Growth and Nutrition of Scots Pine on Drained and Fertilized Purple Moor Grass Fens in Central Finland

KLAUS SILFVERBERG[1], JORMA ISSAKAINEN[2] AND MIKKO MOILANEN[2*]

[1]*Finnish Forest Research Institute, Vantaa Research Unit, P.O. Box 18, FIN-01301 Vantaa, Finland, e-mail: klaus.silfverberg.@metla.fi,*

[2]*Finnish Forest Research Institute, Muhos Research Unit, Kirkkosaarentie 7, FIN-91500 Muhos, Finland, e-mail: jorma.issakainen@metla.fi, mikko.moilanen@metla.fi.*

**The author responsible for correspondence: Mikko Moilanen, Finnish Forest Research Institute, Muhos Research Station, Kirkkosaarentie 7, FIN-91500 Muhos, Finland. Tel.: +358 8 010 211 3743, fax: +358 8 010 211 3701, e-mail: mikko.moilanen@metla.fi.*

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Abstract

While fens dominated by Purple Moor Grass (*Molinia caerulea* (L.) Moench) have generally been considered unsuitable for forest drainage due to their low content of mineral nutrients, the fact that they also are rich in nitrogen has been acknowledged to offer silvicultural possibilities. This study examined the nutrient status and growth of Scots pine stands (with downy birch as a secondary species) on two drainage and fertilization experiments. Both of the sites were nitrogen-rich and originally scarcely wooded or treeless fens. *Nokkapuronsuo* (64º 34' N, 28º 23' E) was drained in the 1950s and fertilized in 1962, 1980 and 2002. *Hanhiselkä* (64º 53' N, 26º 04' E) was drained in 1967 and fertilized in 1980. Disintegrated phosphate, potassium chloride, PK-fertilizer for peatlands and wood ash were used to fertilize the sites. The data included monitoring the foliar nutrient concentrations and post-fertilization stand volume growth during the 27-44 years from fertilizer application.

The needle analyses of Scots pine revealed a severe deficiency of phosphorus (P) and potassium (K) in the unfertilized control trees. Fertilization treatments of P (36–133 kg ha^{-1}) and K (66–361 kg ha^{-1}) improved the respective nutrient concentrations above the deficiency limits. The effect of single P addition was more pronounced and prolonged than that of K addition. In general, the more K included in the single or repeated fertilization treatment, the greater was the growth of trees during the study period.

At both sites, the stand growth of unfertilized trees remained low (less than 0.5 m^3 ha^{-1} a^{-1}). Fertilization increased both stand density and the volume growth of the single trees. On the fertilized plots tree growth remained at considerably higher levels than the control throughout the whole study period. At *Nokkapuronsuo* the highest yields varied between 3 and 4 m^3 ha^{-1} a^{-1} during the 44 years and at *Hanhiselkä* between 5 and 6 m^3 ha^{-1} a^{-1} during the 27 years. In conclusion, refertilizing during the stand rotation, once with phosphorus and twice with potassium, is needed to ensure the continued good nutrient status of trees on *Molinia* fens.

Key words: Phosphorus, potassium, needle analysis, stand growth, nutrient deficiency, nitrogen-rich peat, fertilization

Introduction

More than 5 million hectares of Finland's peatlands have been drained for forestry, which is around half of the total original peatland area (Päivänen 2007). The nutritional characteristics of peatlands are varied (Laiho et al. 2008), but there usually is at least an adequate amount of nitrogen (N). A lack of N in tree-usable form is only found on small-sedge and less fertile sites, and especially in northern Finland (Moilanen and Issakainen 1990, Moilanen 1993, Pietiläinen and Kaunisto 2003). The inadequate amount of mineral nutrients – phosphorus (P), potassium (K), boron (B) – and their imbalance with the abundant nitrogen are factors that limit tree growth, especially on thick-peated, initially treeless or scarcely wooded fens (Kaunisto and Tukeva 1984, Moilanen 1993, Silfverberg and Moilanen 2008). As time passes from the drainage, the peat's N concentration tends to rise as the peat in the stand's root layer compresses and decays (Laiho et al. 2005), which in turn may pronounce the imbalance between N and P. The amounts of K and B bound to the growing stock in a densely forested, advanced age drainage area may even exceed the amounts of the same nutrients in a 20 cm surface layer of peat (Kaunisto and Paavilainen 1988, Kaunisto and Moilanen 1998).

In fertile, originally treeless fen-type sites, the improving effect of drainage often stops because of lack of K during the next tree generation following the drainage (Kaunisto and Tukeva 1984, Kaunisto 1992, Rautjärvi et al. 2004, Pietiläinen et al. 2005). The need for nutrient improvement measures is particularly high on originally treeless sites which have transformed into *Vaccinium vitis-idaea* or *Vaccinium myrtillus* types (PtkgII or MtkgII; for classification see Vasander and Laine 2008) in the post-drainage succession (Silfverberg and Moilanen 2008). Of the total drained peatland area in Finland, one fifth (i.e. 1 million ha) is estimated to be suffering from severe P and K deficiencies (Kaunisto 1997).

Depending on the site type, the addition of P and K (PK-fertilizer) improves the growth of Scots pine (*Pinus sylvestris* L.) on northern Finland's peatlands between 1 and 3 m^3 ha^{-1} a^{-1} (Moilanen 2005). The effect of fertilizer P is visible in needle P concentrations for at least 25–30 years, while the effect of K is visible for 15–20 years (Silfverberg and Moilanen 2008).

A type of fen in the above-mentioned group of nutrient-imbalanced drained peatlands is the *Molinia caerulea* fen (Huikari 1952, Heikurainen 1960, Reinikainen 2000). While the presence of *Molinia caerulea* (L.) Moench has been considered an indicator of at least a decent suitability for cultivation in agriculture (Valmari 1951, Reinikainen 2000), *Molinia* fens have long been seen as poor candidates for forest drainage (Lukkala 1951, Huikari 1952, Metsänheimo 1961, Huikari et al. 1963). In Huikari's (1952) site type classification, the additional attribute '*Molinia*' indicates poor suitability for silviculture.

In contrast, *Molinia* (Purple Moor Grass) fens have been considered suitable for forestry in Britain (Cimingham 1949), where the grass is seen as a weed hindering forest growth (MacLeod 1985). Compared to Finland, the better availability of mineral nutrients (resulting from the coastal location and climate) (Gore 1961, Morton 1977) may explain the good wood production on *Molinia* fens in Britain.

Molinia caerulea is relatively common in northern Finland (Table 1), where it is estimated to be dominant in over 100 000 ha of drained peatlands (Reinikainen 2000, Kaakinen et al. 2008a,b). It is quite undemanding plant regarding habitat requirements (Reinikainen 2000). In addition to the fens, it is common on lake shores. In peatlands, it is associated with high peat nitrogen concentration (Issakainen 2003, Silfverberg et al. 2005) and severe P and K deficiencies in the trees (Heikurainen 1960, Reinikainen 2000, Lenkkeri 2008). *Molinia caerulea* is also rather common in medium fertility mesotrophic peatlands (Heikurainen 1953, Eurola et al. 1990), and remains strong for decades following drainage (Pienimäki 1982, Laukkanen 1989, Hotanen et al. 1999). Thus, it is an indicator of site fertility more or less independently of forest improvement measures (Kotilainen 1958, Eurola et al. 1994, Reinikainen 2000).

Table 1. *Molinia caerulea* coverage in northern Finland's peatlands during the past 20th century according to National Forest Inventory (VMI 3, 8 and 9) (Reinikainen 2000). Results include both pristine and drained mires

	VMI 3 (in 1951–53)	**VMI 8** (in 1985–86)	**VMI 9** (in 1995)
Mean coverage, %	0,91	0,84	0,47
Frequency, %	5,3	11,9	10,5
Occurrence rank	63.	56.	61.

Tree growth and yield data from *Molinia* drainage sites is scarce (Päivänen 2007). Some separate results from old fertilization experiments of Finnish Forest Institute (Metla) suggest that drained *Molinia* fens may transform into quite high-density forests when fertilized (Silfverberg and Huikari 1985, Veijalainen 1999, Reinikainen 2000, Moilanen and Issakainen 2003).

This study examined the effect of mineral nutrient treatments (disintegrated phosphate, potassium chloride, PK-fertilizer and wood ash) on the nutrient status and growth of Scots pine on two drained *Molinia* fens. The hypotheses are as follows: drainage alone has only a slight effect on growth, while applying fertilizers containing P and K, growth and yield will improve considerably.

Material and methods

Experimental stands

Located in a valley between fells in Ristijärvi, Kainuu, the *Nokkapuronsuo* experimental stand was, prior to drainage, an almost treeless fen sparsely scattered with Scots pine saplings (Moilanen and Issakainen 2003). The initial site type was determined to be *Molinia* herb-rich tall-sedge fen (Mol(Rh)SsN, Huikari 1952). The peat thickness varied from 50 cm to over 100 cm (Table 2). Following drainage, Nokkapuronsuo is undergoing change into *V. vitis-idaea* (partly *V. myrtillus*) transformed type II (PtkgII, MtkgII). A contiguous growth of *Polytrichum* forms the ground layer in one part of the area. Apart from *Molinia*, other indicators of high nitrogen availability are rowans, junipers and *Rhamnus frangula* (Moilanen and Issakainen 2003).

Nokkapuronsuo was drained by ditch plow during the 1950s. A supplementary drainage was carried out in the 1960s with a tractor excavator, which halved the earlier strip width of 60 meters to 30 meters. In the fall of 1979, ditches were also dug at the plots' boundaries, across strips and every 35 meters. The current tree stand consists of Scots pine and small amount of downy birch (*Betula pubescens* Ehrh.) as a mixed tree species (Figure 1). The stand is naturally born and soon at the stage of thinning maturity. An understory of Norway spruce has occurred naturally below the dominant Scots pine. Drainage alone has resulted in only a slight growth increase. Because of the modest yield, current recommendations for peatland forestry would classify *Nokkapuronsuo* as an unsuitable site for forestry (Ruotsalainen 2007).

Figure 1. Nokkapuronsuo in September 2009. Above: unfertilized, below: fertilized plot (PK 1962 and 1980, K 2002). By Jorma Issakainen

Table 2. Site characteristics, experiment details and dates of data collection

	Nokkapuronsuo	Hanhiselkä
Coordinates	64º 34´ N, 28º 23´ E	64º 53´ N, 26º 04´ E
Elevation a.s.l., m	176	77
Temperature sum, d.d.°C (1951–1980)	936	1019
Original site type	Mol(Rh)SsN [a)]	MolSsN [b)]
Peat thickness, cm	60–100+	20–60
Peat humification (von Post, H 1-10)	H 4–5	H 6
Peat type	SC-t [c)]	SC-t [c)]
Time of drainage, year	1950s and 1960s, 1979	1967 and 1979
Strip width, m	30	10
Time of fertilization	Spring 1962, 1980, 2002	June 1980
Plot area, m^2	730–1260	80
Plots / replications	26 / 2	18 / 3
Pine stand age in 2006, years	55–60	25–30
Stand measurements, month/year	11/1996, 8–10/2006	5/2007
Needle sampling, month/year	3/1999, 3/2006	3/1987, 3/2005
Peat sampling, month/year	6/1999	8/2006

a) *Molinia* herb-rich tall-sedge fen, b) *Molinia* tall-sedge fen, c) *Sphagnum-Carex* peat type

Hanhiselkä site, locating north of the river Oulu in Muhos, was originally a *Molinia* tall-sedge fen (MolSsN) with isolated, stunted Scots pine trees (Table 2). The first drainage was carried out in 1967 and a supplementary one in 1979, when the experiment was established and the plots separated with smaller ditches of 50 cm depth. The peat dug from these smaller ditches (which also contained some mineral soil) was spread on nearby strips as growth substrate. The peat thickness ranged from 25 to 60 cm.

Hanhiselkä fen was forested in the summer of 1980 by planting containerized Scots pine seedlings (density 4750 plants ha^{-1}). During the following 27 years, the pines were accompanied by naturally born downy birch especially on the fertilized plots (Figure 2). The drainage effects have transformed the site into *V. Vitis-idaea* transformed type II (PtkgII). *Molinia* was still visible in 2000—especially at the sparsely wooded areas.

During the study period, *Molinia caerulea* was found on almost all plots of the both sites. According to the commonness estimation in the fall of 2009 at Nokkapuronsuo, the coverage range of *Molinia* was on 0,13-1,28 %, depending of the fertilization treatment.

Figure 2. Hanhiselkä in August 2009. The plot fertilized with wood ash in 1980 was thinned in 2007, when especially some *Betula pubescens* was removed. By Jorma Issakainen

Experiment set-up and data collection

The original experiment at *Nokkapuronsuo* consisted of eight approximately 0,5 ha plots. The initial fertilization experiment in 1962 included an unfertilized control, a phosphate treatment, a potassium chloride treatment (KCl) and a phosphate–KCl treatment, each carried out twice (Table 3). Six plots, fertilized in 1980, were each divided into four subplots (area 0.07–0.13 ha), of which three were further supplemented with PK-fertilizer, and one left untreated. Furthermore, two of the refertilized subplots in each plot were supplied with extra mineral nutrients: one received copper and one copper + manganese. Another supplementary fertilization was carried out in 2002: twelve of the subplots that were PK-fertilized in 1980 received either a PK or a K + micro nutrient treatment. The doses in a single fertilizer application varied between 35 and 72 kg ha^{-1} for P and between 66 and 100 kg ha^{-1} for K.

The fertilization at *Hanhiselkä* was carried out in spring 1980. The area had been set up with 18 plots of 0.01 ha, each of which included the following six treatments: the unfertilized control, four PK treatments that differed in their macro and micronutrient amounts, and a wood ash treatment (Table 3). The treatments were repeated three times with randomization. The fertilizers used were grainy PK-fertilizer, KCl, and wood ash from a residential district heating plant at Vihanti. The doses in a single treatment were from 36 to 133 kg ha^{-1} for P and from 66 to 361 kg ha^{-1} for K.

Table 3. The fertilization treatments, dosages and amounts (subscript) of nutrients (kg ha-1)

NOKKAPURONSUO

Base fertilization 1962	First supplementary fertilization 1980	Second supplementary fertilization 2002
Unfertilized	-	-
	-	-
	3) PK 400 ($P_{35}K_{66}B_1$)	-
1) Hf 500 (P_{72})	PK 400 ($P_{35}K_{66}B_1$) + 4) (Cu_3Mn_{10})	3) PK 602 ($P_{54}K_{96}$)
	PK 400 ($P_{35}K_{66}B_1$) + (Cu_3)	5) Kh 333 ($K_{100}B_1Zn_1$)
	-	-
	PK 400 ($P_{35}K_{66}B_1$)	-
2) Ks 200 (K_{83})	PK 400 ($P_{35}K_{66}B_1$) + (Cu_3Mn_{10})	PK 602 ($P_{36}K_{96}$)
	PK 400 ($P_{35}K_{66}B_1$) + (Cu_3)	Kh 333 ($K_{100}B_1Zn_1$)
	-	-
Hf 500	PK 400 ($P_{35}K_{66}B_1$)	-
+ Ks (100)200	PK 400 ($P_{35}K_{66}B_1$) + (Cu_3Mn_{10})	PK 602 ($P_{36}K_{96}$)
(P_{72} K_{41-83})	PK 400 ($P_{35}K_{66}B_1$) + (Cu_3)	Kh 333 ($K_{100}B_1Zn_1$)

HANHISELKÄ

Fertilization 1980
Unfertilized
3) PK 400 ($P_{35}K_{66}B_1$)
PK 400 ($P_{35}K_{66}B_1$) + Micronutrients ($Mg_{38}Zn_4Mn_3Cu_1B_1Se_{0.001}$)
PK 400 ($P_{35}K_{66}B_1$) + KCl (K_{75})
PK 400 ($P_{35}K_{66}B_1$) + 6) Wood ash 500 ($P_{13}Ca_{100}K_{36}B_{0.15}$)
Wood ash 5000 ($P_{133}K_{360}Ca_{1000}B_{1.5}$)

1) Hf = disintegrated phosphate
2) Ks = potassium chloride (KCl)
3) PK = PK-fertilizer (8.7% P, 16.6% K, 0.2%B)
4) Copper sulphate (25% Cu) and manganese sulphate (26% Mn)
5) Kh = KCl + micro (30% K, 1,5% Ca, 7% Mg, 6% S, 0,4% B, 0,4% Zn)
6) Wood ash (2.8% P, 7.6% K, 20.4% Ca, 0.03% B)

The stands were measured in 1996 and 2006 (*Nokkapuronsuo*) and 2007 (*Hanhiselkä*). Trees over 30 mm in diameter were measured for diameter at breast height ($d_{1.3,}$ mm). Trees were included from a circle (r = 9 m) in the middle of the plot (*Nokkapuronsuo*), or from the whole plot (Hanhiselkä). From 15 to 25 pines (and additionally approximately 10 downy birches in the case of *Hanhiselkä*) of various diameter classes were selected from each plot by sampling. From these trees, also height and height growth of the preceding 10-year period was measured. Stand characteristics, like basal area and stand volume, were calculated using Metla's KPL software (Heinonen 1994).

The needle samples were collected in 1999 and 2006 (*Nokkapuronsuo)* and in 1987 and 2005 (*Hanhiselkä)*. Previous year needles were collected from the upper whorls of 6–8 trees per plot for analysis of N, P, K and B. The needles were dried for 48 hours at +65 °C and were analyzed for total N concentration (the Kjeldahl method), K concentration (atomic absorption spectrophotometer, AAS), B concentration (the azomethine-H method) and P concentration (the vanado-molybdate method) (Halonen et al. 1983). In addition, the dry mass (grams per 100 needles) was measured to determine the needle nutrient content (g per 100 needles).

The peat samples were collected from the unfertilized control plots in June 1999 (*Nokkapuronsuo*) and in August 2006 (*Hanhiselkä*). Six subsamples from different parts of the plot were collected to form the sample from each plot. A sample included a 10 cm layer of surface peat below the vegetation layer. The peat samples were analyzed for N, P, K and B concentrations using the same methods as with the needles. By weighing the samples, nutrient concentrations (g kg^{-1}, mg kg^{-1}) were converted into total nutrient contents (kg ha^{-1}).

The interpretation of the analysis results was based on the nutrient limit values proposed in earlier work (Paarlahti et al. 1971, Reinikainen et al. 1998, Moilanen et al. 2005a):

Nutrient	**Poor**	**Adequate**	**Optimal**
N	< 12	12 – 13	13 – 18
P	< 1.3	1.3 – 1.6	1.6 – 2.2
K	< 4.0	4.0 – 4.5	4.5 – 5.5
B	< 5	5 – 10	10 – 30

The effects of fertilization treatments on stand growth and needle nutrient concentrations were tested with analysis of variance (SPSS 15.0), with Bonferron's test used with the pairwise comparisons of the treatments. The micronutrient fertilizer that was used combined with the PK fertilizer had no effect on stand growth or needle nutrient concentrations, which is why PK and PK+micro were combined in the final analysis.

Results

Nutrients in peat

Both sites proved to be rich in nitrogen. The total N concentration, determined from the dry matter of the surface peat, was nearly 3% and 2.5% at *Nokkapuronsuo* and *Hanhiselkä,* respectively (Table 4). The total content was 3000–4000 kg N ha^{-1}. The K concentration was (0.23 and 0.20 mg g^{-1}) at both sites, and the total K content at *Hanhiselkä* was 30 kg ha^{-1}, which is low compared to the potassium amounts bound by the tree stand during the rotation (e.g. Kaunisto and Paavilainen 1988). The differences between the sites in peat P, K and B concentrations were small, as were the differences within each experiment.

Table 4. Surface peat (0-10 cm layer) nutrient concentrations at Nokkapuronsuo and Hanhiselkä unfertilized control plots

Experiment	Plot	N, %	P, g kg^{-1}	K, g kg^{-1}	B, mg kg^{-1}
Nokkapuronsuo	1	2.76	0.92	0.26	1.5
	40	3.01	0.84	0.19	1.8
Hanhiselkä	9	2.41	0.99	0.18	2.3
	16	2.65	1.05	0.21	1.2
	17	2.40	0.97	0.22	1.4

Stand nutrient status

While the trees in unfertilized control plots of *Nokkapuronsuo* had an abundance of available nitrogen, they were suffering from severe P and K deficiencies (Table 5a). The trees, which had received P at the initial fertilization in 1962, still had satisfactory amounts of P at the end of the 1990s, but by 2006, their needle P concentration had fallen near to or below the deficiency level. K from the initial fertilization, however, was no more visible during the 1990s.

The trees that were refertilized with PK in 1980 had a good P status still after 20 growing seasons (year 1999), and their needle P concentrations were significantly higher (F = 9.6) than of those that had not been refertilized (Table 5a). During the following 7 years, the P levels seemed to have diminished, but the concentrations in the refertilized trees were still significantly higher (F = 5.4) than those of the unfertilized plots or those plots that had received the initial fertilization only.

The effect of PK-refertilization on K concentrations was visible in the needles still at the end of the 1990s, but not that much in 2006. The differences were not statistically significant. Trees that received a second refertilization (PK or K+micronutrients) in 2002, however, had their needle K concentrations clearly above the deficiency limit four years later (Table 5b).

The nitrogen availability was adequate or good for trees in all plots (Table 5a,b). Compared to the fertilized plots, needle N concentrations were significantly higher (F = 11.9) on the unfertilized plots both in 1999 and 2006. This was due to the so-called "dilution" effect, as the uptaken nitrogen gets distributed in the larger needle mass induced by the fertilization (e.g. Paarlahti et al. 1971). However, fertilization did not weaken the trees' N status by decreasing the foliar N concentration below the deficiency level. Furthermore, in both experiments, N concentrations were significantly higher (F = 16.0) in 2006 than in 1999.

Boron concentrations were rather low in all plots except the plots that received a second refertilization in 2002 (Table 5 a, b). Differences in B concentrations were small, both between the plots and the points of time.

Tables 5a and 5b. Needle nutrient concentrations (N, P, K mg g^{-1}, B mg kg^{-1}) at Nokkapuronsuo in 1999 and 2006 by fertilizer treatment. Highlighted values are below the severe deficiency limits (P<1.3 mg g^{-1}, K<4.0 mg g^{-1})

5a

Treatments		Dose, kg ha^{-1}		Needles in 1999				Needles in 2006			
1962	1980	P	K	N	P	K	B	N	P	K	B
Unfertilized	-	0	0	16.8	1.02	3.18	10.8	19.7	0.98	3.34	10.6
Hf	-	72	0	13.3	1.61	3.32	8.5	15.6	1.42	3.25	10.2
Ks	-	0	83	16.4	1.06	3.64	10.5	17.3	0.99	3.52	13.5
Hf + Ks	-	72	42/83	14.2	1.43	3.41	6.4	15.3	1.29	3.57	8.9
Hf	PK	107	66	14.4	2.08	3.72	8.9	16.3	1.61	3.61	8.2
Ks	PK	35	150	14.4	1.65	3.99	12.1	15.5	1.25	3.63	10.9
Hf + Ks	PK	107	109/150	13.7	1.94	3.77	10.5	15.9	1.48	3.65	11.8

5b

Treatments			Dose, kg ha^{-1}		Needles in 2006			
1962	1980	2002	P	K	N	P	K	B
Unfertilized	-	-	0	0	19.7	0.98	3.34	10.6
Hf	PK	Kh	107	166	14.9	1.44	5.27	31.3
Hf	PK	PK	143	162	15.4	1.69	5.16	31.8
Ks	PK	Kh	35	250	14.9	1.30	5.53	35.5
Ks	PK	PK	71	246	15.2	1.65	5.42	32.4
Hf+Ks	PK	Kh	107	208/250	15.0	1.51	5.33	31.9
Hf+Ks	PK	PK	143	204/246	1.60	1.47	5.15	31.6

Hf = disintegrated phosphate, Ks = KCl, PK = PK-fertilizer, Kh = KCl+micro

At *Hanhiselkä*, the 1987 needle analysis revealed a severe P deficiency with every treatment. K concentrations were below the deficiency limit everywhere except the plots that had received the very highest doses of PK or wood ash (Table 6). Only seven years had passed from the fertilization at that time. N levels, in contrast, were good both on the unfertilized plots (needle N concentration 1.62 %) and the fertilized plots (14.3–14.6 mg g^{-1}). Needle B concentrations were relatively high throughout the experiment (15–26 mg kg^{-1}), and there were statistically significant differences between the control and the fertilized plots. In comparison to the control plots, B levels were higher in fertilized plots, and K levels were higher in plots that had received a high amount of K.

While the needle P concentrations in *Hanhiselkä*'s treated plots were near to or above the deficiency limit in 2005, the unfertilized plots suffered from a severe P deficiency. The concentrations of K were highest on those plots that had received the highest doses of K (Table 6). No significant differences in any nutrients were detected between different treatments. Compared to the situation in 1987, the concentrations of the main nutrients (N, P, K) were significantly ($p = 0.000$) higher, and the concentrations of B were significantly lower.

Table 6. Needle nutrient concentrations (N, P, K mg g^{-1}, B mg kg^{-1}) at Hanhiselkä in 1987 and 2005 by fertilizer treatment. Underlined values differ significantly ($p < 0.05$ in Bonferroni test) from the control. Highlighted values are below the severe deficiency limits (P<1.3 mg g^{-1}, K<4.0 mg g^{-1})

Treatment	Dose,. kg ha^{-1}		Needles in 1987				Needles in 2005			
	P	K	N	P	K	B	N	P	K	B
Unfertilized	0	0	16.2	0.99	2.63	14.8	21.3	1.13	3.95	10.3
PK	36	68	14.6	1.09	2.76	22.3	21.3	1.29	3.90	7.6
PK + micro	36	68	14.3	1.08	3.23	25.6	24.5	1.32	3.84	10.2
PK + KCl	36	143	14.4	1.15	4.01	23.2	22.5	1.36	4.20	6.8
PK + Wood ash	49	104	14.6	1.09	3.36	16.6	22.0	1.35	4.20	8.1
Wood ash	133	361	14.3	1.14	3.95	21.0	20.4	1.45	4.62	10.2

Tree stand

Stand density and dominant height

Fertilization increased stand density at both experiments significantly (Table 7). At *Nokkapuronsuo* at the end of the study period, the number of trees over 3 cm in diameter was on average 669 stems ha^{-1} on the unfertilized plots and 1569–1965 stems ha^{-1} on the fertilized plots, i.e. 2 – 3-fold when compared to the control. The effect was even greater at *Hanhiselkä*: the combined number of Scots pine and downy birch was 1375 stems ha^{-1} on the control plots and 5458–8708 stems ha^{-1} on the treated plots. Fertilization had an effect on the amount of downy birch especially, which was on fertilized plots 10–15-fold compared to the unfertilized plots. The increase in Scots pine was 2–4-fold.

At *Nokkapuronsuo*, stand dominant height at the end of the study period was significantly higher on the treated plots (12–14 m) than on the control plots (7 m) (Table 7). Also at *Hanhiselkä*, the trees on the treated plots were higher on average (dominant height 7–10 m, compared to 6 m on the control plots). The treatments increased height growth significantly during the 10 years preceding the measurements at both experiments.

Table 7. Stand density and dominant height at the end of the study period with mean annual height growth from the preceding 10 years by fertilizer treatment. See treatment details on Table 3. Values marked with matching letters (a, b, c) do not significantly differ from each other ($p > 0.05$ in Bonferroni test)

Nokkapuronsuo

Treatment			Density,	Hdom,	Annual height growth,
1962	1980	2002	stems ha^{-1}	m	1997-2006, cm
Unfertilized			669 a	7 a	14 a
Hf+Ks	-	-	1569 b	12 ab	24 b
Hf+Ks	PK	-	1692 b	14 b	30 b
Hf+Ks	PK	PK	1965 b	14 b	33 b
Hf+Ks	PK	Kh	1644 b	14 b	32 b

Hanhiselkä

Treatment	Density,	Hdom,	Annual height growth,
1980	stems ha^{-1}	m	1997-2006, cm
Unfertilized	1375 a	6 a	24 a
PK	5458 ab	7 ab	29 b
PK + micro	7666 b	8 b	29 b
PK + KCl	6291 b	8 ab	31 b
PK + Wood ash	7916 b	9 b	32 b
Wood ash	8708 b	10 b	40 c

Stand volume

Stand growth at the control plots at *Nokkapuronsuo* had been very slow following the drainage (Figure 3). In 2006, the stand volume was a mere 8 m^3 ha^{-1}. The plots that received phosphorus (Hf) in 1962 had a clearly larger stand volume than the control plots and the plots that only received potassium (Ks). The most effective initial treatment (93 m^3 ha^{-1}) proved to be combination of phosphorus and potassium (Hf+Ks), which also yielded the strongest volume growth of the last 10-year period (3.6 m^3 ha^{-1} a^{-1}).

The effect of the PK refertilization in 1980 on volume growth at *Nokkapuronsuo* was strong and long-lasting (Figure 3). On the refertilized plots, stand volume in 2006 varied between 101 and 162 m^3 ha^{-1} depending on the treatment. The strongest volume growth of the last 10-year period (7.2 m^3 ha^{-1} a^{-1}) was gained with the combination of P and K in 1962 and

1980. The absence of K in the initial treatment resulted in smaller stand volumes. The difference in stand volume between refertilized plots and plots that received only initial fertilization was statistically significant both in 1996 and 2006 ($F = 12.1$ and 22.5). Furthermore, the volume growth during the last 10-year period was significantly higher on refertilized stands ($F = 22.5$).

At *Nokkapuronsuo*, the effect of the second refertilization (PK or K+micro in 2002) on stand growth was just beginning in 2006 (Figure 3). Stand volume (119–164 m^3 ha^{-1} depending on the treatment) was generally higher on plots that were refertilized a second time compared to plots refertilized only once. The highest growth of the last 10-year period (7.9 m^3 ha^{-1} a^{-1}) was gained with the combination of P and K in 1962, 1980 and 2002. Again, the absence of K in the initial treatment resulted in smaller stand volumes.

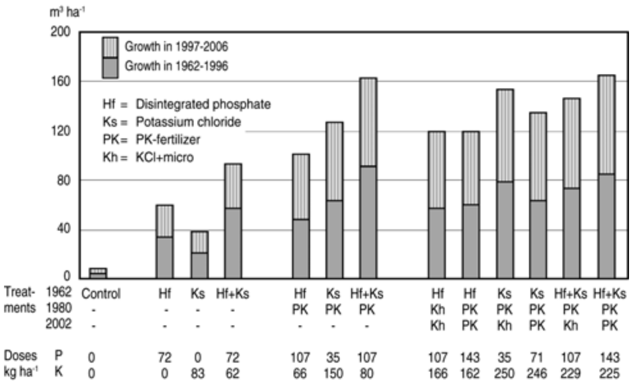

Figure 3. Stand volume by fertilization treatments at Nokkapuronsuo in 1996 and 2006

At *Hanhiselkä*, fertilization increased the growth of Scots pine remarkably. The mean volume of trees on the treated plots was 2–4-fold compared to the trees on the untreated plots (Figure 4). Thus, the effect of fertilization on individual tree's growth was of the same order of magnitude than the effect on stand density. Downy birch also showed an increase in the growth following fertilization, but on a clearly smaller scale than Scots pine. Stand volumes at *Hanhiselkä* varied greatly depending on the treatment, and the plots that received wood ash showed the highest volume growth. Over 27 years stand total yield (10–152 m^3 ha^{-1}) was related both to the amounts of P and K they received in the treatments, as well as to needle P and K concentrations. Because of high variance, the only statistically significant difference in stand volume was between the control and wood ash treatment. Of total stand volume, the ratio of downy birch was at its highest (15–25%) on the plots treated with PK, and lowest (12%) on the control plots and plots treated with wood ash.

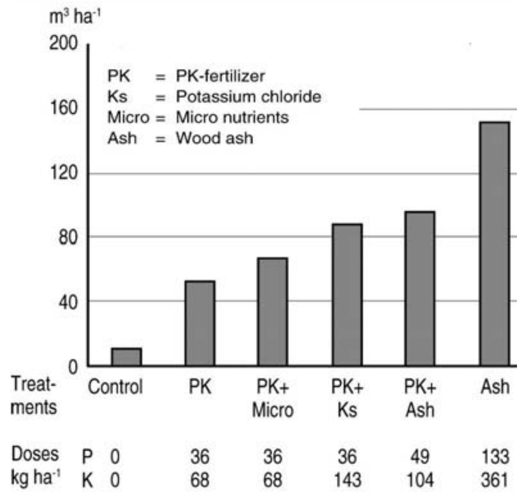

Figure 4. Stand volume by fertilization treatments at Hanhiselkä in 2006

Discussion and conclusions

Molinia fens have generally been considered poor candidates for silvicultural measures (Huikari 1952, Heikurainen 1960, Reinikainen 2000). The results of this study confirm the assessment of *Molinia* fens as problematic in terms of stand nutrient status and poor yield potential. A fundamental problem is the imbalance in the availability of nutrients: there is an abundance of usable nitrogen but very scarce amounts of phosphorus and potassium. The NP-ratio in the surface peat was 33 at *Nokkapuronsuo* and 25 at *Hanhiselkä*, while the NK-ratios were 128 and 124. The NP-ratios in needles were, depending on the time, between 17 and 20 at *Nokkapuronsuo* and between 16 and 29 at *Hanhiselkä*, while a balanced ratio is considered to be 11 (Puustjärvi 1962a). The needle NK- ratios were between 5.3 and 5.9 at *Nokkapuronsuo* and between 5.4 and 6.2 at *Hanhiselkä*, when a balanced ratio would be 3.5 (Puustjärvi 1962b).

Molinia caerulea often indicates high nitrogen presence in the growth substrate. Peat analysis confirmed that nitrogen was, in fact, in abundance, but also that mineral nutrients were scarce. The main nutrient concentrations and contents in peat were at similar levels to those presented in earlier studies on herb-rich tall-sedge fens (Kaunisto and Paavilainen 1988, Moilanen et al. 1996, Kaunisto and Moilanen 1998, Laiho et al. 2008).

Drainage alone had not increased tree growth even in the long run at either site, and the Scots pine stands suffered from severe deficiencies of phosphorus and potassium. Growth remained low on the unfertilized control plots (less than 0.5 m^3 ha^{-1} a^{-1}). Treatment with a fertilizer containing phosphorus and potassium increased not only stand growth, but also stand density. At *Hanhiselkä*, especially the number of downy birch increased. It is probable, that as a result of nutrient deficiencies the mortality of young tree saplings has been higher on the unfertilized plots in both experiments. A significant number of trees were also stunted and withered, being less than 1.3 m in height. However, the effects of fertilization on the natural regeneration of pine or birch and the initial development of saplings were not investigated in this study.

A single PK treatment resulted in as high as a 10-fold increase in yield compared to the control. Mean annual volume growth was, at its highest, 3–4 m^3 ha^{-1} a^{-1} at *Nokkapuronsuo* and 5–6 m^3 ha^{-1} a^{-1} at *Hanhiselkä*. The strong effect of fertilization at both experiments was noticeably better than the effects which were obtained in earlier studies concerning similar sites and climate conditions (e.g. Moilanen 1993, Moilanen et al. 2005b, Pietiläinen et al. 2005).

At both experiments, the stands were still in a phase of strong growth at the end of the study period. The last 10-year yield at the twice refertilized *Nokkapuronsuo* was comparable with the 35-year period preceding it.

Earlier research has shown that a single P fertilization ensures an adequate phosphorus availability for trees for more than 30 years (Silfverberg and Moilanen 2008). The needle analyses of the present study show that sufficient P status in the growing stock can be maintained applying one or two treatments also in *Molinia* fens. The analysis also suggests that the third application of P is likely unnecessary.

The effect of K treatment on stand nutrient status proved to be, as expected, of clearly shorter duration than the effect of P. Maintaining sufficient K status would require even three separate treatments during rotation, at least when the water-soluble K fertilizers were used (Silfverberg and Moilanen 2008). Both at *Nokkapuronsuo* and *Hanhiselkä*, the stand usually had the more pronounced growth response, the more K was applied in the treatments.

At *Nokkapuronsuo*, the stand showed considerably increased growth on the treated plots even after needle analysis suggested the effect of fertilizer K to have run out. The explanation can be the increased total stand volume, which allowed the stand growth to remain higher than the control, even with nutrient deficiencies.

The needle analyses from *Hanhiselkä* experiment produced considerably different results at different times. An unexpected result was that the trees suffered from P and K deficiencies as early as 7 years after the fertilization. The result is inconsistent with earlier research on the duration of the fertilization effect (eg. Moilanen 1993, Silfverberg and Moilanen 2008) and with the fact that contemporary stand growth on the fertilized plots was increased remarkably, in spite of the low foliar P and K concentrations. Moreover, K status of unfertilized trees at *Hanhiselkä* seemed surprisingly to have improved within time. The explation for these unexpected results remained unclear.

PK-fertilization is necessary on *Molinia* fens to improve the peat's nutrient balance and to ensure the yield, which is high enough for profitable silviculture. In the stands, which were planted even a single PK treatment results in a considerable increase in growth. But the best effect is gained with one or two applications of P and two or three applications of K, when starting from seedlings with the objective being of producing timber. As Molinia fens are rich in nitrogen, with proper supplementary fertilization, they have high round wood production potential and possibility for energy wood production as well. Concurrently the fens are transformed probably into natural carbon sinks.

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РОСТ И ПИТАТЕЛЬНАЯ БАЗА ДРЕВОСТОЯ НА ОСУШЕННЫХ И УДОБРЕННЫХ ЛЕСНЫХ УЧАСТКАХ С ПРЕОБЛАДАНИЕМ МОЛИНИИ (*MOLINIA CAERULEA)* В ФИНЛЯНДИИ

К. Сильферберг, Й. Иссакайнен и М. Мойланен

Резюме

Болота с преобладанием молинии голубой считаются, как правило, непригодными к осушению из-за скудности минеральных питательных веществ. С другой стороны, известно, что высокие концентрации азота в торфяниках благоприятствуют выращиванию леса. В рамках настоящего исследования с помощью экспериментального осушения и удобрения изучались питательная база и рост древостоя на двух участках торфяников с преобладанием молинии голубой. Оба объекта отличались высоким содержанием азота, и изначально представляли собой редколесные или безлесные болота. Расположенное в Ристиярви болото *Nokkapuronsuo* (64° 34' N, 28° 23' E) было осушено в 1950-ых годах, а удобрение почвы проводилось в 1962, 1980 и 2002 годах. Болото *Hanhiselkд* (64° 53' N, 26° 04' E) в Мухос было осушено в 1967 году, а удобрения вносились одновременно с облесением (посадками сосны) в 1980 году. В результате лесохозяйственных мероприятий опытные участки насаждений перешли в тип брусничных осушенных болот (PtkgII) с преобладанием сосны. На обоих объектах молиния голубая (*Molinia caerulea* (L.) Moench), как правило, сохранилась в травяном ярусе и после осушения. В древесном ярусе преобладающим видом была сосна обыкновенная (*Pinus sylvestris* L.), а примесью к главной породе береза пушистая (*Betula pubescens* Ehrh*.)*. В качестве удобрений в экспериментах применялись фосфат, калиевая соль, PK-удобрение для торфяников и древесная зола. После внесения удобрений на болоте *Nokkapuronsuo* проводился мониторинг питательной базы и роста древостоя в течение 44 лет, а на *Hanhiselkд* – в течение 27 лет. Научный материал содержит показатели концентраций питательных веществ в образцах торфа и хвои, а также данные по вычисленному на основе толщины и высоты приросту по объёму модельных деревьев после подкормки.

Анализ хвои показал, что контрольные деревья, оставленные без подкормки, испытывали серьёзный дефицит фосфора (P) и калия (K) на обоих опытных участках насаждений. Подкормка фосфором (P 36 - 133 кг/га$^{-1}$) и калием (K 66 - 361 кг/га$^{-1}$) вывела содержание фосфора и калия в сосновой хвое на уровень, превышающий нижний предел концентраций. Влияние удобрения на изменение концентрации фосфора в хвое оказалось более эффективным и продолжительным по сравнению с калием. С другой стороны, повторная подкормка калием заметно улучшила питательную базу и рост древостоя. В целом, в течение исследованного периода прирост древостоя был тем лучше, чем больше в подкормке содержалось калия.

За счёт внесения удобрений количество жизнеспособных деревьев увеличилось в обоих экспериментах. На болоте *Nokkapuronsuo* густота древостоя на опытных участках, где вносились удобрения, была в 2 – 3 раза больше (1569 – 1965 деревьев на 1 гектар), а на болоте *Hanhiselkд* в 4 – 6 раз больше (5458 – 8708 деревьев на 1 гектар) по сравнению с участками без подкормки. Внесение удобрений повысило, в особенности, количество берёзы пушистой.

На обоих контрольных участках без внесения удобрений прирост древостоя был низким (менее 0,5 м^3/га$^{-1}$/год$^{-1}$). На удобренных участках прирост древостоя, по сравнению с контрольными участками, сохранялся на значительно более высоком уровне до конца исследованного периода. На болоте *Nokkapuronsuo* прирост древостоя составил до 3 – 4 м^3/га$^{-1}$/год в течение 44 лет, а на *Hanhiselkд* – до 5 - 6 м^3/га$^{-1}$/год в течение 27 лет. Это позволяет сделать вывод о том, что внесение минеральных удобрений улучшает питательный баланс в древостое и обеспечивает усвоение насаждениями обильных запасов азота в торфе. С другой стороны, необходимо повторное проведение (один или два раза) подкормки в период роста насаждений для поддержания достаточного питательного режима древостоя на осушенных лесных болотах с преобладанием молинии голубой.

Ключевые слова: Фосфор, калий, анализ хвои, прирост древостоя, дефицит питательных веществ, богатый азотом торф, внесение удобрений