Fertiliser addition is important for tree growth on cut-over peatlands in eastern Canada

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SUMMARY

Fertilisation is considered essential for tree growth on cut-over peatlands. However, little research has been carried out on these managed ecosystems in North America. Two experiments were conducted on peatlands planted with black spruce (*Picea mariana* (Mill B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch). The first experiment compared the efficiency of six different localised and soil-incorporated fertilisers, applied at planting time, in promoting the growth and survival of seedlings. A second experiment evaluated the nutritional needs of previously established black spruce and tamarack plantations that exhibited stagnating growth. Growth and survival of black spruce seedlings were best improved with the commercial Forest Pak™ fertiliser (2N-0.5P-0.7K g per plant), whilst for tamarack the optimum was reached with an experimental formulation fertiliser (7N-3P-5K g per plant). Spot fertilisation with granulated PK fertiliser (0N-3.1P-5.7K g per plant) led to lower success for both species. For re-fertilisation, the shortage of phosphorus was the most growth-limiting factor for both tree species. Tamarack showed a beneficial response to a complementary application of potassium, whereas for black spruce the application of nitrogen and potassium in addition to phosphorous induced an additional growth increase.

KEY WORDS: cut-over bog, restoration, reclamation, rehabilitation, NPK fertilisation, tree plantation.

INTRODUCTION

Ombrotrophic bog ecosystems are significantly disturbed when subjected to the modern method of peat extraction that uses large vacuum collectors. The vegetation is stripped away and extensive drainage work is carried out to permit access by the necessary heavy machinery. As a result, the environmental conditions when peat extraction ceases are very different from those found in natural ombrotrophic mires (McNeil *et al*. 2000, Groeneveld & Rochefort 2002, Campbell *et al*. 2002, Price *et al*. 2003).

In North America, the favoured rehabilitation option for cut-over peatlands is ecological restoration to wetland, and an effective method has been developed since 1990. The short and long term goals, as well as the different steps of this method, are clearly presented by Rochefort *et al*. (2003) and Rochefort & Lode (2006).

Some portions of cut-over peatlands may be unsuitable for ecological restoration with *Sphagnum* mosses. In these cases, tree planting can be the ideal complementary option for re-establishing vegetation. Trees can be used to recreate forested borders around cut-over peatlands that resemble the laggs surrounding natural peatlands. They can also be planted to promote habitat heterogeneity by forming thickets in parts of the cut-over sites that are not suitable for moss growth, for example where the soil is too dry or along former access roads. Trees could also be planted to form windbreaks or to screen active and abandoned peat extraction sites.

Cut-over peatlands are harsh environments for planted tree seedlings. The residual peat is characterised by nutrient concentrations similar to, but more variable than, those found in poor fens (Wind-Mulder *et al.* 1996). It also has a low nitrogen to phosphorous ratio (Kaunisto & Aro 1996) and so offers imbalanced nutrition for trees. Especially in North America, where only horticultural-quality peat is extracted, the peat layer remaining afterwards is often relatively thick. As the trees that can grow there have shallow roots (Kaunisto & Viinamäki 1991, Aro 2000, Aro & Kaunisto 2003), they have no access to mineral elements from below because only the deepest part of the peat profile can be enriched through proximity to the underlying mineral soil (Aro & Kaunisto 1998a). As a consequence, tree seedlings planted on unfertilised cut-over peatlands rapidly suffer from nutrient deficiencies that lead to poor growth and low survival (Aro & Kaunisto 1998b, Letho 2005, Leupold 2005, Bussières *et al.* 2008). Fertilisation at planting is thus necessary to ensure their success (Carey *et al*. 1985, Valk 1986, Aro &

Kaunisto 1998b, Leupold 2005). However, the positive effect of an initial fertiliser application is short-lived, lasting for 4–6 years (Kaunisto & Aro 1996, Aro & Kaunisto 1998a, Jones & Farrell 1997, 2000). Consequently, re-fertilisation of plantations must be considered if tree growth is to be maintained once the beneficial effect of the first application has attenuated.

Few studies of tree growth on cut-over peatlands have been undertaken in Canada (Bussières *et al*. 2008), and most of the current scientific knowledge on this topic comes from work carried out in Europe. The objectives of the research reported here were: 1) to compare the efficacy of six localised fertiliser treatments, applied at planting time, in promoting the growth and survival of black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) seedlings planted on a cut-over peatland with thick residual peat; and 2) to determine the nutritional needs for nitrogen (N), phosphorous (P) and potassium (K) of four-year-old black spruce and tamarack showing symptoms of growth stagnation in plantations on cut-over peatlands.

METHODS

Fertilisation at planting experiment

Site description

The initial fertilisation experiment was conducted on the Pointe-au-Père cut-over peatland (48° 29' N, 68° 27' W), which is located in the Bas-Saint-Laurent region of the province of Quebec, Canada. The mean annual temperature is 3.9°C and the lowest and highest monthly averages are -11.7°C for January and 18.2°C for July. The mean annual precipitation is 915 mm, with 272 mm falling as snow (Environment Canada 2006). Peat extraction activities ceased in 1997 and the thickness of the remaining peat ranges from 1 m to more than 1.5 m. For the uppermost 5–10 cm of peat, the mean pH is 4.5 and the mean N concentration is 0.51%.

The two tree species planted for this experiment were black spruce (*Picea mariana* (Mill.) BSP) and tamarack (*Larix laricina* (Du Roi) K. Koch). The root plug sizes of the containerised seedlings were 110 cm^3 for black spruce and 90 cm^3 for tamarack. Planting density was 1,100 trees per hectare (3 m x 3 m).

Experimental design

The experimental setup was a randomised block design in which six localised fertiliser treatments were repeated in three blocks for both tree species. Twelve cut-over peat fields of 30 m width, separated by drainage ditches, were used for the experiment. The basic experimental unit was a plot of 150 trees (10 x 15) receiving the same fertiliser treatment. Three unfertilised comparison plots of 50 trees (10 x 5) were also planted with each species. Only a few unfertilised plots were established because previous studies had shown that tree survival rates were very low without fertilisation (Leupold 2005, Bussières *et al*. 2008).

The trees were planted in mid-June 2004, and they were fertilised at planting. The six localised fertiliser treatments included three experimental and two commercial formulations applied as slow-release fertiliser pockets placed below ground, as well as one experimental mix of granulated rock phosphate (0-13-0) and muriate of potash (0-0-60; Table 1) applied to the peat surface. Dosages were chosen to resemble the fertiliser treatment recommended by Aro (2001), which is approximately 3 g of P and 5 g of K for each tree. However, it was impossible to obtain fertiliser pockets without N because N is inherent to the coating polymer used to achieve slow release of the fertiliser. The fertiliser pockets were produced by Restoration Technologies International (RTI) of Salinas, California. Each pocket was buried at 5 cm depth in a slit made at a distance of 5 cm from the seedling plug. The granulated treatment was applied to the peat surface, in a circle of radius 15 cm around each seedling.

Measured variables

Five sample plots were randomly placed within each experimental unit. Each plot included three trees, oriented diagonally. Tree height was measured immediately after planting in three of these plots per experimental unit. Terminal shoot length was measured in all five plots at the end of the second growing season (October) following planting.

Seedling survival rate was determined for each experimental unit at the end of the second growing season. At the same time, five entire trees were gently uprooted. The trees were immediately returned to the laboratory where their roots were washed with running water to remove adhered peat. The trees were then oven-dried for 72 hours at 105°C before weighing.

Data analyses

The data collected for each tree species were analysed using ANOVA (analysis of variance), following the randomised block design of the experiment. The data were checked with respect to

Table 1. Formulation of the localised fertiliser treatments applied at planting to black spruce and tamarack seedlings, for the initial fertilisation experiment. “Experimental” indicates custom-made formulations designed by the researchers but produced and delivered in the same ‘tea bag’ (pocket) format as the commercial pack (Pak™), by the same manufacturer.

		Formulation (%)			Element content (g per plant)		
Fertiliser	Abbreviation	N	P_2O_5	K_2O	N	P	K
PK granular	PK	0	11	10	0	3.1	5.7
Experimental 1	E1	10	48	0	1.4	3	0
Experimental 2	E2	10	23	20	3.2	3	5
Experimental 3	E3	18	17	15	7	3	5
Restoration Pak™	Rp	11	17	9	1.1	0.7	0.7
Forest Pak™	Fp	20	11	9	2	0.5	0.7

normality and heterogeneity before each ANOVA test, and it was found that no data transformations were necessary. A first ANOVA was performed on the data collected immediately after planting, to determine whether there were any differences between the experimental units at the outset of the experiment. Data collected at the end of the second growing season were subjected to another ANOVA to investigate whether growth differed amongst the fertiliser treatments. A protected LSD (Fisher’s Least Significant Difference) test was applied when a significant treatment effect was present, to determine the differences between individual treatments. Data from the unfertilised comparison plots were not included in the analyses because they were not part of the randomised block design; the high mortality and poor growth would have created great heterogeneity in the data. The α level of the statistical tests was set at 0.05.

Re-fertilisation experiment

Site description

The re-fertilisation experiment was carried out on the cut-over peatlands of Bay-du-Vin (47° 02’ N, 65° 06’ W) and Baie-Sainte-Anne (47° 00’ N, 64° 52’ W) in the province of New-Brunswick. Here, the mean annual temperature is 5.0°C, and the lowest and highest monthly averages are -10.0°C for January and 19.3°C for July. The mean annual precipitation is 1,274 mm with 400 mm falling as snow (Environment Canada 2006). Peat extraction activities at the sites ceased in 2000 and the remaining peat thickness ranges from 27 to 144 cm at Bay-du-Vin and from 22 to 183 cm at Baie-Sainte-Anne (Bussières *et al.* 2008). The mean pH of the uppermost 5–10 cm of peat for both sites is 4.1. The average N concentration of the surface peat is 0.46% for the Bay-du-Vin site and 0.49% for the Baie-Sainte-Anne site.

Trees were planted on both peatlands in the spring of 2001; black spruce at Bay-du-Vin and tamarack at Baie-Sainte-Anne. Seedlings grown in 110 cm^3 containers were planted out at a density of 2,500 plants per hectare (at 2 m spacing). Each tree was fertilised at planting time with a fertiliser tablet of Evergro Tab™ (10 g per plant, 20-10-5 [N-P_2O_5-K_2O], 2N-0.4P-0.4K g per plant) produced by the Evergro Group of Companies of Delta, British Columbia (Canada).

Experimental design

The experimental unit of this study was a plot of 30 trees (3 x 10), all receiving the same re-fertilisation treatment. However, only the central eight trees in the central row of each plot were sampled in order to avoid edge effects.

The treatments involved three factors (N, P and K) at two levels (presence or absence), and all of the eight possible fertiliser combinations were tested. A randomised block design was employed. This had a full factorial treatment structure which was replicated four times.

The trees at both sites were re-fertilised at the beginning of their fifth growing season, in May 2005. Granulated fertilisers were applied to the peat surface in a circle of 1 m diameter around each tree. This application method was used rather than the usual broadcast application in order to limit weed invasion from active peat extraction fields close to the experiment. The sources of N, P and K used were urea (46-0-0 [N-P_2O_5-K_2O]), rock phosphate (0-13-0) and muriate of potash (0-0-60). When included in a treatment, the quantity applied to each tree was 87 g for urea, 159 g for rock phosphate and 31 g for muriate of potash. This translates to elemental application rates of 40 g of N, 9 g of P and 15 g of K per tree. These dosages were chosen with consideration of the fertiliser quantities used in a Japanese larch (*Larix leptolepis* (Sieb. Zucc.) Gord.) plantation on a drained peatland in Newfoundland, Canada (Wells 1991) and for forestry plantations on cut-over peatland in Finland (Aro 2001).

Measured variables

Tree height was measured immediately after treatment application. Tree growth was assessed by measuring the lengths of terminal shoots at the end of the second growing season following re-fertilisation (in October).

Foliar samples were collected at the end of the first growing season following re-fertilisation. Tamarack was sampled in mid-August before the onset of nutrient retranslocation preceding needle abscission (Tilton 1977, Tyrrell & Boerner 1987, Mugasha *et al*. 1999), and the black spruce samples were collected in October when the needle nutrient concentration is stable. Current-year shoots from two lateral branches of the upper third of each sampled tree were harvested. For tamarack, only the short shoots with determinate growth were selected (Clausen & Kozlowski 1967). All shoots harvested from each experimental unit were pooled to form composite samples. The samples were immediately brought to the laboratory and oven-dried at 65°C for 48 hours. The needles were then detached from the shoots and sub-samples of 500 needles were separated for mass determination. The samples were then ground with a coffee grinder and sent to the chemical analysis laboratory of the Forest and Wood Science Department at Laval University, where foliar concentrations of N, P and K were determined using the method described by Parkinson & Allen (1975).

Data analyses

The correlation between terminal shoot growth during the second season after re-fertilisation and tree height at the beginning of the experiment was evaluated to confirm that this variable was independent of initial tree size.

The growth data collected at the end of the second growing season were subjected to an ANOVA following the factorial arrangement of the treatments, to check for the effects of the factors N, P and K as well as their interactions. The α level of the statistical tests was set at 0.05. We checked that the normality and heterogeneity of the data conformed to the requirements for analysis of variance, and no data transformations were needed.

The nutrient content of the needles was calculated as the product of foliar mass and foliar concentration, and these data were used to construct vector diagrams showing the nutritional responses of the trees to the different treatments (Timmer 1991, Haase & Rose 1995). Foliar mass, foliar nutrient concentration and nutrient content of the fertilised trees were standardised to the values obtained for unfertilised trees (=100). This allowed simultaneous graphical presentation of the effects of individual nutrients and direct comparison of the effects of the different treatments.

RESULTS

Fertilisation at planting experiment

The height and diameter at ground level measured immediately after planting showed that the trees were not different at the beginning of the experiment (height: black spruce $P = 0.67$, tamarack $P = 0.72$; diameter: black spruce $P = 0.35$, tamarack $P = 0.10$). The mean total height of black spruce was 50 ± 3 cm and that of tamarack was 22 ± 2 cm. The mean diameter at ground level was 5.4 ± 0.5 mm for black spruce and 3.3 ± 0.3 mm for tamarack.

Black spruce

Terminal shoot length in the second year indicated that the growth of all fertilised trees exceeded that of unfertilised trees. For five of the treatments, mean terminal shoot length in the second year was 5–6 cm and gave little indication of differences between treatments. Growth was slower for the PK treatment, which resulted in a mean terminal shoot length of 4 cm (Figure 1).

Treatment E2 (NPK 3.2-3-5 g per plant) clearly resulted in the highest biomass accumulation; mean tree dry mass after two growing seasons was 36 g (Figure 1, Table 2). The other pack formulations (Treatments E1, E3, Rp and Fp) gave intermediate results with mean dry mass ranging from 27.4 to 32.5 g per tree. The trees fertilised with granular PK applied to the peat surface accumulated least biomass (12.3 g) over the two growing seasons. For comparison, the mean dry mass of unfertilised trees was 9.8 g.

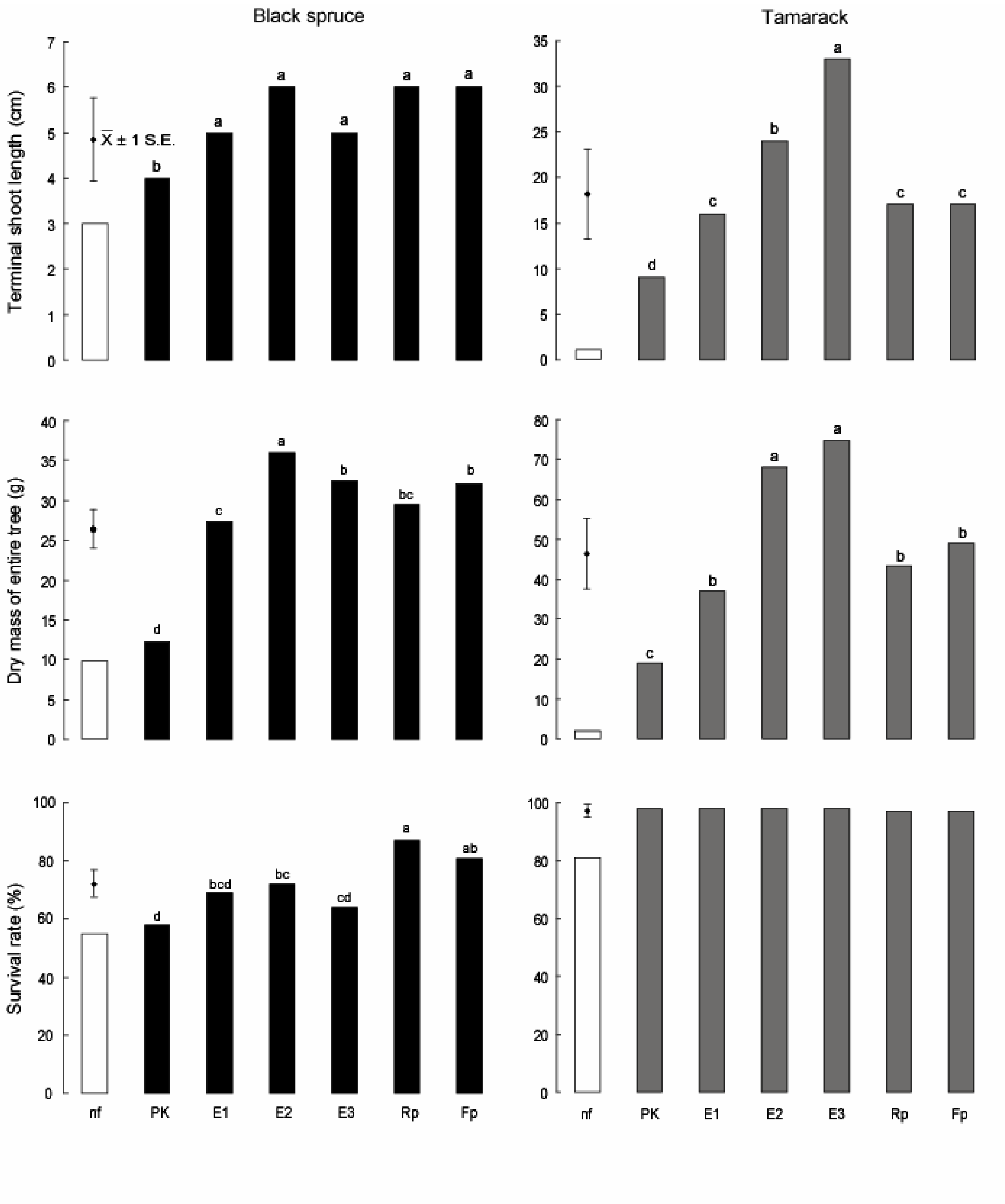

Figure 1. Terminal shoot (**S**pruce : $F_{5,\ 10}$ = 5.82; P = 0.0089; **T**amarack : $F_{5,\ 10}$ = 27.80; P < 0.0001), whole tree dry mass (**S** : $F_{5,\ 10}$ = 63.33; P < 0.0001; **T** : $F_{5,\ 10}$ = 18.66; P < 0.0001) and survival rate (**S** : $F_{5,\ 10}$ 6.22; P = 0.0071; **T** : $F_{5,\ 10}$ = 1.26; P < 0.35;) of black spruce and tamarack two growing seasons after fertilisation with six localised fertiliser treatments, applied at planting. See Table 1 for descriptions of the treatments. Treatments labelled with different letters in the same graph are significantly different (protected LSD test at α level of 0.05). Error bars represent the mean value ± the pooled SE. Data for unfertilised trees were not used in the statistical tests, therefore mean values for the unfertilised trees are presented for comparative purposes only.

Table 2. Analysis of variance for the initial fertilisation experiment

	Black spruce				Tamarack			
Source of variation	d.f.	mean square	F	P	d.f.	mean square	F	P
Terminal shoot length								
Block	2	3	0.8		2	651	6.2	
Fertiliser	5	22	5.8	**0.0089**	5	2,916	27.8	**<0.0001**
Experimental error	10	4			10	105		
Sampling error	180				241			
Total	197				258			
Dry mass of whole tree								
Block	2	41	2.5		2	244	0.7	
Fertiliser	5	1,046	63.3	**<0.0001**	5	6,376	18.7	**<0.0001**
Experimental error	10	17			10	342		
Sampling error	71				71			
Total	88				88			
Survival rate								
Block	2	0.003	0.5		2	0.004	3.0	
Fertiliser	5	0.033	6.2	**0.0071**	5	0.015	1.3	0.35
Sampling error	10	0.005			10	0.001		
Total	17				17			

The highest survival rates were obtained with the two commercial fertiliser packs Rp (87%) and Fp (81%) (Figure 1, Table 2). The surface-applied PK treatment gave the lowest survival rate (58%). Unfertilised trees had a survival rate of 55%.

Tamarack

The experimental pack treatments E2 and E3 (N 3.2 or 7, P-K 3-5;) resulted in the highest growth rates, indicated by mean values of 24 cm and 33 cm for terminal shoot length and 68.1 g and 74.8 g for tree dry mass respectively (Figure 1, Table 2). Again, least growth was observed for trees treated with surface-applied PK, for which terminal shoot length was 9 cm and tree dry mass 18.9 g. However, all fertiliser treatments resulted in more growth than occurred in unfertilised trees, whose terminal shoot length was only 1 cm and dry mass 1.8 g.

All fertiliser treatments led to similar survival rates (P = 0.094 for fertiliser effect; Table 2, Figure 1), which ranged from 92% to 98%. Unfertilised trees had a survival rate of 81%.

Re-fertilisation experiment

Correlation analyses showed that there were no significant relationships between the initial height of either tree species and the length of their terminal shoots two growing seasons after re-fertilisation (black spruce : $r^2 = 0.017$, P = 0.80; tamarack : $r^2 = 0.012$, P = 0.86).

Black spruce

Significant interactions occurred between the effects of the three factors N, P and K on terminal shoot length (P = 0.0097 for N*P*K term, Table 3). The strongest effect of re-fertilisation on black spruce growth was the positive influence of P (Figure 2). Terminal shoot length in trees fertilised with formulations containing this element was 13–23 cm. The highest growth values were obtained by combining all three elements (40-9-15 g of NPK per tree), and the second most effective fertiliser was P alone (9 g per tree). When P was not supplied, terminal shoot length was 4–7 cm.

Vector analysis of foliar content, concentration and mass also indicates that the most important nutritional function of re-fertilisation was associated with P (Figure 3). The presence of P had a significant positive effect on foliar mass, as indicated by the large slope differences between the two dotted lines for treatments including P. Vector length indicates the importance of absorption of one element relative to that of others, and the longest vectors were obtained (for P) where P was applied. In addition, the orientation of the vector in the direction of increased foliar concentration, content

Table 3. Analysis of variance of the re-fertilisation experiment.

	Black spruce				Tamarack			
Source of variation	d.f.	mean square	F	P	d.f.	mean square	F	P
Terminal shoot length								
Block	3	19	0.2		3	283	1.3	
N	1	2	0.02	0.89	1	45	0.2	0.65
P	1	8,505	110	**<0.0001**	1	157,420	730	**<0.0001**
K	1	164	2.1	0.16	1	4,187	19.4	**0.0002**
N*P	1	140	1.8	0.19	1	37	0.2	0.68
N*K	1	951	12.3	**0.0021**	1	43	0.2	0.66
P*K	1	144	1.9	0.19	1	4,217	19.6	**0.0002**
N*P*K	1	629	8.1	**0.0097**	1	0.2	0.00	0.97
Experimental error	21	78			21	216		
Sampling error	215				196			
Total	246				227			
Foliar mass								
Block	3	1,704	0.5		3	40,365	14.3	
N	1	698	0.2	0.65	1	13,530	4.8	**0.040**
P	1	68,280	21.1	**0.0002**	1	1,740	0.6	0.44
K	1	246	0.08	0.79	1	288	0.1	0.75
N*P	1	466	0.1	0.71	1	2,450	0.9	0.36
N*K	1	527	0.2	0.69	1	5,100	1.8	0.19
P*K	1	2,125	0.7	0.43	1	45	0.02	0.90
N*P*K	1	976	0.3	0.59	1	2,485	0.9	0.36
Experimental error	20	3,235			21	2,820		
Total	30				31			

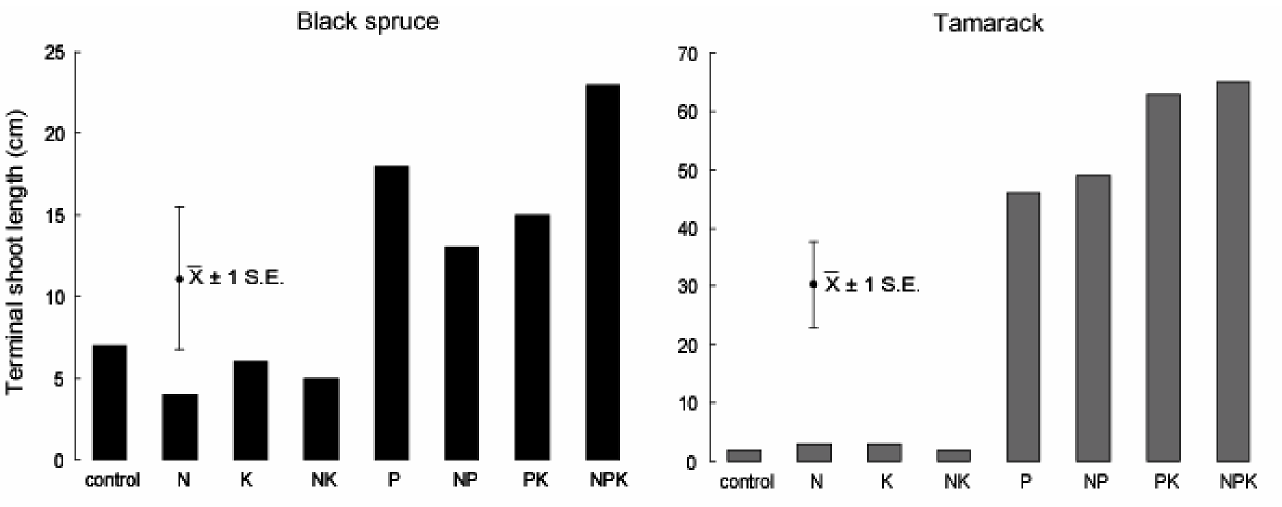

Figure 2. Terminal shoot length of black spruce and tamarack two growing seasons after re-fertilisation with a factorial combination of nitrogen, phosphorous and potassium applied at two levels (presence, absence). Black spruce N*P*K interaction: $P = 0.0097$; $F_{1, 21} = 8.11$. Tamarack P*K interaction: $P = 0.0002$; $F_{1, 21} = 19.56$. The error bars represent the mean value ± the pooled SE.

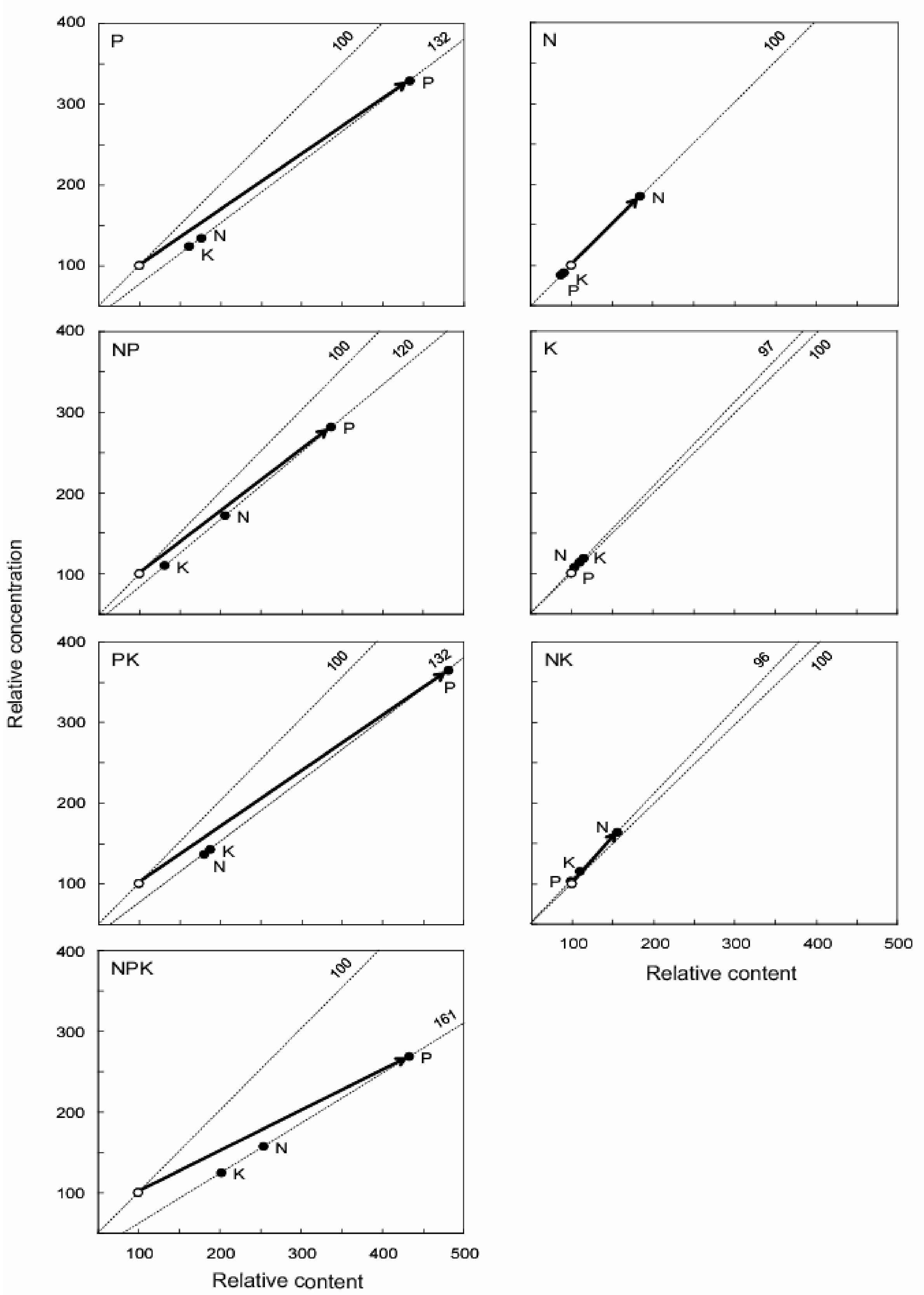

Figure 3. Nutritional effect, after one growth season, of the re-fertilisation of black spruce with a factorial combination of nitrogen, phosphorous and potassium applied at two levels (presence, absence). Dotted lines represent relative foliar mass. Foliar mass: phosphorus single effect P = 0.0002; $F_{1, 21} = 21.10$. Nutrient status of unfertilised trees (open symbol) is adjusted to 100 for comparison with trees treated with fertiliser (solid symbols). The vector is drawn for the greatest nutritional response observed.

and mass shows clearly that the unfertilised reference trees were suffering from P deficiency. Uptake of N and K also increased in trees to which P was applied, even when these elements were absent from the fertiliser. When P was absent from the fertiliser, foliar mass hardly changed and there were small increases in absorption of N only.

Tamarack

Phosphorus was also the most effective of the three elements in promoting tamarack growth (Figure 2). Terminal shoot length was 46–65 cm when P was present in the treatment and only 2–3 cm when it was absent. K was effective in increasing growth only in the presence of P (P*K term P = 0.0002, Table 3), terminal shoot length increasing by 35% when both P and K were applied.

Fertiliser addition had no effect on the foliar mass of tamarack (Figure 4). However, the longest vector in the diagrams was consistently associated with P when this element was applied. When N was included in the treatment, its uptake by needles increased when P was also supplied; but when P was applied alone or with K only, N content decreased. K absorption increased by a small amount when it was applied without P, and its uptake was also enhanced by the presence P. When P was not present in the applied fertiliser, we observed very limited nutritional responses. Application of N or K alone had small effects on absorption, and combining N and K led to a small increase in P uptake.

DISCUSSION

Fertilisation at planting experiment

For black spruce, terminal shoot length did not respond to the different fertiliser treatments. However, clear differences among the treatments were apparent for the dry mass of entire trees. This phytomass variable was more sensitive than terminal shoot length because it integrated all aspects of tree growth (e.g. root system, foliage density and branch growth). Consequently, we determined that the best fertiliser to promote black spruce growth is the experimental formulation E2 (3.2-3-5 g of NPK per tree planted), followed by the experimental fertiliser E3 (7-3-5 g of NPK per tree planted) and finally, the commercial Forest Pak™ (2-0.5-0.7 g of NPK per tree planted).

For tamarack, terminal shoot length and the dry mass of entire trees showed similar responses to the different fertiliser treatments. Experimental fertiliser E3 (7-3-5 g of NPK per tree planted) was the most efficient in promoting growth in height and biomass accumulation in tamarack.

The two experimental fertiliser formulations that promoted the growth most effectively (E2 and E3) contained slowly available N provided directly by the fertilisers as well as P and K. The amounts of P and K in these fertilisers are similar to those recommended by Aro (2001), i.e. approximately 3 g of P and 5 g of K for each tree. However, black spruce seedlings also responded well to the Forest Pak™ (2-0.5-0.7 g of NPK per tree planted), which contained one-sixth of the recommended quantity of P and one-seventh of the recommended dosage of K.

Early access to essential nutrients is of prime importance for the successful establishment of newly planted trees (Margolis & Brand 1990) because the seedlings must rapidly develop new leaves and roots for resource acquisition. Rapid root growth is important for acquisition of soil nutrients and to ensure access to a sufficient water supply (Margolis & Brand 1990). Water supply can be critical in cut-over peatlands, which often present drought conditions during the summer (Price 1997). The root system also anchors the tree in the soil, and trees with well developed roots are less prone to uprooting by animals and less sensitive to the frost heaving that often occurs in cut-over peatlands (Groeneveld & Rochefort 2002).

The fertilisers that promoted tree growth most effectively were not necessarily those that best supported survival. For black spruce, tree survival was highest with the Restoration Pak™ and the Forest Pak™, which contained the smallest quantities of fertiliser trialled. Black spruce survival may be adversely affected by over-fertilisation, as shown by Bussières *et al.* (2008). Oskarsson & Sigurgeirsson (2001) also observed that the survival of locally fertilised trees declined when fertiliser levels were too high. In contrast, tamarack survival did not vary with fertiliser treatment. To optimise both growth and survival of the trees at plantation, the Forest Pak™ (2-0.5-0.7 g of NPK per tree planted) was the most appropriate fertiliser for black spruce, while tamarack had the highest establishment success when it was fertilised with experimental treatment E3 (7-3-5 g of NPK per tree planted).

According to Finnish studies, only PK fertilisation is important for the successful establishment of trees on cut-over peatlands (Aro & Kaunisto 1998b, Aro 2001), as there is apparently sufficient N to sustain tree growth bound within the organic matter of cut-over peat in Finland

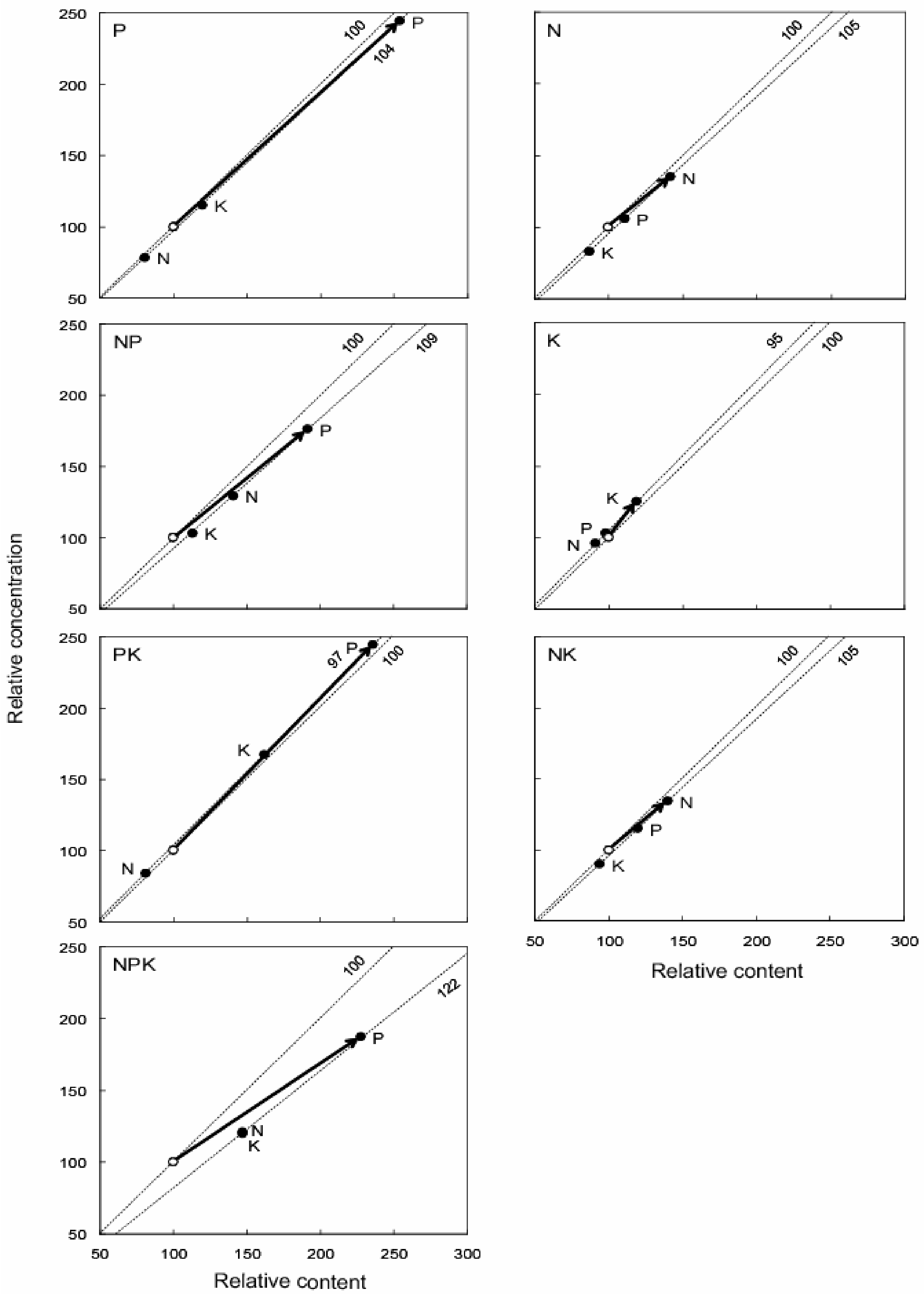

Figure 4. Nutritional effect, after one growth season, of the re-fertilisation of tamarack with a factorial combination of nitrogen, phosphorous and potassium applied at two levels (presence, absence). Dotted lines represent relative foliar mass. Foliar mass: block effect $P < 0.0001$; $F_{3, 21} = 14.31$. Nutrient status of unfertilised trees (open symbol) is adjusted to 100 for comparison with trees treated with fertiliser (solid symbols). The vector is drawn for the greatest nutritional response observed.

(Paavilainen & Päivänen 1995, Aro & Kaunisto 1998a). Furthermore, P fertilisation stimulates microbial activity in the soil, increasing N mineralisation (Finér 1992, Wells & Williams 1996). As a result, the recommended fertiliser treatment in Finland provides P and K only (Aro 2001). The recommended initial fertilisation in Finland is similar to the granular PK treatments used in the present experiment. In our case, this treatment resulted in the slowest growth of terminal shoots and whole tree dry mass for both black spruce and tamarack, and was associated with the lowest survival rate of black spruce. This fertiliser lacked the readily accessible N source provided by the most effective fertilisers in the experiment and the increase in N mineralisation caused by the application of P to the peat was probably too low to provide sufficient N to meet the requirements of the trees. In eastern Canada, N seems to be important for the fertilisation of coniferous trees planted on cut-over peatlands. One possible cause of this difference from the Scandinavian results is the fact that peatlands are mined more deeply in Europe because the peat is used as a combustible (Kaunisto 1997). Thus the trees are planted in more decomposed residual peat whose N concentration is higher because of its higher bulk density (Westman 1981) and potentially higher mineralisation rate. Otherwise it may be due to a lower rate of nitrogenous atmospheric deposition in north-eastern North America (Holland *et al.* 2005).

This initial fertilisation experiment does not allow us to evaluate the duration of the beneficial effect of the treatments. According to the manufacturer of the commercial fertiliser packs, the lifespan of the slow release fertilisers is 2–3 years (Restoration Technologies International, personal communication). Finnish studies show that the effect of PK spot fertilisation using rock phosphate and muriate of potash lasts for 4–6 years (Kaunisto & Aro 1996). In Ireland, nutrient deficiencies, mainly of P, were already present five years after a broadcast PK fertilisation (Jones & Farrell 1997, 2000). The results of the re-fertilisation experiment presented here show that nutrient deficiencies appeared less than four years after an initial dose of the commercial fertiliser Evergro Tab™ (2-0.4-0.4 g of NPK per planted tree).

Re-fertilisation experiment

Of all the nutrients applied in the re-fertilisation experiment, P influenced the growth and nutrition of black spruce and tamarack most. For both species, P application was absolutely necessary for growth improvement to occur, as is also the case for Scots pine (*Pinus sylvestris* L.) plantations on Estonian cut-over peatlands (Valk 1986, Pikk & Valk 1996).

The importance of P application to tree nutrition is illustrated clearly by the vector analysis diagrams. The vector representing P is oriented in the direction of an increase in needle concentration and content, indicating that the growth response to this element was proportionally greater than the response to the other nutrients. The foliar mass of black spruce also increased in response to P application; this mass increase is a good indicator of future tree growth (Timmer & Morrow 1984). The application of P alleviated an apparent deficiency that was impairing growth. In contrast, P fertilisation had no effect on the foliar mass of tamarack but did lead to an increase in tamarack growth.

The lack of a clear relationship between foliar mass and tamarack height growth response to P complicates vector analysis interpretations. The absence of a positive effect of P on foliar mass suggests luxury consumption of this element. In fact, the growth habit of tamarack may present problems for interpretation of foliar mass response; tamarack leaves are borne on short shoots with determinate growth as well as on long shoots with indeterminate growth (Clausen & Kozlowsky 1967). Because the number of needles produced by a bud originating on a short shoot in a given growing season is fixed at the end of the preceding growing season, growth variation during the season should be expressed by a change in needle mass, and therefore needles for mass measurements and vector analysis are harvested from short shoots. In our re-fertilisation experiment, it seems that the effect of P on the needle mass of the short shoots was diluted by growth of the long shoots. The trees seem to have allocated the supplementary nutrition provided by fertilisers to growth of long shoots, and thus the expected foliar mass response of short shoots did not occur. Moreover, the decreased N uptake by the needles of short shoots when P was applied alone or with K (P and PK treatments in Figure 4) indicates possible re-location of N from the short shoots to other parts of the tree.

Apart from its direct influence on tree nutrition, P fertilisation may also have favoured tree growth *via* indirect effects on the uptake of other nutrients. For example, N absorption by black spruce increased when P fertiliser was applied. Phosphorus application is known to promote microbial activity, and since residual peat contains N bound in organic form (Paavilainen & Päivänen 1995, Aro & Kaunisto 1998a), this increased activity favours N mineralisation (Wells & Williams 1996). However, N must be present in the peat in sufficient amounts for the trees to benefit from the increased mineralisation (Pietilänen *et al*. 2005). In general, elimination of a major nutrient deficiency can lead to increased uptake of other elements (Finér 1992). In the present case, alleviating the P deficiency also promoted greater absorption of K by both black spruce and tamarack.

Fertilisation with N and K also had important effects on the growth in height of black spruce and tamarack. For black spruce, growth was favoured by N and K additions when P was also applied. However, we cannot ascribe this positive effect to either one of the two nutrients since it seems that both were required in addition to P to ensure a growth response. If only N or K was added with P, a smaller growth response was observed. This result is difficult to interpret since, according to the vector analysis, the four P treatments had similar nutritional effects. It is possible that black spruce fertilised with N and P only or K and P only expressed a growth increase in some other way than by increasing height.

The growth in height of tamarack increased further on treatment with K when P was also applied. It is possible that the rapid growth promoted by P fertilisation was eventually limited by shortage of K. On the other hand, addition of N did not improve tamarack growth even though the trees took up additional N. Thus it appears that increased N mineralisation in the peat, combined with P fertilisation and possible re-allocation of needle N to long shoot growth, was sufficient to support the trees' nutritional requirements. In a similar experiment on fertilisation of Scots pine plantations on drained peatlands, Sundström (1995) showed that adding N with P and K did not promote tree growth if the peat contained sufficient N.

On both study sites, we observed that the application of N when P was present in the fertiliser combination led to massive invasion by competing vegetation. However, this did not occur when N was applied alone or with K only.

Since our measurements were carried out over two growing seasons only, we cannot determine the duration of the beneficial effect of re-fertilisation on tree growth. The localised spot fertilisation used in this experiment differs from the usual method of broadcast fertilisation used for re-fertilisation work. Consequently, we applied proportionally less fertiliser to the peat than other workers conducting similar studies. Such studies have shown that the positive effect of applying P in a slowly soluble form lasts for 25–30 years in forested peatlands (Silfverberg & Hartman 1999, Rautjärvi *et al*. 2004) but the effect is shorter-lived - generally about 15 years - on cut-over peatlands, (Aro & Kaunisto 2003). The effect of K, applied as readily soluble muriate of potash, also lasts about 15 years in naturally forested peatlands that have been drained (Rautjärvi *et al*. 2004, Pietilänen *et al*. 2005).

CONCLUSION

Fertilisation at planting time is of great importance for successful afforestation of cut-over peatlands. The growth and survival of black spruce and tamarack seedlings is favoured by the application of fertilisers that contain an easily accessible N source. Nitrogen promotes rapid growth of branches and leaves, as well as root systems, during the first few growing seasons. The fertiliser must also contain sufficient quantities of P and K to sustain tree growth. In the light of our results, we consider that the Forest Pak™ (2N-0.5P-0.7K g per plant) is an appropriate fertiliser for local application when black spruce seedlings are planted. For tamarack, the experimental fertilisers E2 (3.2N-3P-5K g per plant) or E3 (7N-3P-5K g per plant) are recommended. However, the positive effect of the initial fertilisation may be short-lived, as suggested by the results of the re-fertilisation experiment.

The growth stagnation of the older black spruce and tamarack plantations at Bay-du-Vin and Baie-Sainte-Anne was due to nutrient deficiencies that arose less than four years after the Evergro Tab™ (2N-0.4P-0.4K g per plant) fertiliser tablets were initially applied. Re-fertilisation was thus necessary in order to sustain tree growth. For both species, growth limitation was due primarily to shortage of P, although tamarack growth also responded positively to a complementary application of K. For black spruce, the application of N and K in addition to P induced a further growth increase. However, N application favoured colonisation by competing vegetation. We recommend that P only should be used for re-fertilisation of black spruce plantations, while tamarack should be re-fertilised with both P and K.

The knowledge gained from the experiments would be improved by monitoring tree growth over a longer time period. The duration of the beneficial effects of initial fertilisation and re-fertilisation could then be estimated and a follow-up treatment considered if required. However, the effort invested to improve tree growth on cut-over peatlands must depend on the landscape function objectives for each plantation.

While these results could potentially be used to inform wood production on cut-over peatlands, tree-planting trials in these disturbed landscapes are presently directed towards peatland restoration, to re-create either forested peatlands or forested borders and tree thickets for otherwise more open restored peatlands. It will be important to assess the compatibility between tree fertilisation and the re-introduction of mosses typical of natural peatlands in the implementation of large scale restoration plans that include a forest component. One should also define an acceptable final tree size and tree stand volume as part of the overall restoration objectives, in order to guide the intensity of fertiliser treatments.

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REFERENCES

Aro, L. (2000) Root penetration of Scots pine and silver birch on cut-away peatlands. In: Rochefort, L. & Daigle, J.-Y. (eds.) *Sustaining Our Peatlands*, Proceedings of the 11th International Peat Congress, Volume II, Canadian Society of Peat and Peatlands, Shippagan, Canada & International Peat Society, Jyväskylä, Finland, 932–936.

Aro, L. (2001) Afforestation of cutaway peatlands in Finland. In: Åman, P. (ed.) *Re-use of Peat Production Areas,* Proceedings of the International Seminar, Oulu, Finland, 19–20 June 2000, EU Northern Periphery Programme, Copenhagen, Denmark, 43–46.

Aro, L. & Kaunisto, S. (1998a) *Afforestation of Peat Cutaway Areas (Field Guide): Aitoneva, Kihniö*. Finnish Forest Research Institute, Parkano Research Station, 24 pp.

Aro, L. & Kaunisto, S. (1998b) Forestry use of peat cutaway areas in Finland. In: Sopo, R. (ed.) *The Spirit of Peatland – 30 Years of the International Peat Society,* Proceedings of the International Peat Symposium, International Peat Society, Jyväskylä, Finland, 185–187.

Aro, L., & Kaunisto, S. (2003) Jatkolannoituksen ja kasvatustiheyden vaikutus nuorten mäntymet-siköiden ravinnetilaan sekä puuston ja juuriston kehitykseen paksuturpeisella suonpohjalla (Effect of re-fertilisation and growing density on the nutrition, growth and root development of young Scots pine stands in a peat cutaway area with deep peat layers). *Suo*, 54(2), 49–68 (in Finnish).

Bussières, J., Boudreau, S. & Rochefort, L. (2008) Establishing trees on cut-over peatlands in eastern Canada. *Mires and Peat*, 3, 10, 1–12.

Campbell, D.R., Lavoie, C. & Rochefort, L. (2002) Wind erosion and surface stability in abandoned milled peatlands. *Canadian Journal of Soil Science*, 82, 85–95.

Carey, M.L., Hammond, R.F. & McCarthy, R.G. (1985) Plantation forestry on cutaway raised bogs and fen peats in the Republic of Ireland. *Irish Forestry*, 42, 106–122.

Clausen, J.J. & Kozlowski, T.T. (1967) Seasonal growth characteristics of long and short shoots of tamarack. *Canadian Journal of Botany*, 45, 1643–1651.

Environment Canada (2006) *National Climate Data and Information Archive*. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_f.html. Consulted in May 2006.

Finér, L. (1992) Nutrient concentrations in *Pinus sylvestris*, growing on an ombrotrophic pine bog, and the effects of PK and NPK fertilization. *Scandinavian Journal of Forest Research*, 7, 205–218.

Groeneveld, E.V.G. & Rochefort, L. (2002) Nursing plants in peatland restoration: on their potential use to alleviate frost heaving problems. *Suo*, 53 (3–4), 73–85.

Haase, D.L. & Rose, R. (1995) Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments. *Forest Science*, 41(1), 54–66.

Holland, E.A., Braswell, B.H., Sulzman, J. & Lamarque, J.-F. (2005) Nitrogen deposition onto the United States and Western Europe: synthesis of observations and models. *Ecological Applications*, 15, 38–57.

Jones, S.M. & Farrell, E.P. (1997) *Survey of Plantation Forests on Bord na Móna Cutaway Bog.* Forest Ecosystem Research Group Report Number 20, Department of Environmental Resource Management, University College

Dublin, Dublin, Ireland.

Jones, S.M. & Farrell, E.P. (2000) *Research Program to Develop a Forest Resource on Industrial Cutaway Peatland in the Midlands*. Forest Ecosystem Research Group Report Number 52, Department of Environmental Resource Management, University College Dublin, Dublin, Ireland, 145 pp.

Kaunisto, S. (1997) Peatland forestry in Finland: problems and possibilities from the nutritional point or view. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R. & Jeglum, J.K. (eds.) *Northern Forested Wetlands Ecology and Management*. CRC Lewis Publishers, Boca Raton, Florida, USA, 387–401.

Kaunisto, S. & Aro, L. (1996) Forestry use of cut-away peatlands. In: Vasander, H. (ed.) *Peatlands in Finland*. Finnish Peatland Society, Helsinki, Finland, 130–134.

Kaunisto, S. & Viinamäki, T. (1991) Lannoituksen ja leppäsekoituksen vaikutus mäntytaimikon kehitykseen ja suonpohjaturpeen ominaisuuksiin Aitonevalla (Effect of fertilisation and alder (*Alnus incana*) mixture on the development of young Scots pine (*Pinus sylvestris*) trees and the peat properties in a cutover area at Aitoneva, southern Finland). *Suo*, 42(1), 1–12 (in Finnish).

Letho, B. (2005) *Skogstillväxten ca 20 år efter plantering på Flakmossen - dikningens och gödslingens betydelse vid beskogning på en avslutad torvtäkt i Värmland* (*Stand growth 20 years after planting on Flakmossen - the significance of drainage and fertilisation in an afforestation trial on a peat harvesting field in the province of Värmland, West Central Sweden*). Graduate Thesis in Biology, Department of Forest Ecology, Swedish University of Agricultural Sciences, Umeå, Sweden, 28 pp. (in Swedish).

Leupold, S. (2005) *Vegetation succession and biomass production after peat ash and PK-fertilization on the cutaway peatland of Näsmyran in Hälsingland, Sweden.* Graduate Thesis in Biology, Department of Forest Ecology, Swedish University of Agricultural Sciences, Umeå, Sweden, 30 pp.

Margolis, H.A. & Brand, D.G. (1990) An ecophysiological basis for understanding plantation establishment. *Canadian Journal of Forest Research*, 20, 375–390.

McNeil, P., Waddington, J.M., Lavoie, C., Price, J.S. & Rochefort, L. (2000) Contemporary and long-term peat oxidation rates in a post-vacuum harvested peatland. In: Rochefort, L. & Daigle, J.-Y. (eds.) *Sustaining Our Peatlands*, Proceedings of the 11th International Peat Congress, Volume II, Canadian Society of Peat and Peatlands, Shippagan, Canada & International Peat Society, Jyväskylä, Finland, 732–741.

Mugasha, A.G., Pluth, D.G. & Macdonald, S.E. (1999) Effects of fertilization on seasonal patterns of foliar mass and nutrients of tamarack and black spruce on undrained and drained minerotrophic peatland sites. *Forest Ecology and Management*, 116, 13–31.

Oskarsson, H. & Sigurgeirsson, A. (2001) Fertilization in Icelandic afforestation: evaluation of results. *Scandinavian Journal of Forest Research*, 16, 536–540.

Paavilainen, E. & Päivänen, J. (1995) *Peatland Forestry, Ecology and Principles*. Springer-Verlag, Berlin, Germany, 248 pp.

Parkinson, J.A. & Allen, S.E. (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. *Communications in Soil Science and Plant Analysis*, 6(1), 1–11.

Pietilänen, P., Moilanen, M. & Vesala, H. (2005) Nutrient status and growth of Scots pine (*Pinus sylvestris* L.) on drained peatlands after potassium fertilization. *Suo*, 56(3), 101–113.

Pikk, J. & Valk, U. (1996) Results of afforestation experiments of cut-over peatlands in Estonia. In: Lüttig, W. (ed.) *Proceedings of the 10th International Peat Congress,* Volume 2, International Peat Society, Stuttgart, Germany, 219–224.

Price, J.S. (1997) Soil moisture, water tension, and water table relationship in a managed cutover bog. *Journal of Hydrology*, 202, 21–32.

Price, J.S., Heathwaite, A.L. & Baird, A.J. (2003) Hydrological processes in abandoned and restored peatlands: an overview of management approaches. *Wetlands Ecology and Management,* 11(1–2), 65–83.

Rautjärvi, H., Kaunisto, S. & Tolonen, T. (2004) The effect of repeated fertilizations on volume growth and needle nutrient concentrations of Scots pine (*Pinus sylvestris* L.) on a drained pine mire. *Suo*, 55(2), 21–32.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K.W. & Malterer, T.J. (2003) North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetlands Ecology and Management*, 11(1–2), 3–20.

Rochefort, L. & Lode, E. (2006) Restoration of degraded boreal peatlands. In: Wieder, R.K. & Vitt, D.H. (eds.) *Boreal Peatland Ecosystems*. Ecological Studies, Vol. 188, Springer-Verlag, Berlin, 381–423.

Silfverberg, K. & Hartman, M. (1999) Effects of different phosphorus fertilisers on the nutrient status and growth of Scots pine stands on drained peatlands. *Silva Fennica*, 33(3), 187–206.

Sundström, E. (1995) The impact of climate, drainage and fertilization on the survival and growth of *Pinus Sylvestris* L. in afforestation of open, low-production peatlands. *Scandinavian Journal of Forest Research*, 10, 190–203.

Tilton, D.L. (1977) Seasonal growth and foliar nutrients of *Larix laricina* on three wetland ecosystems. *Canadian Journal of Botany*, 55, 1291–1298.

Timmer, V.R. (1991) Interpretation of seedling analysis and visual symptoms. In: van den Driessche, R. (ed.) *Mineral Nutrition of Conifer Seedlings*, CRC Press, Boca Raton, Florida, USA, 113–134.

Timmer V.R. & Morrow, L.D. (1984) Predicting fertilizer growth response and nutrient status of jack pine by foliar diagnosis. In: Stone, E.L. (ed.) *Forest Soils and Treatment Impact*, Proceedings of the 6th North American Forest Soils Conference, Department of Forestry, Wildlife and Fisheries, University of Tenessee, Knoxville, USA, 335–351.

Tyrrell, L.E. & Boerner, R.E.J. (1987) *Larix laricina* and *Picea mariana*: relationships among leaf life-span, foliar nutrient patterns, nutrient conservation, and growth efficiency. *Canadian Journal of Botany*, 65, 1570–1577.

Valk, U. (1986) Estonian cut-over peatlands and their use in forestry. In: *Socio-economic Impacts of the Utilization of Peatlands in Industry and Forestry*, Proceedings of the International Peat Society symposium, International Peat Society, Jyväskylä, Finland, 265–276.

Wells, E.D. (1991) Effects of refertilization of an 18-year-old Japanese larch (*Larix leptolepis*) peatland plantation in western Newfoundland, Canada. In: Jeglum, J.K. & Overend, R.P. (eds.) *Proceedings, Symposium '89, Peat and Peatlands, Diversification and Innovation, Volume 1 - Peatland Forestr*y, The Canadian Society for Peat and Peatlands, Quebec, Canada, 129–138.

Wells, E.D. & Williams, B.L. (1996) Effects of drainage, tilling and PK-fertilization on bulk density, total N, P, K, Ca and Fe and net N-mineralization in two peatland forestry sites in Newfoundland, Canada. *Forest Ecology and Management*, 84, 97–108.

Westman, C.J. (1981) Fertility of surface peat in relation to the site type and potential stand growth. *Acta Forestalia Fennica*, 172, 77 pp.

Wind-Mulder, H.L., Rochefort, L. & Vitt, D.H. (1996) Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. *Ecological Engineering*, 7, 161–181.

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