Biomass Production and Nutrient Uptake of Short-Rotation Plantations

Jyrki Hytönen, Anna Saarsalmi & Pekka Rossi

Hytönen, J., Saarsalmi, A. & Rossi, P. 1995. Biomass production and nutrient uptake of short-rotation plantations. Silva Fennica 29(2): 117–139.

The biomass production and nutrient uptake of silver birch (*Betula pendula*), downy birch (*B. pubescens*), grey alder (*Alnus incana*), native willows *Salix triandra* and *S. phylicifolia* and exotic willows *S.* × *dasyclados* and *S.* 'Aquatica' growing on a clay mineral soil field (Sukeva) and on two cut-away peatland areas (Piipsanneva, Valkeasuo) were investigated.

Biomass production of downy birch was greater than that of silver birch, and the biomass production of the native willows greater than that of the exotic ones. The performance of *S. phylicifolia* was the best of the studied willow species. Exotic willows were susceptible to frost damage and their winter hardiness was poor. The production of all species was lower on the clay mineral soil field than on the cut-away peatland areas. Fertilization of birches and alder – or the double dose given to the willows – increased biomass production. After 6 growing seasons the leafless biomass production of fertilized silver birch at Piipsanneva was 21 t ha^{-1}, of downy birch 25 t ha^{-1} (at Valkeasuo 34 t ha^{-1}) and of grey alder 24 t ha^{-1}, and after five growing seasons the leafless biomass production of *S. triandra* was 31 t ha^{-1}, of *S. phylicifolia* 38 t ha^{-1} and of *S.* × *dasyclados* 16 t ha^{-1}.

6-year-old stands of silver birch bound more nutrients per unit biomass than downy birch stands. Grey alder bound more nitrogen, calcium and copper but less manganese and zinc per unit biomass than silver birch and downy birch. On the field more phosphorus was bound in grey alder per unit biomass compared to downy birch. The willows had more potassium per unit biomass than the other tree species, and the exotic willow species more nitrogen than the native ones. Less nitrogen, potassium and magnesium were bound per unit biomass of *S. phylicifolia* compared to the other tree species.

Keywords biomass production, nutrient uptake, *Betula pendula*, *B. pubescens*, *Alnus incana*, *Salix triandra*, *S. phylicifolia*, *S.* × *dasyclados*, *S.* 'Aquatica'.
Authors' addresses *Hytönen*, The Finnish Forest Research Institute, Kannus Research Station, P.O. Box 44, FIN-69101 Kannus, Finland; *Saarsalmi*, The Finnish Forest Research Institute, Vantaa Research Centre, P.O. Box 18, FIN-01301 Vantaa, Finland; *Rossi*, The Finnish Forest Research Institute, Suonenjoki Research Station, FIN-77600 Suonenjoki, Finland **Fax** to *Hytönen* +358 68 871 164 **E-mail** jyrki.hytonen@metla.fi
Accepted July 27, 1995

1 Introduction

Short-rotation forestry refers to the cultivation of fast-growing deciduous tree species, regenerating through sprouts, using short rotation periods, intensive methods and dense stocking. In Finland the short-rotation cultivation of willows, birches and grey alder has been studied most. Cut-away peatland areas that are relatively rich in nitrogen, but poor in phosphorus and potassium, and relatively infertile agricultural fields in the central and northern parts of Finland have been considered to be suitable sites for short-rotation forestry (Energiametsätoimikunnan ... 1979, 1981). However, now large areas of agricultural land are being set aside from conventional use for afforestation or alternative crops (Ferm et al. 1993).

Silver birch (*Betula pendula* Roth) and downy birch (*B. pubescens* Ehrh.) differ from each other in their chromosome number, many morphological properties, growth rhythm and, to some extent, also their geographical distribution (Raulo 1981). Silver birch grows almost exclusively on mineral soils, whereas downy birch is also common on peatlands (Ferm 1993). Downy birch thrives on the wet and poorly-aerated sites where silver birch cannot grow (Raulo 1981). When growing in the same habitat, silver birch is larger and of better quality than downy birch (Heiskanen 1957), although there are no significant differences between the growth rates of these two species until they have reached an age of 15 years (Raulo 1981). The cultivation of birch is somewhat problematic owing especially to vole and moose damages and fungal diseases (Hytönen 1995). Also the feasibility of utilizing coppice management in naturally regenerated downy birch stands in Finland has been studied (Ferm 1990a).

Grey alder (*Alnus incana* (L.) Moench) is a vigorously sprouting and fast growing species. Its biomass production is high at a young age on both mineral (Saarsalmi et al. 1985) and peat soils (Rytter et al. 1989). Nitrogen fertilization does not increase the production of grey alder (Saarsalmi et al. 1985, Rytter et al. 1989), but can even have a detrimental effect (Sørensen 1936, Saarsalmi et al. 1992). What makes alder especially important is that it is capable of fixing atmospheric nitrogen. Phosphorus also plays an important role in this process (Sprent 1979), and has been the only nutrient which has increased the growth of alder in fertilization experiments (McVean 1956, Themliz and Behrens 1957, Junack 1961, Saarsalmi et al. 1991). Moreover, alder leaf litter is rich in nitrogen and easily mineralized (Slapokas and Granhall 1991).

Alder's ability to fix nitrogen can be utilized by growing it together with other tree species. An admixture of alder has increased, e.g. the biomass production of poplars (*Populus* spp.) (Hansen and Dawson 1982, Coté and Camiré 1987, Radwan and DeBell 1988) and the growth of Scots pine (*Pinus sylvestris* L.) (Mikola 1966, Schalin 1966, Kaunisto and Viinamäki 1991). However, alder can suppress more slowly growing tree species; for instance, growing silver birch (Saarsalmi et al. 1992) or Norway spruce (*Picea abies* (L.) Karsten) (Höglind and Nilsson 1989) together with alder has not been successful due to differential growth patterns.

Much work has been done in short-rotation forestry in Finland with exotic willow species; such as *Salix* 'Aquatica', *S.* × *dasyclados* Wimmer which are morphologically very similar species, and *S. viminalis* L. There is serious problem with cultivation of these species in central and northern Finland because of poor winter hardiness (Pohjonen 1977, Lumme et al. 1984, Lumme and Törmälä 1988). Little is known about the biomass production of native Finnish willow species in dense cultivations. *S. phylicifolia* L., which grows throughout Finland, is the most common native willow species (Jalas 1965b). *S. triandra* L. occurring on a wide range of sites is grown for basketry in United Kingdom and central Europe (Nordberg 1919, Stott 1956, Jalas 1965a). It is also a native – although rare – species in Finland, the most extensive stands occurring in the Liminganlahti watercourse area and along the banks of the Torniojoki River (Siira et al. 1981).

Studies on the nutrient uptake of willow species in Finland have mainly concentrated on *S.* 'Aquatica'. It requires large amounts of nitrogen, phosphorus and potassium to grow well (Kaunisto 1983, Hytönen 1984, 1986, Saarsalmi 1984, Ferm 1985). The growth of *S.* 'Aquatica' on cut-away peatland areas is very poor without fertilization (Hytönen 1982, 1986, Ferm and Hytönen 1988, Lumme 1989). On mineral soils and even on nitrogen-rich cut-away peatland areas nitrogen fertilization has increased the production of willow (Hytönen 1987, Kaunisto 1983, Ferm and Hytönen 1988). On limed cut-away peatland areas the phosphorus fertilizer has to be in an easily soluble form (Kaunisto 1983, Hytönen 1986). Special attention should also be paid to soil pH when cultivating willows (Lattke 1969, Aldhous 1972, Ericsson and Lindsjö 1981, Ferm and Hytönen 1988).

Comparative studies on the biomass production and nutrient uptake of decidious tree species used in short-rotation forestry have not so far been made in Finland. Therefore in this study the biomass production and nutrient uptake of silver birch (*Betula pubescens*), downy birch (*Betula pendula*), grey alder (*Alnus incana*), *Salix triandra*, *S. phylicifolia*, *S.* × *dasyclados* and *S.* 'Aquatica' grown on a mineral soil field and two cut-away peatland areas were compared. Also the effects of fertilization on the biomass production and nutrient uptake of these tree species was studied. In addition, whether part of the nitrogen requirements of *S. triandra* can be satisfied by growing it together with grey alder was also studied. The study lasted for 6 years.

2 Material and Methods

2.1 Establishment and Management of the Experiments

Field experiments were established in spring 1984 on cut-away peatland areas at Piipsanneva, Haapavesi (64°06'N, 25°36'E), and at Valkeasuo, Tohmajärvi (62°19'N, 30°14'E), and on an abandoned mineral soil field at Sukeva, Sonkajärvi (63°54'N, 27°29'E). The field had been ploughed in autumn 1983. Before planting all the areas were harrowed. The cut-away peatland areas were limed (6000 kg ha^{-1}) before harrowing, and at the beginning of the second growing season the field was limed (2500 kg ha^{-1}) using dolomitic limestone.

Several deciduous tree species were planted at all sites in the latter half of May 1984 (silver birch, downy birch, grey alder, *S. triandra* (clone P6010 originating from Liminka), *S. phylicifolia*, *S.* × *dasyclados* (clone P6011) and *S.* 'Aquatica' (clone E4856). Mixed stands of grey alder and *S. triandra* were also established. However, grey alder stands and mixed stands were not planted at Valkeasuo. 1-year-old silver birch transplants used at Piipsanneva (height 47 ± 19 cm) and Sukeva (height 55 ± 8 cm) originated from Pyhäntä, and 2-year-old transplants used at Valkeasuo (height 69 ± 14 cm) from northern Savo. The downy birch transplants, originating from Punkaharju, were planted as 1-year-old seedlings at Sukeva (height 71 ± 16 cm) and 2-year-old seedlings at Piipsanneva (height 78 ± 19 cm) and Valkeasuo (height 70 ± 17 cm). The birch seedlings had been grown in polystyrene blocks. The grey alder transplants (height 23 to 25 cm) originated from Suonenjoki and were planted as 1-year-old containerised seedlings. The willows were planted as 20 cm long cuttings with 1 cm of the cutting length above ground.

The planting density of silver birch, downy birch, grey alder and mixed stands was 20 000 plants ha^{-1}, and that of willows 40 000 cuttings ha^{-1}. In the mixed stands, grey alder and *S. triandra* were planted in alternate rows. The presence of actinomycete *Frankia* in the mineral soil was ensured by adding soil containing root nodules from a neighbouring alder stand around the root balls of the grey alder transplants during planting. At Piipsanneva soil from an alder stand was spread around the transplants after outplanting. After the first growing season the willows were cut back to 5 to 10 cm long stumps in order to increase the sprouting. Dead willow cuttings at Piipsanneva were replaced with new ones during the first two years, and at Valkeasuo during the first year. At Piipsanneva weeds were controlled during the first three growing seasons by hand and mechanically and at Valkeasuo by hand during the second year. At Sukeva weeds were controlled during the first growing seasons chemically: in the middle of July paraquat (10 %) and at the end of July glyphosate (18 %) were applied using wipe method (Weed Wiper). During the second, third and fourth growing seasons weed control was done mechanically.

Two different NPK fertilizer application rates for willows were studied (Table 1). The treat-

Table 1. Fertilization treatments.

	Nutrient kg ha^{-1}	*Salix*[5)]	*B. pendula*[6)] *B. pubescens*[6)]	*A. incana*[6)] Mixed stand[6)] (*A. incana* and *S. triandra*)
Treatment 1	N[1)]	50	-	-
	P[2)]	20	-	-
	K[3)]	40	-	-
	micro[4)]	30	-	-
Treatment 2	N[1)]	100	100	-
	P[2)]	40	40	40
	K[3)]	70	70	70
	micro[4)]	40	40	40

1) Ammonium nitrate with lime (N 27.5 %, Ca 4 %, Mg 2.2 %)
2) Superphosphate 1984–1988 (P 8.7 %, Ca 20.5 %, Mg 0.2 %)
Double superphosphate 1988–89 (P 19.6 %, Ca 15.2 %, Mg 0.3 %)
3) Potassiumsulphate (K 41.5 %, Ca 0.6 %, Mg 0.4 %)
4) Micronutrients in 1984 and 1986 (K 7.1 %, Mn 5.5 %, Cu 12.8 %, Zn 5.5 %, B 1 %)
5) Fertilization every year except micronutrients
6) Fertilization every second year except micronutrients

ments for the birches were control and NPK fertilization, and for alder and the mixed stands control and PK fertilizer application. Micronutrients were also applied (Table 1). The willows were fertilized annually, and the other tree species and mixed stands every second year. The fertilizer treatments were started in the year of establishment. The experimental design consisted of randomized blocks with two replications at each locality. The plot size was 100 m^2 and unplanted buffers between the plots were 3 m, except at Valkeasuo where buffers were 1 m wide.

At Sukeva the air temperature was monitored during the growing seasons at a height of 1.5 m above the ground using a thermograph and a precision thermometer. Measurements of Nivala (close to Haapavesi) and Tohmajärvi weather stations were used for Piipsanneva and Valkeasuo respectively. Frost occurred every growing season (June–August) at all three localities: two times in the cut-away peatland areas each year, and on the field 14 times. The statistical probability of frost is greater at Sukeva than at the other localities (Solantie 1987). Sukeva field was located in a less favourable growing zone for woody ornamental plants than Piipsanneva and Valkeasuo with respect to the effective temperature sum and frost (Solantie 1986).

2.2 Soil Fertility

Soil samples (0 to 10 cm topsoil) comprising five sub-samples were taken from each plot on the cut-away peatland areas before liming and fertilization. On the field soil samples (0 to 20 cm topsoil) consisted of seven sub-samples taken before liming and fertilization, and ten sub-samples at the end of the experiment. pH was measured from a soil-water suspension (15:25 V/V) and soluble nutrients were determined by extraction with acidic ammonium acetate at pH 4.65 (Halonen et al. 1983) with atomic emission spectrometry (ICP/AES ARL 3580). Total nitrogen was determined from the cut-away peatland area samples by the Kjeldahl method, and from the field samples using a CHN analyser (LECO CHN 600).

The mean thickness of the peat layer at Piipsanneva was 81 cm, and at Valkeasuo 94 cm. The pH and available calcium content in the cut-away peatland areas before liming was low from the point of view of willow cultivation (Table 2). According to the guidelines for field cultivation (Viljavuustutkimuksen ... 1991), the contents of phosphorus and potassium in both cut-away peatland areas were rather low for agricultural purposes.

The field soil was mainly clay, overlaid by a

Table 2. The concentrations of total nitrogen and carbon, acid ammonium acetate extractable phosphorus, potassium, calcium and magnesium and $pH_{(H_2O)}$ in the 0–10 cm soil layer at Piipsanneva and Valkeasuo and in the 0–20 cm soil layer at Sukeva. n.d. = not determined, s = standard deviation.

Nutrient		Piipsanneva 1984		Valkeasuo 1984		Sukeva 1984		Sukeva 1989	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
N	%	1.7	0.1	1.8	0.2	1.0	0.5	1.2	0.6
C	"	n.d.		n.d.		n.d.		24	12
P	mg l^{-1}	1.1	0.9	1.1	0.3	13	5	21	5
K	"	12	5	37	9	159	57	161	65
Ca	"	742	103	465	54	1596	355	1481	303
Mg	"	n.d.		n.d.		275	92	253	57
pH		4.8	0.1	4.2	0.3	4.6	0.2	4.7	0.2

layer of mull of variable thickness. According to the guidelines for field cultivation (Viljavuustutkimuksen... 1991), the contents of phosphorus, calcium and magnesium in the Sukeva field prior to liming and fertilization were satisfactory for agricultural purposes, and of potassium passable but the pH of the field soil was rather low. At the end of the study period the phosphorus content of the field soil was higher, but the other nutrients and pH were of the same order of magnitude as at the start of the experiment (Table 2). Fertilization had no clear effect on the nutrient content in the soil. The mean C/N ratio of the soil was 20, indicating that nitrogen was not a limiting factor for the growth of micro-organisms decomposing organic matter.

2.3 Determination of Biomass and Nutrients Bound in the Biomass

The stand biomass was determined at the end of August when the leaves were still green after the sixth growing season; the willow sprouts were 5 years old due to cutting-back. Four sample trees representing different diameter classes were taken from each birch and grey alder plot, five from each willow plot, and four alders and five willows from each mixed stand plot. The sample trees were cut at a height of 10 cm above the ground, and their height and stump diameter ($d_{0.1}$) measured to an accuracy of 1 cm. The breast height diameter ($d_{1.3}$) of the birch and grey alder plants was also measured from two sides to an accuracy of 1 mm. The same parameters were also measured on the other trees on each plot at the end of the sixth growing season. The border rows were excluded to eliminate the edge effect (Zavitkovski 1981).

The sample trees were divided into stem, branch and leaf compartments, except for willows whose stem and branches were kept as one woody compartment. Stem, branch and leaf samples (representing the base, central and crown portions) were taken from the sample trees at the same time for the determination of nutrient concentrations. After drying (leaves 60 °C, other compartments 105 °C) the dry mass of each sample tree was determined by weighing to an accuracy of 0.1 g.

Biomass equations were calculated for the biomass compartments on the basis of the sample tree material (Table 3) (Hytönen et al. 1987, Hytönen 1986). The product of the square of the stump diameter and height (d^2h) was used as the independent variable in the equations because it gave a slightly higher coefficient of determination than the diameter alone. The coefficients of determination of the stem and branch mass equations were higher than those of the leaf mass equations (Table 3). The equality of the regression lines were tested with F test. Because some

Table 3. Biomass equations for different tree species and compartments. Equations have the form $Y = aX^b$, which have been corrected after logarithmic transformation with $s_e^2/2$. Y = dry mass (g), $X = d^2h$, d = diameter at the base (mm), h = height (cm), a and b = constants, R^2 = coefficient of determination, V = coefficient of variation. PI = Piipsanneva, VA = Valkeasuo, SU = Sukeva.

Species	Experiment	Stem mass a	Stem mass b	Stem mass R^2 %	Stem mass V %	Branch mass a	Branch mass b	Branch mass R^2 %	Branch mass V %	Leaf mass a	Leaf mass b	Leaf mass R^2 %	Leaf mass V %
B. pendula	PI	0.0122	0.8203	94.1	14.7	0.0032	0.8756	89.6	21.4	0.0119	0.7255	72.5	32.4
	VA	0.0091	0.8510	99.1	7.1	0.0353	0.6961	78.2	32.5	0.0033	0.7925	67.4	50.3
	SU	0.0072	0.8579	98.8	9.5	0.0007	1.0163	95.4	22.7	0.0068	0.7480	78.9	37.7
B. pubescens	PI	0.0231	0.7748	93.2	11.6	0.0068	0.8248	69.0	31.4	0.2521	0.4843	40.1	33.6
	VA	0.0031	0.9355	99.1	8.0	0.0003	1.0628	94.7	22.8	0.0001	1.0242	88.7	33.2
	SU	0.0143	0.8066	96.6	11.2	0.0018	0.9231	83.6	31.0	0.0003	0.9583	79.1	37.7
A. incana	PI	0.0033	0.9139	98.5	10.9	0.0001	1.1150	91.7	32.9	0.0009	0.9305	91.3	28.0
	SU	0.0041	0.9011	91.6	14.6	0.0001	1.1328	85.6	25.1	0.0015	0.8807	63.5	36.7
S. triandra	PI	0.0023	0.9671	98.0	10.4					0.0017	0.8448	81.2	31.3
	SU	0.0100	0.8469	76.2	33.3					0.0007	0.9440	75.7	37.9
S. phylicifolia	PI	0.0013	1.0238	94.3	16.7					0.0002	1.0014	88.7	23.9
	VA	0.0030	0.9608	97.1	14.6								
	SU	0.0006	1.0928	97.7	11.4					0.0015	0.8657	87.0	23.0
S. dasyclados	PI	0.0023	0.9673	97.5	17.2					0.0060	0.7708	89.3	29.9
	VA	0.0015	1.0320	98.5	1.8					0.0594	0.5096	62.1	49.1
	SU	0.0006	1.0910	98.9	7.4					0.0049	0.8003	86.3	21.0
S. 'Aquatica'	PI	0.0025	0.9549	90.8	40.5					0.0008	1.0213	85.6	57.0
	VA	0.0020	1.0049	96.9	30.3					0.0107	0.7313	91.7	36.2

of the equations at the different localities differed statistically significantly from each other, locality-specific equations were used. The effects of fertilization and tree species on biomass production was studied using analysis of variance.

After drying, the samples taken for the determination of nutrient concentrations were combined by tree compartment and sample plot. Total nutrients (P, K, Ca, Mg, Mn, Cu, Zn, B) were determined by ashing at 550 °C followed by extraction of the ash with hydrochloric acid (Halonen et al. 1983). The concentrations were determined by atomic emission spectrometry (ICP/AES ARL 3580). Total nitrogen was determined using a CHN analyser (LECO CHN 600). The differences in nutrient concentrations between the tree species and the effects of fertilization on the nutrient concentrations were investigated using analysis of variance. The amounts of nutrients bound in the stand were calculated using the dry masses and nutrient concentrations of the different compartments.

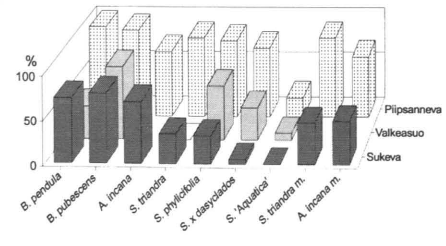

Fig. 1. Survival of different tree species after the sixth growing season. Alder and mixed stands were not planted at Valkeasuo. m = mixed stand.

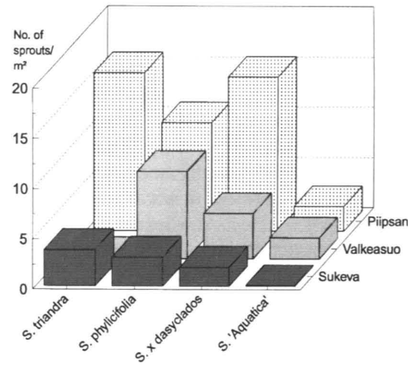

Fig. 2. Number of sprouts per square meter in willow stands after the sixth growing season.

3 Results

3.1 Survival and Number of Sprouts

Survival of the birches remained high at all the localities throughout the course of the 6-year period apart from that of downy birch grown at Valkeasuo (Fig. 1). After 6 growing seasons, the survival of alders was 57 to 75 %. Fertilization treatment had no clear effect on the survival of any tree species.

Survival of the willows varied between species and between the localities (Fig. 1). The survival of all willows was highest at Piipsanneva and lowest at Sukeva field. The survival of native willows (*S. phylicifolia*, *S. triandra*) was on each locality almost without exception higher than survival of exotic willows (*S.* 'Aquatica', *S.* × *dasyclados*). Even at Valkeasuo the survival of *S. triandra* was at the end of the first growing season higher than the survival of exotic willows, but due to complete destruction of the plots by hares after the first growing season the survival was later very low. Survival of *S.* × *dasyclados* was clearly higher than that of *S.* 'Aquatica' at all localities. At Valkeasuo and Sukeva almost all *S.* 'Aquatica' had died before the end of the sixth growing season.

The number of sprouts of the willow stands was the highest at Piipsanneva and lowest on the field at Sukeva (Fig. 2). *S. triandra* sprouted the best at Piipsanneva. The high density of the *S.* × *dasyclados* stands at Piipsanneva was due to resprouting after frost damage. Doubling the amount of fertilizer had no statistically significant effect on the number of sprouts.

3.2 Biomass

The production of downy birch was greater than that of silver birch at all three localities, although the difference was small at Piipsanneva (Fig. 3). The production of the native willows (*S. triandra*, *S. phylicifolia*) was greater than that of the exotic ones at all localities.

There were large differences between the localities in the biomass production of the individual tree species (Fig. 3). The production of all the tree species at Piipsanneva was greater than that at the other localities, apart from downy birch which grew best at Valkeasuo. The results on the Sukeva field were the poorest. The relative differences between the productivity of the different species were smaller at Sukeva than at the other localities.

Fertilization increased significantly the production of birch and alder when all the localities were tested together. The interaction between the treatments and localities was statistically significant. The effect of the double fertilizer dose given to the willows in a corresponding analysis was nearly significant owing to the death of certain willows in the experiments. At Piipsanneva the effect of the quantity of fertilizer given to the willows on production was relatively greater than at the other localities. However, only the increases in production for alder ($p < 0.001$) and *S.* × *dasyclados* ($p < 0.05$) were statistically significant. At Valkeasuo fertilization increased significantly ($p < 0.001$) biomass production of downy birch. Biomass production of *S.* × *dasyclados* at Valkeasuo decreased ($p < 0.05$) when fertilizer dose doubled. At Sukeva the fertilizer treatments had no significant effects on biomass production.

The leafless biomass production of NPK fertilized downy birch was 24.9 t ha^{-1} at Piipsanneva, 33.7 t ha^{-1} at Valkeasuo and 13.9 t ha^{-1} at Sukeva and the productivity of silver birch was 20.5t ha^{-1}, 33.9 t ha^{-1}, 13.8 t ha^{-1} respectively. Biomass production of grey alder in pure stands was 24.1 t ha^{-1} at Piipsanneva and 7.2 t ha^{-1} at Sukeva. The leafless biomass production of *S. phylicifolia* was 37.7 t ha^{-1} at Piipsanneva, 21.3 t ha^{-1} at Valkeasuo and 12.1 t ha^{-1} at Sukeva. Biomass of *S. triandra* was 31.2 t ha^{-1} at Piipsanneva and 9.4 t ha^{-1} at Sukeva. Biomass production of exotic willows at all localities was very low.

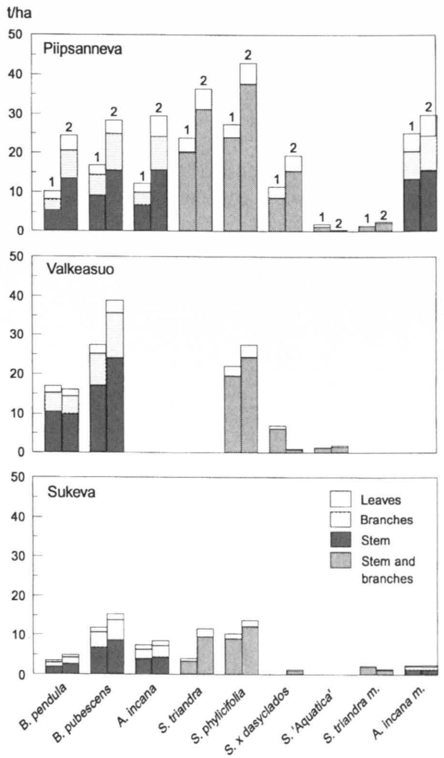

Fig. 3. Biomass of different tree species after the sixth growing season. Willow stands 5-year-old. See Table 1 for explanation of treatments 1–2. m = mixed stand.

At Piipsanneva the mean annual biomass production of *S. phylicifolia* was 7.5 t ha^{-1} and of *S. triandra* 6.2 t ha^{-1}. The proportion of leaves of the total above-ground biomass was 19 % for grey alder, 16 % for silver birch, and 12 % for both *S. phylicifolia* and downy birch.

S. triandra did not grow well in the mixed stands at either locality. The production of unfertilized grey alder at Piipsanneva in the mixed stand was double that in the pure stands, and in mixed stands with PK-fertilization the same as that in the pure stands. The production of both *S. triandra* and grey alder on the field at Sukeva was clearly lower in the mixed stand than in the pure stand.

3.3 Nutrient Uptake

In general, the nutrient concentrations in the trees growing on the field were higher than those on the cut-away peatland areas (Appendix 1). The differences in the nutrient concentrations between the treatments were usually apparent only in the leaves, and on the cut-away peatland areas more clearly than on the field. The foliar potassium concentrations of all the tree species were higher and the corresponding magnesium concentrations lower in treatment 2 than in treatment 1. On the cut-away peatland areas the foliar nitrogen and phosphorus concentrations and at Piipsanneva also the calcium and manganese concentrations were higher in treatment 2 than in treatment 1. Statistically significant differences between the treatments were mainly restricted to the foliar phosphorus and potassium concentrations of birches growing on the cut-away peatland areas (Appendix 1).

In the Sukeva field, the foliar phosphorus, magnesium, copper and zinc concentrations and the stem and branch nitrogen, phosphorus and zinc concentrations of silver birch were significantly higher than the corresponding concentrations in downy birch. The differences in the nutrient concentrations between silver birch and downy birch on the cut-away peatland areas were lower than those on the field. At Piipsanneva the foliar nitrogen and zinc concentrations of silver birch were significantly higher than the corresponding concentrations in downy birch, and at Valkeasuo the foliar boron concentration of silver birch was significantly lower than in downy birch.

The foliar, branch and stem nitrogen concentrations of grey alder were significantly higher than the corresponding concentrations in the birches. Similarly, the foliar calcium and copper concentrations in alder were significantly higher, but the manganese and zinc concentrations significantly lower than in the birches. On the field at Sukeva the foliar potassium concentration of grey alder was also significantly higher than that of the birches. At Sukeva there were also differences in the nutrient concentrations of the other compartments between grey alder and the birches. Stem and branch potassium, calcium and copper concentrations were significantly higher in grey alder, and the zinc concentrations lower than in the corresponding compartments of the birches. Similarly, the stem and branch phosphorus concentrations in grey alder were significantly higher, but the leaf phosphorus concentration significantly lower than in the corresponding compartments of the birches.

The foliar nitrogen, phosphorus, potassium and magnesium concentrations of *S. phylicifolia* were lower than those of the other willows. However, at Piipsanneva and Sukeva the foliar calcium concentrations of *S. phylicifolia* were clearly the highest. The foliar manganese and boron concentrations of the exotic willow species were significantly lower than those of the native willows. In contrast, there were no differences between the exotic and native willows in the nutrient concentrations in the woody compartments.

Differences in nutrient concentrations between mixed and pure stand were small. Only on the Sukeva field the foliar potassium concentration of *S. triandra* was significantly lower in the mixed stand than in the pure stand.

Less copper and zinc, but generally more of the other nutrients, had been bound in the leaves of silver birch, downy birch and grey alder than in the other tree compartments (Fig. 4a, b and c). Nitrogen, phosphorus, potassium, calcium and magnesium had been bound in the biomass in the ratio 100:13:36:37:13 in silver birch, 100:10:36:39:11 in downy birch, and 100:8:28:33:9 in grey alder. The fertilizer treatments did not have any effect on the amounts of nutrients bound in unit biomass produced, but the different localities did (Tables 4, 5 and 6).

Nitrogen, phosphorus, potassium, calcium and magnesium were bound in the willows in the ratio 100:15:58:53:14. More calcium was bound in relationship to nitrogen in *S. phylicifolia* than in the other willows (100:67). More nitrogen was bound in the leaves of all willows at Piipsanneva, but less calcium, copper, zinc and boron than in the woody compartments (stem and branches) (Fig. 4a). More phosphorus potassium and magnesium, but less manganese were bound in the woody compartments of the native willows than in the leaves: the nutrient ratios in the wood and leaves

Table 4. Amounts of nutrients bound in one tonne of above-ground biomass in the 6-year-old stands at Piipsanneva. Willow stands 5-year-old. 1 = treatment 1, 2 = treatment 2. See Table 1 for explanation of treatments. m = mixed stand.

Tree species		N	P	K	Ca	Mg	Mn	Cu	Zn	B
				kg t^{-1}				g t^{-1}		
B. pendula	1	9.8	1.1	3.6	3.0	1.5	546	4	66	9
	2	7.7	1.1	3.3	3.0	1.1	493	5	91	7
B. pubescens	1	6.8	0.8	3.0	2.7	1.1	484	5	49	9
	2	6.6	0.8	2.7	2.5	0.8	542	3	61	8
A. incana	1	12.6	0.9	3.1	4.0	1.2	214	7	32	8
	2	12.3	1.0	3.4	4.1	1.1	186	10	44	9
A. incana m.	1	12.6	0.9	3.3	4.0	1.3	155	8	52	9
	2	13.1	1.1	3.5	5.1	1.2	240	7	52	10
S. triandra	1	7.3	1.4	7.1	3.4	1.5	513	12	87	12
	2	7.9	1.3	4.8	3.8	1.2	726	6	98	12
S. triandra m.	1	7.8	0.9	4.1	2.6	1.2	443	5	112	11
	2	8.1	1.3	5.0	3.3	1.3	521	6	145	14
S. phylicifolia	1	5.4	1.3	4.1	4.8	1.1	437	9	60	11
	2	6.5	1.3	4.4	4.5	1.0	468	9	55	10
S. dasyclados	1	9.1	1.4	6.6	4.3	2.1	417	6	120	11
	2	9.2	1.4	5.8	4.2	1.7	374	8	83	9
S. 'Aquatica'	1	14.3	1.7	8.6	4.3	1.7	437	6	129	11
	2	18.2	2.3	9.1	5.7	2.3	807	8	144	11

Table 5. Amounts of nutrients bound in one tonne of above-ground biomass in the 6-year-old stands at Valkeasuo. Willow stands 5-year-old. 1 = treatment 1, 2 = treatment 2. See Table 1 for explanation of treatments.

Tree species		N	P	K	Ca	Mg	Mn	Cu	Zn	B
				kg t^{-1}				g t^{-1}		
B. pendula	1	6.1	0.7	1.4	2.7	1.0	91	3	66	7
	2	7.3	0.8	2.4	2.3	0.7	138	2	67	8
B. pubescens	1	5.9	0.6	1.7	2.5	0.7	87	2	57	7
	2	6.6	0.6	2.2	2.4	0.6	71	2	47	8
S. phylicifolia	1	7.2	0.8	2.3	4.8	0.6	61	3	62	7
	2	8.1	0.9	2.8	3.8	0.5	65	3	62	7
S. dasyclados	1	11.2	1.7	4.7	4.1	1.0	41	4	99	8
	2	12.5	2.2	4.8	4.1	0.4	45	5	94	8
S. 'Aquatica'	1	12.6	2.9	7.2	5.7	1.7	46	7	147	9
	2	13.6	1.8	6.0	6.1	1.2	58	4	95	12

Table 6. Amounts of nutrients bound in one tonne of above-ground biomass in the 6-year-old stands at Sukeva. Willow stands 5-year-old. 1 = treatment 1, 2 = treatment 2. See Table 1 for explanation of treatments. m = mixed stand.

Tree species		N	P	K	Ca	Mg	Mn	Cu	Zn	B
				kg t^{-1}				g t^{-1}		
B. pendula	1	10.1	1.5	3.4	3.2	1.2	198	5	134	7
	2	9.9	1.3	3.1	3.3	0.9	421	5	128	8
B. pubescens	1	7.4	0.7	2.7	2.7	0.7	292	4	856	
	2	7.5	0.7	2.8	2.8	0.8	268	4	738	
A. incana	1	13.5	1.2	3.9	4.8	1.1	171	10		407
	2	13.9	1.4	4.0	4.7	1.1	186	10		449
A. incana m.	1	13.8	1.4	3.3	5.3	1.2	388	8		417
	2	13.9	1.3	4.4	4.6	1.1	172	9		379
S. triandra	1	11.4	1.5	5.5	3.8	1.3	315	7	173	14
	2	11.0	1.3	6.0	3.5	1.1	421	5	140	12
S. triandra m.	1	10.4	1.5	3.9	4.1	1.7	296	7	170	11
	2	10.8	1.0	4.8	3.3	1.0	272	5	129	13
S. phylicifolia	1	7.8	0.9	3.1	5.6	0.7	351	6		887
	2	7.2	1.0	3.9	5.7	0.6	261	5		858

of the exotic willows were the opposite. There was as much nitrogen and potassium in the leaf and woody compartments of the exotic willows at Valkeasuo: the amounts of all other nutrients in the willows were greater in the woody compartments than in the leaves (Fig. 4b). In general there was more potassium and manganese and in *S. triandra* also magnesium and boron in the leaves of the willows on the Sukeva field, and less of the other nutrients than in the woody compartment (Fig. 4c). Most of the nitrogen in *S. phylicifolia* was bound in the woody compartment, and in the other willows in the leaves.

4 Discussion

4.1 Growing Conditions

Frost and poor winter hardiness hindered the growth of the exotic willows at all the localities, and especially at Sukeva. The clay soil at Sukeva also presumably slowed the rooting of the cuttings. Although *S. triandra* and *S.* × *dasyclados* grow on land subjected to flooding, they require a well-aerated, light soil (Skvortsov 1968). This requirement is presumably also the case with *S.* 'Aquatica' and *S.* × *dasyclados*. Clay soils have traditionally been avoided in willow cultivation (Nordberg 1928). The heaviness of the field soil at Sukeva was also most probably reflected in the low productivity of silver birch compared to downy birch (cf. Raulo 1981). Grey alder presumably does not thrive well on clay soils, either. However, the fertility of the soil in the Sukeva field was considerably better than that of afforested mineral soil fields in western Finland (Wall, oral comm.).

Because some willow species are very demanding with respect to pH, the soil pH may have had an effect on the growth of some willow species (Skvortsov 1968, Lattke 1969, Alhdous 1972). At Sukeva the pH was below 5; the limit for the good development of roots and shoots of *S. viminalis* (Ericsson and Lindsjö 1981). The pH of

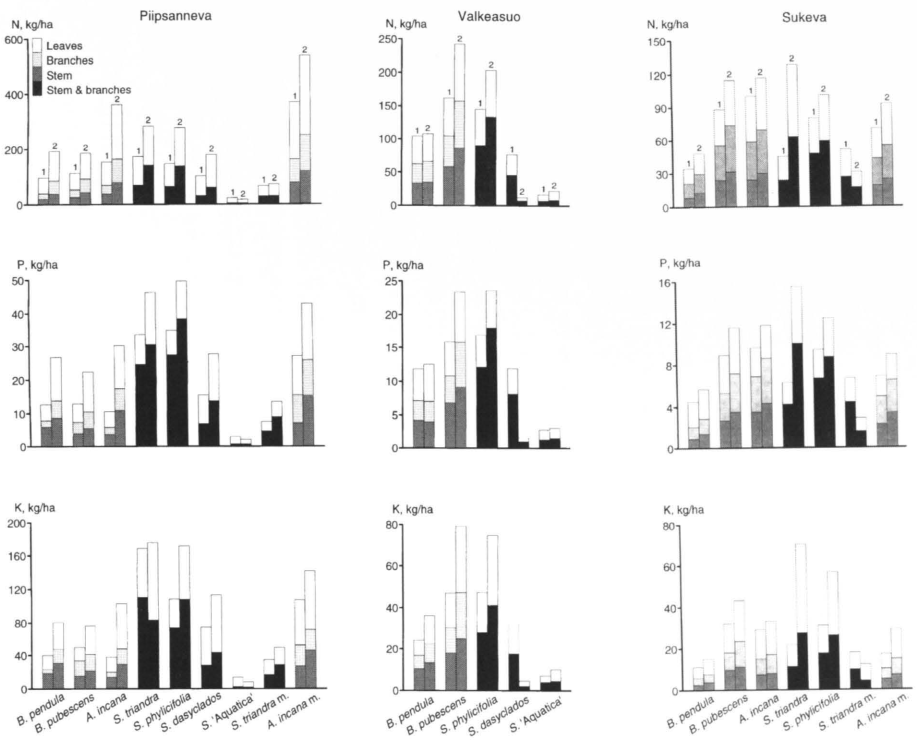

Fig. 4a. Amounts of nitrogen, phosphorus and potassium bound in the tree biomass after the sixth growing season. Willow stands 5-year-old. See Table 1 for explanation of treatments 1–2. m = mixed stand.

the cut-away peatland areas was not determined at the end of the experiments. Of the willows included in this study, the native willows *S. triandra* and *S. phylicifolia* presumably grow better at lower pH values than *S.* × *dasyclados* and *S.* 'Aquatica'.

4.2 Biomass

When comparing the biomass production of different tree species, besides different spacings for willows and other tree species it should be noted that willow sprouts were one year younger than alders and birches. There were also some differences in fertilization treatments between the tree species.

Downy birch clearly grew better on the cut-away peatland areas than on the clay field, and on all the localities better than silver birch; silver birch is not suitable for cultivation on wet and poorly aerated soils (Raulo 1981, Ferm 1993). The comparability of the birches was reduced to some extent by the fact that the transplants of silver birch and downy birch were not the same age at all the localities, and there were differences in their geographical origin. Downy birch appears to have gained competitive advantage over silver birch due to its more southerly origin. Based upon the mean annual production, downy

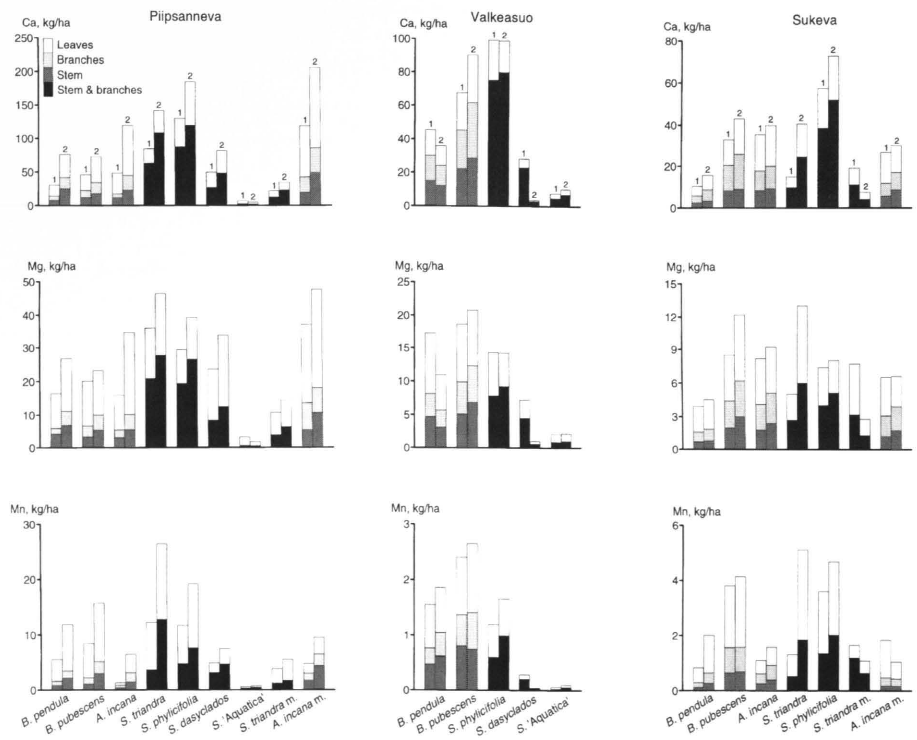

Fig. 4b. Amounts of calcium, magnesium and manganese bound in the tree biomass after the sixth growing season. Willow stands 5-year-old. See Table 1 for explanation of treatments 1–2. m = mixed stand.

birch grew better at Valkeasuo, and as well at Piipsanneva, than naturally regenerated young downy birch stands on peat soils (Björklund and Ferm 1982, Ferm 1990b). Silver birch, on the other hand, had a higher production on the cut-away peatland areas than a 9-year-old silver birch plantation on a mineral soil field in southern Finland (Saarsalmi et al. 1992). Although fertilization has not increased the production of mature birch stands (Viro 1974, Rosvall 1980, Oikarinen and Pyykkönen 1981, Puro 1982, Moilanen 1985), N fertilization has increased the growth of young birch stands on mineral soil (Viro 1974, Saarsalmi et al. 1992), and PK and NPK fertilization on cut-away peatland areas (Kaunisto 1987, Ferm and Hytönen 1988). The results of this study suggest that the production of young silver birch and especially downy birch can be increased by fertilization.

Fertilization significantly increased the biomass production of grey alder on the cut-away peatland area. The main explanation for this result appears to be phosphorus, such sites usually having rather low phosphorus contents (Kaunisto 1982, 1986, Ferm and Hytönen 1988). High phosphorus availability promotes the formation of root nodules and hence nitrogen fixation (Sprent 1979). Grey alder did not thrive as well on the Sukeva field as on the cut-away peatland area, and phosphorus had no effect on its production (see

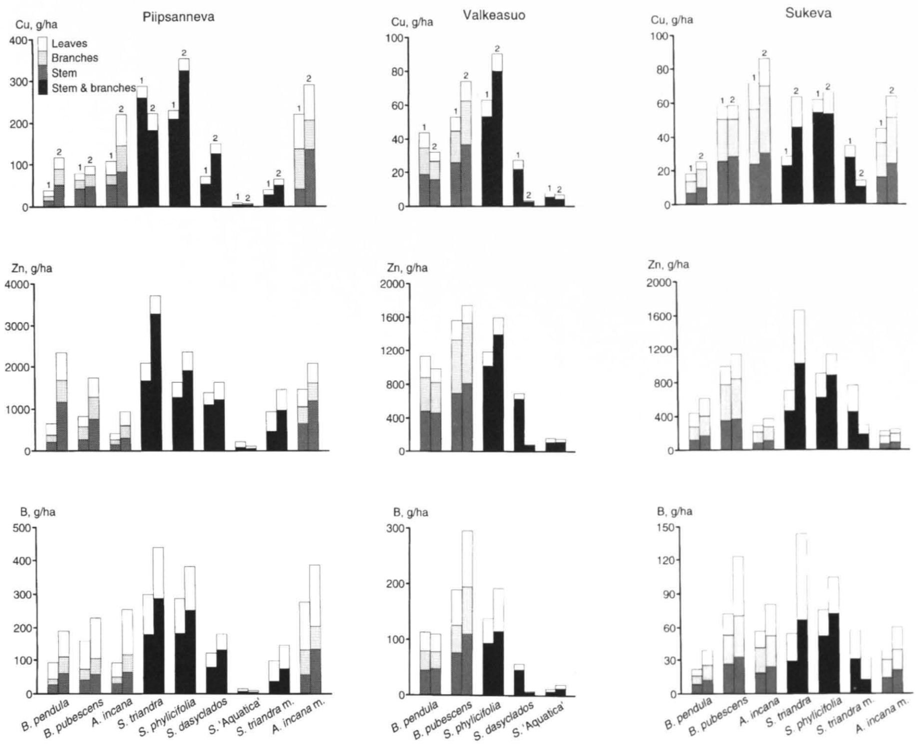

Fig. 4c. Amounts of copper, zinc and boron bound in the tree biomass after the sixth growing season. Willow stands 5-year-old. See Table 1 for explanation of treatments 1–2. m = mixed stand.

also Saarsalmi et al. 1985 and 1992). On mineral soils phosphorus fertilization has significantly increased the production of a coppiced grey alder stand following whole tree harvesting (Saarsalmi et al. 1991). The biomass production of fertilized grey alder on the cut-away peatland area was 24 t ha^{-1}, i.e. about the same as the production of a 9-year-old grey alder plantation of the same planting density on mineral soil in southern Finland (Saarsalmi et al. 1992), or the production of an 7-year-old grey alder plantation of double the stocking density on peat soil in central Sweden (Rytter et al. 1989). The 5-year production of a grey alder plantation on a field in southern Finland has been as much as 30 t ha^{-1} (Saarsalmi et al. 1985) with a stocking density twice that of the grey alder plots used in this study.

The native willows grew better than the exotic ones at all the localities, apart from the *S. triandra* stands at Valkeasuo which were damaged by hares. Frosts damaged willows during the growing season. The continued growth of the willows of southern origin late in the autumn slows down the onset of hardening and makes them susceptible to frost damage at the end of the growing season (von Fircks 1992). The survival of *S.* 'Aquatica' was especially low at all localities. Winter damages of *S.* 'Aquatica' have been reported to be common in the province of Oulu (Hytönen 1982 and 1986, Lumme et al. 1984).

Eventhough *S.* × *dasyclados* seemed to be climatically better adapted than *S.* 'Aquatica' its growth was poor and survival low. Thus cultivation of *S.* × *dasyclados* can be recommended only in more favourable conditions than those prevailing in the study areas.

It would appear that the production of native willows on cut-away peatland areas in central and southern Finland, using a 5-year rotation period, can be as high or even higher as that of exotic willows, because they are considerably better climatically adapted. *S. phylicifolia* grew the best of all the willows at all three localities, but clay soil was not suitable for this species. The annual production of *S. phylicifolia* at Piipsanneva was almost as high as that of exotic willow species in southern Finland (Ferm 1985, Hytönen 1988). Biomass production of *S.* 'Aquatica' and *S.* × *dasyclados* can be considerably increased by fertilization (Hytönen 1982, 1984, 1988, 1994). According to the present study it also appears that the production of native willows can be increased by fertilization on both cut-away peatland areas and on field soil.

Growing *S. triandra* and grey alder as mixed stands was not successful: on the field at Sukeva both species grew poorly, and on the cut-away peatland area grey alder occupied all the growing space. Planting density for grey alder could be lower than that employed in the pure stands of this study (20 000 plants/ha). Although the density of grey alder in the mixed stand was one-half that in the pure stand, there were no differences between the production of grey alder in either type of stand on the cut-away peatland area. A similar result has earlier been obtained by Saarsalmi et al. (1992). Special attention should be paid in experiments with mixed stands to the growth dynamics of the tree species. The tree species grown together with grey alder in a mixed stand should be either fast-growing ones or species that withstand shade. Another alternative is to plant grey alder at a later stage in the mixed stand.

4.3 Nutrient Uptake

The foliar nitrogen, phosphorus and potassium concentrations of young silver birch and downy birch in this study were generally higher than those of mature birch stands (cf. Viro 1955, Mälkönen 1977, Mälkönen and Saarsalmi 1982). On mineral soil field the foliar phosphorus concentration of silver birch were especially high compared to mature stands but in agreement with results from young silver birch stands on mineral soil field (Saarsalmi et al. 1992), in seedling nurseries (Rikala and Petäistö 1986), and on cut-away peatland areas (Lumme and Törmälä 1988). The foliar manganese concentrations of silver birch and downy birch at Piipsanneva were high, but no signs of toxicity were detectable (cf. Raitio 1982).

Fertilization increased the foliar phosphorus concentration of silver birch and downy birch on the cut-away peatland areas, but not on the clay mineral soil field. Birch foliar phosphorus concentration have increased on drained peatlands with wood ash fertilization (Tamm 1951) and on mineral soils with phosphorus fertilization (Schmitt et al. 1981).

The nutrient concentrations of the leaf, branch and stem compartments of grey alder did not differ from the values presented earlier (Viro 1955, Mikola 1966, Saarsalmi et al. 1985, 1991, 1992). In contrast to the findings of Saarsalmi et al. (1991), PK fertilization did not increase the phosphorus concentrations of the different grey alder compartments in the study in hand.

The foliar nitrogen, phosphorus and potassium concentrations of *S.* 'Aquatica', *S.* × *dasyclados* and *S. triandra* were of the same order of magnitude, and those of *S. phylicifolia* lower than the values earlier presented for *S.* 'Aquatica' (Näsi and Pohjonen 1981, Kaunisto 1983, Ferm 1985, Hytönen 1986, 1987, 1994). Fertilization has usually increased the nutrient concentrations of willows on cut-away peatland areas (Kaunisto 1983, Hytönen 1986, 1987, 1994, Ferm and Hytönen 1988), but in the study in hand the effect of fertilization was not statistically significant.

There were differences between the localities in the amount of nutrients bound in unit biomass. For example more of all the nutrients were bound in the biomass of silver birch and downy birch per unit biomass at Piipsanneva than at Valkeauso, apart from zinc which was bound in similar amounts. The fertility of the substrate did not explain these differences. There were no differences in the nutrient uptake of the willows between the two cut-away peatland areas. On the Sukeva field all the tree species had more nitrogen and zinc per unit biomass and, apart from grey alder, less manganese than at Piipsanneva. More phosphorus, potassium and calcium were bound in the biomass of grey alder per unit biomass on the field than on the cut-away peatland areas.

The tree species included in this study had differences in nutrient uptake. In the 6-year-old stands more nutrients were bound in the biomass of silver birch per unit biomass compared to that of downy birch, which is in agreement with earlier findings (Sarvas 1956). On the field as much as twice the amount of phosphorus was bound in the biomass of silver birch per unit biomass compared to that of downy birch. On the Sukeva field clearly more manganese was bound in the biomass of silver birch per unit biomass, and the same or to some extent smaller amounts of other nutrients (e.g. calcium, magnesium) than on mineral soil in the study of Saarsalmi et al. (1992). Manganese is in a water-soluble form in acidic soils. The soil pH at Sukeva was considerably lower than that in the study of Saarsalmi et al. (1992), which would explain the difference in manganese uptake.

On the Sukeva field as much nitrogen, potassium, calcium and boron were bound in the biomass of grey alder per unit biomass and greater amounts of the other nutrients compared to that of the grey alder plantations on mineral soil fields in southern Finland (Saarsalmi et al. 1985, 1992). The amounts of nitrogen, calcium and copper per unit biomass produced were higher, but manganese and zinc lower for grey alder that for silver birch and downy birch. According to hydroponic studies (Ingestad 1981) grey alder uses more phosphorus but less potassium than silver birch. However, on the mineral soil field at Sukeva and in an earlier study (Saarsalmi et al. 1992) more potassium was bound in the biomass of grey alder per unit biomass compared to that of silver birch.

S. 'Aquatica' had more nitrogen, phosphorus, potassium, magnesium and zinc per unit biomass than the other willow species, and *S. phylicifolia* had the smallest amounts. The high nutrient uptake of *S.* 'Aquatica' was most probably due to low biomass production and high bark content. More potassium and also more phosphorus on the cut-away peatland areas were bound in the biomass of different willow species per unit biomass compared to that of the other tree species. The high potassium uptake of willow has been also reported in other studies (Viro 1955, Ingestad 1979, 1980, Ericsson 1981a, 1981b, Elowson and Rytter 1988).

Acknowledgements

The manuscript has been read by Risto Lauhanen, Lic. For., Kristina Palmgren, M.Sc., Risto Rikala, B.Sc. and Anneli Viherä-Aarnio, Lic. For. Mr. John Derome has translated the Finnish manuscript into English. We would like to thank the above as well as all the other persons who have contributed to the successful completion of this study.

References

Aldhous, J.R. 1972. Nursery practice. Forestry Commission Bulletin 43. 184 p.

Björklund, T. & Ferm, A. 1982. Pienikokoisen koivun ja harmaalepän biomassa ja tekniset ominaisuudet. Abstract: Biomass and technical properties of small-sized birch and grey alder. Folia Forestalia 500. 37 p.

Côté, B. & Camiré, C. 1987. Tree growth and nutrient cycling in dense plantings of hybrid poplar and black alder. Canadian Journal of Forest Research 17: 516–523.

Elowson, S. & Rytter, L. 1988. Dynamics of leaf minerals, leaf area, and biomass from hardwoods intensively grown on a peat bog. Trees 2: 84–91.

Energiametsätoimikunnan mietintö I. 1979. Komiteanmietintö 1979:49. Helsinki. 111 p.

Energiametsätoimikunnan mietintö II. 1981. Komiteanmietintö 1980:50. Helsinki. 77 p.

Ericsson, T. 1981a. Effects of varied nitrogen stress on growth and nutrition in three Salix clones. Physiologia Plantarum 51: 423–429.

— 1981b. Growth and nutrition of three Salix clones in a low conductivity solutions. Physiologia Plantarum 52: 239–244.

— & Lindsjö, I. 1981. Tillväxtens pH-beroende hos några energiskogsarter. Abstract: The influence of pH on growth and nutrition of some energy forest tree species. Sveriges Lantbruksuniversitet, Projekt energiskogsodling, Teknisk rapport 11. 7 p.

Ferm, A. 1985. Jätevedellä kasteltujen lehtipuiden alkukehitys ja biomassatuotos kaatopaikalla. Summary: Early growth and biomass production of some hardwoods grown on sanitary landfill and irrigated with leachate waste-water. Folia Forestalia 641. 35 p.

— 1990a. Coppicing as a means for increasing hardwood biomass production. Biomass 22: 107–121.

— 1990b. Nuorten vesasyntyisten hieskoivikoiden kehitys ja lahoisuus turvemaalla. Summary: Development and decay of young Betula pubescens coppice stands on peatland. Folia Forestalia 744. 17 p.

— 1993. Birch production and utilization for energy. Biomass and Bioenergy 4(6): 391–404.

— , Henttonen, H. & Hytönen, J. 1993. Towards better management practices in afforestation of agricultural land in Finland. Proceedings of workshop: Silvicultural Implications for the Establishment and Early Maintenance on New Woodlands, Edinburgh, 13 –14 October 1993. In press.

— & Hytönen, J. 1988. Effect of soil amelioration and fertilization on the growth of birch and willow on cut-over peat. VIII International Peat Congress, Leningrad 1988. Proceedings, Section III: 268–279.

Fircks, H.A. von. 1992. Frost hardiness of dormant Salix shoots. Scandinavian Journal of Forest Research 7: 317–323.

Halonen, O., Tulkki, H. & Derome, J. 1983. Nutrient analysis methods. Metsäntutkimuslaitoksen tiedonantoja 121. 28 p.

Hansen, E.A. & Dawson, J.O. 1982. Effect of Alnus glutinosa on hybrid Populus height growth in a short-rotation intensively cultured plantation. Forest Science 28(1): 49–59.

Heiskanen, V. 1957. Rauduskoivun- ja hieskoivun laatu eri kasvupaikoilla. Summary: Quality of the common birch and the white birch on different sites. Communicationes Instituti Forestalis Fenniae 48. 99 p.

Höglind, E. & Nilsson, T. 1989. Inverkan av al på markegenskaper och samplanterade granars utveckling på en torvmark. Summary: The effect of alder on soil properties and growth of mixed Norway spruce on a peatland. Swedish University of Agricultural Sciences, Department of Forest Soils, Report No 61. 40 p.

Hytönen, J. 1982. Istutustiheyden ja lannoituksen vaikutus vesipajun (Salix cv. aquatica) kuiva-ainetuotokseen ja kasvuston kehitykseen. Metsäntutkimuslaitoksen tiedonantoja 70: 67–77.

— 1984. Suitability of various phosphorus and nitrogen fertilizers for fertilizing willow stands of cut-over peatlands. In: Egneus, H. & Ellegård, A. (eds.). Bioenergy 84. Vol 2: 114–118.

— 1986. Fosforilannoitelajin vaikutus vesipajun biomassan tuotokseen ja ravinteiden käyttöön turpeennostosta vapautuneella suolla. Summary: Effect of some phosphorus fertilizers on the biomass production and nutrient uptake of Salix 'Aquatica' in a peat cut-away area. Folia Forestalia 653. 21 p.

— 1987. Lannoituksen vaikutus koripajun ravinnetilaan ja tuotokseen kahdella suonpohja-alueella. Summary: Effect of fertilization on the nutrient status and dry mass production of Salix viminalis on two peat cut-away areas. Metsäntutkimuslaitoksen tiedonantoja 245. 31 s.

— 1988. Biomass production of Salix 'Aquatica' on an abandoned field in South Finland. Metsäntutkimuslaitoksen tiedonantoja 304: 74–90.

— 1994. Effect of fertilizer application rate on nutrient status and biomass production in short-rotation plantations of willows established on cut-away peatland areas. Suo 45(3): 65–77.

— 1995. Taimien alkukehitys pellonmetsitysaloilla. In: Hytönen, J. & Polet, K. (eds.). Metsäntutkimuspäivä Kälviällä 1994. Metsäntutkimuslaitoksen tiedonantoja 540: 12–21.

— , Lumme, I. & Törmälä, T. 1987. Comparison of methods for estimating willow biomass. Biomass 14: 37–49.

Ingestad, T. 1979. Nitrogen stress in birch seedlings II. N, P, K, Ca and Mg nutrition. Physiologia Plantarum 45: 149–157.

— 1980. Growth, nutrition and nitrogen fixation in grey alder at varied rate of nitrogen addition. Physiologia Plantarum 50: 353–364.

— 1981. Nutrition and growth of birch and grey alder seedlings in low conductivity solutions and at varied relative rates of nutrient addition. Physiologia Plantarum 52: 454–466.

Jalas, J. 1965a. Salix triandra L. Jokipaju. In: Jalas, J.

(ed.). Suuri kasvikirja, Vol. II. Otava, Helsinki. p. 21–23.
— 1965b. Salix phylicifolia L. Kiiltopaju. In: Jalas, J. (ed.). Suuri kasvikirja, Vol. II. Otava, Helsinki. p. 38–39.
Junack, H. 1961. Ein erfolgreicher Düngungsversuch mit Algierphosphat. Forst- und Holzwirtschaft 16(18): 390–394.
Kaunisto, S. 1982. Afforestation of peat cut-away areas in Finland. Proceedings of the IPS Symposium Commission IV and II. Minsk 1982. p. 144–153.
— 1983. Koripajun (Salix viminalis) biomassatuotos sekä ravinteiden ja veden käyttö eri tavoin lannoitetuilla turpeilla kasvihuoneessa. Summary: Biomass production of Salix viminalis and its nutrient and water consumption on differently fertilized peats in greenhouse. Folia Forestalia 551. 34 p.
— 1986. Peatlands before and after harvesting. In: Socio-economic impacts of the utilization of peatlands in industry and forestry. Proceedings of the IPS Symposium, Oulu, Finland, June 9–13, 1986. p. 241–246.
— 1987. Lannoituksen ja muokkauksen vaikutus männyn ja rauduskoivun istutustaimien kasvuun suonpohjilla. Summary: Effect of fertilization and soil preparation on the development of Scots pine and silver birch plantations on peat cutover areas. Folia Forestalia 681. 23 p.
— & Viinamäki, T. 1991. Lannoituksen ja leppäsekoituksen vaikutus mäntytaimikon kehitykseen ja suonpohjaturpeen ominaisuuksiin Aitonevalla. Summary: Effect of fertilization and alder (Alnus incana) mixture on the development of young Scots pine (Pinus sylvestris) trees and the peat properties in a peat cutover area at Aitoneva, southern Finland. Suo 42: 1–12.
Lattke, H. 1969. Untersuchungen zur Säurverträglichkeit von Weiden in Wasserkultur. Summary: Investigations on the acidity tolerance of willows cultured in water. Archiv für Forstwesen 18: 301–309.
Lumme, I. 1989. On the clone selection, ectomycorrhizal inoculation of short-rotation willows (Salix spp.) and on the effects of some nutrient sources on soil properties and plant nutrition. Biological Research Reports from the University of Jyväskylä 14. 55 p.
— & Tikkanen, E., Huusko, A. & Kiukaanniemi, E. 1984. Pajujen lyhytkiertoviljelyn biologiasta ja viljelyn kannattavuudesta turpeentuotannosta poistuneella suolla Limingan Hirvinevalla. Summary: On the biology and economical profitability of willow biomass production on an abandoned peat production area. Oulun yliopisto, Pohjois-Suomen tutkimuslaitos, C 54. Oulu. 48 p.
— & Törmälä, T. 1988. Selection of fast growing willow (Salix spp.) clones for short rotation forestry on mined peatlands in northern Finland. Tiivistelmä: Nopeakasvuisten pajukloonien valinnasta Pohjois-Suomen turvetuotannosta poistuvilla soilla. Silva Fennica 22(1): 67–88.
Mälkönen, E. 1977. Annual primary production and nutrient cycle in a birch stand. Seloste: Vuotuinen primäärituotos ja ravinteiden kiertokulku eräässä koivikossa. Communicationes Instituti Forestalis Fenniae 91(5). 35 p.
— & Saarsalmi, A. 1982. Hieskoivikon biomassatuotos ja ravinteiden menetys kokopuun korjuussa. Summary: Biomass production and nutrient removal in whole tree harvesting of birch stand. Folia Forestalia 534. 17 p.
McVean, D.N. 1956. Ecology of Alnus glutinosa (L.) Gaertn. III. Seedling establishment. Journal of Ecology 44: 195–218.
Mikola, P. 1966. The value of alder in adding nitrogen in forest soil. Final report of research conducted under grant authorized by U.P. Public Law 480. 95 p. [Available at Forestry Library, University of Helsinki, Finland].
Moilanen, M. 1985. Lannoituksen ja harvennuksen vaikutus hieskoivun kasvuun ohutturpeisilla ojitetuilla rämeillä. Summary: Effect of fertilization and thinning on the growth of birch (Betula pubescens) on the drained mires with thin peatlayer. Folia Forestalia 629. 29 p.
Näsi, M. & Pohjonen, V. 1981. Green fodder from energy forest farming. Maataloustieteellinen aikakauskirja 53: 161–167.
Nordberg, P. 1919. Pajun viljelys ja sen edellytykset meillä. Kansanvalistusseuran Käsiteollisuuskirjasto 24: 3–57.
— 1928. Vertaileva katsaus pajun viljelykseen ja sen edellytyksiin ulkomailla ja Suomessa. Deutsches Referat: Die Weidenkultur und ihre Voraussetzungen im Ausland und Suomi (Finnland). Silva Fennica 9. 60 p.
Oikarinen, M. & Pyykkönen, J. 1981. Harvennuksen ja lannoituksen vaikutus turvekankaan hieskoivikon kehitykseen Pohjanmaalla. Abstract: The effect of thinning and fertilization on the growth of pubescent birch (Betula pubescens) on drained Myrtillus spruce swamp in Ostrobothnia. Folia Forestalia 486. 15 p.
Pohjonen, V. 1977. Metsäpuiden lyhytkiertoviljely. Tuloksia ensimmäisen vuoden kokeista Oulussa. Oulun yliopisto, Pohjois-Suomen tutkimuslaitos, C 8. Oulu. 42 p.
Puro, T. 1982. Lannoitusajankohdan merkitys eri puulajien kasvureaktiossa. Summary: Effect of fertilization time on growth reaction of different tree species. Folia Forestalia 507. 14 p.
Radwan, M.A. & DeBell, D.P. 1988. Nutrient relations in coppiced black cottonwood and red alder. Plant and Soil 106: 171–177.
Raitio, H. 1982. Rauduskoivun kasvuhäiriö Torajärven koekentällä. Summary: Growth disturbance of Betula pendula in the Torajärvi experimental field. Folia Forestalia 536. 15 p.
Raulo, J. 1981. Koivukirja. Gummerus. Jyväskylä. 131 p.
Rikala, R. & Petäistö, R-L. 1986. Lannoituksen vaikutus koulittujen rauduskoivun taimien ravinnepitoisuuteen, kasvuun ja versolaikkuisuuteen. Summary: Effects of fertilization on the nutrient concentrations, growth and stem spotting in barerooted birch transplants. Folia Forestalia 642. 16 p.
Rosvall, O. 1980. Prognosfunktioner för beräkning av gödslingseffekten. Föreningen Skogsträdsförädling–Institutet för Skogsförbättring, Årsbok 1979: 70–130.
Rytter, L., Slapokas, T. & Granhall, U. 1989. Woody biomass and litter production of fertilized grey alder plantations on a low-humified peat bog. Forest Ecology and Management 28: 161–176.
Saarsalmi, A. 1984. Vesipajun biomassan tuotos sekä ravinteiden ja veden käyttö. Summary: Biomass production and nutrient and water consumption in Salix 'Aquatica Gigantea' plantation. Folia Forestalia 602. 29 p.
— , Palmgren, K. & Levula, T. 1985. Leppäviljelmän biomassan tuotos sekä ravinteiden ja veden käyttö. Summary: Biomass production and nutrient and water consumption in an Alnus incana plantation. Folia Forestalia 628. 24 p.
— , Palmgren, K. & Levula, T. 1991. Harmaalepän vesojen biomassan tuotos ja ravinteiden käyttö. Summary: Biomass production and nutrient consumption of the sprouts of Alnus incana. Folia Forestalia 768. 25 p.
— , Palmgren, K. & Levula, T. 1992. Harmaalepän ja rauduskoivun biomassan tuotos ja ravinteiden käyttö energiapuuviljelmällä. Summary: Biomass production and nutrient consumption of Alnus incana and Betula pendula in energy forestry. Folia Forestalia 797. 29 p.
Sarvas, R. 1956. Puulajit. Metsäkäsikirja. Kustannus Oy Kivi, Helsinki. p 454–474.
Schalin, I. 1966. Harmaalepän merkityksestä käytännön metsätaloudessa. Summary: Alnus incana (L.) Moench in forestry practice. Metsätaloudellinen Aikakauslehti 83(9): 362–366.
Schmitt, M.D.C., Czapowskyj, M.M., Safford, L.O. & Leaf, A.L. 1981. Biomass and elemental uptake in fertilized and unfertilized Betula papyrifera Marsh. and Populus grandidentata Michx. Plant and Soil 60: 111–121.
Siira, J., Heino, E. & Pohjonen, V. 1981. Harvinainen jokipaju (Salix triandra) – tulvarantojen vaeltaja. Summary: Salix triandra – a rare inhabitant of alluvial river shores. Dendrologian Seuran tiedotuksia 12(1): 11–20, 58.
Skvortsov, A. 1968. Ivy SSSR. [Willows of the USSR. A taxonomic and geographic revision.] Publishing Office "Nauka", Moscow. 262 p.
Slapokas, T. & Granhall, U. 1991. Decomposition of litter in fertilized short-rotation forests on a low-humified peat bog. Forest Ecology and Management 41: 143–165.
Solantie, R. 1986. Suomen hedelmäpuiden ja puuvartisten koristekasvien menestymisvyöhykkeet – tarkennusta entiseen. [The growing zones for fruit trees and woody ornamental plants in Finland – revision of earlier divisions]. Sorbifolia 17(4): 201–209.
— 1987. Hallojen loppuminen keväällä ja alkaminen syksyllä. Abstract: Last spring frosts and first autumn frosts in Finland. Ilmatieteen laitos, Meteorologisia julkaisuja 6. 60 p.
Sørensen, H. 1936. Orienterende undersøgelser over kunstgødningens virkning til forskellige unge træplanter. Hornum 1931–1935. Summary: Effect of artificial fertilizers on young trees at Hornum. Tidsskrift for Planteavl. København 41: 747–763.
Sprent, J.I. 1979. The biology of nitrogen fixing organisms. McGraw-Hill Company, London. 196 p.
Stott, K.G. 1956. Cultivation and uses of basket willows. Quarterly Journal of Forestry 50: 103–112.

Tamm, C.O. 1951. Chemical composition of birch leaves from drained mire, both fertilized with wood ash and unfertilized. Svensk Botanisk Tidskrift 45(2): 309–318.

Themlitz, R. & Behrens, W.U. 1957. Untersuchungen zu Düngungsversuchen mit Rhenaniaphosphat im Forstamt Gartow und zur Phosphorsäureaufnahme aus radioaktivem Phosphat. Allgemeine Forstzeitung 12: 232–234.

Viljavuustutkimuksen tulkinta peltoviljelyssä. 1991. Viljavuuspalvelu Oy. 64 p.

Viro, P.J. 1955. Investigations on forest litter. Seloste: Metsäkariketutkimuksia. Communicationes Instituti Forestalis Fenniae 67(7). 49 p.

— 1974. Fertilization of birch. Seloste: Koivun lannoitus. Communicationes Instituti Forestalis Fenniae 81(4). 38 p.

Zavitkovski, J. 1981. Small plots with unplanted plot border can distort data in biomass production studies. Canadian Journal of Forest Research 11: 9–12.

Total of 81 references

Appendix 1. The mean nutrient concentrations of different tree compartments in treatments 1 and 2 after the sixth growing season. Willow stands 5 years old. Statistical significance of difference in nutrient concentrations between treatments 1 and 2 are indicated by asterisks (* = $p < 0.05$). Nutrient concentrations for *A. incana* and *S. triandra* are presented only for pure stands.

	N		P		K		Ca		Mg		Mn		Cu		Zn		B	
	g kg^{-1}										mg kg^{-1}							
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Leaves																		
Piipsanneva																		
B. pendula	29.7	1.5	3.0*	0.8	8.7	1.7	8.9	1.0	4.8	0.6	2223	555	7.3	0.5	162	30	23.4	2.6
B. pubescens	25.2	2.3	2.8*	0.7	8.3*	2.2	10.0	1.2	4.5	1.0	2705	739	5.9	0.5	111	31	34.8	6.4
A. incana	36.1	2.5	2.2	0.3	8.8	2.7	13.5	2.5	4.5	1.0	394	290	13.6	0.9	63	6	21.4	7.4
S. triandra	28.5	0.7	2.8	0.4	17.2	1.8	6.2	0.6	3.9	0.7	2534	185	7.8	0.2	103	31	30.8	9.2
S. phylicifolia	25.5	1.8	2.3	0.3	11.5	2.9	12.8	1.4	2.7	0.4	2181	370	5.7*	0.4	92	30	28.3	4.6
S. dasyclados	28.1	2.8	3.3	0.3	17.4	2.4	8.3	0.6	5.5	0.7	670	192	6.4	0.5	106	17	14.3	3.9
S. 'Aquatica'	29.4	4.6	3.6	0.7	17.6	2.8	7.4	0.6	3.8	0.3	638	232	7.3	1.1	182	27	13.1	2.4
Valkeasuo																		
B. pendula	26.6	2.7	3.1	0.7	6.9*	2.7	8.4	2.0	4.4	1.4	530	177	4.4	1.7	127	53	21.2	2.3
B. pubescens	26.8	1.7	2.4	0.3	9.0*	1.8	9.6	0.5	3.4*	0.7	430	47	3.8	0.7	86	28	30.8	4.2
S. phylicifolia	23.6	2.0	2.0	0.1	9.6	2.1	8.4	2.2	2.2	0.5	247	36	3.5	0.5	74	18	23.3	4.7
S. dasyclados	37.2	3.6	4.5	0.4	17.3	1.8	6.1	0.7	3.1	0.2	101	8	6.0	0.7	79	11	13.0	3.7
S. 'Aquatica'	34.6	3.8	5.1	1.4	13.4	2.9	9.5	1.1	3.5	0.7	116	4	7.2	0.2	154	71	16.1	1.6
Sukeva																		
B. pendula	28.3	1.1	4.9	1.5	11.3	1.3	10.5	1.8	4.6	0.7	1585	903	8.1	1.3	347	84	17.8	6.7
B. pubescens	27.6	3.0	3.0*	0.2	12.7	0.3	11.0	0.6	3.7	0.3	1716	651	5.7	0.9	187	20	25.1	11.1
A. incana	38.3	0.7	2.5	0.2	13.0	1.6	16.4	1.4	3.5	0.3	519	302	13.4	1.3	73	7	18.2	6.1
S. triandra	30.8	0.9	2.8	0.3	17.5	3.0	7.7	0.2	3.4	0.3	1283	457	8.0	0.5	316	81	35.3	9.8
S. phylicifolia	24.3	2.0	2.1	0.2	13.1	4.5	13.8	1.4	2.2	0.5	1484	568	6.2	1.4	192	42	18.0	1.7

Appendix 1 continued.

	N		P		K		Ca		Mg		Mn		Cu		Zn		B	
	g kg^{-1}										mg kg^{-1}							
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Branches																		
Piipsanneva																		
B. pendula	6.7	0.7	0.7	0.1	1.9	0.4	2.1	0.4	0.6	0.2	206	100	4.3	1.1	56	34	5.9	2.2
B. pubescens	5.4	0.4	0.6	0.2	2.9	1.8	1.9	0.4	0.6	0.1	214	147	3.5*	0.6	56	12	5.4	2.2
A. incana	10.4	0.9	0.7	0.3	2.1	1.0	2.3	0.7	0.7	0.4	177	80	7.4	4.7	38	5	6.0	3.6
Valkeasuo																		
B. pendula	6.6	1.0	0.7	0.1	1.7*	0.5	2.9	0.4	0.7	0.1	86	45	2.8	0.7	83	8	7.2	0.9
B. pubescens	6.1	0.5	0.6	0.1	1.8*	0.3	3.0	0.2	0.6	0.1	66	6	2.4	0.5	72	11	7.0*	0.8
Sukeva																		
B. pendula	11.0	0.8	1.0	0.1	2.6*	0.3	3.2	0.3	0.7	0.1	176	85	6.5	0.4	141	11	7.5	0.9
B. pubescens	8.1	0.6	0.7	0.1	2.2	0.2	3.1	0.2	0.6	0.0	186	72	5.2	1.3	100	17	6.9	0.5
A. incana	13.6	0.9	1.4	0.1	3.1	0.2	3.7	0.1	0.9	0.0	175	88	13.4	0.5	55	3	9.4	1.4
Stem																		
Piipsanneva																		
B. pendula	3.2	0.7	0.8	0.5	2.7	1.4	1.6	0.3	0.6	0.3	145	71	3.2	0.7	64	26	4.5	1.1
B. pubescens	2.8	0.3	0.4	0.1	1.6	0.4	1.2	0.2	0.3	0.1	150	65	4.0	2.2	40	13	4.1	0.6
A. incana	5.3	0.7	0.6	0.1	2.0	0.2	1.6	0.3	0.4	0.1	72	30	6.5	2.0	21	4	4.4	0.6
Valkeasuo																		
B. pendula	3.6	0.6	0.4	0.1	1.2	0.3	1.4	0.2	0.4	0.1	61	36	1.7	0.3	49	9	4.8	1.0
B. pubescens	3.6	0.4	0.4	0.0	1.1	0.1	1.3	0.1	0.3	0.0	39	10	1.6	0.3	38	4	4.6	0.5
Sukeva																		
B. pendula	4.7	0.4	0.6	0.1	1.5	0.2	1.4	0.2	0.3	0.1	79	37	3.9	0.6	69	8	4.7	0.3
B. pubescens	3.6	0.2	0.4	0.0	1.4	0.1	1.2	0.2	0.3	0.1	85	32	3.5	0.5	48	8	3.9	0.2
A. incana	6.7	0.6	1.0	0.1	1.9	0.1	2.2	0.3	0.5	0.1	84	44	6.5	1.0	24	3	5.1	0.7

Appendix 1 continued.

	N		P		K		Ca		Mg		Mn		Cu		Zn		B	
	g kg^{-1}										mg kg^{-1}							
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Stem (including branches)																		
Piipsanneva																		
S. triandra	4.1	0.7	1.1	0.2	4.1*	1.7	3.2	1.2	0.9	0.4	295	166	9.0	7.4	90	25	8.7	3.3
S. phylicifolia	3.2*	0.6	1.2	0.7	3.2	1.6	3.5	0.6	0.8	0.5	210	69	9.5	5.2	53	8	7.8	4.5
S. dasyclados	3.8	0.5	0.9	0.1	3.0	0.3	3.1	0.9	0.9	0.2	318	235	7.3	2.8	100	60	8.6	3.4
S. 'Aquatica'	6.8	2.9	0.9	0.4	2.9	0.9	3.3	1.8	0.9	0.4	512	338	6.4	2.5	103	28	9.1	3.3
Valkeasuo																		
S. phylicifolia	5.6	1.2	0.7	0.1	1.7	0.2	3.8	0.6	0.4	0.0	40	8	3.3	0.6	60	10	5.1	0.6
S. dasyclados	8.3	1.4	1.4	0.2	2.8	0.5	3.9	0.6	0.8	0.1	35	3	3.9	1.1	99	6	7.6	1.0
S. 'Aquatica'	7.1	1.0	1.3	0.3	4.3	1.7	5.2	0.5	0.9	0.1	33	10	4.7	1.7	111	32	8.6*	1.7
Sukeva																		
S. triandra	6.9	0.6	1.2	0.1	3.2	0.4	2.8	0.3	0.7	0.1	168	72	5.8	1.5	122	26	7.8	1.4
S. phylicifolia	5.1	0.3	0.8	0.1	2.1	0.2	4.4	0.5	0.5	0.1	137	65	5.5	1.1	71	5	5.9	0.3