Effect of Repeated Fertilizer Application on the Nutrient Status and Biomass Production of *Salix* 'Aquatica' Plantations on Cut-Away Peatland Areas

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The effects of repeated fertilizer treatment on biomass production and nutrient status of willow (*Salix* 'Aquatica') plantations established on two cut-away peatland areas in western Finland were studied over a rotation period of three years. Comparisons were made between single fertilizer applications and repeated annual fertilization.

The annually repeated fertilizer application increased the amounts of acid ammonium acetate extractable phosphorus and potassium in the soil as well as the concentrations of foliar nitrogen, phosphorus and potassium compared to single application. Depending on the fertilizer treatment and application rate, annual fertilizer application resulted in over two times higher biomass production when compared to single fertilizer application over a three-year rotation period. The effect of phosphorus fertilizer application lasted longer than that of nitrogen. The optimum fertilization regime for biomass production requires that nitrogen fertilizer should be applied annually, but the effect of phosphorus can last at least over a rotation of three years. Potassium fertilizer treatment did not increase the yield in any of the experiments during the first three years. The leafless, above-ground yield of three-year-old, annually NP-fertilized willow plantations was 9.5 t ha^{-1} and the total biomass, including stems, leaves, roots and the stump, averaged 17 t ha^{-1}.

Keywords biomass production, fertilization, peatlands, *Salix*, fuelwood.
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1 Introduction

Short-rotation forestry management practises are under development in many countries (Coombs et al. 1990, Ledin and Alriksson 1992, Mitchell et al. 1992). Woody biomass plantations are genetically improved, intensively cultivated, closely spaced, and consist mainly of broad-leaved species, which can be repeatedly harvested (coppiced) using short cutting cycles.

Mainly exotic *Salix* species have been used in the short-rotation experiments conducted in Finland. Cut-away peatland areas have been suggested as being suitable for intensive short-rotation cultivation. The thickness of the remaining peat layer on cut-away peatland areas varies, and it is usually well humified (Kaunisto 1986). Its total nitrogen concentration is usually quite high. The phosphorus and potassium concentrations in the peat layer are often very low. The considerably low soil pH on cut-away peatland areas (Kaunisto 1986) should be increased to 5.0–5.5 by liming or ash application (Ericsson and Lindsjö 1991, Ferm and Hytönen 1988).

Short cutting cycles entail the removal of large quantities of nutrients. Small-sized trees contain high amounts of nutrient-rich bark and sapwood (Kaunisto 1983, Saarsalmi 1984, Ferm 1985, Hytönen 1986). If foliage, too, is harvested, nutrient removal is considerably increased. This has led to concern over the maintenance of nutrient supplies.

Fertilizer application has significantly increased the survival and yield of short-rotation willow plantations on cut-away peatland areas (Hytönen 1982, 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988, Lumme 1989). There are indications that fertilization requirements of different peat extraction sites may vary (Ferm and Hytönen 1988). The experiments conducted show that nitrogen is the key element, even in nitrogen-rich areas, in increasing yield (Hytönen 1982, 1985, 1986, Kaunisto 1983, Ferm and Hytönen 1988). In peatland forests, refertilization is recommended only after ten years have passed from the first fertilizer application (Paavilainen 1979, Jukka 1988). Spreading fertilizer in dense short-rotation plantations is technically difficult and each unnecessary management operation reduces the cost effectiveness of biomass production systems. So far, however, no results are available on whether, from the biomass production point of view, plantations should be fertilized annually, or whether fertilization could be restricted to a single application at the beginning of the rotation. We do not know whether higher fertilizer doses could compensate for renewed application using smaller amounts. In experiments conducted in Sweden, fertilization was carried out during the growing season with weekly (ideally daily) additions of complete, liquid fertilizer by means of an irrigation system (Ingestad and Ågren 1984, Christersson 1986).

The aim of this investigation was to study the effects of repeated fertilizer application on biomass production and foliar nutrient concentration of willow and the effects of fertilization on the nutrient concentrations of soil.

2 Material and Methods

Willow plantations were established on cut-away peatland areas at Haapavesi Piipsanneva (64°06'N, 25°36'E) and Ruukki Paloneva (64°27'N, 25°26'E). The experimental areas were limed (6000 kg ha^{-1} dolomite lime) prior to planting, and fertilized with PK-fertilizer for peatlands (P 44 kg ha^{-1}, K 83 kg ha^{-1}) and ammonium nitrate with lime (N 50 kg ha^{-1}) after planting. Willow (*Salix* 'Aquatica', clone V769) was planted on a density of 40 000 cuttings (20 cm long) per hectare in late May–early June 1983, and the one-year old sprouts were cut back in the autumn of 1983. Supplementary planting was done later in the season in 1983, and during the following year. The fertilization experiments were established in the spring of 1984. The experimental areas were fenced and manual and mechanical weeding was done. The experimental period was three years.

The fertilization treatments consisted of NPK-fertilization at two levels (N = N 100 kg ha^{-1}, N_2 = N 200 kg ha^{-1}, P = P 30 kg ha^{-1}, P_2 = P 60 kg ha^{-1}, K = K 40 kg ha^{-1}, K_2 = K 80 kg ha^{-1}) using combinations of PK, NP, NK and NPK and N_2PK, NP_2K, NPK_2. One fertilization treatment, applied in 1984, was used as the reference and compared with repeated fertilizations applied in 1984, 1985 and 1986. Thus, the total number of treatments was fourteen. The fertilizers used were ammonium nitrate with lime, superphosphate, and potassium salt. The experimental plots were 56–80 m^2 in size. The experimental design consisted of randomized blocks with three replications.

Willow height and the base diameter on the experimental plots were measured after each growing season using systematic sampling. At Piipsanneva, the number of measured sprouts varied between 6169 (in 1984) and 10 945 (in 1986), while at Paloneva the corresponding figures were 4017 and 3737. The number of living and dead stools was also recorded. Annually, 26–56 sample trees were cut down in each experiment generally at the end of August. The diameter and height of the sprouts were measured and their foliage, bark and wood were separated and dried to constant weight. The dry-mass equations, of the form $Y = aX^b$, were calculated for foliage, bark and wood mass. The independent variable in the equations was the product of diameter squared multiplied by height (d_2h). Diameter alone would have been almost equally as good as an independent variable. The coefficient of determination of the wood and bark equations was high (91–99 %) and the coefficient of variation (11–26 %) of the same order as in earlier studies (Hytönen 1985, 1986, 1987, 1988, Hytönen et al. 1987). The coefficient of determination of the foliage's dry-mass equations were lower (78–96 %) while the coefficients of variation were higher (18–33 %).

Twelve to twenty stools (including stems and roots) were dug up annually from the experi-

Table 1. Dry-mass equations for root mass. The equations have the form Y = a + bX, where Y = root mass of one stool (g), a and b = constants ja X = dry-mass of the sprouts of one stool (g).

Experiment	Age of sprouts, years	a	b	r^2	s
Piipsanneva	1	6.33304	0.34555	96.5	3.57
	2	7.46486	0.23113	90.9	8.95
	3	4.83201	0.28280	85.3	26.58
Paloneva	1	3.32209	0.43416	96.7	1.70
	2	3.40780	0.36406	91.5	12.51
	3	23.8268	0.20847	83.1	17.40

Table 2. Dry-mass equations for stump mass. The equations have the form $Y = a + bX_1 + cX_2$, where Y = stump mass of one stool (g), a, b and c = constants, X_1 = mass of sprouts in one stool (g) and X_2 = number of sprouts per stool.

Experiment	Age of sprouts, years	a	b	c	r^2	s
Piipsanneva	1	0.71100	0.14597	0.97987	96.0	1.98
	2	2.03299	0.09198	1.01715	92.7	3.37
	3	10.6375	0.07350	-	84.1	5.52
Paloneva	1	0.29186	0.28063	0.42055	97.3	1.20
	2	0.37064	0.08948	1.90248	98.8	1.39
	3	0.64473	0.05939	2.80102	88.6	4.37

mental plots, and their sprouts, stumps (ground level to 10 cm height) and roots were separated and their dry-masses were determined after drying the material to constant weight at 105 °C. Linear dry-mass equations for the stump and root mass were calculated using the dry-mass of all sprouts on a stool as the independent variable for root mass and also the number of sprouts per stool for the stump mass (Tables 1 and 2). The number of living stools in each plot was used when converting the calculated masses to area basis.

Leaves from at least five randomly selected, uneven-sized sprouts were taken from each plot in late August or early September in 1984–1986 for nutrient analysis. Foliar N, P and K concentrations were determined from the 1984 samples, while the 1985 and 1986 samples were also examined for their foliar concentrations of Ca, Mg, Fe, Mn, Zn, and Cu (Halonen et al. 1983).

Soil samples (composed of five subsamples) were taken in August 1986 from the 0–10 cm top soil layer on the study plots. The samples were analyzed for their pH, acid ammonium acetate (pH 4.65) extractable phosphorus, potassium, calcium, and magnesium (mg l^{-1}, volume determined in laboratory). The total nitrogen concentration (Kjeldahl), analyzed from randomly selected samples (33), in the organic matter at Paloneva was 3.2 % and at Piipsanneva 2.3 %.

The effects of repetition of fertilization, fertilization treatments and their interactions on the measured parameters was studied with analysis of variance. The treatment means were compared with Tukey's multiple range test.

3 Results

3.1 Soil Characteristics

The average pH at Piipsanneva was 5.7 and at Paloneva 5.2. The annual fertilizer treatment reduced the soil's pH compared with the single fertilizer application. On plots fertilized three times, the pH at Piipsanneva was 0.3 pH-units ($p < 0.001$) and at Paloneva 0.2 pH-units ($p < 0.05$) lower than on plots fertilized only once.

In both experimental areas, the annual fertilizer application significantly increased the soil's acid ammonium acetate extractable phosphorus concentrations compared to single fertilization (Fig. 1). At Piipsanneva, the peat's phosphorus concentration in the plots fertilized three times with phosphorus was 2.5 and at Paloneva 3.5 times as high as in the plots fertilized only once. The phosphorus concentration in the soil was higher on the plots fertilized with phosphorus than on the plots fertilized with NK. Similarly, a doubled phosphorus fertilizer dose (P 60 kg ha^{-1}) increased the soil's phosphorus concentration more than a smaller dose (P 30 kg ha^{-1}) did. The effects of high single application amounts of phosphorus fertilizer (P 60 kg ha^{-1}) manifested themselves in the soil analysis results even after three growing seasons. The effect of the corresponding (P 60 kg ha^{-1} a^{-1}) fertilizer application, repeated annually, was greater. Increasing the nitrogen fertilization amount from 100 kg N ha^{-1} a^{-1} to 200 kg N ha^{-1} a^{-1} decreased the soil's extractable phosphorus concentrations, most probably due to increased utilisation of phosphorus by willow.

The annual fertilizer application significantly increased the soil's ammonium acetate extractable potassium concentration compared to the single fertilization; at Piipsanneva, on average, by 10 mg l^{-1} and at Paloneva by 16 mg l^{-1} (Fig. 1). The peat's potassium concentration at Paloneva was lower than at Piipsanneva. The effect of high single application amounts of potassium fertilizer (K 80 kg ha^{-1}) did not manifest itself in the soil after three growing seasons.

The repeated fertilizer application did not affect the soil's extractable calcium and magnesium concentrations. At Piipsanneva, the peat's calcium concentration averaged 1379 mg l^{-1} (s 135 mg l^{-1}) and at Paloneva far less, only 648 mg l^{-1} (s 104 mg l^{-1}). Similar site-to-site differences were also observed in regard to the soil's magnesium concentrations (Piipsanneva 459 mg l^{-1}, Paloneva 188 mg l^{-1}).

3.2 Foliar Nutrient Concentrations

Compared to the single application, the annual fertilizer application significantly increased the

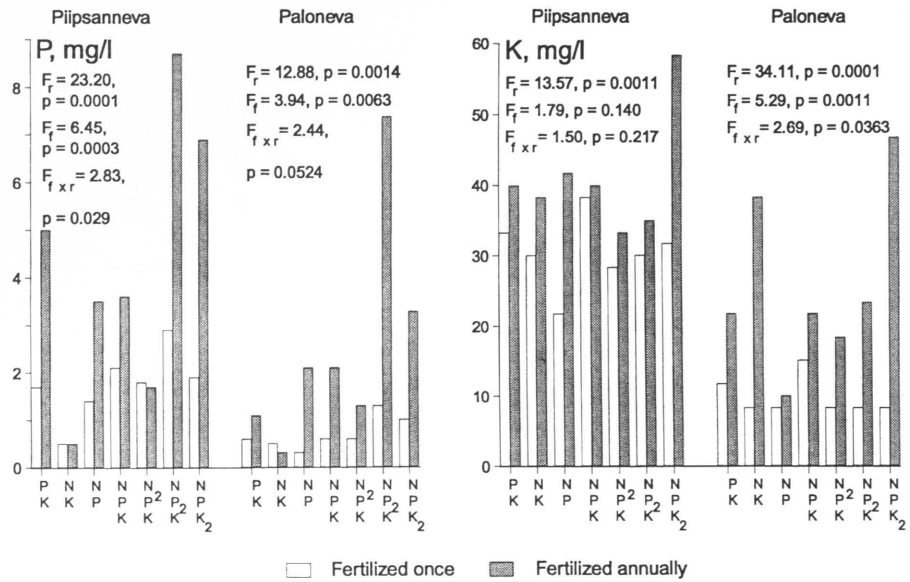

Fig. 1. Effect of fertilization on the concentrations of ammonium acetate extractable phosphorus and potassium in the soil. N = 100 kg N ha^{-1}, P = 30 kg P ha^{-1}, K = 40 kg K ha^{-1}, N_2 = 200 kg N ha^{-1}, P_2 = 60 kg P ha^{-1}, K_2 = 80 kg K ha^{-1}. Statistical significance (F and p values) of repetition of fertilization (F_r), fertilizer treatment (F_f) and their interaction (F_{rxf}) are shown in the figure.

foliar nitrogen, phosphorus and potassium concentrations of two- and three-year-old willow in both experimental areas (Table 3). The effect of the fertilizer treatment on the foliar nutrient concentrations was also significant in both experimental areas. The second and third growing season's foliar nitrogen concentrations of willow fertilized with 200 kg N ha^{-1} of 100 kg N ha^{-1}, given as single application, did not differ. On the other hand, annual applications of 200 kg N ha^{-1} increased the foliar nitrogen concentration compared to the effect of an annual application of 100 kg N ha^{-1}.

The foliar phosphorus and potassium concentrations were lowest when the corresponding nutrient was not applied at all, or when the nitrogen fertilizer amount was high. Thus, at Paloneva, NK-fertilizer application increased foliar nitrogen concentrations, especially during the third growing season, while the concentration of foliar phosphorus decreased. The effects of the single application with high potassium amounts manifested themselves even during the third growing season as increased foliar potassium concentrations in both experimental areas. In the case of the phosphorus fertilizer application, a corresponding increase was significant only at Paloneva. The foliar phosphorus and potassium concentrations were also high when no nitrogen was applied.

Compared to the single application, the annual fertilization at Piipsanneva decreased significantly the third growing season's concentrations of foliar calcium from 9 to 8 mg g^{-1}, magnesium from 4.7 to 4.3 mg g^{-1}, manganese from 710–742 to 550–602 mg kg^{-1}, and zinc from 115 to 92 mg kg^{-1}. At Paloneva, the annual fertilizer treatment decreased significantly the third growing season's concentration of foliar zinc from 298 to 227 mg kg^{-1}. The foliar zinc concentrations at Paloneva were two times higher than at

Table 3. Effect of fertilization on the foliar concentrations of nitrogen, phosphorus and potassium during the second and third growing seasons.

Nutrient	Age, years	No. of fertilizations	PK	NK	NP	NPK	N_2PK	NP_2K	NPK_2	$F_{fert.}$[1)]	F_{repeat}	F_{fxr}
			Fertilization treatment									
Piipsanneva												
N, mg g^{-1}	2	1	21.7	21.3	21.7	22.1	19.8	18.4	20.1	2.69*	67.24***	3.11*
		2	22.7	31.3	29.2	28.5	35.2	26.8	25.7			
	3	1	27.0	26.1	26.1	25.8	23.6	25.8	24.1	2.84*	42.14***	5.10**
		3	24.2	34.4	30.2	31.7	42.2	34.6	30.0			
P, mg g^{-1}	2	1	2.4	1.8	2.4	2.4	2.0	2.3	2.3	5.24**	35.17***	1.40
		2	3.0	2.1	2.8	3.0	2.7	3.3	2.5			
	3	1	2.7	2.3	2.4	2.4	2.2	2.5	2.4	3.98**	36.80***	2.70*
		3	3.0	2.3	2.7	3.0	3.2	3.4	2.6			
K, mg g^{-1}	2	1	16.0	14.6	13.1	14.2	14.1	14.7	17.4	2.96*	24.09***	1.25
		2	16.6	18.5	16.0	18.6	16.1	16.5	18.3			
	3	1	14.7	13.1	10.3	11.9	10.7	12.6	13.5	1.24	7.02*	0.47
		3	14.3	15.3	12.9	13.9	14.1	14.9	14.4			
Paloneva												
N, mg g^{-1}	2	1	22.2	27.9	21.1	2.59	27.6	22.9	23.5	6.60***	50.62***	3.93**
		2	21.4	29.4	30.3	3.12	33.8	33.9	33.7			
	3	1	24.5	26.7	20.6	22.2	2.27	25.9	23.1	1.79	15.79***	0.62
		3	26.6	34.8	24.7	29.5	3.25	28.5	28.0			
P, mg g^{-1}	2	1	1.8	1.2	1.5	2.0	1.9	2.3	1.8	8.92***	33.59***	1.56
		2	3.1	1.3	2.3	2.5	2.4	2.8	2.6			
	3	1	1.9	1.2	1.7	1.7	1.8	2.5	1.9	13.93***	2.62***	4.02**
		3	3.3	1.4	2.1	3.2	2.7	2.8	2.5			
K, mg g^{-1}	2	1	13.0	14.3	7.5	14.2	14.2	9.4	14.5	36.76***	19.13***	3.60**
		2	15.6	16.3	7.2	13.7	14.7	14.0	16.5			
	3	1	10.1	12.7	7.8	8.8	9.4	9.6	12.3	18.70***	27.10***	4.80**
		3	13.2	16.0	4.4	13.4	12.8	11.1	18.3			

1) Statistical significance of F-values indicated by asterisks; * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

Piipsanneva. The differences between the sites in their concentrations of foliar calcium, magnesium and manganese were small.

3.3 Biomass Production

The biomass production of willow fertilized two and three times was significantly ($p < 0.001$) higher compared with the biomass production resulting from single application (Fig. 2). The differences were statistically significant in regard to all the biomass components measured. The biomass production of willow fertilized twice with nitrogen and phosphorus was 2.0 times as high as that resulting from the single fertilizer treatment; in the case of willow fertilized three times, the corresponding factor was 2.2.

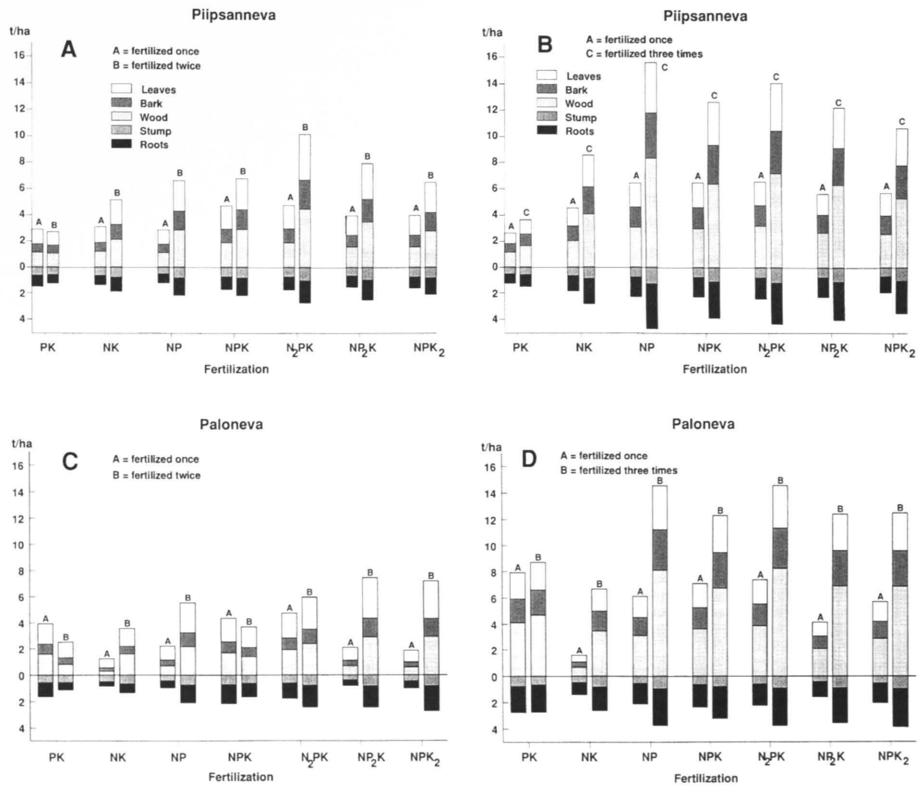

Fig. 2. Effect of fertilization on the biomass production of willow. The willow shown in A and C is two years, and in B and D three years old. For nutrient amounts applied, see Fig. 1.

According to the results of analysis of variance, the fertilization treatments also affected biomass production significantly (Piipsanneva: $p < 0.001$, Paloneva: second year $p < 0.05$, and third year $p < 0.001$). Best growth was recorded for willow fertilized with nitrogen and phosphorus. Repeated PK-fertilizer treatment did not increase the yield when compared to the effect of single application. However, at Paloneva, PK-fertilized willow grew much better than at Piipsanneva and the effect of adding nitrogen was lower than at Piipsanneva. Thus, the significance of phosphorus fertilizer application was higher at the nitrogen-rich Paloneva site than at Piipsanneva. At Paloneva, PK-fertilized willows grew better than NK-fertilized willows; at Piipsanneva, vice versa. At Paloneva, the single NPK fertilization treatment did not increase willow yield compared to PK fertilization. At both experimental areas, doubled doses of nitrogen, phosphorus or potassium in NPK fertilization, given as a single application, did not increase the yield when compared to lower single application rates.

Biomass production during the first growing season was low. The second growing season's leafless above-ground biomass of willow fertilized annually with nitrogen and phosphorus was 5.0 t ha^{-1} at Piipsanneva and 3.5 t ha^{-1} at Paloneva. After three growing seasons, the leafless, above-ground biomass at Piipsanneva was 9.7 t ha^{-1} and at Paloneva 9.5 t ha^{-1}, and at both sites 1.8 times higher when the roots and stump were included.

4 Discussion

The imbalance in nutrient ratios typical of cut-away peatlands – high concentrations of peat nitrogen and low concentrations of phosphorus, potassium and calcium – was at its most extreme at Paloneva. The phosphorus and potassium fertilizer treatments increased the concentrations of acid ammonium acetate extractable phosphorus and potassium in the soil the more of the corresponding nutrient was applied. Since the single fertilization treatment using superphosphate at the beginning of the experiment increased the concentration of the soil's extractable phosphorus over the entire three-year rotation period, so-called storage fertilization with phosphorus for a rotation period of at least three years seems possible. However, whether this can be done with rock phosphate or apatite is open to question since they have failed to increase the concentration of extractable phosphorus in limed peat soils (Salonen 1986, Kaunisto 1983, Hytönen 1986). For the growth of willow to be good, cut-away peatlands have to be limed (Ericsson and Lindsjö 1981, Ferm and Hytönen 1988). An increase in the amount of nitrogen fertilizer led to a decrease in the concentration of the soil's extractable phosphorus probably due to increased consumption by willows.

The nitrogen, phosphorus and potassium fertilizer treatments increased the corresponding foliar nutrient concentrations; this has been observed in many previous studies (Kaunisto 1983, Hytönen 1987, Ferm and Hytönen 1988). The annual fertilizer treatment increased the second and third growing season foliar nitrogen, phosphorus and potassium concentrations when compared to the single application. Partly this is due to higher fertilizer rates. After two growing seasons, it was possible to compare similar fertilizer amounts given either annually or in single fertilization. In every case, the foliar concentrations of N, P and K of the annually fertilized willows were higher than the corresponding concentrations of willows fertilized only once. However, high single fertilizer amounts of phosphorus and potassium (storage fertilizer) were observed to increase the foliar nutrient concentrations even after two and three years from the fertilizer treatment. Only when the nitrogen fertilizer treatment was repeated annually did the foliar nitrogen concentrations remain at high levels. The reaction to higher nitrogen fertilizer amounts (N 200 kg ha^{-1}) given as single applications did not correspond to that of lower (N 100 kg ha^{-1} a^{-1}) annual nitrogen fertilizer doses.

The leafless, above-ground yield of three-year-old willow in this study (9.5 t ha^{-1}) was less than has been reported previously for three-year-old *S. viminalis* on cut-away peatland sites in southern Finland and much less than the biomass production of *S.* 'Aquatica' on a mineral soil field or on a landfill site in southern Finland (Ferm 1985, Hytönen 1987, 1988).

Earlier investigations have shown that although PK fertilization significantly increases the biomass production of willow, the effect of also adding nitrogen is high even on nitrogen-rich cut-away peatland areas (Hytönen 1982, 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988). The biggest difference between the two experimental areas in terms of their response to fertilizer treatment was that willow growth, following PK-fertilizer treatment, at Paloneva was higher than at Piipsanneva. This was probably due to the fact that the peat's nitrogen concentration at Paloneva was high while the concentrations of phosphorus and potassium were very low. The high concentration of nitrogen in the peat at Paloneva was also reflected in the fact that, at the end of three growing seasons, there were no differences in yields between single PK and NPK fertilization treatments. However, at Piipsanneva, with its lower total nitrogen concentrations, even the single application of NPK yielded more biomass than PK fertilization.

In this study, the repetition of PK fertilization did not increase the yield of willow. However, when maximizing the yield, it is extremely important to apply nitrogen fertilizer annually. The importance of annual nitrogen fertilizer application was underscored by the observation that the growth reaction induced by a single application of nitrogen, amounting to 200 kg ha^{-1}, did not correspond to that induced by an annual fertilizer application of 100 kg ha^{-1} of nitrogen. Compared with the amounts given in fertilization, S. 'Aquatica' in this study probably bound considerably small amounts of nitrogen, phosphorus and potassium in its biomass (Saarsalmi 1984, Ferm 1985, Hytönen 1986). Especially during the the first study year fertilization with lower nitrogen fertilizer amounts should most probably have been appropriate. Part of the nitrogen could have been leached and part may have been bound to the organic matter in soil. Nitrogen fertilization amounts similar to those used in this study have increased the growth of pine on drained peatlands for five to eight years (Paavilainen 1972, Moilanen and Issakainen 1990).

Ideally, small amounts of nutrients, applied in the correct proportions, should be made available to the plants daily in order that maximum growth might be maintained (Ingestad and Ågren 1984, Christersson 1986, 1987). Production physiology studies conducted in Sweden are based on Ingestad's nutrient status studies and theories (Ingestad 1987). Accordingly, nutrients are added repeatedly in appropriate proportions in small amounts so that the rate of growth is regulated by the nutrient flux, the amount of nutrients per unit of time available for plant uptake, and not by the concentration of nutrients around the roots (Ingestad 1987). Swedish guidelines for practical short-rotation forestry recommend that fertilizers should be applied twice during the growing season (Sennerby-Forsse and Johansson 1989). According to these results, nitrogen fertilizer application should be repeated annually. However, in the case of phosphorus and potassium it seems that it could be possible to apply, at the beginning of the rotation, bigger doses of fertilizer to last at least three years.

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