization, all stands, except one, became P deficient within 10 years old and half of the plots were N deficient before 13–15 years. This confirms that trees growing on cutaway peatlands rely mostly on applied P to grow, and that only a small fraction of the total N content in the peat becomes available to the trees over the first ten years after planting. On

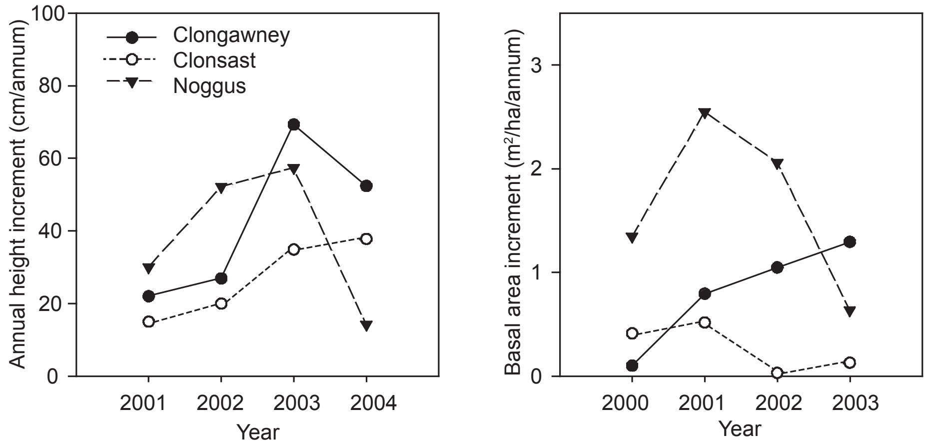

Fig. 4. Mean height and basal area increment against year in three Sitka spruce stands re-fertilized in July 2001.

Finnish cutaway peatlands, initial PK fertilization supplied pine and birch seedlings with mineral nutrients for 4 to 6 years (Kaunisto 1997), and for 15 years when the remaining peat was not deeper than 60 cm (Aro 2003). On deep oligotrophic peat in Northern Ireland, Sitka spruce which received "a handful of basic slag at planting", became extremely P- and N-deficient four years later (Dickson and Savill 1974). The same authors concluded that the growth of Sitka spruce is sustained during the first 10 years following planting on deep peat by applying 90 kg/ha P and 100 kg/ha K at time of planting, followed by 100 kg/ha N as urea applied at the beginning of the eighth growing season.

4.2 Factors Influencing Foliar Nutrient Status

Nutrient deficiencies may be induced by several factors including 1) human-induced factors: e.g. inadequate prescribed fertilizer type or method of application, fertilization during unsuitable weather or to areas with high risk of leaching; 2) physiological factors: e.g. the use of nutrient-demanding or fast growing species; and 3) physico-chemical factors: e.g. inherent poor site properties.

1) In a number of studies, substantial leaching of applied phosphorus from drained forest peatlands has been observed (Malcolm and Cuttle 1983, Nieminen and Ahti 1993). While it is not possible to confirm that leaching took place following initial fertilization of these plantations, other experiments showed loss of fertilizer-P from afforested cutaway peatlands (Renou et al. 2000, Renou and Cummins 2002) and a split application of rock phosphate has now been recommended as best practice (Renou and Farrell, unpubl.). Unlike in mineral soils, P leaching from peat soils occurs because they generally contain low concentrations of Al and Fe oxides – which are able to form complexes with phosphate (Nieminen and Jarva 1996, Silfverberg and Hartman 1998). Peat containing higher Fe content, is more likely to adsorb applied P. Results from our study showed a positive relationship between P and Fe concentrations in the peat as reported in other works (Silfverberg and Hartman 1999, Rautjärvi et al. 2004). Fe contents were found to be particularly low in *Sphagnum* peat, implying a reduced P sorption capacity which renders this peat type prone to P leaching.

2) While *Picea* species are more nutrient demanding species than either *Pinus* or *Larix* (Van Goor 1970, Miller 1995), differences can also occur among *Picea* species themselves. This study showed that Sitka spruce stands became P and N deficient sooner than Norway spruce stands. It has been argued that mycorrhizae associated with different species may help the nutritional status of the tree (Harley and Smith 1983, Bowen 1984). A survey of mycorrhizae fruit bodies carried out in 1998 showed that ectomycorrhizal species were present in similar quantity and quality in both the Norway and Sitka spruce stands investigated in this study (Cassidy 2000). Although this survey was limited to fruiting bodies, nutritional benefits resulting from such association would appear to be similar for both species. Differences in the two species may however occur during the early growth development. It has been observed that Norway spruce grows slowly for the first year after planting (Horgan et al. 2003), particularly on cutaway peatlands (Renou and Farrell, unpubl.). Sitka spruce, on the other hand, has a rapid early growth rate (Joyce and O Carroll 2002), and is known to favour nutrient-rich leaves, twigs and fine roots. In this study, the rate of accumulation of nutrients by Sitka spruce might have peaked earlier than with Norway spruce. When planted on very nutrient-poor medium such as *Sphagnum* peat, nutrient deficiency can be predicted to occur sooner in Sitka spruce than in Norway spruce thus requiring earlier re-fertilization for the former. Planting less nutrient demanding species, such as pine, may be a better choice on *Sphagnum* peat.

3) The chemical composition of the peat inevitably affects tree nutrition. Peat nutrient concentrations showed an imbalance especially between N and P. The ratio of N:P was on average 100:2 in the peat across the studied sites whereas trees need N and P in the ratio of 100:10–13 (Kaunisto and Aro 1996). The imbalance between N and P in this study was comparable, if not slightly more pronounced than in Finish (Aro 2003) or Canadian (Andersen et al. 2006) cutaway peatlands. Foliar N content significantly reflected the N content in the peat and changes in foliar N concentrations varied according to peat type that displayed different total peat N status. *Sphagnum* peat contained significantly lower amounts of N than *Phragmites* and woody fen peat. Several other authors have also pointed out that nitrogen content in sedge peats was higher than in *Sphagnum* peats (Isotalo 1951, Kaunisto 1987). Values measured in this study (mean of 10.7 g/kg) are well below the 13–15 g/kg suggested by Paavilainen and Päivänen (1995) for satisfactory tree growth on peat. Results from this study would lead to conclude that Sitka or Norway spruce plantations growing on *Sphagnum* peat will undoubtedly become N deficient before reaching canopy closure. Foliar N was also positively correlated with peat calcium concentrations. Peat with higher Ca content (i.e. higher pH), such as *Phragmites* peat may have allowed for faster microbial activity to decompose the peat and release organically bound N. On the other hand, the correlation between peat P and foliar P concentrations was very poor and similar results have been found in other studies (Mannerkoski 1973, Kaunisto and Paavilainen 1988). This is probably due to the fact that only minor differences in total P occurred between the peat types. The fact that trees became P deficient earlier in *Phragmites* peat which contains higher P content than *Sphagnum* peat may be due to the fact that the former contained twice the concentration of Ca and almost triple that of Fe (Table 2), thus increasing its P adsorption capacity (Nieminen and Jarva 1996). While this is generally recognised, Nieminen and Penttilä (2004) found that peat types can differ in their P bio-availability due to their variable P fractions. They found that Fe-P and Al-P complexes, which are more abundant in certain peat types, may be more effective source of P to trees than Ca-P. Since P is a key element for satisfactory growth on cutaway peatlands, clarification on such relationship would be useful.

It is clear that peat total P contents found across all the study sites are too small to sustain spruce plantations during the establishment, forcing the trees to rely solely on applied P. Peat P values found in this study (maxima of 0.46 g/kg for *Phragmites* peat and 0.34 g/kg for *Sphagnum* peat) were lower than means recorded in Finnish cutaway peatlands (Aro 2003) but similar to those in Sweden (Nilsson and Lundin 1996). A mean P concentration of 0.27 g/kg combined with a bulk density of 150 kg/m^3 (Renou, unpublished data) would give the total P concentration in the 0–20 cm peat layer of 81 kg/ha. This value is lower than the 150–200 kg/ha recommended by Kaunisto (1982) and Holmen (1969) for satisfactory tree growth peat. It is thus likely that re-fertilization with P is needed on all Sitka and Norway spruce cutaway peatland plantations that received the standard initial P fertilization.

Foliar K concentrations remained above deficiency threshold during the whole monitoring period except in 2001 during which cumulative rainfall was much lower (670 mm) compared with the mean rainfall for the period 1951–2004 (845 mm) (data from Boora met station, Board na Móna). In terms of tree nutrition, the supply of potassium displays a certain dependency on water supply and potassium deficiency is often triggered by drought period (Nilsen 2004, Wilpert 2004); this process is also likely to occur when the peat dries out. It should also be noted that although K deficiencies were not widespread, total K concentrations were very low in *Phragmites* and *Sphagnum* peat with a calculated equivalent of 40 kg/ha.

4.3 Re-fertilization Effects

The growth response to re-fertilization with P and N was different across the three stands. Trees growing on the superior site (Noggus) responded best to the re-fertilization in terms of DBH and basal area but height growth response was slightly better at the poorest site (Clongawney). Response was smallest on the intermediate site (Clonsast). This confirms that the growth of trees at both Clongawney and Noggus was limited by low nutrient supply. In Clonsast, on the other hand, the lack of growth response as well as the lack of P and N uptake in the foliage points towards another growth-limiting factor. Foliar copper concentrations, that were measured in 2004 only, were below deficiency threshold (< 2.5) at Clonsast with 2.3 mg/kg compared to 5.6 mg/kg in Clongawney and 5.16 mg/kg in Noggus. Cu deficiency in Sitka spruce have been reported in peats fertilized with high level rock phosphate (Binns et al. 1980, Forest Service 1980, Kaunisto 1987, Joyce and O Carroll 2002).

At the two responsive sites, the duration and pattern of the foliar nutrient response differed between P and N. Foliar P concentrations increased during the four years following re-fertilization. This would suggest that re-fertilization with rock phosphate affected rather slowly the foliar P concentrations and this emphasizes the significance of a sufficiently early re-fertilization to minimize loss of productivity due to P shortages. Conversely, foliar N concentrations increased significantly the first year and subsequently decreased linearly. The different foliar response between N and P created an imbalance the first year after application in the most P-deficient site (Clongawney). Due to a very high N:P ratio (N:P > 30, Fig. 3), trees visibly suffered from the acute shortage of P compared to N by displaying large-scale browning of current-year needles. Similar phenomenon has been observed with Scots pine on drained mires in Finland following re-fertilization with N (Kaunisto 1987). The reason why foliar N concentrations dropped below deficiency levels four years after re-fertilization may be partly explained by an excellent growth in 2003 (Fig. 4) which may have caused the dilution of foliar N concentrations. However, the fact that height growth increment dropped in 2004 for the two sites showing very low foliar N concentrations and satisfactory foliar P level, demonstrates that these sites have become N-limited. If this is substantiated, a second N application may be required to sustain tree growth during the rotation, thus questioning the economics of this whole enterprise.

Further monitoring is required as these plantations are now approaching a closed canopy and there is not evidence to suggest that after canopy closure, adequate P and N uptake and growth can be maintained without repeated application. It would be also interesting to test whether N and P deficient trees would still need N application before canopy closure, if the trees were to be re-fertilized solely with P before reaching severe deficiency levels (Farrell and McAleese 1972).

Finally, this study confirmed that foliar mineral analysis is a useful tool for managing the fitness of tree plantations (Mead 1984, Perry 1994). Several concepts have been developed to interpret foliar data but their application may be limited: for example, the Diagnosis and recommendation integrated system (DRIS was described first by Beaufils 1973), requires large and specific database to establish its standard reference values; while the Graphic Vector analysis method (Timmer and Stone 1978, Braekke 1996) requires specific field plans for fertilization and sampling. The classical approach which compares foliar nutrient concentrations (together with nutrient ratios) measured in the dormant season with defined nutrient concentration ranges associated with deficient, critical and optimum levels, may be more easily applied and interpreted by practitioners who rely principally on the visual symptom approach. This study also showed that soil analyses, which give a measure of the total amounts of nutrients in the peat, can indicate the potential capacity of the site for tree production and can also give some guidance about the need for fertilizer. This method is more expensive however and interpreting the results can be difficult. An assessment of the peat type would be a minimum requirement to assess the potential future nutrient status of cutaway peatland plantations.

5 Conclusion and Practical Applications

Growth and development of trees on cutaway peatlands planted in Ireland in the late 1980s (with minimal site preparation) were restricted by inadequate P and N supply. The duration of the initial standard fertilization was limited to 10 years for P and 13–15 years for N. Results from this study demand a change of standard fertilization practices, which should be related more specifically to site type and species requirements. New guidelines should review planting spruce on very poor peat (such as *Sphagnum* peat). On such sites, managers should consider using less demanding species such as pine, grown either pure or as a nursing mixture with Sitka or Norway spruce. Poor initial species choice has long term implications for fertilizer input to a site and it is likely to be more difficult to justify the application of P and N in the future both on sustainable forestry and economic grounds. The effects of aerial N and P re-fertilization were also site specific and although P deficiency was cured, the trees were found to suffer from nutrient imbalance. From both silvicultural and environmental viewpoints, two applications of lower rates of rock phosphate may be more beneficial during the establishment period. The use of foliar nutrient data in conjunction with soil information should inform the need for N and K application. Since none of these cutaway peatland plantations have yet completed a full rotation and given the likelihood of further nutrient deficiencies, complete fertilizer trials should be set up to ascertain the need for re-fertilization both prior to and post canopy closure. In the context of sustainable forest management on cutaway peatlands, foliar analysis monitoring should become a standard management tool.

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