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Biomass and Nutrition of Naturally Regenerated and Coppiced Birch on Cutaway Peatland During 37 Years

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Biomass production and nutrient use of birch thickets with a mixture of willow on a cutaway peatland in southern Finland over a period of 37 years was studied. Dense, naturally regenerated 16-year-old birch stands were cut down, fertilized with either wood ash (P 108 and K 339 kg ha^{-1}) or PK fertilizer (P 50 and K 95 kg ha^{-1}) or left unfertilized. The biomass production of the coppiced stands and one uncut stand was monitored for a period of 21 years. Soil nutrient and foliar nutrient concentrations were analyzed several times during the study period. Ash fertilization supplied more nutrients than PK fertilization and increased the soil nutrient amounts more. The foliar phosphorus concentration of birch on control plots indicated a severe phosphorus deficiency which was removed by PK and ash fertilization. Fertilization did not increase nutrient concentrations of the stem (wood + bark) nor the amount of nutrients bound in the biomass. Two energy wood rotations (16+21 years) produced 124–158 Mg ha^{-1} of leafless, above-ground biomass altogether corresponding to 61–78 Mg ha^{-1} of carbon. The highest biomass yield was achieved with a rotation of 37 years in the uncut stand (211 Mg ha^{-1}). Corresponding values for mean annual increment (MAI) were 3.4–4.3 Mg ha^{-1} and 5.7 Mg ha^{-1}. This study shows that the length of the rotation for birch in energy wood production should be longer than 21 years. PK and ash fertilization increased the biomass of coppiced 21-year-old birch by 23 Mg ha^{-1} and 33 Mg ha^{-1}, respectively.

Keywords *Betula*, biomass production, coppicing, fertilization, PK fertilizers, wood ash
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1 Introduction

The value of renewable energy obtained from forests is increasing due to the need to reduce greenhouse gas emissions. In Finland wood-based fuels' share of total energy consumption in 2009 was 20% (Finnish Statistical … 2010). In recent years the utilization of forest chips made of logging residues from final fellings and trees harvested in thinnings for energy production has increased rapidly. In 2009, the total consumption of forest chips was 5.4 million m^3 (Finnish Statistical … 2010). It is planned to increase up to 13.5 million m^3 by 2020 (Ministry of Employment and the Economy 2010). In addition to using wood fuels derived from existing forests, the establishment and utilization of woody biomass energy plantations gaining new interest in many countries.

Mechanical peat harvesting for fuel started in Finland in 1944, but large-scale peat harvesting started relatively late, at the beginning of the 1970s. At present, peat is harvested on an area of roughly 70 000 hectares with an additional 80 000 ha having been reserved for peat harvesting in the future. Forestry is considered to be the main reuse option for cutaway peatlands in Finland (Selin 1999) and Ireland (Renou and Farrell 2005). It is estimated that in Ireland approximately 50 000 ha of cutaway peatlands are likely to become available for afforestation over the next 30 years (Renou and Farrell 2005). In Sweden afforestation has been considered as an appropriate reuse option for cutaway peatlands, also in respect of growing energy forests (Hånell et al. 1996). Peat cutaway areas differ considerably from forested peatland sites in regard to their soil properties. They are characterized by variation in peat thickness, low pH levels, high nitrogen concentration, and low phosphorus and potassium concentrations (Aro et al. 1997). Afforestation of cutaway peatlands may encounter nutritional problems and consequently success in afforestation in many cases depends on fertilization (e.g. Hytönen et al. 1995, Aro et al. 1997).

When peat harvesting has ceased the non-vegetated residual peat decomposes aerobically and leads to CO_2 emissions (Tuittila and Komulainen 1995, Sundh et al. 2000). C fixation by developing peat vegetation decreases emissions (Tuittila and Komulainen 1995). Afforestation of cutaway peatlands could be seen as a possible means of offsetting soil CO_2 emissions due to an increase in sequestration of atmospheric CO_2-C into the growing tree biomass. However, the annual CO_2 emissions of the peat even on afforested cutaway peatlands can be quite high and these areas may act as sources of C released into the atmosphere (Mäkiranta et al. 2007).

Short-rotation forestry refers to the cultivation of fast-growing deciduous tree species, regenerated through sprouts, using short rotation periods (3–5 years), intensive methods and dense stocking. Exotic *Salix* species (e.g. *Salix viminalis* L., Salix 'Aquatica', *Salix* × *dasyclados* Wimm.) have mainly been used in the short-rotation experiments conducted in Finland (Hytönen 1996). Exotic willow species need costly establishment with cuttings, soil preparation, and an increase of pH by liming (Hytönen 1996, 2005). Also NPK fertilization of peat cutaway areas is necessary and N fertilization should be repeated annually in order to maximize biomass production (Hytönen 1995a, 1995b).

With longer rotations native birch, silver birch (*Betula pendula* Roth) and downy birch (*B. pubescens* Ehrh.), could also be attractive for biomass production on cutaway peatland areas. On well-drained and acid cutaway peatlands both birch species have thrived well and fertilization has increased their growth (Kaunisto 1987, Aro et al. 1997, Renou et al. 2007, Hytönen and Saarsalmi 2009). In addition, birch does not need liming like exotic *Salix* species (Hytönen 2005). Also, it is possible to seed or use natural seeding when establishing dense birch thickets for biomass energy production (Kaunisto 1981, Aro et al. 1997, Huotari et al. 2008, Renou-Wilson et al. 2010). Birch forests on peatlands are mostly dominated by downy birch, while silver birch grows mostly on moist and rich upland forest soils (e.g. Hynynen et al. 2010). Thus the growing of birch for biomass would be an interesting alternative especially if the price of energy wood increases close to the level of pulp wood. In biomass production regeneration after clearcutting could be done by making use of the coppicing ability of birch. When cut, birch produces stump sprouts mostly from dormant basal buds (Kauppi et al. 1991). The early development of birch sprouts is more vigorous than that of seedlings (Kauppi et al. 1988).

In this investigation, we quantified the biomass production of naturally regenerated mixed birch and willow stands grown for biomass using coppicing regeneration in a peat cutaway area. We compared the biomass production and carbon sequestration of two consecutive coppice rotations (ages 16 and 21 years) with one rotation of 37 years. We also studied the effect of applying 5000 kg ha^{-1} wood ash or 575 kg ha^{-1} PK fertilizer on soil nutrient amounts, biomass production and the amount of nutrients bound in the biomass.

2 Material and Methods

2.1 Study Site and Treatments

The material was collected from dense, mixed stands of silver birch (*Betula pendula*), downy birch (*Betula pubescens*) and willow (*Salix* spp.) located in one of the oldest peat harvesting areas in Finland, at Aitoneva, Kihniö (62º12'N, 23º18'E), 158 m a.s.l. Originally Aitoneva was a large (564 ha) treeless bog where the thickest peat layers were more than 6 m. Pine swamps were dominating in the border areas of the bog before peat harvesting started in 1944. The stands had regenerated naturally after the end of peat production on the site in the mid 1960s. In 1981 experimental plots (sized 300–500 m^2) were established in the stands (see Ferm and Kaunisto 1983). After measuring the trees at the age of 16 years (average biological age), all trees on nine of the sample plots were cut down, and trees on one sample plot were left to grow as a dense thicket. Ferm and Kaunisto (1983) reported biomass results for the first rotation period.

A fertilization experiment with three treatments and three replications using randomized block design was laid out on the plots after the clearcutting of the stand. The treatments were as follows: unfertilized control, PK fertilization (575 kg ha^{-1} PK fertilizer; P 86 g kg^{-1}, K 166 g kg^{-1}, B 300 mg kg^{-1}) and wood-ash fertilization (5000 kg ha^{-1}; P 21.6 g kg^{-1}, K 67.7 g kg^{-1}, Ca 213 g kg^{-1}, B 374 mg kg^{-1}, Cu 289 mg kg^{-1}, Mn 15 g kg^{-1}, Zn 2.2 g kg^{-1}). The amounts of PK fertilizer and wood ash were selected according to their usage in practice at the time. This resulted in higher nutrient amounts in the wood ash than in the PK application. In PK fertilizer and ash applications the amount of P was 50 and 108 kg ha^{-1}, K 95 and 339 kg ha^{-1} and B 1.7 and 1.9 kg ha^{-1}, respectively. The fertilizers were spread in the spring of 1982. The naturally regenerated stand was not fertilized. The mean effective temperature sum was 1139 d.d. (min 894 d.d. in 1987, max 1367 d.d. in 2002) and mean annual precipitation 668 mm (min 542 mm in 2002, max 810 mm in 1988) during 1981–2002. Climatic variables were calculated using the method described by Ojansuu and Henttonen (1983).

2.2 Measurements and Analysis Methods

Peat depth on the plots was on average 38 cm, varying from 18 to 54 cm. Volumetric peat samples composed mainly by 5-cm-thick layers (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–30 cm and in some cases down to 50 cm) were taken for nutrient analysis with a square-shaped peat sampler (39 mm x 47 mm) in August 1991. On each plot one composite sample consisted of 5 subsamples. Four subsamples were taken halfway between the plot centre point and the plot corner. One subsample was taken in the plot centre. Peat samples were dried at 60ºC and ground to pass through a 2 mm sieve. The bulk density in the 0–5 cm peat layer was 298 g dm^{-3} on average. The ash content of the peat was determined from analyses of loss on ignition (550ºC). The mean soil organic matter content was 63% (range 32–96%). The samples were analyzed for their total concentrations (HCl extraction of ignition residue) and extractable concentrations (acid ammonium acetate, AAc, pH 4.65) of P, K, Ca and Mg. Total N (Kjeldahl) and B (in H_3PO_4-H_2SO_4) were also analyzed. Soil acidity was measured from dried soil-water suspension (v/v 1:5).

The mineral soil under the peat layer (subsoil) was sampled (5 subsamples pooled into one sample) in May 1982 for the determination of nutrient contents and in October 1994 for the determination of soil texture. The particle size distribution was determined by the sieving method. The mineral subsoil was mostly coarse sand (81.7%) having median particle diameter of 0.44 mm. The share of gravel was 4.4% and that of fine sand 11.7%. The proportion of fine fractions (< 0.06 mm) was 2.0%. The pH in the subsoil was 4.5 and its organic matter content 1.7%. The total P concentration in the subsoil was 275 mg l^{-1} and that of AAc extractable 3.2 mg l^{-1}. For K the corresponding figures were 1220 mg l^{-1} and 10.2 mg l^{-1} and for Ca 896 mg l^{-1} and 196 mg l^{-1}.

Foliar samples from downy and silver birch were taken in August from the upper crown of the trees eight times at 5 to 21 growing seasons after fertilization (in 1986, 1988, 1989, 1995, 1996, 1997, 1998 and 2002). The foliar samples were analyzed for their N, P, K, Ca, Mg, Mn and B concentration units using standard methods (Halonen et al. 1983).

In circular subsample plots, covering 16% of the area in each plot, all stems were measured on height and diameter at breast height at several times during the study period (21 years) after clearcutting (1983, 1984, 1985, 1986, 1988, 1989, 1991, 1992, 1996, 2002). The total study period was 37 years. Biomass sample trees (minimum two trees per plot), selected according to the stand diameter distribution, were felled in December 2002. After felling, the tree diameter ($d_{1.3}$) and height were measured, branches and stem discs sampled (Fig. 1), and branches and stems weighed separately in the field. The subsamples of branches and stem were dried to a constant weight at 60ºC and ground in a laboratory mill. The N, P, K, Ca, Mg, Zn and B concentrations of the stems and branches were analyzed and moisture content (105ºC) determined (Halonen et al. 1983). The C concentration of the samples was analysed on a CHN analyzer (Leco CHN-2000). All values were corrected for dry matter content (105ºC). Amounts of nutrients bound into the standing biomass were calculated by multiplying nutrient concentrations with biomass.

The above-ground woody biomass (stem and branch dry mass) of the trees was calculated using allometric biomass equations. In the calculation of the equations, biomass sample trees taken earlier (see Hytönen and Kaunisto 1999) were also used so that the total number of sample trees in the construction of the models was 77–87 for birch and 31 for willows. Above-ground, woody biomass was calculated with the following equations:

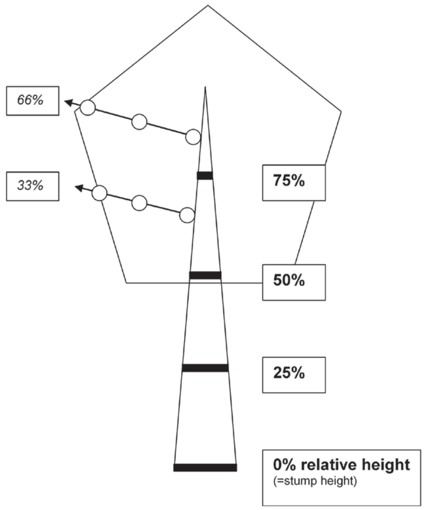

Fig. 1. Sampling of branches (sample branches from relative heights of 33 and 66% in living crown; branch specimens for dry mass and nutrient determinations from the base, middle and head of the branch) and stem (sample discs from relative heights of 0, 25, 50 and 75% of the stem).

1) Birch stem biomass: $0.083 \times d_{1.3}^{2.734}$
   $N = 77, R^2 = 0.991$
2) Birch branch biomass: $0.195 \times d_{1.3}^{2.201}$
   $N = 87, R^2 = 0.987$
3) Willow, above-ground biomass: $0.61052 \times d_{1.3}^{2.307}$
   $N = 31, R^2 = 0.985$

where biomass = Dry mass (g, in 105ºC) and
$d_{1.3}$ = stem diameter at breast height (mm).

The effect of fertilization treatments on foliar nutrient concentrations, height, diameter ($d_{1.3}$) and biomass production of birch was tested applying repeated measures analysis of variance. The data for biomass was analyzed after logarithmic transformation to reduce heteroscedasticity. Testing of nutrient amounts in the peat was restricted to the upper 20 cm layer due to the variation of peat depths in the plots. Nutrient amounts in the peat were tested statistically with repeated measures ANOVA with the soil layers (5 cm thick layers) as within-subject factors and fertilization as a between-subject factor (SPSS 16.0, PASW Statistics).

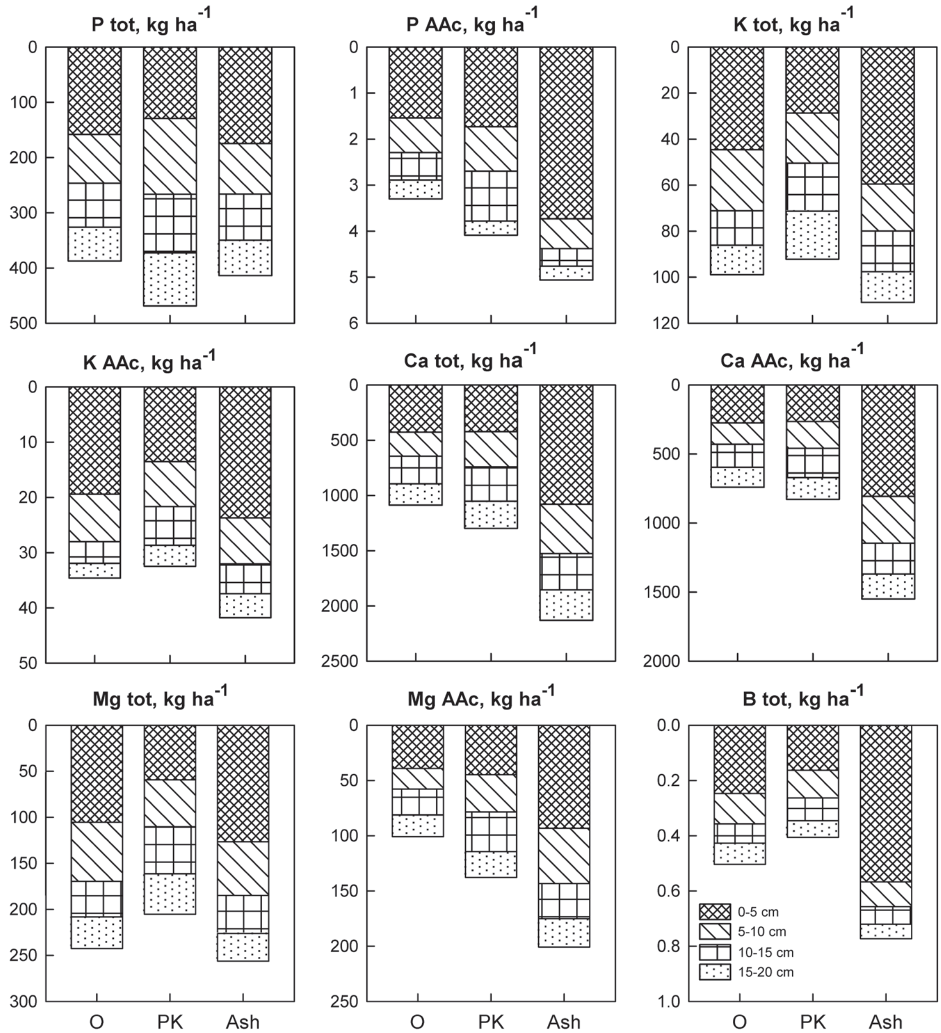

Fig. 2. Peat total and acid ammonium acetate extractable (AAc) P, K, Ca and Mg amounts and total B amounts in 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm soil layers ten years after fertilization.

3 Results

3.1 Nutrient Amounts in Soil

Ten years after fertilization the nutrient amounts in different peat layers differed significantly from each other (Table 1, Fig. 2) so that the nutrient contents were highest in the top 5 cm layer and decreased downwards. Predominantly fertilization only affected nutrient amounts in the upper peat layer (0–5 cm). This was mostly seen as a significant interaction between layer and fertilization in most studied nutrients (except for total N and total P). The amounts of total N, P and K in the 0–20 cm layer were on average 6020 kg ha^{-1}, 420 kg ha^{-1} and 100 kg ha^{-1}, respectively. Ash treatment increased soil pH in the 0–5 cm layer from 4.5 to 5.5. In the 5–10 cm layer the increase was smaller (4.4 vs. 4.8) and in the 10–15 cm layer there were no differences in pH due to ash application (4.4 vs. 4.5). Higher rates of P, K and B in the form of ash fertilization,

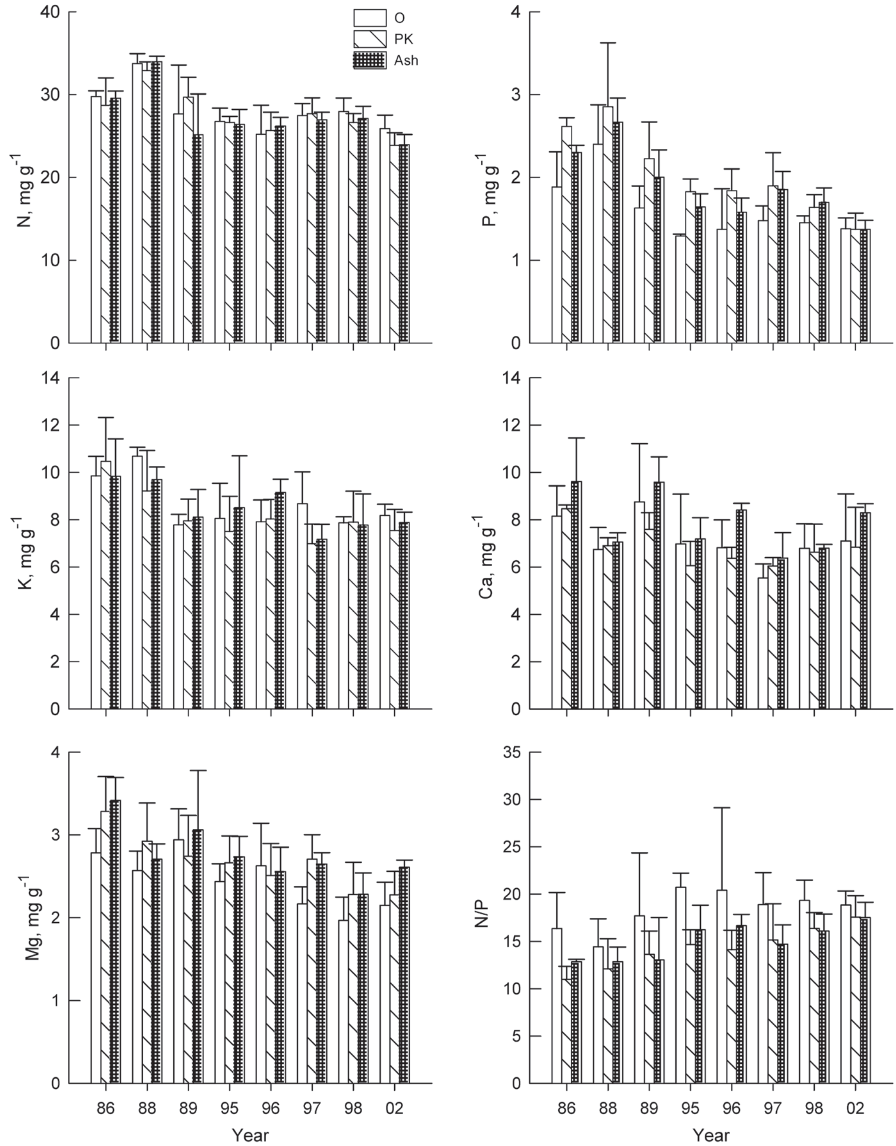

Fig. 3. Foliar N, P, K, Ca and Mg concentrations and N/P ratios of birch in different fertilization treatments. Standard deviation is marked on top of the bars. See Table 2 for statistical analyses.

increased soil nutrient amounts most. In the total nutrient amounts this was most clearly seen in the increase of Ca in the 0–5 cm layer. Ash fertilization increased the amount of B in the 20 cm soil layer from 0.5 kg ha^{-1} to 0.8 kg ha^{-1}. PK fertilizer and ash increased soil acid ammonium acetate extractable P amounts by 0.8 kg ha^{-1} and 1.8 kg ha^{-1}, respectively. Ash increased soil total and extractable K amounts in the upper layer but PK fertilizer did not. Ash fertilization also increased soil extractable Mg and Ca amounts by 100 kg $ha^{-1}$and 810 kg ha^{-1} compared to the control.

3.2 Foliar Nutrient Concentrations in Birch

Foliar nutrient concentrations of the coppiced stands were analyzed altogether 8 times during

Table 1. Effect of fertilization on peat nutrient amounts measured in 5 cm layers from 0 to 20 cm. Statistically significant ($p<0.05$) differences marked in bold.

Variable	Fertilization p	Layer p	Fertil. × Layer p
N tot	0.409	**0.004**	0.260
P tot	0.427	**<0.001**	0.158
P AAc	0.315	**<0.001**	**0.011**
K tot	0.687	**<0.001**	**0.002**
K AAc	0.494	**<0.001**	**0.045**
Ca tot	0.168	**<0.001**	**0.005**
Ca AAc	0.101	**<0.001**	**0.001**
Mg tot	0.801	**<0.001**	**0.009**
Mg AAc	0.119	**<0.001**	**0.001**
B tot	**0.018**	**<0.001**	**<0.001**

Table 2. Effect of fertilization on the nutrient concentrations in birch leaves. Statistically significant ($p<0.05$) differences marked in bold.

Variable	Fertilization p	Year p	Fert. × Year p
N	0.484	**<0.001**	0.443
P	**0.035**	**<0.001**	0.711
K	0.728	**<0.001**	0.397
Ca	0.396	**<0.001**	0.749
Mg	0.394	**<0.001**	0.059
Mn	**0.016**	**0.007**	0.375
B	0.484	**0.013**	0.907
N/P	**0.016**	**0.005**	0.587
N/K	0.755	**0.002**	0.360
P/K	0.100	**<0.001**	0.439

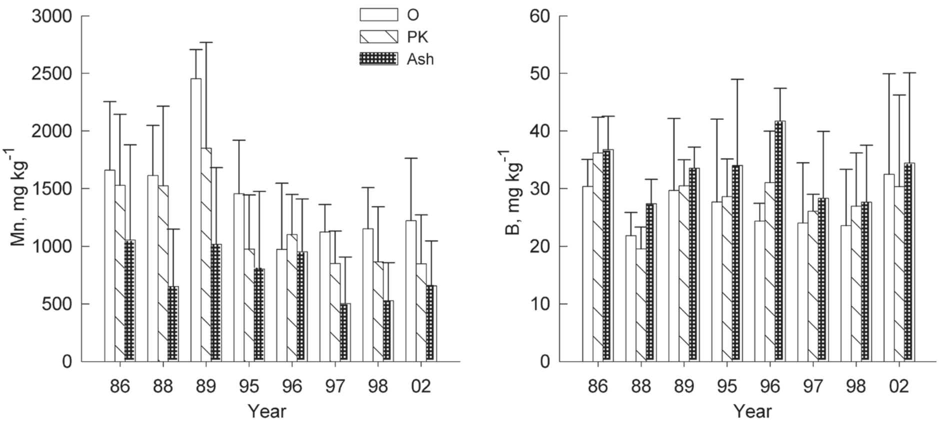

Fig. 4. Foliar Mn and B concentrations of birch in different fertilization treatments. Standard deviation is marked on top of the bars. See Table 2 for statistical analyses.

the investigation starting at the age of 5 years and ending at the age of 21 years (Fig. 3). Ash and PK fertilization increased foliar P concentrations (Table 2, Fig. 3). There were also significant differences in P concentrations between the years. The phosphorus concentration, especially that of the fertilized trees, decreased towards the end of the study period. A similar phenomenon was observed in K and Mg concentrations. Finally, there were no differences in the foliar P concentration between fertilized and unfertilized trees in the last analysis 21 years after fertilization. Fertilization treatments did not affect foliar N, K, Ca, Mg and B concentrations (Table 2, Figs. 3 and 4). Even though fertilization did not significantly affect foliar N concentrations, the foliar N/P ratio was highest in the unfertilized trees (Fig. 3). PK and especially wood ash fertilization decreased foliar Mn concentrations (Fig. 4). The year to year variation in nutrient concentrations was significant but there were no interactions between year and fertilization (Table 2).

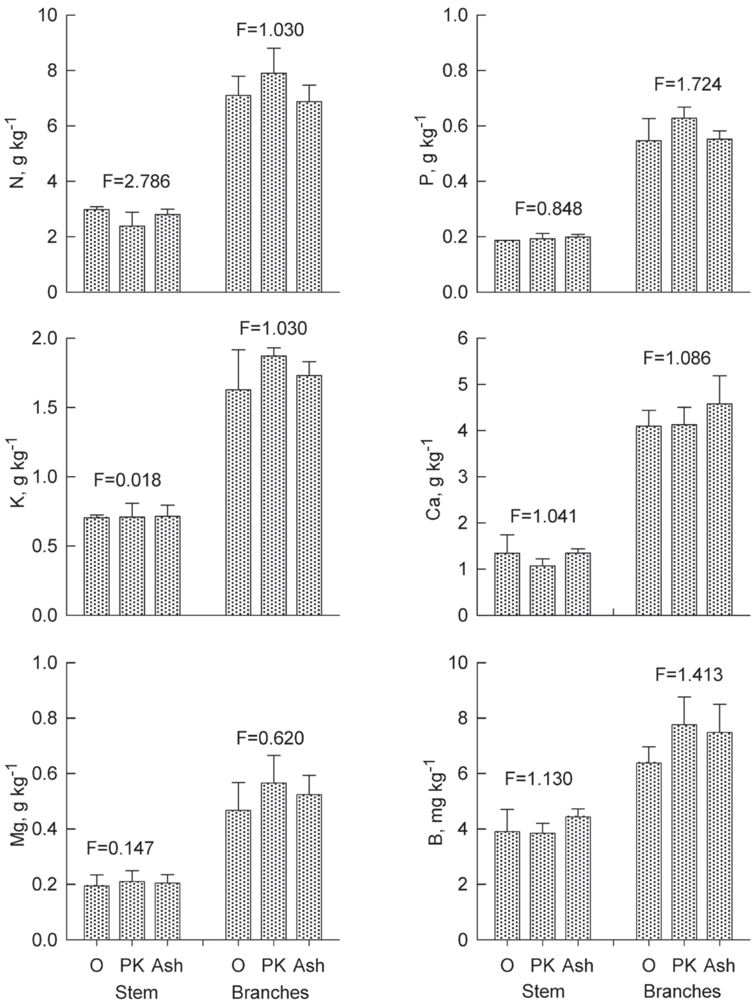

Fig. 5. Nutrient concentrations of birch stems and branches 21 years after fertilization. Standard deviation is marked on top of the bars.

3.3 Carbon and Nutrient Concentrations of Birch and Willow

At the end of the 2nd rotation period (age of trees 21 years) fertilization did not significantly affect N, P, K, Ca, Mg or B concentrations in birch stems or branches (Fig. 5). The nutrient concentrations in birch branches were in most cases more than double compared to corresponding concentrations in stems. Fertilization did not significantly affect nutrient concentrations in the leafless, above-ground biomass of willow. The mean nutrient concentrations (and standard deviations) for N, P, K, Ca and Mg were 5.3 (0.4), 0.4 (0.1), 1.8 (0.2), 5.9 (1.0) and 0.5 (0.1) mg g^{-1}, respectively.

Fertilization did not affect ($p = 0.693$) the carbon concentration of birch stems, the mean being 49.2%. However, fertilization had a significant effect ($p = 0.030$) on the carbon content of birch branches. The unfertilized trees' branches had a lower C content (49.1%) than that of birch branches fertilized by PK (49.6%) or ash (49.7%). The mean C concentration in leafless, above-ground biomass of willow was 49.2%. PK fertilized willows had the lowest C concentration (48.9%, $p = 0.014$).

3.4 Stand Density, Mean Height and Diameter

The mother stand was clear cut at the age of 16 years and had on average 11 000 stems ha^{-1} (*B. pendula* 69%, *B. pubescens* 4% and willows 27%). Due to sprouting the stem number increased 7-fold and was 75 500 stems ha^{-1} two years after clear-cutting (Fig. 6). A decline in stem numbers started soon and the decrease was highest during the first 8–10 years after clear-cutting. Due to self-thinning the stem number had declined to 8700 stems ha^{-1} at the age of 21 years. The species composition had also changed so that now downy birch was the dominating birch species (*B. pendula* 11%, *B. pubescens* 60% and willows 29%). The plot that had grown uncut (part of the mother stand) for 37 years had an average of 4100 stems ha^{-1}. Fertilization treatments did not significantly affect stand density or species composition.

The mean diameter ($d_{1.3}$) and height of silver birch were considerably greater than those of downy birch (Fig. 7). At the end of the experiment the height of fertilized silver birch was 10.0–11.2 m and that of downy birch 6.8–6.9 m. Fertilization had significantly increased the height (p = 0.005) and diameter (p = 0.028) of silver birch. Fertilized silver birches were 1.2–2.5 m taller and 1.3–2.5 cm thicker than unfertilized trees. Even though fertilized downy birches were at the end of the experiment 1 m taller and 1.3 cm thicker than unfertilized trees, the effect of fertilization was not significant ($p_{height} = 0.193$, $p_{d1.3} = 0.367$).

In the uncut plot, where trees had grown for

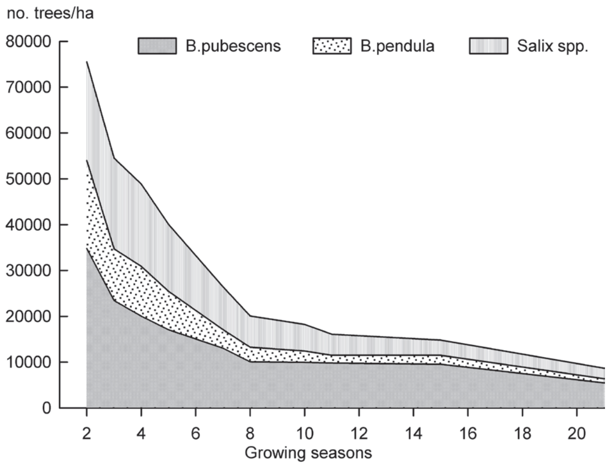

Fig. 6. Number of stems (trees ha^{-1}) of different tree species in the coppiced birch stands after clearcutting (second rotation, 21 years).

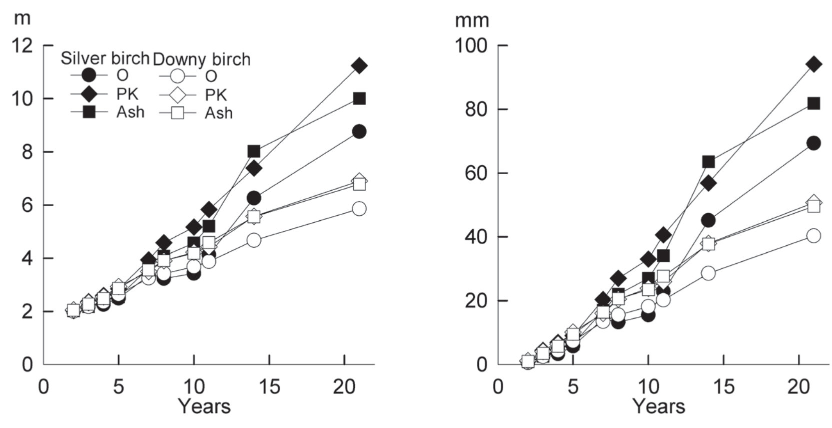

Fig. 7. Mean height (m) and breast height diameter (mm) of silver birch and downy birch.

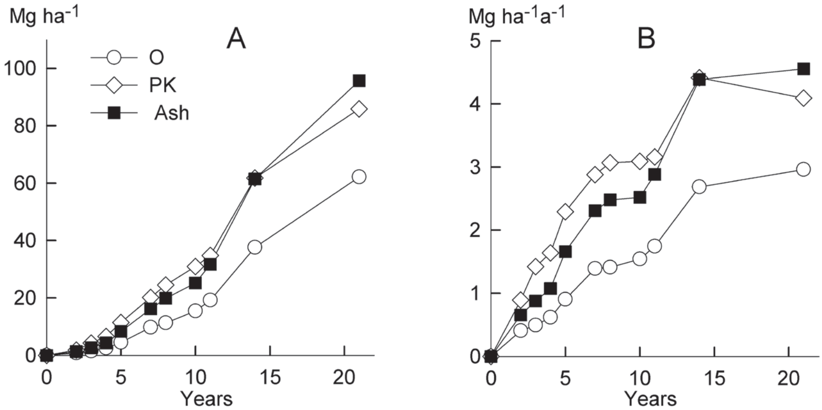

Fig. 8. The above-ground biomass (A) and mean annual increment (B) of the stands during the second rotation.

37 years, the height of silver birch was 16.9 m and that of downy birch 12.9 m. Corresponding diameters at breast height were 12.9 and 8.0 cm.

3.5 Biomass Production

The leafless, above-ground biomass production of the birch stands before clearcutting at the age of 16 years was 62.3 Mg ha^{-1} (Ferm and Kaunisto 1983). After clearcutting the sprouts were allowed to grow for 21 years. In the second rotation unfertilized stands had 62.1 Mg ha^{-1} leafless, above-ground biomass. Fertilization with PK and ash increased significantly ($p = 0.033$) the leafless, above-ground biomass production by 23 Mg ha^{-1} and 33 Mg ha^{-1}, respectively. PK fertilization gave a slightly faster initial response than ash fertilization but later the situation was reversed (Fig. 8).

During the first 16-year long rotation the mean annual increment (MAI) was 3.9 Mg ha^{-1} (Fig. 9). After coppicing the mean annual increment of the birch stands increased up to the age of 15 years and remained at the same level from 15 to 21 years. The MAI increment of the 21-year-old fertilized stands was 4.1–4.6 Mg ha^{-1} and that of unfertilized ones 3.0 Mg ha^{-1}.

When the first 16-year long rotation (unfertilized) is taken into consideration the birch stands produced in 37 years on unfertilized, PK fertilized and ash fertilized plots altogether 124.4, 148.2 and 158.0 Mg ha^{-1} of biomass, respectively. Corresponding values for the MAI increment were 3.4, 4.0 and 4.3 Mg ha^{-1}.

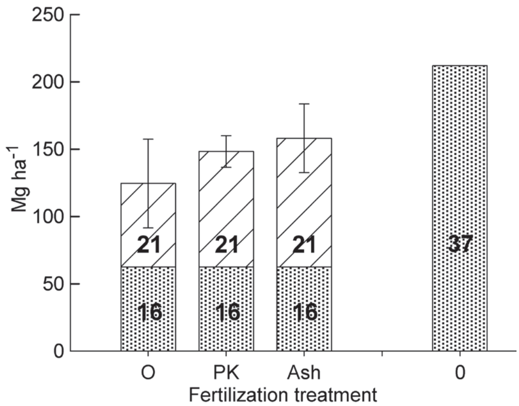

Fig. 9. Biomass production of the first (16 years unfertilized) and second (21 years, fertilization treatments 0, PK and Ash) rotation of the coppiced stands and the biomass of the uncut 37-year-old stand. Standard deviation for the second rotation is marked on top of the bars. Ages of the stands are marked inside the bars.

The uncut 37-year-old stand had the greatest standing biomass (211.9 Mg ha^{-1}) and consequently also the highest MAI during the whole 37-year study period (5.7 Mg ha^{-1} a^{-1}).

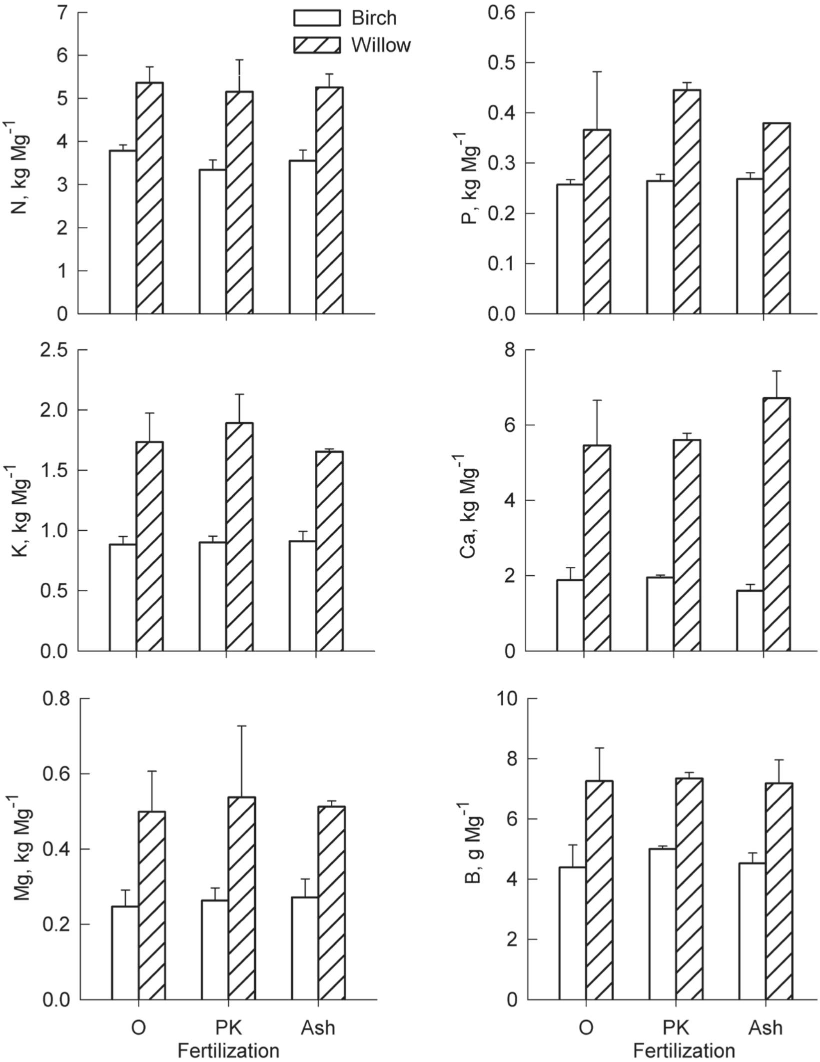

Fig. 10. Concentration of nutrients in leafless, above-ground biomass of birch and willow 21 years after fertilization. Standard deviation is marked on top of the bars.

3.6 Nutrients and Carbon Bound into the Biomass

Fertilization did not significantly affect the nutrient content of the willow or birch biomass (Fig. 10). Willow had more bound N, P, K, Ca, Mg and B than birch in the leafless, above-ground biomass ($p < 0.001$, Fig. 10). One ton of leafless, above-ground willow and birch biomass contained 4.0 kg N, 0.3 kg P, 1.1 kg K, 2.9 kg Ca, 0.3 kg Mg and 5.3 g B, on average (the proportion of willow was 27%). On average 493 kg of carbon was bound in one tonne of leafless biomass. Thus during the 37-year study period (rotation periods of 16 and 21 years) unfertilized, PK and ash fertilized stands had bound carbon levels of 61, 73 and 78 Mg ha^{-1}, respectively. Therefore the fertilized stands had annually 2.0–2.1 Mg ha^{-1} of bound C in their leafless, above-ground biomass. The uncut stand had, at the age of 37 years, the highest annually bound carbon (2.8 Mg ha^{-1}).

4 Discussion

4.1 Biomass Production

The mean annual woody biomass production was 3.0–4.6 Mg ha^{-1} a^{-1} in the coppiced birch stands over a 21-year period. Fairly similar yields (2.3–5.3 Mg ha^{-1} a^{-1}) have been reported in naturally regenerated, young (7–23 years) and dense birch thickets on peatlands in southern Finland (Björklund and Ferm 1982, Ferm 1990). Renou-Wilson et al. (2010) estimated yields of 3.1–5.8 Mg $ha^{-1}a^{-1}$ in naturally regenerated birch stands on cutaway peatlands in Ireland. In Sweden Johansson (1999) reported variable yields ranging from 0.5 Mg $ha^{-1}a^{-1}$ to 4.4 Mg $ha^{-1}a^{-1}$ from stands he studied on former arable land. In this study we measured the highest yield (5.7 Mg $ha^{-1}a^{-1}$) in the stand that had been grown uncut for 37 years. Similar high biomass yields (5.7–5.9 Mg $ha^{-1}a^{-1}$) have also been reported earlier from densely planted (planting density 20 000 seedlings ha^{-1}), 19-year-old, intensively fertilized downy and silver birch stands growing on cutaway peatland in Central Finland (Hytönen and Saarsalmi 2009). In biomass production, birch is not suited to very short rotations (Hytönen and Issakainen 2001). This study indicates that a rotation period longer than 21 years should be used in order to maximize biomass production in dense downy birch stands. This is indicated by the fact that the 37-year-old stand had a higher biomass and MAI than the stands with two rotations (16 + 21 years) of birch.

For comparison, annual biomass production in reed canary grass plantations has varied from 0.6 to 6.3 Mg ha^{-1} on fertilized and limed cutaway peatlands in northern Finland (only one year monitoring period, Parviainen 2007) and from 1.7 to 4.0 Mg ha^{-1} in eastern Finland (monitoring period four years, Shurpali et al. 2009). Also, compared with short rotation willow, the biomass production of birch in this study was high, e.g. much higher than that obtained with exotic willows on cutaway peatlands in Finland (Hytönen 1996) or even higher than yields reported from commercial willow plantations in Sweden (Mola-Yudego 2011). Furthermore, both reed canary grass and willow species need liming as well as annual fertilization with nitrogen and regular fertilization with mineral nutrients. For exotic willows annual nitrogen fertilization even on nitrogen rich cutaway peatlands is necessary (Hytönen 1995a). Moreover, biomass production of exotic willows also is more limited by climate conditions (e.g. frost) than birch.

The development of ground vegetation (Huotari et al. 2009) followed by the establishment of the tree stand changes the carbon balance on cutaway peatlands. Fertilization with fertilizer containing P and K enhances the formation of vegetation on cutaway peatland (Salonen and Laaksonen 1994, Huotari et al. 2007). The annual soil CO_2 emissions due to decomposition of the remaining peat layer from the same afforested cutaway peatland area (Aitoneva, Kihniö) was measured to be 381 g C m^{-2} a^{-1} 15–43 years after stand establishment, on average (Mäkiranta et al. 2007). In our study the coppiced and fertilized birch stands (16a + 21a rotations) had 200–210 g C m^2 a^{-1} bound in their above-ground biomass and the stand that had grown uncut for 37 years had 280 g C m^{-2} a^{-1}. If the root biomass of birch is assumed to be 30% of the above-ground biomass (e.g. Finér 1989), most of the plots would still be sources of C to the atmosphere. The uncut 37-year-old stand would sequestrate almost as much carbon as is emitted from the peat. However, afforestation with birch would considerably compensate for the high CO_2 emissions of cutaway peatlands.

4.2 Growing Silver and Downy Birch as Dense Thickets

Both downy and silver birch can be successfully established on cutaway peatlands by planting (Kaunisto 1987, Aro et al. 1997, Renou et al. 2007, Hytönen and Saarsalmi 2009), but also considerably cheaper natural regeneration and direct seeding of birch have given good results on fertilized cutaway peatlands (Kaunisto 1981, Aro et al. 1997, Huotari et al. 2008, 2009). For example, Kaunisto (1981) reported 150 000–200 000 birch seedlings ha^{-1} on fertilized and cultivated cutaway peat if the distance to the seeding trees was less than 40 m. Besides natural regeneration, the cheap establishment of stands can also be achieved by direct seeding. The seeding of birch

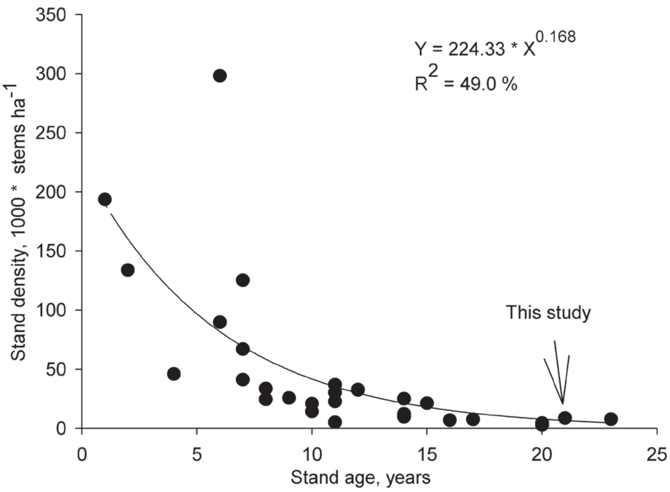

Fig. 11. Development of stand density of natural, initially dense downy birch stands from 1 to 23 years of age. Data from Ferm (1990), Björklund and Ferm (1982), Ferm and Kaunisto (1983), Hytönen and Issakainen (2001), Hytönen and Kaunisto (1999), Johansson (1999) and this study.

on three cutaway peatlands (Aro et al. 1997) was considered successful with downy birch on 50–69% and with silver birch on 58–69% of the seeded area. On the successfully regenerated areas the number of seedlings two years after direct seeding was 112 000–200 000 seedlings ha^{-1} (Aro et al. 1997). In this study the number of stems was 75 500 stems ha^{-1} after the second growing season following coppicing. The stem number in young stands can be much higher, even more than double the figure measured in this study (Fig. 11).

Self-thinning of the dense coppiced birch stands was highest during the first years after clear-cutting. After 8–10 growing seasons the self-thinning rate decreased (see also Fig. 11). Despite of this, the naturally regenerated, initially dense birch stands can have a high number of stems even at the age of 20 years. In this study the stem number in the coppiced stands was still 8700 stems ha^{-1} at the age of 21 years. Self-thinning led to almost the same stand density (9000–11 200 stems ha^{-1}) in planted (20 000 seedlings ha^{-1}), 19-year-old stands of downy birch and silver birch also growing in cutaway peatland areas (Hytönen and Saarsalmi 2009). In the uncut plot grown for 37 years, the self thinning had progressed further, but still 4100 stems ha^{-1} were alive in the stand. Nowadays, even for growing pulpwood, quite high growing densities are recommended for downy birch: the optimum density is 2000 stems ha^{-1}, but small-diameter timber can be produced with an initial density of 4000–5000 stems ha^{-1} (Niemistö 1991).

Silver birch, which is not considered suitable for cultivation on peatlands and wet, poorly aerated soils has, however, grown better than downy birch, e.g. in some peat field afforestation areas (Saramäki and Hytönen 2004). Silver birch has also been shown to thrive on cutaway peatland areas (Ferm and Kaunisto 1983, Kaunisto 1987, Aro et al. 1997, Hytönen and Kaunisto 1999, Renou et al. 2007, Hytönen and Saarsalmi 2009). In this study the height and diameter growth of silver birch in a peat cutaway area was considerably greater than that of downy birch, while Hytönen and Saarsalmi (2009) reported the opposite for 19 years old planted stands. Even though silver birch grew better than downy birch, the stand structure changed during the study period of 21 years so that the stands initially mostly dominated by silver birch were dominated by downy birch by the end of the experiment. This was most probably due to the better sprouting ability, more abundant natural seeding and more pronounced seedling establishment of downy birch.

4.3 Nutrition of Birch Thickets

Generally, compared to peatland forests, it has been reported that the peat N store in cutaway peatlands is higher, that of P mostly equal and that of K lower (Ferm and Kaunisto 1983, Kaunisto 1987, Kaunisto and Viinamäki 1991, Aro 1995, Aro et al. 1997, Aro and Kaunisto 2003, Hytönen 1995a, 1995b). In this study the total amounts of N (6020 kg ha^{-1}) and K (100 kg ha^{-1}) in the 0–20 cm peat layer corresponded well with the results published previously from cutaway peatlands, but that of P (420 kg ha^{-1}) in this experiment was greater than has been reported earlier. On the other hand, the proportion of extractable P out of the total P was small, only 1% on average, which is typical for drained peatlands in Finland (e.g. Kaunisto and Paavilainen 1988). In addition, mineral soil was mixed into the peat (37% on average) on our study plots, and consequently the iron content may have been high and reduced the availability of P considerably (Nieminen and Jarva 1996). Due to the imbalance between P and N stores in peat and low K stores, nutritional problems may occur on cutaway peatlands.

Several studies have shown that in peatlands the amounts of total N and P correlate with the wood production of the site, but the amount of K in peat does not indicate the fertility of the site (e.g. Paarlahti et al. 1971, Westman 1987, Kaunisto and Paavilainen 1988). In this study the amounts of N and P were 2 to 3-fold as compared to a fertile, pine-growing mire (RhSR in Finnish classification, see Laine and Vasander 2005) in its natural state (Westman 1981). Also the amount of P was almost twofold as compared to fertile spruce growing mires (RhK, MK) or fertile, drained, pine-growing mires (VSR, RhSR, Kaunisto and Paavilainen 1988). Furthermore, the amounts of N and P in the 20 cm thick surface peat layer were approximately equal to the amounts that Westman and Laiho (2003) reported for the 30 cm thick surface peat on drained peatland forests of a herb-rich type. Westman and Laiho (2003) reported that trophy levels in peatland forests can be best explained by the amount of Ca in the peat. In our study the total amount of Ca in surface peat (0–20 cm) was 1310 kg ha^{-1}, on average, which was 20% more than in the 30 cm thick layer of *Vaccinium myrtillus* site type I (MtkgI, see description of the type in Vasander and Laine 2008) but slightly less than in the surface peat (0–20 cm) of Herb-rich site type (Rhtkg, see Vasander and Laine 2008) in their study. Consequently, the studied cutaway site was very fertile, having high wood production potential.

Fertilization mostly affected the nutrient amounts in the upper peat layer. Ash fertilization, containing more nutrients than PK fertilization, increased soil nutrient amounts most, especially those of Ca and Mg. Ash is also a good liming agent (Saarela 1991, Hytönen 2005), and this was seen in a 0.9 unit increase in pH in the top most soil layers with a 5 Mg ha^{-1} ash dose ten years after ash application. Even though the amount of B, both in ash and PK fertilizer, were almost equal, only ash increased the soil B amount. Boron could be in a more soluble form in PK fertilizer than in wood ash and consequently it may have leached into deeper soil layers after the PK fertilizer was applied. The difference in K amounts applied in the ash and PK fertilization was great, but the measured difference in the amounts in the soil was smaller. Most of the applied K have probably already leached out to groundwater and surface waters in the ditches, or leached to deeper soil layers, even though this was not found in the soil analyses.

In this study foliar analyses showed that the main limiting factor for the growth of the birch was a severe shortage of P. The concentrations of other elements indicated a mainly satisfactory N, K, Ca, Mg, Mn and B nutrition of birch (e.g. Reinikainen et al. 1998). Fertilization with ash or PK had removed the P shortage. However, the effect of fertilization was decreasing since P concentrations were decreasing during the latest years.

Fertilization did not increase the nutrient concentrations of birch stems and branches in this study. Similar results for both downy and silver birch have been obtained earlier (Hytönen et al. 1995, Hytönen and Kaunisto 1999, Hytönen and Saarsalmi 2009). These results suggest that the fertilization of birch does not increase the amount of nutrients removed from the site per unit of biomass. The amount of N (3.6 kg Mg^{-1}) contained in one ton of leafless dry mass was at the same level as earlier reported for 6–20 year old downy birch stands (Mälkönen and Saarsalmi 1982, Hytönen and Kaunisto 1999, Hytönen and

Saarsalmi 2009). The amounts of P and K were almost identical to the previous studies. Willows are more demanding species than birch and use more nutrients in their unit biomass than birch (Hytönen and Saarsalmi 2009). In this study willows had 47%, 33%, 100%, 210% and 66% more N, P, K, Ca and Mg, respectively, bound in their unit biomass than birch. Willow used especially high amounts of K and Ca. The high K and Ca uptake of willows has been reported in other studies as well (e.g. Hytönen 1996, Hytönen and Saarsalmi 2009). Thus, the growing of willows on cutaway peatlands having low pH and K concentrations is particularly more challenging than the growing of birch in respect of the nutrient demands of the tree species.

4.4 PK and Wood Ash Fertilization

Nutritional problems may be encountered when afforesting cutaway peatlands and consequently the success of afforestation will, in many cases, depend on soil amelioration and fertilization (Valk 1986, Kaunisto 1987, Hytönen et al. 1995, Hånell et al. 1996, Aro et al. 1997, Hytönen and Kaunisto 1999, Aro and Kaunisto 2003). In this study fertilization with ash and PK fertilizer was carried out after clearcutting of the 16-year-old stand. Following clearcutting the spreading of fertilizers, and especially that of ash, is technically easy. Recycling of wood ash could promote sustainable forestry on cutaway peatland sites and significantly reduce the waste problem, that may arise when wood fuels are used for energy production. Ash and PK fertilization have earlier been shown to increase the biomass production of naturally regenerated or seeded birch stands on cutaway peatland after four growing seasons (Huotari et al. 2009). In our study PK and ash fertilization significantly increased stand biomass in 21 years by 23 and 33 tonnes ha^{-1}, respectively. Ash had a slower initial effect on biomass increment than PK fertilizer, but after 21 years the response from ash was slightly better than that obtained with PK fertilizer. Similar results have been reported for peatland forests where wood ash had better response to stem volume growth of Scots pine than PK fertilizer only 15 years after fertilization (Moilanen et al. 2004). Based on the research results from peatland forests with pine, one can expect that the response of trees to ash fertilization will last 30–40 years, and longer than that of PK fertilization (Silfverberg and Huikari 1985, Silfverberg 1996). Earlier, similar (14–37 Mg ha^{-1}) biomass increases in 19-year-old planted silver birch and downy birch stands on cutaway peatland have been reported by Hytönen and Saarsalmi (2009). Young birch stands have been shown to respond well to PK, NPK and ash fertilization on cutaway peat in greenhouses (Hytönen 2005) and in fields (Kaunisto 1987, Hytönen et al. 1995, Aro and Kaunisto 1996, Aro et al. 1997, Hytönen and Saarsalmi 2009). However, fertilization has not increased the yield of mature birch stands on drained peatlands (Oikarinen and Pyykkönen 1981, Moilanen 1985).

The mineral nutrient stores in the mineral soil beneath the peat layer may compensate the fertilization requirements. Aro (2000) studied the root penetration of silver birch in five cutaway peatland areas and reported 17-year-old birch stands having a mean root penetration of 6–15 cm. Fertilization is an intensive management tool that is essential for successful, high and sustainable biomass production on cutaway peatlands when the peat layer is too thick for roots to penetrate into the subsoil. Since the peat depth in this study varied from 18 to 54 cm it might be that the trees on some plots were able to utilize mineral soil nutrient resources. However, the mineral soil underneath was mainly sand with a very small proportion of finer particles, and thus not very fertile.

5 Conclusions

Large areas of peat production fields will be available for other uses in the near future. According to this study birch could be an interesting alternative to willows and reed canary grass in biomass production on cutaway peatlands. Our results suggest that the rotation period of birch should be longer than 21 years in order to maximize biomass production. While birch rotation is three to five times longer than that of willow or reed canary grass, higher yields and reduced number of harvests are clear advantages. Willows are more demanding species in their nutrient use than birch. Also, comparing birch with reed canary grass and exotic willows, soil amelioration to increase the soil pH level is not needed and fertilizer application can be repeated at longer intervals, probably even only once in a rotation if wood ash is used. Biomass production with birch could also help to sequester carbon and considerably decrease the carbon loss from the peat during the first rotation. In addition, the amount of carbon bound into above-ground biomass can be increased by fertilization. More experimentation is needed to confirm the biomass yields that could be achieved in different peat cutaway areas, and the dependence of yield on peat quality and peat thickness.

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