

# Biomass production and nutrition of short-rotation plantations

**Jyrki Hytönen**

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# BIOMASS PRODUCTION AND NUTRITION OF SHORT-ROTATION PLANTATIONS

**Jyrki Hytönen**

ACADEMIC DISSERTATION

To be presented with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in Auditorium II of Metsätalo, Unioninkatu 40 B, Helsinki, on February 23th 1996, at 12 o'clock noon.

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The concept of short-rotation management comprises the establishment of stands of closely-spaced, fast-growing trees and the application of intensive cultivation practices and repeated harvesting, using short cutting cycles and regeneration of subsequent crops via sprouts. Short-rotation plantations established on cut-away peatland areas and abandoned mineral soil agricultural land were studied. The tree species included in the study were mainly exotic willows. The amount of biomass produced and different methods of biomass estimation were compared. Factors affecting the regeneration of the plantations were studied. The development of stand structure in the course of intense competition was followed during a period of ten years. Special attention was focused on nutritional matters, the effects of fertilizer application on biomass production and the amount of nutrients bound in the biomass.

Regression estimation using easily measured dimensional variables proved to accurately describe willow wood, bark and leaf mass as well as leaf area. Due to the non-destructive nature of this method, it is especially appropriate when the plantation is to be grown further or when estimates of annual biomass production are needed. Cutting of exotic willows during the summer led to an increase in mortality and decrease in biomass production during the following year. Short stumps gave higher yields than longer ones. Damage to the stumps in the harvesting phase decreased biomass production, especially in a young stand. In a dense willow plantation internal within-stand competition started already during the first growing season. It manifested itself in the form of skewed and bimodal stem frequency distributions. The smallest sprouts died and only one tenth of the original first year shoots survived to the end of the seven-year rotation. Fertilization in cut-away peatland areas was essential for achieving and maintaining high biomass production. In limed cut-away peatland areas only readily soluble phosphorus fertilizers increased the growth of willows and the amount of acid ammonium acetate extractable phosphorus in soil. Nitrogen fertilizer should be applied annually in order to maintain high productivity. Phosphorus and potassium could be applied at longer intervals. Analysis of soil extractable nutrients could be used to establish guidelines for determining the fertilization requirements of short-rotation willow plantations. Willows bound high amounts of nutrients in their biomass. Almost half of the nutrients were in the foliage. With increase in age, the amount of wood and bark out of the total production increased and consequently the amount of nutrients bound per unit biomass decreased.

Key words: Short-rotation plantations, biomass estimation, *Salix*, *Populus*, fertilization, nutrient uptake, sprouting, cutting time, stump height.

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ORIGINAL PAPERS (I-IX)

This thesis is based on the following publications, which are referred to in the text by their roman numerals.

I Hytönen, J., Lumme, I. & Törmälä, T. 1987. Comparison of methods for estimating willow biomass. Biomass 14:39-49.

II Hytönen, J. 1994. Effect of cutting season, stump height and harvest damage on coppicing and biomass production of willow and birch. Biomass and Bioenergy 6(5):349-357.

III Hytönen, J. 1995. Ten-year biomass production and stand structure of Salix 'Aquatica' energy forest plantation in southern Finland. Biomass and Bioenergy 8(2):63-71.

IV Ferm, A., Hytönen, J. & Vuori, J. 1989. Effect of spacing and nitrogen fertilization on the establishment and biomass production of short rotation poplar in Finland. Biomass 18:95-108.

V Hytönen, J. 1985. Teollisuuslietteellä lannoitetun vesipajun lehdetön maanpäällinen biomassatuotos. Abstract: Leafless above-ground biomass production of Salix 'Aquatica' fertilized with industrial sludge. Folia Forestalia 614. 16 p.

VI Hytönen, J. 1986. Fosforilannoitelajin vaikutus vesipajun biomassatuotokseen 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.

VII 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.

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

IX Hytönen, J. 1995. Effect of repeated fertilizer application on the nutrient status and biomass production of Salix 'Aquatica' plantations on cut-away peatland areas. Silva Fennica 29(2):107-116.

# 1 INTRODUCTION

The concept of short-rotation management includes the establishment of closely-spaced stands of fast-growing trees and the application of intensive cultivation practices and repeated harvesting, using short cutting cycles, regeneration of subsequent crops via sprouts or suckers, and a high degree of mechanization (e.g. Sirén 1974, 1979, Pohjonen 1980, Pelkonen & Rossi 1984, Sirén et al. 1984). Since the introduction of the concept by McAlpine et al. in 1966, short-rotation production practices have been under study in many countries (Coombs et al. 1990, Mitchell et al. 1992) with the maximization of the biomass growth of selected woody species as the goal. The characteristics of the ideotypes of the different tree species suitable for short-rotation cultivation have been outlined; e.g. by IEA's (International Energy Agency) forest energy working groups (Koski & Dickmann 1992). The criteria often used when selecting poplar and willow clones include the following: good rooting ability, fast and vigorous growth (especially at an early age), the capacity to grow as closely-spaced stands, good coppicing ability, resistance to pests, and, nowadays, also good quality of the wood produced for biomass utilization (e.g. Leikola 1976, Pohjonen 1977, Sirén et al. 1984, Zsuffa & Gambles 1992, Mitchell 1992). Willows have been considered to possess several traits desirable in short-rotation tree species. Besides willows, especially the cultivation of alders and birches, applying longer rotations, has also been investigated in Finland (Saarsalmi et al. 1985, 1991, 1992, Ferm 1990, 1993).

Willows have a long history of cultivation in Finland and Europe (Pohjonen 1984, 1987, 1991). For centuries, they have been the target of selection in Europe and they have been grown in closely-spaced plantations to produce material for the basket industry (Wasielewski 1982, Pohjonen 1984). The first mention of willow plantations as a fuel source in Finland is from the year 1753 (Lithander, ref. Pohjonen 1984) and the first Finnish report on basket willow cultivation was published as early as in 1882 (Flinta 1882). At the beginning of this century Nordberg (1928) studied and propagated for cultivation of willows for basketry in Finland. In the 1950s, willow cultivation and studies were initiated in Finland by Tapio (Tapio 1965). However, despite considerable inputs into research and development, basket willow cultivation in Finland did not reach the level of practical farming. At the beginning of the 1970s, nearly all merchantable stemwood in Finland found industrial use and the country's forest industry was occasionally confronted by shortages of raw material (Hakkila et al. 1979). First field trials established in 1973 by Pohjonen (1974) suggested that willows have considerable yield potential. Studies on the mass production of small-sized broadleaved trees were subsequently initiated. Especially at the end of the 1970s, studies on domestic fuels were stepped up and the PERA project was started at the Finnish Forest Research Institute (Hakkila 1985). The emphasis in research was placed on existing small-tree and logging residue reserves, harvesting techniques, productivity, measuring, improvement of chip quality, and reduction of procurement costs. Biomass production systems using the short-rotation management principles, including a wide variety of topics from basic biology to the practical aspects of growing and harvesting crops, were also

included in the sphere of research.

Mainly *Salix* species have been used in the short-rotation experiments conducted in Finland and Sweden. Both the genera *Polulus* L. and *Salix* L. belong to the family *Salicaceae* and they are widely distributed in the northern hemisphere. The genus *Salix* is divided into three subgenera: *Salix*, *Vetrix* and *Chamaetia*. The majority of *Salix* species are shrubby. Most willow species and clones investigated in short-rotation experiments belong systematically to the subgenus *Vetrix* (shrub willows) of the genus *Salix*. The provenances, nomenclature and position in plant systematics of several willows used in short-rotation cultivation is not fully known (Stott 1984, Pohjonen 1987, Viherä-Aarnio 1991, Gullberg 1993). The taxonomic difficulties are biggest in the subgenus *Vetrix* (Pohjonen 1991). Of the indigenous willow species, *S. myrsinifolia* Salisb. or *S. phylicifolia* L. could be promising ones for short-rotation forestry (Pohjonen 1991, Honkanen 1994, Hytönen et al. 1995). *Salix viminalis* L., widely used in Swedish practical short-rotation plantations (Sennerby-Forsse 1994), has also been tested in Finland (Rossi 1982, Hytönen 1987, Tahvanainen 1995). *Salix* 'Aquatica' (*S.* 'Aquatica Gigantea') originating from Denmark has also been widely used in short-rotation energy forest research in Europe. Its cultivation history in Finland has been reviewed in detail by Pohjonen (1987). *Salix x dasyclados* Wimm., a hybrid most likely between *S. cinerea* and *S. viminalis* (Pohjonen 1991, Hämet-Ahti et al. 1989) and *Salix* 'Aquatica' resemble morphologically each other, even though some differences have been recognised (Heino 1982, Pohjonen 1987, Hämet-Ahti et al. 1989). Some doubt even exists whether the clones cultivated in Finland as *S. x dasyclados* are true *S. x dasyclados* hybrids (Pohjonen 1987, 1991). Pohjonen (1987) suggests that nearly all clones of *S.* 'Aquatica' and *S. x dasyclados* Wimm. in Finland belong to the one and the same Siberian species, *Salix burjatica* Nasarov. A properly marked and registered clone has been the basic unit in short-rotation research. Best willow clones have commercial cultivar names in Sweden. Pohjonen (1991) even considers that in practical short-rotation forestry all taxons between species and clones are unnecessary.

In many respect, willows are very rewarding breeding material. Wide genetic variation both within and between species, polyploid cellular structure, promising hybridization potential, flowering at an early age, and plentiful seed production offer a good basis for the selection and breeding of willows (Malmivaara et al. 1971, Sennerby-Forsse et al. 1983, Ager et al. 1986, Zsuffa & Mosseler 1986, Hall 1986, Lumme & Törmälä 1988, Viherä-Aarnio 1988, 1991, Gullberg 1989). Early selection is possible when short rotation periods are utilized. In most willow species, clonal selection of individuals is possible due to easy vegetative propagation and thus increases the likelihood of finding superior combinations. Clonal selection from $F_1$-progenies of planned crossings is likely to increase selection efficiency (Viherä-Aarnio 1988, Pohjonen 1991, Viherä-Aarnio & Saarsalmi 1994). In the 1980s, both exotic and indigenous willow species and clones were selected in Finland; this is described in detail by Pohjonen (1991) and Viherä-Aarnio (1991).

Careful site selection, including site-clone matching, is necessary for satisfactory establishment and yield from intensively cultivated willow plantations (e.g. Leikola 1976, Hakkila et al. 1979). Sites should be fertile and well-drained and free of stones. Mechan-

ization of plantation establishment, plantation management and harvesting also influence site selection. The Finnish Energy Forest Committee (Energiametsätoimikunnan ... 1979, 1981) calculated that 550 000 ha of potentially suitable sites could be available for intensive short-rotation forestry. Mainly marginal lands, e.g. former fields, open mires, cut-away peatland areas, powerlines, roadsides, and land formerly under water, have been suggested to be used for short-rotation forestry (Sirén 1974, Leikola 1976, Hakkila et al. 1979, Energiametsätoimikunnan ... 1979, 1981). Short-rotation plantations have been studied in cut-away peatland areas besides in Finland also in Ireland and Estonia (Neenan 1983, Valk 1986, Kirt 1994). Nowadays, high quality agricultural lands are becoming available not only in Finland, but also in many other European countries (Ferm & Polet 1991, Christersson et al. 1993, Järvenpää et al. 1994, Hytönen 1995). Due to surplus production in agriculture, it is estimated that as much as 500 000 - 1 000 000 ha of arable land should be taken out of agricultural production in Finland (Järvenpää et al. 1994, Toivonen et al. 1994).

Intensive site preparation and weed control are essential prior to planting. Especially during the planting year, willows and poplars planted as cuttings are intolerant of competition from weeds and competing vegetation can damage the plantation (Andersson et al. 1983, McElroy & Dawson 1986, Bowersox et al. 1988, Dawson 1988). Efficient weed control is a prerequisite for the establishment of productive plantations. Short-rotation willow plantations are usually established using unrooted stem cuttings which develop adventitious roots when planted. Willows generally root easier from cuttings than poplars do (Sirén & Sivertsson 1976, Leikola & Rossi 1977, Pohjonen 1977, Ferm 1985a). Cuttings offer a good possibility for using cloned material and their production, storage and planting are easy and can be mechanized (Rossi 1983, Harstela & Tervo 1983). The length of cuttings has generally been 20 cm with a minimum thickness of 5 mm. Special treatment of willow cuttings, e.g. soaking or hormone treatments has generally enhanced their good rooting ability only little (Rossi 1979a, 1979b). Planting should be done as early in the spring as possible and cuttings should be planted in an upright position even though they root quite well also when planted horizontally if the soil is moist enough (Hytönen 1983). Short-rotation willow plantations are often cut-back after the first growing season. This increases the number of sprouts per stump and alters the shoot-root ratio.

The ability to coppice or re-sprout after harvesting is one important characteristic of tree species suitable for short-rotation forestry. A critical aspect of biomass plantations is the sustainability of the system, especially its ability to withstand repeated harvesting (Sennerby-Forsse et al. 1992). The coppicing ability of tree species varies considerably; e.g. willows are considered to sprout well compared with birches (Ferm & Issakainen 1981, Ali-Alha 1987). The initial development of sprouts is often much faster than that of seedlings of the same tree species (Blake 1980, Kauppi et al. 1988). Several factors, both internal and external, influence the regeneration of growth from stumps. It has been shown with many tree species that factors such as season of cutting, cutting tool, stump height, growing site, tree diameter, tree age, spacing and rotation length influence re-sprouting (Heikinheimo 1930, Mikola 1942, Leikola & Mustanoja 1961, Etholén 1974, Moilanen & Oikarinen 1980, Blake & Raitanen 1981, Ferm & Issakainen 1981, Sennerby-Forsse et al. 1992). Though

extensively used in short-rotation cultivations, willows have not been studied in this respect. Knowledge of factors affecting coppice regeneration are necessary for the determination of cutting schedules and development of harvesting techniques. Besides the cultivation factors, knowledge of the physiology and morphology of sprout-producing buds and their development into sprouts is essential (Ferm & Kauppi 1990).

High planting densities in willow cultivation (often 40 000 cuttings $ha^{-1}$) have been used in Finland (Hytönen 1993). Following cutting-back after the first growing season, the number of sprouts in *S.* 'Aquatica' plantations can exceed 300 000 $ha^{-1}$ (Hytönen 1988). The post-harvesting stand densities increase due to the increased amount of shoot-producing buds (Paukkonen et al. 1992). Within-stand competition in such dense plantations is high. Willow growth and within-stand competition is further enhanced by fertilizer application. Competition-induced shoot mortality before the end of the rotation period is also high (Verwijst 1991b, Willebrand & Verwijst 1993).

Special attention should be directed at the nutrient status of soil when practising short-rotation forestry. Repeated harvesting of the above-ground biomass at short cutting cycles, even though excluding the foliage, promotes the loss of nutrients. Short-rotation willows bind considerable amounts of nitrogen, phosphorus, potassium and other nutrients into their biomass (Saarsalmi 1984, Ferm 1985a). Frequent repetition of such nutrient drains could result in nutrient depletion of the site. An important objective of research programmes developing woody biomass plantations is to establish fertilization regimes optimizing growth with minimal adverse environmental consequences (Miegroet et al. 1994). Correct fertilization regime, with respect to timing and rates, is one of the most important ways to improve crop production. Our knowledge of the factors influencing the fertilizer reaction of short-rotation plantations (inc. nutrient status of the substrate, species and its stage of development, type and amount of fertilizer) is inadequate. Determining the need for fertilization before the plantation is established should be based on site classification according to the natural nutrient status (soil analyses). Later on, foliar analyses and nutrient deficiency symptoms could also be used (Paavilainen 1979, Miller 1983). With nutrient physiology studies as the basis, trials have been conducted in Sweden using small amounts of liquid fertilizer, administered even daily (Ericsson 1981a, Ingestad & Ågren 1984, Christersson 1986, 1987). Yields have been estimated to have increased considerably by applying nutrients, especially nitrogen, during the growing season at the same rate as they are bound by the plants (Ingestad & Ågren 1984).

The optimum pH for good development of willow root systems varies from species to species. The roots of *S. pentandr*a L. and *S. cinerea* L. have developed almost as well in a hydroponic culture under pH 3.5 as under pH 5.0 (Lattke 1969). However, many willows used in short-rotation cultivation require rather high pH (5.0 - 6.0) levels of the substrate (e.g. *S. viminalis*, *S.* 'Aquatica', *S x dasyclados*) (Ericsson & Lindsjö 1981, Ferm & Hytönen 1988). The pH of cut-away peatland areas is generally quite low (e.g. Kaunisto 1980, 1982a, Hytönen 1984, Ferm & Kaunisto 1983, Lumme et al. 1984). The soils of cultivated fields generally have pH values exceeding 5 (Kurki 1982, Viljavuustutkimuksen ... 1992).

Cut-away peatland areas are characterized by their variable peat thickness, low pH and

high nitrogen concentrations and low phosphorus and potassium concentrations (Kaunisto 1979, Ferm & Kaunisto 1983, Lumme et al. 1984, Lehtonen & Tikkanen 1986, Ferm & Hytönen 1988, Kaunisto & Viinamäki 1991). The nutrient status of agricultural soils shows wide variation (Kurki 1982, Viljavuustutkimuksen... 1992). Afforestation of cut-away peatland areas, and especially of peatland fields, may be confronted by nutritional problems (Raitio 1979, Veijalainen 1983, Hytönen & Ekola 1993, Aro 1995). Research results show that success in the afforestation of cut-away peatland areas depends a lot on fertilization (Kaunisto 1979, 1986, 1987a, Valk 1986, Ferm & Hytönen 1988, Aro 1995). Fertilization and soil amelioration are probably also the most important factors affecting the biomass production of short-rotation plantations in cut-away peatland areas (Hytönen 1982, 1987, Kaunisto 1983, Ferm & Hytönen 1988, Lumme 1989). It is especially important to optimize nitrogen application because of the high cost of fertilizer nitrogen. Besides commercial fertilizers, also the recycling of wood ash and utilization of nutrients in sludges could offer ecologically and environmentally interesting alternatives for soil amelioration and fertilization in short-rotation plantations (Kaunisto 1983, Ferm 1985a, Lumme & Laiho 1988, Lumme 1989). However, the need for repeating fertilization and the duration of the fertilizer effect are poorly known.

Dry mass is more useful than volume as a parameter for depicting the value of the raw material for industrial purposes focusing on the production of pulp, chemicals and energy (Hakkila 1989). Dry-mass production of a short-rotation plantation can be measured with different methods varying greatly in the amount of work and destructiveness they involve. Determination of the current annual yield requires annual measurements by a non-destructive method so as not to influence the future development of the plantation. Especially for research purposes, the composition of the produced biomass should be described; e.g. the chemical and physical composition of wood differs considerably from bark. Chemical and physical properties can play an important role in the efficiency of most energy conversion processes.

Many biotic and abiotic factors influence the biomass production of short-rotation plantations. According to simulation models, the annual variation in radiation and temperature can cause considerable year-to-year variation in biomass production (Eckersten et al. 1983, Nilsson & Eckersten 1983, Sievänen 1983, Perttu et al. 1984, Nilsson 1985, Eckersten 1985, Eckersten et al. 1987). In the case of some soil types and weather conditions, the availability of water can also be a limiting factor (Grip 1980a, 1980b, 1981, Grip & Perttu 1982, Kaunisto 1983, Kowalik & Eckersten 1984, Saarsalmi 1984). Early summer frosts can considerably decrease the biomass production of willow plantations (Christersson et al. 1982, 1984, Ericsson et al. 1983, Ahola 1987, Fircks 1992). Production may also be severely reduced by the susceptibility of the species or clones to pests and diseases (Rossi 1982, Larsson & Wiren 1981, Hubbes 1983, Morris 1983, Rönnberg-Wästljung & Gunnerbeck 1985, Tahvanainen et al. 1985, Larsson et al. 1986, Royle & Hubbes 1992).

The productive period of a short-rotation willow plantation is expected to be 20-25 years (Anderson et al. 1983, Ledin et al. 1992). Studies on the development of short-rotation plantations have usually been confined to the first years after establishment. Very few

reports include records of long-term biomass production and survival, matters of crucial importance for the success of such ventures. Varying views have been expressed in regard to the biomass yields that can be achieved in short-rotation plantations; these have been based on both simulation models and field experiments. Rather high yields (even 30-40 t $ha^{-1}$ $a^{-1}$ dry-mass) have been considered possible (Pohjonen 1974, 1980, Sirén & Sivertsson 1976, Sirén 1979, Hathaway 1979, 1980, Linder & Lohammer 1982, Christersson 1986, 1987, White et al. 1989). The reliability and generalizability of yield results obtained in connection with field experiments is hindered by matters such as smallness of sample plots and exceptionally intensive management (Cannell 1989).

## 2 AIMS OF THE STUDY

The general objectives of the studies reviewed in this paper were to obtain more thorough understanding of the silvicultural and nutritional prerequisites of growing short-rotation forests on cut-away peatland areas and abandoned farmlands. In order to achieve this the following problem areas were studied:

1. Biomass estimation methods. Accurate biomass measurements provide the basis for biomass estimation and nutrient uptake studies. The aim of the first investigation in this study was to compare different biomass estimation methods and evaluate their suitability for the determination of short-rotation biomass production (I).
2. Stand establishment and coppice regeneration. The objective of several studies was to evaluate the success of plantation establishment (II, IV, VI-IX). Lack of knowledge of critical factors affecting the sustainability of coppice regeneration systems was an impetus for research which focused on cultural factors influencing coppicing (II).
3. Stand development and biomass production. The aims were to study the effects of within-stand competition and stand structure (III), effects of planting density on biomass production (IV), and biomass production and its allocation in different compartments (leaves, bark, wood, stump, roots) (IV-IX).
4. Fertilization and nutritional requirements of short-rotation plantations. The specific objectives were to study the effects of fertilizer nitrogen, phosphorus and potassium and their combinations, application rates, repetition of the fertilizer application, the effect of solubility of fertilizer phosphorus and sludge application on the biomass production and nutrition of short-rotation willows in cut-away peatland areas (IV-IX). One of the main aims in investigations concerned with nutrition of short-rotation plantations was to study the nutrient concentrations in the above-ground biomass, amounts of nutrients bound in the above-ground biomass, biomass production and the effects of fertilizer application (IV-IX). In order to gain better understanding of nutrition, biomass, nutrient concentrations, and nutrient uptake of different above-ground compartments was studied (VI-VII). The possibility of utilizing soil analysis for determination of fertilization regime was evaluated.

## 3 MATERIAL AND METHODS

The field experiments were established on two types of sites potentially suitable for short-rotation cultivation: cut-away peatland areas and abandoned farmland (Table 1, Fig. 1). The species and clones used in the different studies are presented in Table 1. All the experimental short-rotation plantations were established using unrooted, 20-25 cm long cuttings, except III and V where rooted cuttings were used. Study II also included naturally established stands of willow and birch. The willows were planted in rows: the space between the rows was 70 cm (in III and V: 80 cm) and the distance between the cuttings in the rows was 35 cm (planting density 41 000 cuttings $ha^{-1}$, in III,V: 36 000 cuttings $ha^{-1}$). Mechanical and manual weeding was done during the planting year and in some cases later on, too.

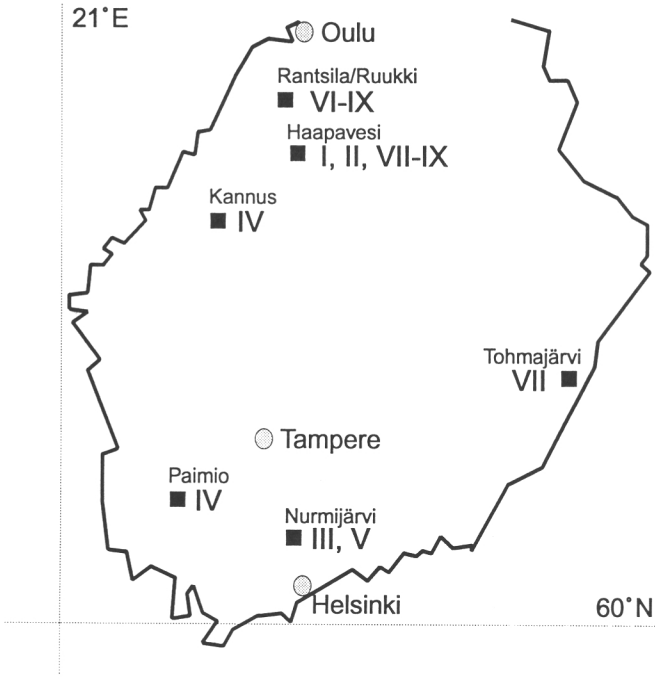


Figure 1. Location of the field experiments.

Table 1. Location of the field experiments, soil types and species used in the different studies.

| Study | Soil type | Species and clones |
|---|---|---|
| I, VII, VIII, IX | Cut-away peatland area | *S.* 'Aquatica' (V769) |
| VI, VII | " | *S.* 'Aquatica' (E4856) |
| II, VII, VIII | " | *S. x dasyclados* (P6011) |
| I | " | *S. triandra* (P6010) |
| I | " | *S. triandra* (P6291) |
| II | " | *S. viminalis* (E7901) |
| II | Peat field | *S. phylicifolia*, *S. pentandra* |
| II | " | *B. pubescens* |
| II | Mineral soil field | *S.* 'Aquatica' (E4856) |
| II | " | *S. x dascylados* (V761) |
| III, V | " | *S.* 'Aquatica' (V769) |
| IV | " | *P.* x *rasumowskyana* |

Different methods of measuring willow biomass production of *Salix* 'Aquatica' and *S. triandra* were compared (I). The **harvesting method** consisted of cutting the willow to a stump height of 10 cm after which the sprouts were gathered into bundles and weighed immediately. Six sprouts of different sizes were sampled from each plot and their leafless fresh-mass and dry-mass were determined. In the **mean stool method**, all the sprouts from stools selected at random were cut to a stump height of 10 cm with the sampling covering 7% of the total number of the stools. The total number of the stools on sample plots was counted. The dry-mass was obtained by multiplying the dry-mass of the average stool with the number of stools. When **regression estimation** was used, height and diameter distributions of the willows were determined by systematic sampling, which, on average, covered 10 - 13% of the area of the sample plots. Thirty sprouts from each willow clone were sampled. The sample sprouts were then cut back to a stump height of 10 cm and their length, diameter and dry-mass were determined. The independent variable in the dry-mass equations ($Y = aX^b$) was diameter measured at 10 cm height ($d_{0.1}$) and total height (h) combined into a single variable ($d^2h$). Prior to computing the dry-mass, the stump height of 10 cm was subtracted from the willow height measurements.

The effects of cutting season on the survival, coppicing and growth of *S. viminalis*, *S.* 'Aquatica', *S.* x *dasyclados*, *S. phylicifolia* and *S. pentandra* mixture, and *B. pubescens*) were studied in a cut-away peatland area, mineral-soil and peat-soil fields at Haapavesi (II, Fig. 1, Table 1). At each of the 32-36 or 53 cutting times 20-30 stools were cut down. At Haapavesi, the effect of stump height on the survival and biomass production of *Salix* 'Aquatica' was also studied by cutting back one-year-old sprouts in 1983 to stump heights of 0, 10, 20 and 40 cm on plots sized 60 $m^2$ (II). Randomized block design with four replications was used. Survival and biomass were measured in 1985, 1987 and 1990, when the willows were cut to their initial stump heights.

The effects of harvesting damage on the sprouting and biomass production of *S.* 'Aquatica' was studied at Haapavesi on a cut-away peatland area and at Nurmijärvi on a mineral-soil field (II, Fig. 1). One-year-old willows at Haapavesi were cut using (A) secateurs, resulting in a smooth cutting surface, and (B) a brushsaw, leaving a rougher cutting surface. In addition, half of the stumps were damaged manually with a sledge-hammer in both treatments. Randomized block design with four replications was used. The survival, number of sprouts per stump, and the height of the tallest sprout in each stool were measured. The dry-mass of the willows was determined in 1985, 1987 and 1990 using the harvesting method. At Nurmijärvi, eight-year-old sprouts were cut with a chainsaw or with a brushsaw (II). The treatments including a control (A), light-weight forwarder driving on the row of stumps (B), and manual damaging of the stumps using a sledge-hammer (C) were replicated three times in a randomized block design. The height of the sprouts and the number of sprouts per stool were measured after one growing season. The dry-mass per stool was calculated using dry-mass equations.

The long-term biomass production and stand structure of *S.* 'Aquatica' was studied on a limed mineral soil field in Nurmijärvi (III, Fig. 1, Table 1). The willows were planted in 1982 and fertilized with sludge. The willow harvest took place in 1985, three growing seasons after planting. Sludge fertilization was renewed after the harvest, but the nutrient amounts applied were small (18 - 70 kg N $ha^{-1}$). The second harvest took place at the end of the seven-year rotation in 1992. The leafless above-ground biomass was determined annually using allometric dry-mass equations. The stand structure at different ages was studied by constructing equal-interval frequency distribution histograms of willow diameter. The third ($g_1$) moment about the mean, a measure of the skewness of the distribution, and the fourth moment ($g_2$), a measure of kurtosis of the distribution, were also calculated.

The effects of spacing (35 000, 15 000, 5000 stems $ha^{-1}$) on the biomass production of *Populus* x *rasumowskyana*, planted using cuttings in 1981, was studied on a former cultivated mineral soil field of satisfactory fertility under pH of 6.1 - 6.9 at Paimio (IV, Fig. 1, Table 1). The poplars were fertilized in 1981 using a multi-nutrient fertilizer (48 kg N $ha^{-1}$, 21 kg P $ha^{-1}$, 39 kg K $ha^{-1}$). A corresponding trial at Kannus (Fig. 1) was destroyed by frost the next year and thus only the first year's data are available. The various spacing treatments were replicated twice on the plots (size 400 $m^2$) selected at random. In the autumn after the first growing season, the longest shoot on each stool was left to grow.

The effect of fertilization on the biomass production, foliar, bark and wood nutrient concentrations and the nutrient uptake of willows (V-IX) and poplar (IV) was studied in field experiments established on mineral soil agricultural fields (IV, V) and cut-away peatland areas (VI-IX). The effect of fertilization treatments on soil properties were also studied. The fertilizer application treatments are presented in Table 2. The sizes of the experimental plots were 56 - 80 $m^2$ (VII-IX), 225 $m^2$ (IV, VI) or 300 $m^2$ (V). The willow cuttings were planted at a density of 36 000 (V) or 41 000 cuttings (VI-IX) per hectare. The planting density for poplars was 15 000 cuttings per hectare (IV). The sprouts were cut back after the first growing season (VI-IX) or cut back leaving the longest shoot on each stool (IV). The experimental design used consisted of randomized blocks (VII-IX) or fully

randomized treatments (IV, VI, Table 2).

The diameter and height distribution of the willow sprouts on the experimental plots were measured each year. The number of living and dead stools was also recorded. Allometric dry-mass equations, based on sample sprouts selected according to the size distribution of the sprouts in the plots with base diameter ($d_{0.1}$) or the product of base diameter squared and height ($d^2h$) as an independent variable, were constructed. Sample sprouts were dried to constant weight at 105° C (stem, branches, bark and wood) or at 80° C (leaves). Dry-mass equations were calculated for the leafless above-ground mass, but in VI-IX also for leaf, bark and wood mass and in IV for branch mass. Root and stump masses were calculated in VII-IX with equations based on randomly selected stools (including stems and roots) dug up annually. The independent variable in the 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.

Foliar samples were collected from the fertilization experiments V-IX from each plot for nutrient analysis mostly in late August or early September (Table 2) (Halonen et al. 1983). The nutrient concentrations of the bark and the wood were also determined in VI and VII. Soil samples (composed of five subsamples) were taken from the 0 - 10 cm top soil layer on all the plots (V-IX, Table 2). The samples were stored in freezer (-20 °C). The pH of the dried samples was analyzed in distilled water (V/V 1:5). Soil total nitrogen (Kjeldahl, V-IX), ammonium and nitrate nitrogen (VI), acid ammonium acetate (pH 4.65) extractable phosphorus, potassium, calcium, and magnesium (IV-IX) were also determined (mg $l^{-1}$, volume determined in laboratory) (Halonen et al. 1983).

Table 2. Fertilization treatments in studies IV - IX. See figure 1 for the location of the study sites.

| Study | Species and clones | No. repli-cations | Fertilization treatments[1] | Fertilizer application year | Soil samples year | Foliar samples[2] year |
|---|---|---|---|---|---|---|
| IV | *P. x rasymowskyana* | 2 | O, N, 2N, 3N (N = 100 kg N $ha^{-1}$) | 1981, 1982 | - | - |
| V | *S.* 'Aquatica' | 3 | NPK, Sludge 30, 60, 120 $m^{-3}$ $ha^{-1}$ | Sludge: 1982, NPK: 1982,1983,1984 | Spring 1983, Spring 1984 | 1983, 1984 |
| VI | *S.* 'Aquatica' | 4 | 0, NK, $NP_{sf}K$[3], $NP_{rf}K$, $NP_{ap}K$ (N=200 kg N $ha^{-1}$, P = 87 kg P $ha^{-1}$, K = 166 kg K $ha^{-1}$) | 1981, 1983 | Autumn 1983 | 1983 |
| VII | *S.* 'Aquatica' | 3 | 0, P, K, N, PK, NK, NP, NPK (N = 100 kg N $ha^{-1}$, P = 30 kg P $ha^{-1}$, K = 40 kg K $ha^{-1}$. | 1983, 1984, 1985 | August 1985 | 1983, 1984, 1985 |
| | *S. x dasyclados* | 3 | | | | |
| | *S.* 'Aquatica' | 3 | | | | |
| | *S.* 'Aquatica' | 4 | | | | |
| | *S.* 'Aquatica' | 4 | | | | |
| VIII | *S.* 'Aquatica' | 3 | Fife N (0, 50, 100, 150, 200 kg $ha^{-1}$), P (0, 15, 30, 45, 60 kg $ha^{-1}$) and K (0, 20, 40, 60, 80 kg $ha^{-1}$) levels. When the amount of one of the nutrients in NPK-fertilization was changed others remained unchanged (N 100, P 30 and K 40 kg $ha^{-1}$). | 1983, 1984, 1985 | August 1985 | 1983, 1984, 1985 |
| | *S.* 'Aquatica' | 3 | | | | |
| | *S. x dasyclados* | 3 | | | | |
| IX | *S.* 'Aquatica' | 3 | PK, NP, NK, NPK, $N_2PK$, $NP_2K$, $NPK_2$, where N = 100, $N_2$ = 200 kg N $ha^{-1}$, P = 30, $P_2$ = 60 kg $ha^{-1}$, K = 40, $K_2$ = 80 kg $ha^{1}$. Reference treatment fertilized in 1984 compared with repeated fertilizations in 1984, 1985, 1986. | Annual:1983, 1984, 1985 Once:1983 | August 1985 | 1983, 1984, 1985 |
| | *S.* 'Aquatica' | 3 | | | | |

1) Prior to planting all experimental fields were limed with 6 000 kg $ha^{-1}$ of dolomite lime, except IV (no soil amelioration) and Valkeasuo (VII) where either 12 000 kg $ha^{-1}$ wood ash or 12 000 kg $ha^{-1}$ dolomite lime were used. In VII-IX Piipsanneva and Paloneva experimental areas also basic fertilization with NPK and in Valkeasuo limed area with PK.
2) In VI and VII also wood and bark samples were collected.
3) sf = superphosphate, rf = rock phosphate, ap = apatite.

# 4 RESULTS AND DISCUSSION

## 4.1 Estimation of biomass

Small experimental plots (even less than 1 $m^2$ in area) have often been used in research on short-rotation cultivation (e.g. Pohjonen 1974, 1977, Lepistö 1978, Hathaway 1979, 1980). Even though small plots can be effective in screening clones or fertilizer treatments, it must be taken into consideration that the biomass production figures obtained from such small plots can be biased due to errors caused by the so-called edge effect (Zavitkovski 1981). Trees growing at the borders of experimental plots may be in more advantageous or disadvantageous positions regarding nutrients, moisture, radiation and temperature than trees growing in the interior parts of the sample plots. Biomass production in the border areas is generally much higher than in the central parts of the plots (Zavitkovski 1981, Stott et al. 1983). The early literature often includes biased results from small plots expressed as production per hectare (Cannell & Smith 1980); e.g. early production figures of *Populus* in Wisconsin based on small plots have been revised from 25-30 t $ha^{-1}a^{-1}$ to about 10 t $ha^{-1}a^{-1}$ (Isebrands et al. 1979). Yields of *S.* 'Aquatica' on square plots (50-70 $m^2$) were 20-30% lower when one border row was excluded (Stott et al. 1983). According to Stott et al. (1983) one outside row could suffice for the elimination of the edge effect for up to 3-year-old willows (10,000 - 40,000 plants $ha^{-1}$, 40-70 $m^2$ plot size), but two would allow the 'safe' assessment of production per hectare. In all the studies (I-IX) the practice has been to always exclude one, usually two or more, border rows from being measured. The said studies also meet the criteria set by Cannell and Smith (1980) concerning the stipulatum that the ratio of the height of the measured trees (inside the plots) to their distance from the edge of the plot (i.e. the border width) should not exceed four.

Most methods for the determining of the dry-mass of a tree involve the measurement of the moisture content of sample trees and of their different compartments (for woody compartments usually by weighing green, drying at 105 °C to constant weight and reweighing). Accurate determination of the moisture content is extremely important in biomass estimation (I, Ferm & Hytönen 1984). The moisture content in a tree varies; e.g. by tree species, tree age and size, longitudinally along the stem, by season and even the time of day, weather, growing site and fertilization (I, Hytönen & Ferm 1984, Ferm 1985b, Hytönen 1987, Hakkila 1989). There are several sources of error related to sampling for moisture content, storage of moisture samples and measurement of these samples. Determining the mean moisture content of a single willow sprout using one sample is more difficult than with birch (Hytönen & Ferm 1984, Hakkila 1979, Auclair & Metayer 1980, Björklund & Ferm 1982). The green mass of the moisture samples should be measured without delay, since the moisture content of the samples decreases during storage depending on the duration and method of storage (Ferm & Hytönen 1984). Incorrect storage methods can cause even losses of dry-matter; e.g. when dealing with foliage samples (Nilsson 1983). The drying time should be long enough to allow water to leave the sample. Many sources

of error related to sampling and subsampling for moisture content were avoided by taking entire sprouts as samples (I-III, V-IX).

The harvesting method, where all material within a unit area is harvested and the biomass is subsequently weighed, is also subject to various errors (I). Accurate measurement of the harvested area is important. Even the actual cutting height has a significant effect on the amount of biomass harvested (I). The weighing technique may be another source of error (Björklund & Ferm 1982) and weighing large biomass amounts is labour intensive. The harvesting method is not well suited for determination of biomass compartments. This is also true for the mean tree method. A single tree of mean dimensions will not provide mean weight for all biomass compartments. The mean stool method, where all the shoots of a number of stools are cut and weighed, is better suited for coppice biomass estimation.

The most common method for estimating tree biomass is through the use of regression analysis (Hitchcock & McDonnell 1979, Crow & Schlaegel 1988). Generally the dry weights of destructively harvested sample trees and their compartments are related by regression equations to a readily measurable dimension or combination of dimensions. The dimensions most frequenctly used in regression analysis and describing the allometric structure of trees include tree height and diameter. Often the measurement of diameter alone is adequate since adding height into the models together with diameter ($d^2h$) increases the degree of determination only little (I, V, VI, Payandeh 1981, Björklund & Ferm 1982, Ferm & Kaunisto 1983, San Miguel & Cancio 1985, Hakkila 1989).

The most widely used biomass model is the allometric model $y_i = aX_i^b e_i$; where $y_i$=the weight of the ith sample tree, $X_i$ = the value of the independent variable of the ith sample tree, a and b = the model intercept (a) and slope (b), $e_i$ = the random error associated with estimating the weight of the ith sample tree, i = represents any one of the sample trees (Crow & Schlaegel 1988). Logarithmic transformations, likely to equalize the variance over the range of y-values, have been used to linearize this allometric equation ($\ln Y_i = \ln a + b \ln X_i + \ln e_i$). When untransformed arithmetical units are desired, several procedures to correct the slight underestimation caused by logarithmic transformation (Satoo & Madgwick 1982) have been advocated, and that proposed by Meyer (1941) is most often used (correction with $s^2_e/2$, where s is the residual of the equation). This correction was usually slight (II, VI). Logarithmic transformations and the subsequent linear regression of biomass on tree dimensions may result in biased estimates when a non-zero intercept is present in the untransformed data (Verwijst 1991a). This bias was avoided by taking the diameter measurements at harvest level (I, III-IX). Besides the power function, several other regression models (e.g. weighed linear regression) have been used (e.g. Cunia & Briggs 1984, Crow & Schlaegel 1988). The stem, bark, wood, and leaf mass, and also the leaf area of willow were accurately described by allometric regression equations (I, III-IX). Since the allometric exponent b in the biomass equations ($Y = aX^b$) changed with age (III-VII) generalized biomass equations should most probably be age-specific. With increase of age the growth form and density of willow bark and wood change (Hytönen & Ferm 1984).

The number of sample trees sacrificed in fitting models in previous studies has varied from less than ten to over a hundred. Usually, however, as in the present studies (I, III-IX),

this has been between twenty and thirty. Biomass equations based on smaller number of sample trees have also been used (e.g. 5-6: Gholz et al. 1979, 7-9 Finér 1989, 1991). The most cost-effective means of increasing the precision of biomass estimation would be to sacrifice more trees to fit the models or to sample larger areas in the stand; more sophisticated models would have little effect on the error (Woods et al. 1991). The sample trees often need to be subsampled. The representativeness of internal sampling should be carefully considered. On the part of leaf mass and leaf area, the time of the year when sampling is done can lead to errors: leaf mass and leaf area reach their maximum in central Finland in late August (Ahola 1987), and in Sweden between between early August and late September (Nilsson 1985, Nilsson & Ericsson 1986). The sampling in the present studies was mostly done in late August (VII-IX), but in the case of VI so late that the leaf mass was already declining.

Sometimes the regression models used can lead to inaccuracies. A common problem is the poor additivity of the masses obtained using dry-mass equations for the different compartments of a sampled tree. When the dry-mass equations for the different compartments are calculated independently, and when the sampling errors of the different compartments differ, the result might be a group of regression equations behaving irrationally with respect to each other (Cunia & Briggs 1984). Also, missing data for some compartments can hinder additivity (Kozak 1970). Several procedures for solving the problem have been presented (see Jacobs & Cunia 1980, Cunia & Briggs 1984, Chieynda & Kozak 1984). In the present experiments, the same independent variables were used in the dry-mass models for the different compartments except for root and stump mass (IV, VI-IX). It should especially be kept in mind that extrapolation over the sample tree range can cause considerable errors, but predictions from allometric equations can be extrapolated more readily than from weighted linear equations, for instance (Crow & Schlaegel 1988). Thus, major errors in estimating of dry-matter production per hectare may be caused by poor sampling and by the regression equations used (Cannell 1989).

All biomass figures were calculated supposing a cutting height of 10 cm. In Sweden a fixed cutting height of 5 cm above ground level has been used (Telenius & Verwijst 1995). Since the actual stool height following harvesting with brush saw or commercial willow harvesters has been 10-20 cm (I, Telenius & Verwijst 1995) biomass estimates differ from the actual amount of harvested biomass.

Height and diameter distribution have to be measured when calculating the biomass using dry-mass equations. Similar systematic sampling procedure than used in I, III, V-IX gives according to Telenius and Verwijst (1995) goood estimate of the stem frequency distribution. It is often difficult to measure the height of willows accurately, especially of clones with contorted stems (I, V). Usually, there are many small sprouts in a willow stand. Even though the number of small sprouts is high, their biomass is very small compared to the mass of the larger sprouts (III). It would have been possible, when measuring the one-year-old plantation, to omit over 50% of the sprouts without underestimating the stem mass by more than 5%. The tallest 10% of sprouts contained 45% out of the dry-mass. When the dominant height of willows was 200 cm, all sprouts shorter than 110 cm could have been

left unmeasured. The amount of work can, therefore, be considerably reduced and the measurements can be concentrated on sprouts containing the highest amount of biomass.

The various methods for measuring the biomass of short-rotation plantations produced some differences between the biomass estimates (I). The basal area ratio method, sometimes used in biomass studies consistently overestimated the willow biomass (I). The most laborious method was the harvesting method, whereas the amount of work and expense incurred in the other methods were less. Regression estimation as a non-destructive method is especially suitable when the plantation is to be grown further or when estimates of annual biomass production during a sequence of years are needed.

## 4.2 Establishment, regeneration and stand structure

The establishment of the short-rotation plantations with cuttings was successful (IV, VI-IX). While the percentage of rooted cuttings was high additional planting was done to secure the evenness of the plantations. The size of the poplar cuttings (IV) had a significant effect on sprouting and early sprout growth. Thicker willow and poplar cuttings root easier and develop longer and thicker sprouts during the first growing season (IV, Singh & Chaukiayal 1983, Koo et al. 1986, Burgess et al. 1990, Rossi 1991).

Short-rotation forestry utilizes the exceptional growth rates of coppice shoots. The reasons for the rapid early development of coppice shoots are not fully understood, but altered shoot-root ratios and large root systems are important factors. A factor critical to biomass plantations is the viability of the coppice system over several successive rotations (Sennerby-Forsse et al. 1992). Several factors, both internal and external, influence the regeneration of stumps following cutting (Kauppi 1989, Ferm & Kauppi 1990, Paukkonen et al. 1992). Many cultivation-related factors, e.g. stump diameter, age of the tree, site quality, spacing and the harvesting cycle, influence coppicing.

The timing of cutting had a marked impact on the height growth, biomass production, and survival of the exotic willow species (II). The best regrowth occurred when the plants were cut during the dormant stage, i.e. between late autumn and early spring. Cutting at the end of July, or beginning of August, had a highly detrimental effect on survival. Besides willows, many other species also exhibit seasonal variation in coppicing, the dormant season being superior in minimizing mortality and usually also increasing the number and growth of the resulting sprouts (DeBell & Alford 1972, Anderson 1979, Belanger 1979, Blake & Raitanen 1981, Blake 1981, Harrington 1984, Webley et al. 1986). Short-rotation willow plantations should be harvested during the dormant period as recommended in old textbooks on the cultivation of basket willows (II, Flinta 1882, Nordberg 1914, 1928). Thus, the harvesting of protein-rich leaves for fodder (as suggested by, for example, Näsi & Pohjonen 1981, Näsi 1983, Pohjonen & Näsi 1983) during the growing season would markedly decrease the vitality of the plantations.

There are considerable inter-species differences in the reaction to the timing of cutting

(Blake 1981, Blake & Raitanen 1981, Webley et al. 1986). This was most clearly evident in regard to survival (III). Contrary to the behaviour of exotic willows, the survival of downy birch or indigenous willow species was not affected by the timing of cutting; their survival exceeded 80% throughout. In the case of birch, this has been observed to be the case also in earlier studies (Etholén 1974, Johansson 1992a). As in other experiments, the height growth of birch was slightly affected by the timing of cutting, with a minimum in June - July (II, Heikinheimo 1930, Mikola 1942, Leikola & Mustanoja 1961, Andersson 1966, Etholén 1974, Moilanen & Oikarinen 1980, Ferm & Issakainen 1981, Ali-Alha 1987, Johansson 1992b). This was also true of native willow (II). Differences in the height growth of birch caused by the timing of cutting levelled off within seven years. Initial differences caused by the timing of cutting may thus disappear later on (Ciancio & Menguzzato 1985).

The reasons for differences in coppicing due to timing of the cutting are not fully understood. Some earlier studies reviewed by Blake (1981) have linked differences in sprout growth to differences in the levels of carbohydrate reserves in the roots of parent trees in the season of cutting. However, the carbohydrate levels have been shown to be adequate for coppicing under most conditions (Blake 1981, Blake & Raitanen 1981, Johansson 1992a, Blake 1983) and carbohydrate concentrations and sprout growth do not correlate well. The highest number of sprouts for downy birch resulted from being cut back in the summer. Sycamore (*Platanus occidentalis* L.) produced most sprouts when cut in July (Belanger 1979). Also the buds of exotic willow species burst even when cut in late summer or early autumn (II). In the beginning of winter such sprouts are small and their moisture content is high. One reason for poor coppicing vigour and increased stump mortality following late-autumn cutting may, thus, be in the death of these small sprouts due to frost. Mikola (1942) and Johansson (1992a,b) considered frost risk to be considerable for birch, too. The axillary buds of downy birch do usually burst only after winter dormancy, but the tree is unable to maintain the same control over its basal buds (Kauppi et al. 1987). Also, the proportion of frost-hardy internodes of sugar maple (*Acer saccharum* Marsh.) in sprouts arising following post-growing-period cutting decreased with each successive cut (MacDonald & Powell 1985).

In this study (II), harvest damage had a negative effect on the survival, height growth and biomass production (26 - 54% in different rotations) of a young plantation of *S.* 'Aquatica'. In the older, well-established plantation (II), the number of sprouts per living stool and the biomass per stool was slightly lower following harvest damage caused by a mini-forwarder driven on the stumps. However, these differences were not statistically significant. Damage to birch stumps has not been observed to affect the survival or height growth of sprouts (Mikola 1942, Leikola & Mustanoja 1961, Ferm & Issakainen 1981). The differences between birch and willow in relation to the effects of harvest damage may be due to the location of the sprout-producing buds. About 90% of the basal buds of birch are located below ground level (Kauppi et al. 1987, 1988) while most buds of *Salix* 'Aquatica' are above ground level (Paukkonen et al. 1992). In willow coppice most sprouts originate from the axillary bud groups located on the remaining basal parts of the previously harvested stems (Sennerby-Forsse et al. 1992). Thus, harvesting damage may have more

serious effects on willow than on birch regeneration. Contrary to instructions on the harvesting of willow with a sharp blade without damaging the bark (Nordberg 1914, 1928, Tapio 1965), smooth cutting surfaces did not give any better coppicing results than rougher cutting surfaces made with a brushsaw (II). The sustainability of the coppice system should be taken into account when designing willow harvesters.

Stump height seems to have only a minor effect on the first rotation's yield (II) of willow and on the sprouting of poplar (*Populus trichocarpa*: DeBell & Alford 1972). However, in successive rotations, stump height was of crucial importance, with short stumps producing more biomass (as much as 70%) than high stumps (II). This is in agreement with the recommendation to cut willows at ground level (Nordberg 1928). However, according to the results obtained, stumps as high as 10 cm could be used without decreasing production. The shoots on low-cut stumps are more likely to be connected to individual roots, and this is believed to give some advantage in terms of availability of water and metabolites (Sennerby-Forsse et al. 1992). High stumps may increase the risk of fungal infection and decay and increased breaking away of sprouts from the stumps.

*Salix* 'Aquatica' is able to withstand several repeated harvests (Paukkonen et al. 1992). However, the coppicing ability of some tree species decreases if they are coppiced using short rotations (*Platanus occidentalis*: Steinbeck & Brown 1976, *Populus*: Strong 1989). The productive period of the plantations has been estimated to exceed 20 years (Anderson et al. 1983, Ledin et al. 1992). In this study (III), stool mortality increased year by year. After 10 years from the establishment of the stands, over one-third of the stools had died. In closely spaced poplar and willow stands, stool mortality is higher than in wider spacing (IV, Heilman et al. 1972, Bowersox & Ward 1976, Hytönen 1982). Due to mortality, the initial differences in spacing are reduced during the rotation (IV, Hytönen 1982). Increasing the supply of nutrients intensifies the competition process (Ford 1984). Nitrogen fertilization was shown to increase stool mortality (VIII) and decrease the rooting of cuttings (Hytönen 1984). Despite a stool mortality of 34%, the plantation (III) was still productive, containing approx. 24 000 live stools per hectare, which is more than the planting density currently used in Sweden (Sennerby-Forsse & Johansson 1989). The planting density could, most probably, be much lower if longer rotations were applied.

Increased post-harvesting coppicing compensates for the loss of stools and increases the number of sprouts by three to four times (III). After harvesting, the number of sprouts was 339 000 $ha^{-1}$ (III). Thus, during the second and following rotations, canopy closure proceeds faster than during the first rotation. This implies that competition should start earlier in subsequent rotations (III, Willebrand & Verwijst 1993). Stool mortality (III) was most probably due to competition, especially during the second seven year long rotation. The reduction in the number of sprouts with increase in stand age was an indication of high within-stand competition (III). The number of living sprouts in the stand was much smaller than the total number of standing sprouts. Altogether 40% of the first year's initial shoots survived to the end of first three-year-long rotation and only 13% to the end of the second seven-year-long rotation (III). Similar cumulative shoot mortality has been observed also in a *Salix viminalis* plantation in Sweden after three years (Verwijst 1991b). Mortality was at

its greatest between the ages of one and two years (III, Verwijst 1991b). Already after the first growing season, 13% (first rotation) and 20% (second rotation) of the total number of standing shoots were dead. Standing dead stems in the plantation are, however, harvestable. Because standing dead stems were lost by breaking, their number remained constant during the second rotation even though shoot mortality continued. Thus, besides the decrease in the wood density of the dead shoots (Verwijst 1991b), more biomass is probably lost as the result of breaking off of dead shoots.

Competition changes the size and weight distributions in a population. In this study (III), the diameter distribution of one- and four-year-old sprouts was clearly bimodal as described also in connection with dense, even-aged, single-species stands by Ford (1975) and Mohler et al. (1978). The majority of the sprouts were short and thin. Even though their number may be high, the biomass of declining sprouts, which die at a later stage, is very small compared to the mass of larger sprouts. The death of the smallest sprouts, i.e. the first peak in the distribution, began during the first growing season. The second, smaller peak, was made up of the group of dominant sprouts. The significance of the second peak in height and diameter distribution is more important, however, from the viewpoint of the total sprout dry-mass. The positive skewness of the weight and size distributions reaches a maximum immediately before the suppressed plants begin to die (Mohler et al. 1978, Willebrand & Verwijst 1993). This phenomenon manifested itself already before the end of the first growing season (III). The basal axillary buds in willow consist of a single bud scale covering three shoot primordia, the larger one in the middle giving rise to taller shoots than the two laterally placed buds (Brunkener 1984, Paukkonen et al. 1992). This may have contributed to the first year's bimodality in the distributions.

In the stand of willow, (III), the second self-thinning phase began at the age of four years and manifested itself as renewed bimodality of the stem diameter frequency distribution. It seems that self-thinning proceeds slower during the second self-thinning phase. The death of bigger stems is probably a slower process than the death of one-year-old sprouts. Reduction in the skewness caused by the death of the most suppressed plants, as self-thinning proceeded, was observed in the frequency distributions. Kalela (1962) has also reported a death peak in stands of *Salix caprea* at the age of seven years with another mass death peak expected ten years later. According to Ford (1975) and Ford & Newbould (1971), bimodality of the stem diameter distribution indicates a disjunct distribution in growth rates. The increase in the relative growth rate from small plants to large is not uniform throughout the range of plant sizes and depends on the competition process (Ford & Newbould 1971). In coppice stands, there is competition between large shoots in the upper parts of the canopy where leaves receive direct radiation. However, once a shoot is overtopped, it exists in a markedly less favourable, but fairly constant, environment of diffuse radiation (Ford 1975).

## 4.3 Nutrition

### 4.3.1 Site characteristics

The short-rotation plantations monitored in this study were established in cut-away peatland areas and on abandoned mineral-soil agricultural fields. Mineral and peat soils differ from each other not only by their physical properties but also in regard to their biological and chemical characteristics. The greatest differences are in their pore volume, the proportions of organic and inorganic matter, and in the amounts of nutrients bound in them (Kaunisto & Päivänen 1985, Westman 1991). There were some marked differences between the cut-away peatland areas regarding their nutrient concentrations (VI-IX). Generally, it has been reported that nitrogen concentrations of cut-away peatland areas are high and those of potassium and phosphorus low (Table 3, Kaunisto 1979, 1982a, 1983, Ferm & Kaunisto 1983, Lehtonen & Tikkanen 1986, Hytönen 1987, Ferm & Hytönen 1988, Lumme 1989, Kaunisto & Viinamäki 1991). Especially at Paloneva, peat nitrogen concentrations were high, but phosphorus, potassium and calcium concentrations low compared with the other experimental areas (VI-IX, Table 3). According to the classification system of cultivated soils applied in Finland, the extractable phosphorus concentration in all the cut-away peatland areas (Table 3) was poor (< 2.0 mg $l^{-1}$), and that of potassium and calcium also poor (K < 30 mg $l^{-1}$, Ca < 600 mg $l^{-1}$) and only exceptionally rather poor (Viljavuustutkimuksen.... 1992).

In peatlands, especially in the deeper layers, only a small proportion of the total phosphorus is available to plants and and as much as 80-95% of the total phosphorus may be in the organic form (Kaila 1956). According to Aro (1995), cut-away peatland areas may contain phosphorus in amounts similar to natural nitrogen-rich peatlands. Potassium is concentrated in the surface layers of peatlands and the potassium concentration is very low in the deeper layers (Kaila & Kivekäs 1956, Pakarinen & Tolonen 1977). Most of the potassium in peat is exchangeable. Potassium as a monovalent cation is bound only loosely in organic soils. Thus, part of the potassium can be lost through leaching, especially if high doses of potassium are used (Ahti 1983). Mixing soil from ditches, soil cultivation and basic fertilization before the start of some of the experiments (VII-IX) increased the site-to-site variation; e.g. mixing clay mineral soil into peat fields, a common practice in Finland, has increased the amounts of total potassium in soil. Peat layer in the experimental fields was so thick, over 30 cm, that willow roots most probably did not penetrate into the subsoil (Ericsson et al. 1983, Ericsson 1984, Elowson & Rytter 1984).

The pH of cut-away peatland areas is almost without exception too low for the cultivation of many willow species (Lattke 1969, Ericsson & Lindsjö 1981, Ferm & Hytönen 1988). In terms of their pH, all the areas would be classified as poor or fairly poor compared with cultivated soils (Viljavuustutkimuksen... 1992). Therefore, all experimental fields in the cut-away peatland areas were limed or ash fertilized (VI-IX). The pH of agricultural fields can be high enough for the cultivation of many willow species (IV, Kurki 1982, Viljavuustutkimuksen... 1992). Even though liming and application of ash increased

the pH of the cut-away peatland areas, it still remained below the optimum for *S. viminalis* root growth (Ericsson & Lindsjö 1981) but probably did not limit willow growth even at the Valkeasuo site, where the pH was the lowest (VII, Ferm & Hytönen 1988). The amounts of liming agents should be fairly high in order to increase the low soil pH of cut-away peatland areas to 5.0 - 5.5 for the lifetime of the plantation throughout the soil-tilling and root zone.

Table 3. Ash content, pH, total nitrogen, acid ammonium acetate extractable phosphorus, potassium, calcium and magnesium concentrations of unfertilized cut-away peatland areas according to some investigations conducted in Finland.

| Area[1] | pH no amelio-ration | Ash content, % | Peat depth, cm | N tot., % | P mg $l^{-1}$ | K mg $l^{-1}$ | Ca mg $l^{-1}$ | Mg mg $l^{-1}$ | Author |
|---|---|---|---|---|---|---|---|---|---|
| Aitoneva | 3.8 | - | - | 1.8[3] | - | - | - | - | Kaunisto 1982a |
| Aitoneva | 3.7 | 14 | - | 1.7 | - | - | - | - | Kaunisto 1983 |
| Aitoneva | 3.9 | - | 55-87 | 2.4[3] | - | - | - | - | Kaunisto 1987a |
| Aitoneva | 3.6 | 16 | 38 | 1.7 | 2.8 | 55 | - | - | Ferm & Kaunisto 1983 |
| Aitoneva | 3.9 | - | - | 1.4 | 1.7 | 15 | 350 | 77 | Ferm & Hytönen 1988 |
| Hirvineva | 4.5-5.0 | 39 | - | 1.5 | 0.8 | 10 | 679 | 110 | Lumme et al. 1984 |
| Hirvineva | 4.5 | - | 10-100 | 1.5 | 0.8 | 11 | 216 | 39 | Lehtonen & Tikkanen 1986 |
| Hirvineva | 4.8 | - | 20-40 | 2.0 | 0.0 | 9 | 520 | 87 | Lumme & Törmälä 1988 |
| Katinhännänsuo | - | - | >100 | 1.6 | 1.6 | 50 | 2670[2] | 132[2] | Hytönen 1987 |
| Paloneva | 4.9 | - | - | 2.4 | 1.2 | 7 | 618 | | Hytönen 1984 |
| Paloneva | 4.9 | - | - | 2.7 | 1.3 | 13 | 488 | 98 | Ferm & Hytönen 1988 |
| Paloneva | 4.1 | 6-10 | 152 | 3.0 | 0.9 | 8-15 | 533[2] | 157[2] | VII-IX, Hytönen unpubl. |
| Paloneva | - | - | 91 | 2.7 | 1.9 | 5 | 675 | 244 | VI |
| Paloneva | - | 10 | - | 2.5 | 1.1 | 10 | 650[2] | 171[2] | Hytönen 1987 |
| Piipsanneva | 3.9 | 39 | - | 1.4 (2.4[3]) | - | - | - | - | Kaunisto 1982a, 1983 |
| Piipsanneva | 3.9 | - | 59 | 3.4 | - | - | - | - | Kaunisto 1987a |
| Piipsanneva | 4.8 | - | - | 2.1 | 1.0 | 5 | 660 | 100 | Ferm & Hytönen 1988 |
| Piipsanneva | 4.2 | 16-29 | 40-58 | 1.8 | 0.2-1.8[4] | 12-22[4] | 830-1430[2] | 210-520[2] | VII-IX |
| Piipsanneva | 4.8 | - | 81 | 1.7 | 1.1 | 12 | 742 | - | Hytönen et al. 1995 |
| Osmanginsuo | 4.5 | - | 40-74 | 2.5,2.4[3] | - | - | - | - | Kaunisto 1982a, 1987a |
| Valkeasuo | 4.3 | - | - | 1.4 | 1.2 | 5 | 450 | 35 | Ferm & Hytönen 1988 |
| Valkeauso | 4.2 | - | - | 2.3 | 2.2 | 13 | - | - | Hytönen 1984 |
| Valkeasuo | 3.9 | 24-28 | 42-46 | 1.5 | 1.2 | 17 | 322 | 45 | VII, Hytönen unpubl. |
| Valkeasuo | 4-5 | - | - | - | 0.4 | 20 | 420 | 32 | Heikkilä 1986 |
| Valkeasuo | 4.2 | - | 94 | 1.8 | 1.1 | 37 | 465 | - | Hytönen et al. 1995 |

1) Location of cut-away peatland areas: Aitoneva at Kihniö, Hirvineva at Liminka, Katinhännnsuo at Vihti, Paloneva at Rantsila/Ruukki, Piipsanneva at Haapavesi, Valkeasuo at Tohmajärvi, Osmanginsuo at Kiuruvesi. 2) Liming. 3) From organic matter. 4) Basic fertilization with PK or NPK four years before analysis

### 4.3.2 Effect of fertilization on soil nutrients

In cut-away peatland areas fertilization with phosphorus (superphosphate) and potassium (potassium chloride) increased the amounts of the corresponding acid ammonium acetate extractable nutrients in soil manyfold (often tenfold) compared to the control plots (VI-IX). However, even after two or three annual PK fertilizer applications, the extractable phosphorus and potassium concentrations in peat were rather poor (VI-IX) and only on the experimental field ameliorated with wood ash the P and K concentrations were good (VII)

according to the classification system for cultivated soils in Finland (VI-IX, Kurki 1982, Viljavuustutkimuksen... 1992). Also the phosphorus and potassium concentrations of mineral soil fields were low (V) or satisfactory (IV) according to the classification system applied.

Changes in peat phosphorus and potassium concentrations depended on the amount of nutrients given in the fertilizer applications (VIII, IX, Kaila 1959, Saarela 1982, Hytönen 1987) and in the case of phosphorus on the type of the phosphorus fertilizer (VI). The higher the phosphorus fertilizer amount the higher the soil phosphorus concentration after three year study period. Single-application of 60 kg $ha^{-1}$ of fertilizer phosphorus could be detected in soil analysis after three years from fertilization. Phosphorus from easily soluble compounds increased the acid ammonium acetate extractable peat phosphorus concentration (VI). On limed peatland sites, slowly soluble phosphorus fertilizers (rock phosphate, apatite) failed to increase the amount of extractable phosphorus in the substrate and did not ensure the availability of phosphorus for willows (VI, Kaunisto 1983, Yli-Halla & Lumme 1987). This is probably due to the fact that a rise in pH caused by liming decreases considerably the solubility of apatite (Salonen 1968, Karsisto 1973, 1976). Since the solubility of phosphorus in wood ash is greater than that in rock phosphate ash fertilization increases considerably the extractable phosphorus concentrations in peat (VII, Kaunisto 1983, Ferm & Hytönen 1988, Lumme & Laiho 1988). In *Carex* peat readily soluble phosphorus can be bound tightly by Al and Fe (Yli-Halla & Lumme 1987). Besides commercial fertilizers also wood ash can be used to increase the soil potassium concentration (VII, Kaunisto 1983, Ferm & Hytönen 1988). Fertilization with nitrogen only decreased the peat phosphorus and potassium concentrations (VII, cf. Ferm & Hytönen 1988). This was probably due to the higher biomass production and increased phosphorus and potassium utilisation of willows fertilized with nitrogen.

### 4.3.3 Nutrient concentrations in willow

Analysis of foliar mineral nutrient concentrations has been used for a long time to diagnose nutrient status and the fertilization need of trees (e.g. Paarlahti et al. 1971, Paavilainen 1979). The time of leaf sampling is important since foliar nutrient concentrations change during the growing season. Towards autumn the foliar nitrogen and phosphorus concentrations of willow decrease while that of calcium increases and that of potassium may increase or decrease (Lehtonen & Tikkanen 1986, Saarsalmi 1984, Elowson & Rytter 1988, Rytter & Ericsson 1993). Because the foliar nutrient concentrations of willows (e.g. *S.* 'Aquatica', Lehtonen & Tikkanen 1986) vary also from the base to the top of the shoot, subsampling of foliage from different parts of the shoot can also cause variation in the results. In these studies, foliar samples were taken along the whole length of the shoots and mainly at the end of August (VII-IX), but in studies V and VI from the upper parts of the shoots. According to Rytter and Ericsson (1993), the most appropriate time for leaf sampling of *S. viminalis* is during the phase of the most intensive growth. Samples for bark and wood nutrient analysis included whole shoots, with wood and bark separated, thus

avoiding possible errors related to subsampling (VI, VII).

Foliar nitrogen, phosphorus and potassium concentrations of fertilized *S.* 'Aquatica' and *S. x dasyclados* have mainly been in the range of 23 - 42 g $kg^{-1}$, 2 - 5 g $kg^{-1}$ and 10 - 24 g $kg^{-1}$, respectively, in experiments conducted in Finland (V-IX, Table 4, Lumme et al. 1984, Saarsalmi 1984, Ferm 1985a). The willows in this study, VI-IX, responded readily to fertilizer applications: as in other studies, nitrogen, phosphorus and potassium fertilization increased the corresponding foliar nutrient concentrations (Kaunisto 1983, Hytönen 1987, Ferm & Hytönen 1988). According to Ericsson (1981b), the decisive factor governing mineral uptake in *Salix* is the rate of nutrient supply. Response was related to the amount of nutrients applied (VIII), the number of applications (IX), the concentrations of soil nutrients (VII, VIII) and, in the case of phosphorus, also to the type of fertilizer (VI). Only superphosphate increased the phosphorus concentration in the foliage, bark and wood, while concurrently slightly decreasing their potassium concentrations (VI).

Annual fertilizer treatment is needed in order to keep foliar nitrogen concentrations at a high level, whereas higher application rates of phosphorus and potassium at the establishment phase may compensate for the effect of annually repeated fertilization (IX). Fertilizer application can be used to adjust foliar nitrogen, phosphorus and potassium concentrations and also foliar nutrient ratios; e.g. the foliar nitrogen concentrations of willow clones demonstrating good production have been 30 - 40 g $kg^{-1}$ (Rytter & Ericsson 1993) and foliar nitrogen concentrations of short-rotation poplar should be maintained at a level of over 30 g $kg^{-1}$ to achieve good growth (Hansen et al. 1988). Sludge fertilization increased foliar nitrogen concentrations the more the higher the amount of sludge used, but decreased foliar phosphorus concentration at the same time (V, Lumme & Laiho 1988, Lumme 1989, Simon 1989a, 1989b).

Nitrogen fertilization increased the nitrogen concentration of bark by 1 - 3 mg $g^{-1}$ and phoshorus fertilization increased the phosphorus concentration in both the bark (0.2 - 0.4 mg $g^{-1}$) and wood (0.2 - 0.5 mg $g^{-1}$) (VI, VII). Potassium fertilization increased foliar potassium concentrations but not those of wood and bark (VII). Especially the nutrient concentrations in the bark and wood, but in some cases also that in leaves, changed with increase in willow age, so that older willows tended to have lower nutrient concentrations (VII). Especially nitrogen, phosphorus and potassium concentrations in one-year-old willow bark were high (VII, Table 4). However, the phosphorus and potassium concentrations in the wood changed only little with increase in age. Bark calcium concentrations increased with age (VII). Differences in nutrient concentrations in the bark and wood are high (VI, VII, Ferm 1985a). Some of the clonal and between-species differences that have been found in some studies in stem (wood and bark) nutrient concentrations of willow sprouts (Viherä-Aarnio & Saarsalmi 1994) can be attributed to differences in sprout size and consequently the varying amounts of wood and bark in the stem biomass.

Table 4. Nutrient concentrations (mg $g^{-1}$) in the above-ground parts of some tree species at different ages (years) according to the results of some investigations conducted in Finland.

| Species | Age | Nitrogen | | | Phosphorus | | | Potassium | | | Calcium | | | Magnesium | | | Author |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | years | Foliage | Bark | Wood | Foliage | Bark | Wood | Foliage | Bark | Wood | Foliage | Bark | Wood | Foliage | Bark | Wood | |
| *S.* 'Aquatica' | 1 | 22 | - | - | 4.8 | - | - | 17 | - | - | 10 | - | - | 3 | - | - | Viherä-Aarnio & Saarsalmi 1994 |
| " | 1 | 24-37 | 18-21 | 5-6 | 1.7-2.7 | 1.8-2.5 | 0.6-0.8 | 8-20 | 8.0-8.6 | 1.5-2.5 | - | - | - | - | - | - | VII, IX |
| " | 1 | 27-38 | - | - | 5.4-15.5 | - | - | 5-17 | - | - | 2-12 | - | - | 2-11 | - | - | Lehtonen & Tikkanen 1986 |
| *S. x dasyclados* | 1 | 30-35 | - | - | 2.1-2.4 | - | - | 16-21 | - | - | - | - | - | - | - | - | VII, IX |
| *S.* 'Aquatica' | 2 | 23-39 | 11-22 | 3-6 | 1.9-4.7 | 1.4-2.2 | 0.6-0.9 | 11-19 | 6.9-7.3 | 2.1-2.6 | 7-10 | 7-8 | 0.9-1.3 | 4-6 | 2 | 0.4-0.7 | V, VI, VII, VIII, IX |
| *S. x dasyclados* | 2 | 24-34 | - | - | 2.3-3.0 | - | - | 14-24 | - | - | 6-8 | - | - | 5-6 | - | - | VII, IX |
| *S.* 'Aquatica' | 3 | 29-42 | 11-13 | 2-3 | 2.3-3.8 | 1.5-1.7 | 0.7-0.8 | 10-18 | 5.9-7.9 | 1.7-3.0 | 8-12 | 8-9 | 1.1-1.3 | 4-7 | 2 | 0.5-0.6 | V, VII, VIII, IX |
| *S. x dasyclados* | 3 | 27-35 | 9 | 3 | 2.7-3.3 | 1.4 | 0.8 | 14-18 | 5.4 | 1.8 | 7-8 | 7 | 1.2 | 5-6 | 1.7 | 1.2 | VII, IX |
| *A. incana* | 4 | 36 | 17 | 5 | 2.7 | 1.6 | 0.7 | 16 | 4.7 | 1.8 | 11 | 7 | 1.0 | 2 | 0.9 | 0.3 | Saarsalmi et al. 1985 |
| " | 6 | 36-40 | 16 | 4 | 2.1-2.2 | 1.4 | 0.5 | 15 | 4.6 | 1.2 | 11-14 | 6 | 1.2 | 3 | 0.9 | 0.3 | Saarsalmi et al. 1985, 1992 |
| " | 10 | 36 | - | - | 2.0 | - | - | 15 | - | - | 12 | - | - | 2 | - | - | Saarsalmi et al. 1992 |
| " | 25 | 28 | 11 | 2 | 1.1 | 0.8 | 0.2 | 11 | 3.4 | 0.9 | 9 | 8 | 0.8 | 2 | 0.6 | 0.2 | Saarsalmi et al. 1991 |
| *B. pendula* | 6 | 29 | - | - | 4.0 | - | - | 10 | - | - | 8 | - | - | 3 | - | - | Saarsalmi et al. 1992 |
| " | 10 | 27 | - | - | 4.3 | - | - | 11 | - | - | 10 | - | - | 3 | - | - | Saarsalmi et al. 1992 |
| *B. pubescens* | 40 | 24 | 5 | 0.8 | 1.9 | 0.4 | 0.1 | 10 | 3.9 | 0.4 | 11 | 6 | 0.6 | - | - | - | Mälkönen 1977 |
| " | 40-60 | 24 | 5 | 1 | 1.5 | 0.3 | 0.06 | 7 | 1.1 | 0.3 | 10 | 5 | 0.5 | 3 | 0.4 | 0.1 | Finér 1989 |
| *P. sylvestris* | 28-47 | 12-13 | 3-4 | 0.6-0.7 | 1.5-1.6 | 0.5-0.6 | 0.04-0.06 | 6-8 | 1.9-2.3 | 0.3-0.4 | 2 | 3-6 | 0.5-0.6 | - | - | - | Mälkönen 1974 |
| " | - | 14-17 | 4-6 | 0.4 | 1.6-2.3 | 0.5-0.7 | 0.07 | 4-5 | 1.4-2.6 | 0.3-0.4 | - | - | - | - | - | - | Paavilainen 1980 |
| " | 40-60 | 14-16 | 4-5 | 1 | 1.4-1.9 | 0.3-0.6 | 0.03-0.05 | 5 | 1.3-1.5 | 0.2-0.3 | 2 | 3 | 0.5 | 1 | 0.4-0.6 | 0.2 | Finér 1989 |
| " | 85 | 11 | 4 | 0.6 | 1.4 | 0.4 | 0.03 | 5 | 1.4 | 0.3 | 2 | 3 | 0.5 | 1 | 0.5 | 0.1 | Finér 1992 |
| *P. abies* | 100 | 14.3 | 5 | 0.6 | 1.6 | 0.5 | 0.03 | 5.7 | 1.7 | 0.3 | 4 | 10 | 0.7 | 1.0 | 0.7 | 0.1 | Finér 1989 |

All willows were fertilized with NPK, except those in V (sludge), Viherä-Aarnio & Saarsalmi (1994) (no fertilization), Lehtonen & Tikkanen (1986) (N+peat ash). Also the birch, pine and spruce stands of Finér (1989) were fertilized with NPK. Alders (Saarsalmi et al. 1985, 1992) were fertilized with wood ash and birches (Saarsalmi et al. 1992) were fertilized with N + wood ash. The growing sites were mineral soil fields in V, Saarsalmi et. al. 1985, 1992, Viherä-Aarnio & Saarsalmi 1994, cut-away peatland areas in VI, VII, VIII, IX, Lehtonen & Tikkanen 1986, *Vaccinium* type and *Myrtillus* type forest soils in Mälkönen 1974, *Oxalis-Myrtillus* type forest soils in Saarsalmi et al. 1991 and in Mälkönen 1977 (*Betula pubescens* 84%, *B. pendula* 16%). The birches in Finér 1989 were growing on a herbrich sedge pine mire and pines on a herbrich pine mire and on an ordinary sedge pine mire and spruces on a *Vaccinium myrtillus* spruce mire. The pines in Paavilainen 1980 were growing on a dwarf shrub pine swamp and in Finér 1992 on a low-shrub pine bog.

Even though the foliar nutrient concentrations in the fertilized willow stands were generally high as compared to Scots pine or silver birch or downy birch, the greatest differences between these tree species were noted in the nutrient concentrations in the wood and bark (V-IX, Table 4). The nitrogen, phosphorus and potassium concentrations in willow bark were two to three times higher than in birch or pine (Table 4). The nitrogen concentrations in willow wood at the age of three years were 2- 5 times higher, those of phosphorus 7 - 20 times higher, and those of potassium 5 - 8 higher than in pine, spruce or birch. Higher nitrogen concentrations in all the compartments in grey alder and similar or lower foliar phosphorus and potassium concentrations than those of willows in these studies have been reported (Table 4). The magnesium concentrations in willow bark were 2-3 times higher than in grey alder and the calcium concentrations in spruce bark were even higher than in willow.

### 4.3.4 Nutrients bound into the biomass

The amount of nutrients bound in a short-rotation plantation is affected by the allocation of biomass among the tree compartments and the nutrient concentrations of the compartments. By far the highest proportion of nutrients was bound in the foliage (VI, VII). The foliage accounted for 21-23% of the above-ground biomass in a two- and three-year-old willow stand, but 40-64% of the nutrients (VI, VII). The proportion of bark out of the total biomass was 23% and the proportions of most nutrients in the bark varied within the range 20-23% (VII) or 26-30% (VI). Calcium was an exception; the bark contained 40% of the total calcium (VII). The proportion of wood in the biomass was 54-56% (VI, VII), but the percentages of most nutrients in the wood varied between 15-22%. The percentage of phosphorus (30-31%) was, however, clearly higher. The high proportion of phosphorus in the willow wood was also clear in the study by Ferm (1985a). As mentioned earlier, also age affects considerably the nutrient concentrations in the biomass compartments. With increase in age and size, the percentage of compartments containing most nutrients (foliage, bark) decreases and the percentage of wood increases (VI-IX).

Compared with the amounts given in fertilization, the willow stands in this study (VI, VII) bound considerably smaller amounts of nitrogen, and especially of phosphorus and potassium, into their biomass. Only in the fastest growing *S. x dasyclados* stands was the amount of nitrogen in the biomass of the same order as given in fertilization if the nitrogen bound into the leaves during three years is also considered (VII). At the age of three years, the difference in the amounts of nitrogen bound into the above-ground leafless biomass between the control and NPK-fertilized plots was 12 - 16% of the nitrogen given in fertilization (VII). The recovery was similar to that reported in short-rotation (Miegroet et al. 1994) and conventional tree plantations studies (Paavilainen 1979, Ballard 1984).

The amount of phosphorus, potassium and calcium bound into one metric tonne of willow biomass (VI, VII) was at the same level as in earlier investigations (Table 5) except that by Saarsalmi (1984) which reports higher amounts of bound potassium. With an

increase in willow age from one to two or three years the amount of nitrogen bound into one metric tonne of biomass decreased by 13 - 30%, and as much as by 60%, in a nitrogen-rich (VII) area and by 42% in a *S. viminalis* stand in Sweden (Nilsson & Ericsson 1986). This has been considered to be an expression of the increased nutrient use efficiency of older shoots (Nilsson & Ericsson 1986). Thus, short rotations entail the removal of higher quantities of nitrogen and also potassium per harvested unit biomass than longer rotations (Table 5). Contrary to the behaviour of nitrogen and potassium, the amount of phosphorus bound into one metric tonne of willow biomass did not decrease, or decreased only slightly, with increasing age or yield because of the fairly high phosphorus concentration in willow wood (VI, VII). Unit biomass of young grey alder and birch contains equal amounts (but unit biomass of older alder or birch considerably less) of nitrogen compared to the three-year-old willows in this study (Table 5). The unit biomass of Scots pine contains considerable smaller amounts of N, P, K, Ca and Mg even when the stands are equal in terms of their amounts of biomass (Table 5). Birch, as regards its nutrient requirements, is a demanding species compared to Scots pine (Mälkönen 1977) and willows are even more demanding (Table 5). Since the fertilization regime (VI, VII), tree age and size (VII) affect the amount of nutrients bound in one metric tonne of biomass, one should be careful when making conclusions on the nutrient requirements of different tree species based on these figures (VII, Table 5).

Willow stands bind high amounts of nutrients into their biomass (VI, VII, Saarsalmi 1984, Ferm 1985a, Nilsson 1985, Nilsson & Ericsson 1986, Hytönen et al. 1995). Two to three-year-old willow stands may contain nitrogen, phosphorus and potassium (VI: N 228, P 21, K 84 kg ha, VII: N 196, P 26, K 101, Ca 47, Mg 37 kg $ha^{-1}$) in amounts equal to or even exceeding those of an advanced 40-year-old birch stand, a pole-sized Scots pine stand, an 85-year-old Scots pine stand (above-ground biomass 62 t $ha^{-1}$) or a 100-year-old Norway spruce stand (Mälkönen 1977, Paavilainen 1980, Finér 1989, 1991). Stands of grey alder (with above-ground biomasses of 24 - 32 t $ha^{-1}$) have been found to bind considerably more nitrogen into their biomass, but equal amounts or less of phosphorus, potassium, calcium and magnesium, than the willow stand of 18 t $ha^{-1}$ examined in this study (VII, Saarsalmi et al. 1985, 1991, 1992).

The ability of willows to utilize high amounts of nutrients can be exploited in the treatment of waste waters in sanitary landfills (Ferm 1985a, Ettala 1987, 1988) or in the removal of nutrients from other wastewaters and sludges. Such vegetation filters could act as both economically and environmentally sound biological purification systems (Aronsson & Perttu 1994). There were marked site-to-site differences, especially in the foliar zinc, but also in copper, manganese and iron concentrations (V, VII, VIII). Some willow clones can accumulate high amounts of heavy metals (especially cadmium) and thus they could be used to remove heavy metals from polluted soil (Landberg & Greger 1994).

Table 5. Dry-mass (t $ha^{-1}$) and the amounts of nutrients bound into above-ground biomass (kg $t^{-1}$) of some tree species at different ages (years) according to investigations conducted in Finland. Figures calculated from data presented in the publications.

| Species and clones | Age | Dry-mass | N | P | K | Ca | Mg | Author |
|---|---|---|---|---|---|---|---|---|
| *Salix* 'Aquatica' | 5 | 0.4 | 18.2 | 2.3 | 9.1 | 5.7 | 2.3 | Hytönen et al. 1995 |
| " | 1 | 0.5 | 22.9 | 1.8 | 7.3 | - | - | VII |
| " | 1 | 1.0 | 15.8 | 1.3 | 9.8 | - | - | VII |
| " | 1 | 2 | 16.3 | 2.0 | 10.9 | 4.6 | 1.2 | Ferm 1985a, Ettala 1987 |
| " | 2 | 3.7 | 18.3 | 1.8 | 8.4 | 5.6 | 2.6 | VII |
| " | 2 | 6.8 | 13.8 | 1.6 | 8.9 | 5.1 | 2.1 | VII |
| " | 1 | 11.0 | 12.4 | 1.9 | 13.6 | 4.8 | 1.5 | Saarsalmi 1984 |
| " | 3 | 12.3 | 10.6 | 1.5 | 5.2 | 4.5 | 1.9 | VII |
| " | 3 | 12.6 | 12.9 | 1.5 | 7.0 | 5.1 | 2.0 | VII |
| " | 2 | 13.1 | 17.3 | 1.6 | 6.3 | - | - | VI |
| " | 1 | 17 | 11.5 | 1.4 | 9.5 | 3.7 | 0.8 | Ferm 1985a |
| *S. x dasyclados* | 3 | 18.4 | 10.5 | 1.4 | 5.4 | 4.0 | 2.0 | VII |
| " | 5 | 19.4 | 9.2 | 1.4 | 5.8 | 4.2 | 1.7 | Hytönen et al. 1995 |
| *S.* 'Aquatica' | 3 | 25 | 9.1 | 1.0 | 6.2 | 5.7 | 0.6 | Ferm 1985a |
| " | 2 | 34 | 10.4 | 1.3 | 6.8 | 5.8 | 0.6 | Ferm 1985a |
| " | | | | | | | | |
| *Salix phylicifolia* | 5 | 43.0 | 6.5 | 1.3 | 4.5 | 4.5 | 1.0 | Hytönen et al. 1995 |
| *Alnus incana* | 6 | 9.0 | 17.5 | 1.6 | 4.8 | 6.6 | 0.9 | Saarsalmi et al. 1992 |
| " | 4 | 15.9 | 11.4 | 1.2 | 4.3 | 3.6 | 0.7 | Saarsalmi et al. 1985 |
| " | 10 | 25.1 | 9.6 | 0.9 | 3.4 | 3.7 | 0.5 | Saarsalmi et al. 1992 |
| " | 7 | 29.5 | 12.3 | 1.0 | 3.4 | 4.1 | 1.1 | Hytönen et al. 1995 |
| " | 6 | 31.1 | 8.8 | 0.8 | 2.9 | 3.0 | 0.6 | Saarsalmi et al. 1985 |
| " | 35 | 33.6 | 6.8 | 0.5 | 1.9 | 3.1 | - | Saarsalmi & Mälkönen 1989 |
| " | 35 | 69.2 | 5.8 | 0.4 | 1.5 | 2.7 | - | Saarsalmi & Mälkönen 1989 |
| *P. x rasymowskyana* | 3 | 15 | 8.1 | 1.0 | 7.7 | 6.0 | 0.8 | Ferm 1985a |
| *Betula pendula* | 6 | 3.8 | 10.3 | 1.4 | 3.8 | 4.3 | 1.0 | Saarsalmi et al. 1992 |
| " | 7 | 4.9 | 9.9 | 1.3 | 3.1 | 3.3 | 0.9 | Hytönen et al. 1995 |
| " | 10 | 12.9 | 6.5 | 1.0 | 2.5 | 3.0 | 0.7 | Saarsalmi et al. 1992 |
| " | 8 | 15.2 | 7.3 | 0.8 | 2.4 | 2.3 | 0.7 | Hytönen et al. 1995 |
| " | 7 | 24.4 | 7.7 | 1.1 | 3.3 | 3.0 | 1.1 | Hytönen et al. 1995 |
| *Betula pubescens* | 20 | 38.3 | 3.9 | 0.5 | 1.3 | 2.5 | - | Mälkönen & Saarsalmi 1982 |
| | 40-60 | 38.6 | 2.7 | 0.2 | 0.7 | 2.0 | 0.3 | Finér 1989 |
| " | 40 | 90.2 | 2.4 | 0.2 | 1.2 | 2.0 | - | Mälkönen 1977 |
| " | 40 | 120.3 | 2.6 | 0.2 | 0.9 | 1.6 | - | Mälkönen & Saarsalmi 1982 |
| *Pinus sylvestris* | 28 | 17.9 | 3.0 | 0.4 | 1.5 | 2.2 | - | Mälkönen 1974 |
| " | 47 | 41.9 | 2.6 | 0.3 | 1.1 | 1.2 | - | Mälkönen 1974 |
| " | 40-50 | 50.0 | 2.5 | 0.3 | 0.7 | 1.1 | 0.3 | Finér 1989 |
| " | 40-60 | 52.4 | 1.4 | 0.1 | 0.1 | 0.8 | 0.2 | Finér 1989 |
| " | 85 | 53.4 | 2.1 | 0.2 | 0.8 | 1.3 | 0.3 | Finér 1991 |
| " | - | 75.2 | 2.3 | 0.3 | 0.8 | 1.3 | 0.4 | Paavilainen 1980 |
| " | 45 | 75.9 | 2.0 | 0.2 | 1.0 | 1.3 | - | Mälkönen 1974 |
| *Picea abies* | 100 | 121.9 | 2.6 | 0.2 | 0.9 | 2.6 | 0.2 | Finér 1989 |

All willows were fertilized with NPK, except those in Ferm (1985) and Ettala (1987) with wastewater leachate. The birch, pine and spruce stands of Finér (1989) were also fertilized with NPK. Alders in Saarsalmi et al. (1985, 1992) were fertilized with wood ash and birches in Saarsalmi et al. (1992) were fertilized with N + wood ash. Alders in Hytönen et al. (1995) were fertilized with PK and birches with NPK.

In the lysimeter experiment by Saarsalmi (1984), the amounts of N and K leached from soil (limed *Sphagnum* peat) was only 0.5 - 0.6% of the amounts added in fertilization and the plants received more nutrients with the rain than was lost through leaching. In a short-rotation sycamore (*Platanus occidentalis* L.) plantation the lowest nitrate leaching losses

were observed when the fertilizer was added in small, periodically administered amounts (Miegroet et al. 1994). Since this resulted in no benefits to biomass production, it would probably not be cost-effective in commercial operations (Miegroet et al. 1994). No leaching of nitrogen was observed in fertilized and irrigated willow stands on an abandoned sandy field in Sweden (Christersson 1987). Besides leaching, part of the nitrogen may have been bound into the organic matter in soil.

### 4.3.5 Nutrient cycling

At the end of August, when leaf mass probably is close to its maximum (Ahola 1987), the leaves contained over half of N, K and Ca, and almost half of the amounts of P and Mg bound into the above-ground biomass of two and three-year-old willow stands, but only one fifth of the above-ground biomass (VI, VII, Ferm 1985a). Internal nutrient cycling is important in many tree species, and its significance often becomes enhanced following canopy closure. The significance of nutrient cycling in willow cultivation has been emphazised by Ingestad and Ågren (1984) and Christersson (1986). The growth of willow in this study ceased with the first autumn frosts; the leaves were shed green, and thus the amount of translocated nutrients was probably quite low. Thus less nutrients were removed from the site. Hence the annual removal of nitrogen in the stems is only 3-6 kg N $ha^{-1}$ per dry metric tonne of harvested stems and that of phosphorus 1 kg $ha^{-1}$, potassium 3 kg $ha^{-1}$ and calcium 3-4 kg (VI, VII). The leaves contained 125 kg N $ha^{-1}$, 12 kg P $ha^{-1}$ and 58 kg K $ha^{-1}$ in a three-year-old stand at the end of August (VII). In a one-year-old *S.* 'Aquatica' stand, 33-49% of the nutrients bound in the above-ground biomass may be returned to the ground in litter (Saarsalmi 1984). The rate at which litter decomposes and the nutrients become available is important. Willow litter decomposes easily, and especially potassium, but also nitrogen and phosphorus, are released quickly (Slapokas & Granhall 1991). It has been estimated that about one third of the annual nutrient demand may be met from litter mineralization in well-established willow plantations, and thus the need for fertilization could decrease considerably (Ingestad & Ågren 1984, Christersson 1986).

### 4.3.6 The response of willow to fertilization

The survival of willows in limed cut-away peatland areas without fertilization has been poor. This indicates the inadequateness of natural nutrient resources in such areas (VI, Hytönen 1982, 1987, Ferm & Hytönen 1988). Even the survival of Scots pine on unfertilized cut-away peatland has been low (0-51%, Aro 1995). Mortality among unfertilized poplars was very high on mineral soil field (IV), but fertilization can in some cases also promote the mortality of willows and poplars (VII, Hytönen 1982, Hansen et al. 1988). The high

willow survival on the control plots in experiments VII-IX was probably due to both reinforcement planting and basic fertilization (Hytönen 1982, 1985, 1987, Valk 1986, Ferm & Hytönen 1988).

Fertilization with low nitrogen rates, or with no nitrogen being applied at all, in cut-away peatland areas during the establishment phase could be appropriate. Young willows bind only small amounts of nitrogen into their biomass (15-20 kg N $ha^{-1}$). However, nitrogen application increased significantly the biomass production in the first growing season on most experimental fields, but the increases in yield were small (less than 1 t $ha^{-1}$, VII). The smallest nitrogen amounts (50 kg N $ha^{-1}$) were adequate (VIII). According to Swedish recommendations for practical energy forestry cultivation using willows, nitrogen fertilization is not needed on mineral soils during the planting year (Ledin et al. 1992, 1994), or it is recommended only in small amounts (30 - 60 kg N $ha^{-1}$) (Sennerby-Forsse & Johansson 1989). During the first production year following cutting-back nitrogen fertilization with higher amounts is recommended (45 kg N $ha^{-1}$: Ledin et al. 1994, 60-80 kg N $ha^{-1}$: Sennerby-Forsse & Johansson 1989, Ledin et al. 1992). Since weeds are the major nutrient source, weed control during the first years in short-rotation plantations can reduce the need for fertilization (Hansen et al. 1988).

During the second and third year, the importance of nitrogen fertilization for biomass production increased, but an increase in annual fertilizer nitrogen application rate in excess of 100 kg N $ha^{-1}$ did not lead to considerable increases in yields. In the nitrogen-rich cut-away peatland area application rates in excess of 50 kg N $ha^{-1}$ $a^{-1}$ did not increase the three-year biomass production (VIII). Fertilizer nutrient amounts should be adjusted according to stand development. In Sweden, the latest instructions are to apply fertilizer nitrogen on mineral soils during the second growing season at rates of 100 - 150 kg N $ha^{-1}$ and 90 - 120 kg N $ha^{-1}$ during the third growing season (Ledin et al. 1994). Earlier 60 - 80 kg N $ha^{-1}$ $a^{-1}$ was recommended (Sennerby-Forsse & Johansson 1989, Ledin et al. 1992). A heavy fertilizer nitrogen dose (200 kg N $ha^{-1}a^{-1}$) proved to be a very inefficient way of fertilizing willow plantations; the growth gains were small and they did not last (VIII, IX).

Nitrogen fertilization increased three-year biomass production 1.5 - 2.7 fold when compared to control plots (VII). In areas where peat phosphorus concentrations were highest, only nitrogen increased willow growth. According to the results of this study, it is extremely important to repeat the nitrogen fertilizer treatment annually when endeavouring to maximise willow yield (IX). This has also been observed also in short-rotation sycamore (*Platanus occidentalis* L.) plantations on mineral soil (Miegroet et al. 1994). The earlier Swedish recommendations for practical short-rotation forestry stated that fertilizers (NPK) should be applied twice during the growing season (Sennerby-Forsse & Johansson 1989), but currently only one application of nitrogen each spring is recommended (Ledin et al. 1994).

Nitrogen fertilization, even when the nitrogen concentration of peat is high (Table 3) seems to be necessary for good willow growth (VII-IX). This has also been the case in previous field and greenhouse experiments also (Hytönen 1982, 1985, 1987, Kaunisto 1983, Ferm & Hytönen 1988). Willow is much more nitrogen demanding species than eg. pine

seedlings, the growth of which is satisfactory if the peat nitrogen concentration exceeds 1.15 - 1.30% (Kaunisto 1982b) and nitrogen fertilization is not needed in cut-away peatland areas (Kaunisto 1979, 1982a, 1987a). Also, fertilizer nitrogen application has been observed to result only in modest increases in the growth of birch in cut-away peatland areas (Kaunisto 1979, 1987a).

Peat nitrogen concentration affects the fertilizer nitrogen application requirements: the higher the nitrogen concentration in the substrate, the lower the required annual nitrogen application rate (VIII, Hytönen 1987). On nitrogen-rich site also, the effect of fertilizer nitrogen was less pronounced than that of fertilizer phosphorus (VII). Nitrogen mineralization is highly dependent on the pH of the substrate. Soil respiration and nitrogen mineralization in peat can be increased through ash fertilization (Karsisto 1979, Honkanen & Vuorinen 1984, Weber et al. 1985). Liming may increase (Küster & Gardiner 1968) or decrease (Küster & Gardiner 1968, Gardiner 1975, Kaunisto & Norlamo 1976) nitrogen mineralization. This depends on peat nitrogen concentration. In low nitrogen conditions nitrogen is bound into the microbial biomass and liming may decrease even the growth of Scots pine (Kaunisto 1982b, 1987b). Due to the high nitrogen concentrations in cut-away peatland areas liming should increase the net mineralization. Since liming may change the composition of the microflora both quantitatively and qualitatively nitrification is not increased immediately after addition of calcium (Küster & Gardiner 1968). However, mineralization of nitrogen bound in peat is not alone enough to secure the nitrogen supply of willows despite the high nitrogen concentrations in peat of cut-away peatland areas.

Nitrogen is probably the nutrient most likely to limit biomass production in short-rotation plantations established on mineral soil agricultural fields. Willows fertilized with nitrogen-rich sludge grew equally well, or even better, when compared to a treatment using commercial fertilizers (V, Nielsen 1994). Biomass production (V) over a three-year period was at its maximum when 60 $m^3$ $ha^{-1}$ of sludge was applied (18.4 t $ha^{-1}$) and at its minimum when subjected to an annual multinutrient fertilizer treatment (9.1 t $ha^{-1}$). Lumme (1989), too, has observed that domestic sewage sludge is well suited for fertilization of short-rotation plantations, even though in his experiment it did not promote the growth of willows. Nitrogen fertilization has been effective in increasing the diameter and height growth and biomass production of poplars (IV, Heilman et al. 1972, Wittwer et al. 1978, Hansen et al. 1988) and young silver birch stands (Saarsalmi et al. 1992), but has not increased the growth of grey alder (Saarsalmi et al. 1985, 1992). For grey alder phophorus is more important as a nutrient than nitrogen (Saarsalmi et al. 1985, 1992). The need to increase the growth of fast-growing trees without nitrogen fertilization resulted in experimentation with short-rotation plantations mixed with $N_2$-fixing plants. The use of nitrogen-fixing tree species such as alder in mixture with other tree species is particularly problematic in short-rotations due to the often different growth patterns of genotypes (DeBell & Harrington 1993, Hytönen et al. 1995).

Due to the great variation in the nutrient concentrations of sludges, they should be analysed before use and the fertilizer application amounts adjusted accordingly. Especially potassium concentrations can be so low that additional fertilization might be needed (V,

Simon 1989a). The nitrogen concentration of sludge can be quite high and most nitrogen in the sludge is bound into organic matter. The reduced solubility of nitrogen in sludge compared to that of commercial fertilizers may be an advantage in short-rotation cultivation. The number of fertilizer applications can be reduced if the effect of nitrogen fertilization lasted longer. Also, less soluble commercial nitrogen fertilizers should be tested in this respect. Sludges can also increase soil microbial activity and change soil physical characteristics. Technically, the spreading of sludge in short-rotation plantations at the establishment phase is easy and reapplication is possible (V, Hytönen 1988). High levels of some metals (e.g. aluminium) in some sludges may limit growth (Siira et al. 1984, Landberg & Greger 1994).

The effect of phosphorus fertilization on biomass production of willow in cut-away peatland areas depended on the amount of extractable phosphorus in soil (VI, VII). This has been demonstrated earlier in a greenhouse experiment (Ferm & Hytönen 1988). Only on sites with low concentrations of soil phosphorus did fertilizer phosphorus increase the above-ground leafless mass compared with the control plots (VII). High nitrogen concentration in soil promotes the significance of phosphorus fertilization (VII-IX, Ferm & Hytönen 1988). Slowly-soluble phosphorus fertilizers did not prove to be suitable for fertilization of short-rotation willow plantations in cut-over peatland areas since they did not increase the amount of extractable phosphorus in the limed soil and had no effect on biomass production (VI). The above-ground biomass of two-year-old willows was 4 - 6 times higher when fertilized with superphosphate than when fertilized with other phosphorus fertilizers (VI). Increasing the annual phosphorus application rate to over 15 kg $ha^{-1}$ did not increase the yields on any of the sites (VIII). Also the economical application rates of fertilizer phosphorus for leys on peatfields in Finland is generally 15 kg P $ha^{-1}$, and increasing the phosphours fertilization rate from 15 to 60 kg $ha^{-1}$ has increased yields by only 5% (Saarela & Elonen 1982). Annual fertilizer phosphorus amounts of 15 - 40 kg $ha^{-1}$ are proposed, depending on soil type, after the planting year in the Swedish recommendations for practical energy forestry (Sennerby-Forsse & Johansson 1989). Since the annual repetition of PK fertilization did not increase the yield of willows compared to a single application (IX), phosphorus fertilization at the beginning of each rotation of 3 -5 years could be adequate. Moreover, also the latest Swedish recommendation is to fertilize with PK for the entire rotation in the autumn prior to planting (Ledin et al. 1994). The recommendation for annual fertilizer phosphorus amounts for cut-away peatland areas (90 kg P $ha^{-1}$ $a^{-1}$) given by Lumme and Kiukaanniemi (1987) is too high.

Potassium fertilization has not increased the biomass production of willows in field experiments (VII, VIII) nor in a greenhouse experiment using cut-over peat substrate (Ferm & Hytönen 1988). In Ireland, too, *Salix vitellina* was found not to respond to potassium fertilization on cut-away peatland area (Neenan 1983). These results are surprising considering that the potassium stores generally observed in the 0-20 cm top soil layer of cut-away peatland areas are small (Kaunisto & Viinamäki 1991, Aro 1995). Partly this result may be due to basic potassium fertilization on the experimental fields (VII-IX). At Piipsanneva and Valkeasuo the mineral soil from ditch spoils was mixed into the root layer

of willows and this increased the amounts of total potassium in the willow root zone. Pine and birch seedlings in cut-away peatland areas have grown as well as on PK-fertilized plots when ditch spoil contained enough mineral soil (Kaunisto 1987). The addition of mineral soil has had a long-lasting effect in agricultural peat fields, increasing the yields of agricultural crops and decreasing the need for potassium fertilization (Anttinen 1957, Pessi 1961, Salonen & Tainio 1961). Addition of mineral soil has more than doubled the amount of total potassium in the plough layer of peat fields (Wall 1995). In peat soils, the first agricultural crops have grown well without potassium fertilization, but subsequent fertilization increased considerably the production (Salonen & Tainio 1961, Saarela 1982). Most probably potassium will become a nutrient limiting the growth of short-rotation plantations established on peat-cut away areas in some stage of their development. The potassium fertilization amount (150 kg $ha^{-1}$ $a^{-1}$) suggested by Lumme and Kiukaanniemi (1987) would appear to be an overestimation.

In contrast to its success in evaluating soil fertility in agriculture, soil analysis has rarely proved to be a good indicator when determining the fertilizer treatment needs on forest soils (Miller 1983) and has had only limited application with forest species (Heilman 1992). It is difficult to assess the ability of soil to satisfy the nutrient requirements of a tree stand merely on the basis of the available nutrient amounts revealed by soil analysis (Mälkönen 1974). However, according to the results of this study (VI, VII-IX), analyses of the extractable phosphorus concentrations of peat can provide good guidelines for determining the need for phosphorus fertilization in short-rotation willow plantations in cut-away peatland areas. Site-to-site differences in the response to fertilization could be related to differences in soil nutrient concentrations (VII, IX). The analysis of soil extractable phosphorus is also recommended as basis for determining phosphorus application rates in agriculture (Saarela & Elonen 1982, Viljavuustutkimusen... 1992). Also, soil nitrogen concentration could be used to adjust fertilizer nitrogen application requirements in cut-away peatland areas. According to the results obtained for most cut-away peatland areas, both nitrogen and phosphorus fertilization are required (cf. Ferm & Hytönen 1988) and most probably during the second rotation also potassium fertilization is necessary. Fertilization also increased considerably the proportion of harvestable (wood and bark) biomass out of the total biomass (VII). Although there are differences between the willow species in regard to their nutritional demands, these results most probably give a good picture of the significance of fertilizer application in short-rotation cultivation of exotic willows.

### 4.4 Biomass production

In short-rotation forestry, appropriate spacing and rotation length are crucial when optimizing the yield of biomass over time. Very close spacings were applied in these (I-IX) experiments. Close spacing gives initially high yields, but with an increase in the rotation length, the subsequent competition and self-thinning stabilises the number of plants

surviving to the end of the rotation (Heilman et al. 1972, Saucier et al. 1972, Pohjonen 1974, Bowersox & Ward 1976, Wittwer et al. 1978, Cannell 1980, Hytönen 1982, Lee et al. 1987). The survival of poplars was directly proportional to stand density (IV). The number of the trees in plots with a spacing of 35 000 stems $ha^{-1}$ had declined after six years to one-fifth of the initial value, i.e. to 6650 stems $ha^{-1}$ and in plots with the lowest density (5 000 stems $ha^{-1}$), the stem number was halved (2400 stems $ha^{-1}$). Maximum woody biomass of poplars (IV) occurred on plots with a spacing of 15 000 stems $ha^{-1}$ at the age of four years. It can be postulated that the highest biomass may well have occurred in the densest stands at an earlier age. By the end of the fifth year, the medium-spaced poplar plots still had the highest stem biomass, but the most widely spaced plots now equalled them in terms of branch biomass; after the sixth growing season, the latter were ahead on both counts. The six-year above-ground dry-mass figures, excluding foliage, were 8.9 t $ha^{-1}$, 11.2 t $ha^{-1}$ and 13.7 t $ha^{-1}$, respectively, from the closest to most widely spaced plots. The dependence of willow production on plant spacing diminishes in later rotations (Hytönen 1982, McElroy & Dawson 1986, Willebrand & Verwijst 1993). Spacing also affects the allocation of biomass and even the suitability of the produced biomass for different end uses; e.g. an increase in stand density increases the proportion of foliage and bark in the above ground biomass and decreases the proportion of stem wood (Saucier et al. 1972, Wittwer et al. 1978). The proportion of branches in wide spacing is higher than in dense spacing (IV, Cannell 1980).

Generally, willows are cut-back after the first growing season. The biomass production of the one-year-old sprouts at the end of the rooting year and following cutting-back has been quite low (less than 1 t $ha^{-1}$) (III, V-VIII, Hytönen 1982, 1987, Lumme et al. 1984, Lehtonen & Tikkanen 1986, McElroy & Dawson 1986, Nilsson et al. 1987, Tiefenbacher 1991). The first rotation one-year-old stands had not fully closed canopy and their leaf-area index was low (VII, Elowsson & Rytter 1988).

The dry-mass production in the second year is much higher, often manyfold (e.g. in III 6 times higher) and that in the third growing season often higher than the production in the second year (III, VI, VII, Hytönen 1987, 1988, Fig. 2). This is partly explained by the faster development of leaf area during the spring in a stand with one-year-old sprouts than in a stand that has been coppiced (Nilsson 1985, Ahola 1987, Elowson & Rytter 1988). Older shoots probably also have larger initial assimilate and nutrient stores. The maximum leaf area was reached during the second or third growing seasons (III, VII). They were equal or slightly lower than the maximum leaf-area indexes in the other studies (Nilsson & Eckersten 1983, Nilsson 1985, Cannell et al. 1988, Elowson & Rytter 1988).

'Wood grass' concept, growing of willows with one-year-rotation, has been studied intensively in the State of New York (White et al 1989). Earlier also in Finland even one-year rotation was considered feasible when growing short-rotation crops. However, the present and other studies recommend longer rotations. The cumulative biomass production of annual harvests has been considerably lower than production over longer rotations (*Platanus occidentalis*: Steinbeck & Brown 1976, *Salix*: Willebrand et al. 1993). Wright (1988) reported that in 83% of the cases she studied the production of one four-year rotation

was higher than that of two two-year rotations. The optimal rotation length for willow plantations is probably three to six years (III, Stott et al. 1983, McElroy & Dawson 1986, Dawson 1988, Willebrand et al. 1993) and that of poplar plantations even longer. Also, when longer rotations and fertilization are used, more of the biomass produced is in the stems (VII, VIII). Longer rotations also showed lower nutrient losses per produced dry-weight unit of stem mass (VII). Generally, the basic density of willow wood and bark increases and the moisture content decreases with increase in age (Hytönen & Ferm 1984, Flower-Ellis & Olsson 1981, Sennerby-Forsse 1985, Mitchell et al. 1988, Mosseler at al. 1988). Also the length of fibres grows (Sennerby-Forsse 1985), the ash content decreases (Äijälä 1982), and the productivity of harvesting increases (Siekkinen 1986) with increasing age. Thus, the use of wider spacing (10 000 - 20 000 cuttings $ha^{-1}$) would be appropriate (III).

First-rotation biomass production is significantly affected by the low production of the establishment year (McElroy & Dawson 1986). Thus, the production phase on mineral soils begins after a year long establishment phase, but on peat soils this establishment period can last two years (Elowson & Rytter 1988). The second rotation's mean annual biomass production in short-rotation plantations (*Salix* spp., *Populus* spp., *Platanus occidentalis*) has generally been considerably higher than those obtained from the first harvest (III, Heilman et al. 1972, Steinbeck & Brown 1976, Cannell 1980, Neenan 1983, Stott et al. 1983, Lumme et al. 1984, McElroy & Dawson 1986, Lehtonen & Tikkanen 1986, Hytönen 1987, Bowersox et al. 1988, Dawson 1988, Wright 1988, Strong 1989, Willebrand et al. 1993). Especially second rotation one-year-old sprouts have yielded manyfold compared to first rotation sprouts (III).

Even though the leafless above-ground current annual increment (CAI) of NPK-fertilized *S.* 'Aquatica' and *S. x dasyclados* has at its best been 8 - 9 t $ha^{-1}$ $a^{-1}$ in the cut-away peatland areas (VI-VIII) in central Finland, their mean annual increment (MAI) has only exceptionally exceeded 5 - 6 t $ha^{-1}$ $a^{-1}$ (Fig. 2). On a mineral soil field, the CAI of *S.* 'Aquatica' was 9-10 t $ha^{-1}$ $a^{-1}$ at its highest and the MAI almost 8 t $ha^{-1}$ $a^{-1}$ (III, V). The main reason for the low mean annual increment is in the low production of the one-year-old sprouts. The MAI of poplars with six-year-long rotation was 4.2 t $ha^{-1}$ $a^{-1}$ (IV). Similar MAI figures (4.8 t $ha^{-1}$ $a^{-1}$) for a three-year-long rotation have been reported for poplar (*Populus x euroamericana* Guinier) in Iowa and Wisconsin (Lee et al. 1987).

The amount of total biomass (including stems, roots, stumps and leaves) was approximately two times higher than the leafless above-ground biomass (VII-IX). However, the biomass of fine roots, not measured, may increase significantly the amount of total biomass (Nadelhoffer & Raich 1992). As the yield and stand age increased more of the biomass was allocated in the above-ground wood and less in the stump and roots (VII). The maximum total production of 30.6 t $ha^{-1}$ $3a^{-1}$ was composed of 44% wood, 18% bark, 17% foliage, 16% roots and 5% stumpwood (VIII). The proportion of wood in the total mass had increased considerably (from 23% to 44%) from the first growing season.

Much higher biomass production figures than those measured in the present studies were initially thought to be achievable in short-rotation forestry in Finland (Energiametsätoimikunnan ... 1979). In some Finnish and Swedish intensively-treated willow plantations

quite high biomass production figures have been achieved (13 - 16 t $ha^{-1}a^{-1}$: Ferm 1985a, Christersson 1986, 1987). However, in practical willow plantations in Sweden, the biomass production has been at the same level as in the plantation on mineral soils in this study (III, Olsson 1986, Sammanfattande... 1994). Similar biomass production has also been achieved using five year rotation on cut-away peatland area with native willow (*S. phylicifolia*: Hytönen et al. 1995). In Denmark, the mean annual increment during the years 1989 - 1992 varied between 6.3 - 7.6 t $ha^{-1}$ $a^{-1}$ (Matthesen 1993), and in Austria the production of the best clones during the second year has been 8 t $ha^{-1}$ (Tiefenbacher 1991). The biomass production of willow plantations was, however, higher than the yields reported for natural dense downy birch (*Betula pubescens*) stands (Ferm 1990) or for cultivated dense grey alder (*Alnus incana*) or silver birch (*Betula pubescens*) plantations (Saarsalmi et al. 1991, 1992).

Cannell and Smith (1980) and Cannell (1989) have carried out a critical review of the biomass production figures reported in short-rotation studies in temperate regions and in Europe and they have deleted results that probably were susceptible to edge effect, based on small plots or results in which the biomass estimation methods used contained considerable errors. According to these reviews covering central and northern Europe, the highest leafless biomass production varied between 10 - 12 t $ha^{-1}$ $a^{-1}$, which is also the expected mean annual biomass production in Sweden (Sennerby-Forsse 1994).

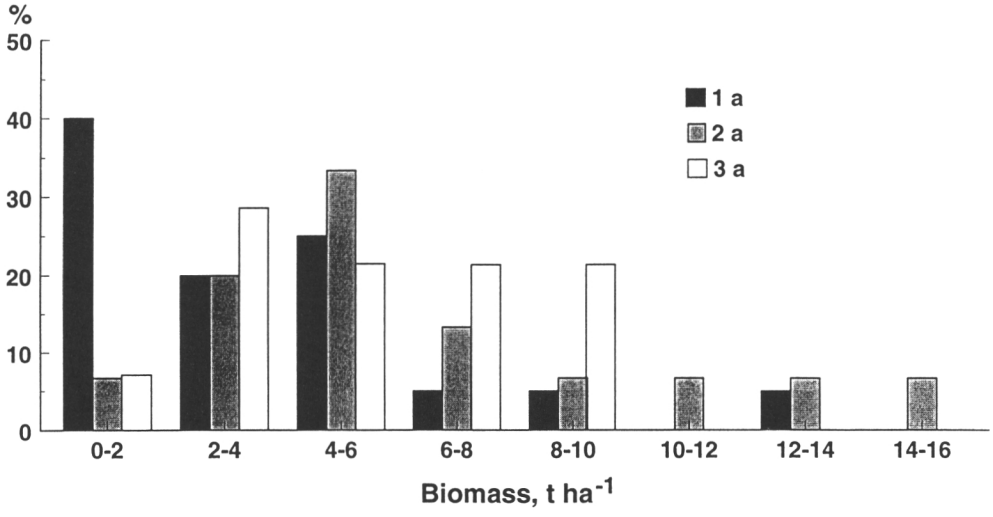


Fig. 2. Frequency distribution of the leafless mean annual increment (% of biomass figures) of one- to three-year-old *Salix* 'Aquatica' and *Salix x dasyclados* according to the results of studies conducted in Finland where the sample plot sizes have been over 50 $m^2$. The best treatments from each study are included. Results are from III, V, VI, VII, VIII, IX, Rossi 1982, Ferm 1985, Heino 1984, Lumme et al. 1984, Lehtonen & Tikkanen 1986, Ettala 1987, Lumme & Kiukaanniemi 1987.

In this study (III), the year-to-year variation in the CAI was high (38%). Simulation models that relate stand dynamics to environmental factors have given somewhat lower variation for annual yield of one-year-old willow plantations (15-25%, Sievänen 1983, Eckersten et al. 1987). This is probably due to the fact that models contain only some of the many variables involved in climatic variation. The annual variation in the harvest yields of farm crops can be as high as 50% of the mean (Varjo 1978). Much of the variation is explained by variations in weather during the growing seasons, (e.g. temperature sum) as indicated by many growth models (Nilsson & Eckersten 1983, Sievänen 1983, Eckersten et al. 1987). Exceptional weather conditions, especially the cold summer of 1987, clearly had an effect and resulted in inferior growth (III).

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 in stand density (number of stems per hectare) (VII-IX). Weeds can seriously reduce the successful establishment of plantations; ash fertilization increased the amount of competing vegetation despite weed control disturbing willow growth, and probably also decreased survival (VII). In Swedish practical willow plantations weeds were estimated to be the most important single reason for failures and low production figures (Sammanfattande ... 1994). Our knowledge of possible biological risks in large-scale plantations is inadequate. A monoclonal plantation can increase the risk of biological hazards, although there is little evidence that polyclonal plantings reduce risks more than monoclonal plantings (DeBell & Harrington 1993). Rusts (*Melampsora* spp.) (III), which are considered to be one of the most important diseases in willow and poplar cultivation (Royle & Hubbes 1992), voles (IV), hares and moose (Rossi 1982) have damaged experimental plantations. Following a *Melampsora* infection, willows have shown enhanced susceptibility to frosts (Verwijst 1990), probably because the infection prevents shoots from entering dormancy in time.

Early summer frosts, common to all the experimental fields in central Finland, damaged exotic willows and decreased their biomass production (VII, Ericcson et al. 1983, Christersson et al. 1984, Lumme et al. 1984, Hytönen et al. 1995). The poplar (IV) planted at Paimio hardly suffered at all from frost damage and overwintering appears to have been successful throughout. The Kannus plantation, on the other hand, was almost totally destroyed by frosts following coppicing at the end of the first growing season. Willows from central Europe (Pohjonen 1984) continue to grow late in the autumn, and consequently autumn frosts can damage shoots because of incomplete winter-hardening (von Fircks 1992). The fall in willow survival due to nitrogen fertilization may be associated with an increased risk of autumn frost damage and increased susceptibility to winter damage due to poor winter hardening (von Fircks 1992) and increased growth of weeds. In a one-year-old *S.* 'Aquatica' stand, 23 - 45% of the leafless above-ground biomass was damaged by frost (VI). *S.* x *dasyclados*, which grew best (VII, VIII), is more winter-hardy whereas *S.* 'Aquatica' is susceptible to autumn frost in central Finland and its usefullness for cultivation in eentral Finland is uncertain (Hytönen 1982, Lumme et al. 1984, Lumme & Kiukaanniemi 1987, Lumme & Törmälä 1988, Hytönen et al. 1995). Negative correlation between the first-year

growth and winter hardiness of willow roots (Lumme & Törmälä 1988) indicates that a compromise between productivity and hardiness has to be achieved. Due to heavy damage by autumn frost in certain years, *Salix* 'Aquatica' should not be cultivated in central Finland. More frost resistant willow clones, willow species (e.g. native *S. myrsinifolia*, *S. phylicifolia*: Pohjonen 1991, Honkanen 1994, Hytönen et al. 1995), birches or alders should be tested instead. Even though the biomass production of native willow species is much lower than that of the introduced southern clones during the first years after planting with longer rotations, they can be quite productive (Hytönen et al. 1995).

Most field experiments were established using untested material. This was due to the lack of selection test results and the limited availability of selected material for field tests. Use of improved plant material, more intensive management regimes, and cultivation treatments would most probably have increased the yield of willow in these studies. Considerable differences in the biomass production of willow species and clones have been observed in experimental plantations and many willow clones have grown much better than those used in this study (Lepistö 1978, Lumme & Törmälä 1988, Viherä-Aarnio & Saarsalmi 1994). The target of a Swedish breeding programme is to raise willow biomass yields by an average of 25% within 10 years (Larsson 1994). Interspecific hybridization has been successfully applied when trying to combine the good winter hardiness of domestic species with the high production of exotic clones (Viherä-Aarnio 1991, Viherä-Aarnio & Saarsalmi 1994).

## 5 CONCLUSIONS

There are several alternatives available for the measurement of biomass in willow plantations. The choice of method depends on matters such as the amount of work, the required accuracy, the computational requirements and the future growing of the stand. The harvesting method is destructive and can be quite laborious and time-consuming when large amounts of biomass have to be measured. Subsampling for moisture content is required. Destructive sampling can influence the future development of stands. Biomass equations offer a reliable non-destructive method for determining willow biomass. Age-specific generalized biomass equations for the main willow species for biomass estimation should be developed. For practical purposes, diameter is the only variable needed since the addition of height together with diameter ($d^2h$) increases the degree of determination only little. Diameter could be measured at 30 - 60 cm above ground level, the but breast height diameter commonly used in forestry is probably too high for willows. Small sprouts could be omitted in the formulation of stand tables. They contribute very little to the total biomass of the stands. The amount of work can, therefore, be considerably reduced and the measurements concentrated on sprouts containing the highest amount of biomass.

Willow and poplar short-rotation plantations can be established successfully with cuttings. Cutting size is an important factor influencing early plantation performance. Small cuttings should not be planted.

A factor critical to biomass plantations is the viability of the coppice system over several successive rotations. In order to achieve this, willow plantations should be harvested only in the dormant season. Cutting of exotic species and clones during the growing season decreases the productivity of the stand and considerably increases mortality. Harvesting methods that cause considerable damage to stumps are not suitable for biomass willow plantations. Willow plantations should be harvested leaving short stumps (0-10 cm) as higher stumps have resulted in significantly lower yields and may, in the longer run, increase the risk of fungal infection and decay. Willow harvesting machines should be designed in such a way that they take into account factors affecting the sustainability of the plantations (e.g. stump height should be low and stools should not be disturbed).

Internal competition in dense willow stands starts already during the first growing season. Before the onset of density-dependent mortality of shoots, the size distribution of willows is altered and becomes increasingly positively skewed. Competition is also manifested as the bimodality of stem frequency distributions and a hierarchy of shoot sizes is formed already during the first growing season. The smallest shoots die and only one tenth of the initial sprouts survive to the end of the rotation. Competition in dense stands also causes stool mortality and may seriously affect the sustainability of the plantations. Post-harvesting coppicing increases considerably the number of sprouts and compensates for the loss of stools.

Willow biomass production on mineral soils, and in southern Finland, is higher than on cut-way peatland areas in central Finland. Thus, willow cultivation should, in the first place,

be considered on better quality agricultural lands in the southern parts of the country. Marginal lands requiring intensive soil amelioration should not in the first place be used for the cultivation of these demanding tree species. Restructuring of Finnish agriculture and the subsequent reduction of agricultural land by 0.5 mill. ha, creates a need for alternative end uses for former agricultural land. Short-rotation cultivation, being an intermediate form between agriculture and forestry, could be accepted by farmers as one feasible alternative land use form.

In central Finland, frosts are the major risk for the cultivation of *S.* 'Aquatica' and *S. x dasyclados*. Especially in peatland areas, frosts can cause considerable damage to plantations. Frost-hardy clones should be introduced and tested in central Finland, and the cultivation of most exotic willow species should be restricted to southern Finland. One option is the cultivation of native willow species, e.g. *S. myrsinifolia* or birch and alder.

The productive period of short-rotation willow plantations is estimated to be 20 - 25 years, although results are available only from the first post-planting years. *Salix* 'Aquatica' plantations on mineral soils proved to be viable and productive in the 10-year study period, indicating that several repeated harvests are possible in good conditions.

Extremely short rotation times of one to two years are not to be recommended for willow cultivation. The CAI has been higher than the MAI for the first years after planting. The rotation length should probably be 3-5 years. From the point of view of several characteristics (e.g. biomass production, nutrition, wood characteristics and productivity of harvest) the rotation length of willows should be longer than has been previously suggested. Poplars are not particularly well adapted to short-rotations of less than 10 years, for instance. Planting densities much wider than those used in these studies (35 000 - 40 000 cuttings $ha^{-1}$) should be used; probably 15 000 - 20 000 cuttings $ha^{-1}$ is adequate.

Willows bind high amounts of nutrients into their biomass. With increase in willow age, the amount of nutrients, especially of nitrogen, bound into unit biomass decreases considerably. The proportion of nutrient-rich leaves and bark in the total above-ground biomass decreases. The choice of tissues to harvest and stand age can result in large differences in the amounts of nutrients removed from the site. Willows could be used in the treatment of wastewater and sludge by using plant nutrients for the production of biomass fuels and at the same time eliminating their harmful effects. Such biological purification systems, "vegetations filters", could be of great benefit both environmentally and economically. The concentrations of some heavy metals can be high in certain willow clones. When biomass containing high amounts of heavy metals is burned, most metals are retained in the ashes. Recycling of such ashes to short-rotation plantations, arable land or even to forest ecosystems is questionable.

Fertilization is an intensive management tool that is essential for succesfull high sustained biomass production. Correct fertilization regime with respect to timing and application rates is of utmost importance for the high biomass production of short-rotation plantations. With correct fertilization in cut-away peatland areas it was possible to achieve manyfold biomass production compared to control plots. During the establishment year, because of the low biomass production of willows fertilization is not necessary and when

done only small nutrient amounts should be used. During the following years annual nitrogen fertilizer application is needed even though the annual fertilizer nitrogen amounts on nitrogen-rich sites can be less than on sites containing less nitrogen. Optimization of the nitrogen fertilization regime is also important both environmentally and economically. In the case of phosphorus and potassium, it seems that it could be possible already at the beginning of the rotation to apply higher doses of fertilizer to last at least three years. It should be noted that the need for liming when growing exotic willow species in peat cut-away areas decreases the solubility of rock phosphates and apatite to such an extent that they cannot be used. Due to the high phosphorus requirements of willows, only readily soluble phosphorus fertilizers are recommended. Analyses of the extractable phosphorus concentration of soil can give guidelines for determining the need for phosphorus fertilization requirements in cut-away peatland areas. Also the total nitrogen concentration, as well as extractable potassium concentration, should be analysed. Soil analyses are also necessary for determining soil pH and consequent liming requirements before the establishment of plantations.

Due to the great variation in the nutrient concentrations of sludges, they should be analysed before use and the fertilizer amounts adjusted accordingly. Especially potassium concentrations can be so low that additional fertilization might be needed. The nitrogen concentration in sludge can be quite high and most nitrogen in sludge is bound into organic matter. The reduced solubility of nitrogen in sludge compared to that in commercial fertilizers can be an advantage in short-rotation cultivaton. The number of fertilizer applications could be reduced if the effect of nitrogen fertilization lasted longer. Also slowly-soluble commercial fertilizers should be tested in this respect.

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# I

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# Comparison of Methods for Estimating Willow Biomass

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*ABSTRACT*

*The harvesting method, mean stool method, regression method and ratio methods were compared for estimating dry mass of* Salix *'Aquatica' and* Salix triandra *(L.). The types of error which may occur with each method are discussed. The results indicate that all these methods are suitable for determining leafless above-ground biomass on short-rotation plantations, but they differ in level of destructiveness, amount of work, numbers of measurements involved and their computational requirements. The regression method and in some cases the mean stool method were the best methods for estimating biomass in short-rotation plantations.*

*Key words:* Willow, *Salix*, biomass estimation.

## INTRODUCTION

The idea of short-rotation plantations for fuel purposes utilizing regeneration by sprouting is under intensive study all over the world. Dry mass production on such plantations is measured with methods



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whose accuracy and mutual comparability are often unknown, and which vary greatly in the amount of work and destructiveness which they involve.

When using a one-year rotation, or when measuring biomass at the end of a rotation period, relatively destructive methods may be used, perhaps even entailing the cutting of the entire crop and weighing of the plant mass. Such a method is highly laborious, however, when the sample plots and biomass to be measured are large. Also the ratio between fresh and dry mass has to be known in order to estimate the latter. In any case, it often happens that one needs to know the yield of a plantation before the end of the full rotation period. Determination of the current annual yield, for example, requires annual measurements by a non-destructive method so as not to influence the future development of the plantation.

The regression method is that most commonly used for estimating the biomass of trees. In most cases the dependent variable, dry mass, is expressed as a function of dimensional variables by allometric equations. Such dry mass equations have been developed for willows in Finland and Sweden.[1–5] Another possibility is to cut and weigh clumps of sprouts, calculate the biomass of an average sprout clump and work out the ratio between the fresh and dry weights. In the basal area ratio method the ratio between total mass and basal area is determined in sample trees and multiplied by the basal area of the entire plot.[6–9]

Since little is known about the comparability between these methods of estimating biomass in short-rotation plantations, the aim of this investigation is to compare leafless above-ground dry mass estimates obtained by the regression, mean stool, harvesting and ratio methods. The investigation also deals with possible sources of error.

## MATERIALS AND METHODS

### Sample plots

Four *Salix* 'Aquatica' and six *S. triandra* plots were used for comparing the measuring methods. The sprouts of *S.* 'Aquatica' were one year old and those of *S. triandra* two and three years old. The age of the root system varied from four to seven years. Planting density was 4·1–7·1 cuttings per square metre and the plots varied in size from 29 to 85 $m^2$.

The heights and diameters of the willow shoots were obtained in the course of measuring the stem frequency distribution. The dominant height (tallest sprout in each clump) was 1·4–2·0 m and the dominant diameter 9–12 mm (Table 1). The two-year-old *S. triandra* had the

**TABLE 1**
Characteristics of the Study Plots

| *Plot no.* | *Species* | *Clone* | *Dominant height (cm)* | *Dominant diameter (mm)* | *No. of sprouts stump$^{-1}$* | *No. of sprouts m$^{-2}$* | *Proportion of sproutless stools (%)* | *Dry matter content (%)* |
|---|---|---|---|---|---|---|---|---|
| 1 | *Salix* 'Aquatica' | V761 | 156·0 | 9·8 | 9·5 | 29·4 | 27·5 | 42·4 |
| 2 | *Salix* 'Aquatica' | V761 | 160·0 | 10·8 | 8·4 | 28·0 | 16·3 | 36·9 |
| 3 | *Salix* 'Aquatica' | V761 | 156·7 | 10·1 | 8·2 | 34·2 | 10·9 | 42·5 |
| 4 | *Salix* 'Aquatica' | V761 | 192·9 | 10·9 | 9·5 | 29·4 | 48·6 | 43·9 |
| 5 | *S. triandra* | P6010 | 182·4 | 10·3 | 15·7 | 77·2 | 5·7 | 42·3 |
| 6 | *S. triandra* | P6010 | 165·5 | 9·1 | 13·1 | 64·6 | 9·3 | 42·9 |
| 7 | *S. triandra* | P6010 | 196·8 | 11·3 | 16·2 | 79·7 | 6·4 | 41·5 |
| 8 | *S. triandra* | P6291 | 125·3 | 8·9 | 2·6 | 14·0 | 23·7 | 44·5 |
| 9 | *S. triandra* | P6291 | 169·9 | 11·8 | 3·0 | 17·4 | 11·4 | 44·7 |
| 10 | *S. triandra* | P6291 | 142·8 | 10·4 | 3·3 | 19·6 | 14·3 | 43·5 |

largest number of sprouts per stool. The proportion of sproutless stools (6–49%) was calculated by checking each row and each planting spot (Table 1).

### Harvesting method

Willows were cut at the end of the growing season in 1985 with a clearing saw (except in the border rows), leaving 10 cm stumps, after which the trees were gathered in bundles and weighed immediately to an accuracy of 10 g (fresh mass). The actual mean stump height varied in the range 9·2 – 13·0 cm.

In order to determine the ratio between fresh and dry mass, six sprouts of unequal size were taken from each plot and their leafless fresh mass determined immediately to an accuracy of 0·1 g. The samples were dried at 105°C for two days and weighed again to obtain the dry mass. The moisture content of the smaller sprouts of *S.* 'Aquatica' was considerably higher than that of the larger ones, whereas moisture content varied very little with sprout size in *Salix triandra.* Dry matter content was therefore calculated as a mean weighted by reference to the fresh mass of the sample sprout (Table 1).

### Mean stool method

Dry mass was determined by cutting all the sprouts from randomly chosen stools (10 cm stump height), weighing them, assessing their dry mass as above. The sampling percentage was 7% out of the total number of stools in a plot and 5–15% out of the dry mass of the stand.

The number of sproutless, dead clumps was determined before cutting, including all the sprout clumps in the particular sample plot in the calculation. The proportion of sproutless stools is given in Table 1. The dry mass of willows per unit area was calculated by multiplying the mean dry weight of the sprout clumps by the number of living stool groups, as follows:

$$Y = \left( \frac{\Sigma_1^n (M)}{n} \times D \times N \right) / A$$

where: $Y$ = dry mass of willows per unit area; $M$ = fresh mass of measured sprout clump; $D$ = dry matter content; $N$ = number of live sprout clumps in the plot; $A$ = area of the plot.

Thus the prerequisite for using the method is that the ratio of dry to fresh mass should be determined, the number of viable sprout clumps counted and the area of the plot measured.

**Regression method**

The stem frequency distribution of the willows was determined by systematic sampling, i.e. by separating out four to six sampling stretches of 1 or 2 m in the direction of the planted rows.[2,3] The stretches covered 10–13% of the area of the plot, except on plots 4 and 8, which had an 8·5% coverage. The height of the willows was measured from the ground level to the top of the shoot to an accuracy of 1 cm and the diameter at 10 cm from the ground to an accuracy of 1 mm.[2,4] Simultaneously the number of sprouts per stool was counted. The border rows were omitted.[10,11]

Thirty sprouts were sampled from each willow clone according to the size distribution of sprouts in the plot. These were cut at 10 cm from the ground level and their height, diameter at cutting height and dry mass after drying at 105°C for two days were determined.

Dry mass equations of the form $Y = aX^b\varepsilon$ were calculated for the leafless above-ground mass of the willows and transformed logarithmically to linear form. The slight underestimation caused by the transformation was corrected by adding to the constant a correction coefficient $s^2/2$, in which $s$ is the variation in the residual of the equation. The independent variable in the equations was the product of the diameter squared multiplied by the height ($d^2h$) (Table 2). The equations had a high coefficient of determination and the coefficient of variation was of the same order as in earlier studies.[1–3]

The dry mass of the willows was determined using the summation technique, subtracting the cutting height of 10 cm before calculation.

**Ratio method**

In the basal area ratio method, sample trees should be chosen in proportion to the stem frequency distribution in each plot.[8] Stratified random sampling using diameter strata has been shown to be only slightly better than random sampling.[6] Sample trees may also be taken closest to those trees with mean basal area.[9] A mass estimate per unit area is obtained by multiplying the ratio of the summed mass and basal area of the sample trees by the basal area of the trees on the whole plot.

$$W = \frac{\Sigma w.\, G}{\Sigma g.\, A}$$

in which $W$ = biomass per unit area; $w$ = mass of sample trees; $G$ = sum total of the basal areas of the trees on the plot; $g$ = basal area of the sample trees; $A$ = area of the plot.

**TABLE 2**
Dry Mass Equation for Willows $Y = aX^b\varepsilon$

| *Species* | *Clone* | $x = d^2h$ | | | | $x = d$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *a* | *b* | $R^2$ (%) | *V* (%) | *a* | *b* | $R^2$ (%) | *V* (%) |
| *Salix* 'Aquatica' | V769 | 0·00261 | 0·94559 | 99 | 9·9 | 0·04445 | 2·72709 | 97 | 16·7 |
| *S. triandra* | P6011 | 0·00166 | 0·99330 | 99 | 12·4 | 0·04022 | 2·80470 | 97 | 17·1 |
| *S. triandra* | P6291 | 0·00274 | 0·95725 | 99 | 12·4 | 0·04238 | 2·78167 | 98 | 15·0 |

$Y$ = Leafless above-ground dry mass (g)
$a$ and $b$ = constants
$h$ = height (cm)
$d$ = diameter at stump height (mm)
$V$ = coefficient of variation.

The basal area ratio was calculated from the sample sprouts used in the regression method and the basal area of the sprouts in the plot from the stem frequency distribution.

In the regression equations (regression method) tree weight was related to tree diameter ($d$) or $d^2h$. The exponent for diameter in these equations was 2·8 and that for $d^2h$ almost 1 (Table 2). Thus the ratios

$$W=\frac{\Sigma w.D}{\Sigma d^{2\cdot8}.A}$$

and

$$W=\frac{\Sigma w.D^2H}{\Sigma d^2h.A}$$

could also be calculated. The ratio estimates were calculated on the basis of all 30 sample sprouts, although sampling of every third sprout or of the smallest, largest or medium size sample sprouts was also tested.

## RESULTS

The basal area ratio method overestimated the mass of the *S.* 'Aquatica' plots by an average of 22% and that of the *S. triandra* plots by 18 and 19% in comparison to the harvesting method (Fig. 1). The basal area ratio calculated from the 10 sprouts nearest to the mean value did not improve the estimate, but some improvement was gained by using the diameter squared in the ratio, and by increasing the diameter exponent to 2·8, as in the regression equations. The dry mass of *S.* 'Aquatica' was then overestimated by only 4%, that of the two-year-old *S. triandra* plots underestimated by 8% and that of the three-year-old *S. triandra* plots overestimated by 0·3%. Equally good or slightly better results in comparison to the harvesting method were obtained using the diameter squared and height of the sprouts ($d^2h$) in the ratio estimation equation, whereupon the mass of *S.* 'Aquatica' was overestimated by 2·1% on average and that of the two- and three-year-old *S. triandra* plots underestimated by 7·8 and 6·7%. The use of every third tree, i.e. 10 sample trees, led to almost equally good results. No great differences resulted from the use of smaller, larger or medium-sized sample sprouts.

The mass of *S.* 'Aquatica' as measured by the mean stool method deviated by −27–24% (−0·8–0·8 t ha$^{-1}$) from the figures obtained by the harvesting method on individual plots, the mean being an over-

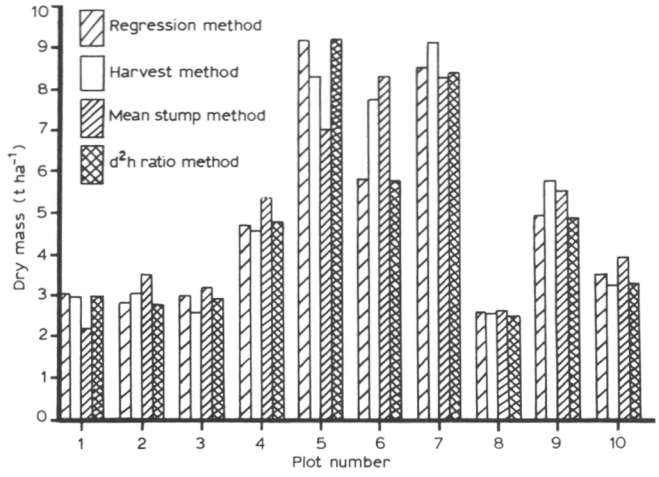


**Fig. 1.** Leafless above-ground dry mass of willows estimated by different methods.

estimation of 7%, corresponding to 0·3 t $ha^{-1}$. Use of the mean stool method underestimated the dry mass of the two-year-old *S. triandra* plots by 6% and overestimated that of the three-year-old plots by 9% in comparison to the harvesting method.

The mass of *S.* 'Aquatica' estimated by the regression method differed from that obtained by the harvesting method by −8–17% (−0·2–0·4 t $ha^{-1}$). The mean degree of overestimation was 4%, corresponding to 0·1 t $ha^{-1}$. The dry mass of two-year-old *S. triandra* on sample plot 6 calculated by the regression method was 25% lower than that obtained by the harvesting method (Fig. 1), probably implying a sampling error when determining the stem frequency distribution. As a mean of three sample plots, the degree of underestimation was 7%. The regression method produced an average 1% underestimation for the three-year-old *S. triandra* plots.

All the methods tested both overestimated and underestimated the masses in comparison to the harvesting method, except for the basal area ratio method, which consistently overestimated them by 18–20%. The differences between the results obtained with the mean stool and regression methods were greater than those between either method individually and the harvesting method. The results of the ratio method performed using $d^{2\cdot8}$ or $d^2h$ deviated only slightly from the dry mass estimates gained with the regression method. The differences in the case

of *S.* 'Aquatica' were −2·9–1·3% (−0·1–0·06 t ha$^{-1}$) when the ratio was based on $d^2h$ and −5·7–5·0% (−0·27–0·16 t ha$^{-1}$) when based on $d^{2\cdot8}$. The mean values did not differ. When the sample plots were ranked by mass the order was almost identical with the different methods.

## DISCUSSION

The harvesting method had proved impracticable according to a preliminary experiment carried out in a three-year-old *S.* 'Aquatica' stand where the fresh mass on a plot exceeded 1 000 kg and therefore willow stands of smaller mass were chosen for this experiment. Even so the weighing technique may have caused errors. Errors related to the storage of moisture samples were eliminated here[12] and sampling errors were reduced by taking uneven sized whole sprouts for the moisture samples. The moisture content of *S.* 'Aquatica' depended on the fresh mass of the sprouts, the smaller the fresh weight, the higher being the moisture content. Hence the weighted mean moisture content value was used in the calculations. Moreover, there were great differences, of as much as 6%, between the plots in the moisture content of willow shoots. Thus calculation of the dry biomass of the willows in a plot on the basis of the moisture content on some other plot could cause as much as a 19% error in the dry mass estimate. More samples for moisture determination should be taken and sampling should occur in relation to the mass distribution of the sprouts. Sampling for moisture determination among unevenly sized, aged and treated willow stands requires further investigation. The size of the sample plot should also be carefully measured. Consequently the harvesting method, often considered as 'absolute', is also subject to various errors.

The reliability of the results obtained with the dry mass equations is affected e.g. by the representativeness and optimum number of sample trees. The regression models may also lead to inaccuracies. Also, it is often difficult to measure the height of willows accurately, especially those over one year old, which often have contorted stems.

When using equations for the determination of dry mass it was necessary to subtract 10 cm for the stool height from the height of the sprouts, the actual stool heights varying around this figure. The effect of stool height on the mass estimates could be investigated by subtracting the actual stool height in dry mass equations instead of 10 cm. Use of an actual stool height (12·6 cm) in this way for plot 4 gave a calculated mass that was 2% lower than that calculated with a 10 cm stool height, or correspondingly a 2·4% lower figure for plot 5 using an actual stool

height of 13·0 cm. Even a few centimetres' difference between the actual and assumed stool height can lead to a difference of several per cent in the mass estimates. Apart from one plot, use of the actual stool height would actually have improved the compatibility of the mass estimate with the harvesting method to a considerable extent.

In this study the basal area ratio method led to major overestimation of the dry mass, in contrast to the earlier results.[6,7] Stratified sampling of trees using diameter strata could have improved the dry mass estimates, although it has been shown that stratification is only slightly better than random sampling.[6] The ratio estimators produced almost the same dry mass estimate as with regression method when $d^2h$ or $d^{2\cdot8}$ was used. One reason for the good results is the similarity to allometric dry mass equations (Table 2). Contrary to our results, earlier studies suggest that this kind of theoretical improvement in the basal area ratio method is a negligible consequence in practice.[7]

Although the various methods produced some differences between the mass estimates in individual plots, the average masses obtained were quite similar. All these methods are practicable for determining the leafless above-ground willow biomass in short-rotation plantations, each involving different possible sources of error. Estimation of branch, bark and leaf masses would require further investigation, and the suitability of ratio methods for estimating willow biomass should also be studied further. The most laborious was the harvesting method, whereas the amounts of work and expense required by the other methods are smaller. The regression method, and in some cases the mean stool method, are best suited for determining current annual yield or total above-ground leafless dry biomass in willow plantations.

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# EFFECT OF CUTTING SEASON, STUMP HEIGHT AND HARVEST DAMAGE ON COPPICING AND BIOMASS PRODUCTION OF WILLOW AND BIRCH

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*(Received 10 February 1994; accepted 14 March 1994)*

**Abstract**—The effect of cutting season on coppicing and growth of exotic (*S.* 'Aquatica', *S. x dasyclados*, *S. viminalis*) and local willows (*S. phylicifolia*, *S. pentandra*), and downy birch (*B. pubescens*) was studied in two experiments. At each of the 32–36 or 53 cutting times, 20–30 stools were cut down. Cutting of exotic willows at the end of July or beginning of August had a very detrimental effect on the survival, height growth and biomass production. Even though the height of local willows and downy birch was significantly shorter when cut during the growing period, their survival was not affected.

Stump height (0, 10, 20 or 40 cm) affected markedly the biomass production of *S.* 'Aquatica' from the second rotation on. In the third rotation willows cut to 40-cm stump height yielded 68% less and those cut to 20-cm stump height 28% less than those cut to 10-cm stump height.

Manual harvesting damage simulating the effects of harvesting machines had a negative effect on survival, height and biomass production in a young *S.* 'Aquatica' plantation. In older, well established plantations the effect was not significant. Differences between cutting methods were small.

**Keywords**—*Salix*, birch, regeneration, cutting season, harvest damage, stump height, biomass production.

## 1. INTRODUCTION

The concept of short-rotation management includes the establishment of closely spaced, fast-growing trees and the application of intensive cultivation practices, repeated harvesting using short cutting cycles, regeneration of subsequent crops via sprouts or suckers, and the use of a high degree of mechanization. Short-rotation forestry utilizes the exceptional growth rates of coppice shoots. A factor critical to the success of biomass plantations is the sustainability of the coppice system over successive harvests.[1]

Several factors, both internal and external, influence regeneration from stumps.[1] Many external factors and practical management measures such as cutting season, stump diameter, stump height, cutting method, fertilization, site quality, rotation length and spacing have been shown to influence coppicing vigour. However, there are considerable between-species differences in sprouting ability.[2,3] Generally cutting during the active growing period will increase mortality and decrease growth compared to dormant season cutting.[3] However, willows, even though now used extensively in short-rotation forestry, have not been subject to intensive study.[1]

Knowledge of the influence of factors affecting the coppicing ability and biomass production of short-rotation plantations is necessary for the determination of cutting schedules and development of harvesting techniques. The aim of this study was to investigate the effects of cutting season, stump height and harvest damage on the sprouting of willows and downy birch.

## 2. MATERIAL AND METHODS

### 2.1. *Cutting season*

The effects of cutting season on coppicing and growth of willows and downy birch were studied in two experiments at Haapavesi, central Finland (Table 1). The study sites were former peat excavation sites, and mineral soil and peat soil fields. Exotic willows were planted using cuttings and they were grown on limed and NPK-fertilized substrates. Natural willows and downy birch had become established along the ditches of an abandoned field. Mean weekly temperatures for the second experiment are from a weather station situated 10 km from the study site (Fig. 1).

At each cutting time, 20–30 stools (or birch trees) were cut using a brush saw to a stump-

Table 1. Experiments on the effects of cutting season

| Species | No. cutting cycles | No. trees or stools felled | No. sprouts measured | Age of sprouts/ age of stumps | Site |
|---|---|---|---|---|---|
| Experiment 1: | | | | | |
| *S. viminalis* (clone E7901) | 36* | 660 | 5976 | 1/2 | Cut-away peatland |
| *S. x dasyclados* (clone P6011) | 32‡ | 419 | 3857 | 1/1 | Cut-away peatland |
| Experiment 2: | | | | | |
| *S. viminalis* (clone E7901) | 53† | 1737 | 12 929 | 1/4 | Cut-away peatland |
| *S. x dasyclados* (clone P6011) | 53† | 2053 | 29 897 | 1/3 | Cut-away peatland |
| *S. x dasyclados* (clone V761) | 53† | 870 | 5966 | 1/4 | Mineral soil field |
| *S.* "Aquatica' (clone E4856) | 53† | 1657 | 3896 | 1/4 | Mineral soil field |
| *S. phylicifolia*, *S. pentandra* | 53† | 1907 | 12 770 | 10–15/? | Peat-based field |
| *Betula pubescens* | 53† | 1066 | 6460 | 10–15/10–15 | Peat-based field |

*First cutting 23 July 1982, last cutting 12 August 1983. Measurements in October 1993.

†First cutting 10 November 1983, last cutting 8 November 1984. Measurements of cutting dates (clones V761, E4856, and P6011) 10 November 1983–7 June 1984 in May 1985 and 14 June–8 November 1994 in September 1985. Clone E7901 was measured in September 1985. Birch and local willows were measured in 1985, 1987 and 1991.

‡First cutting 23 July 1982, last cutting 15 July 1983. Measurements in October 1983 and in May 1985.

height of 10 cm. One or two border rows were excluded. In the first experiment cutting was done weekly during the summer and less frequently during the winter. In the second experiment, cutting was done weekly during 1 year on the same day of the week starting in November. The survival of stools, height of tallest sprout and number of sprouts in each stool were measured after one or two growing seasons. Because the cuttings of clone P6011 were planted in a horizontal position, their survival and the number of sprouts per stool were not measured. Willows were harvested after measurements and their leafless above-ground biomass was determined. Samples for determination of moisture content were taken from each treatment. Birch and natural willows were measured after 1, 3 and 7 growing seasons. Moving averages of the measured parameters were calculated.

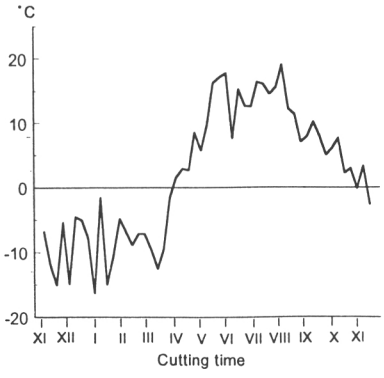


Fig. 1. Mean temperatures of the week following cutting in the second cutting-time experiment.

### 2.2. *Stump height*

The effect of stump height on the growth and coppicing of *Salix* 'Aquatica' (clone V769) was studied at Haapavesi on a limed and NPK-fertilized former peat extraction site. One-year-old sprouts were cut back to stump heights of 0, 10, 20, and 40 cm on plots sized 60 $m^2$ in autumn 1983. Harvested biomass was not measured. Randomized block design with four replications was used. The height of all sprouts as well as survival were measured before treatment. According to the results of analysis of variance, the dominant height of the sprouts and their survival did not differ within the study plots assigned to each treatment before cutting. Survival and biomass were measured in 1985, 1987 and 1990. Willows were cut to their initial stump heights (0, 10, 20 and 40 cm) and their mass determined (excluding border rows). Moisture samples taken from each of the 16 study plots were dried at 105°C for constant weight. Analysis of variance and covariance were made. Height and survival before treatment were used as the covariates.

### 2.3. *Harvesting damage*

Effects of harvesting damage on the sprouting and biomass yield of willows was studied at

Haapavesi (central Finland) on a limed and NPK-fertilized former peat excavation site and at Rajamäki (southern Finland) on a mineral soil field. At Haapavesi, *S.* 'Aquatica' cuttings were planted in spring 1983. In autumn 1983 willows were cut using (A) secateurs resulting in a smooth cutting surface and (B) a brush saw leaving a rougher cutting surface. In addition, half of the stumps were damaged manually with a sledge hammer in both treatments. The height and survival were measured before treatment in 1983. Randomized block design with four replications was used. The treatments were repeated when the willows were harvested in 1985 and 1987 after 2-year rotations. Final harvesting was done in 1990. The survival, number of sprouts per stump and the height of the tallest sprout in each stool were measured in 1985 and 1987 before harvesting. The dry mass of the willows was determined using the harvesting method in 1985, 1987 and 1990.

The plantation at Rajamäki was of *S.* 'Aquatica' (clone V769) established in 1982. The 8-year-old sprouts were cut in the autumn of 1991 in experiment 1 with a chainsaw and in experiment 2 with a brush saw. The treatments consisted of 4-m long tracks laid out along the rows of planted willow. The treatments included a control (A), a light-weight Farmi Trac forwarder driving on the row of stumps (B) and manual damaging of the stumps using a sledge hammer (C). In both experiments, the treatments were replicated three times in a randomized block design. The height of the sprouts and

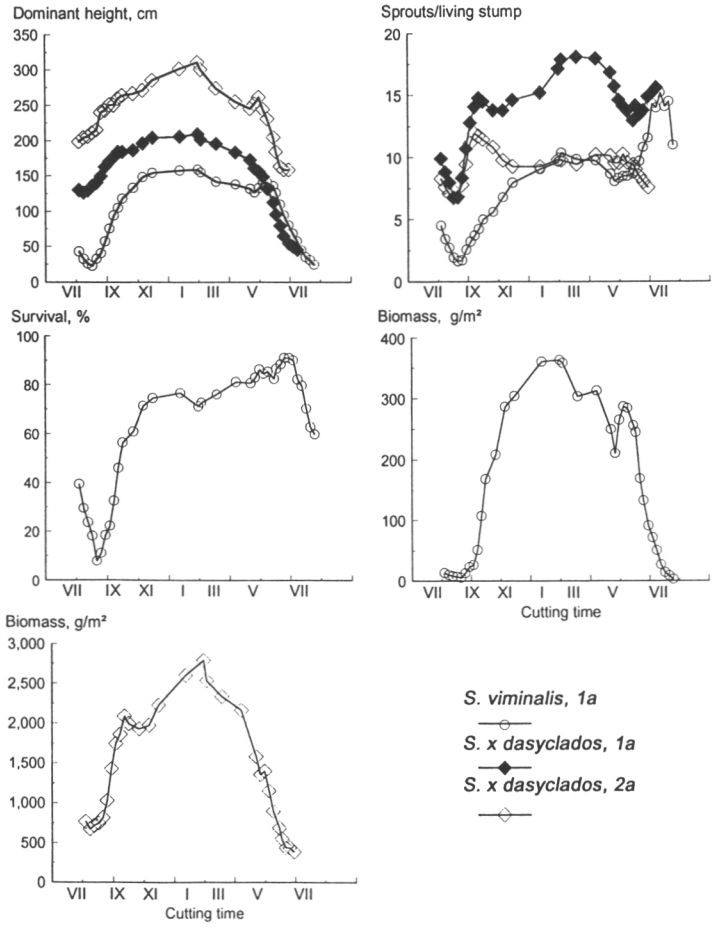


Fig. 2. Dominant height of sprouts, number of sprouts per living stump, survival of *Salix viminalis* stools, and leafless above-ground dry mass of 1-year-old *S. viminalis* and 2-year-old *S. x dasyclados*.

the number of sprouts per stool were measured after one growing season in autumn 1992. The dry mass per stool was calculated using dry-mass equations.[4]

## 3. RESULTS

### 3.1. *Cutting season*

The dominant height of exotic willow one growing season after summer cutting was in most cases less than half of that when the cutting was done during the dormant period (Figs 2 and 3). The effect of the cutting season even after two growing seasons was marked on the height growth and yield of *S. x dasyclados* (Fig. 2). The heights of downy birch and local willows one growing season after cutting were also affected by the cutting season (Fig. 4). With birch, the initial differences in height caused by cutting season levelled off after three and seven growing seasons (Fig. 4).

Cutting during the growing period decreased the survival of exotic willows (Figs 2 and 3). Distinctly low survival was noted when cutting was done at the end of July–beginning of August. However, the survival of local willow species and downy birch was not affected by the cutting season, and survival exceeded 80% throughout (Fig. 4).

The number of willow sprouts per living stump was lowest when cutting was done during the summer (Figs 2 and 3). It was, however,

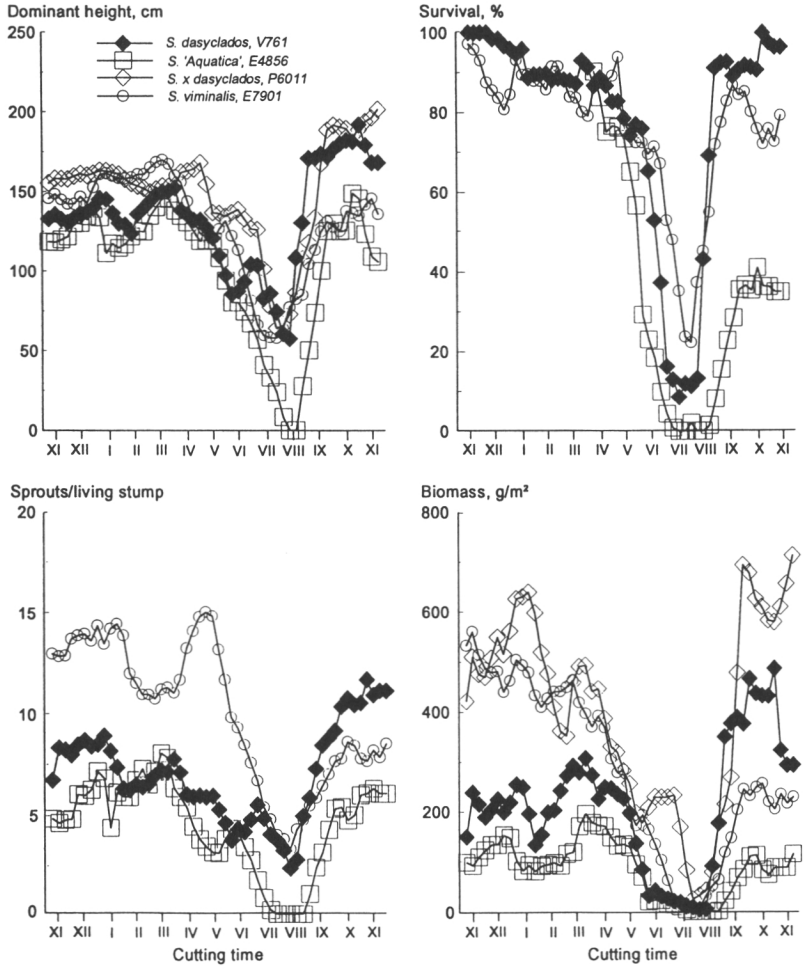


Fig. 3. Dominant height of sprouts, survival of stools, number of sprouts per living stump and dry mass of willow clones cut at different times of the year.

noted that willows also sprouted when cut during the summer. Measurements were generally done after winter. In the first experiment measured in the autumn following cutting, willows cut during the summer produced an abundance of short sprouts (Fig. 2). Short sprouts died during the winter and were not found in the following spring. The number of birch sprouts per living stump was highest when the trees were cut during the summer (Fig. 4). This was also the case with local willow. Differences in the number of birch sprouts per stump levelled off after seven growing seasons.

Biomass production of exotic willows was very low following cutting during growing season (Figs 2 and 3).

### 3.2. *Stump height*

The effect of stump height on stool mortality was not significant during the first and second 2-year rotations. However, after the first rotation, survival of willows cut at ground level decreased by 10% and those cut to 10- and 20-cm stump heights by 5% and those cut to 40-cm stump height by 2%.

Stump height did not affect dry mass production during the first rotation (Fig. 5). In the second rotation, biomass production increased with the decreasing stump height. The differences between the treatments were statistically significant. Willows cut to 40-cm stump height yielded 70% less and those cut to 20-cm stump height 45% less than willows cut at ground level (Fig. 5). Short stumps (10 cm) gave almost as good a result as cutting to ground level. Stump height continued to have a significant effect on dry mass production also during the third rotation. Now the best yield was achieved with 10-cm stump height and only slightly lower with stumps cut to ground level. Willows cut to 40-cm stump height yielded 68% less and those cut to 20-cm stump height 28% less than those cut to 10-cm stump height.

### 3.3. *Harvesting damage*

At Haapavesi, the differences in the measured parameters between cutting methods (i.e. seca-

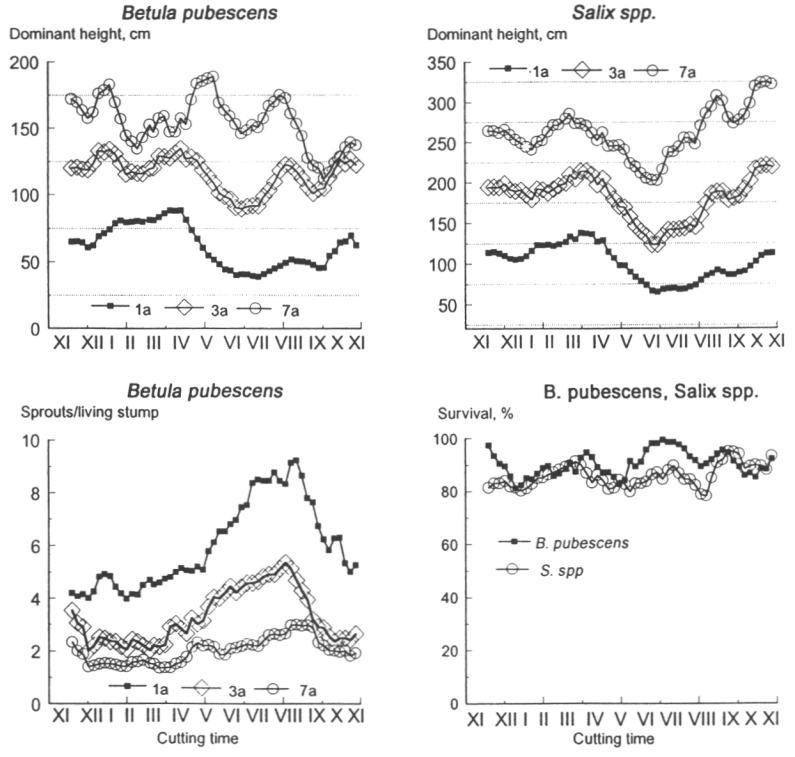


Fig. 4. Dominant height of *Betula pubescens* and *Salix* spp. sprouts, number of sprouts per living *B. pubescens* stump and survival after one, three and seven growing seasons.

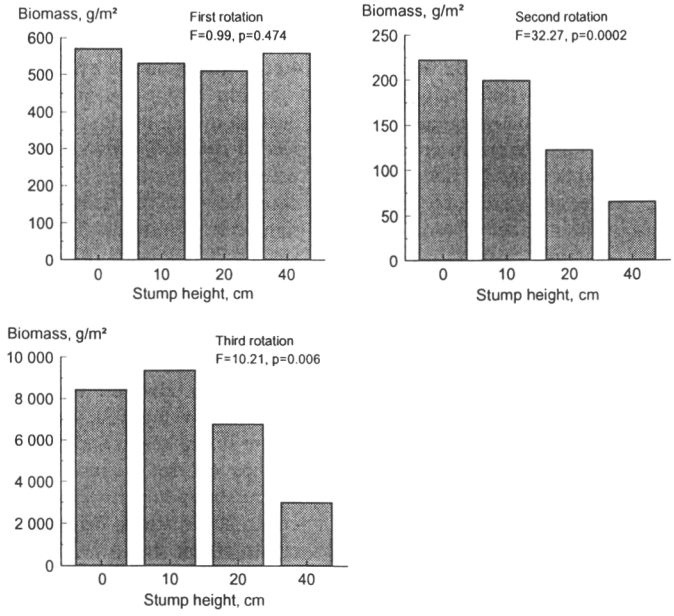


Fig. 5. Effect of stump height on dry mass production of *S.* 'Aquatica' in the first, second and third rotation.

teurs leaving smooth cutting surface and brush saws leaving rougher cutting surface) were small during all three rotation periods (Figs 6 and 7). The only statistically significant difference was in the number of sprouts per living stool during the second rotation. In stools cut with the brush saw, there were, on average, 1.2 sprouts more per stool than in stools cut with secateurs ($p = 0.0070$).

Damaging of *S.* 'Aquatica' stools decreased

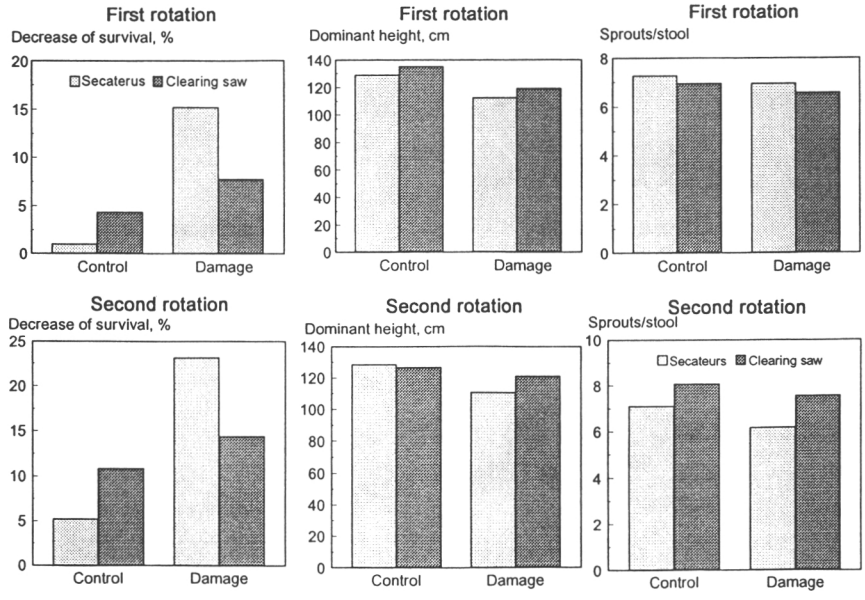


Fig. 6. The effect of cutting method and harvesting damage on the decrease in survival, dominant height and number of sprouts per living stool of *S.* 'Aquatica' at Haapavesi.

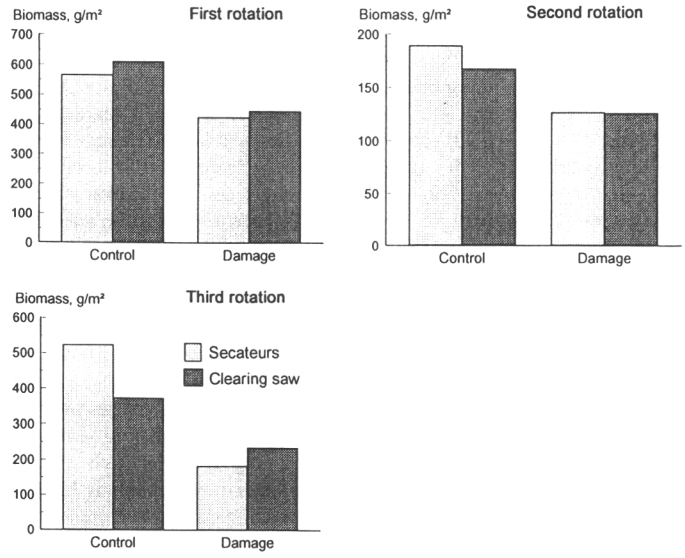


Fig. 7. The effect of cutting method and harvesting damage on the biomass production of *S.* 'Aquatica' at Haapavesi.

survival during the first rotation by 8.8%-units ($p = 0.035$) and during the second rotation by 10.7%-units ($p = 0.025$). After seven growing seasons the decrease in survival was 16.8%-units ($p = 0.0035$). Also, the height of sprouts produced by the damaged stools was lower; during the first rotation by 16 cm ($p = 0.005$), and during the second by 12 cm ($p = 0.025$). The

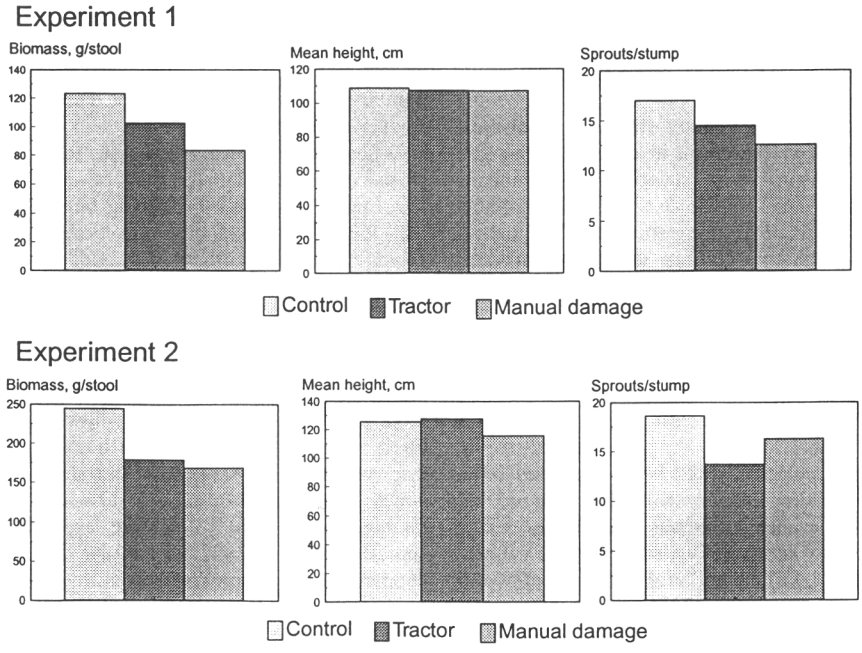


Fig. 8. The effect of harvesting damage on the biomass, mean height and number of sprouts per living stool of *S.* 'Aquatica' at Rajamäki.

first-rotation biomass production on the plots in which stools were damaged was 26% ($p = 0.003$) lower than on plots where stools were not damaged, the corresponding figure for the second rotation was 29% ($p = 0.026$) and for the third rotation 54% ($p = 0.001$) (Fig. 7). There were 0.3 (first rotation) and 0.7 (second rotation) sprouts less per living stool on the damaged plots as compared with those of undamaged plots. However, these differences were not statistically significant.

At Rajamäki, in the older stand, the number of sprouts per living stool and biomass per stool was slightly lower following harvest damage caused by the mini-forwarder driving on the stumps (Fig. 8). Manual damage, thought to be more severe, caused similar effects. However, the differences between the treatments were not statistically significant.

## 4. DISCUSSION

The cutting season affected markedly height growth, biomass production and survival of exotic willows. Best regrowth occurred when the plants were cut during the dormant stage, i.e. between late autumn and early spring. Cutting at the end of July or beginning of August had a very detrimental effect on survival. Variation in the sprouting and biomass production was affected by the initial variability of the study stands.

Besides willows, many other species also exhibit seasonal variation in coppicing; the dormant season being superior in minimizing mortality and usually also increasing number and growth of resulting sprouts.[2,3,5–9] Short-rotation willow plantations should be harvested during the dormant period as recommended in old textbooks for cultivation of basket willows.[10] Thus, the harvesting of protein-rich leaves for fodder as suggested e.g. by Näsi[11] and Näsi and Pohjonen[12] during the growing season would markedly decrease the vitality of the plantations.

There are considerable between-species differences in the reaction to cutting season.[2,9] In these experiments, this was most clearly evident in terms of survival. Contrary to exotic willows, the survival of downy birch or local willow was not affected by the cutting season. For birch this has also been observed earlier.[13,14] As in other experiments, the height growth of birch was slightly affected by cutting season with a minimum in June–July.[13–18] Differences in height growth of birch caused by cutting season levelled off in 7 years.

The reasons for seasonal differences in coppicing are not fully understood. Some earlier studies related differences in sprout growth to carbohydrate reserve levels in the roots of parent trees.[2,3] However, carbohydrate levels have been shown to be adequate for coppicing under most conditions,[2,3,14,19] and carbohydrate concentrations and sprout growth are not well correlated. The largest number of sprouts for downy birch resulted from cutting in summer. Sycamore also produced most sprouts when cut in July.[5] In these experiments, the buds of exotic willows species also burst even when cut in late summer or early autumn. At the beginning of winter such sprouts are small and their moisture content is high. One reason for poor coppicing and increased stump mortality following late autumn cutting might, thus, be the death of such small sprouts caused by frost damage. Mikola[15] and Johansson[14,18] considered the frost-risk to be considerable for birch too. The proportion of frost-hardy internodes of sugar maple on sprouts arising after growing period cuts also decreased with each successive date of cut.[20]

Contrary to results with birch,[15,17] harvest damage had a negative effect on survival, height growth and biomass production of a young *S.* 'Aquatica' plantation. In older, well established plantations the effects of harvest damage were smaller and not significant.

Differences between species in relation to effects of harvest damage may be due to the location of the sprout-producing buds. About 90% of birch's basal buds are located below ground[21,22] while most of the buds of *Salix* 'Aquatica' are above ground level.[23] In coppiced *S. viminalis* most (85–90%) of the sprouts originate from the axillary bud groups located on the remaining basal parts of the previously harvested stems.[1] Thus, harvesting damage may have more serious effects on willow than on birch regeneration. In old textbooks one is instructed to harvest willows with a sharp blade which gives a smooth cutting surface without damaging the bark.[10] In these experiments, smooth cutting surfaces did not give any better coppicing results than rougher cutting surfaces made with a brush saw. It has been shown that even the cutting angle affects the sprouting of *Alnus rubra*[8] but not that of *Populus trichocarpa*.[6] Thus, in the design of willow har-

vesters their effects on the sustainability of the coppice system should be taken into account.

Stump height did not affect the yield of *Salix* 'Aquatica' during the first rotation. Cutting height had no effect on the first rotation sprouting of stumps of *Populus trichocarpa* established from cuttings.[6] However, in successive rotations stump height was of crucial importance, short stumps producing more biomass than long stumps, thus confirming traditional recommendations to cut willows at ground level.[10] According to the results, even 10-cm long stumps could be used without decreasing production. Short stumps did not increase the mortality of willows contrary to alder.[8,24] Shoots on low-cut stumps are more likely to be connected to individual roots, and this is believed to give some advantage in terms of availability of water and metabolites.[1,25] According to Johansson[14] cutting of birch seedlings to 0-cm high stumps decreased survival compared with that of cutting to 10-cm long stumps. Long stumps may increase the risk for fungal infection and decay, and increased breaking away of sprouts from the stumps. Between species variation in the effects of stump height on sprouting could partially be due to location of sprout-producing buds.

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# TEN-YEAR BIOMASS PRODUCTION AND STAND STRUCTURE OF *SALIX* 'AQUATICA' ENERGY FOREST PLANTATION IN SOUTHERN FINLAND

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**Abstract**—The biomass production and stand structure of *Salix* 'Aquatica' planted on abandoned farmland and harvested after 3 and 7 year rotations was studied in southern Finland for 10 years. Coppicing doubled the stand density to $3.5 \times 10^5$ shoots $ha^{-1}$. Self-thinning began during the first growing season and shoot mortality amounted to 13%–20% at the end of the first growing season. Cumulative shoot mortality of the initial sprout number at the end of the first rotation (3 years) was 60%; the corresponding figure at the end of the second rotation (7 years) was 87%. The diameter distribution at the beginning of self-thinning resembled a bidomal distribution. The second self-thinning phase began at the age of four years. The mean annual leafless above-ground biomass production was higher during the second (7.7 t $ha^{-1}$) than during the first rotation (5.1 t $ha^{-1}$). The annual increment varied highly depending on the temperature sum and losses caused by pathogens. The leaf area index of 1–3 year old sprouts varied between 4.9 and 6.4 $m^2 m^{-2}$.

**Keywords**—Biomass production; competition; self-thinning; shoot mortality; *Salix* 'Aquatica'.

## 1. INTRODUCTION

The concept of short-rotation management includes the establishment of closely spaced stands of fast-growing trees and the application of intensive cultivation practices, repeated harvesting using short cutting cycles, regeneration of subsequent crops via sprouts or suckers, and the use of a high degree of mechanisation. The establishment and management of willow biomass plantations, as well as the production and technical quality of the produced biomass, have been the subject of study in Finland.[1] Even though technologies relating to biomass production and harvesting have progressed significantly, there is a need to establish operational-size plantations.[2] Earlier, short-rotation forestry research was almost exclusively confined to marginal lands. However, nowadays it is considered, both in Finland and elsewhere in Europe, that large areas of agricultural land should be set aside from conventional use and be afforested or used for producing other kinds of crops.[3,4] According to the results of a survey conducted in Finland,[5] young active farmers are especially interested in establishing short-rotation plantations.

High planting densities in willow cultivation (often 40,000 cuttings $ha^{-1}$) have been used in Finland.[1] Following cutting-back after the first growing season, the number of sprouts in *S.* 'Aquatica' plantations have been 300,000–370,000 $ha^{-1}$.[6,7] The post-harvesting stand densities increase due to the increased amount of shoot producing buds.[8] Besides close spacing, within-stand competition in such dense plantations is furthermore enhanced by fertilizer application. Furthermore, competition-induced shoot mortality before the end of the rotation period is high.[9,10] Second-rotation yields have in the case of several coppiced short-rotation species been higher than first-rotation yields.[11–17] The productive period of a short-rotation willow plantation is expected to be 20–25 years.[18,19] Studies on the development of short-rotation plantations have been confined to the first years after establishment. Very few reports include records of long-term biomass production and survival, matters of crucial importance for the success of such ventures.

The aim in this study was to investigate, over a 10 year period, the development of a willow plantation established on a moderately fertile abandoned farmland in southern Finland. Biomass, stand density, stem frequency distributions and shoot mortality were recorded annually.

## 2. MATERIAL AND METHODS

The willow plantation monitored for this study was established in the spring of 1982 on a limed (6000 kg ha$^{-1}$) sandy mull field situated in southern Finland (60°32′N, 24°37′E).[19] The willow (*Salix* 'Aquatica', clone V769) was planted applying a density of 36,000 plants ha$^{-1}$ (80 × 35 cm) in the early summer of 1982 using 1 year old rooted cuttings, whose shoots had already been cut back to the stem. Weed control was mechanical using a tractor-drawn harrow during the first summer. The size of the plantation was 0.46 ha. Willow harvest took place in 1985, after three growing seasons, and then once again at the end of the seven-year rotation in 1992. One 300 m$^2$ plot was left unharvested.

A sludge fertilizer experiment (control, 30, 60 and 120 m$^3$ ha$^{-1}$ sludge) was established in three replications in the spring of 1982.[20] Sludge was reapplied in 1985 after harvesting of willow, but owing to low dry-matter content, the considerably lower nutrient content of the sludge and the 50% lower application level, the amount of nutrients applied in the second sludge application was very small. When the control treatment was removed from the analysis, the differences in biomass production between the treatments were, according to the results of an analysis of variance, statistically non-significant during all of the study years. Thus, for the purposes of this study, all the sample plots fertilized with sludge (nine plots) were pooled to monitor the development of the stand. The control plots (three plots) were left outside the analysis.

The diameter and height (for the first four years) distributions of willow sprouts taller than 20 cm were measured each year using a network of systematic sample plots. Sprouts were classified as being alive or dead. Diameter was measured at a height of 10 cm above the ground to an accuracy of 1 mm and sprout height to an accuracy of 1 cm. The diameter distribution in the unharvested sample plot was measured also after the eight growing season. In order to avoid possible edge effects, the rows along the edges of the plantation were not measured.[21,22]

The leafless above-ground willow biomass was determined annually using allometric dry-mass equations.[7,20] The dry-mass equations for the first rotation period have also been presented earlier[20] while the equations for the second rotation period are presented in Table 1. Using similar equations, leaf dry-mass and leaf area were also determined during the three years. The leaf area of the sample sprouts was determined using a Li–Cor leaf-area meter. Heights in 1986–1992 were calculated using equations based on sample sprout data (Table 2).

The stand structure at different ages was studied by constructing equal-interval frequency distribution histograms of willow diameter. The high number of shoots measured annually made it possible to divide them into 18 diameter classes each year in order to compare their frequency distributions. The number of classes in such histograms should be over 10 and the populations should be large (of over 100

Table 1. Dry-mass equations for *Salix* 'Aquatica' sprouts in the second rotation. Equations have the form $Y = aX^b$, which after logarithmic transformation have been corrected with $s_e^2/2$. $Y$ = dry mass (g) or leaf area (cm$^2$), $X$ = diameter at base (10 cm above ground, mm), $a$ and $b$ = constants, $R^2$ = degree of determination, $V$ = coefficient of variation, $N$ = number of sample sprouts

| Sprout age (years) | $N$ | $a$ | $b$ | $R^2$ (%) | $V$ (%) |
|---|---|---|---|---|---|
| *Leafless above-ground mass* | | | | | |
| 1 | 27 | 0.04894 | 2.66544 | 98 | 17 |
| 2 | 23 | 0.04076 | 2.84179 | 99 | 9 |
| 3 | 24 | 0.04845 | 2.76780 | 99 | 14 |
| 4 | 19 | 0.06356 | 2.72433 | 99 | 15 |
| 5 | 24 | 0.05735 | 2.73638 | 99 | 11 |
| 6 | 25 | 0.05427 | 2.76998 | 97 | 25 |
| 7 | 30 | 0.06030 | 2.73468 | 96 | 23 |
| *Leaf mass* | | | | | |
| 1 | 27 | 0.11595 | 2.00704 | 96 | 19 |
| 2 | 23 | 0.02763 | 2.44256 | 95 | 27 |
| 3 | 24 | 0.00698 | 2.84825 | 94 | 30 |
| *Leaf-area* | | | | | |
| 1 | 27 | 55.48100 | 1.64596 | 96 | 17 |
| 2 | 23 | 11.81464 | 2.07046 | 94 | 24 |
| 3 | 24 | 4.79900 | 2.37701 | 95 | 22 |

Table 2. Equations for calculation of willow height in the second rotation. Models: $Y = aX^b$ (corrected with $s_\varepsilon^2/2$). $Y$ = height (cm), $a$, $b$ = constants, $X$ = diameter at base (mm), $V$ = coefficient of variation

| Age (years) | $a$ | $b$ | $R^2$ (%) | $V$ (%) |
|---|---|---|---|---|
| 2 | 17.309 | 1.0101 | 98 | 8 |
| 3 | 26.559 | 0.8309 | 93 | 11 |
| 4 | 30.448 | 0.8201 | 97 | 10 |
| 5 | 29.771 | 0.8115 | 94 | 8 |
| 6 | 29.542 | 0.8177 | 93 | 11 |
| 7 | 38.507 | 0.7372 | 89 | 11 |

individuals).[23–25] The third ($g_1$) moment about the mean, a measure of the skewness of the distribution, and fourth moment ($g_2$), a measure of kurtosis of the distribution, were also calculated.

The effective temperature sum (threshold +5°C) and the mean monthly precipitation at Hyvinkää Mutila weather station (15 km from the experiment site) are presented in Figs 1 and 9. The growing season in the summer of 1987 was exceptionally cold. The summers of 1982 and 1985 were also cooler than the rest, especially in their early part.

## 3. RESULTS

### 3.1. *Stool mortality*

Stool mortality during the first 3 year long rotation was quite low, at only 5%–9%. During the second 7 year rotation, stool mortality increased annually; at the age of 3 years it was 15%, at the age of 4 years 23%, at the age of 5 years 25%, and at the age of 6 years 32%. At the age of 7 years, stool mortality was 34%.

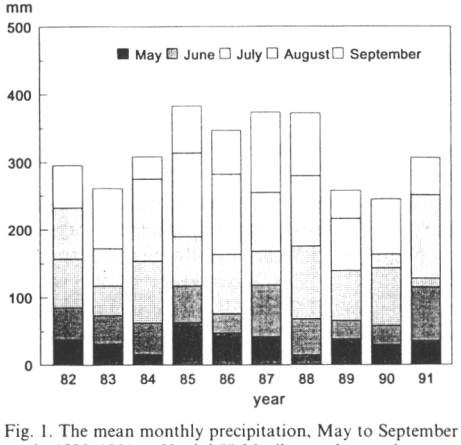


Fig. 1. The mean monthly precipitation, May to September in 1982–1991 at Hyvinkää Mutila weather station.

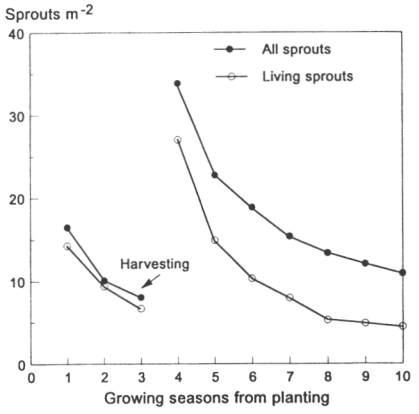


Fig. 2. Stand density of the plantation indicated as the number of all standing (dead and living) and living sprouts per hectare.

### 3.2. *Sprouting and shoot mortality*

The total number of sprouts (live and standing dead) at the end of the first year after planting was 165,000 $ha^{-1}$, but at the end of the first rotation was only half of that (Fig. 2). The post-harvesting number of sprouts was 339,000 sprouts $m^{-2}$. Despite this, and due to the breaking off of small dead sprouts, the number of sprouts fell by 44% by the end of the third year and by 68% by the end of the seventh year of the second rotation.

The number of living shoots in the stand was much smaller than the total number of standing shoots. After the first growing season, 13% (first rotation) and 20% (second rotation) of the total number of standing shoots were dead. Four years into the second rotation there were as many live as dead sprouts in the stand. After seven growing seasons, 60% of all shoots in the stand were dead. Dead standing shoots are, however, harvestable. The loss of dead shoots (fallen to the ground) at the end of the first rotation amounted to 51%; the corresponding figure at the end of the second rotation was 68%. Altogether, 40% of the first year's shoots survived to the end of the first 3 year rotation (Fig. 3). The corresponding figure at the end of the second rotation of seven years was only 13%.

The fall in the number of sprouts per stool was at its maximum during the second growing season in both rotations, but then levelled off during the following years (Fig. 4). Willow coppiced well following harvesting, and had an average of 10.6 sprouts per stool. After the seventh year into the second rotation, there was

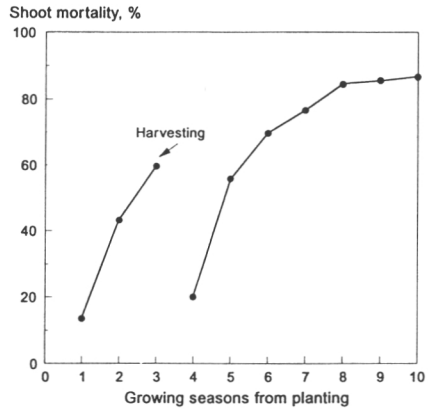


Fig. 3. Cumulative mortality of willow shoots.

an average of 5.0 sprouts per living stool, but over half of them were dead.

### 3.3. *Distribution of sprouts into diameter and height classes*

Both in the first and second rotation, the distribution of the number of 1 year old sprouts into different diameter classes was clearly bimodal (Fig. 5). The death of the smallest sprouts, i.e. the first peak in the distribution, began already during the first growing season. In the second rotation, the positive skewness of the distribution reached its maximum during the first year, and then decreased during the next two years. At the ages of 4 and 5 years, skewness increased again. The diameter distribution was again clearly bimodal at the ages of 4–7 years. The dying of smaller sprouts slowed down more during the second self-thinning phase than during the first.

The significance of the second peak in the height and diameter distribution is more important, however, from the point of view of the total dry-mass of the sprouts. The distribution of the number of sprouts, dry-mass of the stems and leaves and leaf area into different height classes in the 1 year old plantation are presented in Fig. 6. The proportion of short sprouts in the total number of sprouts was considerably high, whereas in terms of biomass it was small. For example, the proportion of sprouts shorter than 110 cm in the number of sprouts was 53%, but their proportion of the total dry-mass of the willow plantation was only 4.6%. The corresponding proportions for the total leaf mass and total leaf area were 9.7% and 13.9%. The ratios between stem mass and leaf mass for small and large sprouts differed. The tallest 10% of sprouts contained 45% of the dry-mass.

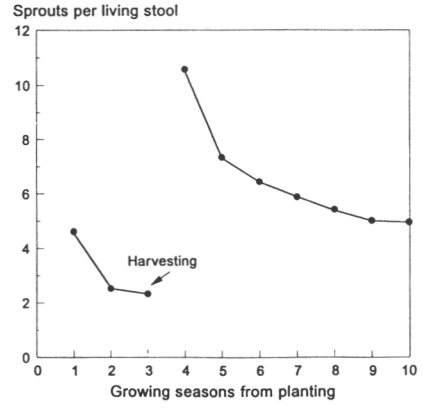


Fig. 4. Number of sprouts per living stool.

### 3.4. *Diameter and height*

The dominant diameter and height (thickest and longest sprout in each stool) and the mean diameter and height increased linearly during the first rotation period (Fig. 7). At the end of the first rotation, the dominant height of the willow was 3.5 m, and at the end of the second, 5.2 m. The post-harvesting height of 1 year old sprouts was equal to that of the 2 year old sprouts during the first rotation period. The difference between dominant height and diameter and the mean height and diameter of the sprouts increased year by year (Fig. 7). Even after 7 years, the mean height and diameter were at the same level as they were at the end of the first 3 year rotation.

### 3.5. *Dry-mass production*

The dry-mass production during the second year was 7 times greater and during the third year as much as 20 times greater than that during the first year (Fig. 8). The post-harvesting dry-mass of 1 year old sprouts was 5.2 t $ha^{-1}$, i.e. about 7 times greater than that of the sprouts of the same age during the first rotation period (Fig. 8). After the first rotation (3 years), the standing dry-mass amounted to 15.3 t $ha^{-1}$ while the corresponding figure for the first three years of the second rotation was 21.7 t $ha^{-1}$. At the end of 7 years, the amount of dry-mass amounted to 45.2 t $ha^{-1}$.

During the first rotation period, both the mean annual increment (5.1 t $ha^{-1}$ $year^{-1}$) and current annual increment (9.5 t $ha^{-1}$ $year^{-1}$) were at

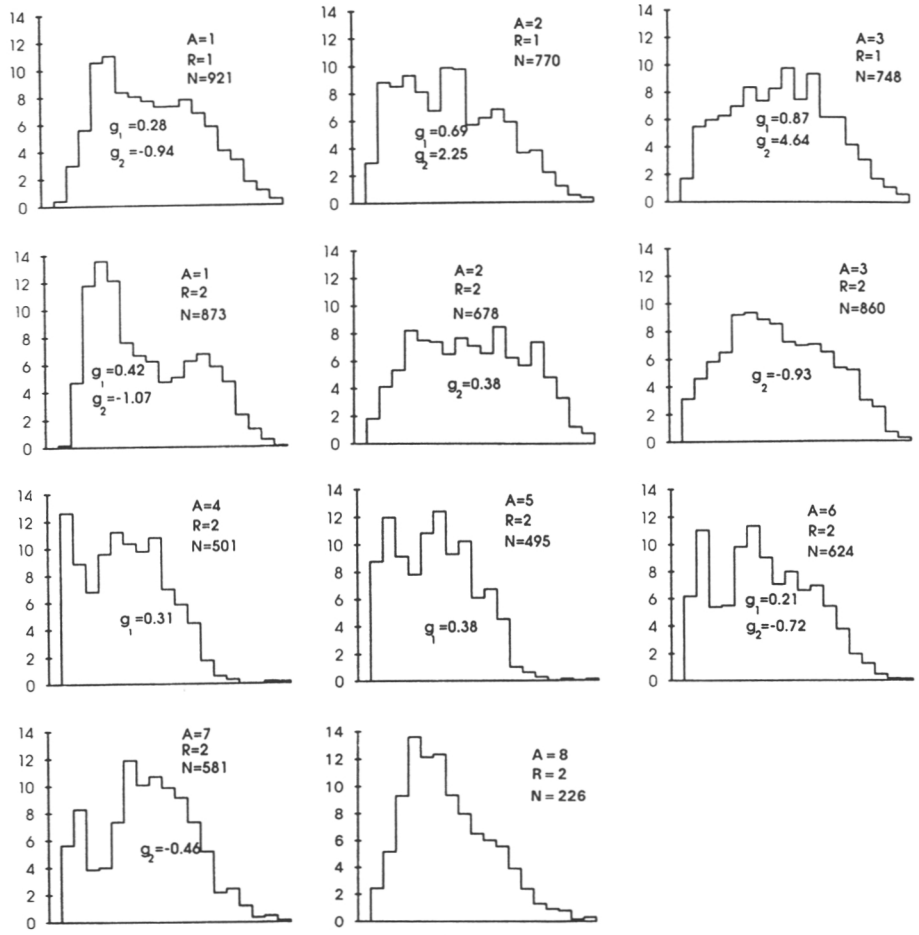


Fig. 5. Frequency histograms of equal interval diameter classes of *Salix* 'Aquatica' of different ages. The number of measured shoots ($N$) and values of $g_1$ and $g_2$ are listed, if statistically significant at 5% significance level. $R$ = rotation, $A$ = age of sprouts.

their maximum at the age of 3 years and during the second rotation after the second growing season (MAI 7.7 t ha$^{-1}$ year$^{-1}$, CAI 10.1 t ha$^{-1}$ year$^{-1}$) (Fig. 9). The year-to-year variation in the current annual increment was considerable. This variation correlated well with the temperature sum except at the age of 5 years during the second rotation. The reason for this is probably in the outbreak of fungal diseases (including leaf rust).

The amount of willow leaf mass measured during the first three years of the second rotation period increased with age, but to a considerably smaller extent than the amount of stem mass. The leaf area index changed only slightly with willow age (Fig. 10).

## 4. DISCUSSION

A factor critical to biomass plantations is the viability of the coppice system over several successive rotations.[26] The willow used in this study is able to withstand several repeated harvests.[8] Besides the ability of stools to produce sprouts, the stump mortality is also important. In this study, stump mortality increased year by year so that after 10 years from establishment over one-third of the stumps had died. Due to the high planting density, the plantation was still productive at the end of the monitoring period, containing approx. 24,000 live stumps per hectare, which is more than the planting density currently used in Sweden.[27] The planting density

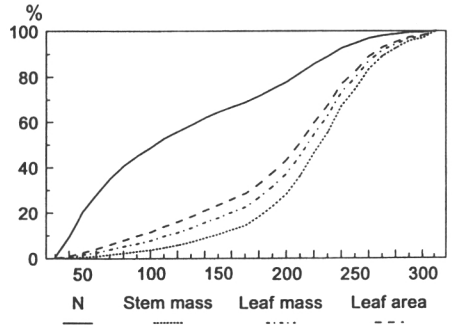


Fig. 6. Cumulative frequency distribution of the number of sprouts, leafless above-ground biomass, leaf mass and leaf area index in height classes with 10 cm class interval. One year old sprouts.

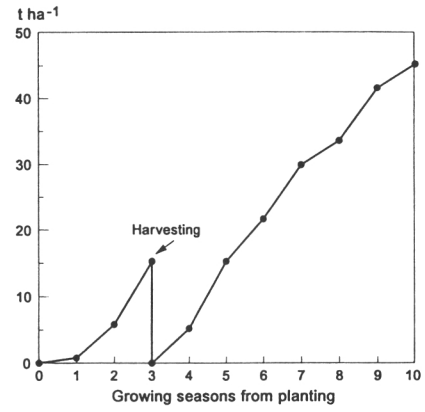


Fig. 8. Leafless above-ground biomass of *Salix* 'Aquatica'.

would most probably be much lower if longer rotations were to be applied. Also, increased post-harvesting coppicing compensated for the loss of stools and increased the number of sprouts by three to fourfold. Stool mortality was most probably due to competition, especially during the longer second rotation.[10]

The reduction in the number of sprouts with increase in stand age was an indication of high within-stand competition. Only 13% of the first year's initial shoots survived to the end of second 7 year rotation. Similar cumulative shoot mortality (87%) has been observed also in a *Salix viminalis* plantation in Sweden after 3 years.[9] The reduction was at its greatest between the ages of 1 and 2 years, which was the stage where the smallest sprouts died. Standing dead stems in the plantation are, however, harvestable. The number of standing dead shoots in the stand remained constant during the second rotation even though shoot mortality continued. This was due to loss of standing dead stems through breaking. Thus, besides the decrease in the wood density of dead shoots,[9] more biomass is probably lost as the result of breaking off of dead shoots. Even though their number is high, the biomass of declining sprouts which die at a later stage is very small compared to the mass of larger sprouts. It would have been possible, when measuring the stand in the 1 year old plantation, to omit over 50% of the sprouts without underestimating the stem mass by more than 5%. The amount of work can, therefore, be considerably reduced and the measurements concentrated on sprouts containing the highest amount of biomass.

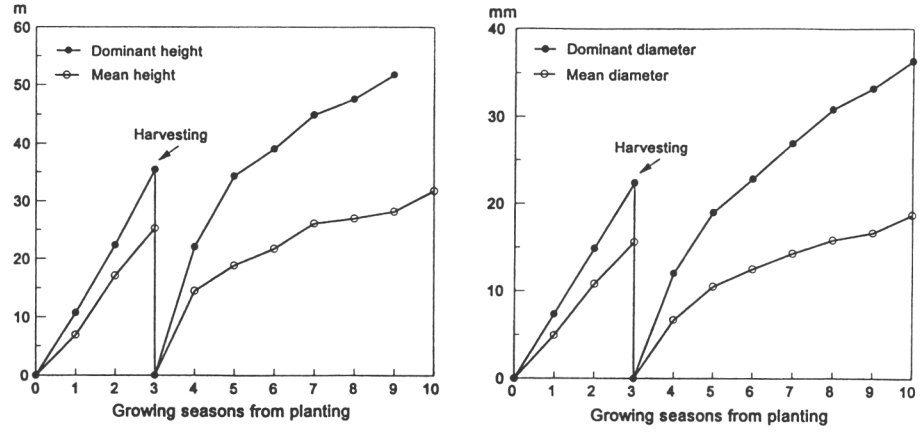


Fig. 7. Dominant and mean diameter and dominant and mean height of willow sprouts.

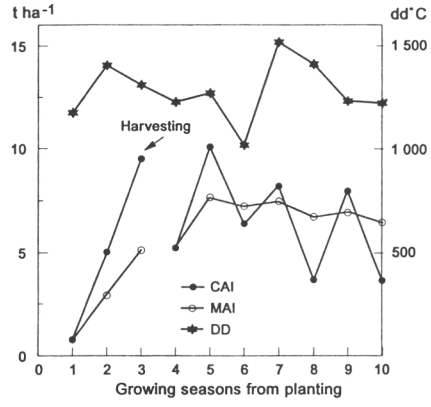


Fig. 9. Mean (MAI) and current annual increment (CAI) and temperature sum (DD > 5°C) in 1982–1992.

Competition changes the size and weight distributions in a population. In this study, the diameter distribution of 1 and 4 year old sprouts was clearly bimodal as described also in connection with dense even-aged stands by Ford[24] and Mohler *et al.*[25] The majority of the sprouts were short and thin. The second, smaller peak, represented the group of dominant sprouts. The positive skewness of weight and size distributions reaches a maximum immediately before the suppressed plants begin to die.[10,25] In the willow stand monitored in this study, this phenomenon manifested itself already before the end of the first growing season. Willow's basal axillary buds consist of a single bud scale covering three shoot primordia, the larger one in the middle giving rise to taller shoots than the two laterally placed buds.[8,28] This may have contributed to the first year's bimodality in the distributions.

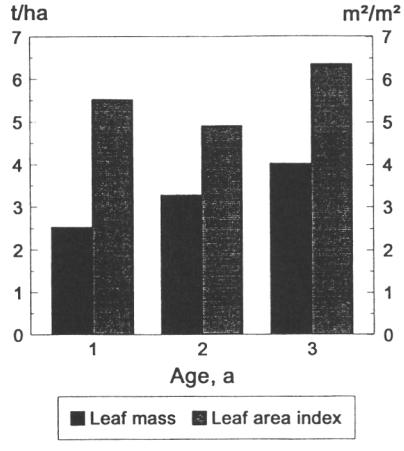


Fig. 10. Leaf mass and leaf area index during the first three years of the second rotation.

In this study's willow stand, the second self-thinning phase began at the age of 4 years and manifested itself as renewed bimodality of the stem frequency distribution. It seems that self-thinning proceeds slower during the second self-thinning phase. The death of bigger stems is probably a slower process than the death of 1 year old sprouts. Also, due to the edge effect, the amount of light reaching the lower canopy could have contributed to this.[21] Reduction in the skewness caused by the dying of the most suppressed plants as self-thinning proceeded was observed in the frequency distributions. In stands of *S. caprea*, death of sprouts has been reported to begin at the age of 4 years and to reach its peak at the age of 7 years with another mass death peak expected at the stand age of 16–17 years.[29] According to Ford[24] and Ford and Newbould,[23] bimodality of the stem diameter distribution indicates a disjunct distribution in growth rates. The increase in relative growth rate from small plants to large is not uniform throughout the range of plant sizes and depends on the competition process.[23] In coppice stands, there is competition between large shoots in the upper parts of the canopy where leaves receive direct radiation. However, once a shoot is overtopped it exists in a markedly less favourable but not greatly changing environment of diffuse radiation.[24]

The age-related changes in the leaf area index observed in this study were minor and they were of the same order as the maximum leaf area index values reported earlier for short-rotation willow plantations.[30]

The second rotation's mean annual increment was higher than that of the first as in several other studies.[11–17] First-rotation biomass production was significantly affected by the low production during the establishment year.[31] Thus, the production phase clearly starts after a 1 year long establishment phase.[19] Even though biomass yields were lower than expected or measured in some other experiments,[19,31,32] the plantation demonstrated to be productive and viable over the 10 year study period. Use of improved plant material, more intensive management regimes and cultural treatments, especially appropriate fertilizer application, would most probably have increased the yield of willow in this study.[1,31,32] The optimum rotation length for the

first rotation was most probably over 3 years and, for the second rotation, 4–6 years.

Variation in the current annual increment during the second rotation was high at 38%. The annual variation in harvest yields of farm crops can be as high as 50% of the mean[33] and in 1 year old basket willow plantations, a simulation model has given values varying within the range of 15–25%.[34] Much of the variation is explained by variations in weather during the growing seasons, e.g. temperature sum as indicated by many growth models.[29,34,35] The exceptional weather conditions in 1987 have clearly had an effect and resulted in inferior growth during the year in question. The outbreak of leaf rust and unidentified fungal diseases decreased the annual yield during one year despite a high temperature sum; recovery was, however, rapid.

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# IV

*Biomass* **18** (1989) 95–108

# Effect of Spacing and Nitrogen Fertilization on the Establishment and Biomass Production of Short Rotation Poplar in Finland

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*ABSTRACT*

*Short rotation trials using cuttings poplar* (Populus × rasumowskyana) *in Southern Finland investigated establishment of poplar plantations and the effects of spacing and application of nitrogen fertilizer on biomass production over a period of 6 years. Thicker cuttings grew better whilst those of less than 1 cm diameter grew only moderately. Nitrogen fertilization improved height and diameter growth and above-ground dry mass yield. Woody biomass production was 4·2 dry tons/ha per year, at 300 kg/ha nitrogen. A spacing of 15 000 stems/ha gave the best yield after 4 years, but 5000 stems/ha was a more productive spacing in the next 2 years.*

*Key words:* biomass production, nitrogen fertilization, *Populus*, short rotation cultivation, planting density.

## INTRODUCTION

Intensive cultivation of poplars is practised in Central and Southern Europe, and breeding of the species has advanced greatly, such that most of the strains cultivated for sawn timber and veneers are hybrids.[1] Stimulated by the 1973 energy crisis, biomass energy projects were set up throughout Europe,[2–4] as well as in North America where studies include extremely short rotation cycles of 1–5 years.[5–8]



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Little research has been carried out using poplars in Finland, although more has been done with the native aspen and its hybrids.[9] The question of the suitability of poplars for Finnish conditions has been raised from time to time and the possibilities of using poplars in short rotation cultivation were considered for the first time under the SITRA short rotation production and utilization project (1975–78).[10] As a result, poplars were found to perform badly in Finland.

The present trials were initiated at a time when short rotation fuelwood research was directed towards the possibilities of cultivating various non-indigenous tree species.[11–13] The objective of this work was to investigate further short rotation cultivation of poplar in relation to the establishment of plantations directly from cuttings, fertilizer requirements, spacing preferences and above-ground biomass production.

## MATERIALS AND METHODS

### Experimental arrangements

The trials were set up in a formerly cultivated field, located at Paimio in south-western Finland (60°30′ N, 22°45′ E). The field had been ploughed the preceding autumn. The soil, clay mixed with fine sand, had a pH of 6·1–6·9, soluble phosphorus concentration of 4·6–9·8 mg/litre, exchangeable potassium concentration of 188–410 mg/litre and calcium 1800–3500 mg/litre. It may thus be classed as being of a satisfactory fertility in relation to the statistics of Kurki.[14]

Cuttings, 20 cm long, of *Populus* × *rasumowskyana* (origin of hybrid unknown, possibly *P. laurifolia* × *P.* × *woobstii*) were planted 18 cm deep on 7 May, 1981. The ground was moist at the time, after two consecutive rainy days. Planting was hampered slightly by the presence of frost in the ground in places. Since the early summer proved to be very dry, the cuttings were watered for the first 2 weeks.

The plots for the spacing trials were of size 400 $m^2$ (20 m × 20 m). The following densities were used:

(A) 35 000 stems/ha, intervals 0·71 m × 0·40 m
(B) 15 000 stems/ha, intervals 0·70 m × 0·95 m
(C) 5 000 stems/ha, intervals 1·40 m × 1·40 m

Corridors of 5 m width were left between the plots. The various spacing treatments were replicated twice on plots selected at random. A multinutrient fertilizer was spread at a rate of 300 kg/ha (nitrogen (N) 16%, phosphorus (P) 7%, potassium (K) 13%) at the beginning of

August, 1981. A corresponding trial was also initiated in a field at Kannus in Central Finland (63°53′ N, 23°55′ E) in spring 1981 but was destroyed by frost next year, so that only the first year data were available for comparison of the effect of the diameter on survival of the cuttings.

Fertilizer trials were conducted on plots of size 225 $m^2$ (15 m × 15 m) at a spacing density equivalent to 15 000 stems/ha. The nitrogen fertilizer treatments, which were replicated twice, were as follows: (A) no fertilizer, (B) N 100 kg/ha, (C) N 200 kg/ha and (D) N 300 kg/ha.

Nitrogen fertilizer was applied as urea (46% N) in late June, 1981, during a period of fairly frequent rain, and again in early June, 1982. One of the non-fertilized control plots failed due to late planting and poor condition of the cuttings. The plots were mechanically weeded in early August, 1981, and the sprouts cut back in the autumn after the first growing season leaving the longest shoot on each stool.

## Measurements

Annual assessments were made of living and dead trees, their heights and diameters at 10 cm above the ground of the living ones. Diameter at breast height was also measured in 1984–86. To avoid border effects, four rows on the outer edges of the plots were ignored.[15]

Twenty-four trees were sampled in autumn 1982 and again in 1986 according to the size distribution of the trees in the plots. The trees were cut, their height and diameter at cutting height were measured and fresh mass weighed to an accuracy of 10 g. Branches were separated only in 1986. In order to determine the ratio between fresh and dry mass, moisture samples from each tree were subsampled and dried at 105°C for 2 days and weighed again to obtain the dry mass.

Dry mass equations of the form $Y = ax^b\varepsilon$ were calculated for the leafless above-ground mass and in 1986 also for the stem and branch mass using logarithmic transformation.[16,17] The independent variable in the equations was the product of diameter squared multiplied by height ($d^2h$) (Table 1). The slight underestimation caused by the transformation was corrected by adding to the constant a correction coefficient $s^2/2$, in which $s$ is the variation in the residual of the equation. The dry masses of the poplars in the plots were calculated by the summation technique. The biomass of one- and two-year-old poplars was calculated using an equation (Table 1) based on two-year-old sample trees and the biomass of three- to six-year-old poplars using equations based on six-year-old sample trees.

## RESULTS

### Effect of cutting diameter

The diameter of the cutting as planted had little effect on its survival at Paimio (Fig. 1), although more of the thinnest class of cuttings, less than 1 cm in diameter, died than the thicker ones. However, at Kannus the poorer survival of the thinnest cuttings was more obvious (Fig. 1). The

**TABLE 1**
Dry Mass Equations for the Poplars, $Y = ax^b\varepsilon$

| *Compartment* | *Age (years)* | *N* | $x = d^2h$ | | | |
|---|---|---|---|---|---|---|
| | | | *a* | *b* | $R^2$ (%) | *V* (%) |
| Total | 2 | 24 | 0·00810 | 0·86524 | 99 | 8·2 |
| Branch | 6 | 24 | 0·00005 | 1·13695 | 93 | 44·4 |
| Stem mass | 6 | 24 | 0·00396 | 0·90079 | 98 | 16·9 |
| Total mass | 6 | 24 | 0·00275 | 0·94753 | 98 | 17·0 |

N = number of sample trees.
*a* and *b* are constants.
*d* = diameter at cutting height (mm).
*h* = height (cm).
$R^2$ = coefficient of determination.
*V* = coefficient of variation.
*Y* = dry mass (g).

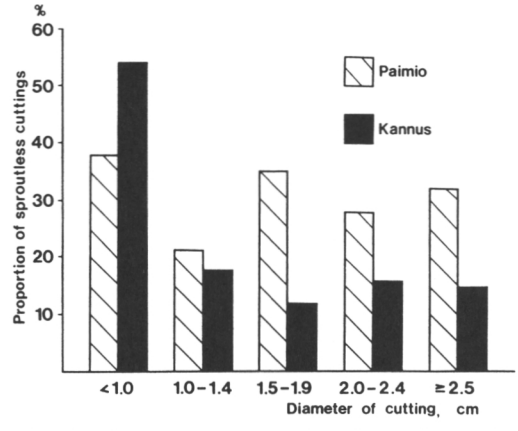


**Fig. 1.** Effect of cutting diameter on the proportion of sproutless cuttings after the first growing season.

cuttings of diameter ≥ 2·5 cm showed no signs of being too thick for the purpose.

The size of the cutting had a significant effect on sprouting and early sprout growth. The number of sprouts per cutting increased with increase in the diameter of the cutting. The smallest cuttings ( < 1·0 cm) had on average 1·3 sprouts per cutting and the largest ( ≥ 2·5 cm) 1·8 sprouts per cutting. The difference between these diameter classes was statistically significant ($p < 0{\cdot}001$). The diameter and height of the first-year sprouts also increased with the increase in diameter of the cutting ($p < 0{\cdot}001$) (Fig. 2). Other species of poplar have also been found to produce better developed sprouts if thicker cuttings are used, up to a limit of 2·5 cm.[18,19]

## Effect of fertilizer application

Over 50% of the non-fertilized cuttings were dead by the first autumn and mortality was almost 100% by the end of the sixth growing season. The lowest mortality rate was achieved with the heaviest application of fertilizer (N 300 kg/ha). In this case mortality was 51% after the sixth growth season, leaving some 7000–8000 living stems per hectare. Mortality figures with the other nitrogen doses were around 80%.

The dominant height (the mean height of the five longest trees on each plot) of the poplars that had received the maximum amount of fertilizer was almost 7 m after 6 years, and the dominant diameter 7·6 cm,

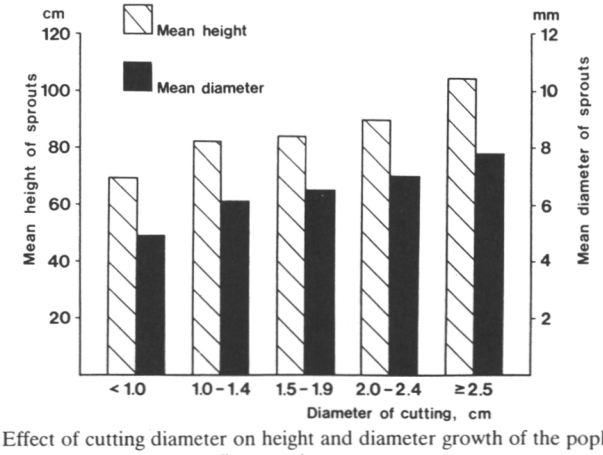


**Fig. 2.** Effect of cutting diameter on height and diameter growth of the poplars in the first growing season.

compared with figures of 4·3 m and 4·9 cm for the non-fertilized trees (Fig. 3).

The yield of woody above-ground dry mass over 6 years was more than 25 t/ha on plots which had received the highest application of nitrogen (Fig. 4), giving a mean annual production of 4·2 t/ha. This

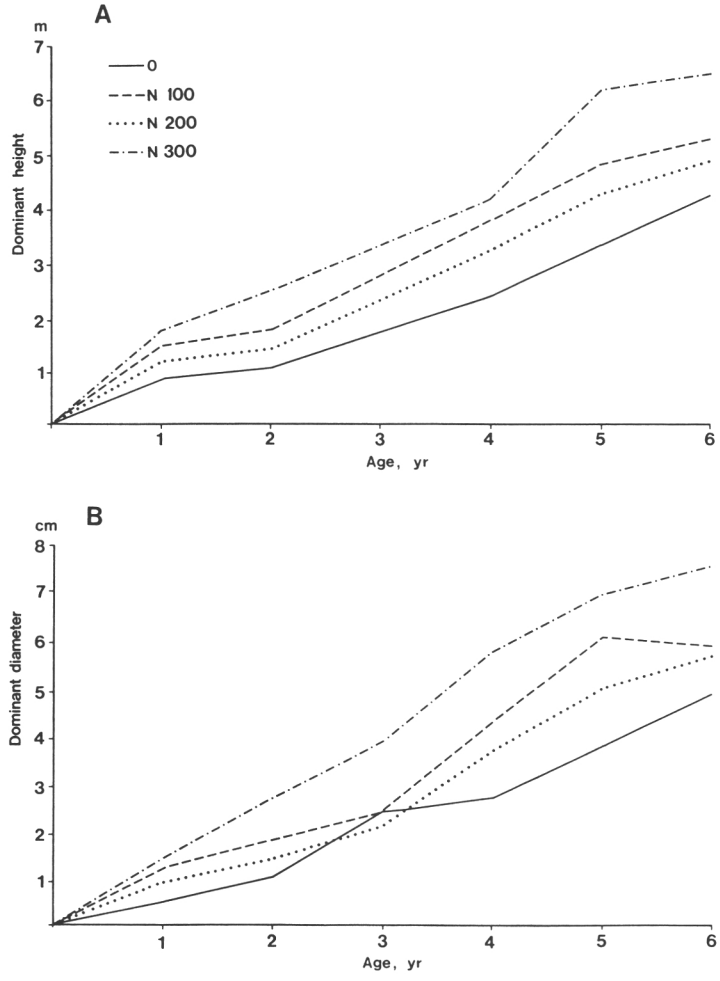


**Fig. 3.** Effect of nitrogen fertilization on the dominant height (A) and dominant diameter (B) of the poplars.

would correspond to a yield of the order of 10–13 $m^3$/ha per year. The corresponding total yield over 6 years on the plots receiving less fertilizer was only 6–7 t/ha (Fig. 4). About 25% of this biomass was accounted for by branches.

## Effect of spacing

After 5 years, survival was directly proportional to stand density, i.e. it was lowest on the plots with the highest density of stems. After 6 years, the number of the trees in the plots with a spacing of 35 000 stems/ha had declined to one fifth of the initial value, i.e. 6650 stems/ha. In plots with a medium spacing of 15 000 stems/ha numbers dropped to a third, 5700 stems/ha, and in plots with the lowest density (5000 stems/ha) numbers fell to half, reaching 2400 stems/ha. Thus, the major initial differences in spacing had essentially evened out over the period studied.

The dominant height of the stands increased by about 1 m/year (Fig. 5). By the end of the fifth and sixth growing season the greatest dominant height was found in the plots with the lowest stand density. However, these differences were not statistically significant. The dominant height in the widest spacing was 7 m, and that for the denser plots was 5·6 m. Mean height was about 1·5 m shorter than the dominant height on all plots.

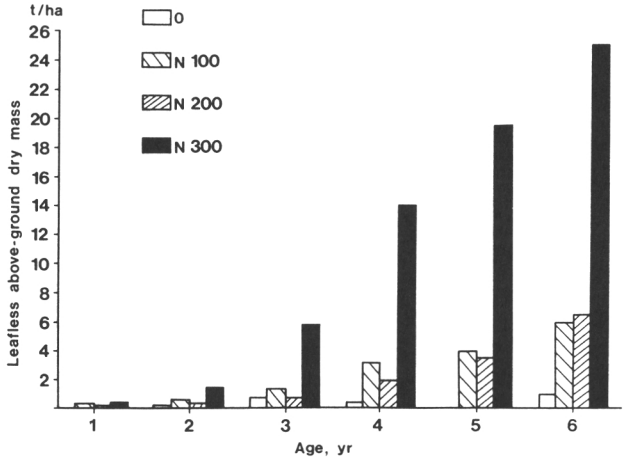


**Fig. 4.** Effect of nitrogen fertilization on the leafless above-ground dry mass of the poplars.

The effect of spacing was more pronounced on dominant diameter than height. The greatest diameter was clearly achieved with the widest

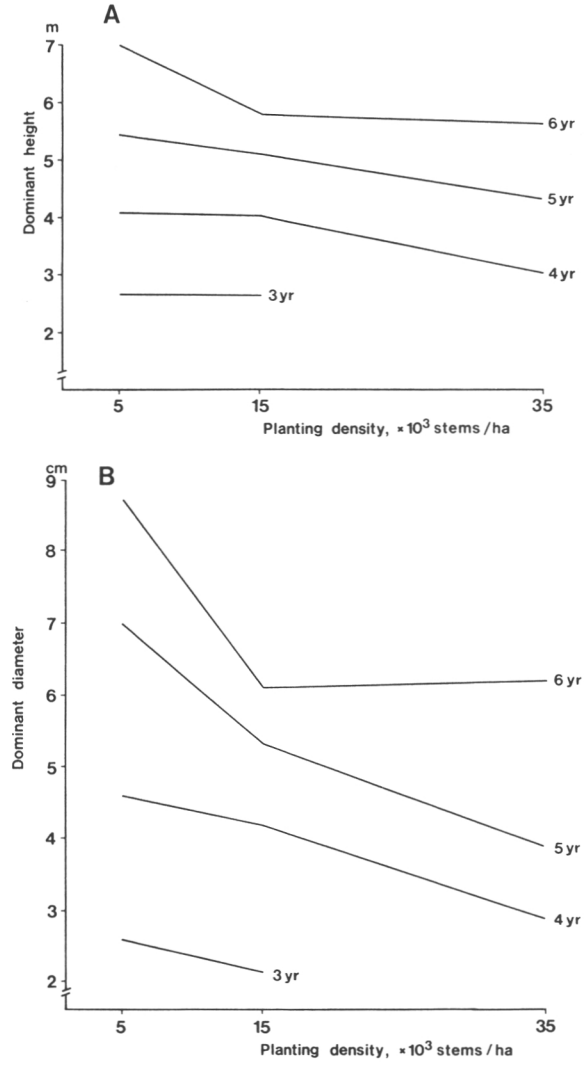


**Fig. 5.** Effect of planting density on the (A) dominant height and (B) dominant diameter of the poplars.

spacing of the stems ($p < 0{\cdot}001$), but possibly reflecting the high mortality, after 6 years the diameter of the most densely planted trees came close to that for those of medium spacing (Fig. 5). The most widely spaced trees had a dominant diameter at stump height of 8·7 cm, while the figure at other stand densities was only 6·2 cm, the corresponding diameters at breast height being 4·9 and 4·4 cm.

By the age of 4 years, the trees achieved the highest woody biomass on the plots with a spacing of 15 000 stems/ha (Fig. 6). It can be postulated that the highest biomass may well have existed in the densest stands at an earlier stage. By the end of the fifth year the medium-spaced poplars still had the highest stem biomass but the most widely spaced trees now equalled them in terms of branch biomass, and after the sixth growing season the latter were ahead on both scores. The eventual above-ground dry mass figures, excluding leaves, were 8·9, 11·2 and 13·7 t/ha respectively, from densest to most widely spaced (Fig. 6). However, these differences were not statistically significant.

## Damage to trees

The poplars planted at Paimio hardly suffered at all from frost damage, either through the cold conditions in winter or through summer frosts,

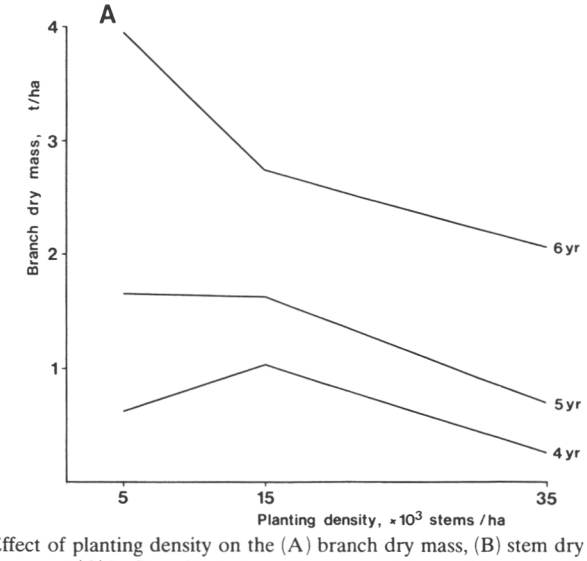


**Fig. 6.** Effect of planting density on the (A) branch dry mass, (B) stem dry mass and (C) leafless above-ground dry mass of the poplars.

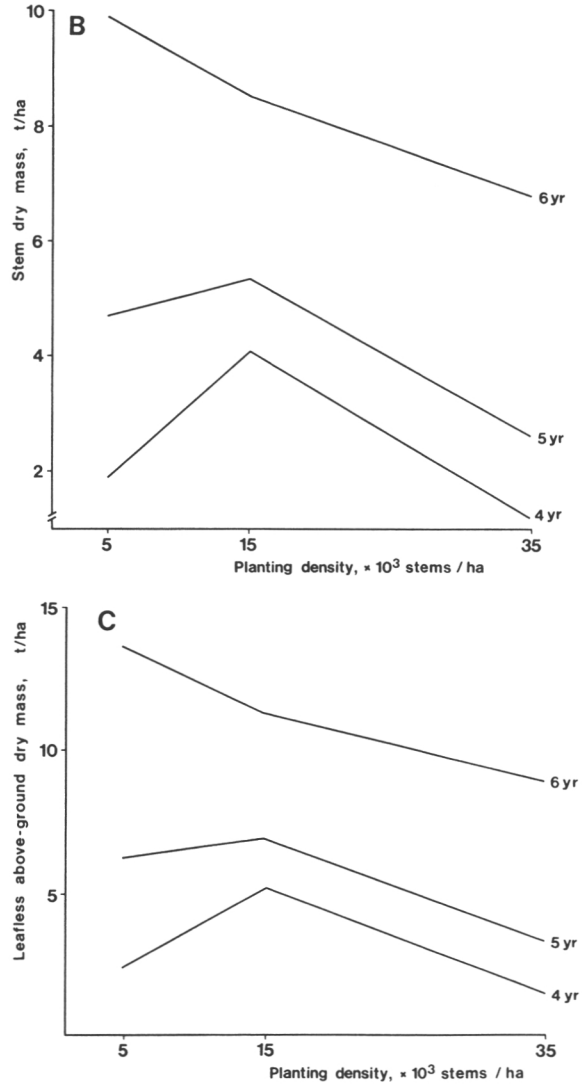


**Fig. 6.** — *contd.*

and overwintering appears to have been successful throughout. The Kannus plantation, on the other hand, was almost totally destroyed by frosts following coppicing at the end of the first growing season, the

sprouts emerging from the stumps the following year being especially susceptible to frost damage. Night frosts were particularly frequent in Finland in the early summer of 1982.

Since voles and hares can inflict substantial damage on poplars, an inventory of damage of this kind was made at Paimio at the end of the sixth year. This showed a mean of 32% of the trees to have been eaten at the base in the fertilizer trial and 18% in the spacing trial, the proportions being independent of the level of fertilizer application or the stand density. The damaged trees were 2–4 cm thinner and more than 2 m shorter than the healthy trees on average. It cannot be determined for certain whether the animals had mainly selected the smaller trees or whether the growth of these specimens had been hampered by the damage inflicted.

## DISCUSSION

In spite of the initial mortality, the present results indicate that the use of cuttings is a good way of starting a poplar plantation under Finnish conditions. Without fertilizer application the establishment of a poplar plantation from cuttings led to a high rate of dead saplings and cuttings. Mortality among poplar has been found to be higher than among willows planted in the same way, and poplars have proved slower rooters than willows.[12,20–22] Establishment can be further improved by selection of the cuttings on the basis of size and ensuring correct storage prior to planting. It is uncertain whether thin cuttings of diameter less than 1 cm will take root, and the minimum diameter for cuttings has been set by various authors at between 1·0 and 1·5 cm.[18,23,24] Thicker cuttings develop longer and thicker sprouts during the first growing season.[18,19] It is also important to soak the cuttings before planting and choose the correct time for planting, i.e. as soon as the ground has thawed after the winter.

Experience with hybrid aspen indicates that any consideration of cultivating *Populus* species in Finland must take account of their resistance to biotic and abiotic damage.[25] The present poplars were attacked by animals to some extent, although this seemed restricted to the smaller trees. The SITRA inventory of damage to poplar seedlings by voles also gave rather high figures, amounting to 20–32% at the peak in vole populations.[10] Overwintering of poplars was successful and no frost damages were encountered at Paimio but further north, at Kannus, poplars were destroyed by frosts.

Poplars which survived grew rapidly throughout the period studied, a particularly significant observation in view of the fact that the trial was

started with unrooted cuttings. These results differ markedly from earlier Finnish experiments, where the poplars grew extremely badly.[10]

The spacing trial showed mortality to be higher the denser the poplar stands, thus indicating the effects of competition. The best woody biomass production after four growing seasons was obtained at a density of 15 000 stems/ha. Similarly, Lee *et al.* had the best yield for *Populus* × *euramericana* when trees were planted at a density of 15 000 stems/ha after the first 3 years.[8] However, the lowest density tested in our study, 5000 stems/ha, proved most productive after 5 and 6 years. It would seem from this that poplars are not suitable for very short rotation cultivation of less than 5 years in Finland. As Kärkkäinen[25] notes in his review of the literature, poplars are not particularly well adapted to short rotation cultivation, i.e. less than 10 years, by comparison with certain other tree species, as they do not grow well in dense stands. Similar conclusions have been reached in comparisons made in natural forests.[26]

The best treatment in the fertilization trial gave a mean annual yield as high as 4·2 t/ha per year, a figure difficult to reach with native tree species in 6 years.[16] The fertilizer trials suggest that a considerable improvement in biomass production of poplars in Finland can be achieved by giving the correct dose of fertilizer, and the outcome could perhaps have been improved still further with a greater number of applications and possibly the use of a multinutrient fertilizer. The soil analyses, for instance, suggest that additional phosphorus could have been useful. Species and clone selection should be emphasized with respect to the frequent early summer frost and cold winters prevailing in Finland.

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# V

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Jyrki Hytönen

# TEOLLISUUSLIETTEELLÄ LANNOITETUN VESIPAJUN LEHDETÖN MAANPÄÄLLINEN BIOMASSATUOTOS

## Leafless above-ground biomass production of *Salix* 'Aquatica' fertilized with industrial sludge

*Approved on 8.3.1985*

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HYTÖNEN, J. 1985. Teollisuuslietteellä lannoitetun vesipajun lehdetön maanpäällinen biomassatuotos. Abstract: Leafless above-ground biomass production of *Salix* 'Aquatica' fertilized with industrial sludge. Folia For. 614: 1—16.

Tutkimuksessa selvitettiin Rajamäelle (60°32′ N, 24°37′ E) entiselle peltomaalle viljellyn ja jätelietteellä lannoitetun vesipajun *(Salix* 'Aquatica') kolmen vuoden biomassatuotos. Lietettä levitettiin koeruuduille 30, 60 ja 120 $m^3$/ha. Vertailulannoituksessa käytettiin vuosittain toistettuna Normaali Y-lannosta (470 kg/ha/a). Lietteen typpipitoisuus oli korkea (9,6 % kuiva-aineesta), fosforia (1,3 %) ja kaliumia (0,4 %) oli jo niukemmin etenkin suhteessa typen määrään. Lietteen raskasmetallipitoisuudet olivat alhaiset.

Tyviläpimittaan sekä tyviläpimitan neliön ja pituuden tuloon perustuvat biomassayhtälöt selittivät kuivamassaa hyvin, selvästi paremmin kuin pelkkään pituuteen perustuvat yhtälöt. Pajujen lehdetön maanpäällinen kuivamassa oli kaikilla lietelannoitustasoilla suurempi kuin vertailulannoituksella ja suurin keskimmäisellä (60 $m^3$/ha) lietelannoitustasolla. Kuivamassaa eri lannoituskäsittelyillä oli ensimmäisen kasvukauden jälkeen 0,5 ... 0,9 t/ha, toisen 3,1 ... 6,9 t/ha ja kolmannen kasvukauden jälkeen 9,1 ... 18,4 t/ha. Toisen kasvukauden kasvu oli kuusi kertaa ja kolmannen kasvukauden 9 ... 15 kertaa suurempi kuin ensimmäisen vuoden kasvu. Parhaalla käsittelyllä (60 $m^3$/ha lietettä) kolmannen kasvukauden tuotos oli 11,5 t/ha.

Lannoituskäsittelyt eivät vaikuttaneet maan liukoisten ja vaihtuvien ravinteiden määriin. Lietelannoitus lisäsi pajujen lehtien typpipitoisuutta sitä enemmän mitä enemmän lietettä käytettiin, fosforipitoisuus sen sijaan laski lietteen määrän lisääntyessä. Normaali Y-lannoksella lannoitettujen pajujen lehtien typpipitoisuus oli alhaisin ja fosforipitoisuus korkein. Lehtien kalium-, rauta-, sinkki- ja kuparipitoisuuksiin lietelannoituksella ei ollut selvää vaikutusta.

The biomass production and effect of sludge fertilization on the yield of three-year-old *Salix* 'Aquatica' planted on abandoned farmland in 1982 at density of 36 000 seedlings per hectare at Rajamäki (60°32′ N, 24°37′ E) was studied. Sludge was used 30, 60 and 120 $m^3$/ha. The yearly applied multinutrient fertilizer was used as comparison (470 kg/ha, N 16,0 %, P 7,0 %, K 13,3 %). The nitrogen content of sludge was high (9,6 % out of dry matter), the phosphorus (1,3 %) and potassium (0,4 %) contents were lower especially in relation to the amount of nitrogen. The heavy metal content of sludge was low. Willow received more nitrogen from sludge than from the multinutrient fertilizer. The differences between the amounts of phosphorus were small, while the amount of potassium was higher in the control than in sludge.

Biomass equations with the product of base diameter squared and height as an independent variable functioned well, clearly better than equations based on height only. The leafless above-ground biomass of willow was higher when fertilized with sludge than with the multinutrient fertilizer and highest when 60 $m^3$/ha of sludge was used. The dry mass of willow in different fertilization treatments was 0,5 ... 0,9 t/ha after the first, 3,1 ... 6,9 t/ha after the second and 9,1 ... 18,4 t/ha after the third growing season. The growth in the second growing season was six times and in the third 9 ... 15 times higher than in the first growing season. In the best treatment, 60 $m^3$/ha of sludge, the yield of the third growing season was 11,5 t/ha.

Fertilizer treatments did not affect the amounts of exchangeable and soluble nutrients in soil. Sludge fertilization increased the foliar nitrogen content of willow the more, the higher the amount of sludge used, while the foliar phosphorus content decreased with increasing amounts of sludge. The foliar nitrogen content of willow fertilized with the multinutrient fertilizer was lowest and phosphorus content highest. Sludge fertilization did not have a clear effect on the foliar potassium, iron, zinc and copper contents.

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# 1. JOHDANTO

Pajujen lyhyeen kiertoaikaan perustuva intensiivinen massatuotanto vaatii voimakasta lannoitusta (Pohjonen 1980). Pajut käyttävät huomattavia määriä sekä typpeä että muita kivennäisravinteita sitoen niitä lehtien lisäksi runsaasti myös puuaineeseen ja kuoreen (Kaunisto 1983). Maan riittävästä ravinteisuudesta huolehtiminen onkin keskeinen osa lyhytkiertoviljelyä. Kemiallisten lannoitteiden ohella on viime aikoina kiinnostuttu myös erilaisten jätteiden sisältämien ravinteiden hyväksikäytöstä. Tuhkan käytöstä metsälannoitteena on turvemailla saatu hyviä tuloksia (Pietiläinen ja Tervonen 1980).

Jätevedenpuhdistamoilla erotetaan kiintoaines lietteenä ja sen mukana suurin osa ravinteista. Lietteen määrät ovat lisääntyneet ja tällä hetkellä lietettä arvioidaan syntyvän maassamme noin 100 000 tonnia kuiva-ainetta vuodessa (Ferm ja Takalo 1981). Nykyisen hyötykäytön osuus on vain noin 35 % (maatalous ja viherrakentaminen). Loput viedään pääasiassa kaatopaikoille (Koskela 1980).

Liete on tärkeimmiltä ominaisuuksiltaan verrattavissa karjanlantaan. Lietteellä on humusvaikutus ja se parantaa maan rakennetta sekä vedenpidätyskykyä. Lietteen ravinteet ovat sitoutuneet orgaaniseen ainekseen ja siten niiden vapautuminen kasvien käyttöön tapahtuu vähitellen. Eräillä puhdistusmenetelmillä tuotetun lietteen typpipitoisuus on suuri, jopa 4 % lietteen kuiva-ainesisällöstä (Ferm ja Takalo 1981). Fosforia lietteet sisältävät usein paljon, sen sijaan kaliumia on vähän suhteessa typpeen ja fosforiin.

Raskasmetallipitoisuudet ja mahdolliset hajuhaitat ovat lietteen maatalouskäytön ongelmina. Terveysviranomaisten antamien ohjeiden mukaan lietteen kuiva-ainetta voidaan levittää 20 tonnia hehtaarille viiden vuoden aikana (Koskela 1980). Samoin raskasmetallipitoisuuksille on määrätty enimmäismäärät. Lietteen levitys metsään tarjoaa eräitä etuja maatalouskäyttöön nähden: raskasmetallien ja muiden haitallisten aineiden joutuminen ravintoon minimoituu — tosin raskasmetalleilla voi olla puuston kasvuun negatiivinen vaikutus — ja käyttömäärät voivat olla suurehkoja. Levitys on teknisesti vaikeaa varsinaisilla metsämailla.

Tässä tutkimuksessa tarkastellaan Oy Alko Ab:n Rajamäen tehtaiden puhdistamon viljanpolttimojätelietteen, jota tehtailla syntyy noin 1 800 $m^3$ vuodessa, soveltuvuutta vesipajuviljelmän lannoitteeksi. Päähuomio kiinnitetään pajuviljelmän biomassatuotokseen ja lietteen lannoitusvaikutukseen sekä lehtien ja kasvualustan ravinnepitoisuuksiin kolmen vuoden tutkimusjakson aikana.

Kokeen perustamisen kenttätöistä huolehtivat Työtehoseuran koetila ja Rajamäen metsätyönjohtajakoulu, Tauno Janhosen, Kari Kallelan, Reijo Oravan sekä Osmo Saarisen johdolla. Kenttämittauksista vastasi Esa Heino. Laskentatyössä avusti Seppo Vihanta. Tutkimuksen edistymiseen vaikuttivat monin tavoin Erkki Anttila ja Asko Henttonen Oy Alko Ab:stä. Puhtaaksikirjoituksesta huolehti Maire Ala-Pöntiö. Englanninkieliset tekstinosat tarkasti Leena Kaunisto. Käsikirjoitukseen ovat tutustuneet Erkki Lipas, Eero Paavilainen, Ari Ferm, Seppo Kaunisto ja Paavo Pelkonen. Oy Alko Ab:lle ja kaikille edellä mainituille samoin kuin muillekin tutkimuksessa avustaneille esitän parhaat kiitokseni.

# 2. AINEISTO JA MENETELMÄT

## 21. Koejärjestelyt

Koe perustettiin keväällä 1982 Oy Alko Ab:n Rajamäen tehtaiden läheisyydessä olevalle hietaiselle multamaan pellolle. Koeruudut olivat 10 metriä leveitä ja 30 metriä pitkiä. Kesantona ollut peltomaa muokattiin kyntämällä levittäen samalla dolomiittikalkkia 6000 kg/ha. Liete levitettiin lietteenlevitysvaunuilla koeruuduille loppukeväällä 1982 ennen pajujen istutusta. Lietteen levityksen jälkeen maa äestettiin. Normaali Y-lannoitus, jossa typen määrä oli noin puolet Pohjosen (1980) suosittelemasta, uusittiin joka kevät kolmen vuoden ajan. Kaikki lannoituskäsittelyt toistettiin kolmasti. Koejäsenet olivat seuraavat:

1. Normaali Y-lannos 470 kg/ha/a (N 16,0 %, P 7,0 %, K 13,3 %)
2. Liete 30 $m^3$/ha
3. Liete 60 $m^3$/ha
4. Liete 120 $m^3$/ha

Toukokuussa 1982 analysoitiin neljästä lietenäytteestä Viljavuuspalvelu Oy:ssä pH, kuiva-aineosuus, tuhkapitoisuus, pää- ja hivenravinteita sekä eräitä raskasmetalleja. Lietteen pH oli keskimäärin 6,1, kuiva-ainepitoisuus 13,5 % ja tuhkapitoisuus 11,9 % kuiva-aineesta. Lietteen sekä Normaali Y-lannoituksen sisältämät ravinnemäärät ja annostus on esitetty taulukossa 1. Lietteen typpipitoisuus oli huomattavan korkea, 9,6 % kuiva-aineesta. Fosforia (1,3 %) ja etenkin kaliumia (0,4 %) lietteessä oli huomattavasti niukemmin, etenkin suhteessa typen määrään. Raskasmetallipitoisuudet olivat alhaisia. Ne alittivat selvästi (kadmiumin ja kuparin osalta 3—4-kertaisesti, kromin, koboltin, nikkelin, sinkin ja mangaanin osalta 7—17-kertaisesti ja elohopean ja lyijyn osalta 35—38-kertaisesti) eräille aineille asetetun ylärajan maatalouskäyttöön tarkoitetussa lietteessä (Koskela 1980). Vertailulannoituksen (Normaali Y-lannoitus toistettuna ) typen määrä jäi alhaisemmaksi kuin typen määrä pienimmässäkin annostuksessa lietettä. Fosforin määrä vertailulannoituksessa vastasi keskimäisen lietetason fosforin määrää ja kaliumia vertailulannoituksessa tuli noin kolme kertaa enemmän kuin suurimmassa lietelannoituksessa tarkastelujakson aikana.

Vesipajun *(Salix* 'Aquatica', klooni V769) yksivuotiaat kantoon leikatut pistokastaimet (juurrutetut pistokkaat, joista versot oli leikattu pois) istutettiin kesäkuun alussa 1982 istutuskuokan avulla. Vesat kasvatettiin kolmevuotiaiksi (kuva 1). Istutustiheys oli 80 cm (riviväli) x 35 cm (pistokastaimien väli rivissä); eli keskimäärin 3,6 tainta neliömetrille. Rivivälin valinta tehtiin lietevaunujen raideleveyden perusteella.

Ensimmäisen kesän aikana rikkaruohot torjuttiin

Taulukko 1. Lietteen ja Normaali Y-lannoksen sisältämät ravinnemäärät (kuiva-aineesta) ja annostus.
*Table 1. Nutrient amounts (out of dry mass) and dosage of sludge and multinutrient fertilizer.*

| Ravinne *Mineral* | Lietteen ravinnepitoisuus *Mineral content of the sludge* | Liete — *Sludge*. $m^3$/ha 30 | 60 | 120 | Normaali Y-lannos 470 kg/ha/a | 1410 kg/ha/3a |
|---|---|---|---|---|---|---|
| | | Annostus — *Dosage*. kg/ha | | | Annostus — *Dosage* kg/ha/a | kg/ha/3a |
| N | 9,60 % | 389 | 778 | 1555 | 75 | 226 |
| P | 1,25 % | 51 | 101 | 203 | 33 | 99 |
| K | 0,37 % | 15 | 30 | 60 | 63 | 188 |
| Ca | 0,63 % | 26 | 51 | 102 | 11 | 34 |
| Mg | 0,15 % | 6 | 12 | 24 | 0,5 | 1,4 |
| S | 2,27 % | 92 | 184 | 368 | 9 | 28 |
| Fe | 2,56 % | 104 | 207 | 415 | 0,9 | 2,8 |
| B | 9,5 ppm | 0,04 | 0,08 | 0,16 | 0,24 | 0,71 |
| Cu | 1040 ppm | 4 | 8 | 17 | | |
| Mn | 189 ppm | 0,8 | 1,5 | 3,1 | | |
| Zn | 294 ppm | 1,2 | 2,4 | 4,8 | | |
| Co | 13 ppm | 0,05 | 0,11 | 0,21 | | |
| Cr | 14 ppm | 0,06 | 0,11 | 0,23 | | |
| Pb | 34 ppm | 0,14 | 0,28 | 0,56 | | |
| Cd | 9 ppm | 0,04 | 0,07 | 0,15 | | |
| Ni | 43 ppm | 0,18 | 0,35 | 0,71 | | |
| Hg | 0,66 ppm | 0,003 | 0,005 | 0,011 | | |



Kuva 1. Kolmen vuoden ikäistä vesipajukkoa koealueella. Valok. V. Pohjonen
*Fig. 1. Three-year-old* Salix *'Aquatica' stand in the study area. Photo V. Pohjonen*

mekaanisesti traktorivetoisella sokerijuurikasharalla sekä puutarhajyrsimellä. Seuraavina vuosina rikkaruohoja ei enää torjuttu. Peltosarat, joilla koeruudut sijaitsevat, rajoittuvat metsään. Koealuetta ei aidattu.

## 22. Mittaukset

Vesipajujen kuivamassa koeruuduilla arvioitiin määrittämällä runkolukusarja sekä poimimalla koevesat. Runkolukusarjaa määritettäessä käytettiin satunnaistettua systemaattista otantaa. Otos otettiin istutettujen pajurivien suunnassa mittanauhalla mitattuina yhden metrin (vuonna 1984 kahden metrin) pituisina jaksoina. Otantaväli valittiin sellaiseksi, että näytealoja tuli 11—12 kpl (7—9 kpl vuonna 1984) kullekin koeruudulle, ja että otos jakautui tasaisesti koko ruudun alueelle. Vesoja mitattiin tällöin noin 100 kpl kultakin koeruudulta. Mahdollisen reunavaikutuksen (ks. Cannell ja Smith 1980, Wittwer ym. 1978, Stott ym. 1983, Zavitkovski 1981) pienentämiseksi koeruutujen reunoilla sijaitsevia rivejä ei mitattu. Stott ym. (1983) suosittelevat yhdestä kolmeen vuotiaita eri tiheyksille istutettuja vesipajukasvustoja tutkittuaan kahden ulommaisen rivin poisjättämistä mittauksessa reunavaikutuksen eliminoimiseksi tuotosarvioista. Vesoista mitattiin pituus maan tasalta verson huippuun senttimetrin tarkkuudella ja läpimitta kymmenen senttimetrin korkeudelta maasta (ks. Nilsson 1982) millimetrin tarkkuudella. Samalla saatiin tiedot kasvuston tiheydestä (vesoja, kpl/$m^2$), vesomiskyvystä (vesoja, kpl/kanto), kuolleisuudesta sekä mahdollisista eläintuhoista. Yksivuotiaina vesipajut mitattiin toukokuun alussa v. 1983, kaksivuotiaina syyskuun lopussa v. 1983 ja kolmivuotiaina syyskuun puolivälissä v. 1984.

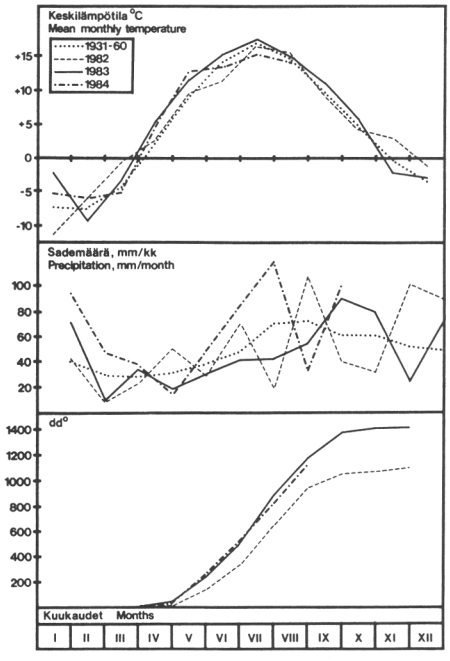
Koepuita otettiin vesojen läpimitta- ja pituusjakauman suhteen mukaisesti kaikilla mittauskerroilla kaikilta koeruuduilta. Ne kaadettiin kymmenen senttimetrin korkeudelta maasta (kantomassaa ei määritetty). Yhden vuoden ikäisiä koevesoja oli 30 kpl, kaksivuotiaita 22—24 kpl ja kolmivuotiaita 21 kpl kustakin lannoituskäsittelystä. Laboratoriossa koepuista mitattiin lehtien poistamisen jälkeen vesojen pituus ja läpimitta kaatokorkeudelta. Kolmevuotiaista vesoista mitattiin tyviläpimitan lisäksi läpimitta tyveltä 20 cm välein aina 210 cm korkeuteen asti. Tämän jälkeen vesat kuivattiin oksineen lämpökaapissa 105° lämpötilassa 1—2 vrk ja niistä mitattiin lehdetön kuivamassa. Taulukossa 2 on esitetty koepuiden tunnuksia.

Keväällä 1983 ja 1984 otettiin kaikilta pajuruuduilta maanäytteet, joista analysoitiin Viljavuuspalvelu Oy:ssä pH, kokonaistyppi, nitraattityppi, happamalla ammoniumasetaatilla uutettu fosfori, vaihtuva kalium ja kalsium sekä happoliukoinen rauta ja lisäksi vuonna 1984 johtoluku, ammoniumtyppi sekä vaihtuva magnesium. Vuoden 1983 ja 1984 syksyllä kerättiin kaikilta koeruuduilta lehtinäytteet pajujen yläosista, ei kuitenkaan aivan latvasta. Lehdistä määritettiin Viljavuuspalvelu Oy:ssä v. 1983 typpi-, fosfori-, kalium- ja rautapitoisuudet sekä v. 1984 lisäksi sinkki- ja kuparipitoisuudet.

Vuoden 1982 kesäkuu, jonka alussa juurakot istutettiin, oli keskimääräistä kylmempi ja sateisempi (kuva

Taulukko 2. Koepuiden tunnuksia.
*Table 2. Characteristics of sample trees.*

| Puutunnus *Characteristic* | Vesojen ikä, a *Age of sprouts* | Käsittely — *Treatment* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Normaali Y-lannos, kg/ha | | | | | | Liete — *Sludge*, $m^3$/ha | | | | | |
| | | 470 | | | 30 | | | 60 | | | 120 | | |
| | | $\bar{x}$ | s | Vaihteluväli *Range* | $\bar{x}$ | s | Vaihteluväli *Range* | $\bar{x}$ | s | Vaihteluväli *Range* | $\bar{x}$ | s | Vaihteluväli *Range* |
| Pituus, cm *Height, cm* | 1 | 86,4 | 34,5 | 35,0—148,0 | 84,4 | 30,8 | 24,5—131,0 | 84,3 | 36,2 | 24,0—166,0 | 84,7 | 33,7 | 27,0—153,0 |
| — ” — | 2 | 180,8 | 75,1 | 46,0—327,0 | 145,6 | 57,9 | 50,0—246,0 | 241,5 | 62,0 | 99,0—315,0 | 214,4 | 73,2 | 83,0—366,0 |
| — ” — | 3 | 308,4 | 98,4 | 106,0—516,0 | 373,0 | 88,1 | 147,0—483,0 | 356,0 | 124,8 | 96,0—525,0 | 265,6 | 75,5 | 137,0—393,0 |
| Tyviläpimitta, mm *Diameter at base, mm* | 1 | 6,0 | 1,8 | 2,7—8,4 | 6,0 | 2,1 | 2,5—10,1 | 6,0 | 2,2 | 2,3—10,7 | 6,2 | 1,9 | 2,2—9,8 |
| — ” — | 2 | 12,2 | 4,4 | 5,0—21,0 | 10,4 | 3,8 | 5,0—18,0 | 15,2 | 4,7 | 6,0—22,0 | 14,6 | 5,7 | 5,0—29,0 |
| — ” — | 3 | 20,6 | 7,7 | 7,0—36,0 | 23,3 | 8,0 | 7,0—39,0 | 22,4 | 8,1 | 6,0—33,0 | 17,7 | 6,2 | 8,0—30,0 |
| Yhden vesan kuivamassa, g *Dry mass of one sprout, g* | 1 | 8,4 | 6,8 | 0,4—27,0 | 7,7 | 6,3 | 0,4—23,5 | 9,0 | 8,4 | 0,3—36,4 | 8,1 | 6,9 | 0,3—27,7 |
| — ” — | 2 | 68,3 | 59,5 | 1,9—235,0 | 41,9 | 39,1 | 2,3—141,1 | 113,5 | 73,8 | 7,1—232,9 | 106,7 | 105,6 | 4,4—471,5 |
| — ” — | 3 | 273,4 | 241,6 | 7,2—911,4 | 379,8 | 274,3 | 10,0—999,9 | 385,2 | 300,4 | 6,0—996,9 | 194,4 | 158,1 | 12,3—557,1 |




Kuva 2. Keskilämpötilat ja sademäärät sekä lämpösumman kehitys Hyvinkään Mutilan säähavaintoasemalla vuosina 1982—1984.
*Fig. 2. Mean monthly temperatures, precipitation and development of degree day sum at Hyvinkää's Mutila weather station during 1982–1984.*

2). Vuodet 1983 ja 1984 olivat keskimääräistä lämpimämpiä, etenkin toukokuun osalta.

## 23. Kuivamassan laskenta

Koepuista mitattuja tunnuksia käyttäen laskettiin kuivamassayhtälöt biomassatutkimuksissa yleisesti käytettyjen regressiomallien avulla. Kuivamassayhtälöt laskettiin erikseen eri ikäisille pajuille lannoituskäsittelyittäin. Ennusteyhtälöt olivat muotoa:

$$Y = a \cdot X^{b\epsilon}$$

jossa Y = puun massa, X = puun koon mitta; a ja b ovat vakioita. Vakiotermien ratkaisemiseksi yhtälö muutettiin logaritmiseen lineaariseen muotoon:

$$\ln Y = \ln \alpha + \beta \ln X + \ln \epsilon.$$

Selittävinä tekijöinä mallissa vertailtiin tyviläpimittaa, pituutta ja tyviläpimitan neliön ja pituuden tuloa sekä vuonna 1984 eri korkeuksilta mitattua läpimittaa. Läpimitan mittauskorkeuden vaikutusta tutkittiin sijoittamalla tyviläpimittaan sekä pituuden ja tyviläpimitan neliöön perustuviin yhtälöihin läpimitaksi kolmivuotiaiden vesojen eri korkeuksilta mitatut läpimitat ja laskemalla vastaavat regressioyhtälöt. Variaatiokertoimet yhtälöille laskettiin Björklundin ja Fermin (1982) esittämällä tavalla. Ruuduittaisen kuivamassan laskennan helpottamiseksi yhtälöt muutettiin aritmeettiseen muotoon. Samalla logaritmimuunnoksen aiheuttamaa pientä aliarviota (ks. esim. Madgwick ja Satoo 1975, Satoo ja Madgwick 1982) korjattiin lisäämällä vakioon a Meyerin (1941) ja myöhemmin Baskervillen (1972) ehdottama korjauskerroin $s_\epsilon^2/2$, missä $s_\epsilon$ on yhtälön jäännöshajonta. Ennen kuivamassalaskentaa pajujen pituuksista vähennettiin 10 cm:ä (kannonkorkeus). Tämä siksi, että vesojen alkupiste ei ole maantasalla (ks. Nilsson 1982).

# 3. KUIVAMASSAYHTÄLÖT

Eri-ikäisten vesipajujen kuivamassayhtälöt (ilman lehtiä) sekä lannoituskäsittelyittäin että yhdistetyillä koepuuaineistoilla laskettuina on esitetty taulukossa 3. Esitetyissä yhtälöissä ovat selittävinä tekijöinä tyviläpimitta, pituus sekä tyviläpimitan neliön ja pituuden tulo. Kaikkien tutkittujen mallien selitysaste on korkea. Pelkkä pituus antoi kuitenkin huonomman selityksen kuin läpimitta. Pituuden ja tyviläpimitan tulon käyttö lisäsi vain hieman selitystä sekä pienensi jäännösvaihtelua pelkkään läpimittaan verrattuna. Kaikkien koepuiden kuivamassan ja tyviläpimitan riippuvuus sekä kolmivuotiaiden pajujen läpimittaan perustuvalla yhtälöllä lasketut vesojen kuivamassat on esitetty kuvassa 3. Parhaaksi läpimitan mittauskorkeudeksi saatiin kolmivuotiailla vesoilla 30 cm. Tuolloin selitysaste oli korkein ja jäännöshajonta pienin (kuva 4a). Myöskin tyvi ja 50 cm:n korkeus antoivat vielä hyvän selityksen. Yhtälöiden eksponentin arvot pienenivät ja vakion a arvot kasvoivat läpimitan mittauskorkeuden ollessa ylempänä (kuva 4b). Virheellinen läpimitan mittauskorkeus heikentäisi tulosten luotettavuutta.

Yhdistetystä koepuuaineistosta laskettujen kuivamassayhtälöiden variaatiokertoimet olivat läpimitan ollessa selittävänä tekijänä eri-ikäisillä pajuilla 15,6—19,4 % ja pituuden ollessa selittäjänä 27,8—34,1 %. Variaatiokertoimet olivat pienimmät, 12,1—14,3 %, kun selittävänä tekijänä oli läpimitan neliön ja pituuden tulo. Eksponentin b arvot kasvoivat ja vakion a pienenivät pajujen iän lisääntyessä, kun selittäviä tekijöitä olivat pituus ja läpimitan neliön ja pituuden tulo. Sensijaan kun läpimitta oli selittäjänä, eri ikäisille pajuille laskettujen yhtälöiden eksponentin ja vakion arvojen vaihteluväli oli melko pieni.

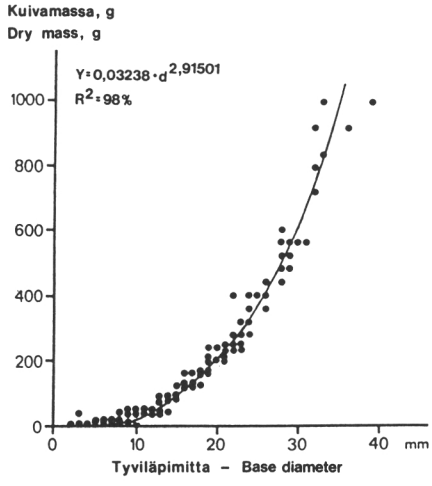
Koerper ja Richardsson (1980) suosittelevat eri alueille ja kasvupaikoille käytettäväksi

Taulukko 3. Vesipajun eri-ikäisten vesojen kuivamassayhtälöt. Yhtälöt ovat muotoa $Y = aX^b\epsilon$, jotka on logaritmimuunnoksen jälkeen korjattu kertoimella $e^{s_\epsilon^2/2 + a}$. Y = kuivamassa (g), h = pituus (cm) ja d = läpimitta 0,1 m:n korkeudelta (mm).

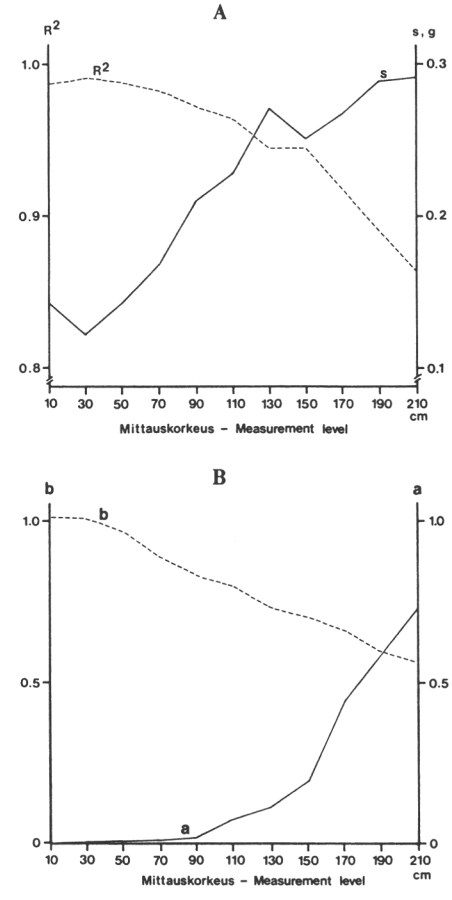
*Table 3. Dry mass equations of uneven-aged* Salix *'Aquatica' sprouts. From of equations is* $Y = aX^b\epsilon$, *which after logarithmic conversion were corrected with coefficient* $e^{s_\epsilon^2/2 + a}$. *Y = dry mass (g), h = height (cm) d = diameter at 0,1 m height (mm).*

| Käsittely[1] *Treatment* | Vesojen ikä, a *Age of sprouts* | $x = d^2h$ | | | | | $x = d$ | | | | | $x = h$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | a | b | $R^2$ % | V % | a | b | $R^2$ % | V % | | a | b | $R^2$ % | V % | |
| 1 | 1 | 30 | 0,00406 | 0,92198 | 99 | 10,8 | 0,02788 | 3,05300 | 98 | 15,9 | | $51 \times 10^{-5}$ | 2,14077 | 92 | 29,0 | |
| — " — | 2 | 24 | 0,00241 | 0,97615 | 99 | 15,6 | 0,01800 | 3,17017 | 98 | 19,2 | | $18 \times 10^{-5}$ | 2,42985 | 95 | 29,5 | |
| — " — | 3 | 21 | 0,00092 | 1,04330 | 99 | 10,9 | 0,02527 | 2,97112 | 99 | 11,3 | | $0,1 \times 10^{-5}$ | 3,33041 | 94 | 31,6 | |
| 2 | 1 | 30 | 0,00387 | 0,91591 | 99 | 12,3 | 0,03431 | 2,87719 | 98 | 16,8 | | $16 \times 10^{-5}$ | 2,38834 | 95 | 25,6 | |
| — " — | 2 | 23 | 0,00261 | 0,97139 | 99 | 9,6 | 0,02707 | 3,01068 | 97 | 20,6 | | $12 \times 10^{-5}$ | 2,51284 | 95 | 27,2 | |
| — " — | 3 | 21 | 0,00116 | 1,02061 | 99 | 10,9 | 0,05440 | 2,74393 | 99 | 12,2 | | $0,005 \times 10^{-5}$ | 3,79634 | 95 | 31,0 | |
| 3 | 1 | 30 | 0,00311 | 0,95573 | 99 | 12,1 | 0,02369 | 3,09715 | 99 | 13,8 | | $14 \times 10^{-5}$ | 2,44064 | 97 | 21,5 | |
| — " — | 2 | 22 | 0,00316 | 0,94336 | 99 | 9,3 | 0,06883 | 2,65927 | 99 | 10,2 | | $0,4 \times 10^{-5}$ | 3,08511 | 94 | 23,9 | |
| — " — | 3 | 21 | 0,00096 | 1,04035 | 99 | 13,8 | 0,04039 | 3,09740 | 99 | 17,0 | | $0,5 \times 10^{-5}$ | 3,03578 | 96 | 31,0 | |
| 4 | 1 | 30 | 0,00338 | 0,93461 | 99 | 13,6 | 0,02537 | 2,96151 | 94 | 26,2 | | $38 \times 10^{-5}$ | 2,20399 | 91 | 32,6 | |
| — " — | 2 | 23 | 0,00275 | 0,95742 | 99 | 11,3 | 0,05141 | 2,74216 | 98 | 14,5 | | $1 \times 10^{-5}$ | 2,94887 | 93 | 30,9 | |
| — " — | 3 | 21 | 0,00146 | 1,01913 | 99 | 12,3 | 0,03238 | 2,91501 | 99 | 13,7 | | $0,2 \times 10^{-5}$ | 3,30344 | 93 | 29,3 | |
| Kaikki | 1 | 120 | 0,00356 | 0,93294 | 99 | 12,9 | 0,02924 | 2,99311 | 97 | 19,4 | | $25 \times 10^{-5}$ | 2,30072 | 94 | 27,8 | |
| *All* | 2 | 92 | 0,00300 | 0,95201 | 99 | 12,1 | 0,03336 | 2,91962 | 98 | 18,3 | | $10 \times 10^{-5}$ | 2,54124 | 94 | 30,9 | |
| — " — | 3 | 84 | 0,00133 | 1,01528 | 99 | 14,3 | 0,03238 | 2,91501 | 98 | 15,6 | | $0,3 \times 10^{-5}$ | 3,13650 | 93 | 34,1 | |

1) Katso taulukkoa 8. *See Table 8.*




Kuva 3. Koevesojen kuivamassan riippuvuus tyviläpimitasta (N = 296).
*Fig. 3. Dependence of the dry mass of sample trees on diameter at base (N = 296).*




Kuva 4. Läpimitan mittauskorkeuden vaikutus yhtälön $Y = a\,(d^2h)^b$ selitysasteeseen ja jäännöshajontaan (A), sekä vakion a ja eksponentin b arvoihin (B). Y = vesan kuivamassa, g.
*Fig. 4. The effect of measurement level of diameter on the coefficient of determination and standard deviation (A) and on the constant a and exponent b (B) of the equation $Y = a\,(d^2h)^b$. Y = dry mass of one sprout, g.*

paikallisia regressioyhtälöitä, mikäli metsiköt eroavat toisistaan ravinteisuus yms. ominaisuuksiltaan. Tämän tutkimuksen eri käsittelyille lasketut regressioyhtälöt eivät poikenneet toisistaan eivätkä yhdistetyllä koepuuaineistolla lasketuista yhtälöistä tilastollisesti merkitsevästi, kun vertailu tehtiin F-testillä. Lopullisessa laskennassa käytettiinkin yhdistetyllä koepuuaineistolla laskettuja regressioyhtälöitä, joissa selittäjinä olivat vesan tyviläpimitan neliön ja pituuden tulo. Kun yksittäisten koeruutujen kuivamassat laskettiin koko aineistosta muodostetulla yhtälöllä, olivat erot kunkin käsittelyn omalla yhtälöllä saatuun massaan yksivuotiailla pajuilla −6,8...+6,2 % ja kaksivuotiailla −7,9... +4,4 %.

# 4. TULOKSET

## 41. Kuolleisuus, vesojen pituus ja läpimitta sekä kasvustojen tiheys

Vesipajun pistokastaimien kuolleisuus oli pieni, vaihdellen 1,3...5,3 %:iin eri lannoituskäsittelyillä. Lietelannoitus ei vaikuttanut taimien kuolleisuuteen. Jänis- ja hirvituhot sekä vesojen talviaikainen paleltuminen jäivät hyvin vähäisiksi.

Lietteellä lannoitettujen vesipajujen elävien vesojen keskipituus ja -läpimitta olivat kaikkina vuosina suurempia kuin Normaali Y-lannoksella lannoitettujen pajujen (taulukko 4, kuva 5). Lietemäärä 60 $m^3$/ha antoi vuosittain parhaan, lietemäärä 120 $m^3$/ha toiseksi parhaan ja lietemäärä 30 $m^3$/ha huonoimman tuloksen keskipituuden ja -läpimitan osalta. Vuosittain toistetulla Normaali Y-lannoksella lannoitetuilla koeruuduilla pajut jäivät joka vuosi kaikkein lyhyimmiksi ja ohuimmiksi. Varianssianalyysissä erot eivät kuitenkaan osoittautuneet tilastollisesti merkitseviksi.

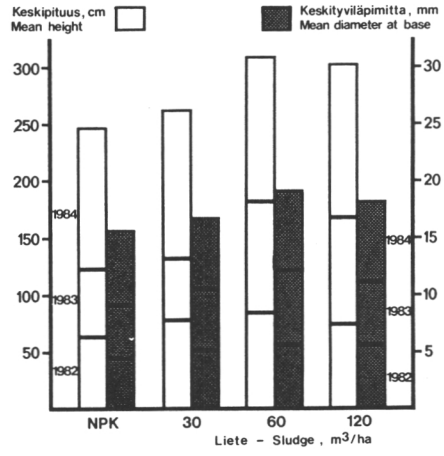
Lietelannoitus ei vaikuttanut pajujen vesomiseen, eikä myöskään kasvustojen tiheyteen, mikä taulukossa 4 on esitetty vesojen lukumääränä neliömetriä kohti. Sekä vesojen lukumäärä laskettuna elävää kantoa kohden että kasvuston tiheys on pienentynyt huomattavasti toisen ja kolmannen kasvukauden aikana ja samalla eri käsittelyjen väliset tiheyserot ovat tasoittuneet. Kasvustojen harveneminen ja vesojen lukumäärän vähentyminen johtuu pienten vesojen kuolemisesta. Ensimmäisen kasvukauden jälkeen kuolleita vesoja oli 2,0 kpl/$m^2$ ja niiden keskipituus oli 22 cm. Kaksi- ja kolmivuotiaassa kasvustossa vastaavat luvut olivat 0,6 kpl/$m^2$, 40 cm ja 1,4 kpl/$m^2$ ja 58 cm.

## 42. Biomassatuotos

Eri tavoin lannoitettujen vesipajujen lehdetön maanpäällinen biomassatuotos ensim-

Taulukko 4. Puustotunnuksia.
*Table 4. Tree characteristics.*

| Tunnus *Characteristic* | Kasvuston ikä, a *Age of stand* | Käsittely — *Treatment* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Normaali Y-lannos, 470 kg/ha/a | | Liete — *Sludge*, $m^3$/ha 30 | | 60 | | 120 | |
| | | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s |
| Keskipituus, cm *Mean height, cm* | 1 | 64,7 | 6,6 | 76,0 | 6,5 | 83,7 | 6,1 | 76,5 | 7,5 |
| —"— | 2 | 128,5 | 26,8 | 156,2 | 33,6 | 185,3 | 14,5 | 171,6 | 59,7 |
| —"— | 3 | 248,0 | 37,9 | 266,3 | 38,1 | 316,4 | 34,8 | 302,7 | 60,5 |
| Keskiläpimitta ($D_{0.1}$), mm *Mean diameter at base, mm* | 1 | 4,7 | 0,4 | 5,2 | 0,2 | 5,7 | 0,4 | 5,4 | 0,7 |
| —"— | 2 | 8,9 | 1,4 | 10,6 | 1,8 | 12,1 | 0,8 | 11,3 | 3,4 |
| —"— | 3 | 15,7 | 1,9 | 16,9 | 3,1 | 19,3 | 1,9 | 18,3 | 2,9 |
| Tiheys, vesoja kpl/$m^2$ *Density, no. of sprouts/$m^2$* | 1 | 14,7 | 1,0 | 13,0 | 2,2 | 12,8 | 2,1 | 14,8 | 2,8 |
| —"— | 2 | 10,7 | 1,3 | 10,3 | 2,4 | 10,1 | 1,2 | 9,8 | 0,9 |
| —"— | 3 | 8,6 | 0,2 | 7,7 | 0,7 | 9,0 | 1,3 | 7,4 | 0,4 |
| Vesoja, kpl/kanto *No. of sprouts/stump* | 1 | 4,3 | 0,6 | 3,7 | 0,7 | 3,7 | 0,8 | 4,8 | 0,8 |
| —"— | 2 | 2,6 | 0,3 | 2,4 | 0,4 | 2,5 | 0,3 | 2,7 | 0,5 |
| —"— | 3 | 2,3 | 0,1 | 2,1 | 0,2 | 2,6 | 0,4 | 2,3 | 0,3 |




Kuva 5. Elävien vesojen keskipituudet ja -tyviläpimitat.
*Fig. 5. Mean height and mean diameter at base of living sprouts.*

mäisen kasvukauden jälkeen vaihteli 0,47 t/ha:sta 0,92 t/ha:iin. Toisen kasvukauden jälkeen pajujen kuivamassa eri käsittelyillä vaihteli 3,09 t/ha:sta 6,89 t/ha:iin, ja kolmannen kasvukauden jälkeen 9,08 t/ha:sta 18,41 t/ha:iin (taulukko 5, kuva 6). Kaikkina kolmena vuotena lehdettömän biomassan määrä on ollut suurin lietteellä lannoitetuilla ruuduilla ja pienin toistetun Normaali Y-lannoituksen saaneilla koeruuduilla. Lietelannoitustasoista selvästi parhaan tuloksen, ensimmäistä vuotta lukuunottamatta, on antanut keskimmäinen eli 60 $m^3$/ha. Suurimmalla eli 120 $m^3$/ha lietemäärällä pajut kasvoivat hieman huonommin ja pienimmän eli 30 $m^3$/ha lietemäärän saaneilla koeruuduilla tuotos jäi vieläkin alhaisemmaksi. Ainoastaan vertailulannoituksen ja keskimmäisen lietelannoitustason väliset tuotoserot olivat tilastollisesti suuntaa antavia v. 1983 ($p < 0{,}062$) ja v. 1984 ($p < 0{,}056$).

Vesipajun kokonaismassa ja vuotuinen kasvu eri lannoituskäsittelyillä on esitetty taulukossa 5. Pajujen maanpäällinen lehdetön biomassatuotos oli ensimmäisenä vuotena vain 0,70 t/ha. Toisena kasvukautena pajut kasvoivat jo paremmin: keskimääräinen vuotuinen kuivamassatuotos vaihteli 1,54 t/ha:sta 3,44 t/ha:iin ja toisen vuoden juokseva vuotuinen kasvu 2,61 t/ha:sta 6,12 t/ha:iin. Toisen kasvukauden kasvu oli keskimäärin peräti kuusinkertainen ensimmäisen vuoden kasvuun verrattuna.

Vesipajun kasvu lisääntyi huomattavasti kolmantena kasvukautena molempiin aikaisempiin verrattuna. Kolmannen vuoden kasvu vaihteli 6,00 t/ha:sta 11,52 t/ha:iin ja koko tutkimusjakson keskimääräinen kasvu oli 3,03 ... 6,14 t/ha/a. Kolmannen vuoden kasvu oli toisen vuoden kasvuun verrattuna keskimäärin kaksinkertainen ja massan lisääntyminen oli vielä selvempi kun tulosta verrataan ensimmäisen vuoden kasvuun: kolmannen vuoden kasvu oli peräti 7 ... 15 kertaa niin suuri kuin ensimmäisen. Tulosten perusteella tutkimusalueen pajukasvustojen keskimääräinen tuotos ja vuotuinen tuotos lisääntyi kolmanteen ikävuoteen asti, eikä kasvun taantumaa vieläkään havaittu.

### 43. Kasvualustan ja lehtien ravinnepitoisuudet

Taulukossa 6 esitetään kivennäismaan eräitä ominaisuuksia yhden ja kahden vuoden jälkeen kokeen perustamisesta. Maan nitraattityppipitoisuus lisääntyi v. 1983 lietteen määrän kasvaessa; ei kuitenkaan tilastollisesti merkitsevästi. Vaikka lietteessä ja Y-lannoksessa annettujen ravinteiden määrät poikkeavat huomattavasti toisistaan (ks. taulukko 1) eivät lannoituskäsittelyiltä mitattujen maan ominaisuuksien keskiarvot poikenneet toisistaan varianssianalyysissä tilastollisesti merkitsevästi. Maa-analyysien tulosten perusteella arvioiden, kalkituksen ja lietelannoituksen jälkeenkin kasvualusta oli vain huononlaista tai välttävää peltomaata (Kurki 1982).

Nitraattitypen määrä korreloi positiivisesti kokonaismassan ja vuotuisen kasvun, elävien vesojen keskipituuden ja läpimitan kanssa v. 1983 sekä ammoniumtypen määrä vuotuisen kasvun kanssa v. 1984 (taulukko 7). Maan liukoisen fosforin määrän ja massa- ja puustotunnusten välinen korrelaatio oli lievästi negatiivinen ja vaihtuvan kaliumin vastaava korrelaatio lievästi positiivinen. Maan pH:n ja massa- ja puustotunnusten välinen korrelaatio oli positiivinen.

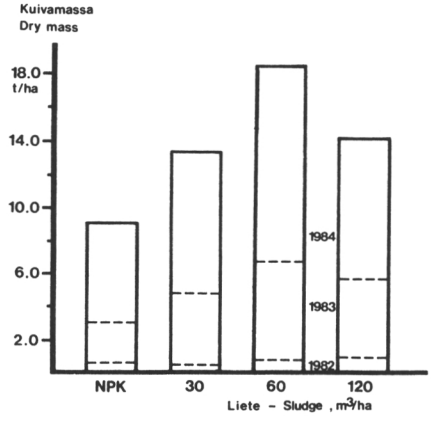
Vesipajun lehtien ravinnepitoisuuksia v. 1983 ja 1984 on esitetty taulukossa 8. Toistuvasti Normaali Y-lannoksella lannoitettujen pajun lehtien typpipitoisuus oli kumpanakin vuonna alhaisin ja fosforipitoisuus korkein.

**Taulukko 5.** Kasvustojen lehdetön maanpäällinen kuiva-ainemäärä ja vuotuinen kasvu.
*Table 5. Above-ground leafless dry mass and annual increment of stands.*

| Tunnus *Characteristic* | Kasvuston ikä, a *Age of stand* | Käsittely — *Treatment* Normaali Y-lannos, 470 kg/ha/a | | Liete — *Sludge*, m³/ha 30 | | 60 | | 120 | |
|---|---|---|---|---|---|---|---|---|---|
| | | x̄ | s | x̄ | s | x̄ | s | x̄ | s |
| Runkomassa, kuiva-ainetta/t/ha *Stem dry mass (inc. bark and branches), t/ha* | 1 | 0,47 | 0,11 | 0,66 | 0,04 | 0,77 | 0,17 | 0,92 | 0,64 |
| —"— | 2 | 3,09 | 1,39 | 4,80 | 1,22 | 6,89 | 1,69 | 5,74 | 3,47 |
| —"— | 3 | 9,08 | 2,72 | 13,38 | 6,66 | 18,41 | 4,17 | 14,20 | 5,89 |
| Juokseva vuotuinen kasvu, t/ha *Current annual increment* | 2 | 2,61 | 1,31 | 4,14 | 1,25 | 6,12 | 1,69 | 4,82 | 2,84 |
| —"— | 3 | 6,00 | 1,48 | 8,58 | 5,77 | 11,52 | 3,82 | 8,46 | 2,62 |

Taulukko 6. Kivennäismaan eräiden ominaisuuksien keskiarvo, keskihajonta ja vaihteluväli koealueella vuosina 1983 ja 1984.
*Table 6. Range, mean and standard deviation of some mineral soil properties.*

| Mitattu ominaisuus *Measured property* | 1983 x̄ | 1983 s | 1983 Vaihteluväli *Range* | 1984 x̄ | 1984 s | 1984 Vaihteluväli *Range* |
|---|---|---|---|---|---|---|
| pH | 5,0 | 0,2 | 4,7—5,3 | 5,1 | 0,2 | 4,8—5,4 |
| Johtoluku — *Conductivity* 10 mS/cm | — | — | — | 0,8 | 0,1 | 0,7—1,2 |
| Tot. N, % | 0,73 | 0,23 | 0,30—1,02 | 0,86 | 0,25 | 0,42—1,12 |
| $NH_4$ — N, mg/l | — | — | — | 18 | 6 | 10—28 |
| $NO_3$ — N, mg/l | 15,2 | 6,9 | 10,0—30,0 | 6,2 | 3,5 | 2,5—14,5 |
| Liukoinen — *Soluble P* mg/l | 7,0 | 1,0 | 6,0—8,4 | 7,8 | 1,5 | 6,1—11,0 |
| Vaihtuva — *Exchangeable K* mg/l | 115 | 11 | 95—125 | 100 | 31 | 52—170 |
| Vaihtuva — *Exchangeable Ca* mg/l | 952 | 133 | 850—1150 | 981 | 176 | 650—1300 |
| Vaihtuva — *Exchangeable Mg* mg/l | — | — | — | 176 | 51 | 115—265 |
| Liukoinen — *Soluble Fe* g/l | 5,0 | 2,3 | 3,0—9,3 | — | — | — |




Kuva 6. Vesipajujen runkomassa eri lannoituskäsittelyillä. Ensimmäisen ja toisen vuoden tuotos erotettu katkoviivalla.
*Fig. 6. Above-ground leafless dry mass of willows in different fertilizer treatments. Production of first and second year separated with dashed line.*

Lietemäärän lisääntyessä lehtien typpipitoisuus kasvoi, v. 1983 tilastollisesti merkitsevästi, ja samalla fosforipitoisuus pieneni. Eri tavoin lannoitettujen pajujen lehtien kaliumpitoisuudet eivät toisen kasvukauden jälkeen eronneet toisistaan. Toistuvasti Normaali Y-lannoksella lannoitettujen pajujen lehtien kaliumpitoisuus v. 1984 oli suurempi kuin lietelannoitettujen pajujen. Lehtien typpi- ja fosforipitoisuudet v. 1984 olivat selvästi, kaliumpitoisuudet vain hieman suuremmat kuin edellisenä vuonna. Lehtien typpi- ja fosforipitoisuuksien suhde oli pienin Normaali Y-lannoksella lannoitetuilla pajuilla ja suhde kasvoi lietemäärän lisääntyessä.

Lietelannoitus ei lisännyt merkitsevästi lehtien rautapitoisuutta, tosin v. 1984 lietelannoitettujen pajujen lehtien rautapitoisuudet olivat hivenen korkeammat kuin Normaali Y-lannoituksen saaneiden pajujen lehtien rautapitoisuudet. Siiran ym. (1984) kasvihuonekokeessakaan lietelannoitus ei vaikuttanut vesipajun lehtien eikä varsien rautapitoisuuteen, sen sijaan juurten rautapitoi-

Taulukko 7. Eräiden massa- ja puustotunnusten ja kivennäismaan ominaisuuksien sekä lehtien N-, P-, K-pitoisuuden ja N/P-suhteen väliset korrelaatiokertoimet.
*Table 7. Correlation coefficients between some mass and tree characteristics and mineral soil properties and N, P, K content and N/P ratio of leaves.*

| Tunnus *Characteristic* | Vesojen ikä, a *Age of stand* | Lehtien ravinnepitoisuus tai ravinnesuhde — *Nutrient content or ratio of leaves* N | P | K | N/P | $NH_4$ | $NO_3$ | Maan ominaisuus — *Soil characteristic* Liuk. P *Soluble P* | Vaihtuva K *Exchangeable K* | Vaihtuva Ca *Exchangeable Ca* | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Kuivamassa | 2 | 0,534 | −0,449 | 0,314 | 0,542 | — | 0,780** | −0,116 | 0,466 | 0,341 | 0,453 |
| *Dry mass* | 3 | 0,632* | −0,785** | −0,331 | 0,870*** | 0,568 | −0,246 | −0,192 | 0,236 | −0,490 | 0,405 |
| Vuotuinen kasvu | 2 | 0,524 | −0,464 | 0,343 | 0,546 | — | 0,785** | −0,111 | 0,473 | 0,286 | 0,455 |
| *Current annual inc.* | 3 | 0,578* | −0,724** | −0,227 | 0,815*** | 0,614* | −0,049 | −0,061 | 0,259 | −0,422 | 0,242 |
| Keskipituus | 2 | 0,607* | −0,528 | 0,350 | 0,613* | — | 0,706* | −0,105 | 0,474 | 0,250 | 0,476 |
| *Mean height* | 3 | 0,580* | −0,717** | −0,289 | 0,793** | 0,376 | −0,380 | −0,217 | 0,085 | −0,357 | 0,633* |
| Keskiläpimitta | 2 | 0,598* | −0,498 | 0,319 | 0,591* | — | 0,736** | −0,133 | 0,489 | 0,274 | 0,437 |
| *Mean diameter* | 3 | 0,634* | −0,783** | −0,321 | 0,865*** | 0,467 | −0,235 | −0,189 | 0,157 | −0,358 | 0,528 |

Taulukko 8. Lietelannoituksen vaikutus vesipajun lehtien ravinnepitoisuuksiin sekä N/P-suhteeseen syksyllä 1983 ja 1984.
*Table 8. Effect of sludge fertilization on mineral content and N/P ratio of leaves in autumn 1983 and 1984.*

| Ravinne tai ravinnesuhde *Nutrient or* | Kasvuston ikä, a *Age of stand* | Käsittely — *Treatment* Normaali Y-lannos, 470 kg/ha/a (1) | | Liete — *Sludge*, $m^3$/ha 30 (2) | | 60 (3) | | 120 (4) | | Erojen merkitsevyys *Significant differences* |
|---|---|---|---|---|---|---|---|---|---|---|
| *nutrient ratio* | | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | |
| N, % | 2 | 2,17 | 0,20 | 2,30 | 0,17 | 2,49 | 0,14 | 2,82 | 0,14 | 1—4**, 2—4** |
| —"— | 3 | 3,42 | 0,22 | 3,47 | 0,30 | 3,59 | 0,31 | 3,61 | 0,16 | |
| P, % | 2 | 0,30 | 0,01 | 0,29 | 0,03 | 0,27 | 0,06 | 0,24 | 0,02 | 1—4* |
| —"— | 3 | 0,42 | 0,05 | 0,36 | 0,04 | 0,33 | 0,03 | 0,33 | 0,02 | 1—3*, 1—4* |
| K, % | 2 | 1,41 | 0,07 | 1,43 | 0,13 | 1,72 | 0,45 | 1,47 | 0,26 | |
| —"— | 3 | 1,76 | 0,10 | 1,54 | 0,09 | 1,67 | 0,09 | 1,53 | 0,05 | 1—2*, 1—4* |
| Fe, ppm | 2 | 85 | 6 | 84 | 7 | 82 | 9 | 90 | 11 | |
| —"— | 3 | 66 | 4 | 70 | 10 | 70 | 8 | 70 | 4 | |
| Cu, ppm | 3 | 8,4 | 0,2 | 8,9 | 0,3 | 8,6 | 0,5 | 8,9 | 0,4 | |
| Zn, ppm | 3 | 397 | 70 | 390 | 49 | 262 | 114 | 277 | 82 | |
| N/P | 2 | 7,1 | 0,5 | 7,8 | 1,6 | 9,5 | 2,7 | 11,7 | 1,5 | 1—4*, 2—4* |
| —"— | 3 | 8,3 | 1,4 | 9,6 | 1,3 | 10,8 | 1,5 | 10,9 | 1,0 | 1—4*, 1—3* |

suus kohosi lietteen määrän kasvaessa selvästi. Suurimman lietemäärän saaneiden pajujen lehtien sinkkipitoisuus oli alhaisin, myös lehtien kuparipitoisuus pieneni lietemäärän lisääntyessä. Erot tosin eivät olleet tilastollisesti merkitseviä. Siiran ym. (1984) kasvihuonekokeessa lietelannoitus lietteellä, joka sisälsi kuparia 2...4 kertaa vähemmän (250...500 ppm) kuin tämän tutkimuksen liete, lisäsi myös hieman vesipajun varsien ja lehtien kuparipitoisuutta.

Massa- ja puustotunnusten sekä eräiden lehtien ravinnepitoisuuksien ja typpi-fosforisuhteen välisiä riippuvuussuhteita on esitetty taulukossa 7. Massa- ja puustotunnukset korreloivat positiivisesti lehtien typpipitoisuuden kanssa ja toisaalta negatiivisesti lehtien fosforipitoisuuden kanssa kumpanakin tarkasteluvuonna. Massatunnusten, elävien vesojen keskipituuden- ja läpimitan ja lehtien typpi-fosfori-suhteen välinen vuorosuhde oli positiivinen ja merkitsevä lukuunottamatta kokonaismassaa ja vuotuista kasvua v. 1983. Esitettyjen massa- ja puustotunnusten ja lehtien kaliumpitoisuuden välinen korrelaatio ei ollut merkitsevä.

# 5. TULOSTEN TARKASTELUA

Viljeltyjen pajujen biomassan määrittämiseen ei Suomessa ole vielä vakiintunut mitään tiettyä menetelmää (Saarsalmi 1983). Yleisesti biomassatutkimuksissa käytetty menetelmä on metsikön runkolukusarjan määritys ja koepuiden otanta. Koepuiden kuiva- ja tuoremassan suhteen selvittämiseksi joudutaan ottamaan tavallisesti kosteusnäytteitä. Tässä tutkimuksessa ei selvitetty tuoremassaa eikä vesojen kosteutta vaan kukin koevesa kuivattiin erikseen. Kosteusnäytteiden ottamiseen, säilytykseen ja kosteuden määrittämiseen liittyvät virhetekijät lienee näin suureksi osaksi vältetty.

Viljeltyjen pajujen runkojen kuivamassan laskemiseksi on Nilsson (1981) esittänyt yksivuotiaassa kasvustossa käytettäväksi regressiomallia, jossa selittävänä tekijänä on pituuden ja läpimitan neliön tulo ($Y = a \cdot d^2h$). Myöhemmin Nilsson (1982) on ehdottanut yksivuotiaiden ja vanhempienkin vesojen massaa määritettäessä käytettäväksi yhtälöä, jossa selittäjänä on vesan läpimitta korotettuna potenssiin 2,7 ($Y = a \cdot d^{2,7}$). Saarsalmi (1983) on puolestaan käyttänyt yksivuotiaalle vesipajulle mallia, jossa selittävänä tekijänä on pituus korotettuna kolmanteen potenssiin ($Y = a \cdot h^3$).

Tässä tutkimuksessa käytettiin biomassatutkimuksissa yleisesti sovellettua allometrista mallia ($Y = a \cdot X^b$). Läpimitta todettiin pituutta paremmaksi vesojen kuivamassaa selittäväksi tunnukseksi. Läpimitalla on muissakin tutkimuksissa todettu saatavan suurempi selitys kuin pituudella (Payandeh 1981, Nilsson 1982). Satoo ja Madgwick (1982) tosin ehdottavat pienille puille pelkän pituuden käyttöä. Pituuden lisääminen malliin $d^2h$-terminä lisäsi selitystä vain hieman. Saman tuloksen ovat saaneet koivulla mm. Björklund ja Ferm (1982), Ferm ja Kaunisto (1983) ja Payandeh (1981). Pelkkää läpimittaa käytettäessä saatiin eksponentin b arvoksi eri ikäisillä vesipajuilla 2,9...3,0 eli hiukan korkeammat arvot kuin Nilssonin (1982) ehdottama 2,7. Eksponentin ja vakion arvot pysyivät myös suhteellisen vakaina eri ikäisten pajujen ollessa kyseessä päinvastoin kuin pituutta tai läpimitan neliön ja pituuden tuloa käytettäessä. Mikäli samaa mallia halutaan käyttää eri ikäisille vesipajuille selittävänä tunnuksena olisikin oltava läpimitta. Lisäksi pajujen usein mutkaisten runkojen vuoksi pituuden tarkka mittaus on vaikeaa.

Läpimitta mitattiin tässä tutkimuksessa 10 cm:n korkeudelta maanpinnasta. Kuitenkin tarkemman analyysin perusteella kolmevuotiaille vesoille osoittautui parhaaksi mittauskorkeudeksi 30 cm. Läpimitan mittauskorkeutena voitaneen käyttää 10...50 cm maan tasalta. Läpimitta on kuitenkin aina mitattava samalta korkeudelta muuten biomassan määritykseen tulee virhettä. Nilsson (1982) on todennut 1...4-vuotiaille vesoille parhaaksi mittauskorkeudeksi 80 cm, mikä tässä tutkimuksessa osoittautui liian korkeaksi. Pajujen erilainen pituus saattaa selittää tämän eron.

Vesottamalla kasvatettavien pajukoiden tuotostuloksia verrattaessa on vesojen iän lisäksi huomioitava myös juuristojen ikä. Monissa tutkimuksissa on todettu pajujen tuotoksen kasvavan yhden vuoden kiertoaikaa käytettäessä ainakin neljä—viisi ensimmäistä vuotta (Wasielewski 1982). Pistokkaiden juurtumiskasvukauden tuotos on alhainen, vesipajulla Saarsalmen (1983) ja Lumpeen (1984) kokeissa 0,6—0,7 t/ha. Tämän tutkimuksen vesipajujen tuotos oli samantasoinen (0,5—0,9 t/ha) ensimmäisenä kasvukautena, vaikka juuristot olivat vuotta vanhemmat. Pistokkailla perustetuilla vastaavilla viljelmillä (kaksivuotias juuristo/yksivuotiaat vesat) vesipajun lehdetön maanpäällinen kuiva-ainetuotos on kenttäkokeissa eri puolilla Suomea parhaimmillaan ollut: 3,4 t/ha (Ruukki), 4,1 t/ha (Liminka), 7,1 t/ha (Haapavesi), 8,5 t/ha ja 8,6 t/ha (Suonenjoki) (Hytönen 1982, 1984, Lumme 1984, Rossi 1982, Saarsalmi 1983).

Kaksi- tai kolmevuotiaista pajukoista on Suomessa toistaiseksi esitetty melko vähän

tuotostietoja. Hytönen (1984) on esittänyt turvetuotannosta vapautuneella suonpohjalla Ruukissa kasvaneen kaksivuotiaan vesipajukon tuotokseksi kahden lannoituskokeen kasvuisimmilla käsittelyillä 10,1 ja 10,8 t/ha (ilman lehtiä), mikä on huomattavasti enemmän kuin tässä tutkimuksessa (3,1—6,9 t/ha). Juuristojen ikä kummassakin kokeessa on sama, mutta Ruukin viljelmä oli istutettu juurruttamattomilla pistokkailla. Vuoden 1982 normaalia kylmempi kasvukausi on saattanut vaikuttaa tämän kokeen kuiva-ainetuotosta alentavasti. Kolmivuotiaista vesipajukoista on käytettävissä vain Lepistön (1978) pieniltä koeruuduilta kloonikokeesta mittaamat tulokset.

Tässä tutkimuksessa toisen vuoden kuivamassatuotos oli kuusi kertaa ja kolmannen vuoden tuotos peräti 9... 15 kertaa suurempi kuin ensimmäisen vuoden tuotos. Kolmannen kasvukauden vuotuinen tuotos parhaalla käsittelyllä oli 11,5 t/ha. Tutkimuksen pajukasvustojen vuotuinen ja keskimääräinen tuotos oli lisääntyvä ainakin kolmanteen ikävuoteen asti, eikä kasvun taantumaa vielä voitu havaita. Vesipajun vuotuisen tuotoksen lisääntymisen ainakin toiseen ja kolmanteen ikävuoteen asti ovat todenneet mm. Hytönen (1984), Rossi (1984) ja Sirén (1983). Vanhemmista pajukoista tuloksia ei Suomessa ole julkaistu, kuten ei myöskään tutkimuksia pajujen kiertoajoista erilaisilla kasvatusvaihtoehdoilla. Sen sijaan Pohjois-Irlannissa Stott ym. (1981) ovat todenneet kolmen vuoden kiertoaikaa käytettäessä pajun keskimääräisen tuotoksen olevan suurempi kuin yhden tai kahden vuoden kiertoajalla kasvatettaessa. Useamman vuoden kiertoaika saattaakin olla jokavuotista korjuuta parempi vaihtoehto. Pajujen suurempi koko ja massa lienee eduksi korjuussa ja jatkokäsittelyssä samoin kuin suurempi kertymä harvemmilla korjuukerroilla.

Maan liukoisten ja vaihtuvien ravinteiden määrään ei liete tässä tutkimuksessa vaikuttanut. Lietteen vaikutus olisikin ehkä paremmin näkynyt kokonaisravinnetilanteessa. Lietteen suuresta humuspitoisuudesta johtuen suuri osa lietteen sisältämistä ravinteista vapautuu kasvien käyttöön vähitellen. Lietteen vaikutus maan pH:hon oli vähäinen, mikä johtunee ennen lietteen levitystä tehdystä kalkituksesta (ks. Hokkanen ja Vuorinen 1984). Pajujen on todettu etenkin typen suhteen olevan vaateliaita kasveja (Kaunisto 1983). Tässä aineistoltaan pienessä tutkimuksessa maan nitraattitypen määrä korreloi parhaiten maan mitatuista ominaisuuksista tuotoksen kanssa v. 1983 ja ammoniumtyppipitoisuus v. 1984, korostaen näin typen merkitystä vesipajun ravinnetaloudessa.

Lietelannoitettujen pajujen lehtien typpipitoisuus oli korkeampi, nousten lietteen määrän kasvaessa, kuin Normaali Y-lannoksella lannoitettujen pajujen. Lehtien fosforipitoisuus käyttäytyi päinvastoin. Lehtien typpi- ja fosforipitoisuuksien suhde kasvoi tässä tutkimuksessa sekä v. 1983 että v. 1984 tilastollisesti merkitsevästi Normaali Y-lannoksesta suurimpaan lietemäärään. Myös Kauniston (1983) kasvihuonekokeessa typpilannoitus vähensi koripajun *(Salix viminalis)* lehtien fosforipitoisuutta. Käytetyillä määrillä liete oli jopa parempi typen lähde kuin Normaali Y-lannos. Sen sijaan fosforia oli lietteessä niukemmin ja Y-lannoksen helppoliukoinen fosfori nosti lehtien fosforipitoisuuden korkeammalle kuin lietelannoitus. Kaliumin osalta lietelannoitus, joka sisälsi hyvin niukasti ko. ravinnetta ja Normaali Y-lannos olivat vielä v. 1983 tasaveroiset, mutta v. 1984 Y-lannoksella lannoitettujen pajujen lehtien kaliumpitoisuus oli jo suurempi.

Täysin lannoittamatonta koejäsentä ei tässä kokeessa ollut. Turvetuotannosta vapautuneilla soilla on todettu pajujen kuolevan muutaman vuoden kuluessa ilman lannoitusta (Hytönen 1982, 1984). Kivennäismaalla näin ei kuitenkaan liene asianlaita. Liete osoittautui tässä tutkimuksessa hyväksi vaihtoehdoksi Normaali Y-lannokselle. Lietelannoitettujen pajujen suurempi kuiva-ainetuotos johtunee osaksi siitä, että lietteessä annettiin ravinteita, etenkin typpeä enemmän kuin vertailulannoituksessa. Käytetty liete soveltunee hyvin pajuviljelmän lannoitteeksi. Sen typpipitoisuus on korkea ja raskasmetallipitoisuus vähäinen. Sen sijaan fosfori- ja kalilannoitus saattaa olla tarpeellinen. Orava (1983) on päätellyt saman lietteen sopivaksi käyttömääräksi viljanviljelyssä 30 $m^3$/ha täydennettynä 50—60 kg/ha vuotuisella typpilannoituksella. Mikäli pajunviljelyssä lietettä käytettäisiin 60 $m^3$/ha esimerkiksi joka kolmas vuosi, Rajamäen tehtaiden lietemäärällä voitaisiin lannoittaa 90 ha:n viljelmä.

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FOLIA FORESTALIA 653

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Jyrki Hytönen

# FOSFORILANNOITELAJIN VAIKUTUS VESIPAJUN BIOMASSATUOTOKSEEN JA RAVINTEIDEN KÄYTTÖÖN TURPEENNOSTOSTA VAPAUTUNEELLA SUOLLA

## Effect of some phosphorus fertilizers on the biomass production and nutrient uptake of *Salix* 'Aquatica' in a peat cut-away area

*Approved on 11.4.1986*

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HYTÖNEN, J. 1986. Fosforilannoitelajin vaikutus vesipajun biomassatuotokseen 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 For. 653: 1—21.

Tutkimuksessa tarkasteltiin kolmen fosforilannoitelajin (superfosfaatti, raakafosfaatti, apatiitti) vaikutusta kalkitulla suonpohjan turpeella kasvatetun vesipajun (*Salix* 'Aquatica') biomassatuotokseen, eri kasvinosien ravinnepitoisuuksiin ja kasvustoon sitoutuneiden ravinteiden määrään. Lisäksi pajuja lannoitettiin myös typellä ja kaliumilla, mikä muodosti lannoittamattomien koeruutujen ohella vertailukäsittelyn.

Ilman lannoitusta pajut eivät kasvaneet kalkitulla (pH 5,9) kasvualustalla, vaan vain 5 % oli mittaushetkellä elossa. Fosforilannoitelajeista ainoastaan superfosfaatti lisäsi pajujen kasvua. Kaksivuotiaiden superfosfaatilla lannoitettujen pajujen lehtimassa oli kolme, kuorimassa neljä ja puuaineen massa viisi kertaa niin suuri kuin muulla tavoin lannoitettujen pajujen. Kaksivuotiaiden typellä, kaliumilla ja superfosfaatilla lannoitettujen pajujen kokonaismassasta (13,1 t/ha) oli lehtien ja kuoren osuus 23 % ja puuaineen 54 %.

Käytetyistä fosforilannoitelajeista ainoastaan superfosfaatti lisäsi pajujen lehtien, puuaineen ja kuoren fosforipitoisuuksia. Samalla eri kasvinosien kaliumpitoisuudet alenivat hieman. Superfosfaattilannoitus lisäsi myös kasvualustan liukoisen fosforin määrää.

Yksivuotiaiden pajujen tuotoksesta oli paleltunut 0,2—0,4 t/ha, mikä vastasi 23—45 % lehdettömästä maanpäällisestä biomassasta.

The effect of three phosphorus fertilizers (superphosphate, rock phosphate, apatite) on the biomass production, mineral nutrient contents of leaves, bark and wood and on the amount of nutrients bound in the stands of *Salix* 'Aquatica' was studied on a limed cut-away area of Paloneva (64°27'N, 25°26'E). Also nitrogen and potassium were applied. NK-fertilized and unfertilized plots were used as comparison treatments.

Without fertilization willow did not grow on limed (pH 5.9) peat. Over 95 % of them died during the experiment. As far as the phosphorus fertilizers were concerned, easily soluble superphosphate was the only one that gave any response. The leaf mass of two-year-old willow was three times, bark mass four times and wood mass five times as high with superphosphate as with other phosphorus fertilizers. The proportion of leaves and bark was 23 % and wood 54 % out of the total above-ground mass (13.1 t/ha) of two-year-old willow fertilized with superphosphate, nitrogen and potassium.

Superphosphate was the only phosphorus fertilizer that increased the phosphorus content of leaves, wood and bark. At the same time the potassium contents of these compartments diminished slightly. Fertilization with superphosphate increased the amount of soluble phosphorus in soil.

One-year-old willow shoots were damaged by the frost on average 26 cm down from the tops. The amount of frozen mass was estimated at 0.2—0.4 t/ha comprising 23—45 % of the leafless above-ground biomass of one-year-old shoots.

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# 1. JOHDANTO

Lyhytkiertoviljelyyn, mm. pajujen intensiiviseen massatuotantoon sopivina alueina on pidetty turpeennostosta vapautuvia suonpohjia (Pohjonen 1980). Turpeennoston päättyessä alueet ovat tasaisia, eikä niillä aluksi ole kilpailevaa kasvillisuutta. Sarkaojitus on kuitenkin usein vajavainen (Kaunisto 1982). Jäljelle jääneen turvekerroksen paksuus vaihtelee pohjamaan pinnanmuodoista, kivisyydestä ja nostotekniikasta riippuen. Turve on yleensä verrattain maatunutta ja sisältää runsaasti orgaanisesti sitoutunutta typpeä (Kaunisto 1982, Hytönen 1984). Sen sijaan fosforia, kaliumia ja muita kivennäisravinteita turpeessa on vähän.

Pajujen on hyvin kasvaakseen todettu tarvitsevan runsaasti typpeä ja muitakin ravinteita (Kaunisto 1983). Osittain tästä syystä pajun kasvatuksessa on huomio keskittynyt runsastyppisiin suonpohjan turpeisiin (Kaunisto m.t.). Typpilannoitus edisti kuitenkin Kauniston (1983) kasvihuonekokeessa fosforin ja kaliumin ohella pajujen kasvua suonpohjankin turpeessa, eikä typpeä ilmeisesti vapautunut riittävästi pajujen käyttöön. Suonpohjan turpeen pH lienee myös ilman maanparannusaineiden käyttöä liian alhainen pajujen juuristojen hyvälle kehitykselle (Ericsson ja Lindsjö 1981).

Paju pystyy käyttämään paitsi suuria typpimääriä myös runsaasti fosforia ja kaliumia (Kaunisto 1983, Saarsalmi 1984). Koska pohjaturpeessa on vähän fosforia ja kaliumia, jouduttaneen lyhytkiertoviljelmiä lannoittamaan näillä ravinteilla. Käytettävissä on useita fosforilannoitelajeja, jotka poikkeavat toisistaan fosforipitoisuudeltaan, liukoisuudeltaan ja hinnaltaan. Soiden metsänlannoituksessa fosforilannoitelajin valinnalla on todettu olevan tärkeä merkitys: superfosfaatti lisää nopeimmin kasvua, mutta vaikuttaa puuston kasvuun lyhyemmän ajan kuin raakafosfaatti (Karsisto 1973, 1976a, 1976b, Paavilainen 1979). Hyviä tuloksia on saatu myös kotimaisilla apatiiteilla (Karsisto 1973, 1976b, Paavilainen 1979).

Tässä tutkimuksessa tarkastellaan kolmen fosforilannoitelajin vaikutusta kalkitulla suonpohjan turpeella kasvatetun vesipajun biomassatuotokseen, eri kasvinosien ravinnepitoisuuksiin sekä kasvustoon sitoutuneiden ravinteiden määrään.

Tutkimus kuuluu osana Pera-projektin C-osaprojektiin, jossa selvitellään mm. energiaviljelmien vesi- ja ravinnetalouden järjestelyä. Koe suunniteltiin ja perustettiin Metsäntutkimuslaitoksen ja Kemira Oy:n yhteistyönä. Kenttäkokeen perustamisesta huolehti Per-Johan Bäckström ja työn toteuttamisen eri vaiheissa avustivat Esa Heino, Seppo Lassila, Väinö Saarelainen, Seppo Vihanta, Maire Ala-Pöntiö ja Keijo Polet. Englanninkieliset tekstinosat tarkasti Leena Kaunisto. Käsikirjoituksen ovat lukeneet Eero Paavilainen, Erkki Lipas, Seppo Kaunisto ja Ilari Lumme tehden siihen varteenotettuja korjaus- ja muutosehdotuksia. Kemira Oy:lle, kaikille edellä mainituille samoin kuin muillekin tutkimuksessa avustaneille esitän parhaat kiitokseni.

# 2. AINEISTO JA MENETELMÄT

## 21. Koejärjestelyt

Koealue sijatsee Palonevalla (64°27'N, 25°26'E) Ruukin kunnan alueella turpeennostosta vapautuneella suolla. Alue on ojitettu 45 m:n levyisiin sarkoihin turpeennoston yhteydessä. Koetta perustettaessa ojamaita tasattiin saroille. Dolomiittikalkkia levitettiin kesäkuun alussa 1981 koko alueelle kalkituskärryillä 6000 kg/ha ja sekoitettiin maahan traktoriäkeellä. Lannoituskäsittelyt, jotka satunnaistettiin täydellisesti neljänä toistona, on esitetty taulukossa 1. Saralle sijoitettiin kaksi 15 m × 15 m:n koealaa vierekkäin. Koe lannoitettiin kesäkuussa 1981 ja lannoitus uusittiin samoilla lannoitelajeilla ja -määrillä keväällä 1983. V. 1983 ei kuitenkaan toistettu hivenlannoitusta ja Siilinjärven apatiitti levitettiin vasta elokuun alussa.



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Taulukko 1. Lannoitus- ja maanparannusainekäsittelyt.
*Table 1. Fertilization and soil amelioration treatments.*

| Koodi *Code* | Dolomiittikalkki *Dolomite lime* 6 t/ha 1981 | N 200 kg/ha | K 166 kg/ha 1981 & 1983 | P 87 kg/ha | Hivenseos[5] *Micronutrient* 200 kg/ha 1981 |
|---|---|---|---|---|---|
| 0 | X | — | — | — | — |
| NK[1] | X | X | X | — | X |
| NKPsf[2] | X | X | X | X | X |
| NKPrf[3] | X | X | X | X | X |
| NKPap[4] | X | X | X | X | X |

[1] N = Oulunsalpietari — *Calcium ammonium nitrate* (27,5 % N), K = kalisuola — *Potassium chloride* (49,8 % K). Vuonna 1983 lisäksi flogobiittiä (K 36 kg/ha) — *in 1983 also flogobite (K 36 kg/ha).*

[2] Psf = superfosfaatti — *Superphosphate* (8,7 % P). NK kuten yllä — *NK as above.*

[3] Prf = raakafosfaatti — *Rock phosphate* (14,8 % P). NK kuten yllä — *NK as above.*

[4] Pap = Siilinjärven apatiitti — *Siilinjärvi apatite* (15,7 % P). NK kuten kyllä —*NK as above.*

[5] 7,1 % K, 3,1 % S, 0,7 % Na, 9,8 % Fe, 1,1 % B, 12,8 % Cu, 5,5 % Mn, 5,5 % Zn, 1,4 % Mo.

Vesipajun (*Salix* 'Aquatica', klooni E4856) 20 cm:n pituiset pistokkaat istutettiin valmiiksi tehtyihin reikiin 3.—17.6.1981 turpeen ollessa vielä märkää. Riviväli oli 70 cm ja pistokkaiden väli rivissä oli 35 cm. Istutustiheys oli näin 4,1 pistokasta neliömetrille. Pistokkaat oli varastoitu koneellisesti jäähdytetyssä kylmähuoneessa.

Ensimmäisen kasvukauden jälkeen vesat kaadettiin ja syntynyttä uutta kasvustoa kasvatettiin kaksi kasvukautta. Kesällä 1982 koelaueella torjuttiin rikkaruohoja puutarhajyrsimellä riviväleistä. Marraskuussa 1982 koealue aidattiin.

## 22. Mittaukset

Runkolukusarja määritettiin käyttäen systemaattista otantaa siten, että lokakuussa v. 1982 otos otettiin istutettujen pajurivien suuntaisesti käyttäen otosyksikkönä istutettua pistokasta ja lokakuussa v. 1983 mittanauhalla mitattua 1,5 m:n pituista jaksoa. Otantaväli valittiin sellaiseksi, että näytealojen määrä v. 1983 oli 5—10 kpl kullakin koeruudulla ja että otos jakautui tasaisesti koko ruudun alueelle. Vesoja mitattiin kumpanakin vuonna 200—270 kpl kaikilta koeruuduilta. Vesoista mitattiin niiden pituus maan tasalta verson huippuun senttimetrin tarkkuudella ja läpimitta yhden millimetrin tarkkuudella kymmenen senttimetrin korkeudelta (ks. Nilsson 1982, Hytönen 1985). Kaikki 20 cm pidemmät vesat mitattiin. Samalla saatiin tietoa kasvustojen tiheydestä (vesoja kpl/m$^2$), vesomisesta (vesoja/kanto) ja kuolleisuudesta. Mitatun alueen pinta-ala laskettiin v. 1982 istutustiheyden ja v. 1983 jaksojen pituuden, lukumäärän ja rivivälin perusteella. Koeruutujen reunoilta jätettiin kaksi riviä mittausten ulkopuolelle mahdollisen reunavaikutuksen eliminoimiseksi (ks. Stott ym. 1983).

Kuivamassayhtälöiden laskemiseksi otettiin punnitusvesoja kaikilla mittauskerroilla (v. 1982 käsittelyittäin syyskuun lopussa ja v. 1983 lokakuun alussa koko alueelta). Koepuut kaadettiin kymmenen senttimetrin korkeudelta maasta, suljettiin lehtineen muovipusseihin ja -säkkeihin ja kuljetettiin laboratorioon. Vuonna 1982 koepuita otettiin n. 30 kappaletta kultakin käsittelyltä (yhteensä 120 kpl) ja v. 1983 koko kokeelta yhteensä 51 kpl. Koevesoista mitattiin läpimitta millimetrin tarkkuudella kaatokorkeudelta ja pituus senttimetrin tarkkuudella. Vuoden 1982 koepuista erotettiin lehdet ja versot, vuoden 1983 koepuut kuorittiin ja erotettiin lehdet, kuori ja puuaine. Vuoden 1983 koepuista oli myöhäisen korjuuajankohdan vuoksi lehtiä jo hieman varissut. Lehtiä kuivattiin yksi vuorokausi 80 °C:ssa ja versoja ja kuorta 1—2 vrk 105 °C:n lämpötilassa, minkä jälkeen niiden kuivamassa mitattiin 0,1 gramman tarkkuudella. Koepuiden tunnuksia on esitetty liitetaulukossa 1.

Keväällä 1983, kun lehdet olivat alkaneet kehittyä, inventoitiin vesojen latvaosien paleltumiset mittaamalla vesojen paleltuneen latvaosan ja terveen tyviosan pituudet, vesojen tyviläpimitta sekä läpimitta paleltuman kohdalta. Samalla kerättiin paleltuneita vesojen latvaosia paleltuneen kuivamassan määrittämistä varten koevesoiksi. Näistä mitattiin pituus, läpimitta sekä kuivamassa.

Turpeen paksuus mitattiin kultakin koealalta viidestä kohdasta: lävistäjiltä n. 5 m:n etäisyydeltä koeruudun nurkista ja keskipisteestä. Turpeen paksuus vaihteli koko koealueella välillä 60—160 cm, keskiarvon ollessa 100 cm (s = 25 cm). Lumen paksuus, joka mitattiin 11.3.1983 kaikilta koeruuduilta viidestä systemaattisesti valitusta kohdasta kuten turpeen paksuuskin, vaihteli 40 ... 80 cm:iin.

Elokuun lopussa v. 1983 otettiin kaikilta koeruuduilta lehtinäytteet pajujen yläosien lehdistä, ei kuitenkaan aivan latvasta. Syyskuussa v. 1983 otettiin vesanäytteet (vähintään viisi vesaa koeruudulta), joista erotettiin puuaine ja kuori. Näytteistä määritettiin Viljavuuspalvelu Oy:ssä typpi-, fosfori- ja kaliumpitoisuudet. Syksyllä 1983 kerättiin kaikilta koealoilta 0—10 cm:n pintaturvekerroksesta turvenäytteet, jotka koostettiin viidestä systemaattisesti eri puolilta koealaa otetusta osanäytteestä. Niistä analysoitiin Viljavuuspalvelu Oy:ssä kokonais-, nitraatti- ja ammoniumtyppi, happamalla ammoniumasetaatilla (pH 4,65) uutettu kalium, kalsium, magnesium ja fosfori, johtoluku ja pH.

Vuoden 1983 kasvukausi oli keskimääräistä lämpimämpi. Vuonna 1982 kesäkuu oli keskimääräistä kylmempi ja kuun puolivälissä koealueella oli halloja.

## 23. Kuivamassan laskenta

Biomassaositteille (lehdet, puu, kuori) ratkaistiin kuivamassayhtälöt, jotka olivat muotoa $Y = ax^b\epsilon$ (ks. Björklund ja Ferm 1982, Hytönen 1985). Vakiotermien

ratkaisemiseksi yhtälöt muutettiin logaritmiseen lineaariseen muotoon. Muunnoksen aiheuttama pieni aliarvio korjattiin lisäämällä vakioon a korjauskerroin $s_\epsilon^2/2$ (Meyer 1941), missä s on yhtälön jäännöshajonta. Korjauksen vaikutus oli vähäinen. Malleissa tutkittiin selittävinä tunnuksina vesojen pituutta, tyviläpimittaa ja pituuden ja tyviläpimitan neliön tuloa. Näistä pituus osoittautui massaa huonoimmin selittäväksi tunnukseksi (ks. Hytönen 1985). Vuoden 1982 koepuuaineisto yhdistettiin, koska eri käsittelyille lasketut yhtälöt eivät eronneet toisistaan F-testillä verrattaessa merkitsevästi.

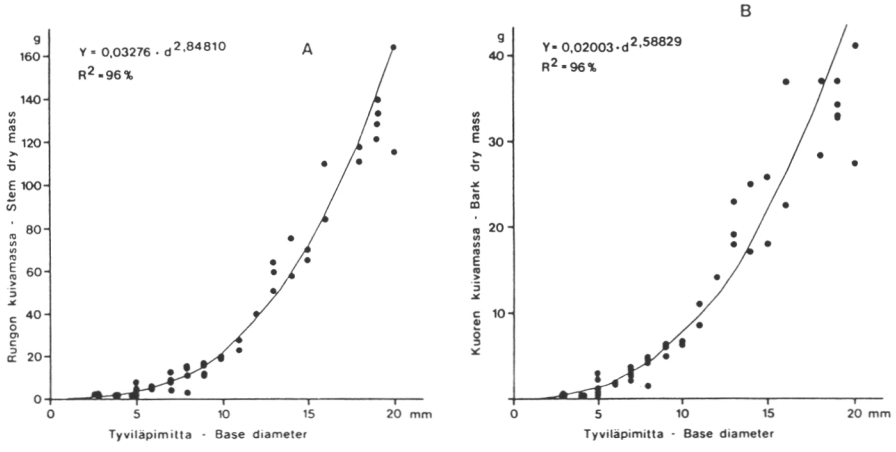
Koealakohtaiset kuivamassat laskettiin yhtälöiden jäännösvaihtelukuvatarkastelun jälkeen summaamismenetelmällä käyttäen runkolukusarjaa sekä taulukossa 2 esitettyjä pituuden ja tyviläpimitan neliön tuloon perustuvia yhtälöitä. Paleltuneille latvaosien koevesoille ratkaistiin kuivamassayhtälöt sekä kuivamassayhtälöä ja runkolukusarjaa käyttäen koealakohtaiset paleltuneiden vesanosien kuivamassat vastaavalla tavalla. Kaksivuotiaiden koevesojen tyviläpimitan ja lehdettömän maanpäällisen kuivamassan sekä kuorimassan riippuvuus on esitetty kuvissa 1A ja 1B.

Taulukko 2. Vesipajun 1- ja 2-vuotiaiden vesojen kuivamassayhtälöt. Yhtälöt ovat muotoa $Y = ax^b\epsilon$, jotka on logaritmimuunnoksen jälkeen korjattu kertoimella $s_\epsilon^2/2$. Y = massa (g), d = tyviläpimitta (0,1 m, mm), h = pituus (cm), a ja b = vakioita, V = yhtälön variaatiokerroin.

*Table 2. Dry mass equations for 1- and 2-year-old sprouts of Salix 'Aquatica'. Equations have the form $Y = ax^b\epsilon$, which after logarithmic transformation have been corrected with $s_\epsilon^2/2$. Y= mass (g), d = diameter at base (mm), h =* height, V = *coefficient of variation.*

| Kasvin osa, Y *Compartment* | Vesojen ikä *Age of sprouts* a | N | $X = d^2h$ a | b | $R^2$ % | V | $X = d$ a | b | $R^2$ % | V |
|---|---|---|---|---|---|---|---|---|---|---|
| Runko [1] | 1 | 120 | 0,00307 | 0,91680 | 98 | 10,6 | 0,00986 | 3,26082 | 91 | 20,8 |
| *Stem* [1] | 2 | 51 | 0,00286 | 0,96382 | 97 | 29,0 | 0,03276 | 2,84810 | 96 | 35,0 |
| Lehdet | 1 | 120 | 0,00832 | 0,74920 | 83 | 25,8 | 0,02084 | 2,68042 | 79 | 29,2 |
| *Leaves* | 2 | 51 | 0,01087 | 0,71727 | 64 | 122,9 | 0,08085 | 2,05420 | 60 | 135,9 |
| Puuaine | 2 | 51 | 0,00117 | 1,01503 | 97 | 31,2 | 0,01541 | 2,99554 | 96 | 38,9 |
| *Wood* | | | | | | | | | | |
| Kuori | 2 | 51 | 0,00225 | 0,87367 | 97 | 30,4 | 0,02003 | 2,58829 | 96 | 33,1 |
| *Bark* | | | | | | | | | | |
| Paleltuneet latvat | 1 | 37 | 0,00423 | 0,88817 | 97 | 21,9 | | | | |
| *Frozen tops* | | | | | | | | | | |

[1] Lehdetön maanpäällinen massa (puuaine ja kuori) — *Leafless above-ground mass (wood and bark)*




Kuva 1. Kaksivuotiaiden koevesojen lehdettömän maanpäällisen kuivamassan (A) ja kuorimassan (B) riippuvuus vesojen tyviläpimitasta.

*Fig. 1. Dependence of the above-ground leafless dry mass (A) and bark mass (B) on base diameter of two-year-old sprouts.*

Rungon, puuaineen ja kuoren sekä lehtimassan laskemiseksi käytettiin samaa mallia, koska tällöin eri massaositteiden yhteenlaskettavuus on parempi (Kozak 1970). Puuaineen massan ja kuoren massan omilla yhtälöillä saatujen lehdettömän maanpäällisen kokonaismassan ja vastaavalla lehdettömän maanpäällisen massan yhtälöillä saatujen massa-arvioiden ero oli vain −0,5 ... 0,4 %. Mallien additiivisuus oli näin ollen varsin hyvä. Kaksivuotiaille pajuille laskettu lehtimassayhtälö oli kuitenkin melko epävarma. Yleensäkin lehtimassan ennustettavuus on huomattavasti huonompi kuin kokonaismassan (ks. Alemdag 1980, Schlaegel 1982, Ferm 1985). Lisäksi tässä tutkimuksessa kaikkia lehtiä ei koepuiden myöhäisen korjuuajankohdan vuoksi saatu talteen.

# 3. TULOKSET

## 31. Kasvualustan ominaisuudet

Kalkituksen jälkeen kasvualustan pH vaihteli 5,4:n ja 6,4:n välillä ja oli näin Ericssonin ja Lindsjön (1981) pajun juurten kasvulle laboratoriokokeessa määrittämän optimialueen (5,0—6,0) rajoissa ja jopa sen yläpuolellakin. Kaunisto (1983) tosin ei havainnut kasvihuonekokeessa Ericssonin ja Lindsjön (1981) kuvailemaa korkean pH:n haitallista vaikutusta 6,6 pH:ssakaan käytettäessä puuntuhkaa. Lannoituskäsittelyt eivät vaikuttaneet pH:hon. Ennen kalkitusta ei maanäytteitä otettu, eikä pH:ta määritetty. Saman turpeennostosta vapautuneen alueen käsittelemättömiltä osilta otettujen näytteiden pH:n keskiarvoksi on esitetty 4,9 (Hytönen 1984). Myös Kurjen (1982) Oulun maatalouskeskuksen alueen saraturvepelloilta esittämään 5,1:een verrattuna pH on korkea. Vaihtuvan kalsiumin määrä (680—1090 mg Ca/l) oli kuitenkin huomattavan alhainen em. Kurjen aineistoon ($\bar{x}$ = 1250 mg Ca/l) verrattuna. Käsittelemättömillä alueilla samalla turvetuotannosta vapautuneella alueella on vaihtuvan kalsiumin määrä ollut keskimäärin 618 mg/l (Hytönen 1984).

Kasvualustan helppoliukoisen fosforin määrään vaikutti eniten superfosfaattilannoitus (taulukko 3). Erot muihin lannotteisiin ja lannoittamattomaan vertailukäsittelyyn nähden olivat moninkertaiset ja Tukeyn testillä keskiarvoja toisiinsa verrattaessa merkitsevät 0,05 %:n riskillä. Raakafosfaatti- ja apatiittilannoitus kohottivat vain hieman maan helppoliukoisen fosforin määrää verrattuna kumpaankin fosforilannoittamattomaan vertailukäsittelyyn. Kaunistonkaan (1983) kasvihuonekokeessa lannoitus raakafosfaatilla ei sanottavasti vaikuttanut maan liukoisen fosforin määrään, vaan jopa raakafosfaatin ja kalkin määrän kaksinkertaistuessa liukoisen fosforin määrä väheni merkitsevästi sekä suopellon turpeessa että polttoturpeessa. Sen sijaan tuhkalannoitetuissa koejäsenissä kasvualustan liukoisen fosforin määrä kohosi voimakkaasti tuhkan määrän lisääntyessä (Kaunisto 1983). Tämän tutki-

Taulukko 3. Turpeen eräiden ominaisuuksien keskiarvo ja hajonta koealueella.
*Table 3. Mean and standard deviation of some peat properties.*

| Mitattu ominaisuus *Measured property* | Lannoitus — *Fertilization* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | | NK | | NKPsf | | NKPrf | | NKPap | | F |
| | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | |
| pH | 5,9 | 0,1 | 5,8 | 0,5 | 6,1 | 0,4 | 6,0 | 0,2 | 6,2 | 0,2 | 1,4 |
| Johtoluku — *Conductivity*, 10 mS/cm | 0,8[a] | 0,1 | 1,4[a] | 0,3 | 1,9[b] | 0,1 | 1,5[a] | 0,3 | 1,6[a] | 0,3 | 12,4*** |
| Liukoinen — *Soluble* P, mg/l | 1,9[a] | 1,0 | 1,7[a] | 0,1 | 18,0[b] | 14,7 | 2,6[a] | 0,4 | 2,5[a] | 1,5 | 4,6* |
| Vaihtuva — *Exchangeable* K, mg/l | 5,0[a] | 0,0 | 60,0[b] | 14,7 | 53,8[b] | 22,5 | 65,0[b] | 9,1 | 66,3[b] | 12,5 | 13,7*** |
| Vaihtuva — *Exchangeable* Ca, mg/l | 675[a] | 65 | 794[a] | 134 | 1088[b] | 148 | 781[a] | 38 | 931[a] | 155 | 7,3** |
| Vaihtuva — *Exchangeable* Mg, mg/l | 244 | 33 | 261 | 73 | 336 | 81 | 264 | 18 | 331 | 86 | 2,1 |
| $NH_4$-N, mg/l | 12,0 | 5,7 | 15,5 | 3,1 | 15,0 | 3,2 | 16,3 | 6,0 | 13,5 | 3,0 | 0,6 |
| $NO_3$-N, mg/l | 9,5[a] | 1,7 | 22,0[b] | 4,5 | 23,8[b] | 8,6 | 20,8[b] | 8,9 | 24,3[b] | 3,2 | 3,9* |
| Tot. N, % | 2,69 | 0,07 | 2,61 | 0,06 | 2,56 | 0,13 | 2,68 | 0,05 | 2,56 | 0,05 | 2,6 |
| Turvesyvyys — *Peat depth*, cm | 91 | 11 | 104 | 30 | 95 | 23 | 114 | 32 | 108 | 11 | 0,7 |

Taulukko 4. Puustotunnuksia.
*Table 4. Tree characteristics.*

| Tunnus *Characteristic* | Kasvuston ikä *Age of stand* a | Lannoitus — *Fertilization* NK x̄ | NK s | NKPsf x̄ | NKPsf s | NKPrf x̄ | NKPrf s | NKPap x̄ | NKPap s | F |
|---|---|---|---|---|---|---|---|---|---|---|
| Elävien vesojen pituus, cm *Height of living sprouts, cm* | 1 | 50,1[a] | 2,1 | 77,9[b] | 8,4 | 53,8[a] | 2,8 | 49,4[a] | 1,6 | 30,0*** |
| — „ — | 2 | 71,8[a] | 11,3 | 131,9[b] | 5,4 | 76,1[a] | 19,8 | 60,2[a] | 14,3 | 21,7*** |
| Elävien vesojen tyviläpimitta, mm *Base diameter of living sprouts, mm* | 1 | 4,7[a] | 0,1 | 5,8[b] | 0,3 | 4,9[a] | 0,2 | 4,7[a] | 0,2 | 28,8*** |
| — „ — | 2 | 5,8[a] | 0,8 | 9,9[b] | 0,5 | 6,1[a] | 1,3 | 5,2[a] | 1,1 | 18,8*** |
| Vesominen, vesoja kpl/kanto *Sprouting, no. of sprouts/stump* | 1 | 6,3[a] | 0,6 | 8,9[b] | 1,2 | 6,2[a] | 0,8 | 5,0[a] | 0,8 | 13,6*** |
| — „ — | 2 | 9,9 | 2,9 | 9,1 | 1,3 | 9,6 | 3,2 | 8,1 | 0,7 | 0,5 |
| Tiheys, vesoja kpl/m$^2$ *Density, no. of sprouts/m$^2$* | 1 | 25,5[a] | 1,6 | 35,6[b] | 5,8 | 24,6[a] | 4,6 | 20,3[a] | 3,2 | 10,2** |
| — „ — | 2 | 39,3 | 12,5 | 37,1 | 5,4 | 36,9 | 11,0 | 32,6 | 2,7 | 0,4 |
| Kuolleita vesoja *No. of dead sprouts/m$^2$* | 2 | 6,7[a] | 2,0 | 12,8[b] | 2,4 | 8,1[ab] | 3,9 | 6,1[a] | 2,5 | 4,7* |

muksen aineistossa vain superfosfaatin muodossa fosforilannoituksen saaneiden pajujen kasvualustan liukoisen fosforin pitoisuus ylitti Kurjen (1982) Oulun maatalouskeskuksen saraturvepelloille esittämät arvot.

Vaihtuvan kaliumin määrä oli 10 ... 13 kertaa suurempi kalisuolalla lannoitetussa kuin lannoittamattomassa turpeessa. Kalisuolalla lannoitettujen pajujen kasvualustan vaihtuvan kaliumin pitoisuus oli samantasoinen ja vaihtuvan magnesiumin pitoisuus oli hivenen korkeampi kuin em. Kurjen vertailuaineistossa.

Turpeen kokonaistyppipitoisuus oli verrattain korkea, keskimäärin 2,6 % (vrt. Kaunisto 1979, 1982, 1983, Ferm ja Kaunisto 1983, Hytönen 1984, Lumme ym. 1984). Typpilannoitus ei vaikuttanut $NH_4$-typen määrään, eikä lannoittamattoman ja typpilannoitettujen kasvualustojen ammoniumtyppipitoisuuden välillä ollut tilastollisesti merkitsevää eroa (taulukko 3). Typpilannoitettujen kasvualustojen nitraattityppipitoisuus oli sen sijaan yli kaksinkertainen typpilannoittamattomiin verrattuna. Kauniston (1981) kasvihuonekokeessa typpilannoitus Oulunsalpietarilla lisäsi kasvualustan $NH_4$- ja $NO_3$-typpipitoisuutta kaikissa tapauksissa.

## 32. Kuolleisuus, pituus ja läpimitta, kasvustojen tiheys ja vesojen paleltuminen

Kuolleisuus (vesattomien kantojen ja kantojen, joissa oli vain kuolleita vesoja osuus) inventoitiin syksyllä 1982 vesojen ollessa yksivuotiaita. Kalkitulla alustalla, mutta ilman lannoitusta kasvaneista pajuista oli tuolloin kuollut 95,5 %. Syynä suureen kuolleisuuteen ei ollut alhainen pH (ks. Ericsson ja Lindsjö 1981, Kaunisto 1983), sillä kalkituksen jälkeen kasvualustan pH oli keskimäärin 5,9 (taulukko 3). Kalkitus voi päinvastoin lisätä kuolleisuutta, koska luontaisen fosforin liukoisuus laskee pH:n muuttuessa 4:stä 5,5:een (Lakanen ym. 1970). Lannoitetuilla koeruuduilla kuolleisuus oli vain 1,2—4,4 %.

Ainoastaan NKPsf-lannoitus lisäsi pajujen läpimitan ja pituuden kasvua (taulukko 4). Erot muihin koejäseniin olivat tilastollisesti erittäin merkitsevät. Ensimmäisen kasvukauden jälkeen NKPsf-lannoitetut pajut olivat muita pajuja 25 cm pidempiä ja 1 mm:n paksumpia ja toisen kasvukauden jälkeen n. 60 cm pidempiä ja n. 4 mm paksumpia. Vesojen pituuden ja läpimitan kehitys ilman fosforilannoitusta oli samanlainen kuin Prf- ja Pap-lannoitettujen pajujen.

Kasvustojen tiheys vesomisen jälkeen oli suuri. Kun pistokkaita istutettiin 4,1 kpl/m$^2$ oli kaksivuotiaissa pajutiheiköissä peräti 33 ... 39 vesaa neliömetrillä. Ensimmäisen kasvukauden jälkeen NKPsf-lannoitetut pajut vesoivat paremmin kuin muut ja myös kasvustojen tiheys oli suurempi. Erot olivat tilastollisesti merkitseviä (taulukko 4). Toisen kasvukauden loppuun mennessä erot kuitenkin tasoittuivat siten, että muilla tavoin lannoitettuihin kasvustoihin syntyi uusia vesoja. Tämä lisävesominen johtui ilmeisesti syksyn

Taulukko 5. Paleltuneiden vesojen tunnuksia.
*Table 5. Characteristics of frozen sprouts.*

| Tunnus *Characteristic* | Lannoitus — *Fertilization* NK x̄ | NK s | NKPsf x̄ | NKPsf s | NKPrf x̄ | NKPrf s | NKPap x̄ | NKPap s | F |
|---|---|---|---|---|---|---|---|---|---|
| Terveen vesan osuuden pituus, cm *Length of healthy part of sprouts, cm* | 21,9[a] | 6,6 | 55,0[b] | 8,6 | 23,9[a] | 10,6 | 20,8[a] | 10,3 | 12,9*** |
| Paleltuneen latvaosan pituus, cm *Length of frost damaged shoot top, cm* | 24,4 | 1,1 | 28,2 | 1,9 | 28,2 | 5,3 | 24,9 | 5,0 | 1,2 |
| Vesan läpimitta paleltuneen ja terveen osan rajalla, mm *Diameter of sprouts at point of frost damage, mm* | 4,1 | 0,1 | 4,0 | 0,2 | 4,2 | 0,3 | 3,8 | 0,3 | 2,2 |
| Paleltuneen vesan massa, g/kpl *Mass of frozen sprout, g/sprout* | 1,1[a] | 0,1 | 1,7[b] | 0,2 | 1,4[a] | 0,4 | 1,0[a] | 0,2 | 7,0** |
| Paleltunut massa, t/ha *Frozen mass, t/ha* | 0,21[a] | 0,03 | 0,37[b] | 0,04 | 0,26[a] | 0,06 | 0,18[a] | 0,04 | 15,4*** |
| Paleltuneen massan osuus kokonaisrunkomassasta, % *Share of frozen mass in total stem mass, %* | 43,4[a] | 6,0 | 23,0[b] | 5,9 | 45,4[a] | 8,3 | 44,6[a] | 9,2 | 8,4** |

tai talven aikana tapahtuneesta paleltumisesta, minkä seurauksena lähelle maanpinnan rajaa paleltuneet pajut vesoivat uudelleen. Superfosfaatilla lannoitettujen pajujen vesoja paleltui eniten (taulukko 4), mutta ne eivät paleltuneet tyvelle asti, jolloin niitä ei laskettu uusiksi vesoiksi. Toisen kasvukauden jälkeen kuolleita vesoja oli huomattavan paljon.

Yksivuotiaiden vesojen latvapaleltumien inventoinnin tuloksia on esitetty taulukossa 5. Parhaiten kasvaneiden, superfosfaatilla lannoitettujen pajujen vesojen paleltumattoman terveen osan pituus oli suurin, 55 cm. Eri tavoin lannoitettujen pajujen paleltuneiden latvaosien pituudet ($\bar{x}$ = 26 cm) ja paksuudet ($\bar{x}$ = 4 mm) paleltuneen versonosan rajalta eivät poikenneet tilastollisesti merkitsevästi toisistaan. Sen sijaan keskimääräisen paleltuneen vesan latvaosan massa oli suurin NKPsf-lannoitetuilla koeruuduilla. Lumen paksuuden ja paleltuneen versonosan massan välinen korrelaatio oli positiivinen (r = 0,548*). Vesojen latvaosat olivat ilmeisesti paleltuneet ennen lumen tuloa. Paleltuneen vesanosan massan ja maan liukoisen fosforin määrän välillä oli positiivinen, merkitsevä vuorosuhde (liite 2). Regressioanalyysissä riippuvuutta kuvasi suora Y = 0,022X+1,15 (F = 8,11*, $R^2$ = 36,7 %). Puuaineen ja lehtien fosforipitoisuuden ja keskimääräisen paleltuneen vesanosan massan välinen vastaavuussuhde oli merkitsevä ja positiivinen sekä lehtien kaliumpitoisuuden ja keskimääräisen paleltuneen vesan latvaosan massan vastaavuussuhde negatiivinen (liite 3). Lehtien ja puuaineen ravinnesuhteista K/P-suhde korreloi parhaiten paleltuneen vesanosan massan kanssa. Askeltavassa regressioanalyysissä paleltuneen vesanosan massaa selittäväksi tekijäksi eri kasvinosien ravinnepitoisuuksista tuli malliin puun fosforipitoisuus (Y = 1,043X+0,720, F = 9,66**, $R^2$ = 49,1 %).

Taulukon 2 yhtälöllä lasketun paleltuneen massan määrä oli 0,18—0,37 t/ha (taulukko 5). Eniten paleltunutta massaa oli parhaiten kasvaneissa NKPsf-lannoitetuissa pajukasvustoissa. Syynä oli huomattavasti suurempi vesojen määrä ensimmäisen kasvukauden jälkeen sekä paleltuneen vesanosan suurempi massa. Paleltuneen massan osuus lehdettömästä kokonaiskuivamassasta oli suuri: 23 % superfosfaatilla lannoitetuissa pajukasvustoissa, muissa peräti 43—45 %.

### 33. Biomassatuotos

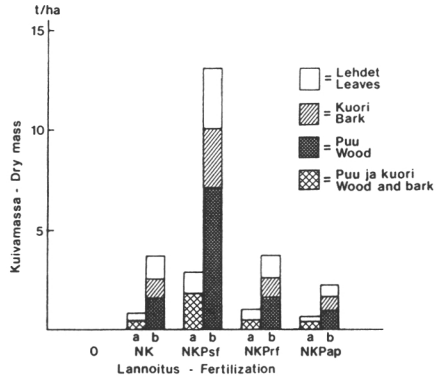
Pajut eivät kasvaneet kalkitulla kasvualustalla ilman lannoitusta (kuvat 2 ja 3), vaan 95,5 % kuoli tarkastelujakson aikana. Fosforilannoitelajeista ainoastaan superfosfaatti (NKPsf) lisäsi pajujen kasvua merkitsevästi verrattuna pelkkään NK-lannoitukseen (taulukko 6, kuvat 2 ja 4). Apatiitilla lannoitetut pajut kasvoivat jopa hieman heikommin kuin NK-lannoitetut pajut.

Yksivuotiaiden NKPsf-lannoitettujen paju-

jen kokonaismassa (lehtineen) ensimmäisen kasvukauden jälkeen oli 2,9 t/ha ja muulla tavoin lannoitettujen pajujen kokonaismassa oli 0,7—1,0 t/ha. Superfosfaatilla lannoitettujen yksivuotiaiden pajujen lehtimassa oli 3,0 ja lehdetön runkomassa 3,6 kertaa suurempi kuin muulla tavoin lannoitettujen pajujen. Kaksivuotiaiden, NKPsf-lannoitettujen pajujen kokonaismassa lehdet mukaanlukien oli 13,1 t/ha. Muulla tavoin lannoitettujen pajujen kokonaismassa toisen kasvukauden jälkeisenä syksynä oli 2,2—3,6 t/ha. Superfosfaatilla lannoitettujen pajujen lehtimassa oli toisen kasvukauden jälkeen 3,1, kuorimassa 4,0 ja puuaineen massa peräti 5,0 kertaa niin suuri kuin vastaavat massat muilla koejäsenillä.

NKPsf-lannoitettujen pajujen toisen kasvukauden lehdetön maanpäällinen kuivamassatuotos oli peräti 4,8 (muulla tavoin lannoitettujen pajujen 2,7 ... 4,1) kertaa niin suuri kuin ensimmäisen kasvukauden tuotos.

Kuiva-ainetuotoksesta oli huomattava osa lehdissä ja kuoressa. Mitä suurempi kasvusto oli, sitä pienempi oli näiden ositteiden osuus. Yksivuotiaassa kasvustossa NKPsf-lannoitettujen pajujen kokonaismassasta lehtien osuus oli 40,7 % (muulla tavoin lannoitetuilla pajuilla keskimäärin 42,9 %). Kaksivuotiaiden superfosfaatilla lannoitettujen pajujen lehtimassan osuus kokonaismassasta oli 23,1 %, kuorimassan 22,9 % ja puuaineen massan 54,0 %. Muilla koejäsenillä lehtimassan (31,6 %) ja kuorimassan (23,5 %) osuus oli suurempi ja vastaavasti puuaineen massan osuus pienempi (44,9 %).




Kuva 2. Vesipajujen kuivamassa ensimmäisen (a) ja toisen (b) kasvukauden jälkeen.
*Fig. 2. Dry mass of willows after the first (a) and second (b) growing season.*

Taulukko 6. Kasvustojen massatunnuksia.
*Table 6. Dry mass of stands.*

| Tunnus *Characteristic* | Kasvuston ikä *Age of stand* | Lannoitus — *Fertilization* NK | | NKPsf | | NKPrf | | NKPap | | F |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | x̄ | s | x̄ | s | x̄ | s | x̄ | s | |
| Lehtimassa, t/ha *Leaf mass* | 1 | 0,38 | 0,04 | 1,14 | 0,37 | 0,44 | 0,11 | 0,31 | 0,05 | 15,7*** |
| Runkomassa, t/ha[1] *Stem mass*[1] | 1 | 0,49 | 0,06 | 1,74 | 0,64 | 0,59 | 0,16 | 0,40 | 0,07 | 14,5*** |
| Kokonaismassa, t/ha *Total mass* | 1 | 0,87 | 0,10 | 2,89 | 1,01 | 1,02 | 0,27 | 0,71 | 0,11 | 15,0*** |
| Lehtimassa, t/ha *Leaf mass* | 2 | 1,12 | 0,11 | 3,03 | 0,68 | 1,09 | 0,30 | 0,72 | 0,31 | 26,3*** |
| Kuorimassa, t/ha *Bark mass* | 2 | 0,87 | 0,11 | 3,01 | 0,71 | 0,86 | 0,33 | 0,53 | 0,29 | 29,5*** |
| Puuaineen massa, t/ha *Wood mass* | 2 | 1,64 | 0,27 | 7,10 | 1,74 | 1,66 | 0,78 | 0,96 | 0,62 | 31,9*** |
| Runkomassa, t/ha[1] *Stem mass*[1] | 2 | 2,51 | 0,38 | 10,11 | 2,45 | 2,52 | 1,11 | 1,48 | 0,90 | 31,2*** |
| Kokonaismassa, t/ha *Total mass* | 2 | 3,62 | 0,47 | 13,14 | 3,11 | 3,60 | 1,38 | 2,20 | 1,22 | 30,0*** |

[1] Lehdetön maanpäällinen massa (puuaine ja kuori) — *Leafless above-ground mass (wood and bark)*



Kuva 3. Etualalla lannoittamaton koeruutu.
*Fig. 3. Unfertilized plot in the foreground.*



Kuva 4. Etualalla raakafosfaatilla (NKPrf) ja taustalla superfosfaatilla (NKPsf) lannoitettuja pajuja.
*Fig. 4. Willows fertilized with rock phosphate (NKPrf) in the foreground and with superphosphate (NKPsf) in the background.*

## 34. Eri kasvinosien typpi-, fosfori- ja kaliumpitoisuudet

Fosforilannoitelajeista superfosfaatti nosti lehtien fosforipitoisuutta tilastollisesti merkitsevästi verrattuna täysin lannoittamattomaan tai NK-lannoitettuun koejäseneen sekä muihin fosforilannoitelajeihin (kuva 5). Sen sijaan apatiitilla ja raakafosfaatilla lannoitettujen pajujen lehtien fosforipitoisuus oli vain hieman korkeampi kuin täysin lannoittamattomien tai NK-lannoitettujen pajujen. Nämä erot eivät olleet tilastollisesti merkitseviä. NPKsf-lannoitettujenkin pajujen lehtien fosforipitoisuus oli selvästi alhaisempi kuin Näsin ja Pohjosen (1982), Saarsalmen (1984) sekä Hytösen (1985) aineistoissa.

Pajun lehtien typpipitoisuus oli alhaisin (3,3 %) täysin lannoittamattomilla koealoilla, poiketen tilastollisesti merkitsevästi muista käsittelyistä (kuva 5). Typpilannoitettujen pajujen lehtien typpipitoisuus oli 3,6—3,9 %. Vesipajujen lehtien typpipitoisuus oli selvästi suurempi kuin Saarsalmen (1984) tai Näsin ja Pohjosen (1981) aineistossa sekä hieman korkeampi kuin Hytösen (1985) lietelannoituskokeessa.

Superfosfaattilannoitus laski pajujen lehtien kaliumpitoisuuden tilastollisesti merkitsevästi alhaisemmaksi kuin muut fosforilannoitelajit (kuva 5). Lannoittamattomien pajujen lehtien kaliumpitoisuus oli alhaisin (0,88 %). Ero NKPsf-lannoitukseen (K-pitoisuus 1,37 %) ei kuitenkaan ollut merkitsevä. Tämän tutkimuksen vesipajujen lehtien suurin kaliumpitoisuus oli samantasoinen kuin Näsin ja Pohjosen (1981) aineistossa, mutta huomattavasti alhaisempi kuin Saarsalmen (1984) esittämä.

Eri tavoin lannoitettujen ja lannoittamattomienkin pajujen kuoren ravinnepitoisuudet eivät poikenneet toisistaan tilastollisesti merkitsevästi (kuva 5). Kuoren typpipitoisuus oli keskimäärin 2,1—2,2 %, fosforipitoisuus 0,12—0,22 % sekä kaliumpitoisuus 0,7—1,1 %. Superfosfaatilla lannoitettujen pajujen kuoren fosforipitoisuus oli korkeampi kuin muilla fosforilannoitelajeilla lannoitettujen pajujen, mutta ero ei ollut tilastollisesti merkitsevä. Kuoren typpipitoisuus oli korkea, kuitenkin alhaisempi kuin lehtien, sen sijaan kuoren fosforipitoisuus oli NKPsf-lannoitusta lukuunottamatta jopa korkeampi kuin lehtien.

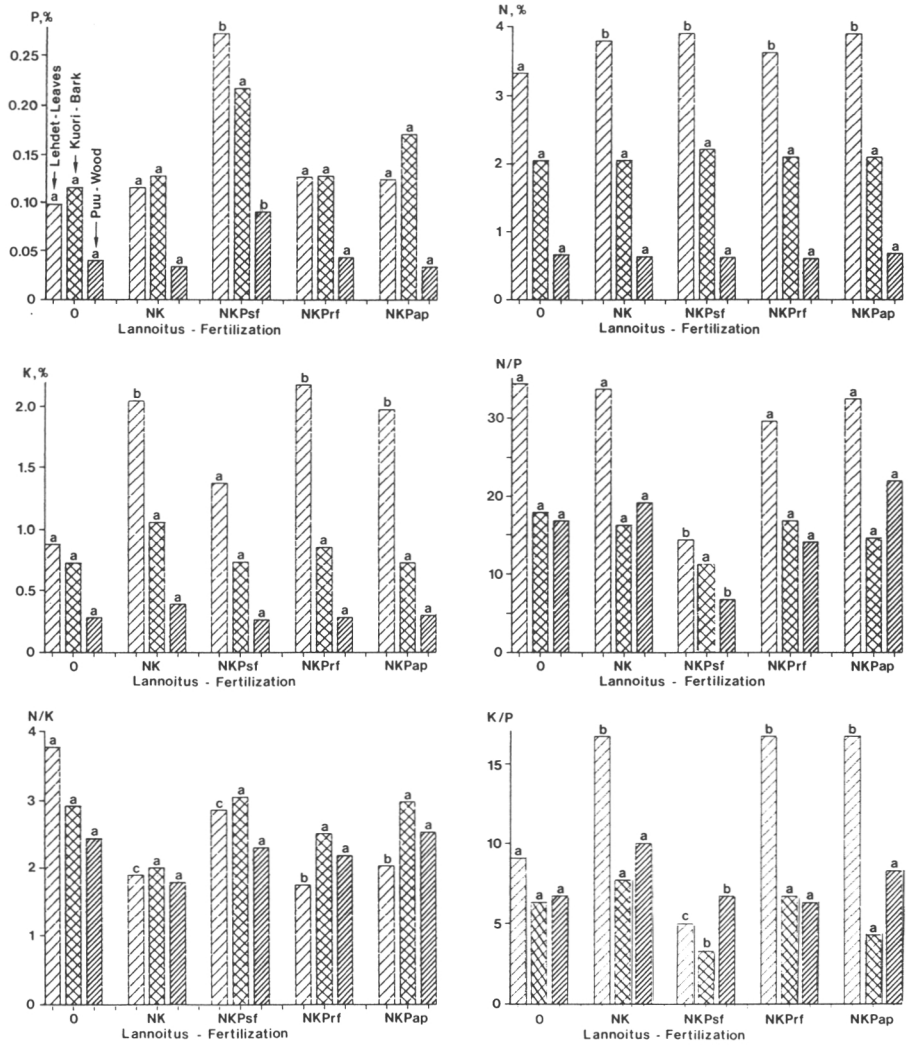
Puun ravinnepitoisuudet olivat selvästi alhaisempia kuin kuoren (kuva 5). Puun typpipitoisuus oli 0,6—0,7 %, fosforipitoisuus 0,03—0,09 % ja kaliumpitoisuus 0,3—0,4 %. Fosforilannoitelajeista ainoastaan superfosfaatti nosti puuaineen fosforipitoisuutta tilastollisesti merkitsevästi. Muita fosforilannoitteita käytettäessä puuaineen fosforipitoisuudet eivät poikenneet täysin lannoittamattomien tai NK-lannoitettujen pajujen puuaineen fosforipitoisuuksista. Eri tavoin lannoitettujen pajujen puuaineen typpi- ja kaliumpitoisuudet eivät poikenneet toisistaan. Lannoittamattomien ja superfosfaatilla lannoitettujen pajujen puuaineen kaliumpitoisuus oli alhaisin vaikkakaan erot eivät olleet tilastollisesti merkitseviä.

NKPsf-lannoitettujen pajujen lehtien, kuoren ja puuaineen N/P-suhde oli alhaisin. Ero oli Tukeyn testillä keskiarvoja verrattaessa merkitsevä vain lehtien ja puuaineen ravinnesuhteiden osalta. Lehtien N/P-suhde oli korkea verrattuna Hytösen (1985) aineistoon, jossa suurimmalla lietemäärällä (120 $m^3$/ha) lannoitettujen pajujen N/P-suhde kivennäismaalla oli 11—12 ja Normaali Y-lannoksella lannoitettujen vain 7—8. NKPsf-lannoitus nosti tämän tutkimuksen pajujen lehtien, kuoren ja puuaineen N/K-suhdetta ja laski K/P-suhdetta verrattuna muihin fosforilannoitelajeihin.

## 35. Massa- ja puustotunnusten riippuvuus kasvualustan ja eri kasvinosien ravinnepitoisuuksista

Kasvualustan liukoisen fosforin määrä korreloi positiivisesti lehtien, kuoren ja puuaineen fosforipitoisuuksien kanssa (liite 4). Myös maan vaihtuvan kalsiumin määrän ja eri kasvinosien fosforipitoisuuksien välillä oli merkitsevä positiivinen vuorosuhde. Kasvualustan nitraattitypen määrän ja lehtien typpipitoisuuden välillä oli positiivinen tilastollisesti merkitsevä vuorosuhde. Sen sijaan turpeen totaalitypen ja lehtien typpipitoisuuden välinen korrelaatio oli negatiivinen ja melkein merkitsevä. Myös maan vaihtuvan kaliumin määrän ja lehtien kaliumpitoisuuden välinen korrelaatio oli positiivinen ja tilastollisesti erittäin merkitsevä.

Mitatuista maan ominaisuuksista eräiden massa- ja puustotunnusten kanssa korreloivat parhaiten maan liukoisen fosforin ja vaihtuvan kalsiumin määrät, fosfori tilastollisesti erittäin merkitsevästi ja kalsium melkein merkitsevästi (liite 2). Askeltavassa re-

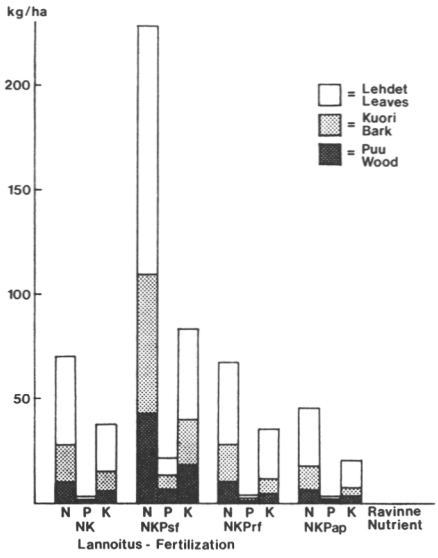



Kuva 5. Eri tavoin lannoitettujen vesipajujen lehtien, kuoren ja puuaineen typpi-, fosfori- ja kaliumpitoisuudet sekä ravinnesuhteet. Samalla kirjaimella merkitty ne lehtien, kuoren ja puun ravinnepitoisuudet tai ravinnesuhteet, jotka eivät poikkea toisistaan ($p = 0{,}05$).

*Fig. 5. Nitrogen, phosphorus and potassium content and nutrient ratios of leaves, bark and wood of differently fertilized willows. Nutrient contents or ratios of leaves, bark and wood marked with the same letter do not differ from each other ($p = 0{,}05$).*

gressioanalyysissä tuotosta selittäväksi muuttujiksi malliin tulivat mukaan kasvualustan liukoisen fosforin (x1) ja vaihtuvan kaliumin (x2) määrät. Lehdettömän maanpäällisen kuivamassan riippuvuutta kasvualustan ominaisuuksista kuvasi taso $Y = 33{,}36(x1) - 11{,}35(x2) + 904{,}21$ ($F = 20{,}61^{***}$, $R^2 = 72{,}3\ \%$).

Lehtien fosforipitoisuus korreloi positiivisesti ja erittäin merkitsevästi eräiden massa-




Kuva 6. Kaksivuotiaisiin pajukasvustoihin sitoutuneiden ravinteiden määrä.
*Fig. 6. Amount of nutrients bound in two-year-old willow stands.*

Taulukko 7. Kaksivuotiaisiin eri tavoin lannoitettuihin vesipajukasvustoihin sitoutuneiden ravinteiden määrä.
*Table 7. Amount of nutrients bound in differently fertilized two-year-old willow stands.*

| Ravinne *Nutrient* | Lannoituskäsittely — *Fertilization treatment* NK | NKPsf | NKPrf | NKPap |
|---|---|---|---|---|
| N, kg/t | 19,5 | 17,3 | 18,7 | 20,7 |
| P, kg/t | 0,8 | 1,6 | 0,9 | 1,0 |
| K, kg/t | 10,6 | 6,3 | 9,8 | 9,5 |

ja puustotunnusten kanssa (liite 3). Lehtien typpipitoisuuden ja massa- ja puustotunnusten välinen vuorosuhde oli sen sijaan vähäinen. Kuoren ja puuaineen ravinnepitoisuuksista fosforipitoisuus ja K/P-suhde korreloivat parhaiten massa- ja puustotunnusten kanssa. Puuaineen osalta vuorosuhteet olivat tilastollisesti erittäin merkitseviä. Askeltavassa regressioanalyysissä lehdetöntä maanpäällistä kuivamassaa selitti parhaiten puuaineen fosforipitoisuus. Riippuvuutta kuvasi suora $Y = 1438{,}94x - 270{,}70$ ($F = 41{,}88^{***}$, $R^2 = 78{,}8\ \%$).

## 36. Kasvustoon sitoutuneiden ravinteiden määrä

Pajuihin kahden kasvukauden jälkeen sitoutuneiden ravinteiden määrät laskettiin eri tavoin lannoitettujen pajujen lehtien, kuoren ja puuaineen ravinnepitoisuuksien ja kuiva-ainemassojen keskiarvoja käyttäen. NKPsf-lannoitettuihin pajuihin ravinteita oli sitoutunut selvästi eniten (kuva 6). Noin puolet ravinteista oli sitoutunut lehtiin. Pajujen kuoreen ravinteita oli sitoutunut selvästi enemmän kuin puuaineeseen. Tosin lehtinäytteet otettiin pajujen yläosista, missä lehtien kaliumpitoisuus on alhaisempi ja fosforipitoisuus korkeampi kuin alaosan lehdissä (Kaakinen 1983). Lehtien osalta tuloksiin saattaakin sisältyä kaliumin osalta aliarviota ja fosforin osalta yliarviota. Lisäksi myöhäisen keräysajankohdan vuoksi osa ravinteista oli jo saattanut siirtyä lehdistä muihin kasvinosiin.

Kahden kasvukauden ikäisiin NKPsf-lannoitettuihin vesipajuihin oli yhtä tuotettua biomassayksikköä kohti sitoutunut enemmän fosforia, mutta vähemmän typpeä ja kaliumia kuin muulla tavoin lannoitettuihin pajuihin (taulukko 7). Määrät ovat fosforin osalta, kun fosforilannoitteena käytettiin superfosfaattia, samantasoiset kuin Saarsalmen (1984) yksivuotiaille pajuille ja hieman alhaisemmat kuin Fermin (1985) yksi- ja kaksivuotiaille vesipajuille esittämät arvot. Typpeä tämän tutkimuksen pajuihin oli sitoutunut tuotettua biomassayksikköä kohti huomattavasti enemmän kuin Saarsalmen (1984) tai Fermin (1985) kokeissa. Kaliumin määrä, etenkin NKPsf-lannoitetuissa pajuissa, on erityisen alhainen verrattuna Saarsalmen arvioon, mutta samantasoinen Fermin tulosten kanssa.

# 4. TULOSTEN TARKASTELUA

Kalkituksen jälkeen kasvualustan pH oli hyvin Ericssonin ja Lindsjön (1981) pajujen juurten kasvulle esittämällä pH-optimialueella ainakin turpeen pintaosissa. Kuitenkin pajut kasvoivat erittäin huonosti ja vain 5 % oli elossa kalkitussa, mutta lannoittamattomassa turpeessa. Haapaveden Piipsannevan turpeennostosta vapautuneella alueella pajujen on todettu kuolevan muutamassa vuodessa ilman kalkitusta ja lannoitusta (Hytönen 1982). Kasvualustassa oli liukoista fosforia huomattavasti enemmän lannoitettaessa superfosfaatilla kuin lannoitettaessa kokonaisfosforin osalta vastaavilla raakafosfaatti- tai apatiittimäärillä. Vaihtuvaa kaliumia oli lannoittamattomilla koeruuduilla vain vajaa kymmenesosa siitä mitä kaliumlannoitetuilla koeruuduilla.

Abioottisista tuhoista etenkin kasvukaudenaikaiset hallat ja talven pakkaset saattavat aiheuttaa huomattavia tuotostappioita. Viljeltyjen pajulajien usein eteläinen alkuperä, kasvun jatkuminen pitkälle syksyn pakkasiin asti, voimakas lannoitus sekä tärkeimpien potentiaalisten kasvupaikkojen, kuten turvemaiden ja turvetuotannosta vapautuneiden suonpohjien hallanarkuus lisää paleltumisriskiä. Christerssonin ym. (1982) tutkimilla kaikilla pajulajeilla alkoi solujen jäätymiskristallimuodostus −2 ° ... −4 °C lämpötilassa, minkä seurauksena kasvavat kasvinosat kuolivat. Tämänkin tutkimuksen pajut vioittuivat v. 1982 alkukesän halloissa. Varsinaisesti vesojen latvojen paleltuminen tapahtui kuitenkin vasta syksyn tai alkutalven pakkasten aikana ennen lumen tuloa. Yksivuotiaista pajuista paleltui keskimäärin 26 cm:n pituinen osa pajujen latvasta. Keskimääräisen paleltuneen vesanosan massa oli suurin NKPsf-lannoitetuilla koeruuduilla ja maan liukoisen fosforin määrä sekä puun ja lehtien fosforipitoisuus korreloikin positiivisesti paleltuneen vesanosan massan kanssa. Sen sijaan puun ja lehtien kaliumpitoisuuden ja paleltuneen vesanosan massan välinen korrelaatio oli negatiivinen. Rossin (1977) havaintojen mukaan sama vesipajuklooni (E4856) oli Suonenjoella eräs kestävimmistä. Tosin täysin vauriottomia taimia ei ollut ja noin puolella vesoista oli 1/4 verson latvasta paleltunut ja lopuilla vielä enemmän. Tämän tutkimuksen yksivuotiaan pajutiheikön tuotoksesta oli paleltunut 0,18—0,37 t/ha. Tämä vastasi 23 % NKPsf-lannoituksen saaneiden pajujen ensimmäisen vuoden massasta ja peräti 43—45 % muilla tavoin lannoitettujen pajujen massasta. Paleltuneiden latvaosien massa oli mittaushetkellä vielä käyttökelpoista. Tutkimuksessa ei arvioitu kuinka nopeasti latvaosat katkeavat ja putoavat maahan, joten paleltumisen aiheuttamaa todellista satomenetystä ei saatu arvioiduksi. Rossi (1982) on inventoinut eräällä pajuviljelmällä hirvien syömän latvabiomassan määrän. Satomenetys (0,7 %) oli pieni verrattuna tässä esitettyihin paleltuneen massan osuuksiin. Paleltuminen johti vesojen voimakkaaseen haarautumiseen seuraavan kasvukauden aikana sekä maahan asti paleltuneiden vesojen osalta uusien vesojen syntymiseen.

Yksivuotiaiden pajujen lehdetön maanpäällinen kuivamassa oli parhaalla lannoituskäsittelyllä (NKPsf) 1,7 t/ha ja kaksivuotiaiden 10,1 t/ha. Mielenkiintoista on, että turpeennostosta vapautuneelle alueelle luontaisesti syntyneen koivikon keskimääräinen vuotuinen kuivamassatuotos voi olla yhtä suuri kuin tämän tutkimuksen kaksivuotiaiden vesipajujenkin (Ferm ja Kaunisto 1983). Tässä tutkimuksessa toisen vuoden lehdetön maanpäällinen kuiva-ainetuotos oli huomattavia vaurioita aiheuttaneesta paleltumisesta huolimatta 3—5 kertaa niin suuri kuin ensimmäisen vuoden tuotos ja lietelannoitettujen vesipajujen (Hytönen 1985) toisen vuoden tuotos oli kuusinkertainen ensimmäisen vuoden tuotokseen verrattuna. Tämä antaa epävarmasti talvehtivien kloonienkin osalta aihetta harkita kasvatuksen jatkamista useamman vuoden kiertoajalla.

Yksivuotiaassa kasvustossa lehtimassan osuus kokonaismassasta oli 41—44 % ja kaksivuotiaassa 23—32 %. Mitä suurempi oli kokonaistuotos, sitä pienempi oli lehtien

osuus. Saarsalmen (1984) lysimetrikokeessa istutuksenjälkeisen kasvukauden tuotoksesta (lehdetön tuotos 0,8 t/ha) oli lehtimassan osuus 57 % ja seuraavina vuosina vesomisen jälkeen lehtimassan osuus laski 26—36 %:iin. Tämän tutkimuksen kaksivuotiaassa, NKPsf-lannoitetussa kasvustossa kuorimassan osuus oli kokonaismassasta 23 % ja 30 % lehdettömästä maanpäällisestä massasta. Lehti- ja kuorimassan suhteellisen suuret osuudet vaikuttavat pajujen käyttökelpoisuuteen esimerkiksi energiapuuksi sekä osaltaan korostavat useamman vuoden kiertoajan edullisuutta.

Käytetyistä fosforilannoitteista ainoastaan superfosfaatti nosti selvästi lehtien, kuoren ja puuaineen fosforipitoisuuksia ja laski merkitsevästi lehtien ja hieman myös kuoren ja puun kaliumpitoisuuksia. Muut fosforilannoitelajit, raakafosfaatti ja apatiitti, nostivat vain hieman lehtien fosforipitoisuutta, mutta erot fosforilannoittamattomaan koejäseneen eivät olleet tilastollisesti merkitsevät. Ravinnepitoisuuksien erot näkyivät selvimmin lehdissä. Kalilannoitus nosti selvästi lehtien kaliumpitoisuutta. Lehtien korkea N/P-suhde saattaa viitata lannoituksen epätasapainoisuuteen näiden ravinteiden osalta, etenkin ottaen huomioon turpeen korkean typpipitoisuuden ja suuret lannoitemäärät. Superfosfaattilannoitus laski merkitsevästi N/P-suhdetta. Typpi ei todennäköisesti muodostunut minimiravinteeksi pajujen kasvun kannalta. Tässä, kuten Kaunistonkin (1983) tutkimuksessa, pajun runkopuun ja kuoren ravinnepitoisuudet olivat monikymmenkertaisia mäntyyn ja koivuun verrattuna (ks. Mälkönen 1974, 1977, Paavilainen 1980).

Lehtien ja kuoren suuren osuuden sekä näiden ja puuaineen korkeiden ravinnepitoisuuksien johdosta kasvustoon oli sitoutunut ravinteita huomattavan paljon. Typpeä oli NKPsf-lannoitettuihin pajuihin sitoutunut 228 kg/ha, fosforia 21 kg/ha ja kaliumia 84 kg/ha. Lehtien osalta tuloksiin on suhtauduttava varauksella, sillä ravinnemääritykset tehtiin vain vesojen yläosien lehdistä ja lehtibiomassan määrä lienee myöhäisen korjuuajankohdan vuoksi hieman aliarvioitu. Lehtien osuus biomassatuotoksesta oli 23 %, mutta lehdissä oli sitoutuneesta typestä ja kaliumista yli puolet ja fosforista 40 %. Fermin (1985) kaatopaikalla kasvatettujen ja jätevedellä kasteltujen pajujen lehdissä oli hieman suurempi osuus sitoutuneista ravinteista. Tutkimuksen mukaan pajut käyttävät typpeä, mutta myös fosforia ja kaliumia huomattavan paljon (ks. myös Kaunisto 1983, Saarsalmi 1984, Ferm 1985).

Fosforilannoitelajeista (superfosfaatti, raakafosfaatti, apatiitti) ainoastaan superfosfaatti lisäsi pajujen kasvua. Tutkitut fosforilannoitelajit poikkesivat liukoisuudeltaan toisistaan huomattavasti. Karsiston (1976b) mukaan superfosfaattia voidaan pitää helppo- ja nopealiukoisena, raakafosfaattia vaikea- ja hidasliukoisena ja apatiittia erittäin vaikea- ja hidasliukoisena fosforilannoitteena. Kemiallisilta ominaisuuksiltaan erilaiset fosforilannoitteet soveltuvat eri tavalla pH:ltaan ja kalkkipitoisuudeltaan toisistaan poikkeaville suotyypeille (Karsisto 1976b). Suometsien lannoitukseen on todettu soveltuvan hidasliukoisenkin lannoitteen kuten raakafosfaatin ja apatiitin, mutta superfosfaatilla on saatu nopein reaktio (Huikari 1964, Paarlahti ja Karsisto 1968, Karsisto 1973, 1976a, 1976b, Paavilainen 1979). Sen sijaan nurmen pintalannoitukseen, etenkin kalkitulla suopellolla, on superfosfaatti todettu soveliaammaksi kuin hidasliukoiset thomas- ja hienofosfaatti (Takala 1958, 1961).

Tässä tutkimuksessa raakafosfaatti- ja apatiittilannoituksen vaikutuksen puuttuminen saattaa johtua liian lyhyestä vaikutusajasta näiden lannoitelajien kohdalla ja kasvualustan korkeasta pH:sta. Apatiittilannoituksen uusimisen myöhäisempi ajankohta on myös saattanut vaikuttaa siihen, että NKPaplannoitettujen pajujen tuotos jäi pieneksi verrattuna jopa pelkkään NK-lannoitukseen. Kalkitus on saattanut hidastaa apatiitin liukenemista, sillä happamissa oloissa apatiitin liukoisuus on parempi (Karsisto 1973, 1976b, Salonen 1968). Salosen (1968) ruukkukokeissa kalkitus esti täysin apatiitin vaikutuksen. Karsisto (1976b) on myös todennut apatiitin kasveille käyttökelpoiseen muotoon tulemisen osittain estyneen saraturpeessa. Jos pajun lyhytkiertoviljely suonpohjan turpeessa vaatii kasvualustan pH:n nostamista kalkitsemalla välille 5,0—6,0 (ks. Ericsson ja Lindsjö 1981), on apatiitin käyttökelpoisuus tällöin huono. Kauniston (1982) kolmelta turvetuotantoalueelta keräämässä aineistossa suonpohjan turpeen pH vaihteli välillä 3,6—4,6. Tämä tutkimus ei myöskään puolla raakafosfaatin käyttöä.

Intensiivisessä lyhytkiertoviljelyssä kiertoajat ovat hyvinkin lyhyitä, jopa yksi vuosi (Pohjonen 1980). Tämän vuoksi voimakkaan reaktion saaminen jo heti lannoitusvuonna on tärkeää. Lyhyessä ajassa saatavat reaktiot

vaativat nopeatehoisia lannoitteita (Karsisto 1976b). Maatalouden lannoitustutkimuksissa on todettu, että maksimisatoon pyrittäessä ei hidasliukoisen hienofosfaatin kohdalla ole pystytty määrän nostamisella korvaamaan nopean alkuvaikutuksen puutetta (Karsisto 1973). Tässä tutkimuksessa esitetyt tosin vain yhdeltä turpeennostosta vapautuneelta suonpohjalta olevat tulokset viittaavat nopealiukoisten fosforilannoitteiden parempaan soveltuvuuteen lyhytkiertoviljelyssä (ks. myös Kaunisto 1983). Tosin Kihniön Aitonevalla tätä tutkimusta happamammalla kasvualustalla sijaitsevassa kokeessa raakafosfaatin ja superfosfaatin vaikutukset eivät eronneet toisistaan (Kaunisto 1985). Tulokset kaipaavatkin tuekseen vielä lisäselvityksiä erilaisilta kasvualustoilta.

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# SUMMARY

## Effect of some phosphorus fertilizers on the biomass production and nutrient uptake of *Salix* 'Aquatica' in a peat cut-away area

### Material

The effect of three phosphorus fertilizers (superphosphate, rock phosphate, apatite) on the biomass production, mineral contents of leaves, bark and wood and on the amount of nutrients bound in stands of *Salix* 'Aquatica' grown in a peat cut-away area of Paloneva (64°27'N, 25°26'E) was studied.

The average depth of the peat was 100 cm, and the area was drained using 45 m drain spacing. At the beginning of June 1981 peat was limed with 6 000 kg/ha dolomite. Twenty centrimetre-long cuttings of *Salix* 'Aquatica' (clone V769 originating from Lieto) were planted in density of 4.1 cuttings per square metre (distance between rows 70 cm and distance between cuttings in the rows 35 cm). Besides phosphorus, willow was fertilized with nitrogen and potassium. Fertilizer treatments presented in Table 1 were replicated four times (plot size 15 m × 15 m). The experiment was fertilized in June 1981 and the fertilization was repeated with the same fertilizers and amounts in spring 1983. After the first growing season in October 1982 the

sprouts were cut and the new coppice was grown for two growing seasons.

The diameter and height of willow were determined in autumn 1982 and 1983 by measuring 200—270 sprouts on every plot using systematic sampling. Willow was also measured in spring 1983 after detecting frost-damaged shoot tops. Height was measured from ground level to shoot top and diameter at height of 10 cm above ground. Sample sprouts were taken (120 in 1982, 51 in 1983). Their diameter at stump level and total length were measured. Leaves, and in 1983 also bark, were separated from wood (App. 1). Leaves were then oven dried at 80 °C for 24 hours and stems and bark at 105 °C for 24—48 hours and dry mass was measured with 0.1 g accuracy.

Allometric biomass equations ($Y = ax^b\epsilon$) were developed for the dry mass of leaves, bark and wood using logarithmic linear transformation. The small underestimate caused by logarithmic transformation was corrected by adding a correction term $s_\epsilon^2/2$ to constant. Height, diameter and their combinations were studied as independent variables. Diameter alone gave better fit than height, addition of height as the second variable improved fit only slightly. The dependence of the leafless above-ground mass and bark on diameter is presented in Fig. 1. The dry mass of leaves, bark and wood on the plots was determined using summation technique and equations presented in Table 2.

At the end of August 1983 leaf samples and in September bark and wood samples were collected and analyzed for their nitrogen, phosphorus and potassium content. Soil samples were taken in autumn 1983 and analyzed for total, ammonium and nitrate nitrogen, exchangeable potassium, calcium and magnesium, ammonium-acetate, soluble phosphorus, electrical conductivity and pH.

## Results

After liming peat pH varied between 5.4 and 6.4 (Table 3). Superphosphate increased the amount of easily soluble phosphorus in soil; with rock phosphate and apatite the increase was only slight. Fertilization with potassium salt increased the amount of exchangeable potassium tenfold in peat. The total nitrogen content of peat was considerably high, the mean being 2.6 %.

Without fertilization 95.5 % of the willows had died, but in fertilized plots mortality was only 1.2 % to 4.4 %. Only fertilization with NKPsf increased the height and diameter growth of willow (Table 4). One-year-old willow shoots were damaged by the frost during autumn or winter an average 26 cm down from the tops. The mass of an average frost damaged shoot top was highest when willow was fertilized with superphosphate (Table 5). The amount of mass damaged by the frost was 0.2—0.4 t/ha and its share of the leafless above-ground mass was 23—45 %.

Without fertilization willow did not grow even on limed peat (Figs. 2 and 3). Superphosphate was the only phosphorus fertilizer that increased the biomass of willow compared with basic NK fertilization (Table 6, Figs. 2 and 4). The above-ground dry mass of willow was 2.9 t/ha after the first and 13.1 t/ha after the second growing season when fertilized with NKPsf. The leaf, bark and wood masses of two-year-old willow were 3, 4 and 5 times higher when fertilized with superphosphate than with other fertilizers.

Only superphosphate increased the phosphorus content of leaves, bark and wood, decreasing simultaneously their potassium content slightly (Fig. 5). The mineral content of wood was lower than that of bark. Out of the measured soil properties the amount of soluble phosphorus correlated best with some mass and tree characteristics (App. 2). In regression analysis the biomass production of willow was best explained with the amount of easily soluble phosphorus and exchangeable potassium in peat.

Willow fertilized with NKPsf contained more mineral nutrients than differently fertilized willow (Fig. 6). The share of leaves in the total above-ground biomass production of two-year-old willow (13.1 t/ha) was 23 %, although containing over half of the nitrogen and potassium and 40 % of the phosphorus bound in the willow. The share of bark in the mass was 23 %, containing 29 %, 30 % and 26 % of the N, P and K bound in the willow. Wood (54 % of total biomass) contained 19 %, 30 % and 22 % out of the total N, P and K, respectively.

Liite 1. Koevesojen tunnuksia.
*Appendix 1. Characteristics of sample sprouts.*

| Puutunnus *Characteristic* | 1982 x̄ | s | Vaihteluväli *Range* | 1983 x̄ | s | Vaihteluväli *Range* |
|---|---|---|---|---|---|---|
| Pituus, cm *Height, cm* | 80,8 | 26,9 | 28—150 | 111,2 | 62,5 | 28—228 |
| Tyviläpimitta, mm *Base diameter, mm* | 7,4 | 1,4 | 3—12 | 9,8 | 5,4 | 3—20 |
| Runkomassa, g[1] *Stem mass, g*[1] | 7,5 | 4,9 | 1—27 | 39,1 | 47,4 | 1—164 |
| Lehtimassa, g *Leaf mass, g* | 4,7 | 2,5 | 1—12 | 11,1 | 14,7 | 1—47 |
| Kuorimassa, g *Bark mass, g* | | | | 11,6 | 12,9 | 1—42 |
| Puuaineen massa, g *Wood mass, g* | | | | 27,5 | 34,8 | 1—123 |

[1] Maanpäällinen lehdetön massa (puuaine ja kuori) — *Above-ground leafless mass (wood and bark)*

Liite 2. Eräiden massa- ja puustotunnusten ja maan ominaisuuksien väliset korrelaatiokertoimet. Mukana vain lannoitetut koealat.
*Appendix 2. Correlation coefficients between some mass and tree characteristics and soil properties. Only fertilized plots included.*

| Tunnus *Characteristic* | Maan ominaisuus — *Soil characteristic* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tot. N | $NH_4$ | $NO_3$ | Liuk. P *Soluble P* | Vaihtuva K *Exchangeable K* | Vaihtuva Ca *Exchangeable Ca* | Vaihtuva Mg *Exchangeable Mg* | pH | Johtoluku *Conductivity* |
| Kokonaismassa — *Total mass* | −0,277 | 0,141 | −0,024 | 0,751*** | −0,260 | 0,589* | 0,217 | 0,010 | 0,408 |
| Lehtimassa — *Leave mass* | −0,269 | 0,127 | −0,035 | 0,733*** | −0,267 | 0,585* | 0,205 | 0,012 | 0,396 |
| Kuorimassa — *Bark mass* | −0,284 | 0,115 | −0,027 | 0,749*** | −0,269 | 0,601* | 0,225 | 0,024 | 0,413 |
| Puuaineen massa — *Wood mass* | −0,290 | 0,108 | −0,021 | 0,760*** | −0,269 | 0,610* | 0,235 | 0,030 | 0,425 |
| Keskipituus — *Mean height* | −0,189 | 0,060 | −0,027 | 0,717** | −0,189 | 0,613* | 0,333 | 0,127 | 0,379 |
| Keskiläpimitta — *Mean diameter* | −0,314 | 0,070 | −0,028 | 0,723** | −0,185 | 0,643* | 0,373 | 0,156 | 0,839 |
| Paleltuneen vesan massa — *Mass of frost damaged sprout top* | 0,136 | −0,175 | −0,354 | 0,606* | −0,002 | 0,324 | 0,054 | 0,051 | 0,139 |

Liite 3. Eräiden massa- ja puustotunnusten sekä lehtien, kuoren ja puuaineen ravinnepitoisuuksien tai ravinnesuhteiden väliset korrelaatiokertoimet. Mukana vain lannoitetut koealat.
*Appendix 3. Correlation coefficients between some mass and tree characteristics and nutrient contents and nutrient rations of leaves, bark and wood. Only fertilized plots included.*

| Tunnus *Characteristic* | Lehtien ravinnepitoisuus tai ravinnesuhde *Foliar nutrient content or nutrient ratio* | | | | | | Kuoren ravinnepitoisuus tai ravinnesuhde *Bark nutrient content or nutrient ratio* | | | | | | Puuaineen ravinnepitoisuus tai ravinnesuhde *Wood nutrient content or nutrient ratio* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N/P | N/K | K/P | N | P | K | N/P | N/K | K/P | N | P | K | N/P | N/K | K/P |
| *Kokonaismassa* *Total mass* | 0,181 | 0,891*** | −0,582* | −0,819*** | 0,627** | −0,808*** | 0,377 | 0,574 | −0,301 | −0,540 | 0,437 | −0,573 | −0,073 | 0,903*** | −0,305 | −0,704* | 0,225 | −0,629* |
| Lehtimassa *Leaf mass* | 0,187 | 0,878*** | −0,598* | −0,803*** | 0,634** | −0,809*** | 0,382 | 0,579* | −0,282 | −0,547 | 0,425 | −0,566 | −0,067 | 0,878*** | −0,308 | −0,672* | 0,247 | −0,610* |
| Kuorimassa *Bark mass* | 0,202 | 0,891*** | −0,604* | −0,815*** | 0,644** | −0,820*** | 0,384 | 0,587* | −0,294 | −0,551 | 0,436 | −0,579* | −0,056 | 0,892*** | −0,302 | −0,680* | 0,241 | −0,614* |
| Puuaineen massa *Wood mass* | 0,218 | 0,898*** | −0,613* | −0,819*** | 0,655** | −0,827*** | 0,384 | 0,594* | −0,301 | −0,555 | 0,443 | −0,587* | −0,050 | 0,901*** | −0,295 | −0,686* | 0,232 | −0,616* |
| Keskipituus *Mean height* | 0,009 | 0,901*** | −0,502* | −0,880*** | 0,552* | −0,788*** | 0,209 | 0,472 | −0,252 | −0,531 | 0,302 | −0,510 | −0,194 | 0,848*** | −0,399 | −0,667* | 0,310 | −0,642* |
| Keskiläpimitta *Mean diameter* | 0,033 | 0,891*** | −0,485 | −0,869*** | 0,540* | −0,773*** | 0,254 | 0,479 | −0,292 | −0,515 | 0,367 | −0,535 | −0,150 | 0,835*** | −0,405 | −0,621* | 0,358 | −0,633* |
| Paleltuneen vesan massa — *Mass of frost damaged sprout top* | −0,035 | 0,613* | −0,572* | −0,607* | 0,581* | −0,679** | 0,090 | 0,335 | −0,136 | −0,445 | 0,113 | −0,351 | −0,309 | 0,701* | −0,415 | −0,676* | 0,230 | −0,619* |

Liite 4. Eräiden maan ominaisuuksien ja lehtien, kuoren ja puuaineen ravinnepitoisuuksien väliset korrelaatiokertoimet.
*Appendix 4. Correlation coefficients between some soil properties and nutrient contents of leaves, bark and wood.*

| Maan ominaisuus *Soil characteristic* | Lehtien ravinnepitoisuus *Foliar nutrient content* | | | Kuoren ravinnepitoisuus *Bark nutrient content* | | | Puuaineen ravinnepitoisuus *Wood nutrient content* | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| pH | 0,230 | 0,131 | −0,058 | 0,041 | 0,272 | −0,570* | 0,335 | −0,055 | −0,384 |
| Johtoluku — *Conductivity* | 0,837*** | 0,553* | 0,332 | 0,372 | 0,451 | −0,241 | 0,204 | 0,513 | 0,068 |
| Tot. N | −0,464* | −0,282 | −0,247 | −0,369 | −0,177 | 0,141 | −0,394 | 0,041 | −0,113 |
| $NH_4$ | 0,196 | 0,049 | 0,369 | −0,021 | 0,175 | 0,072 | 0,115 | 0,115 | 0,084 |
| $NO_3$ | 0,651** | 0,318 | 0,469* | 0,133 | 0,072 | −0,128 | 0,081 | 0,170 | 0,077 |
| Liuk. P. — *Soluble P* | 0,396 | 0,666** | −0,211 | 0,189 | 0,590* | −0,279 | −0,045 | 0,783*** | −0,227 |
| Vaihtuva K — *Exchangeable K* | 0,693*** | 0,203 | 0,735*** | −0,127 | 0,180 | 0,095 | −0,318 | 0,051 | −0,086 |
| Vaihtuva Ca — *Exchangeable Ca* | 0,647** | 0,638** | 0,026 | 0,295 | 0,568* | −0,447 | 0,188 | 0,555* | −0,224 |
| Vaihtuva Mg — *Exchangeable Mg* | 0,366 | 0,351 | −0,05 | 0,234 | 0,261 | −0,491 | 0,367 | 0,102 | −0,149 |

# VII

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

Jyrki Hytönen

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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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# 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 $s_\varepsilon^2 / 2$. 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.

| Compartment | Experiment[1)] | One-year-old willow | | | | | Two-year-old willow | | | | | Three-year-old willow | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | a | b | $r^2$ % | V % | N | a | b | $r^2$ % | V % | 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

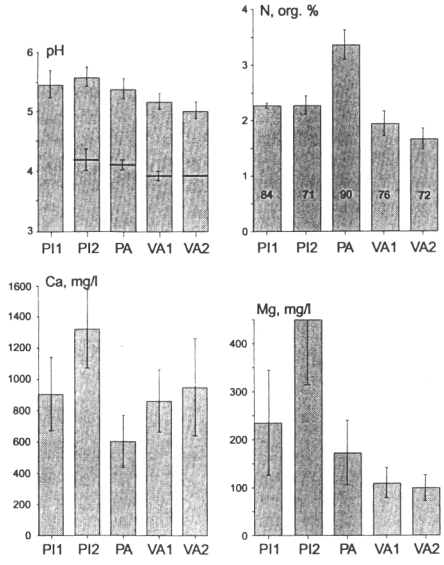


**Fig. 1.** Soil pH, nitrogen content (in organic matter) and concentrations of ammonium acetate extractable (pH 4.65) calcium and magnesium. Standard deviations indicated by lines. pH before amelioration indicated inside the pH columns. The peat's organic matter content (%) marked inside the columns 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

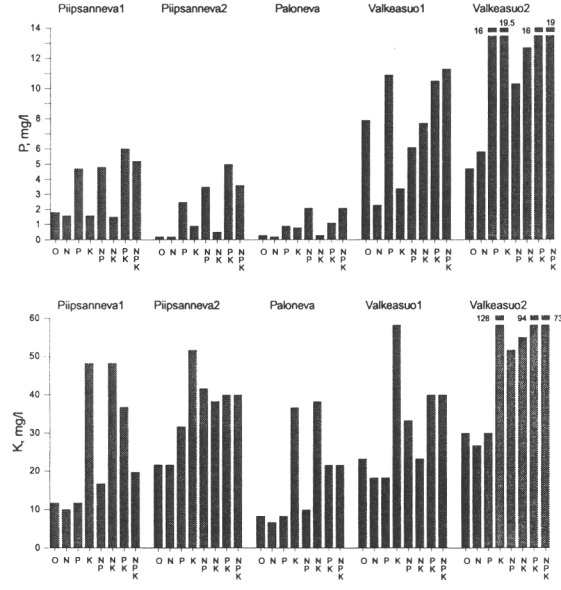


**Fig. 2.** Effect of fertilization on the concentration of ammonium acetate extractable phosphorus and potassium in the soil of the experimental sites.

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

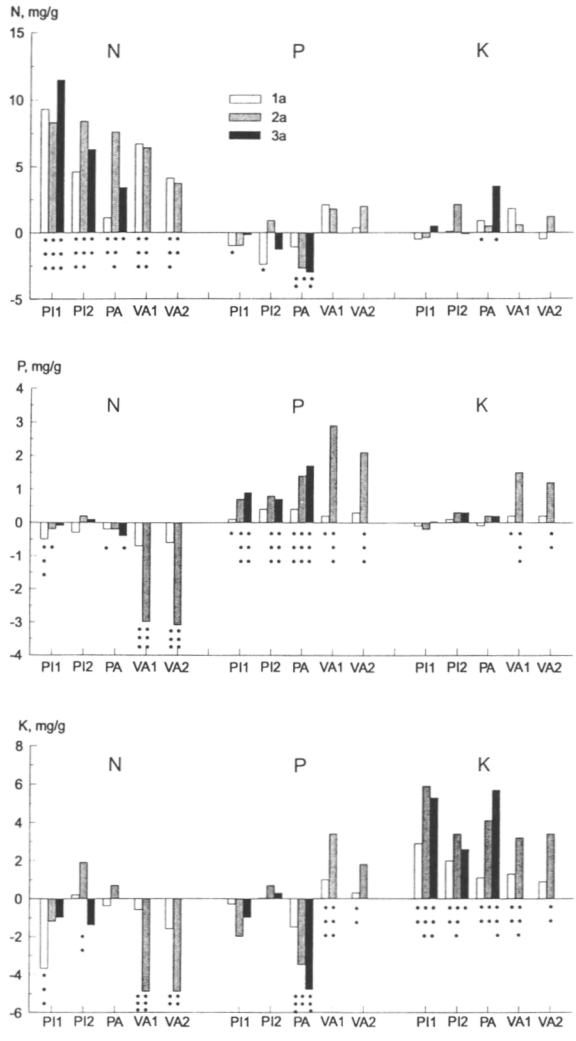


**Fig. 3.** Factorial main effects of nitrogen, phosphorus and potassium fertilizer application on the foliar nitrogen, phosphorus and potassium concentrations. Statistical significance indicated by asterisks (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Willow age between one and three years (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 $ha^{-1}3a^{-1}$ at Piipsanneva 1, while at Piipsanneva 2 and Paloneva the corresponding figures for NP-fertilized willow were 11–12 t $ha^{-1}3a^{-1}$. The total mass (including foliage, bark, wood, stump and roots) in the same treatments at Piipsanneva 1 was 23.4 t $ha^{-1}3a^{-1}$, at Piipsanneva 2, 20.3 t $ha^{-1}3a^{-1}$ and Paloneva 18.3 t $ha^{-1}3a^{-1}$.

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 $ha^{-1}3a^{-1}$, at Piipsanneva 2 by 8.1 t $ha^{-1}3a^{-1}$ and at Paloneva by 5.6 t $ha^{-1}3a^{-1}$.

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-

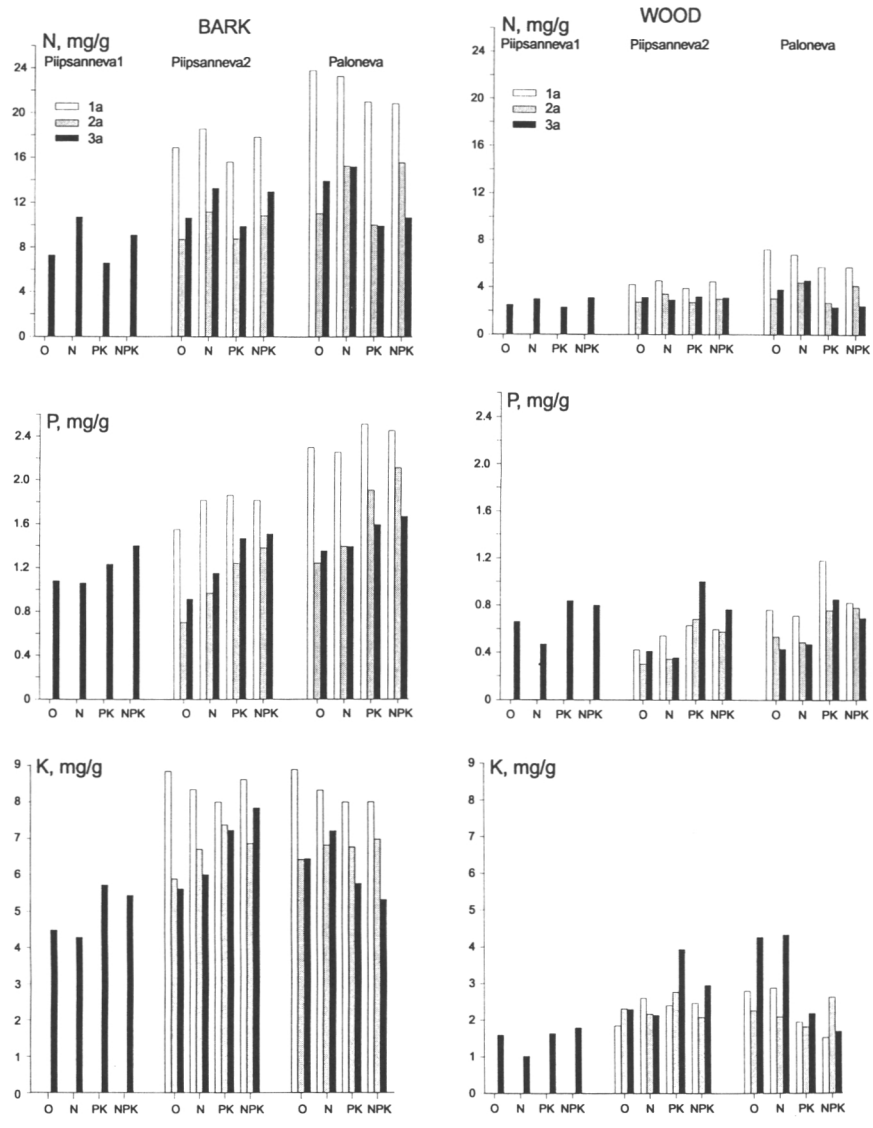


**Fig. 4.** Effect of fertilization on the nitrogen, phosphorus, potassium, calcium and magnesium concentrations of willow bark and wood.

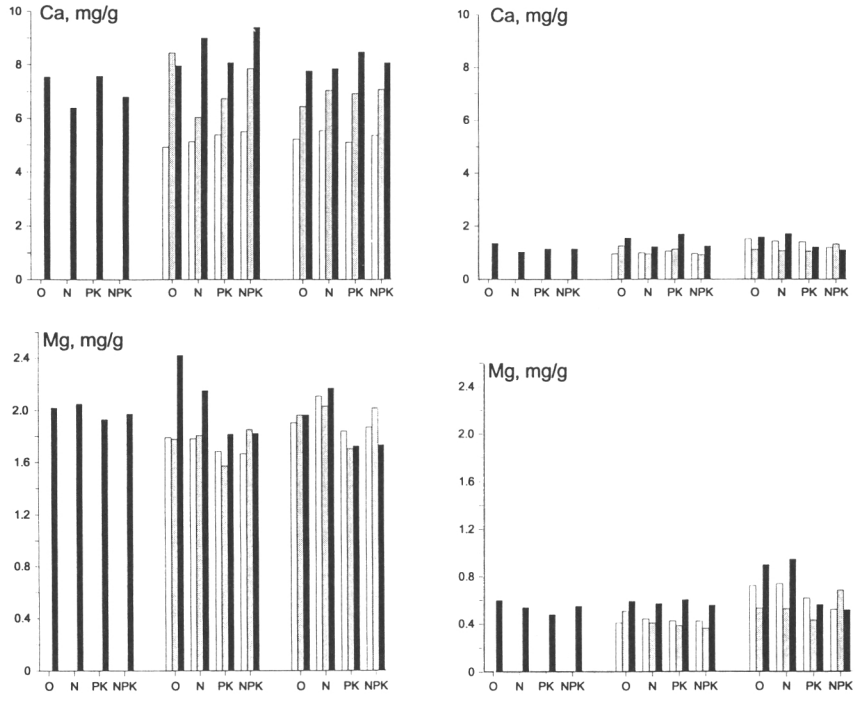


**Fig. 4** continued.

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

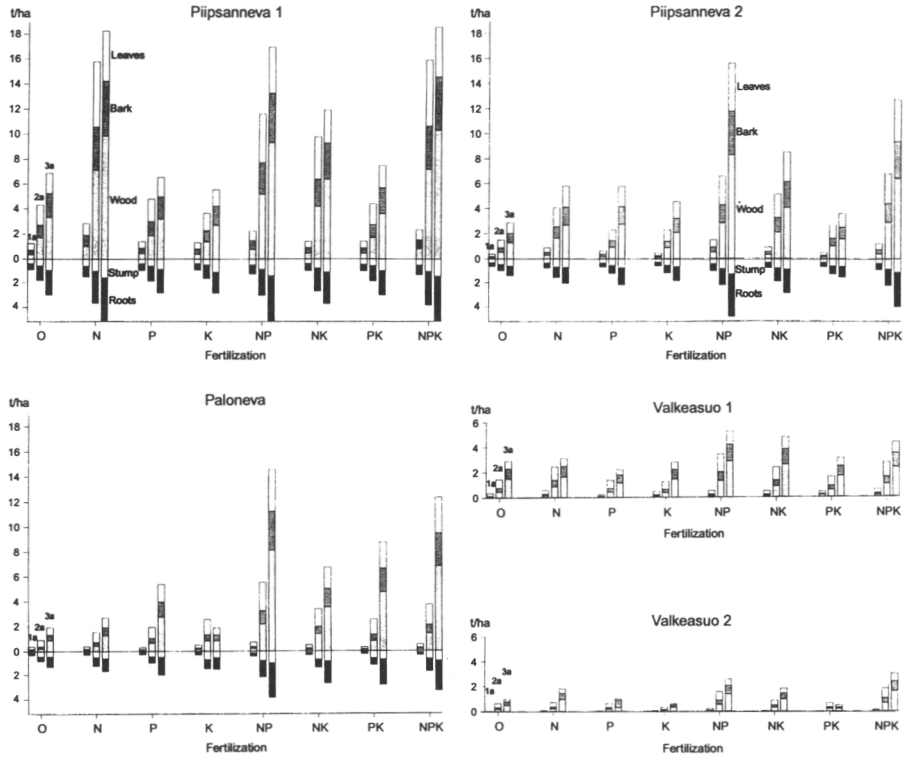


**Fig. 5.** Effect of fertilization on dry-mass production. Willow age one to three years (1a, 2a, 3a).

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

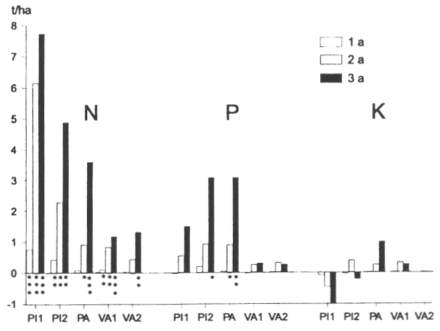


**Fig. 6.** Factorial main effects of nitrogen, phosphorus and potassium fertilizer application on the above-ground, leafless dry-mass yield. Statistical significance indicated by asterisks (* $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Willow age between one and three years (1a, 2a, 3a). For legend,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

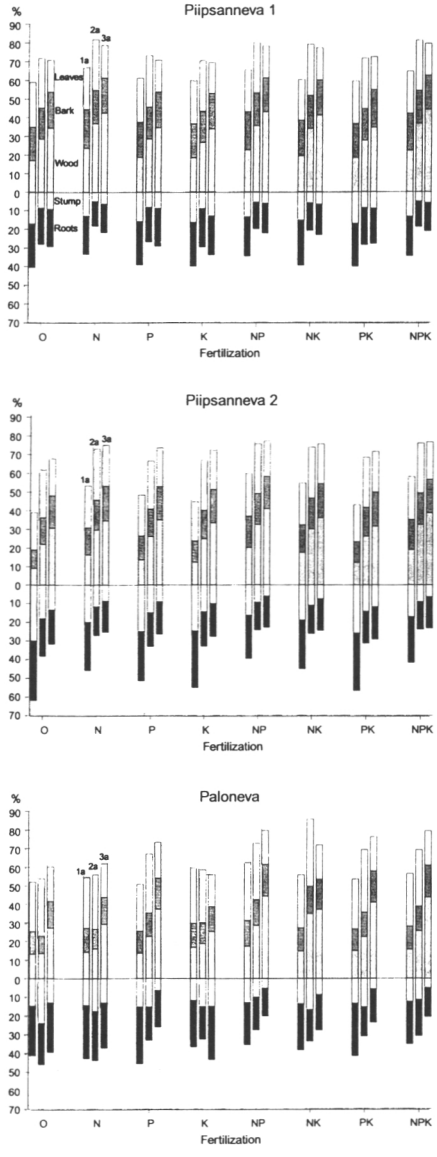


**Fig. 7.** Proportion of one- to three-year-old (1a, 2a, 3a), willow biomass compartments in the total dry-mass.

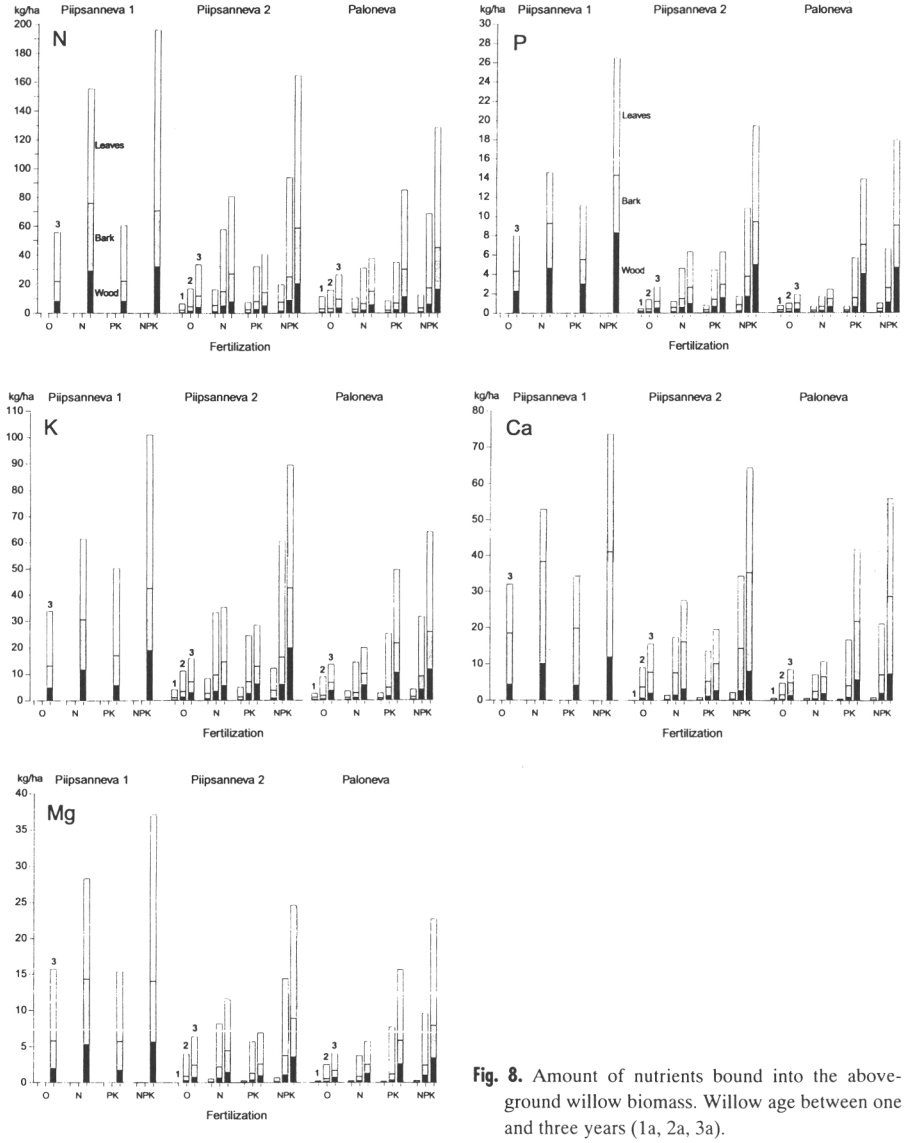


**Fig. 8.** Amount of nutrients bound into the above-ground willow biomass. Willow age between one and three years (1a, 2a, 3a).

**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.

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# VIII

*Suo 45(3): 65–77, 1994*

Jyrki Hytönen

# EFFECT OF FERTILIZER APPLICATION RATE ON NUTRIENT STATUS AND BIOMASS PRODUCTION IN SHORT-ROTATION PLANTATIONS OF WILLOWS ON CUT-AWAY PEATLAND AREAS

## Lannoitemäärän vaikutus lyhytkiertoviljelmien ravinnetilaan ja biomassatuotokseen suonpohjilla.

Hytönen, J. 1994: Effect of fertilizer application rate on nutrient status and biomass production in short-rotation plantations of willows on cut-away peatland areas. (Lannoitemäärän vaikutus lyhytkiertoviljelmien ravinnetilaan ja biomassatuotokseen suonpohjilla.) — Suo 45:65–77. Helsinki. ISSN 0039-5471.

The effects of N, P and K fertilizer application rates on the biomass production, soil properties and foliar nutrient status were studied in willow plantations (*Salix x dasyclados*, *Salix* 'Aquatica') established on cut-away peatland areas at Haapavesi (64°06'N, 25°36'E and Ruukki (64°27'N, 25°26'E). When the amount of one of the nutrients in NPK-fertilization was changed (N 0–200 kg/ha, P 0–60 kg/ha, K 0–80 kg/ha) the others remained unchanged (N 100, P 30, K 40 kg/ha). Three field experiments were made. Increasing phosphorus and potassium application rates increased the concentrations of corresponding soil extractable nutrients. There was a positive correlation between the fertilizer application rate and the concentrations of foliar nitrogen, phosphorus and potassium. During the first growing season, the effect of nitrogen fertilization on biomass production was modest, but during the second growing season the yield of willows increased the most when fertilized with 100–150 kg N/ha. Although phosphorus fertilization increased yields, already the smallest amounts (15 kg/ha) resulted in biomass yields as high when applying the largest phosphorus fertilizer amounts (60 kg/ha). Potassium fertilization did not increase biomass production in any of the experiments. The highest total biomass yields after three growing seasons were 28–30 t/ha. Their compositions were as follows: 44% wood, 18% bark, 17% foliage, 16% roots, and 5% stumpwood.

Key words: biomass production, cut-away peatland, fertilization, energy forestry, Salix

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## INTRODUCTION

The short-rotation management concept includes the establishment of closely-spaced stands of fast-growing trees applying intensive cultivation practices, repeated harvesting at short cutting cycles, regeneration of subsequent crops via sprouts, and using a high degree of mechanization. Cut-away peatlands estimated to amount to 1 500–2 000 ha in 1992 (Lappalainen et al. 1992) and to increase during this decade by 1 500–3 000 ha annually (Kaunisto and Saarinen 1989, Taustatietoa... 1991, Lappalainen et al. 1992), have been considered to be suitable for short-rotation cultivation (Energiametsätoimikunnan... 1979, 1981). Cut-away peatlands are characterized by variable peat thickness, low pH and high nitrogen contents and low concentrations of phosphorus and potassium (Kaunisto 1979, 1985, Ferm and Kaunisto 1983, Lumme et al. 1984, Heikkilä 1986, Lehtonen & Tikkanen 1986, Ferm and Hytönen 1988, Kaunisto and Viinamäki 1991).

Short-rotation willows bind considerable amounts of nitrogen, phosphorus, potassium and other nutrients in their biomass (Saarsalmi 1984, Ferm 1985, Hytönen 1986). The nutrient amounts bound in a young willow stand can be of the same magnitude as those in a stand of 40-year-old birch, a stand of pole-sized Scots pine or a 100-year-old stand of Norway spruce (Mälkönen 1977, Paavilainen 1980, Saarsalmi 1984, Ferm 1985, Hytönen 1986, Finér 1989). Fertilization and soil amelioration are probably the most important factors affecting the biomass production of short-rotation plantations on cut-away peatlands (Hytönen 1982, 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988, Lumme 1989). Due to the rather high pH requirements of *S. viminalis* and *S. x dasyclados* (Ericsson and Lindsjö 1981, Ferm and Hytönen 1988) liming or ash application are necessary (Kaunisto 1983, Lehtonen and Tikkanen 1986, Lumme 1989). The survival and growth of willows on limed but unfertilized cut-away peatlands has been poor (Hytönen 1982, 1986, 1987, Kaunisto 1983, Ferm and Hytönen 1988). Fertilization has considerably increased the biomass production of willow both in field and greenhouse experiments (Hytönen 1982, 1986, Kaunisto 1983, Ferm and Hytönen 1988). The highest biomass production levels have been achieved both in greenhouse and field experiments when nitrogen as well as PK and a liming agent have been added (Hytönen 1982, Kaunisto 1983, Hytönen 1987, Ferm and Hytönen 1988).

Knowledge on the proper fertilizer application amounts in short-rotation cultivation on cut-away peatlands is still inadequate. Doubling of the NPK fertilization amounts from N 150 kg/ha, P 54–67 kg/ha and K 102–124 kg/ha increased biomass production on cut-away peatlands with nitrogen contents of 1.2–1.8%, but not on peatlands with nitrogen contents above 2.3% (Kaunisto 1983, Hytönen 1987). The aim in this investigation was to study the effects of fertilizer application rates on biomass production, soil properties and foliar nutrient concentrations of willows on cut-away peatlands.

## MATERIAL AND METHODS

### Experimental design

Willow plantations were established on two limed (6 000 kg/ha of dolomite lime) cut-away peatlands at Haapavesi Piipsanneva (64°06', 25°36'E) and at Ruukki Paloneva (64°27'N, 25°26'E). Willows (*Salix x dasyclados* clone P6011 at Piipsanneva 1, *Salix* 'Aquatica', clone V769 at Piipsanneva 2 and at Paloneva) were planted at a density of 40 000 cuttings per hectare in the spring of 1983 and cut back to 10 cm long stumps the following autumn. All experimental fields were fertilized using 500 kg/ha of PK fertilizer for peatlands (P 44 kg/ha, K 83 kg/ha) and ammonium nitrate with lime (N 50 kg/ha) in the spring of 1983. Supplementary planting and weed control was carried out on all experimental fields, which were also fenced. The fertilization experiments were established in the spring of 1984 and the willows were cultivated for three years.

Different N, P and K fertilizer application rates were tested in three fertilization experiments. Five nitrogen (N 0, N 50, N 100, N 150, N 200 kg/ha as ammonium nitrate with lime), phosphorus (P 0, P 15, P 30, P 45, P 60 kg/ha as superphosphate) and potassium (K 0, K 20, K 40, K 60, K 80 kg/h as potassium salt) levels were used. When the amount of one of the nutrients in NPK fertilization was changed, the others remained unchanged (N 100, P 30

and K 40 kg/ha). In total, there were thirteen fertilization treatments. The sizes of the experimental plots were 56–80 $m^2$. The experimental design consisted of randomized blocks with three replications. Fertilization was repeated annually in the spring (1984, 1985, 1986).

### Measurements

The height and diameter of the willows on the experimental plots were measured after each growing season (see Hytönen 1985, 1986, Hytönen et al. 1987). The number of living and dead stools were also recorded. The biomass of leaves, bark, wood and stumps and roots was determined annually using dry-mass equations described by Hytönen (1994).

Foliar samples from at least five randomly selected uneven sized willow sprouts were taken from each plot in 1984–1986 for nutrient analysis. Foliar N, P and K concentrations were determined from the 1984 samples. The samples taken in 1985 and 1986 were also analyzed for foliar concentrations of Ca, Mg, Fe, Mn, Zn, and Cu (Halonen and Tulkki 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, volume determined in laboratory). The average peat depth measured from five points on each plot was 150 cm at Paloneva, 60 cm at Piipsanneva 1 and 40 cm at Piipsanneva 2. The organic matter content in the peat was lowest at Piipsanneva 2 (71%), higher at Piipsanneva 2 (84%) and Paloneva (90%). The total peat nitrogen content in the organic matter was at Paloneva 3.2% and at Piipsanneva 2.3%. At Piipsanneva 1, the extractable calcium concentration of the peat averaged 971 mg/l, at Piipsanneva 2 it was 1332 mg/l and at Paloneva 735 mg/l. The corresponding figures for extractable magnesium were 255 mg/l, 422 mg/l, 200 mg/l. The average pH on the experimental sites varied between 5.2 and 5.5.

The BMDP statistical software package was used in the computation of the results and analyses of variance were calculated. The treatment means were compared using Tukey's multiple range test.

## RESULTS

### Soil characteristics

Soil extractable phosphorus and potassium concentrations increased the more the higher the corresponding fertilizer application rate (Fig. 1). The effect of phosphorus fertilization was statistically significant at both Piipsanneva experiments ($p < 0.001$), but not at Paloneva. Only the highest (Piipsanneva 1) or second highest (Piipsanneva 2) fertilizer application rates significantly increased the soil phosphorus concentration to a level higher than that of the control. The highest phosphorus fertilization rates increased the peat phosphorus concentration at Piipsanneva 1 by over 12 times, at Piipsanneva 2 by 17 times and at Paloneva by 25 times as high as on the NK-fertilized control plots. The increase in the soil's potassium concentration was statistically significant only at Paloneva ($p < 0.05$).

The nitrogen, phosphorus or potassium fertilizer application rates did not affect the soil's pH or soil extractable calcium and magnesium concentrations.

### Foliar nutrient concentrations

Increasing the nitrogen fertilization rate increased foliar nitrogen concentrations at the Piipsanneva experiment during all three study years (Fig 2). However, at Paloneva, the nitrogen contents of the foliage during the first growing season were high regardless of the fertilization treatment; neither were the differences statistically significant during the third growing season. At Piipsanneva 1, already the lowest fertilizer application rate (50 kg/ha) increased the foliar nitrogen concentration compared to the control, whereas 100 kg/ha were required at Piipsanneva 2 for the equivalent foliar nitrogen concentration level to be achieved. Nitrogen fertilization had also a highly significant effect on the foliar N/P and P/K ratios, which increased as the amounts of applied nitrogen increased. The foliar N/P ratio of PK-fertilized willows varied between 7 and 10 while that of willows fertilized with 150 kg N/ha varied between 12 and 19.

Phosphorus fertilization increased foliar phosphorus concentrations, although the effect

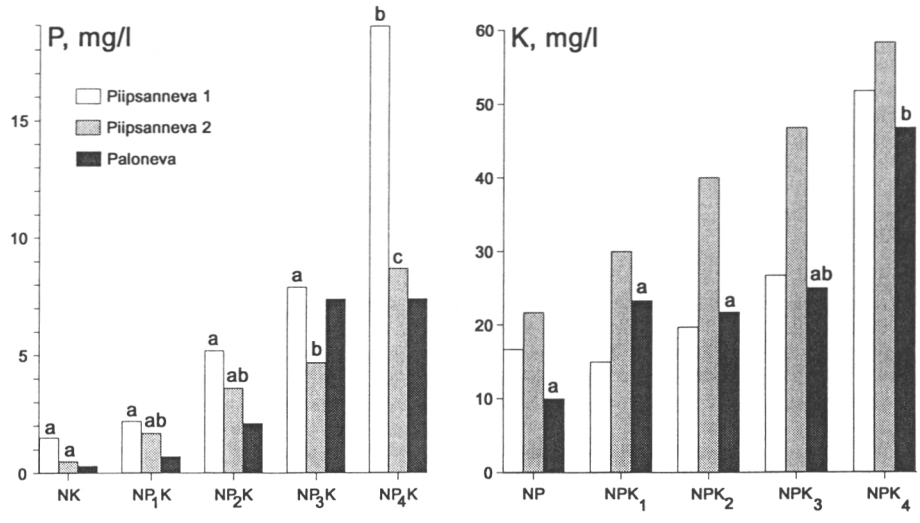



Fig. 1. Effect of fertilizer application rate on the concentration of ammonium acetate extractable phosphorus and potassium in the soil. For nutrient amounts applied, see Figure 2. Means not differing with statistical significance ($p < 0.05$) from each other are marked with the same letter.

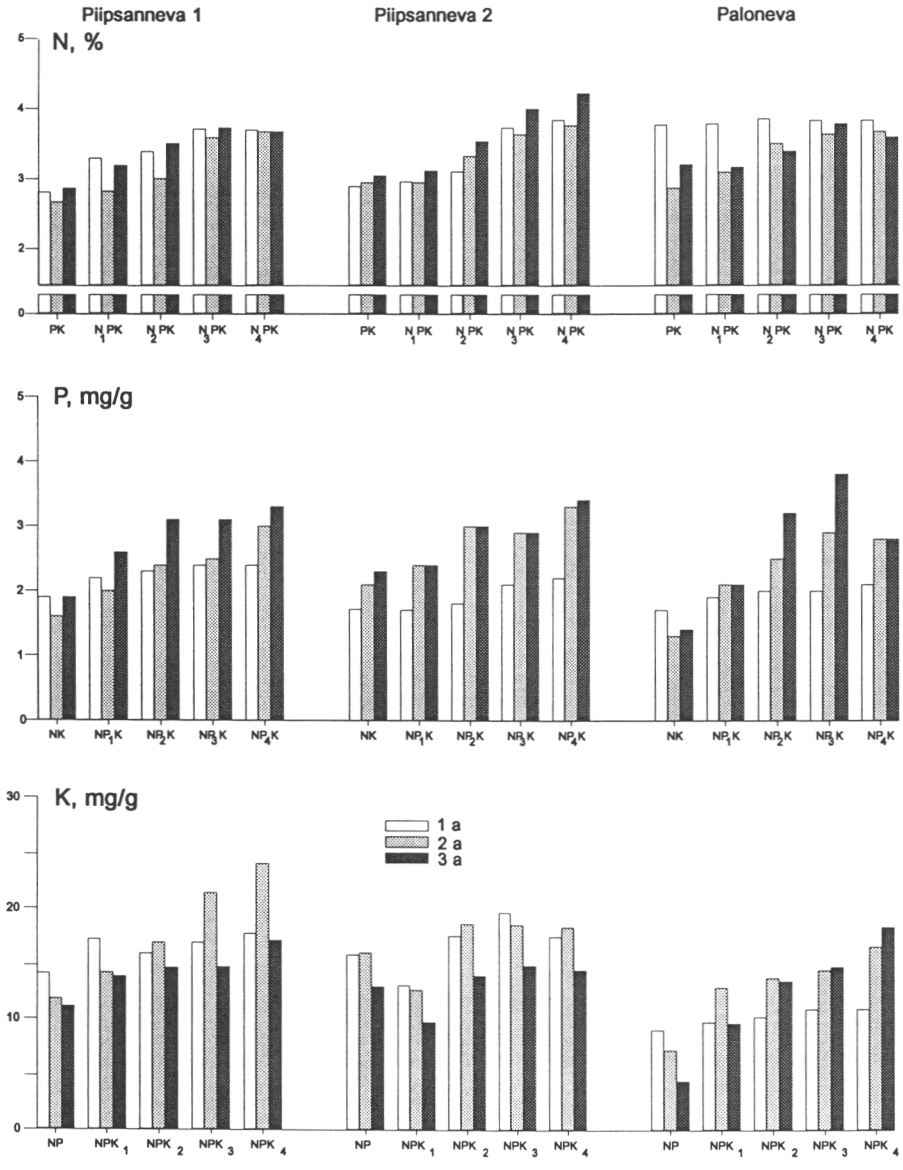
*Kuva 1. Fosfori- ja kaliumlannoitemäärän vaikutus maan happamaan ammoniumasetaattiin uuttuvan fosforin ja kaliumin määrään. Keskiarvot, jotka eivät eroa toisistaan tilastollisesti merkitsevästi ($p < 0,05$) merkitty samalla kirjaimella.*

during the first growing season was significant only at Paloneva ($p < 0.05$) (Fig 2). During the following growing seasons, the effect of phosphorus fertilization was also significant both at Piipsanneva 1 ($p < 0.001$) and Piipsanneva 2 ($p < 0.05$). At Piipsanneva 1, already 15 kg/ha phosphorus increased foliar phosphorus concentration higher than in the control, but at Piipsanneva 2 the corresponding amount was 30 kg/ha. Increasing the annual phosphorus fertilizer application rate from 45 kg/ha to 60 kg/ha did not increase the concentration of foliar phosphorus. Phosphorus fertilization decreased the foliar N/P and K/P ratios from the second growing season on.

The effect of potassium fertilization on the foliar potassium concentration was most pronounced at Paloneva ($p_{1a} < 0.05$, $p_{2a} < 0.001$, $p_{3a} < 0.001$), where the concentration of the peat extractable phosphorus was at its lowest (Fig. 2). At Paloneva, foliar potassium concentrations also decreased from year to year in the control (NP) treatment. At Piipsanneva 1, potassium fertilization increased foliar potassium concentrations during the second growing season ($p < 0.05$). At Piipsanneva 2, the foliar potassium concentration of willows fertilized with NP was higher than that of willows fertilized with a small amount of potassium (K 20 kg/ha).

Fig. 2. Effect of fertilizer application rate on the foliar concentrations nitrogen, phosphorus and potassium during the first (1a), second (2a) and third (3a) growing seasons. $N_1$ = 50 kg N/ha, $N_2$ = 100 kg N/ha, $N_3$ = 150 kg N/ha, $N_4$ = 200 kg N/ha. $P_1$ = 15 kg P/ha, $P_2$ = 30 kg P/ha, $P_3$ = 45 kg P/ha, $P_4$ = 60 kg P/ha. $K_1$ = 20 kg K/ha, $K_4$ = 40 kg K/ha, $K_3$ = 60 kg K/ha, $K_4$ = 80 kg K/ha. Means not differing with statistical significance ($p < 0.05$) from each other are marked with the same letter.

*Kuva 2. Typpi-, fosfori ja kaliumlannoitemäärän vaikutus lehtien typpi-, fosfori- ja kaliumpitoisuuksiin ensimmäisenä (1a), toisena (2a) ja kolmantena (3a) kasvukautena. $N_1$ = 50 kg N/ha, $N_2$ = 100 kg N/ha, $N_3$ = 150 kg N/ha, $N_4$ = 200 kg N/ha. $P_1$ = 15 kg P/ha, $P$ = 30 kg P/ha, $P_3$ = 45 kg P/ha, $P_4$ = 60 kg P/ha. $K_1$ = 20 kg K/ha, $K_4$ = 40 kg K/ha, $K_3$ = 60 kg K/ha, $K_4$ = 80 kg K/ha. Keskiarvot, jotka eivät eroa toisistaan tilastollisesti merkitsevästi ($p < 0,05$) merkitty samalla kirjaimella.*


Piipsanneva 1
Piipsanneva 2
Paloneva
N, %
P, mg/g
K, mg/g
1 a
2 a
3 a
PK
N1PK
N2PK
N3PK
N4PK
NK
NP1K
NP2K
NP3K
NP4K
NP
NPK1
NPK2
NPK3
NPK4

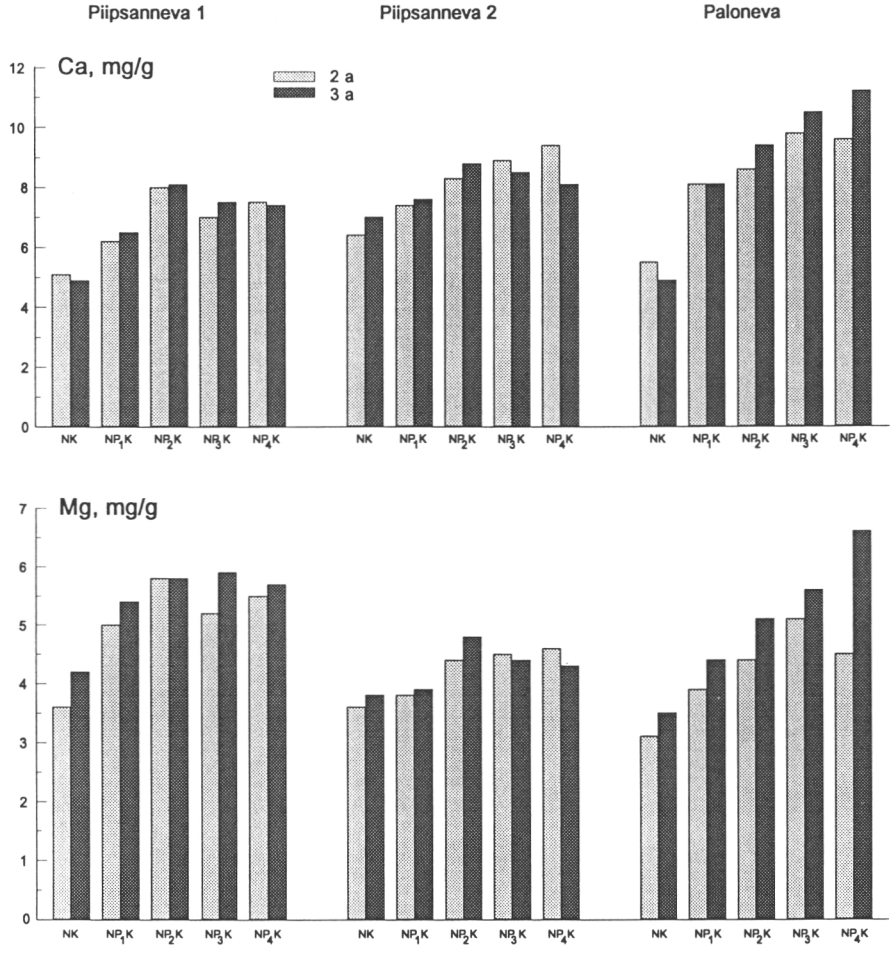



Fig 3. Effect of phosphorus fertilizer application rate on the foliar calcium and magnesium concentrations. For nutrient amounts applied, see Figure 2.

*Kuva 3. Fosforilannoitemäärän vaikutus lehtien kalsium- ja magnesiumpitoisuuksiin. Selitykset kuvassa 2.*

The effect of different fertilizer application rates on other foliar nutrient concentrations was modest. Phosphorus fertilization increased foliar calcium and magnesium concentrations (Fig 3) and at Paloneva it significantly ($p < 0.001$) decreased the foliar copper concentrations. The site-to-site differences in foliar iron, manganese, zinc and copper concentrations were considerable (Fig 4).

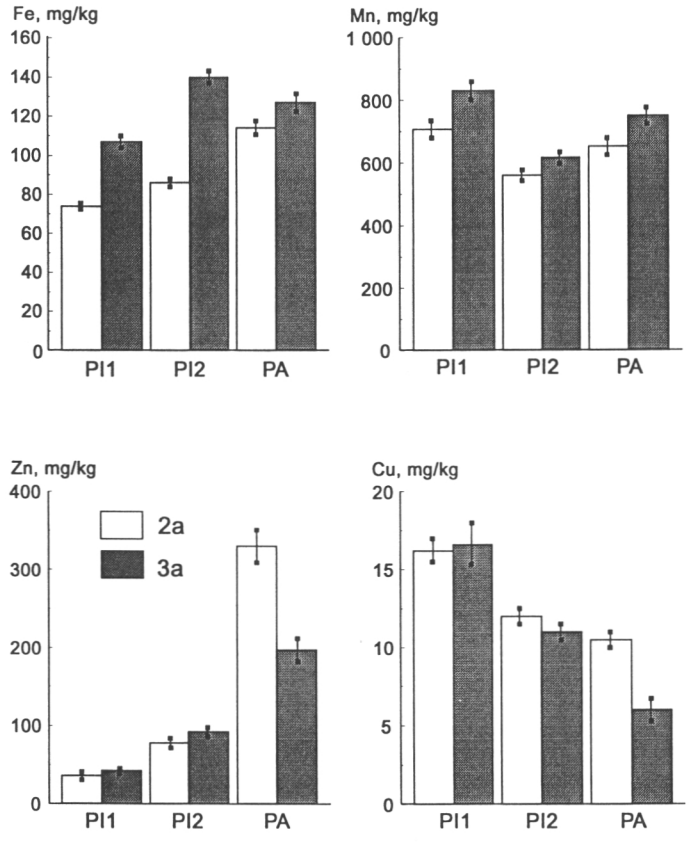



Fig 4. Foliar iron, manganese, zinc and copper concentrations (mg/kg) in the experimental areas. PI1 = Piipsanneva 1, PI2 = Piipsanneva 2, PA = Paloneva. Age of willows 2 (2a) and 3 (3a) years, ±SE marked with line on top of each bar.

*Kuva 4. Pajujen lehtien rauta-, mangaani-, sinkki- ja kuparipitoisuudet koealueilla. PI1 = Piipsanneva 1, PI2 = Piipsanneva 2, PA = Paloneva. Pajujen ikä 2 (2a) ja kolme (3a) vuotta. Keskiarvon keskivirhe merkitty janalla pylväiden päälle.*

## Survival

The survival of willows at the end of the experiments was considerably high (Fig 5). The higher rates of nitrogen fertilizer slightly decreased survival; only at Piipsanneva 2, however, was this decrease significant ($p < 0.05$). At Paloneva, survival decreased with increasing phosphorus fertilizer application rates.

## Biomass production

Although nitrogen fertilization increased biomass production already during the first growing season, the differences between the treatments were not statistically significant (Fig. 6). During the second growing season, biomass production at Piipsanneva was significantly higher than in the control with the nitrogen fertilizer application rates higher than 50 kg/ha. However, amounts exceeding 100 kg/ha no longer increased the biomass production. At Paloneva, only the 150 kg/ha application rate resulted in higher biomass production than the control. During the third growing season at Piipsanneva, fertilizer application rates of 100 kg/ha or more did not differ from each other in terms of the biomass produced; the total biomasses in these treatments varied within the range of 23.4–28.4 t/ha. Increasing the nitrogen fertilizer application rate from 50 to 100–200 kg/ha at Paloneva had no statistically significant effect on biomass production during the third growing season.

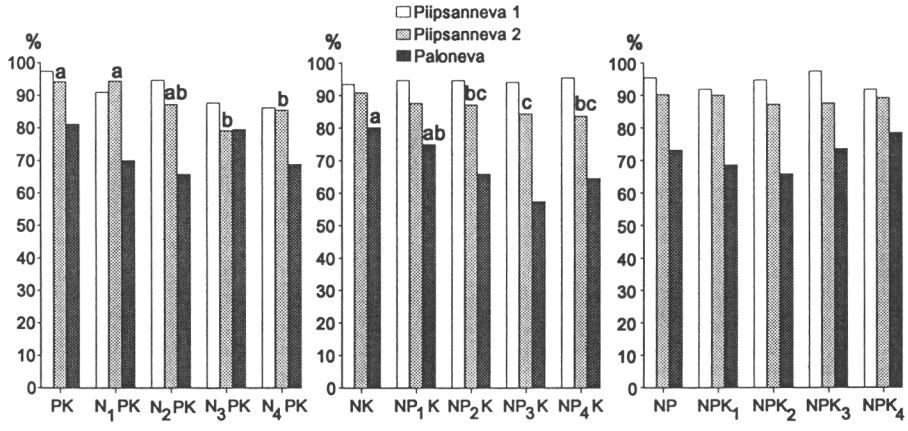



*Fig. 5.* Effect of fertilizer application rate on the survival of willows at the end of the third growing season. Means not differing with statistical significance ($p < 0.05$) from each other are marked with the same letter. For nutrient amounts applied, see Figure 2.

*Kuva 5. Lannoitemäärän vaikutus pajujen elävyyteen kolmannen kasvukauden lopussa. Keskiarvot, jotka eivät eroa toisistaan tilastollisesti merkitsevästi ($p < 0,05$) merkitty samalla kirjaimella. Selitykset kuvassa 2.*

Compared with NK fertilization, phosphorus fertilization enhanced biomass production, but the differences between different phosphorus fertilizer application rates were not statistically significant. Already 15 kg P/ha given annually resulted in as good a yield as the higher amounts of 60 kg P/ha. Compared to NP fertilization, potassium fertilization did not increase biomass production during any of the study years.

The first year's biomass production was low, 1.0–4.0 t/ha (Fig. 6). The composition of the total biomass produced by one-year-old, NPK-fertilized *S. x dasyclados*, 3.2 t/ha, was as follows: 23% wood, 20% bark, 22% foliage, 22% roots and 13% stumpwood. The annual increment during the following years increased manyfold. The mean annual leafless biomass production of NPK-fertilized *S. x dasyclados* (3.0–6.3 t/ha/a) was higher than that of *S.* 'Aquatica' (2.6–4.7 t/ha/a). The maximum total production of 30.6 t/ha/3a was composed of 44% wood, 18% bark, 17% foliage, 16% roots and 5% stumpwood.

## DISCUSSION

Increasing phosphorus and potassium application rates increased the corresponding concentrations of acid ammonium acetate extractable nutrients in the soil. However, even after three annual PK fertilizer applications, the ammonium acetate extractable phosphorus and potassium concentrations in the peat were rather low compared to Finnish tilled soils (Kurki 1982). The imbalance of nutrient ratios, typical for cutaway peatlands – high contents of peat nitrogen but low concentrations of phosphorus and potassium – was at its most extreme at Paloneva (Kaunisto 1979, 1985, Lehtonen & Tikkanen 1986, Ferm and Hytönen 1988, Kaunisto and Viinamäki 1991). At Paloneva, the peat's nitrogen content was exceptionally high (see also Hytönen 1986, 1987, Ferm and Hytönen 1988). Willow growth was probably not limited by the peat's low pH values (Ericsson and Lindsjö 1981, Ferm and Hytönen 1988).

The willows in this study responded readily to the fertilizer application treatments. Fertilizer application can be used to adjust foliar nitrogen, phosphorus and potassium concentrations and also foliar nutrient ratios (also Kaunisto 1983, Hytönen 1985). The results of this and earlier studies suggest that increases in nitrogen fertilizer application rates have less effect on foliar nitrogen concentrations on nitrogen-rich sites than they do on nitrogen-poor sites (Kaunisto 1983, Hytönen 1987).

Compared with the amounts given in fertilization, the willow stands in this study bound considerably small amounts of nitrogen, phosphorus and potassium in their biomass (Saarsalmi 1984, Ferm 1985, Hytönen 1986). During the first growing season, biomass production was low and nitrogen fertilization did not increase it significantly. Thus fertilization using the lowest nitrogen rates, or with no nitrogen being applied during the establishment phase, could be appropriate. This is in good agreement with Swedish recommendations for practical energy forestry cultivation with willows. According to these recommendations, nitrogen fertilization is usually not needed during the first growing season or it is needed in only small amounts (30–60 kg N/ha) (Sennerby-Forsse and Johansson 1989, Ledin and Sennerby-Forsse 1992). During the following years, increases in annual nitrogen fertilizer application rates over 100 kg/ha did not lead to considerable increases in yields. This is also in agreement with the Swedish recommendations for nitrogen fertilization (60–80 kg N/ha) (Sennerby-Forsse and Johansson 1989). On the nitrogen-rich site, the effect of increasing nitrogen fertilizer amount was less pronounced than on the site containing less nitrogen. Similarly, yields produced by mere PK fertilization were higher at the nitrogen-rich, and phosphorus and potassium-poor Paloneva than at Piipsanneva. These results suggest that although nitrogen fertilization is necessary, the need for nitrogen fertilization on nitrogen-rich sites is lower than on nitrogen-poor sites (Hytönen 1987).

Increasing the annual phosphorus fertilizer application rate over 15 kg/ha did not increase yields on any of the sites. Similarly, in the Swedish instructions for practical energy forestry, annual phosphorus fertilization amounts of 15–40 kg/ha are recommended after the planting year, depending on soil type (Sennerby-Forsse and Johansson 1989). Although the remaining peat on cut-away peatlands has a low potassium concentration, potassium fertilization did not increase the yield of willow. The reason for this could be in the basic potassium fertilization prior to the establishment of the experiments. However, potassium fertilization does increase potassium concentrations in the soil and the foliage.

Low biomass production during the first growing season and considerable increase in growth during the following years have been observed in many studies (Hytönen 1982, 1985, 1987, 1988, Lumme et al. 1984, Lehtonen and Tikkanen 1986, Nilsson et al. 1987). Increasing the rotation causes more biomass to be allocated to above-ground parts. The mean annual leafless biomass production of NPK-fertilized *S. x dasyclados* was higher than that of *S.* 'Aquatica'. The leafless biomass yield of three-years-old willow in southern Finland have been much higher (Ferm 1985, Hytönen 1988). Early summer frosts caused some damage, especially to *S.* 'Aquatica', which is frequently susceptible to winter damage in the study area (Lumme et al. 1984, Lumme and Törmälä 1987, Hytönen 1982, 1986) and probably also decreased biomass production (Ericsson et al. 1983, Christersson et al. 1984, Lumme et al. 1984, Hytönen 1986).

## ACKNOWLEDGEMENTS

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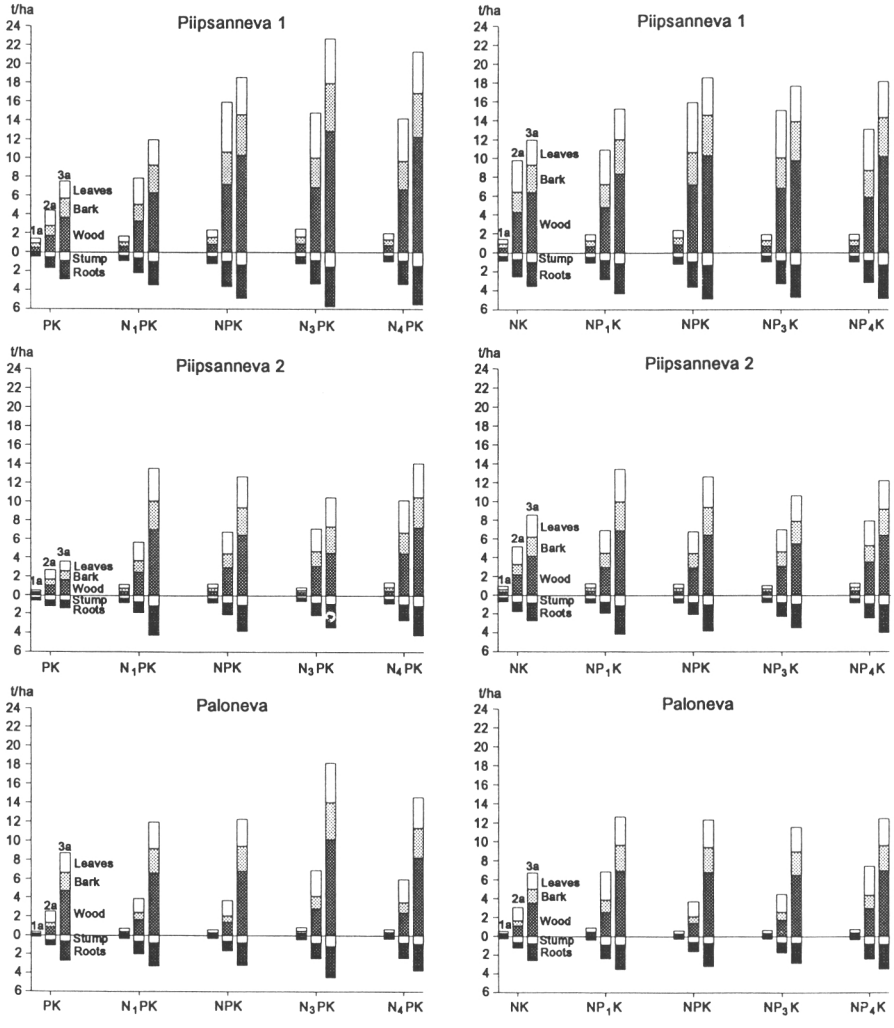
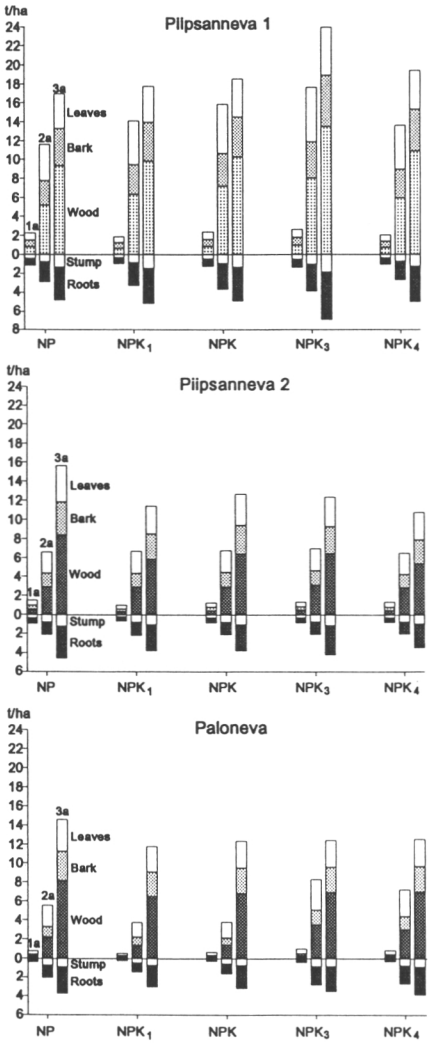



Fig. 6. Effect of fertilizer application rate on the dry-mass yield of willows. Age of willows from one to three years. For nutrient amounts applied, see Figure 2.

*Kuva 6. Lannoitemäärän vaikutus pajujen biomassatuotokseen. Pajujen ikä yhdestä kolmeen vuoteen. Selitykset kuvassa 2.*

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TIIVISTELMÄ:
LANNOITEMÄÄRÄN VAIKUTUS LYHYTKIERTOVILJELMIEN RAVINNETILAAN JA BIOMASSATUOTOKSEEN SUONPOHJILLA

Kolmessa kenttäkokeessa tutkittiin Haapaveden Piipsannevan (64°06', 25°36'E) ja Ruukin Palonevan (64°27'N, 25°26'E) kalkituilla turvetuotannosta vapautuneilla suonpohjilla typpi-, fosfori-, ja kaliumlannoitemäärän vaikutusta vanne- (*Salix x dasyclados*) ja vesipajuviljelmien (*Salix 'Aquatica'*) tuotokseen kolmen vuoden aikana. Lannosmäärän muuttuessa yhden ravinteen osalta kahden muun ravinteen määrät olivat keskimmäisellä tasolla (N 100, P 30 ja K 40 kg/ha). Kokeilta määritettiin maan happamaan ammoniumasetaattiin uuttuvien ravinteiden pitoisuudet, pajujen lehtien ravinnepitoisuudet ja lehtien, kuoren, puuaineen, kannon sekä juurien kuivamassa.

Fosfori- ja kaliumlannoitemäärien lisääminen kohotti vastaavien ravinteiden pitoisuutta turpeessa ja pajujen lehdissä sitä enemmän mitä enemmän ravinteita annettiin. Typpilannoitemäärän kasvu lisäsi pajujen lehtien typpitoisuutta.

Typpilannoituksen vaikutus ensimmäisenä kasvukautena oli vähäinen. Seuraavina vuosina pajujen kokonaistuotos oli korkein typpilannoitusmäärillä 100–150 kg/ha. Tulosten mukaan typpilannoitemäärä runsastyppisillä suonpohjilla voisi olla pienempi kuin vähätyppisillä suonpohjilla. Vaikka fosforilannoitus lisäsi pajujen kasvua, niin pienimmällä lannoitusmäärällä (15 kg P/ha) tuotos oli samantasoinen kuin suurimmalla lannoitusmäärällä (60 kg/ha). Kaliumlannoitus ei vaikuttanut pajujen tuotokseen ensimmäisenä kolmena kasvukautena. Toisen ja kolmannen kasvukauden vuotuinen tuotos oli moninkertainen ensimmäiseen kasvukauteen verrattuna. Suurimmillaan pajujen kokonaismassa oli kolmen vuoden iässä 28–30 t/ha. Tästä oli 44% puuta, 18% kuorta, 17% lehtiä, 16% juuria ja 5% kantoa. Vannepaju kasvoi paremmin kuin vesipaju. Talvivauriot, erityisesti vesipajulla, saattoivat alentaa pajujen biomassatuotosta.

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# IX

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

Jyrki Hytönen

**Hytönen, J.** 1995. Effect of repeated fertilizer application on the nutrient status and biomass production of *Salix* 'Aquatica' plantations on cut-away peatland areas. Silva Fennica 29(2): 107–116.

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

**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 |

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-

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

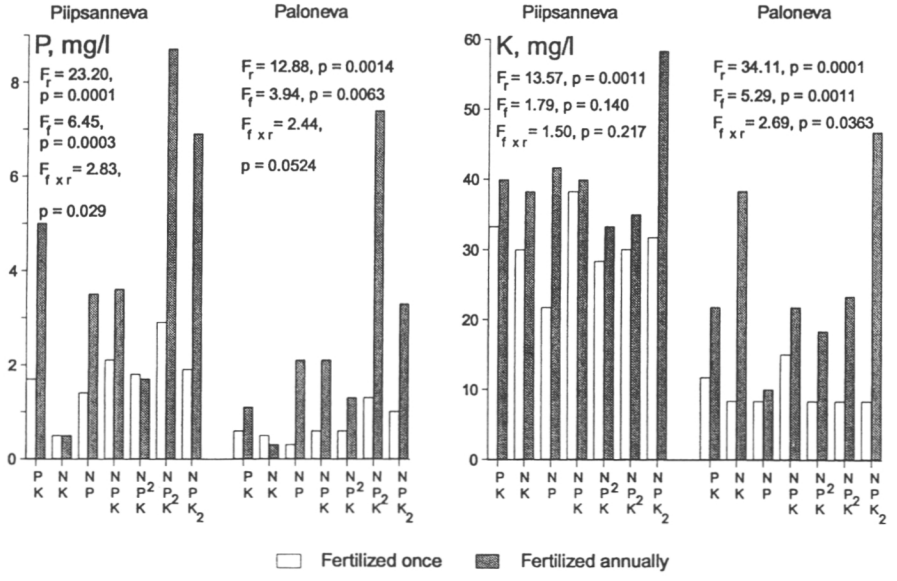


**Fig. 1.** Effect of fertilization on the concentrations of ammonium acetate extractable phosphorus and potassium in the soil. N = 100 kg N $ha^{-1}$, P = 30 kg P $ha^{-1}$, K = 40 kg K $ha^{-1}$, $N_2$ = 200 kg N $ha^{-1}$, $P_2$ = 60 kg P $ha^{-1}$, $K_2$ = 80 kg K $ha^{-1}$. Statistical significance (F and p values) of repetition of fertilization ($F_r$), fertilizer treatment ($F_t$) and their interaction ($F_{rxt}$) 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 | Fertilization treatment PK | NK | NP | NPK | $N_2PK$ | $NP_2K$ | $NPK_2$ | $F_{fert.}$[1)] | $F_{repeat}$ | $F_{fxr}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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.

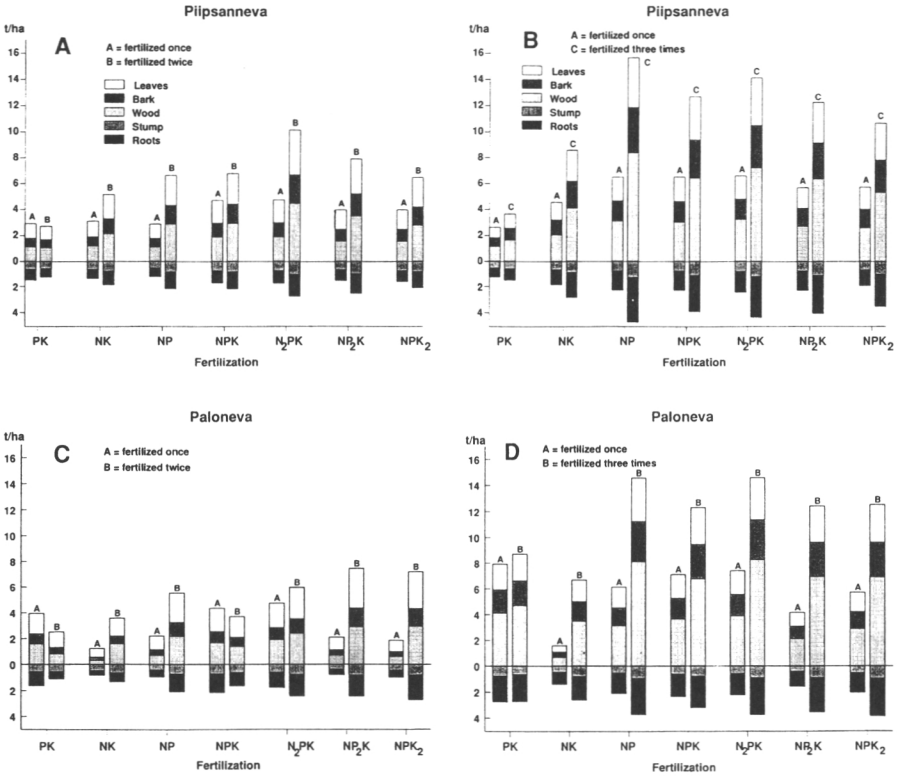


**Fig. 2.** Effect of fertilization on the biomass production of willow. The willow shown in A and C is two years, and in B and D three years old. For nutrient amounts applied, see Fig. 1.

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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