Effect of Fertilizer Treatment on the Biomass Production and Nutrient Uptake of Short-Rotation Willow on Cut-Away Peatlands

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Hytönen, J. 1995. Effect of fertilizer treatment on the biomass production and nutrient uptake of short-rotation willow on cut-away peatlands. Silva Fennica 29(1): 21–40.

The effects of fertilizer treatment on the soil nutrient concentrations, biomass production and nutrient consumption of *Salix* × *dasyclados* and *Salix* 'Aquatica' were studied in five experiments on three cut-away peatland sites in western and eastern Finland during three years. Factorial experiments with all combinations of N (100 kg $ha^{-1}a^{-1}$), P (30 kg $ha^{-1}a^{-1}$) and K (80 kg $ha^{-1}a^{-1}$) were conducted.

The application of P and K fertilizers increased the concentrations of corresponding extractable nutrients in the soil as well as in willow foliage. N-fertilization increased foliar nitrogen concentration. An increase in age usually led to decreases in bark and wood N, P and K concentrations and increases in bark Ca concentrations. N-fertilization increased the three-year biomass yield 1.5–2.7 times when compared to control plots. P-fertilization increased the yield only in those experimental fields whose substrates had the lowest phosphorus concentration. K-fertilization did not increase the yield in any of the experimental fields. The highest total biomass yield of NPK-fertilized willow after three growing seasons, 23 t ha^{-1}, was distributed in the following way: wood 42 %, bark 19 %, foliage 17 %, stumps 6 % and roots 16 %. As the yield and stand age increased, more of the biomass was allocated in above-ground wood. Three-year-old stands (above-ground biomass 18 t ha^{-1}) contained as much as 196 kg N ha^{-1}, 26 kg P ha^{-1}, 101 kg K ha^{-1}, 74 kg Ca ha^{-1} and 37 kg Mg ha^{-1}. By far the highest proportion of nutrients accumulated in the foliage. The bark and wood contained relatively high proportions of calcium and phosphorus respectively. With an increase in age and size, the amount of nitrogen and potassium bound in one dry-mass ton of willow biomass decreased while that of phosphorus remained unchanged.

Keywords biomass production, fertilization, nutrients, consumption, peatland, *Salix*, forests, fuelwood.
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Accepted March 16, 1995

1 Introduction

The concept of short-rotation biomass management includes the establishment of closely-spaced stands of fast-growing trees and the application of intensive cultivation practices. Short-rotation plantations can be established on abandoned farming land but in Finland peatlands could also be potential growing sites (Energiametsätoimikunnan ... 1981). Especially cut-away peatlands, where the peat layer is variable but often quite shallow and terrain smooth and stoneless, could be used for continuous energy production on the same site (Pohjonen 1980). The amount of cut-away peatlands is estimated to increase during this decade by 1500–3000 ha per annum (Taustatietoa ... 1991). Due to the considerably low pH of the remaining peat layer, liming or ash fertilization is necessary when growing certain exotic willow species (Ericsson and Lindsjö 1981, Ferm and Hytönen 1988). The peat of cut-away peatlands is typically relatively rich in nitrogen, but contains only small amounts mineral nutrients such as phosphorus and potassium (Kaunisto 1982, 1986). When cut-away peatlands are afforested, the nutrient regime is a centrally important factor (Kaunisto 1986, 1987, Valk 1986, Ferm and Hytönen 1988). Extremely poor growth and high mortality of exotic willows on limed but unfertilized peat shows the inadequateness of the peat's natural nutrient reserves (Hytönen 1986, 1987, Ferm and Hytönen 1988).

Short-rotation plantations of willow bind considerable amounts of nitrogen, phosphorus and potassium in their biomass (Saarsalmi 1984, Ferm 1985, Hytönen 1986). This has led to concern as to the maintenance of nutrient supplies under short-rotation systems and to the consideration of fertilizer inputs as a regular cultivation operation aimed at maximising yields. Harvesting of biomass at short intervals further increases concern over the adequacy of nutrient supplies.

Nitrogen is commonly a growth limiting nutrient in forestry. Nitrogen fertilization is also important from the economic point of view. Thus, growing of short-rotation crops on nitrogen-rich substrates, such as cut-away peatlands, could positively affect the economics of the cultivation. The use of nitrogen-fixing tree species (e.g. alder) in mixture with other tree species is problematic in short-rotation forestry due to the frequently different genotype-specific growth patterns (DeBell and Harrington 1993). Establishing fertilization regimes that optimize growth with minimal adverse environmental consequences, i.e. adjusting of fertilizer application rates and frequencies to maximize nitrogen utilization and minimize leaching, is an important objective in programmes for the development of woody biomass production systems (Miegroet et al. 1994).

Fertilizer application is an important factor affecting the yield of short-rotation willow plantations on cut-away peatlands (Hytönen 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988, Lumme 1989). PK-fertilization promotes willow growth on cut-away peatlands, but whether this is more due to either the nutrients or their interaction is not known. However, the effect of nitrogen fertilization on biomass production can be more marked than that of PK-fertilization (Kaunisto 1983, Hytönen 1987, Ferm and Hytönen 1988). Although field experiments so far provide little knowledge about whether nutrient requirements vary from site to site, the results obtained from greenhouse studies indicate that the nitrogen concentration of the site could affect the fertilization regime (Ferm and Hytönen 1988). Knowledge on the effects of soil phosphorus and potassium concentration is even more limited. There are no general instructions on the choice of fertilizer treatment based on soil or foliar analyses.

The aim of this study was to determine the effects of nitrogen, phosphorus and potassium fertilizer treatments and their interactions on the biomass production and nutrition of short-rotation willow on cut-away peatlands. Besides looking into the total amount of the biomass and nutrients, measurements were also made of their distribution in the different biomass compartments. The influence on the fertilization regime of the varying soil fertility on the cut-away peatlands was also studied.

2 Material and Methods

2.1 Experimental Design

Five willow plantations were established on three cut-away peatlands at Haapavesi (Piipsanneva 1, Piipsanneva 2: 64°06', 25°36'E), Ruukki (Paloneva, 64°27'N, 25°26'E) and Tohmajärvi (Valkeasuo 1, Valkeasuo 2: 62°19'N, 30°14'E). The Piipsanneva and Paloneva experimental areas were limed by applying 6000 kg ha^{-1} dolomite lime in the spring of 1983. Since even the survival of willows has been very low on unfertilized but limed cut-away peatlands (Hytönen 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988), all the experimental areas were fertilized before the start of the experiment. The Piipsanneva and Paloneva experimental areas were fertilized using ammonium nitrate with lime and PK fertilizer for peatlands (N 50 kg ha^{-1}, P 44 kg ha^{-1}, K 83 kg ha^{-1}) in the spring of 1983. The experimental area of Piipsanneva 1 had already been NPK-fertilized in 1980. Valkeasuo 1 experimental area was limed (12 000 kg ha^{-1} dolomite lime) and fertilized with 550 kg ha^{-1} of PK fertilizer for peatlands (P 48 kg ha^{-1}, K 91 kg ha^{-1}) and at Valkeasuo 2 wood ash was used (12 000 kg ha^{-1}; P 1.6 %, K 4.9 %, Ca 26.5 %, Mg 3.4 %) in 1981.

Willow cuttings (20 cm in length) were planted in the spring of 1983 in rows applying a planting density of 4.1 cuttings m^{-2} (70 cm × 35 cm). *S.* × *dasyclados* (clone P6011) was planted at Piipsanneva 1, *S.* 'Aquatica' clone V769 at Piipsanneva 2 and at Paloneva and *S.* 'Aquatica' clone E4856 at Valkeasuo. A planting machine was used at Valkeasuo (see Harstela and Tervo 1983). Supplementary planting was done on all the experimental fields. In the autumn of 1983, 1-year-old willow sprouts were cut back to increase sprouting. Weed control was done on all the experimental fields; most intensively it was done at Piipsanneva. The experimental fields were fenced.

The fertilizer treatment experiments were started in the spring of 1984. Altogether five factorial fertilization experiments with combinations of nitrogen, phosphorus and potassium (0, P, K, N, PK, NK, NP, NPK) were established. The fertilizers applied were ammonium nitrate with lime (N 100 kg ha^{-1}), superphosphate (P 30 kg ha^{-1}) and potassium salt (K 80 kg ha^{-1}). Fertilization was done in the spring of 1984 and it was repeated with the same fertilizers and amounts in 1985 and 1986. The experimental design consisted of randomized blocks with three (Piipsanneva and Paloneva) or four replications (Valkeasuo). Total number of experimental plots was thus 136. The experimental plots varied in size between 56 and 80 m^2.

2.2 Measurements and Calculation of Biomass

Willow height (h) and base diameter at 10 cm above ground level (d) were measured on the experimental plots (100–200 sprouts per plot) at the end of each growing season (see Hytönen 1986, Hytönen et al. 1987). The number of living and dead stools were also recorded. At least two border rows were excluded from the measurements in order to avoid possible bias from the edge effect (see Zavitkovski 1981, Stott et al. 1983).

Annually 26–56 randomly selected sample sprouts were excised to provide data for dry-mass equations. This was done on each experimental field leaving 10 cm long stumps. The sample trees were generally cut at the end of August, but at Piipsanneva this was done in 1984 on September 24 in 1984 and at Valkeasuo on September 15 in 1986. The base diameter of the sample trees was measured to an accuracy of 1 mm and their height to an accuracy of 1 cm. The leaf area was measured using a Li-Cor leaf area meter and applying an accuracy of 0.01 cm^2. The foliage, bark and wood were separated and dried to constant weight (foliage at 80 °C, bark and wood at 105 °C) and their dry-mass was weighed to an accuracy of 0.1 g. The dry-mass equations, having the form $Y = aX^b$, were calculated for the above-ground compartments (foliage, wood and bark) using logarithmic transformation and d^2h as the independent variable (see Hytönen 1986, Hytönen et al. 1987) (Table 1). The leaf area of the sprouts could be predicted with considerable accuracy using similar models (Table 1). When calculating the mass of the stem, bark, and foliage, and leaf area of the sprouts growing on

Table 1. Dry-mass and leaf area equations for willow. The equations have the form $Y = aX^b$; after logarithmic transformation, these were corrected using $s_e^2/2$. Y = dry-mass or leaf area (g or cm^2), $X = d^2h$, d = diameter at the base (mm), h = height (cm), a and b constants, r^2 = degree of determination, V = coefficient of variation, N = number of sample trees.

Compart-ment	Experi-ment[1]	One-year-old willow N	a	b	r^2 %	V %	Two-year-old willow N	a	b	r^2 %	V %	Three-year-old willow N	a	b	r^2 %	V %
Stem	PI1	41	0.00238	0.9578	98	17.0	56	0.00268	0.9594	98	14.3	26	0.00516	0.9043	99	11.1
	PI2	39	0.00241	0.9430	98	21.2	34	0.00269	0.9499	95	13.2	32	0.00370	0.9351	98	15.3
	PA	40	0.00443	0.8831	98	18.2	33	0.00178	0.9881	99	13.8	28	0.00209	0.9800	99	13.8
	VA	32	0.00372	0.8945	98	16.6	33	0.00291	0.9343	99	14.7	29	0.00257	0.9618	98	13.6
Foliage	PI1	41	0.02046	0.6170	88	28.4	56	0.00543	0.8245	94	22.7	26	0.00461	0.7997	95	18.3
	PI2	39	0.01873	0.6380	92	27.4	34	0.00697	0.7886	78	25.1	34	0.00572	0.7910	94	23.6
	PA	40	0.02581	0.6639	96	22.0	32	0.01672	0.7345	96	25.7	28	0.00566	0.7905	95	32.7
	VA	32	0.00507	0.8774	91	32.8	33	0.02324	0.6756	95	26.7	28	0.00058	0.9737	88	37.8
Wood	PI1	41	0.00047	1.0726	98	20.1	56	0.00104	1.0117	99	12.7	27	0.00159	0.9783	99	11.9
	PI2	39	0.00080	1.0026	98	19.9	34	0.00113	0.9962	96	12.8	33	0.00167	0.9759	99	14.8
	PA	40	0.00139	0.9546	97	25.8	33	0.00062	1.0523	99	15.3	28	0.00078	1.0361	99	13.3
	VA	32	0.00134	0.9471	98	15.8	33	0.00091	1.0096	99	15.8	29	0.00109	1.0056	98	13.3
Bark	PI1	41	0.00274	0.8522	97	19.1	56	0.00243	0.8616	95	20.3	27	0.00783	0.7580	95	16.4
	PI2	39	0.00199	0.8712	97	24.4	34	0.00222	0.8582	91	16.2	33	0.00328	0.8339	97	19.4
	PA	40	0.00353	0.8105	99	15.7	33	0.00170	0.8844	99	16.0	28	0.00204	0.8722	99	17.0
	VA	32	0.00269	0.8352	96	19.2	33	0.00283	0.8275	99	16.2	29	0.00203	0.8777	96	17.4
Leaf area	PI1	41	5.18103	0.5974	81	36.3	56	0.55772	0.8581	95	20.8	27	0.26838	0.8720	96	16.8
	PI2	39	6.33703	0.5673	87	32.2	34	0.93514	0.7968	82	22.9	34	0.95770	0.7831	96	19.7
	PA	40	4.37499	0.6291	94	25.4	32	2.92401	0.7228	96	24.6	28	0.86929	0.7797	95	34.9
	VA	32	0.86387	0.8506	91	31.6	33	4.08544	0.6610	96	24.6	28	0.06383	0.9787	89	37.1

[1] PI1 = Piipsanneva 1, PI2 = Piipsanneva 2, PA = Paloneva, VA = Valkeasuo

sample plots, the 10 cm stump height was deducted from the measured willow height.

Twelve to twenty randomly selected stools (including stems and roots) from each experiment were dug up annually at Paloneva and Piipsanneva. The sprouts (excised at a height of 10 cm from ground level), stumps (ground level to 10 cm height) and roots were separated, and their dry-masses were measured (drying 1–2 days at 105 °C). The independent variable in the linear stump and root dry-mass equations was the dry-mass of all the sprouts on a stool. The stump mass equations also included the number of sprouts per stool as a variable. The coefficient of determination of the root mass equations was 70–97 % and of the stump mass equations 78–98 %. The number of living stools in each plot was used when converting the calculated masses to area basis.

Each year, in late August or early September, a minimum of five different-sized sprouts were sampled to provide material for nutrient analyses of the foliage, bark and wood from each plot at Piipsanneva and Paloneva. Foliar N, P and K concentrations from the 1984 samples, as well as foliar Ca, Mg, Fe, Mn, Zn, and Cu concentrations from the samples taken in 1985 and 1986, were determined using the methods described by Halonen et al. (1983). The corresponding nutrient concentrations in the bark and wood were determined from the Piipsanneva 2 and Paloneva material by accessing the unfertilized plots and N-, PK- and NPK-fertilized plots in 1984, 1985 and 1986 and from the Piipsanneva 1 material in 1986. At Valkeasuo 1 and 2, foliar samples were taken from three blocks out of four in 1984 and 1985 and analyzed for their N, P and K concentrations.

Soil samples (composed of five subsamples) were taken in August 1986 from the 0–10 cm top soil layer on all the study plots at Piipsanneva and Paloneva and at Valkeasuo 1 and 2 from 3 out of 4 blocks. The pH of the dried samples was analyzed in distilled water (V/V 1:5). The soil acid ammonium acetate (pH 4.65) extractable phosphorus, potassium, calcium, and magnesium concentrations were determined (mg l^{-1}, volume determined at laboratory). The total nitrogen content (Kjeldahl) was analyzed from 33 samples. pH was determined also from samples collected in May 1983 prior to liming and fertilization at Piipsanneva 2 (n = 60) and Paloneva (n = 18) and Valkeasuo (n = 12) in November 1984 from the unlimed and non-fertilized area outside the plots. The depth of the peat layer was measured at five points on each of the study plots; it was much greater at Paloneva (152 cm) than at the other areas (40–58 cm).

The annual degree-day temperature sum (threshold +5 °C) at Nivala (close to Haapavesi), Ruukki and Tohmajärvi weather stations during the study years varied between 1026 dd °C (at Ruukki in 1986) and 1252 dd °C (at Tohmajärvi in 1984). The spring in 1984 was very warm and the temperature sum at the end of May at all weather stations exceeded 230 dd °C. Precipitation in June 1986 was quite low; at Nivala it was only 6 mm. Summer frosts were recorded in 1984 at Nivala (12th June, –1.2 °C), Tohmajärvi (11th June, –3.5 °C) and Ruukki (10th and 11th June, –1.2 °C). At the beginning of the growing season in 1985, summer frosts were recorded at all weather stations.

The effects of nitrogen, phosphorus and potassium fertilization and their interactions on the measured parameters were studied by means of three-way analysis of variance. The factorial main effects of N, P and K fertilization on the measured variables was calculated.

3 Results

3.1 pH and Soil Nutrient Concentrations

At Valkeasuo 2, ash application increased the peat's pH by 0.5 pH-units while liming increased it by almost one pH unit. At Piipsanneva and Paloneva, liming increased the pH by more than one pH-unit (Fig. 1). The fertilization treatments did not affect the extractable concentrations of calcium and magnesium. However, there were considerable differences between the experimental fields (Fig. 1). The total nitrogen concentration of the peat and the organic matter content at the end of the experiments were highest at Paloneva and lowest at Valkeasuo 2 (Fig. 1). At Piipsanneva, mixing of the soil from ditches when splitting the initially 20 m wide strips, and

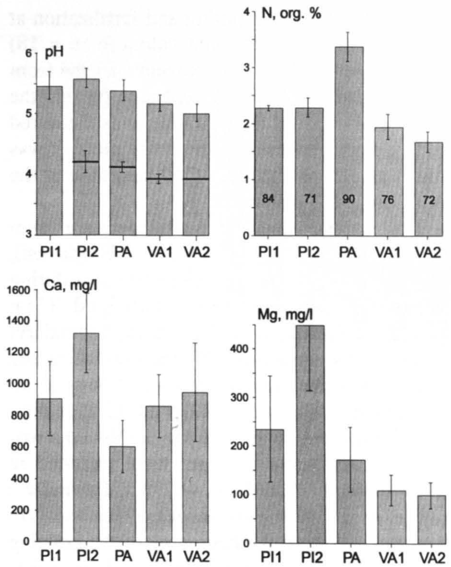


Fig. 1. Soil pH, nitrogen content (in organic matter) and concentrations of ammonium acetate extractable (pH 4.65) calcium and magnesium. Standard deviations indicated by lines. pH before amelioration indicated inside the pH columns. The peat's organic matter content (%) marked inside the columns of total nitrogen content. Study areas: PI1 = Piipsanneva 1, PI2 = Piipsanneva 2, PA = Paloneva, VA1 = Valkeasuo 1, VA2 = Valkeasuo 2.

at Valkeasuo ploughing of the experimental field, probably contributed to a decrease in organic matter content in the top peat layer through the addition of mineral soil into the peat.

The peat's extractable phosphorus concentrations in the control plots (basic fertilization) were lowest at Paloneva and Piipsanneva 2, and manyfold greater at Valkeasuo, especially in the ash-fertilized area (Fig. 2). Phosphorus fertilization significantly increased the extractable phosphorus

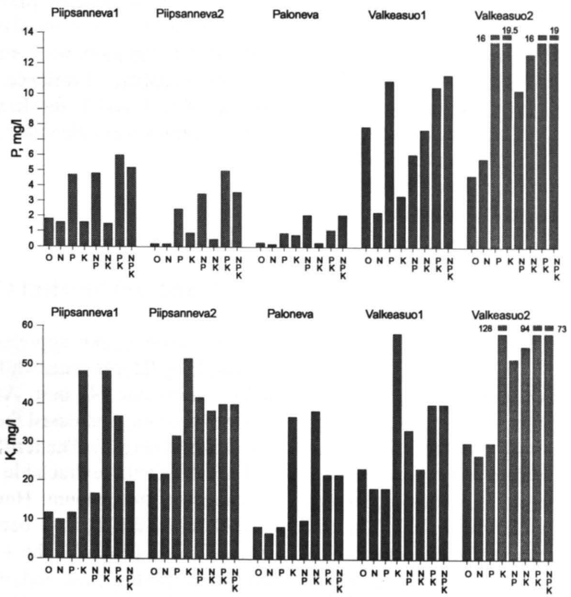


Fig. 2. Effect of fertilization on the concentration of ammonium acetate extractable phosphorus and potassium in the soil of the experimental sites.

concentration in all the experimental areas, except at Valkeasuo 2. The concentrations of extractable potassium in the control plots (basic fertilization) were lowest at Paloneva and Piipsanneva 1, twice as high at Piipsanneva 2 and Valkeasuo 1, and thrice as high at Valkeasuo 2. Potassium fertilization significantly increased the concentration of extractable potassium in all the experimental fields ($p < 0.001$). When willow fertilization consisted only of potassium, the peat's potassium concentration was higher than when compared with fertilizer treatments also containing other nutrients; this was probably due to the poor growth and consequent small uptake of potassium by willow.

3.2 Foliar Nutrient Concentrations

Nitrogen fertilization significantly increased the concentrations of foliar nitrogen; this was observed already during the first growing season in all the experimental areas (Fig. 3). At Paloneva, phosphorus fertilization significantly decreased the foliar nitrogen concentration during all growing seasons; at Piipsanneva this happened only during the first growing season. The first growing season's nitrogen concentrations were higher than those of the following seasons; this was especially so at Paloneva and Valkeasuo. The first growing season foliar concentrations of nitrogen at Piipsanneva on the control plots varied between 22–23 mg g^{-1} and at Paloneva and Valkeasuo 26–36 mg g^{-1}. During the second and third growing season nitrogen concentrations on control plots varied between 17–28 mg g^{-1}; at their highest they were at Paloneva, where the peat total nitrogen content was also highest.

Phosphorus fertilization increased the concentrations of foliar phosphorus. During the first growing season, however, this increase was not significant in all the experimental areas (Fig. 3). The concentrations of foliar phosphorus in fertilized willow increased little year by year, but that of those not fertilized with phosphorus remained unchanged. Foliar phosphorus concentrations, like the soil extractable phosphorus concentrations of willow in the control plots, were lowest at Paloneva and at Piipsanneva 2 (1.1–1.9 mg g^{-1}) and highest at Valkeasuo (2.6–3.9 mg g^{-1}), where the soil's phosphorus concentration was also the highest. Nitrogen fertilization significantly decreased the foliar phosphorus concentrations in many cases (Fig. 3).

Potassium fertilization significantly increased the concentrations of foliar potassium in all the experimental fields (except at Valkeasuo 2) already during the first growing season (Fig. 3). Potassium fertilization increased the third growing season's foliar potassium concentration most of all at Paloneva and Piipsanneva 1, where the peat's extractable phosphorus concentration was at its lowest. Phosphorus fertilization decreased foliar potassium concentrations at Paloneva, but increased it at Valkeasuo. Especially at Valkeasuo, nitrogen fertilization decreased the concentrations of foliar potassium. Foliar potassium concentrations of willow in the control plots was 9–18 mg g^{-1}.

The annual variation in foliar calcium and magnesium concentrations was small. Phosphorus fertilization increased and nitrogen fertilization decreased the foliar concentrations of calcium and magnesium. Foliar zinc concentrations were considerably higher at Paloneva (198–501 mg kg^{-1}) than at Piipsanneva (141–173 mg kg^{-1}). Copper concentrations were highest at Piipsanneva 1 (12–14 mg kg^{-1}) and lower at Piipsanneva 2 (9–15 mg kg^{-1}) and at Valkeasuo (5–17 mg kg^{-1}). Iron and manganese concentrations were highest during the third growing season and lower at Piipsanneva 1 (Fe: 97–130 mg kg^{-1}, Mn: 547–1098 mg kg^{-1}) than at Piipsanneva 2 (Fe: 123–173 mg kg^{-1}, Mn: 531–729 mg kg^{-1}) or at Paloneva (Fe: 102–174 mg kg^{-1}, Mn: 418–691 mg kg^{-1}).

3.3 Nutrient Concentrations of Bark and Wood

The concentrations of nitrogen in both the bark and wood decreased markedly with increase in willow age from one to two years (Fig. 4). At the age of three years, the foliar nitrogen concentrations were 2–3 times higher than those of the bark and the bark's nitrogen concentrations in turn were 2–4 times higher than those of the wood. The nitrogen concentrations of willow bark on N- and NPK-fertilized plots were higher

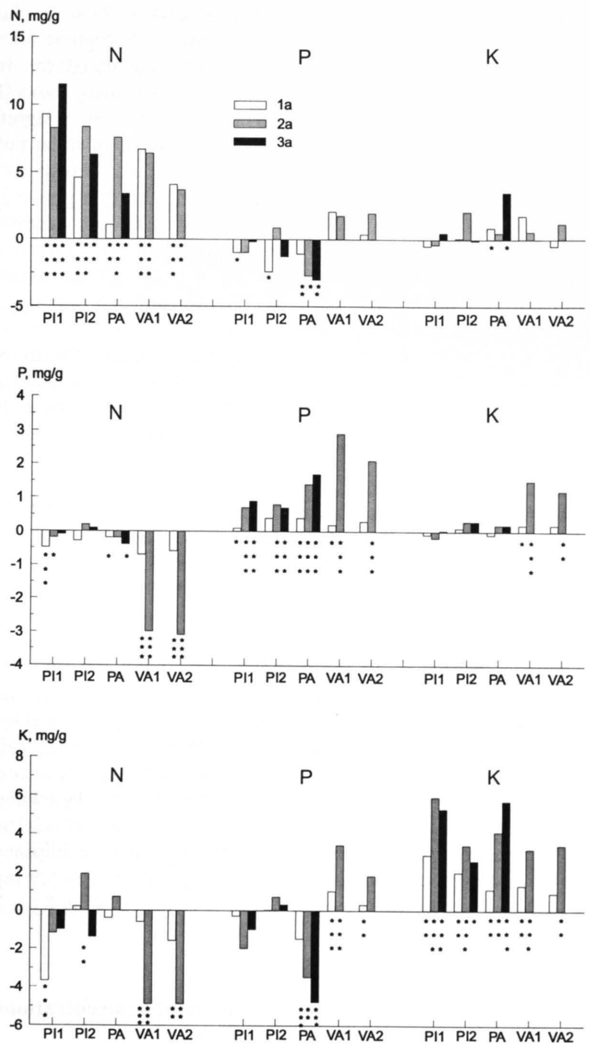


Fig. 3. Factorial main effects of nitrogen, phosphorus and potassium fertilizer application on the foliar nitrogen, phosphorus and potassium concentrations. Statistical significance indicated by asterisks (* = p < 0.05, ** = p < 0.01, *** = p < 0.001. Willow age between one and three years (1a, 2a, 3a). For legend, see Fig. 1.

than in the PK-fertilized plots or control plots.

The first year's high bark phosphorus concentrations fell markedly during the second growing season, but the wood's phosphorus concentrations were almost at the same level after the first and third growing seasons (Fig. 4). At the age of three years, the foliar phosphorus concentrations were generally 1.8–2.6 times higher than those of the bark. At Paloneva, however, both the foliar and bark phosphorus concentrations of willow not fertilized with phosphorus were equal. The phosphorus concentrations of the bark were 1.5–3.5 times higher than those of the wood. Fertilization with PK or NPK increased the phosphorus concentrations of the bark and the wood.

The potassium concentrations of the bark after the first growing season were 3.7 times higher than those of the wood (Fig. 4). The figures for the potassium concentration of the bark decreased and those of wood remained almost at the same level with increase in willow age. The fertilizer treatments did not significantly affect the potassium concentrations of wood and bark.

Both the calcium and magnesium concentrations of the bark were considerably higher than those of the wood (Fig. 4). The bark's calcium concentrations increased annually while those of the wood changed only a little.

3.4 Survival and Sprouting

The survival of willow was high at Piipsanneva (91–97 %) but somewhat lower at Paloneva and Valkeasuo 1 (75–78 %) and lowest at Valkeasuo 2 (52 %) after the third growing season. Nitrogen fertilization increased stool mortality at Piipsanneva 1 only slightly (4 %, $p < 0.001$), but at Valkeasuo the effect was pronounced (Valkeasuo 1:11 %, $p < 0.001$ and at Valkeasuo 2:15 %, $p < 0.001$).

The effect of the fertilizer treatment on the number of sprouts and density of the stands was not marked. However, there were great differences between the experimental fields. The densities of the plantations after the third growing season at Piipsanneva 1, Piipsanneva 2, Paloneva, Valkeasuo 1 and Valkeasuo 2 were, respectively, 26, 37, 15, 12 and 6 sprouts m^{-2}.

3.5 Biomass Production and its Allocation

3.5.1 Biomass Production

There were great differences in the biomass production between the experimental fields after the first growing season (Fig. 5). These differences increased during the following years. Willow grew best at Piipsanneva 1 and production was lowest at Valkeasuo 2. The first year's leafless above-ground mass in all the experimental fields was less than 1.8 t ha^{-1} (Fig. 5). The annual yields produced during the second and third growing seasons were manyfold compared to the yield of the first growing season. The leafless above-ground biomass of N- and NPK-fertilized willow was over 14 t $ha^{-1}a^{-1}$ at Piipsanneva 1, while at Piipsanneva 2 and Paloneva the corresponding figures for NP-fertilized willow were 11–12 t $ha^{-1}a^{-1}$. The total mass (including foliage, bark, wood, stump and roots) in the same treatments at Piipsanneva 1 was 23.4 t $ha^{-1}a^{-1}$, at Piipsanneva 2, 20.3 t $ha^{-1}a^{-1}$ and Paloneva 18.3 t $ha^{-1}a^{-1}$.

There were significant differences between the experimental fields in regard to the effect of the fertilizer treatment on biomass production (Figs. 5 and 6). Nitrogen fertilization significantly increased the biomass production of willow foliage, stem, wood and roots already during the first growing season at Piipsanneva and Valkeasuo 1 and at Paloneva and Valkeasuo 2 from second growing season on. At Piipsanneva 1 and Valkeasuo, where the peat's phosphorus concentrations were at their highest, only nitrogen increased willow growth. The increases in yield induced by nitrogen were high: the leafless above-ground biomass at the end of the third growing season was 1.5–2.7 times higher than that of willow growing in the control plots. Nitrogen fertilization increased the total biomass production at Piipsanneva 1 by 11.6 t $ha^{-1}a^{-1}$, at Piipsanneva 2 by 8.1 t $ha^{-1}a^{-1}$ and at Paloneva by 5.6 t $ha^{-1}a^{-1}$.

Phosphorus fertilization did not increase the willow biomass production during the first growing season at any of the experimental fields. Even later, it had no effect on the biomass production at Piipsanneva 1 and Valkeasuo (Figs. 6, 7). At Paloneva, however, phosphorus fertili-

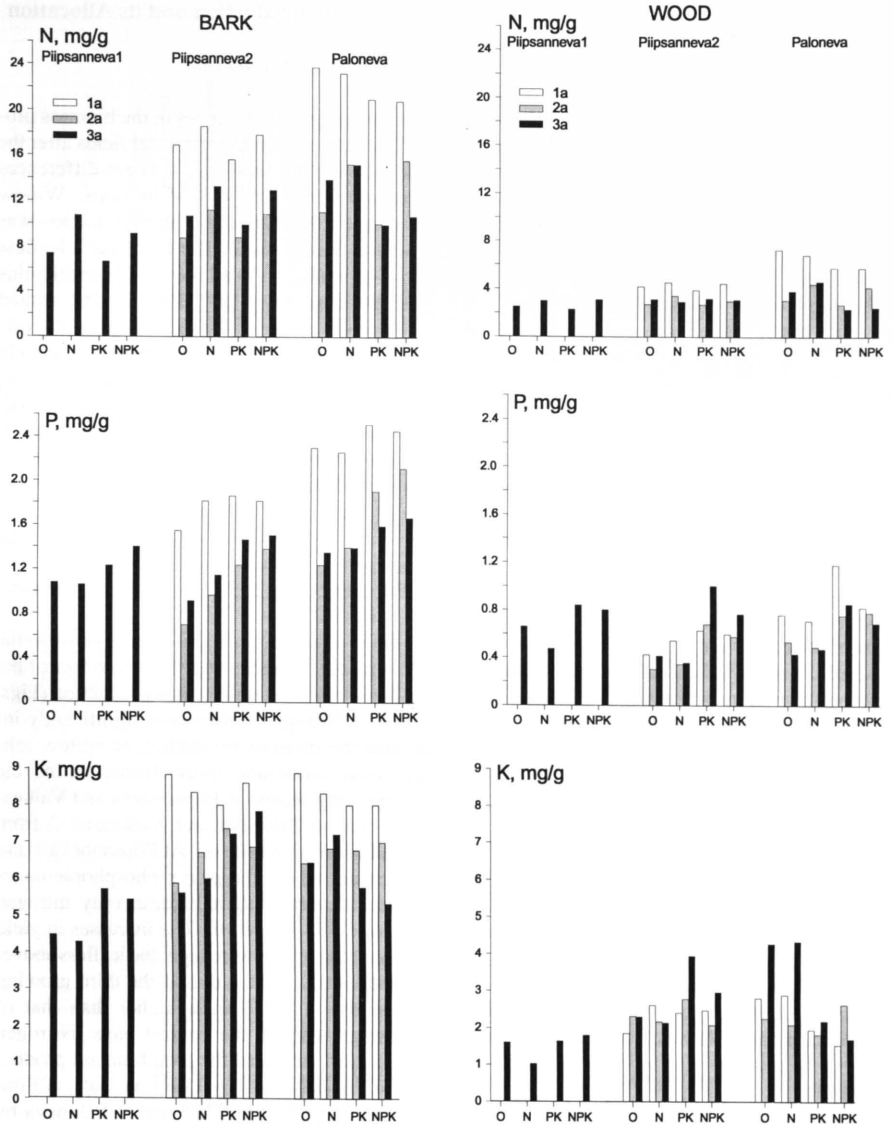


Fig. 4. Effect of fertilization on the nitrogen, phosphorus, potassium, calcium and magnesium concentrations of willow bark and wood.

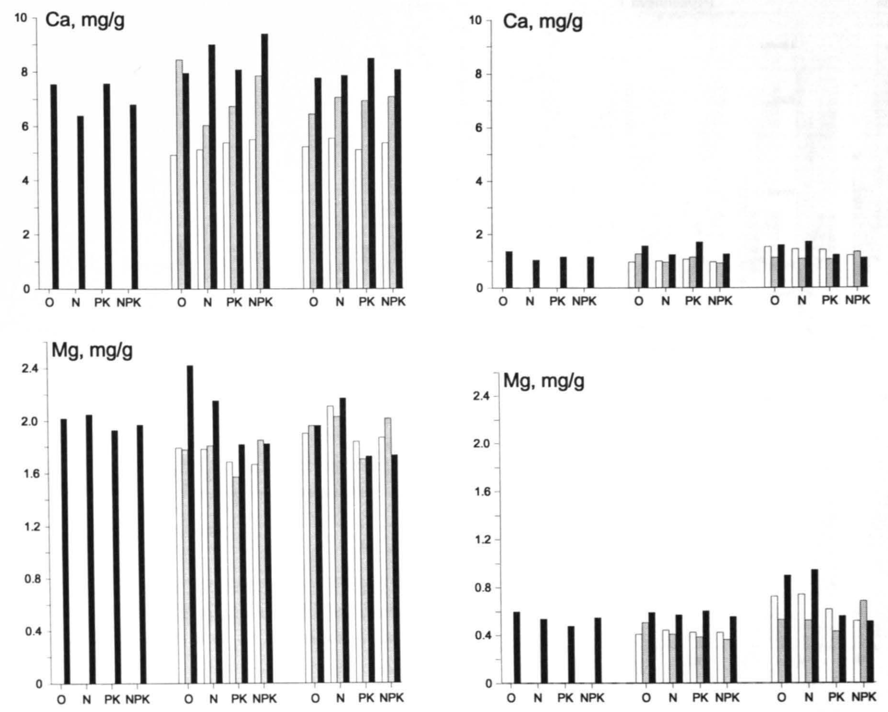


Fig. 4 continued.

zation increased biomass production during two growing seasons by as much as nitrogen did. After the third growing season, phosphorus fertilization had increased production more than nitrogen fertilization.

Potassium fertilization did not significantly increase biomass production in any of the experimental fields during any of the three study years (Figs. 6, 7).

3.5.2 Allocation of Biomass

The allocation of dry-mass into foliage, bark, wood, stump and roots changed with increase in willow age. After the first growing season, the proportions of wood and bark in the total biomass were almost equal. The proportion of wood mass in the total willow biomass increased with increase in willow age but changes in the proportion of bark mass were small (Fig. 7). The proportion of leafless above-ground biomass increased with increase in age; at age one, it was 42 % and at age three it was 62 % at Piipsanneva 1 (NPK-fertilization). NPK-fertilization increased the proportion of harvestable (bark and wood) biomass by 9–19 % at stand ages of two and three years when compared to the control stands.

The proportions of stump and root biomass decreased with age and biomass production. At Piipsanneva 1 and at Paloneva, the proportions of stump and root biomass were 38–40 % and at Piipsanneva 2 as much as 50 % in the total biomass at the age of one year. At the age of three years, the proportions of root and stump biomass in the different experimental fields averaged 26–33 %.

Leaf biomass and leaf-area index were at their

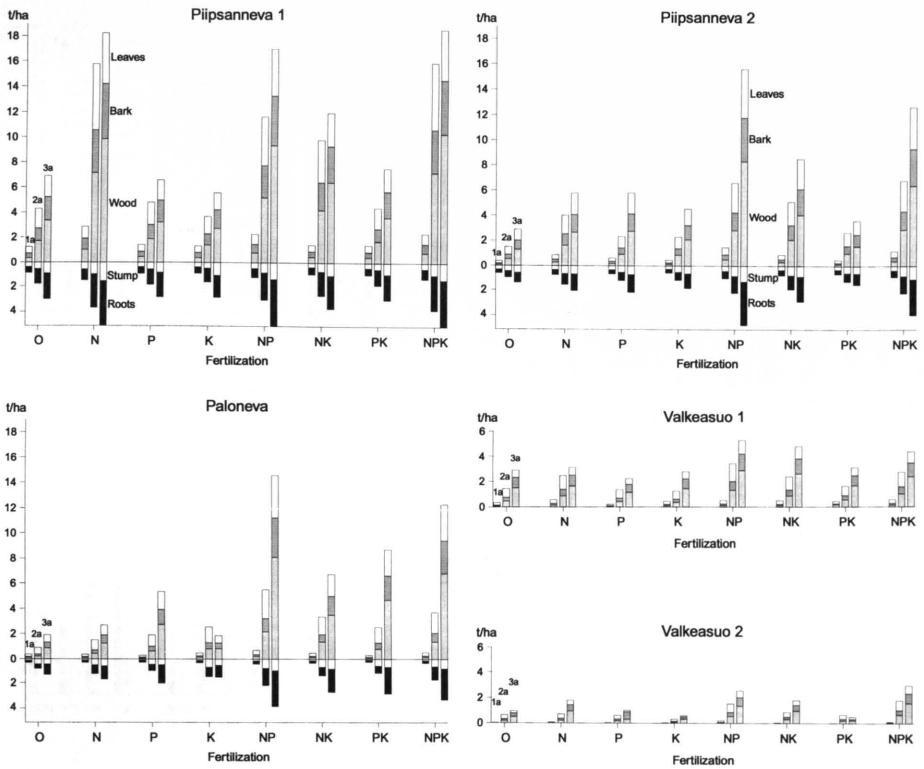


Fig. 5. Effect of fertilization on dry-mass production. Willow age one to three years (1a, 2a, 3a).

greatest during the second and third growing seasons. The proportion of foliage in the total biomass at the end of the second growing season was slightly higher than after the first growing season, but it then decreased again during the third growing season (Fig. 7). Nitrogen fertilization increased leaf-area index on all the experimental areas. In late August, the leaf-area indexes of one-and two-year-old, nitrogen-fertilized willows at Piipsanneva 1 was 1.7 m^2m^{-2} and 7.7 m^2m^{-2} respectively.

3.6 Amount of Nutrients Bound in Willow Stands

The amount of nutrients bound in the plantations in late August or early September was calculated on the basis of the nutrient concentrations of the different compartments and the corresponding dry-masses. Because root samples were not taken from each plot for nutrient analysis, this examination is confined to the nutrient amounts in the above-ground biomass (wood, bark, foliage).

Nitrogen fertilization especially increased biomass production and the amount of bound nitrogen (Fig. 8). During the third growing season, the amount of nutrients bound into the stands equalled, and even exceeded, the amount bound during the first two years. After the third growing season, the above-ground biomass at Piipsanneva 1 on the NPK-fertilized plots exhibited the following nutrient composition: 196 kg N ha^{-1}, 26 kg P ha^{-1}, 101 kg K ha^{-1}, 74 kg Ca

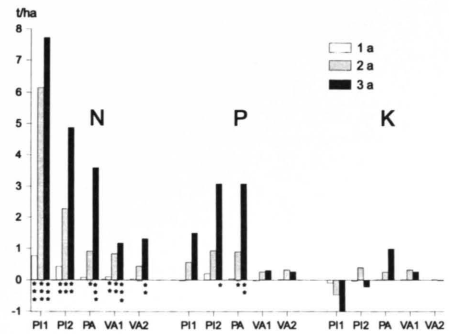


Fig. 6. Factorial main effects of nitrogen, phosphorus and potassium fertilizer application on the above-ground, leafless dry-mass yield. Statistical significance indicated by asterisks (* $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Willow age between one and three years (1a, 2a, 3a). For legend, see Fig. 1.

ha^{-1} and 37 kg Mg ha^{-1} in the ratio of 100:13:52:38:19. The corresponding ratio at Piipsanneva 2 was 100:12:55:39:15 and at Paloneva 100:14:50:43:18.

The following array presents the proportions of dry-mass and nutrients (%) in the wood, bark and foliage of three-year-old stands of willow treated with NPK fertilizer (Piipsanneva 1):

	Wood	Bark	Foliage
Dry mass	56	23	21
N	16	20	64
P	31	23	46
K	19	23	58
Ca	16	40	44
Mg	15	23	62

By far the highest proportion of the nutrients was bound into the foliage. The foliage accounted for 21 % of the above-ground biomass in a three-year-old stand of willow, but 44–64 % of all the nutrients in the above-ground biomass. The proportion of bark in the total biomass was 23 % and the proportions of most nutrients contained in the bark varied within the range of 20–23 %. Calcium was the exception; the bark contained 40 % of the total calcium. The proportion of wood in

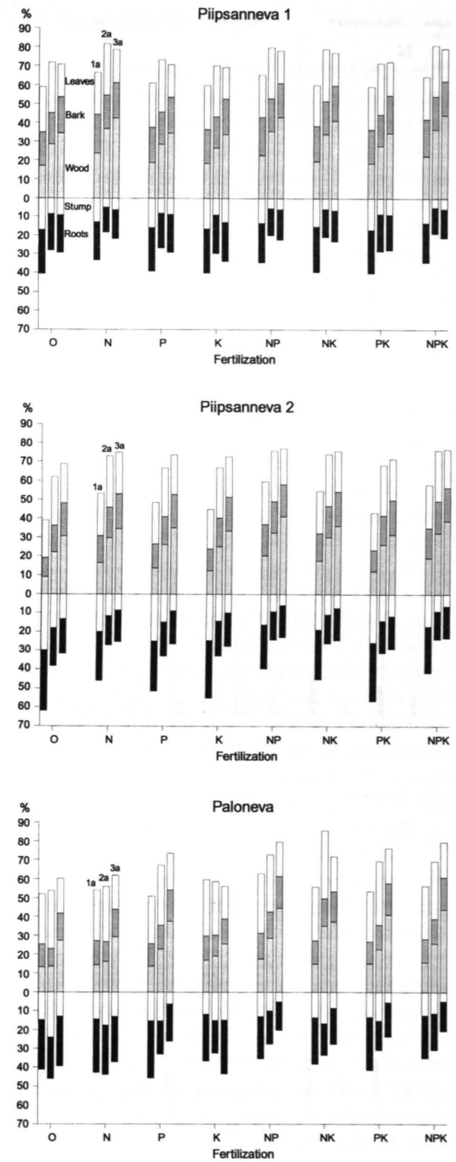
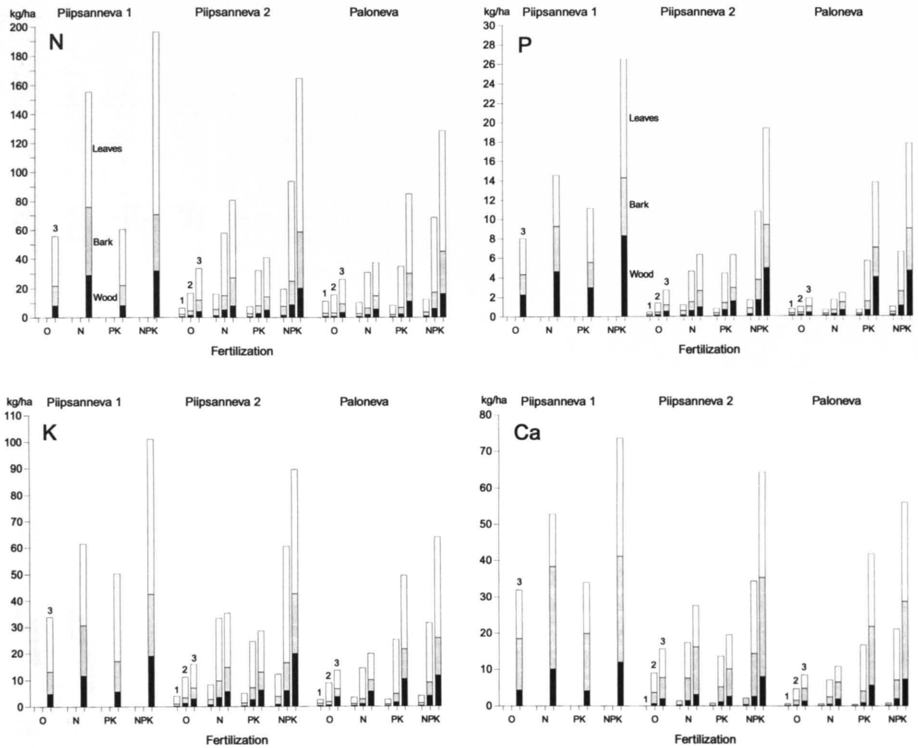


Fig. 7. Proportion of one- to three-year-old (1a, 2a, 3a), willow biomass compartments in the total dry-mass.



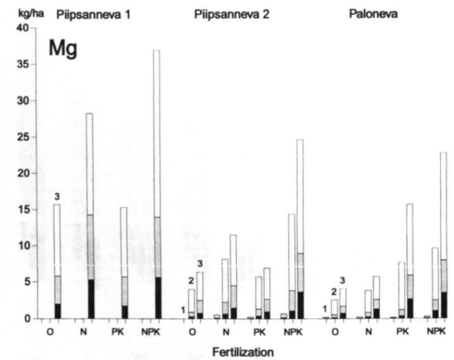


Fig. 8. Amount of nutrients bound into the above-ground willow biomass. Willow age between one and three years (1a, 2a, 3a).

Table 2. Amount of nutrients bound in one ton of above-ground biomass (foliage, wood and bark).

Experiment	Fertilizer treatment	Age,a	Nutrient, kgt^{-1} N	P	K	Ca	Mg
Piipsanneva 1	0	3	8.1	1.1	5.1	4.7	2.3
	N	3	11.3	1.0	4.4	3.3	2.0
	PK	3	8.1	1.5	6.8	4.5	2.0
	NPK	3	10.5	1.4	5.4	4.0	2.0
Piipsanneva 2	0	1	16.8	1.1	10.4		
		2	11.1	0.9	7.2	4.3	2.2
		3	11.6	0.9	5.5	5.4	2.2
	N	1	18.7	1.4	9.1		
		2	14.4	1.1	8.0	4.3	2.2
		3	13.7	1.1	5.9	4.8	2.0
	PK	1	15.2	1.6	10.2		
		2	11.9	1.7	9.2	5.2	2.2
		3	11.3	1.7	7.9	5.4	1.9
	NPK	1	15.8	1.3	9.8		
		2	13.8	1.6	8.9	5.1	2.1
		3	12.9	1.5	7.0	5.1	2.0
Paloneva	0	1	26.5	1.7	6.5		
		2	15.9	1.0	9.6	4.7	2.5
		3	13.7	0.9	7.1	4.5	1.4
	N	1	26.3	1.6	8.4		
		2	20.3	1.1	9.6	4.7	2.5
		3	14.9	0.9	7.9	4.3	2.2
	PK	1	25.1	2.0	8.4		
		2	13.4	2.1	9.6	6.5	2.9
		3	9.9	1.6	5.6	4.8	1.8
	NPK	1	22.9	1.8	7.3		
		2	18.3	1.8	8.4	5.6	2.6
		3	10.6	1.5	5.2	4.5	1.9

the biomass was 56 %, but the percentages of most nutrients contained in the wood varied between 15 % and 19 %. The percentage of phosphorus (31) was, however, clearly higher.

The amount of nitrogen and potassium bound in one dry-mass ton decreased while that of phosphorus changed only little with increase in willow age (Table 2). Nitrogen and phosphorus fertilizations increased the amounts of these nutrients bound in one dry-mass ton of willow.

4 Discussion

Although liming and application of ash increased the pH of the substrate, it was still below the optimum for *S. viminalis* root growth (Ericsson and Lindsjö 1981), but probably did not limit willow growth even at Valkeasuo, where the pH was at its lowest (Ferm and Hytönen 1988). The amounts of liming agents or ash should be quite high in order to increase the low soil pH of cut-away peatlands to 5.0–5.5 pH for the lifetime of the plantation throughout the soil cultivation and root zone. The peat layer in the experimental fields was so thick (over 30 cm), that willow roots most probably did not penetrate into the mineral soil (Ericsson 1984, Elowson and Rytter 1984).

Fertilization with phosphorus (superphosphate) and potassium (potassium salt) increased the amounts of the corresponding acid ammonium acetate extractable nutrients in the soil manyfold compared to control plots. However, even after three annual fertilizer applications, the peat's phosphorus and potassium concentrations were low at Paloneva in terms of the classification system for tilled soils in Finland (Kurki 1982). Only at the Valkeasuo experimental field, ameliorated with wood ash, the P and K concentrations were considered to be good. Fertilization with only nitrogen decreased the peat phosphorus and potassium concentrations (cf. Ferm and Hytönen 1988). This was probably due to the higher biomass production with increased phosphorus and potassium utilisation by willow.

Ash fertilization increased the amount of competing vegetation despite weed control. This disturbed willow growth and was probably the cause of low survival (52 %). The high survival (70–90 %) on the control plots in the other fields was probably due to both reinforcement planting and basic fertilizer treatment since the reported mortalities on unfertilized cut-away peatlands has been very high (Hytönen 1986, 1987, Valk 1986). The fall in survival due to nitrogen fertilizer may be associated with the increased risk of late-autumn frost damage and increased susceptibility to winter damage due to poor winter hardening (von Fircks 1992) and also to increased competition from weeds.

Nitrogen fertilization, even when the nitrogen content of the peat is high, seems to be necessary for the good growth of willow. This has also been observed in previous field and greenhouse experiments (Hytönen 1986, 1987, Berguson et al. 1983, Kaunisto 1983, Ferm and Hytönen 1988). Yield increase induced by nitrogen fertilization was high and only at the nitrogen-rich site was the effect of nitrogen fertilization less than that of phosphorus fertilization. The mineralization of the nitrogen in peat can be promoted by soil amelioration agents (Karsisto 1979). However, contrary to Scots pine (Kaunisto 1987), mineralization alone probably is not enough to secure the nitrogen supply of willow, even in the long run.

The effect of phosphorus fertilization on biomass production was observed to depend on the amount of soluble phosphorus in the soil. This has earlier been demonstrated in a greenhouse experiment (Ferm and Hytönen 1988). On the site with the lowest concentration of soil phosphorus and highest nitrogen concentration, phosphorus fertilization was observed to result in the maximum increase in biomass production. While potassium fertilization did increase potassium concentrations in both the peat and the foliage, it did not increase the stand yield. To some extent, this may be due to basic potassium fertilization on the experimental fields and mixing of the mineral soil with the top layer in some of the fields. Potassium fertilization has not increased the growth of neither willow nor birch in greenhouse experiments established on peat substrates using peat from cut-away peatlands (Ferm and Hytönen 1988). This result is supported by experiences in Estonia on the effect of potassium fertilization on cut-away peatlands (Valk 1986).

The leafless above-ground mass of NPK-fertilized, one-year-old willow was low. One-year-old stands had not developed fully closed canopies because of their low leaf-area index. The annual biomass production during the third growing season was always manyfold that of the first, and in most cases higher than during the second season (cf. Hytönen 1987, 1988). Earlier, three-year-old willow established on a cut-away peatland in southern Finland has been reported to have produced yields equivalent to, and on mineral soils yields higher than, the NPK-fertilized willow in this study (Hytönen 1987, 1988).

The considerable site-to-site variation in yield was not primarily due to nutritional aspects; rather, it was caused by differences in the tending of the stands (e.g. weeding), climate, spring frosts, clones, and especially by differences in stand density (number of stems per hectare). *S.* × *dasyclados*, which grew best in this study, is more winter-hardy than *S.* 'Aquatica' (Lumme et al. 1984, Lumme and Törmälä 1987). Willow species from Central Europe (Pohjonen 1984) continue to grow late in the autumn, and consequently late-autumn frosts can cause damage due to poor winter-hardening (von Fircks 1992). Early summer frosts, common to all the experimental fields, damaged willow and decreased biomass production.

With increase in willow age from one to three years, the proportion of harvestable (wood and bark) biomass in the total biomass produced increased by 20 %. Besides increasing total production, fertilization also considerably increased the proportion of wood and bark mass in the total dry-mass. Especially the nutrient concentrations of bark and wood changed with increase in willow age, so that the older willows tended to have lower nutrient concentrations. Especially nitrogen, phosphorus and potassium concentrations in the one-year old willow bark were high. Wood phosphorus and potassium concentrations changed only little with increase in age.

Willow responds readily to fertilization. In most cases, nitrogen and phosphorus treatments, in addition to increasing the corresponding foliar nutrient concentrations from the first growing season on, also increased the concentrations in the bark and wood (see also Hytönen 1986), but only from the second growing season on. Phosphorus fertilization especially enhanced the phosphorus levels in the wood, but not so much in the bark. Potassium fertilization increased only the concentrations of foliar potassium.

The foliar nutrient concentrations in fertilized stands of willow were considerably higher than in stands of silver or downy birch (Mälkönen 1977, Finér 1989). Nitrogen and phosphorus concentrations in the bark of willow were two to three times higher, and that of potassium was also higher, than in birch. Although the nutrient concentrations of willow wood decreased with increase in age, the nutrient concentrations at the age of three years were manyfold when compared to birch. The concentrations of nitrogen in grey alder were, in all the compartments, higher and those of foliar phosphorus and potassium lower than those previously reported for the willow species included in this study (Saarsalmi et al. 1985, 1991). Calcium concentrations, and especially magnesium concentrations, in the bark of willow were higher than in grey alder (Saarsalmi et al. 1985, 1991). However, the calcium concentrations in spruce bark are even higher than in willow (Finér 1989).

With increase in willow age from one to two or three years, the amount of nitrogen bound in one metric ton of biomass decreased at Paloneva by 60 % and at Piipsanneva by 13–30 %. In a stand of *S. viminalis* this decrease has been reported to have been 42 % in Sweden (Nilsson and Ericsson 1986). This was mostly caused by a decrease in the nitrogen concentrations of the wood, and also of bark, with increase in age, and, moreover, decrease in the proportions of the biomass components (especially of foliage) containing a lot of nutrients, especially nitrogen. Somewhat less nitrogen was bound per mass unit into the high yielding stands studied by Ferm (1985), at ages of two and three years, than was the case with the willow species in this study. Contrary to the behaviour of nitrogen and potassium, the amount of phosphorus bound in one metric ton of willow biomass did not decrease with increase in age or yield because of the high phosphorus concentration of the willow wood. The amount of phosphorus, potassium and calcium bound into one metric ton of above-ground willow biomass was at the same level as in earlier investigations (Saarsalmi 1984, Ferm 1985, Hytönen 1986). Saarsalmi (1984), however, reported higher amounts of potassium bound per biomass unit.

Compared with the amounts of nutrients given in the fertilization, stands at the age of three years contained far less phosphorus and potassium. Only in the fastest growing *S.* × *dasyclados* stands was the amount of nitrogen in the biomass of the same order as given in fertilization, if the nitrogen bound into the foliage during three years is also considered. At the age of three years the difference in the amount of nitrogen bound in above-ground wood and bark of control and NPK-fertilized plots represented at Piipsanneva 16 % and at Paloneva 12 % of the nitrogen given in fertilization. The recovery was similar than reported from other studies of tree plantations (Paavilainen 1979, Ballard 1984, Miegroet et al. 1994). In the lycimeter experiment of Saarsalmi (1984) the amount of N and K leached from the soil (limed Sphagnum peat) was only 0.5–0.6 % of the amounts added in fertilization and the plants received more nutrients from the rainfall than was lost in leaching.

The two- to three-year-old stands of willow of this study contained nitrogen, phosphorus and potassium in amounts equal to, or even exceeding, that of an advanced stand of 40-year-old birch (Mälkönen 1977). Stands of grey alder (with above-ground biomasses of 24–32 t ha^{-1}) have been found to bind more nitrogen, but equal amounts or less phosphorus, potassium, calcium and magnesium in their biomass than the willow stand (18 t ha^{-1}) examined in this study (Saarsalmi et al. 1985, 1991). In late August–early September, the foliage contained 44–64 % of the nutrients bound in the above-ground biomass of a three-year-old willow stand, but only one fifth of the biomass. The internal nutrient cycling in many tree species is high and its significance often becomes enhanced following canopy closure. The growth of willow in this study ceased with the first autumn frosts; the foliage is shed green, and thus the amount of translocated nutrients is probably quite low. Thus, the nutrient concentration of the litter is high, it easily decomposes, and potassium especially, but also nitrogen and phosphorus, are released quickly (Slapokas and Granhall 1991). This may promote the availability of nutrients.

Soil analysis has rarely proved to be a good indicator when determining the fertilizer needs of forest soils (Miller 1983). According to the results of this study, extractable phosphorus can provide guidelines for the need of phosphorus fertilizer in short-rotation willow plantations on cut-away peatlands. On most cut-away peatlands, it is probable that both nitrogen and phosphorus fertilization are needed. More knowledge is needed regarding potassium. Although there are differences between the willow species in their nutritional demands, these results most probably give a good picture of the significance of fertilizer application in short-rotation cultivation on cut-over peatlands.

Acknowledgements

The establishment of the field experiments and their measurement were attended to by Esa Heino, Kaarlo Sirviö and Seppo Vihanta. Numerous people have participated in the field work during the establishment, tending, fertilizer application and measurement stages. The nutrient analyses in the laboratory of the Kannus Research Station were done by Kaisa Jaakola, Riitta Miettinen and Arja Sarpola. Seppo Vihanta and Arto Ketola helped conduct statistical analyses and Keijo Polet helped with the figures. The English language of this report was revised by Erkki Pekkinen. The manuscript has been read and commented upon by Risto Lauhanen, Pekka Rossi and Anna Saarsalmi. My warmest thanks to all who contributed to the completion of this study.

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