AGRICULTURAL AND FOOD SCIENCE IN FINLAND

Non-wood plants as raw material for pulp and paper

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ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Agriculture and Forestry, University of Helsinki, for public criticism at Infokeskus Korona, Auditorium 1, on November 30, 2001, at 12 o'clock.

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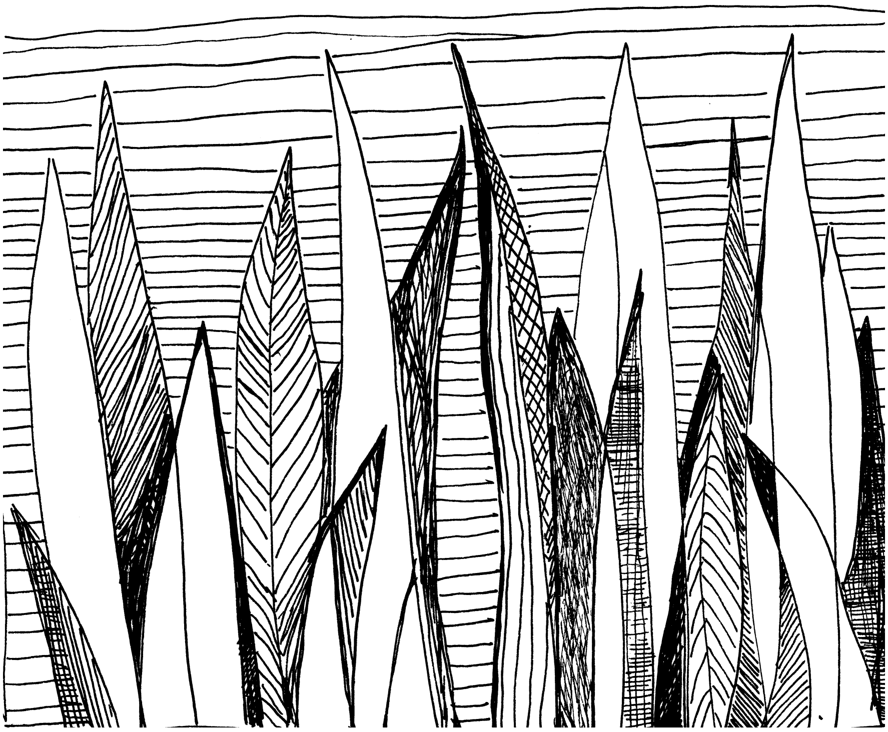

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> "A new fiber crop must fit the technical requirements for processing into pulp of acceptable quality in high yield and must also be adaptable to practical agricultural methods and economically produce high yield of usable dry matter per acre".
>
> Nieschlag et al. (1960)

Preface

The present study was carried out at the MTT Agrifood Research Finland between 1990 and 2000. I wish to extend my gratitude to the Directors of the Crop Science Department, Professor Emeritus Timo Mela and his successor Professor Pirjo Peltonen-Sainio for offering me the financial and institutional framework in which to do this research. The encouragement and friendly support of Professor Pirjo Peltonen-Sainio made it possible to complete this thesis. I also wish to thank Professor Pirjo Mäkelä, for her contribution during the last stages of the work. I am also grateful to Professor Eija Pehu, the former teacher of my subject at the University of Helsinki for her suggestion to work for this thesis.

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Jokioinen, October 2001 *Katri Saijonkari-Pahkala*

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List of abbreviations

AAS	flame atomic absorption spectrometer
CSF	Canadian standard of freeness, measure of drainage
CWT	cell wall thickness
DM	dry matter
ICP	inductively coupled plasma spectrometry
KCL	The Finnish Pulp and Paper Research Institute
LW	length weightened fibre length
NPK	nitrogen-phosphorus-potassium
RCG	reed canary grass
TAPPI	Technical Association of the Pulp and Paper Industry

Glossary of technical terms

Black liquor	The waste liquor from the kraft pulping process after pulping containing inorganic elements and dissolved organic material from raw material.
Bleaching	A treatment of pulps with chemical agents to increase pulp brightness.
Brightness	A term for describing the whiteness of pulp or paper on scale from 0% (black) to 100%. MgO standard has an absolute brightness of about 96%.
Coarseness	Oven-dry mass of fibre per unit length of fibre mg m^{-1}.
CWT index	Cell wall thickness index is indexed value of cell wall thickness measured by the Kajaani FiberLab Analyzer.
Delignification	A process of breaking down the chemical structure of lignin and rendering it soluble in an alkaline liquid.
Dicotyledon	Plants with two cotyledons.
Drainage	Drainage is ease of removing water from pulp fibre slurry.
Fibre	Plant fibres are composed of sclerenchyma cells with narrow, elongated form with lignified walls.
Fibre length	The average fibre length is a statistical average length of fibres in pulp measured microscopically or by optical scanner (number average) or classification with screens (weight average). The weight average fibre length (LW) is equal or larger than the number average fibre length (NW).
Fines	Small particles other than fibres found in pulps. They originate from different vessel elements, tracheids, parenchyma cells, sclereids and epidermis.
Hardwood	Wood produced by deciduous trees.
Kappa number	A measure of lignin content in pulp. Higher kappa numbers indicate higher lignin content.

Monocotyledons	Plants with one cotyledon, for example grass plants.
Opacity	The ability of paper to hide or mask a color or object in back of the sheet. High opacity results in less transparency and it is important in printing papers.
Paper	Paper consists of a web of pulp fibres originated from wood or other plants from which lignin and other non-cellulosic components are separated by cooking them with chemicals in high temperature. Fine paper is intended for writing, typing, and printing purposes.
Pulp	An aggregation of the cellulosic fibres liberated from wood or other plant materials physically and/or chemically such that discrete fibres can be dispersed in water and reformed into a web.
Pulping	A process whereby the fibres in raw material are separated with chemicals or by mechanical treatment
Pulp viscosity	A measure of the average chain length of cellulose (the degree of polymerization). Higher viscosity indicates stronger pulp and paper.
Pulp yield	The amount of material (% of dry matter) recovered after pulping compared to the amount of material before the process.
Recovery of pulping chemicals	A process in which the inorganic chemicals used in pulping are recovered and regenerated for reuse.
Residual alkali	The level of residual alkali after completion of cooking determines the final pH of the liquor. If pH is much lower than 12, it indicates lignin deposition in pulp.
Screenings	Unsufficiently delignified material retained on a Serla Screen laboratory screen with for example 0.25 mm slots.
Softwood	Wood produced by conifers.
Stiffness	Stiffness tests measure how paper resist the bending when handled.
Tear	The energy required to propagate an initial tear through several sheets of paper for a fixed distance. The value is reported in g-cm/sheet.
Tensile strength of paper	A measure of the hypothetical length of paper that just supports its own weight when supported at one end. It is measured on paper strips 20 cm long by 15–25 mm wide.

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This study was begun in 1990 when there was a marked shortage of short fibre raw material for the pulp industry. During the last ten years the situation has changed little, and the shortage is still apparent. It was estimated that 0.5 to 1 million hectares of arable land would be set aside from cultivation in Finland during this period. An alternative to using hardwoods in printing papers is non-wood fibres from herbaceous field crops.

The study aimed at determining the feasibility of using non-wood plants as raw material for the pulp and paper industry, and developing crop management methods for the selected species. The properties considered important for a fibre crop were high yielding ability, high pulping quality and good adaptation to the prevailing climatic conditions and possibilities for low cost production. A strategy and a process to identify, select and introduce a crop for domestic short fibre production is described in this thesis.

The experimental part of the study consisted of screening plant species by analysing fibre and mineral content, evaluating crop management methods and varieties, resulting in description of an appropriate cropping system for large-scale fibre plant production. Of the 17 herbaceous plant species studied, monocotyledons were most suitable for pulping. They were productive and well adapted to Finnish climatic conditions. Of the monocots, reed canary grass (*Phalaris arundinacea* L.) and tall fescue (*Festuca arundinacea* Schreb.) were the most promising. These were chosen for further studies and were included in field experiments to determine the most suitable harvesting system and fertilizer application procedures for biomass production.

Reed canary grass was favoured by delayed harvesting in spring when the moisture content of the crop stand was 10–15% of DM before production of new tillers. When sown in early spring, reed canary grass typically yielded 7–8 t ha^{-1} within three years on clay soil. The yield exceeded 10 t ha^{-1} on organic soil after the second harvest year. Spring harvesting was not suitable for tall fescue and resulted in only 37–54% of dry matter yields and in far fewer stems and panicles than harvested during the growing season.

The economic optimum for fertilizer application rate for reed canary grass ranged from 50 to 100 kg N ha^{-1} when grown on clay soil and harvested in spring. On organic soil the fertilizer rates needed were lower. If tall fescue is used for raw material for paper, fertilizer application rates higher than 100 kg N ha^{-1} were not of any additional benefit.

It was possible to decrease the mineral content of raw material by harvesting in spring, using moderate fertilizer application rates, removing leaf blades from the raw material and growing the crop on organic soil. The fibre content of the raw material increased the later the crop was harvested, being highest in spring. Removing leaf blades and using minimum fertilizer application rates increased the fibre content of biomass.

Key words: field crop, dry matter yield, harvest, fertilizer, mineral content, fibre, pulping, papermaking, reed canary grass, *Phalaris arundinacea,* tall fescue, *Festuca arundinacea*

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1 Introduction

Paper consists of a web of pulp fibres derived from wood or other plants from which lignin and other non-cellulose components are separated by cooking them with chemicals at high temperature. In the final stages of papermaking an aqueous slurry of fibre components and additives is deposited on a wire screen and water is removed by gravity, pressing, suction and evaporation (Biermann 1993). The fibre properties of the raw material affect the quality and use of the paper. For fine papers, both long and short fibres are needed. The long fibres from softwoods (coniferous trees, fibre length 2–5 mm) or from non-woody species such as flax (*Linum usitatissimum* L.), hemp (*Cannabis sativa* L.) and kenaf (*Hibiscus cannabinus* L.), of fibre length 28 mm, 20 mm and 2.7 mm, respectively, form a strong matrix in the paper sheet. The shorter hardwood fibres (deciduous trees, fibre length 0.6–1.9 mm) or grass fibres (fibre length 0.7 mm) (Hurter 1988) contribute to the properties of pulp blends, especially opacity, printability and stiffness. In fine papers, short-fibre pulp contributes to good printability. The principal raw material for papermaking nowadays is wood derived from various tree species.

The main domestic raw materials for fine paper are the hardwood birch (*Betula* spp.) and softwood conifers, usually spruce (*Picea abies* L.) and Scots pine (*Pinus silvestris* L.). Birch pulp in fine paper accounts for more than 60% of all fibre material. However, birch contributes less than 10% to the total forested area in Finland (Aarne 1993, Tomppo et al. 1998). The principal tree species are spruce and Scots pine. The importation of birch for the Finnish paper industry increased during the 1990s from 3.5 to 6.5 million/m^3 and currently exceeds consumption of domestic hardwood (Sevola 2000). One alternative to using birch for printing papers is to use non-wood fibres from herbaceous field crops, as are used in many countries where wood is not available in sufficient quantities. Promising non-woody species for fibre production have been found in the plant families *Gramineae, Leguminosae* and *Malvaceae* (Nieschlag et al. 1960). Of these, most attention in recent years has been focused on grasses and other monocotyledons (Kordsachia et al. 1992, Olsson et al. 1994) as well as on flax and hemp (van Onna 1994). During the beginning of the 1990s, the MTT Agrifood Research Finland and the University of Helsinki, together with the Finnish Pulp and Paper Research Institute, set out to identify the most promising crop species as raw materials for papermaking. The properties considered important were fibre yield and quality and the mineral composition of the plant material. In those studies, reed canary grass (*Phalaris arundinacea* L.), tall fescue (*Festuca arundinacea* Schreb.), meadow fescue (*F. pratensis* L.), goat's rue (*Galega orientalis* L.) and lucerne (*Medicago sativa* L.) were chosen for further study. Field experiments were conducted to determine the optimal harvesting system and fertilizer requirements for biomass production (Pahkala et al. 1994).

During the preliminary stages an intensive research and development programme was begun, covering the entire processing chain, from raw material production to the end product. The aim of this agrofibre project, named "Agrokuidun tuotanto ja käyttö Suomessa – Agrofibre production for pulp and paper" was to develop economically feasible methods for producing specific short-fibre raw material from field crops available in Finland and process it for use in high quality paper production. The project included five components and was carried out between 1993 and 1996. The Ministry of Agriculture and Forestry of Finland financed the project. The five components were:

1. Crop production (crop species, management methods and variety research):
   MTT (Agrifood Research Finland) and University of Helsinki
2. Technology (harvesting, pretreatment, storage methods and production costs):
   MTT, University of Helsinki and Work Efficiency Association

3. Pulp cooking and quality (cooking and bleaching methods):
   KCL (The Finnish Pulp and Paper Research Institute) and Åbo Akademi University
4. Pretreatment of raw material (biotechnological pretreatment and by-products):
   University of Helsinki and VTT (Technical Research Centre of Finland)
5. Paper processing (recycling of chemicals, environmental influences, technological potential of non-wood fibres, logistics and economic analysis): Jaakko Pöyry Oy

Methods developed in the project were applied in September 1995, when bleached reed canary grass pulp was produced on a pilot scale (Paavilainen et al. 1996a). The pulp was mixed with pine pulp and made into paper on the pilot paper machine of KCL. The printability of coated and uncoated agro-based fine paper was tested in offset printing.

The present study describes the crop production experimentation of the agrofibre project outlined above. The aim was to determine the suitability of field crops as raw material for the pulp and paper industry, and to develop crop management methods for the selected species. The experimental part of the study consisted of screening the plant species by analysing fibre and mineral content, and evaluation of crop management methods and varieties. The outcome was description of an appropriate cropping system for large-scale fibre plant production.

2 Review of relevant literature on papermaking from field crops

2.1 Global production of non-wood pulp and paper

The earliest information on the use of non-woody plant species as surfaces for writing dates back to 3000 BC in Egypt, where the pressed pith tissue of papyrus sedge (*Cyperus papyrus* L.) was the most widely used writing material. Actual papermaking was discovered by a Chinese, Ts'ai Lun, in AD 105, when he found a way of making sheets using fibres from hemp rags and mulberry (*Morus alba* L.). Straw was used for the first time as a raw material for paper in 1800, and in 1827 the first commercial pulp mill began operations in the USA using straw (Atchison and McGovern 1987). In the 1830s, Anselme Payen found a resistant fibrous material that existed in most plant tissues. This was termed cellulose by the French Academy in 1839 (Hon 1994). After the invention of new chemical pulping methods paper could also be made from wood. This became the main raw material for paper production in the 20th century.

In many countries wood is not available in sufficient quantities to meet the rising demand for pulp and paper (Atchison 1987a, Judt 1993). In recent years, active research has been undertaken in Europe and North America to find a new, non-wood raw material for paper production. The driving force for searching for new pulp sources was twofold: the shortage of short-fibre raw material (hardwood) in Nordic countries, which export pulp and paper and, parallel overproduction of agricultural crops. At the same time, the consumption of paper, especially fine paper, continued to grow, increasing the demand for short fibre pulp (Paavilainen 1996).

Commercial non-wood pulp production has been estimated to be 6.5% of the global pulp production and is expected to increase (Paavilainen 1998). China produces 77% of the world's non-wood pulp (Paavilainen et al. 1996b, Paavilainen 1998) (Fig. 1). In China and India over 70 % of raw material used by the pulp industry

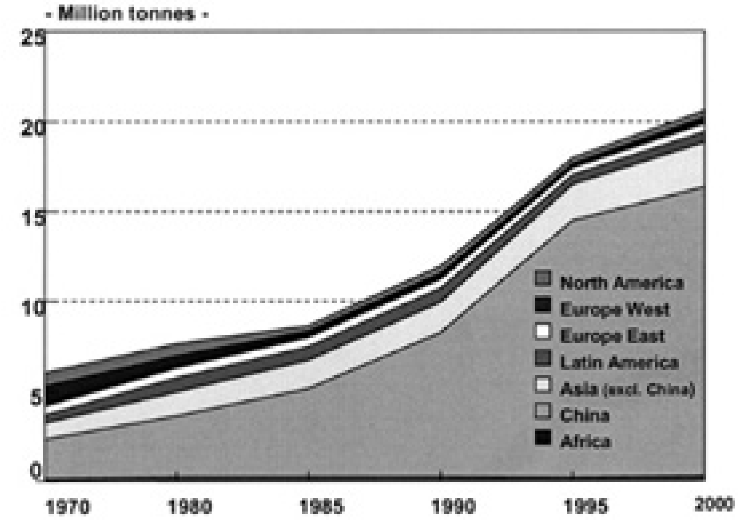


Fig. 1. Global production of non-wood pulps. The figure reprinted with kind permission from Leena Paavilainen. Translated from Paavilainen et al. (1996b).

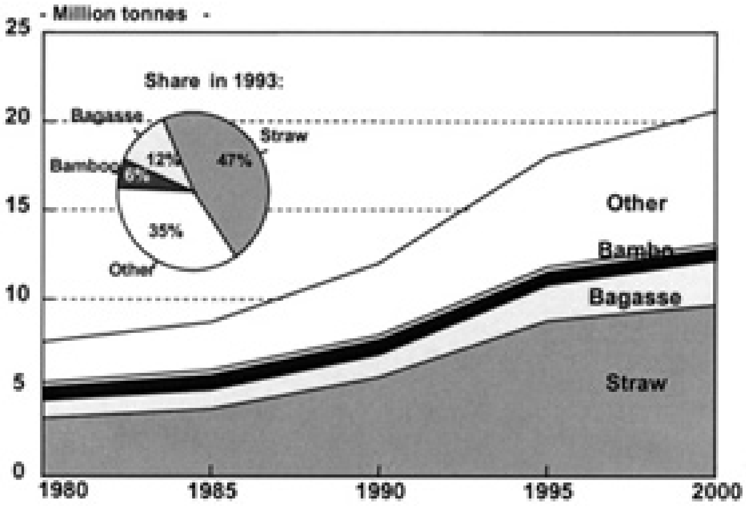


Fig. 2. Consumption of non-wood pulps in paper production from different raw materials. The figure reprinted with kind permission from Leena Paavilainen. Translated from Paavilainen et al. (1996b).

comes from non-woody plants (Fig. 1). The main sources of non-wood raw materials are agricultural residues from monocotyledons, including cereal straw and bagasse, a fibrous residue from processed sugar cane (*Saccharum officinarum* L.) (Fig. 2). Bamboo, reeds and some grass plants are also grown or collected for the pulp industry (Paavilainen et al. 1996b).

The main drawbacks that are considered to limit the use of non-wood fibres are certain difficulties in collection, transportation and storage (McDougall et al. 1993, Ilvessalo-Pfäffli 1995). However, data from Finland show that the transport costs of grass fibre are not critical for the raw material production chain, where they constitute only 14% of the total costs (Hemming et al. 1996). In the case of grass fibres, the high content of silicon (Ilvessalo-Pfäffli 1995) impliess extra costs, as it wears out factory installations (Watson and Gartside 1976), lowers pa-

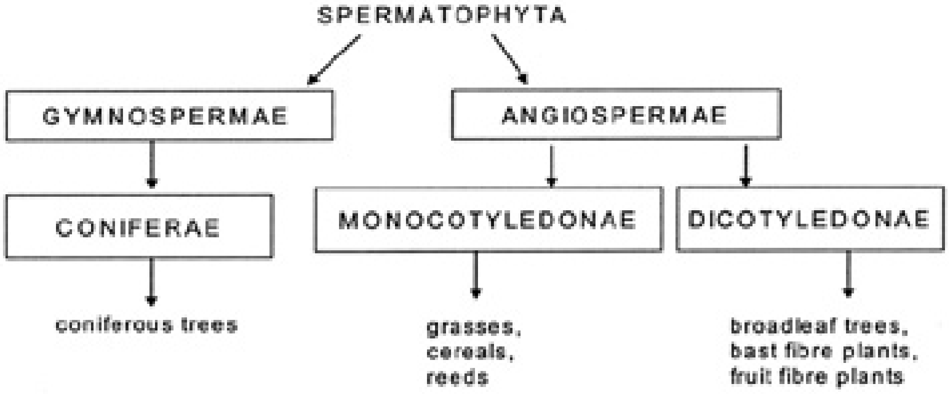


Fig. 3. The taxonomy of fibre plants. Adapted from Ilvessalo-Pfäffli (1995).

per quality (Jeyasingam 1988) and complicates recovery of chemicals and energy in papermaking (Ranua 1977, Keitaanniemi and Virkola 1982, Ulmgren et al. 1990).

2.2 Candidate non-wood plant species for papermaking

Plant species currently used for papermaking belong to the botanical division Spermatophyta (seed plants), which is divided into two divisions, *Angiospermae* (seeds enclosed within the fruit) and *Gymnospermae* (naked seeds), the latter including the class *Coniferae. Angiospermae* include two classes, *Monocotyledonae* and *Dicotyledonae* (Fig. 3). The most common plant species used for papermaking are coniferous trees of the *Gymnospermae* and deciduous trees of the *Dicotyledonae.* Non-wood papermaking plants, such as grasses and leaf fibre plants, belong to the class *Monocotyledonae* and bast fibre and fruit fibre plants are dicotyledons (Ilvessalo-Pfäffli 1995).

Promising new non-wood species for fibre production have been identified in earlier research on the plant families *Gramineae, Leguminosae* and *Malvaceae* (Nieschlag et al. 1960, Nelson et al. 1966). In northern Europe particular interest in recent years has focused on grasses and other monocotyledons (Olsson 1993, Mela et al. 1994). Of several field crops studied, reed canary grass has been one of the most promising species for fine paper production in Finland and Sweden (Berggren 1989, Paavilainen and Torgilsson 1994). Other grasses, such as tall fescue (*Festuca arundinacea* Schr.) (Janson et al. 1996a), switchgrass (*Panicum virgatum* L.) (Radiotis et al. 1996) and cereal straw (Atchison 1988, Lönnberg et al. 1996) can be used for paper production. In central Europe, elephant grass (*Miscanthus sinensis* Anderss.) has been studied as a raw material for paper and energy production (Walsh 1997).

A new fibre crop must fit the technical requirements for processing into pulp of acceptable quality. It must also be adaptable to practical agricultural methods and produce adequate dry matter (DM) and fibre yield at economically attractive levels (Nieschlag et al. 1960, Atchison 1987b). There must also be a sufficient supply of good quality raw material for running the process throughout the year (Atchison 1987b). It has been shown that non-wood species have high biomass production capacity and the pulp yields obtained have in most cases been higher than those from wood species (Table 1).

Table 1. Annual dry matter (DM) and pulp yields of various fibre plants.

Plant species	DM yield t ha^{-1}	Pulp yield t ha^{-1}	Reference
Wheat straw	$^{1)}$2.5	$^{2)}$1.1	FAO 1995, Pahkala et al. 1994
Oat straw	$^{1)}$1.6	$^{2)}$0.7	FAO 1995, Pahkala et al. 1994
Rye straw	$^{1)}$2.2	$^{2)}$1.1	FAO 1995, Pahkala et al. 1994
Barley straw	$^{1)}$2.1	$^{2)}$1.9	FAO 1995, Pahkala et al. 1994
Rice straw	3	$^{3)}$1.2	Paavilainen & Torgilsson 1994
Bagasse (sugar cane waste)	9	$^{3)}$4.2	Paavilainen & Torgilsson 1994
Bamboo	4	$^{3)}$1.6	Paavilainen & Torgilsson 1994
Miscanthus sinensis	12	$^{3)}$5.7	Paavilainen & Torgilsson 1994
Reed canary grass	6	$^{3)}$3.0	Paavilainen et al. 1996b, Pahkala et al. 1996
Tall fescue	8	$^{2)}$3.0	Pahkala et al. 1994
Common reed	9	$^{2)}$4.3	Pahkala et al. 1994
Kenaf	15	$^{3)}$6.5	Paavilainen & Torgilsson 1994
Hemp	12	$^{3)}$6.7	Paavilainen & Torgilsson 1994
Temperate hardwood (birch)	3.4	$^{3)}$1.7	Paavilainen & Torgilsson 1994
Fast growing hardwood (eucalyptus)	15.0	$^{3)}$7.4	Paavilainen & Torgilsson 1994
Scandinavian softwood (coniferous)	1.5	$^{3)}$0.7	Paavilainen & Torgilsson 1994

1) The dry matter yield for cereal straw is estimated by using the harvest index of 0.5.
2) Pulp process soda-anthraquinone
3) Average values, pulping method unmentioned

2.3 Properties of non-wood plants as raw material for paper

Analysis of fibre morphology and chemical composition of plant material has been useful in searching for candidate fibre crops. This has afforded an indication of the papermaking potential of various species (Muller 1960, Clark 1965). The properties of the fibre depend on the type of cells from which the fibre is derived, as the chemical and physical properties are based on the cell wall characteristics (McDougall et al. 1993). Anatomically, plant fibres are composed of narrow, elongated sclerenchyma cells. Mature fibres have well-developed, usually lignified walls and their principal function is to support, and sometimes to protect the plant. Fibres develop from different meristems (Fig. 4), and they are found mostly in the vascular tissue of the plant, but sometimes also occur in other tissues (Esau 1960, Fahn 1974).

2.3.1 Fibre morphology in non-wood plants used in papermaking

Morphological characteristics, such as fibre length and width, are important in estimating pulp quality of fibres (Wood 1981). In fibres suitable for paper production, the ratio of fibre length to width is about 100:1, whereas in textile fibres the ratio is more than 1000:1. In coniferous trees this ratio is 60–100:1, and in deciduous trees 2–60:1 (Hurter 1988, Hunsigi 1989, McDougall et al. 1993). Fibre length and width of non-woody species vary depending on plant species and the plant part from which the fibre is derived (Ilvessalo-Pfäffli 1995). The average fibre length ranges from 1 mm to 30 mm, being shortest in grasses and longest in cotton. The average ratios of fibre length to diameter range from 50:1 to 1500:1 in non-wood species (Table 2) (Hurter 1988). Lumen size and cell wall thickness affect the rigidity and strength of the papers made from the fibres. Fibres with a large

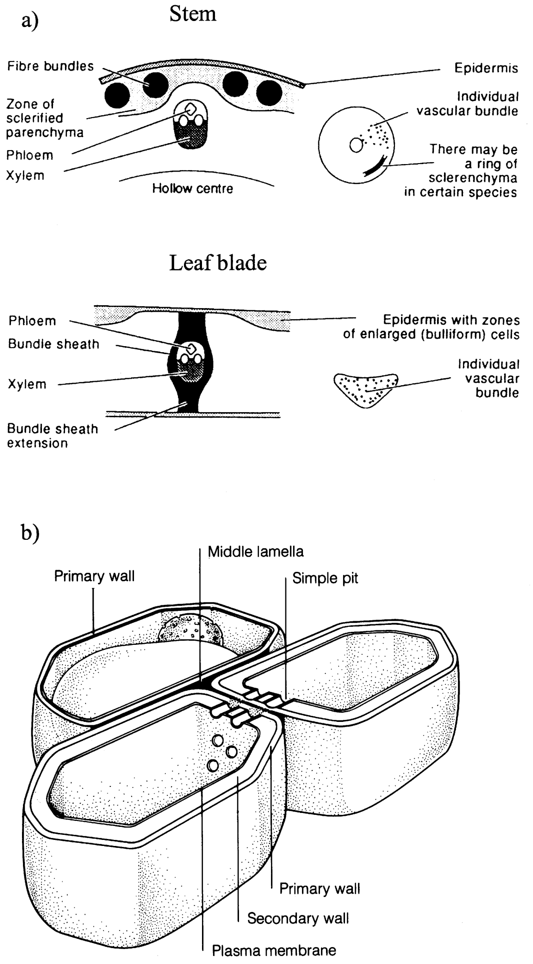


Fig. 4. Schematic representation of a) the location of fibres in stem and leaves of monocotyledonous plants (McDougal et al. 1993), reprinted with kind permission of John Wiley & Sons Ltd and b) primary and secondary cell walls (Taiz and Zeiger 1991).

lumen and thin walls tend to flatten to ribbons during pulping and papermaking, giving good contact between the fibres and consequently having good strength characteristics (Wood 1981). Softwood fibres from coniferous trees are ideal for papermaking since their long, flexible structure allows the fibres to pack and reinforce the sheets. Hardwoods from deciduous trees have shorter, thinner and flexible fibres that pack tightly together and thus produce smooth and dense paper (Hurter 1988, Fengel and Wegener 1989, McDougall et al. 1993).

Non-wood plant fibres can be divided into several groups depending on the location of the fibres in the plant. Ilvessalo-Pfäffli (1995) has described four fibre types: grass fibres, bast fibres, leaf fibres and fruit fibres. Grass fibres are also termed stalk or culm fibres (Hurter 1988, Judt 1993) (Table 2).

Grass fibres

Grass fibres currently used for papermaking are obtained mainly from cereal straw, sugarcane, reeds and bamboo (Atchison 1988). The fibre material of these species originates from the xylem in the vascular bundles of stems and leaves. It also occurs in separate fibre strands, which are situated on the outer sides of the vascular bundles or form strands or layers that appear to be independent of the vascular tissues (Esau 1960, McDougall et al. 1993, Ilvessalo-Pfäffli 1995). Vascular bundles can be distributed in two rings as in cereal straw and in most temperate grasses, with a continuous cylinder of sclerenchyma close to the periphery. The bundles can also be scattered throughout the stem section as in corn (*Zea mays* L.), bamboo and sugarcane (Esau 1960). The average length of grass fibres is 1–3 mm (Robson and Hague 1993, Ilvessalo-Pfäffli 1995) and the ratio of fibre length to width varies from 75:1 to 230:1 (Table 2) (Hurter 1988).

Wheat (*Triticum aestivum* L.) is the monocotyledon that is used most in commercial pulping. However, fibres from rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) are similar to those of wheat (Ilvessalo-Pfäffli 1995) and they could also be used in papermaking. Rice straw (*Oryza sativa* L.) is used in Asia and Egypt. Bagasse is one of the most important agricultural residues used for pulp manufacture. Bagasse pulp is used for all grades of papers (Atchison 1987b). Some reeds (*Phragmites communis* Trin., *Arundo donax* L.) are collected and used in mixtures with other fibres in Asia and in South America as raw material for writing and printing papers. In the case of esparto (*Stipa tenecissima* L.), only leaves are used, whereas bamboo pulp is commonly made from the pruned stem and bagasse pulp from sugarcane waste. When grass species are pulped for papermaking, the entire plant is usually used and the pulp contains all the cellular elements of the plant (Ilvessalo-Pfäffli 1995). The proportion of fibre cells in commercial grass pulp can be 65 to 70% by weight (Gascoigne 1988, Ilvessalo-Pfäffli 1995). In addition to fibre cells, the grass pulp also contains small particles (fines) from different vessel elements, tracheids, parenchyma cells, sclereids and epidermis, which make the grass pulp more heterogeneous than wood pulp, in which all the fibres originate from the stem xylem. Most of the fines lower the drainage of the pulp and thus the drainage time in papermaking is longer (Wisur et al. 1993). However, the amount of fines decreases if the leaf fraction, the main source of the fines, can be restricted to only the straw component of the grass.

Bast fibres

Bast fibres refer to all fibres obtained from the phloem of the vascular tissues of dicotyledons (TAPPI Standard T 259 sp-98 1998). Fibre cells occur in strands termed fibres (Esau 1960, Ilvessalo-Pfäffli 1995). Hemp, kenaf, ramie (*Boechmeria nivea* L.) and jute (*Corchorus capsularis* L.) fibres are derived from the secondary phloem located in the outer part of the cambium. In flax, fibres are mainly cortical fibres in the inner bark, on the outer periphery of the vascular cylinder of the stem (Esau 1960, McDougall et al. 1993, Ilvessalo-Pfäffli 1995). In these plants the length of the fibre cells varies from 2 mm (jute) to 120 mm (ramie) (Esau 1960, Ilvessalo-Pfäffli 1995). Flax fibres consist of up to 40 fibres in bundles of 1 m length. Hemp fibres are coarser than those of flax, with up to 40 fibres in bundles that can be 2 m in length (McDougall et al. 1993). Bast fibres must be isolated from the stem by retting whereby micro-organisms release enzymes that digest the pectic material surrounding the fibre bundles, thus freeing the fibres. With ramie, boiling in alkali is required (McDougall et al. 1993). Bast fibres are used as raw material for paper when strength, permanence and other special properties are needed. Examples include lightweight printing and writing papers, currency and cigarette papers (Atchison 1987b, Kilpinen 1991, Ilvessalo-Pfäffli 1995).

Leaf fibres

Leaf fibres are obtained from leaves and leaf sheaths of several monocotyledons, tropical and subtropical species (McDougall et al. 1993, Ilvessalo-Pfäffli 1995). Strong Manila hemp, or acaba, is derived from leaf sheaths of *Musa textilis* L., and is mainly used in cordage and for making strong but pliable papers. Sisal is produced from vascular bundles of several species in the genus *Agave,* notably *A. sisalana* Perrine (true sisal) and *A. foucroydes* Lemaire (henequen) (McDougall et al. 1993). Leaves of esparto grass produce a fibre used to make soft writing papers (McDougall et al. 1993).

Fruit fibres

Fruit fibres are obtained from unicellular seed or fruit hairs. The most important is cotton fibre, formed by the elongation of individual epidermal hair cells in seeds of various *Gossypium* species (McDougall et al. 1993). The longest fibres of cotton (lint) are used as raw material for the textile industry, but the shorter ones (linters, 2–7 mm long), as well as textile cuttings and rags, are used as raw material for the best writing and drawing papers (Ilvessalo-Pfäffli 1995). Kapok is a fibre produced from fruit and seed hairs of two members of the family *Bombaceae: Eriodendron anfractuosum* DC. (formerly *Ceiba pentandra* Gaertn.) produces Java kapok and *Bombax malabaricum* DC. produces Indian kapok. Kapok fibres originate from the inner wall of the seed capsule. The cells are relatively long, up to 30 mm, with thin and highly lignified walls and a wide lumen (McDougall et al. 1993).

Table 2. Dimensions of fibres obtained from non-wood species. L = fibre length, D = fibre diameter, L:D = ratio fibre length to fibre diameter (Hurter 1988).

	Fibre length µm (L)			Fibre diameter µm (D)			L:D-
Source of fibres	Max.	Min.	Average	Max.	Min.	Average	ratio
Stalk fibres (grass fibres)							
Cereals -rice	3480	650	1410	14	5	8	175:1
-wheat, rye, oats, barley, mixed	3120	680	1480	24	7	13	110:1
Grasses -esparto	1600	600	1100	14	7	9	120:1
-sabai	4900	450	2080	28	4	9	230:1
Reeds -papyrus	8000	300	1500	25	5	12	125:1
-common reed	3000	100	1500	37	6	20	75:1
-bamboo	3500–9000	375–2500	1360–4030	25–55	3–18	8–30	135–175:1
-sugar cane (bagasse)	2800	800	1700	34	10	20	85:1
Bast fibres							
Fibre flax	55000	16000	28000	28	14	21	1350:1
Linseed straw	45000	10000	27000	30	16	22	1250:1
Kenaf	7600	980	2740		20		135:1
Jute	4520	470	1060	72	8	26	45:1
Hemp	55000	5000	20000	50	16	22	1000:1
Leaf fibres							
Acaba	12000	2000	6000	36	12	20	300:1
Sisal	6000	1500	3030		17		180:1
Fruit or seed fibres							
Cotton	50000	20000	30000	30	12	20	1500:1
Cotton linters	6000	2000	3500	27	17	21	165:1
Wood fibres							
Coniferous trees	3600	2700	3000	43	32	30	100:1
Leaf trees	1800	1000	1250	50	20	25	50:1

2.3.2 Chemical composition

Chemical composition of the candidate plant gives an idea of how feasible the plant is as raw material for papermaking. The fibrous constituent is the most important part of the plant. Since plant fibres consist of cell walls, the composition and amount of fibres is reflected in the properties of cell walls (Hartley 1987, McDougall et al. 1993). Cellulose is the principal component in cell walls and in fibres. The non-cellulose components of the cell wall include hemicelluloses, pectins, lignin and proteins, and in the epidermal cells also certain minerals (Hartley 1987, Taiz and Zeiger 1991, Philip 1992, Cassab 1998). The amount and composition of the cell wall compounds differ among plant species and even among plant parts, and they affect the pulping properties of the plant material (McDougall et al. 1993). Some of non-woody fibre plants contain more pentosans (over 20%), holocellulose (over 70%) and less lignin (about 15%) as compared with hardwoods (Hunsigi 1989). They have also higher hot water solubility, which is apparent from the easy accessibility of cooking liquors. The low lignin content in grasses and annuals lowers the requirement of chemicals for cooking and bleaching (Hunsigi 1989).

Except for the fibrous material, plants also consist of other cellular elements, including mineral compounds. While the inorganic compounds are essential for plant growth and development

(Mitscherlich 1954, Epstein 1965, Marschner 1995), they are undesirable in pulping and papermaking (Keitaanniemi and Virkola 1978, Keitaanniemi and Virkola 1982, Jeyasingam 1985, Ilvessalo-Pfäffli 1995).

Cellulose

Cellulose is the principal component of plant fibres used in pulping. It forms the basic structural material of cell walls in all higher terrestrial plants being largely responsible for the strength of the plant cells (Philip 1992). Cellulose always has the same primary structure, it is a –1,4 linked polymer of D-glucans (Table 3) (Aspinall 1980, Smith 1993). It occurs in the form of long, linear, ribbon-like chains, which are aggregated into structural fibrils (Fig. 5). Each fibril contains from 30 to several hundred polymeric chains that run parallel with the laterally exposed hydroxyl groups. These hydroxyl groups take part in hydrogen bonding, with linkages both within the polymeric molecules and between them. This arrangement of the hydroxyl groups in cellulose makes them relatively unavailable to solvents, such as water, and gives cellulose its unusual resistance to chemical attack, as well as its high tensile strength (Philip 1992).

The first layers of cellulose are formed in the primary cell walls during the extension stage of the cell, but most cellulose is deposited in the secondary walls. The proportion of cellulose in primary cell walls is 20 to 30% of DM and in secondary cell walls 45 to 90% (Aspinall 1980). The cellulose content of a plant depends on the cell wall content, which can vary between plant species (Staniforth 1979, Hartley 1987, Hurter 1988) and varieties (Khan et al. 1977, Bentsen and Ravn 1984). The age of the plant (Gill et al. 1989, Grabber et al. 1991) and plant part (Petersen 1989, Grabber et al. 1991, Theander 1991) also affect the cellulose content. Annual plants generally have about the same cellulose content as woody species (Wood 1981), but their higher content of hemicellulose increases the level of pulp yield more than the expected level on the basis of cellulose content alone (Wood 1981). The cellulose and alpha-cellulose contents can be correlated with the yields of unbleached and bleached pulps, respectively (Wood 1981).

Hemicellulose

Hemicelluloses consist of a heterogeneous group of branched polysaccharides (Table 3). The specific constitution of the hemicellulose polymer depends on the particular plant species and on the tissue. Glucose, xylose and mannose often predominate in the structure of the hemicelluloses (Philip 1992), and are generally termed glucans, xylans, xyloglucans and mannans (Smith 1993). Xylans are the most abundant non-cellulose polysaccharides in the majority of angiosperms, where they account for 20 to 30% of the dry weight of woody tissues (Aspinall 1980). They are mainly secondary cell wall components, but in monocotyledons they are found also in the primary cell walls (Burke et al. 1974), representing about 20% of both the primary and secondary walls. In dicots they amount to 20% of the secondary walls, but to only 5% of the primary cell walls. Xylans are also different in monocots and in dicots (Smith 1993). In gymnosperms, where galactoglucomannans and glucomannans represent the major hemicelluloses, xylans are less abundant (8%) (Timell 1965). The hemicelluloses in secondary cell walls are associated with the aromatic polymer, lignin.

Pectins

Pectins, i.e. pectic polysaccharides, are the polymers of the middle lamella and primary cell wall of dicotyledons, where they may constitute up to 50% of the cell wall. In monocotyledons, the proportion of pectic polysaccharides is normally less than this and in secondary walls the proportion of hemicellulose polysaccharides greatly exceeds the amount of pectic polysaccharides (Smith 1993). The pectic substances are characterised by their high content of D-galacturonic acid and methylgalacturonic acid residues (Table 3). Pectins are more important in growing than in non-growing cell walls, and thus they are not a significant constituent in commercial fibres (Philip 1992) except in flax fibre, where pectins are found in lamellae between the

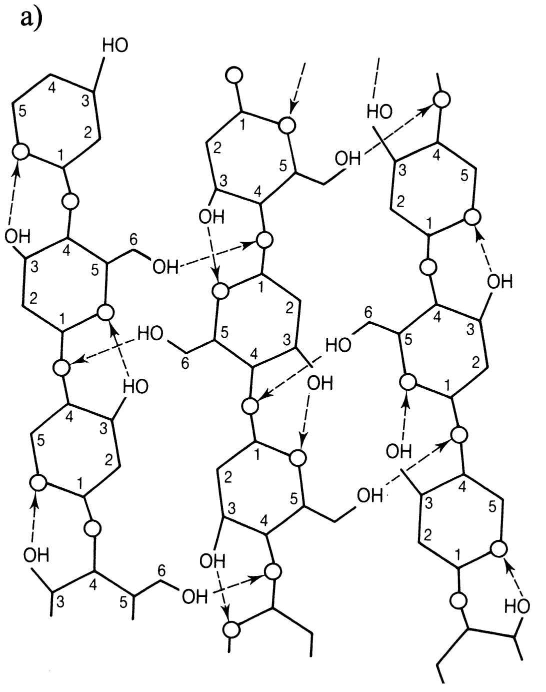


Fig. 5. Schematic presentation of the structure of a) cellulose (Smith 1993), reprinted with kind permission from John Wiley & Sons Ltd and b) lignin (Nimz 1974), reprinted with kind permission from Wiley-VCH.

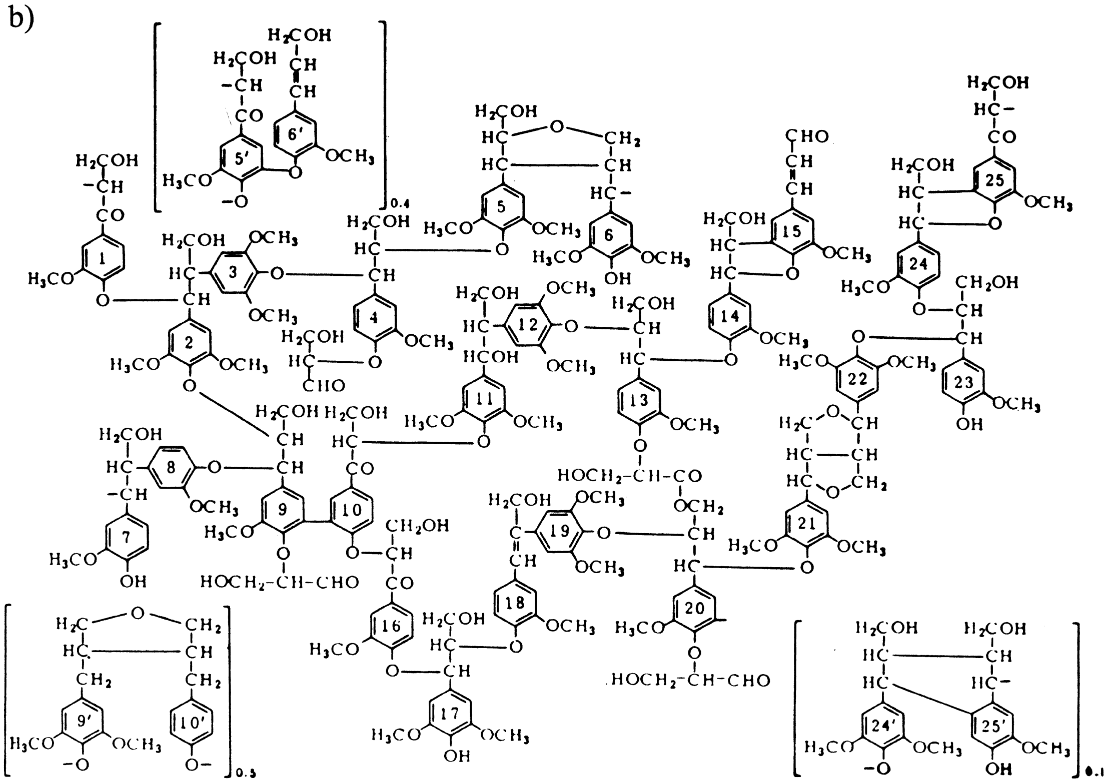


Table 3. The principal polysaccharides of the plant cell wall, showing structure of the interior chains. Glc = glucose, Xyl = xylose, Man = mannose, Gal = galactose, Ara = arabinose, Rha = rhamnose, GalA = galacturon acid (Smith 1993).

Polysaccharide	Interior chain
Cellulose	-Glc-(1→4)-Glc-(1→4)-Glc-(1→4)-
Hemicellulose	
Xyloglucan	-Glc-(1→4)-Xyl-(1→4)-Glc-(1→4)-
Xylan	-Xyl-(1→4)-Xyl-(1→4)-Xyl-(1→4)-
Mannan	-Man-(1→4)-Man-(1→4)-Man-(1→4)-
Glucomannan	-Man-(1→4)-Glc-(1→4)-Man-(1→4)-
Callose	-Glc-(1→3)-Glc-(1→3)-Glc-(1→3)-
Arabinogalactan	-Gal-(1→3)-Ara-(1→3)-Gal-(1→3)-
Pectins	
Homogalacturonan	-GalA-(1→4)-GalA-(1→4)-GalA-(1→4)-
Rhamnogalacturonan	-GalA-(1→2)-Rha-(1→4)-GalA-(1→2)-
Arabinan	-Ara-(1→5)-Ara-(1→5)-Ara-(1→5)-
Galactan	-Gal-(1→4)-Gal-(1→4)-Gal-(1→4)-

fibres and account for 1.8% of dry weight (McDougal et al. 1993).

Lignin

Lignin is the most abundant organic substance in plant cell walls after polysaccharides. Lignins are highly branched phenolic polymers (Fig. 5) and constitute an integral cell wall component of all vascular plants (Grisebach 1981). The structure and biosynthesis of lignins has been widely studied (for a review Grisebach 1981, Lewis and Yamamoto 1990, Monties 1991 and Whetten et al. 1998). The reason for the great interest is the abundance of lignin in nature, as well as its economical importance for mankind. For papermaking, lignin is chemically dissolved because of the separation of the fibres in the raw material. In cattle feeds, lignin markedly lowers the digestibility (Buxton and Russel 1988).

Lignins are traditionally considered to be polymers, which are formed from monolignols: *p*-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol (Fig. 6). Each of the precursors may form several types of bonds with other precursors in constructing the lignin polymer. A great variation in lignin structure and amount exists among the major plant groups and among species (Sarkanen and Hergert 1971, Gross 1980). Great variation in lignin structure and amount exists also among cell types of different age within a single plant (Table 4) (Albrecht et al. 1987, Buxton and Russel 1988, Jung 1989), and even between different parts of the wall of a single cell (Whetten et al. 1998). The structure and biogenesis of grass cell walls is comprehensively described in a review by Carpita (1996).

Gymnosperm lignin contains guaiacyl units (G-units), which are polymerized from coniferyl alcohol, and a small proportion of *p*-hydroxyphenyl units (H-units) formed from *p*-coumaryl alcohol. Angiosperm lignins are formed from both syringyl units (S-units), polymerized from sinapyl alcohol, and G-units with a small proportion of H-units (Sarkanen and Hergert 1971, Whetten et al. 1998). Syringyl lignin increases in proportion relative to guaiacyl and *p*-hydroxyphenyl lignins during maturation of some grasses (Carpita 1996). In grass species the total lignin content varies from 15 to 26% (Higuchi et al. 1967a). For reed canary grass Burritt et al. (1984) found only 1.2%. In grasses and legumes lignins are predominantly formed from coniferyl and sinapyl alcohols with only small amounts of *p*-coumaryl alcohol (Buxton and Russel 1988).

Lignins are considered to contribute to the compressive strength of plant tissue and water

Table 4. Weight of the cell wall component and concentration of lignin in stems of grasses and legumes. Adapted from Buxton and Russel (1988).

	Cell wall g kg^{-1}		Lignin g kg^{-1} cell wall		Lignin % of DM	
Species	Immature	Mature	Immature	Mature	Immature	Mature
Grasses	628	692	74	154	4.6	10.7
Legumes	514	712	212	244	10.9	17.4

impermeability of the cell wall. Lignins aid cells in resistance to microbial attack (Taiz and Zeiger 1991, Whetten et al. 1998), but they do not influence the tensile properties of the cell wall (Grisebach 1981).

Monolignols can also form bonds with other cell wall polymers in addition to lignin. Cross-linking with polysaccharides and proteins usually results in a very complex three-dimensional network (Monties 1991, Ralph and Helm 1993, Whetten et al. 1998). This close connection between phenolic polymers and plant cell wall carbohydrates makes the effective separation and utilization of the fibres more complicated. In woody plants relatively few covalent bonds exist between carbohydrates and lignin compared with those in forage legumes and grasses where the lignin component is also covalently linked to phenolic acids, notably 4-hydroxycinnamic acids, *p*-coumaric acid and ferulic acid (Monties 1991, Ralph and Helm 1993). Lignin and hemicelluloses fill the spaces between the cellulose chains in the cell wall and between the cells themselves. This combined structure gives the plant cell wall and the bulk tissue itself structural strength, and improves stiffness and toughness properties (Robson and Hague 1993).

Minerals

There are 19 minerals that are essential or useful for plant growth and development. The macro nutrients, such as N, P, S, K, Mg and Ca are integral to organic substances such as proteins and nucleic acids and maintain osmotic pressure. Their concentrations in plants vary from 0.1 to 1.5% of DM (Epstein 1965). The micro nutrients, such as Fe, Mn, Zn, Cu, B, Mo, Cl and Ni, contribute mainly to enzyme production or activation and their concentrations in plants are low (Table 5) (Epstein 1965, Marschner 1995). Silicon (Si) is essential only in some plant species. The amount of silicon uptake by plants is described by silica (SiO_2) concentration. The highest silica concentrations (10–5%) are found in *Equisetum*-species and in grass plants growing in water, such as rice. Other monocotyledons, including cereals, forage grasses, and sugarcane contain SiO_2 at 1–3% of DM (Marschner 1995). Si in epidermis cells is assumed to protect the plant against herbivores (Jones and Handreck 1967) and in xylem walls, to strengthen the plant as lignin (Raven 1983). The concentration of a particular mineral substance in a plant varies depending on plant age or stage of development, plant species and the concentration of other minerals (Tyler 1971, Gill et al. 1989, Marschner 1995) as well as the plant part (Rexen and Munck 1984, Petersen 1989, Theander 1991).

In the pulping process the minerals of the raw material are considered to be impurities and should be removed during pulping or bleaching (Misra 1980). The same elements are found both in non-woody and in woody species, but the concentrations are lower in woody plants (Hurter 1988) (Table 6). Si is the most deleterious element in the raw material for pulping, because it complicates the recovery of chemicals and energy in pulp mills (Ranua 1977, Keitaanniemi and Virkola 1982, Rexen and Munck 1984, Jeyasingam 1985, Ulmgren et al. 1990). Si wears out the installations of paper factories (Watson and Gartside 1976) and can lower the paper quality (Jeyasingam 1985). Other harmful elements for the pulping process include K, Cl, Al, Fe, Mn, Mg, Na, S, Ca and N (Keitaanniemi and Virkola 1982). Choosing a suitable plant species

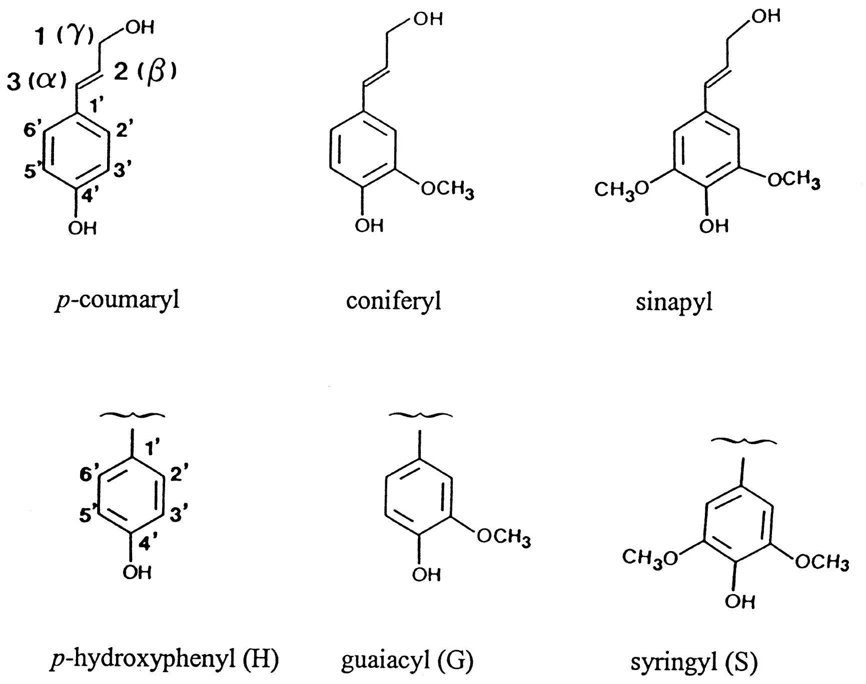


Fig. 6. Structures of the three monolignols and the residues derived from them. Radical group is bonded to the oxygen at the 4-position (Lewis and Yamamoto 1990). Reprinted with kind permission from the Annual Review of Plant Physiology & Molecular Biology.

Table 5. Concentrations of essential elements in plant species (Epstein 1965, Brown et al. 1987).

Element	μmol g^{-1} of DM	mg kg^{-1} (ppm)	%	Relative number of atoms
Mo	0.001	0.1	–	1
Ni	c. 0.001	c. 0.1	–	1
Cu	0.10	6	–	100
Zn	0.30	20	–	300
Mn	1.0	50	–	1000
Fe	2.0	100	–	2000
B	2.0	20	–	2000
Cl	3.0	100	–	3000
S	30	–	0.1	30000
P	60	–	0.2	60000
Mg	80	–	0.2	80000
Ca	125	–	0.5	125000
K	250	–	1.0	250000
N	1000	–	1.5	1000000

Table 6. Content of alpha-cellulose, lignin, pentosan, ash and silica (% of dry matter) in selected fibre plants. Adapted from Hurter (1988).

Plant species	Alpha-cellulose %	Lignin %	Pentosans %	Ash %	SiO_2 %
Stalk fibres (grass fibres)					
Cereals -rice	28–36	12–16	23–28	15–20	9–14
-wheat	29–35	16–21	26–32	4–9	3–7
-oat	31–37	16–19	27–38	6–8	4–7
-barley	31–34	14–15	24–29	5–7	3–6
-rye	33–35	16–19	27–30	2–5	0.5–4
Grasses -esparto	33–38	17–19	27–32	6–8	2–3
-sabai	–	17–22	18–24	5–7	3–4
Reeds -common reed	45	22	20	3	2
-bamboo	26–43	21–31	15–26	1.7–5	1.5–3
-bagasse	32–44	19–24	27–32	1.5–5	0.7–3
Bast fibres					
Fibre flax	45–68	10–15	6–17	2–5	–
Linseed straw	34	23	25	2–5	–
Kenaf	31–39	15–18	21–23	2–5	–
Jute	–	21–26	18–21	0.5–1	<1
Leaf fibres					
Acaba	61	9	17	1	<1
Sisal	43–56	8–9	21–24	0.6–1	<1
Seed and fruit fibres					
Cotton	85–90	3–3.3	–	1–1.5	<1
Cotton linters	80–85	3–3.5	–	1–2	<1
Wood fibres					
Coniferous trees	40–45	26–34	7–14	1	<1
Leaf trees	38–49	23–30	19–26	1	<1

as the raw material for pulping can minimise the amount of undesirable minerals in process. Moreover, using only the plant parts that contain low amounts of minerals such as Si represents an improvement.

2.4 Possibilities for improving biomass yield and quality by crop management

Chemical properties and pulping quality of non-woody plant material fluctuate more than do those of woody species (Judt 1993, Wisur et al. 1993). High variability is mainly due to differences in growing conditions, e.g. soil type, nutrient level, climate and the developmental stage of the plant at the time of harvest. High DM yield, which is important for the economics of production, is highly affected by management practices such as harvest timing, fertilizer application, age of the crop stand and choice of the variety.

2.4.1 Timing of harvest

Harvest timing and age of the ley influence DM yield of forage crops (Tuvesson 1989, Lomakka

1993, Nissinen and Hakkola 1994). On average, the highest yields are harvested in the second ley year (Tuvesson 1989, Nissinen and Hakkola 1994). Forage grasses were favoured by the two cut system over the three cut one (Nissinen and Hakkola 1994). In Swedish studies, the latitude also influenced yield level when reed canary grass was harvested during the growing period. When it was cut only once, the highest yields in central Sweden were recorded in late July, but in northern Sweden in late September (Tuvesson 1989). When reed canary grass harvest was delayed until the following spring, the first yield was 25% lower than that harvested in August, the second spring yield was the same as in August and the third spring yield was 1–2 tons higher than in August (Olsson 1993). Landström et al. (1996) reported increasing yield when reed canary grass was harvested in spring.

Harvest timing greatly influences the chemical composition of harvested biomass due to the critical effect of the developmental stage. With ageing, the relative amount of cell walls increases in plant biomass, because cellulose and lignin deposits increase in the secondary walls (Buxton and Hornstein 1986, Buxton and Russel 1988, Gill et al. 1989). Another determining factor of chemical composition in harvested biomass is the ratio of stems and leaves that changes during the growing season (Muller 1960, Buxton and Hornstein 1986, Petersen 1988).

The specific effect of harvest timing on mineral composition of the harvested plant material depends on the particular element and plant age. The concentrations of N, P and K, the main plant nutrients, decrease as the growing season proceeds (Tyler 1971, Cherney and Marten 1982, Gill et al. 1989). The decrease continues during the following winter (Lomakka 1993). The N, P, and K concentrations are lowest in dead plant material harvested in spring (Olsson et al. 1991, Lomakka 1993, Wilman et al. 1994) as is also the case for Ca, Mg and Mn (Lomakka 1993). In contrast, the concentrations of Si, Al and Fe increase as the season proceeds (Tyler 1971), being highest in dead plant material in spring (Landström et al. 1996, Burvall 1997).

2.4.2 Plant nutrition

Low mineral content in the plant material is preferred for fibre production. However, the undesirable elements may be important plant nutrients that favour plant growth and yield. Nutrients, N and K in particular, are often limiting in plant production and are thus added in the form of fertilizers, resulting in an elevation in their concentration, especially in physiologically active tissues. Increase in the supply of mineral nutrients from the deficiency range improves the growth of crop plants. The effect of N in particular on yield has been studied widely in arable crops and the highly positive yield response is well known in grasses (MacLeod 1969, Hiivola et al. 1974, Allinson et al. 1992, Gastal and Bélanger 1993). However, unfavourable conditions such as drought can restrict the yield response (Marschner 1995). The interaction between different mineral nutrients is also important. For example, potassium has a greater effect on the intake of N than on P (MacLeod 1969). Yield increase is a result of different processes, including increase of leaf area and rate of net photosynthesis per unit leaf area and increase in fruit or seed number. Therefore, when the N or P supply is insufficient, low rates of photosynthesis or insufficient expansion of epidermal cells (MacAdam et al. 1989, Marschner 1995) can limit leaf growth rate. This effect varies among plant species and there is also a diurnal component. In monocotyledons, cell expansion is inhibited to the same extent during the day and night, whereas in dicotyledons the inhibition is more severe in the daytime (Radin 1983).

Mineral nutrition can influence the mineral composition of the plant in addition to affecting the yield response. The effect of N fertilization on mineral composition of forage grasses has been studied widely (Rinne et al. 1974a, Rinne et al. 1974b). N had an effect on other elements, increasing clearly concentrations of K, Ca (Rinne et al. 1974a, Kätterer et al. 1998), Mg, Na, and Zn (Rinne et al. 1974a, Rinne et al. 1974b, Hopkins et al. 1994), but decreasing those of P (Rinne et al. 1974a, Kätterer et al. 1998), Fe, Mo and

Zn (Rinne et al. 1974b, Hopkins et al. 1994) and Si (Wallace et al. 1976, Rinne 1977, Wallace 1989) in grass. The changes caused by N fertilization were affected by the age of the ley, soil type and cutting time (Rinne et al. 1974b, Rinne 1977).

2.4.3 Choice of cultivar

One of the main goals in breeding agrofibre plant cultivars is large DM yield (Lindvall 1992, Mela et al. 1996, Sahramaa and Hömmö 2000a). However, the variation in quantitative traits including yield capacity depends on several genes, the effects of which are often smaller than the variation arising from environmental factors such as climate, nutrition and management (Baltensperger and Kalton 1958, Sachs and Coulman 1983, Østrem 1988a, Falconer and Mackay 1996). There are, of course, traits with a strong genetic component, such as the number of panicles and stems, and the height of the plant that impact on DM yield and quality (Baltensperger and Kalton 1958, Bonin and Goplen 1966, Berg 1980, Østrem 1988b, Sjödin 1991, Lindvall 1992). For production of grass fibre, early maturing varieties are preferred, as late ones tend to have a higher leaf to stem ratio (Berg 1980). Fibre length is another important quality trait, and Robson and Hague (1993) reported differences among varieties in fibre length. Genetic variation in lignification among the ecotypes of fescue and maize genotypes has also been reported (Gaudillere and Monties 1989). Significant differences in lignin content and its monomeric composition were found between upper and lower internodes of maize (Gaudillere and Monties 1989, Monties 1990). Alkaloids found in some grasses are harmful for livestock in feeds, but they may be even beneficial in fibre production because they resist the attack of harmful insects or herbivores (Coulman et al. 1977). Variation in concentration of alkaloids is genetically determined, but environmental factors, including management, have an impact on alkaloid levels (Østrem 1987, Akin et al. 1990).

Low mineral content is a desired quality for raw material for pulp and paper production. Breeding programmes for fibre crops take this into consideration (Lindvall 1997, Sahramaa and Hömmö 2000a) with emphasis on low Si, K and heavy metal concentrations. Jørgensen (1997) reported considerable variation in N and K contents of different *Miscanthus* populations collected from Japan. Mineral concentrations in the spring harvest were related to degree of crop senescence in autumn. The first severe frost in the autumn increased the rate of mineral loss from plant material. Jørgensen (1997) suggested that there are good prospects for future development of plant material with low mineral contents because of the significant within-species variation in relation to the time of senescence, yield and mineral content.

2.5 Pulping of field crops

Pulping for papermaking is a process of delignification, whereby lignin is chemically dissolved permitting the separation of fibres in the raw material. ‘Paper pulp’ is actually an aggregation of the cellulosic fibres that are liberated from the plant material (Biermann 1993). The fibres in the raw material are separated by treatments with alkali, sulphite or organic solvents, which partly remove the lignin and other non-cellulose components from the matrix. Fibres can also be separated in mechanical or chemi-mechanical pulping processes. After the fibres have been removed from the aqueous suspension they are washed and bleached. For the final papermaking process a water suspension of different fibre components and additives is pressed and dried on a fine screen running at high speed, and formed into a thin paper sheet. This procedure makes the fibres bond together and form a layered network. The inter-fibre bonding is important in determining the strength of the paper (Wood 1981, Philip 1992).

The choice of different types of pulps depends on the quality desired in the end product.

In fine papers the amount of short fibre (fibre length 0.6–1.9 mm) is 20–100% (Atchison 1987b). Long fibres from softwoods (coniferous trees) or non-wood plants (flax, hemp, kenaf) are necessary to form a matrix of sufficient strength in the paper sheet. The shorter hardwood fibres (deciduous trees, grass fibres) (Hurter 1988) contribute to the properties of pulp blends; especially opacity, printability and stiffness are improved. The role of the short fibre pulp in fine papers is to give good printability to the paper. On the other hand, the required strength for runnability is adjusted by adding long softwood fibres (Hurter 1988, Paavilainen 1996). In high quality papers such as writing and printing papers, chemical pulps are used. Mechanical and chemi-mechanical pulps are good raw materials for newspapers (Atchison 1987b). One of the main problems in pulping non-wood plants is the high concentration of minerals and especially Si. In alkaline pulping, silica dissolves into the cooking liquor, and when the black liquors are evaporated for recovery, the concentration of SiO_2 increases to such an extent that it may cause problems in the process (Hultholm et al. 1995). Several desilication methods (Judt 1991, Kulkarni et al. 1991) have shown that removal of SiO_2 is possible, but they are seldom used in small pulp mills, where most commercial non-wood pulp is produced (Sadawarte 1995).

2.5.1 Pretreatment of the raw material

Mechanical treatment of agrofibres

Heterogeneity of the biomass can result in variation also in the quality of the pulp when the entire plants are used in pulping (Ilvessalo-Pfäffli 1995). In the pulp mill, however, leaves, dust and dirt can be removed by air fractionation before cooking. Mechanical pretreatment improves the quality by increasing the bleachability of the pulp, and decreasing the silica and other useless particles present in the raw material. SiO_2 can be decreased by 40% through a pretreatment of the grass (Paavilainen et al. 1996b). A dry fractionation system developed in Sweden includes shredding, chopping, milling in a disc mill and screening of reed canary grass. Fractionating produces a chip fraction of mainly internodes for pulp production and a meal fraction of leaves and sheaths that can be used in bioenergy production (Finell et al. 1998, Paavilainen et al. 1999). Because of the large quantity of fines (small particles other than fibres) dewatering ability of pure grass pulps is inferior to that of hard wood pulp (Wisur et al. 1993, Paavilainen et al. 1996b). Thus the drainage time in papermaking is longer, but mechanical fractionation and blending of the grass pulp with long-fibred softwood pulp improves the dewatering and drying properties (Paavilainen et al. 1996a, Paavilainen et al. 1996b).

Biotechnical and enzymatic pretreatments of agrofibres

Besides the mechanical fractionation, decreasing the fines is possible by treating the biomass with white rot fungi (*Phlebia radiata* Fr., *P. tremellosa, Pleurotus ostreatus* Jacq., *Ceriporiopsis subvermispora*) in oxygenated bioreactors before chemical pulping (Hatakka and Mettälä 1996, Hatakka et al. 1996). The fungi first decompose lignin and later attack the cellulose. White rot fungi seem to break down the parenchyma cells effectively and thus, decrease the amount of fines. When spring-harvested, completely dead reed canary grass was used as a substrate and *C. subvermispora* as a fungal treatment, lignin content decreased from 10.4% to 8.2%, cellulose content increased from 47.2 to 50.4% and pulp yield from 47.1 to 48.% (Hatakka et al. 1996). The possibilities for using enzymatic methods for improving pulping and bleaching of fibres have also been studied (Pere et al. 1996).

2.5.2 Commercial and potential methods for pulping non-woody plants

It has been estimated that there are about 40 different processes suitable for pulping non-woody plants, but only a few of them have been used commercially (Ranua et al. 1977). The most used methods include alkaline processes such as sulphate (Kraft)- and soda (NaOH)-methods and also sulphite methods (Table 7). The most commonly used commercial method in pulping non-woody species in countries producing non-wood pulp is still the soda method (Sadawarte 1995). There are also several new methods with good potential to produce high quality pulp from non-woody species (McDougall et al. 1993).

Soda method

The soda process is a common method for producing non-wood or straw pulp (Paavilainen et al. 1996b). In the soda process the cooking chemical is mainly sodium hydroxide. This process leaves more insoluble carbohydrates in pulp and gives a better pulp yield than Kraft method. However, the strength properties and lignin content are similar in pulps produced with the soda and the Kraft processes (Ranua et al. 1977). The soda process was the basis for the development of the straw pulping industry in Europe (Ranua et al. 1977, Winner et al. 1991).

Kraft method

The Kraft or the sulphate method is the most frequently used process in making chemical paper pulp from wood. In Finland about 90% of all the chemical paper pulp is made using the Kraft process (Paavilainen 1996) and globally it is 80% (Ervasti 1996). The raw material is treated with a highly alkaline solution of NaOH, which is known to cleave lignin, but also eliminates a part of the hemicellulose. The undesirable breakdown of hemicellulose is largely avoided by adding Na_2S in the solution, and in this way a very high concentration of NaOH can be avoided in the pulping liquor (McDougall et al. 1993). The Kraft process produces papers with increased fibre strength and density and low electrical conductivity (McDougall et al. 1993).

Sulphite pulping

Sulphite pulping involves heating the raw material in a solution of $NaHSO_3$ and/or Na_2SO_3 (Atack et al. 1980, Costantino et al. 1983). Sulphonates form and are hydrated, and the swelling of fibres helps remove further lignin. In deleterious side reactions, the strongly ionised sulphonic acids increase the acidity of the pulping medium resulting in condensation reactions between phenolic moieties in lignin, forming insoluble resin-like polymers, and degradation of the hemicelluloses and amorphous regions of cellulose. This affects both lignin removal and the quality of the fibres (McDougall et al. 1993). Sulphite pulp is, however, still used to produce papers with specific properties such as sanitary and tissue papers, which must be soft, absorbent and moderately strong (McDougall et al. 1993).

Phosphate pulping

In phosphate pulping the alkaline cooking chemical is trisodium phosphate (Na_3PO_4). In pulping of grass plants anthraquinone is used as a catalytic agent and the cooking temperature is set between 145 to 165°C. The properties of pulps prepared with the phosphate and soda methods are similar (Janson et al. 1996a).

Pulping with organic solvents

Since the 1930s organic solvents, such as alcohols, in different combinations with sodium hydroxide or sodium carbonate, have been studied for pulping (Kleinert and Tayenthal 1931). In the IDE-process (Impregnation – Depolymerisation – Extraction) (Backman et al. 1994) the raw material is first impregnated with a mixture of sodium hydroxide and sodium carbonate, and then at the depolymerisation stage, it is subjected to ethanol-water solution at a temperature of 140–190°C. At the extraction stage, residual lignin is extracted from the pulp with an aqueous ethanol solution. In this process the silica problem remains partly unsolved, but the separation of silica is easier at the impregnation stage than from the black liquor (Hultholm et al. 1995). In the ALCELL process the non-wood raw material is cooked in an ethanol-water blend. On a pilot scale, pulp yields and quality have been comparable with those of conventional market pulps (Winner et al. 1991). The MILOX pulping

Table 7. Commercial and potential pulping methods for non-woody plants.

Process	Major pulping chemical	Commonness	References
Soda	NaOH	Commonly used	Paavilainen et al. 1996b
Kraft	NaOH + Na_2S	Commonly used for wood	Paavilainen 1996
Sulphite	$NaHSO_3$ and/or Na_2SO_3	Commonly used	Atack et al. 1980
Phosphate	Na_3PO_4	Potential method	Janson et al. 1996
Milox	Formic acid	"	Seisto and Sundquist 1996
IDE	NaOH, sodium carbonate, ethanol-water blend	"	Backman et al. 1994
Alcell	Ethanol-water blend	"	Winner et al. 1991

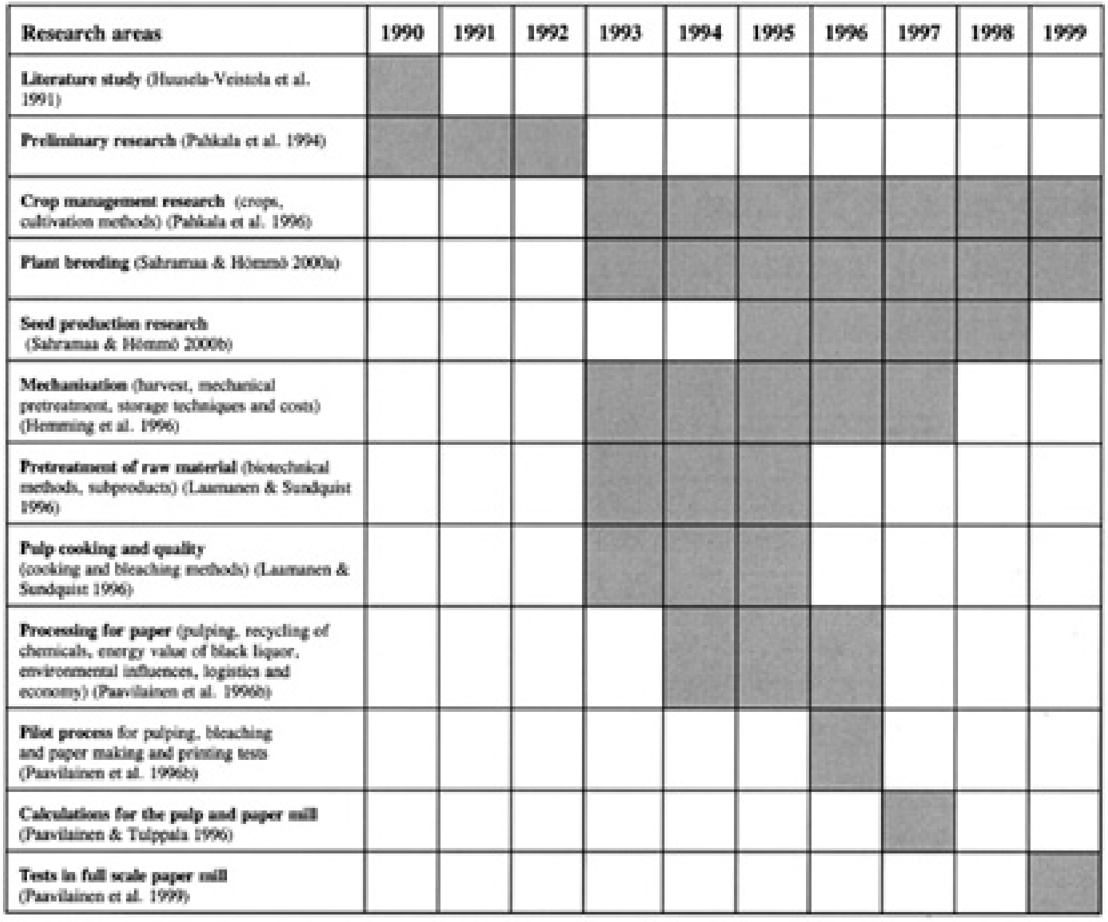
and bleaching method is based on formic acid and hydrogen peroxide. In the acid MILOX process silica remains in the pulp after cooking, but it is possible to dissolve it in alkaline H_2O_2 from the bleaching process (Seisto and Sundquist 1996).

3 Objectives and strategy of the study

The need for producing field crops as raw material for pulp and paper emerged during the beginning of the 1990s when it was estimated that between half and one million hectares of arable land would be set aside from cultivation in Finland. Simultaneously, consumption of paper and importation of hardwood for papermaking increased. Therefore, the National Agrofibre Programme in Finland was set out to develop economically feasible methods for producing specific short-fibre raw material from field crops available in Finland and process it for use in high quality paper production. The program covered the entire processing chain, from raw material production to the end product (Table 8). It proceeded from a literature study and preliminary testing of species, through crop management and post harvesting research, seed production research, studies on pretreatment and pulping methods to the pilot processing for pulping, bleaching, paper making and printing which were carried out in 1995, and to the tests in full scale paper mill in 1999. Calculations for the pulp and paper mill were performed during the programme. A breeding programme for reed canary grass started in 1993 in order to develop a variety for domestic fibre production. The chronology and strategy for the research process of the National Agrofibre Programme in Finland during 1990–1999 is described in Table 8. This thesis covers the results from the crop production experimentation of the Agrofibre Program outlined above, including selection of the plant species in preliminary research in 1990, research on crop management methods 1993 to 1999, and variety research from 1996 to 1999.

The objectives of this thesis were 1) to evaluate the results from crop production experiments in the Agrofibre Program in order to select plant species for non-wood fibre production, and for short fibre pulping and for the fine paper industry in Finland, 2) to develop crop management methods for the selected species and 3) to study possibilities to improve the fibre yield and quality of the selected species through management methods for raw material for pulping, and lastly, 4) to describe an appropriate cropping system for large-scale fibre plant produc-

Table 8. The chronology of the research process of the National Agrofibre Program in Finland since 1990.



Research areas	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Literature study (Huusela-Veistola et al. 1991)	▨									
Preliminary research (Pahkala et al. 1994)	▨	▨	▨							
Crop management research (crops, cultivation methods) (Pahkala et al. 1996)				▨	▨	▨	▨	▨	▨	▨
Plant breeding (Sahramaa & Hömmö 2000a)				▨	▨	▨	▨	▨	▨	▨
Seed production research (Sahramaa & Hömmö 2000b)						▨	▨	▨	▨	
Mechanisation (harvest, mechanical pretreatment, storage techniques and costs) (Hemming et al. 1996)				▨	▨	▨	▨	▨		
Pretreatment of raw material (biotechnical methods, subproducts) (Laamanen & Sundquist 1996)				▨	▨	▨				
Pulp cooking and quality (cooking and bleaching methods) (Laamanen & Sundquist 1996)				▨	▨	▨				
Processing for paper (pulping, recycling of chemicals, energy value of black liquor, environmental influences, logistics and economy) (Paavilainen et al. 1996b)					▨	▨	▨			
Pilot process for pulping, bleaching and paper making and printing tests (Paavilainen et al. 1996b)							▨			
Calculations for the pulp and paper mill (Paavilainen & Tulppala 1996)								▨		
Tests in full scale paper mill (Paavilainen et al. 1999)										▨

tion. Finally, 5) through the results of this thesis, it should be possible to improve our understanding of how to locate, select and introduce a crop for a new purpose.

The first step in this study was to explore the potential and feasibility of cultivating field crops as raw material for pulping. During 1990, data were collected from trials that included 17 candidate species in order to identify the most potentially useful fibre crops. After determining the biomass yield, fibre quality, and mineral composition of the plant material, reed canary grass, tall fescue, meadow fescue, spring barley, goat's rue, red clover and lucerne were selected for the studies in 1991–1993. The selection was carried out based on the mineral and pulping analyses and earlier knowledge and experience on the yielding capacity, adaptability to the Finnish climate conditions, domestic seed production, and low production and harvesting costs. The factors used to select the fibre plants for the subsequent experiments are presented in Table 9. The studies in 1991 and 1992 focused on yielding capacity and biomass quality at different harvest timings and at different fertilizer application rates of the seven species. Most results from the

Table 9. Factors used to select the most potentially useful fibre plant species. Properties of the species. Yes (+), no (–), intermediate (+/–).

Plant species	High yield	Good quality	Adaptability	Domestic seed production	Mechanisation available	Low production costs
Grasses						
Reed canary grass	+	+	+	+	+	+
Tall fescue	+/–	+	+/–	+	+	+
Meadow fescue	+/–	+	+	+	+	+
Timothy	+/–	+	+	+	+	+
Legumes						
Red clover	+	–	–	+	+	+
Lucerne	+	–	–	–	+	+
Goat’s rue	+	–	+/–	+	+	+
Fibre crops						
Linseed straw	+/–	+	+/–	+	+/–	+/–
Hemp	+	+	+/–	–	–	–
Nettle	–	–	–	–	–	–
Cereal straw and oilseed crops						
Winter rye	+/–	+	+	+	+	+
Oats	+/–	+	+	+	+	+
Barley	+/–	+	+	+	+	+
Wheat	+/–	+	+/–	+	+	+
Turnip rape	+/–	+/–	+	+	+	+
Rape	+/–	+/–	+/–	+	+	+
Common reed	+	+	–	–	–	+(1)

(1) harvest costs

years 1991 and 1992 have been published earlier (Pahkala et al. 1994, Pahkala 1997) and are therefore not included in this thesis.

In 1993, only the two most promising crop species, reed canary grass and tall fescue, were included in the study. In 1995, studies with tall fescue ceased, and reed canary grass was chosen as the main crop for the study. The trends in the research strategy for the crop production research of the Agrofibre Programme during 1990–1999 are described in Table 10. The results of three studies are included in this thesis:

I Selection of the plant species for non wood fibre production, carried out in 1990,

II Study of possibilities through management methods to improve the biomass yield and quality of reed canary grass and tall fescue as raw material for paper making, carried out from 1993 to 1999, and

III Study of variation in yielding capacity and quality of commercial reed canary grass cultivars grown for pulping, carried out from 1996 to 1999.

Table 10. Sequence of the crop production research in the National Agrofibre Program, 1990–1999. RCG = reed canary grass. The experiments included in this thesis are printed in boldface.

	Selection of plant species									
I Plant species	**1990**	1991	1992	1993	1994	1995	1996	1997	1998	
	4 grasses **4 cereals** **3 legumes** **2 oil plants** **3 fibre plants** **1 reed**	RCG tall fescue meadow fescue barley goat's rue red clover lucerne	RCG tall fescue meadow fescue barley goat's rue red clover	RCG tall fescue	RCG tall fescue	RCG	RCG	RCG	RCG	
		Preliminary Study		**Crop management experiments**						
II Management research		1991	1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
		RCG tall fescue meadow fescue barley goat's rue lucerne red clover	RCG tall fescue meadow fescue	**RCG** **tall fescue**	**RCG** **tall fescue**	**RCG** **tall fescue**	**RCG**	**RCG**	**RCG**	**RCG**
		Autumn harvest					**Spring harvest**			
III Variety research		1991	1992	1993	1994	1995	**1996**	**1997**	**1998**	**1999**
		RCG tall fescue meadow fescue	RCG tall fescue	RCG tall fescue	RCG tall fescue	RCG tall fescue	**RCG**	**RCG**	**RCG**	**RCG**

4 Materials and methods

4.1 Establishment and management of field experiments

Field experiments were established using a plot seed drill or combine drill. The plot size in the experiments sown using the plot seed drill (Øyjord plot drill, F.Walter and Wintersteiger, Austria) was 1.5 m x 10 m with a net plot width of 1.25 m. Before sowing, the experiments were dressed with the NPK compound fertilizer at 70–14–28 kg ha^{-1}. When the crop was sown using combine drilling (Tume 2000, Nokka-Tume Oy, Finland), with a basal dressing of NPK at 70–14–28 kg ha^{-1}, the plot size was 2–3 m x 10 m and the harvested area 1.5 x 10 m. The plots were oriented across the sowing lines in the field. The sowing rate was 800 to 1000 viable seeds m^{-2} and the sowing depth 1–2 cm. In all experiments, fertilizer was broadcast using a manual Tume plot fertilizer spreader (Nokka-Tume Oy, Finland) in the spring after delayed harvest and before the new growth had started. Herbicide was used (Basagran MCPA, a mixture of bentazone and MCPA with active ingredient of 0.75 kg and 0.375 kg ha^{-1}, respectively) against dicotyledonous weeds and was applied when the crop had two to four leaves and weeds had emerged. The plots were harvested using a Haldrup forage harvester (J. Haldrup A/S, Denmark) during the growing season or at delayed harvest in the spring. Delayed harvest was carried out in late April or in May, when the snow and ice had melted and the soil had dried enough to support a harvester.

4.2 Sampling

For determination of the DM, crude fibre and mineral content, two samples of 200 g (100 g for spring harvested material) were dried at first for two hours at 105°C and then 17 hours at 60°C. To analyse the different plant fractions, a sample of 25 x 50 cm (consisting about 80–120 plants) was taken from each plot, cutting the plants near the soil surface. The dried grass samples were separated into stems, leaf blades, leaf sheaths and panicles. The weight of the plant parts was determined after drying the samples for 17 hours at 60°C. The fresh weight of weeds in harvested biomass was determined from a sample of 500 g.

4.3 Measuring chemical composition of the plant material

For the determination of crude fibre, the dried plants or stems, leaf sheaths and leaf blade fractions of the samples were milled to less than 1 mm diameter. The crude fibre was measured using a modified AOAC method (AOAC 1980) with Fibertec system M (Tecator, Sweden), which consists of hot (1020 Hot Extractor) and cold (1021 Cold Extractor) extraction units. The sample was boiled first in dilute acid (H_2SO_4) and then in dilute alkali (KOH). The residue, not soluble in the acid-alkali treatment, was measured gravimetrically and the results were given as percentage of DM in total biomass.

Mineral composition was analysed after drying. The samples were milled to less than 1 mm in diameter. The concentrations of K, Fe, Mn and Cu were measured using a flame AAS (Perkin Elmer 200 Flame Atomic Absorption Spectrometer, Perkin Elmer Corporation, USA), the concentration of silica (SiO_2) and ash by gravimetry, in both cases after dry ashing at 500°C. Nitrogen content was determined using the Kjeldahl method (Tecator 1981) with Kjeltec Auto 1030 Analyzer (Tecator, Sweden) and P by spectrophotometry (Shimadzu UV-160A, Shimadzu Corporation, Japan). In the comparison of reed canary grass cultivars, Si and K were determined by ICP (inductively coupled plasma spectrometry) (Thermo Jarrell Ash Irish Advantage, Thermo Jarrel Ash Corporation, USA) (Huang and Schulte 1985) after microwave digestion. The plant samples were digested in a mixture of concentrated HNO_3, HF and 30% H_2SO_4. A two step, 15 min, digestion program was used and the sample was diluted with a boron solution before ICP measurement (Fridlund et al. 1994). Chemical analyses were performed at the Chemistry Laboratory of MTT.

4.4 Pulp and paper technical measurements

For evaluation of the plant material in 1990, dried biomass samples of 800 g for each of the 17 plant species were cooked for 10 minutes in NaOH (16% of DM) with anthraquinone (0.1% of DM) at 165°C with time of rise 60 min, using 15-litre electrically heated rotating digesters. The screened pulp yield, the uncooked screenings, the viscosity, the fibre length and the kappa number were determined after cooking and compared with the corresponding values for wood chips, the commercial raw material for pulp mills.

In the comparison of plant fractions of reed canary grass, the sulphate pulping experiments were conducted in 1-litre air-heated autoclaves, where 100 g of plant material was cooked for 10 minutes at 165°C in NaOH solution. The cooking conditions were as follows: heating to 165°C within 30 min, liquor-to-raw material ratio 5 l kg^{-1} oven dried grass material and the charge of effective alkali 4.5 mol kg^{-1} (18% NaOH), sulphidity 38%.

After cooking, the pulps were carefully washed with deionized water, disintegrated in a laboratory mixer for 30 seconds and screened on a flat screen (0.25 mm slots). The pulps were collected on a wire cloth. To avoid loss of fine material in the screening procedure, the filtrate was used as dilution water in screening (closed cycle screening). Total pulp yield (% of DM), amount of screenings (% of DM), kappa number (ISO 302, indicates the lignin content in the pulp, in birch pulp usually about 15–20) and black liquor pH were determined. Brightness (%) was determined as an average of the values measured from both sides of a laboratory sheet. Fibre properties of the pulps (fibre length, coarseness and weight) were measured with Kajaani FS 200 Fiber Analyzer (Kajaani Electronics, Finland). The pulping characteristics were determined at KCL.

4.5 Methods used in individual experiments

4.5.1 Selection of plant species

In 1990, data were collected from several field trials including 16 field crops and one wild species (common reed) to determine the fibre and mineral composition of the plants (Table 11). The properties of non-wood species were compared with those of birch. Grasses were harvested at the silage stage (when about 20–80% of panicles or ears had emerged) in June, or at the seed ripening stage, except for the second cut of reed canary grass that was done at the panicle emergence stage. Lucerne, goat’s rue and red clover were harvested at the full flowering or seed ripening stage. Straw of cereals, linseed, rape, turnip rape and fibre hemp were harvested at the seed maturity stage in September. The samples were dried and chopped into 3 to 5 cm sections with a Skiold straw chopper (Skiold A/S, Denmark).

For analysing the mineral and fibre content, the samples from the field trials were taken as a mixture from two to four replicates, except for birch, common reed and nettle (*Urtica dioica* L), which derived from only one sample.

Table 11. Plant species, their origin and growth stage in the preliminary screening.

Trivial name	Latin name	Origin of the samples	Location	Growth stage at harvest
Reed canary grass	*Phalaris arundinacea* L.	Tuusula	60°25’N, 25°01’E	Culms 40 cm
"	"	"	"	Panicles emerged
Tall fescue	*Festuca arundinacea* Schr.	Viikki	60°13’N, 25°02’E	20% panicles emerged
"	"	"	"	Seed ripening
Meadow fescue	*Festuca pratensis* Huds.	Viikki	"	80% panicles emerged
"	"	"	"	Seed ripening
Timothy	*Phleum pratense* L.	Jokioinen	60°49’N, 23°28’E	40% ears emerged
"	"	"	"	Seed ripening
Common reed	*Phragmites communis* Trin.	Vehmaa	60°35’N, 21°46’E	Anthesis
"	"	"	"	Senescence
Winter rye, straw	*Secale cereale* L.	Jokioinen	60°49’N, 23°28’E	Seed ripened
Oat, straw	*Avena sativa* L.	"	"	Seed ripened
Spring barley straw	*Hordeum vulgare* L.	"	"	Seed ripened
Spring wheat straw	*Triticum aestivum* L.	"	"	Seed ripened
Goat’s rue	*Galega orientalis* L.	Viikki	60°13’N, 25°02’E	Anthesis
"	"	"	"	Seed ripening
Red clover	*Trifolium pratense* L.	Jokioinen	60°49’N, 23°28’E	Anthesis
"	"	"	"	Seed ripening
Lucerne	*Medicago sativa* L.	"	"	Anthesis
"	"	"	"	Seed ripening
Linseed, stem	*Linum usitatissimum* L.	"	"	Seed ripened
Fibre hemp, stem	*Cannabis sativa* L.	"	"	Seed ripened
Nettle	*Urtica dioica* L.	Mikkeli	61°41’N, 27°18’E	Anthesis
Spring turnip rape	*Brassica rapa* L.	Jokioinen	60°49’N, 23°28’E	Seed ripened
Spring rape	*Brassica napus* L.	"	"	Seed ripened
Birch, chipped	*Betula* spp. L.	Commercial raw material		

4.5.2 Crop management research

The field experiments concerning research into crop management of reed canary grass and tall fescue were conducted in Jokioinen (60°49’N, 23°28’E) and Vihti (60°21’N, 24°24’E). Soil types, sowing dates and methods, and harvest years for the experiments included are presented in Table 12.

Experiments for harvest timing, row spacing and fertilizer use
The field experiments for reed canary grass and tall fescue were set up as nested designs, where the main plot factor was harvest timing with three harvests (June+Oct, Aug, May), the subplot factor was row spacing (12.5 and 25 cm) and the sub-sub-plot factor was fertilizer level (N rate at 0, 50, 100, 150 kg ha^{-1}) (Table 13). The experiments were sown with a plot seed drill in 1993 on sandy clay soil in Jokioinen and on organic soil in Vihti.

The first harvest (a1) was carried out when more than half of the panicles were flowering. The regrowth biomass was harvested in October. The total yield (June+Oct) was considered a sum of those two harvests. The second harvest (a2) was adjusted so that seed was fully ripened but not yet shattered. Delayed harvest (a3) was carried out in the following year in May when the soil was dry enough to support a harvester. Sowing rate was 800 seeds m^{-2} with 12.5 cm row space (b1), and 400 seeds m^{-2} in the case of a 25 cm row space (b2). The reed canary grass trials

Table 12. Experiments on crop management of reed canary grass and tall fescue. Sowing method "Plot" = plot seed drill, "Field" = combine seed/fertilizer drill

Crop species	Site	Soil type	Sowing time	Sowing method	Variety	Harvest years
Experiments on harvest timing, row spacing and fertilizer use						
Tall fescue	Jokioinen	sandy clay	12.5.1993	Plot	Retu	1994–95
	Vihti	organic soil	5.5.1993	Plot	Retu	1994–95
Reed canary grass	Jokioinen	sandy clay	12.5.1993	Plot	Venture	1994–96
	Vihti	organic soil	5.5.1993	Plot	Venture	1994–96
Experiment on age of the reed canary grass ley						
Reed canary grass	Jokioinen	sandy clay	23.7.1990	Field	Venture	1991–99
Experiment on sowing time and cover crop of reed canary grass						
Reed canary grass	Jokioinen	sandy clay	30.5–20.9.1995	Plot	Palaton	1996–99
Experiment on timing the delayed harvesting						
Reed canary grass	Jokioinen	sandy clay	25.5.1992	Field	Venture	1994–98

Table 13. Design for the experiments on harvest timing, row spacing and fertilizer application rate for reed canary grass and tall fescue in Jokioinen and Vihti.

Main plot, harvest	Sub-plot, row spacing	Sub-sub-plot, fertilizer rate kg ha^{-1}			
			N	P	K
a1 at flowering stage June, 2nd cut October	b1 12.5 cm (800 seeds m^{-2})	c1	0	0	0
a2 at seed ripening stage in August	b2 25.0 cm (400 seeds m^{-2})	c2	50	4	6
a3 delayed harvest in spring in May		c3	100	8	12
		c4	150	12	18

were harvested in 1994, 1995, 1996 and in spring 1997. The tall fescue trials were harvested in 1994, 1995 and in spring 1996.

Experiment on age of the reed canary grass ley

The effect of the age of the ley on the total DM yield, proportion of plant fractions and mineral and fibre content of reed canary grass was studied in a field experiment established in 1990 on sandy clay soil in Jokioinen. The plot size was 15 m^2. DM yield was measured in 1991–1998, the proportion of the plant parts in 1992–1998, mineral and crude fibre content in 1991–1994 and pulping characteristics in 1991–1992. The field experiment for reed canary grass comprised two levels of NPK (26–2–3) fertilizer (100 and 200 kg N ha^{-1}) that were completely randomised into blocks. The fertilizer treatments were combined with two harvest times in a split-plot design with 3 replicates. The harvest dates from autumn 1991 to spring 1999 are presented in Table 14. Data on DM and stem yields (kg ha^{-1}) were recorded at both harvests.

Experiment on sowing time and cover crop of reed canary grass

The reed canary grass sowing time trial was laid out in Jokioinen in 1995 on sandy clay soil as a randomised block design with four replicates. The sowing rate for reed canary grass (cv. Palaton) was 800 seeds m^{-2} and the plot size was 1.5 x 9 m. The sowing times were 1) May 30th, 2) June 22nd, 3) July 21st, 4) August 22nd, 5) September 22nd. Total DM and stem yields (kg ha^{-1})

were obtained at spring harvests in 1997, 1998 and 1999.

The effect of cover crop was studied in the same trial. Reed canary grass was sown on 30th May either as a pure stand or using barley (cv. Arve) as the cover crop. The sowing rate for barley was 350 seeds m $^{-2}$. The cover crop was removed 1) as silage on August 28th using a grass harvester (Haldrup) or 2) by threshing on September 5th using a plot harvester (Wintersteiger, Austria). The stubble height in both cases was approximately 15 cm. Barley yield was not measured. Total DM and stem yields (kg ha $^{-1}$) were obtained at spring harvests in 1997, 1998 and 1999.

Experiment on timing the delayed harvest
Timing of delayed harvest of reed canary grass was studied in spring using two different stubble heights, 5 cm and 10 cm, on a farm-scale field. The field for the timing of spring harvest was sown using 1000 viable seeds m $^{-2}$ (cv. Venture) as a pure stand in spring 1992. The experiment was harvested on the same field in five successive years (1994–1998). The first harvesting was performed as early as possible when the soil was trafficable. The following three harvests were performed in successive weeks. The plots were fertilized after harvesting on the same day with NPK fertilizer (26–2–3) at the rate of 80 kg N ha^{-1}. The plot size was 15 m^2. The experimental design for the study was a split-plot arrangement with two stubble heights as main plots and four harvest times as subplots (Table 15).

Table 14. The harvest dates (from 1991 to spring 1999) of a reed canary grass crop established in 1990 in Jokioinen.

Harvest year	Harvest dates Autumn	Spring
1	16 Sep 1991	5 May 1992
2	24 Jul 1992	27 April 1993
3	29 Jul 1993	25 April 1994
4	3 Aug 1994	11 May 1995
5	25 Jul 1995	8 May 1996
6	16 Aug 1996	12 May 1997
7	16 Aug 1997	11 May 1998
8	12 Aug 1998	5 May 1999

DM content (%) and DM yield (kg ha^{-1}) of the harvested biomass were determined separately for each plot. The length of green shoots (cm) and the height of the harvestable stand (cm) were measured before each harvest. The height of the growing stand and the number of culms m $^{-2}$ were measured at the end of September. The straw content (% of DM) and the amount of green matter in the biomass (% of DM) were determined from a sample taken from an area of 25 x 50 cm in each plot in September and in May.

4.5.3 Reed canary grass variety trials

The experiments for studying the genetic variation of reed canary grass were conducted in 1993 at seven research sites (Table 16). Ten cultivars and breeding lines of reed canary grass were in-

Table 15. The design of the experiment for timing of delayed harvest. Dates for each harvest are given separately for each year.

Main plot, stubble height	Sub-plot, harvest	Harvest dates yearly 1994	1995	1996	1997	1998
a1 5 cm	b1	5 May	3 May	9 May	6 May	11 May
a2 10 cm	b2	12 May	10 May	17 May	13 May	18 May
	b3	19 May	17 May	23 May	20 May	26 May
	b4	26 May	26 May	30 May	27 May	2 June

cluded in variety trials. The cultivars and breeders were as follows:

Cultivar	Breeder
R-90-7587	Land O'Lakes, USA
Palaton	Land O'Lakes, USA
Vantage	Iowa Agricultural Experiment Station, USA
Rival	University of Manitoba, Canada
Jo 0510	MTT, Jokioinen, Finland
Motterwitzer	DSG-Berlin, Germany
Barphal 050	Barenbrug, the Netherlands
Venture	Land O'Lakes, USA
Lara	Löken Agricultural Research Station, Norway
VåSr 8401	Vågønes, Norway

The trials were established without cover crop in May or early June 1993 using a plot seed drill. Soil type and nutrition level of the trials is given in Table 17. The first harvest was in autumn 1994 at the seed ripening stage. In 1995, only half of the plots were harvested in autumn, the remaining areas (6 to 7 m^2) of the plots were harvested in spring 1996, 1997, 1998 and 1999. In this study DM yield (kg ha^{-1}) was recorded only at spring harvest.

The mineral and fibre composition of different plant parts was studied in three cultivars (Palaton, Venture, and Lara) harvested in Jokioinen, Ylistaro and Ruukki in spring 1997 from three-year-old leys. For the plant part analysis, samples of 25 x 50 cm were separated into stems, leaf blades, leaf sheaths and panicles. Pulping characteristics and crude fibre of plant parts of the cultivar Palaton from the same location were studied in spring 1998.

Table 16. Locations, harvest dates and cultivars for reed canary grass variety trials. Cultivars: 1 R-90-7587, 2 Palaton, 3 Vantage, 4 Rival, 5 Jo 0510, 6 Motterwitzer, 7 Barphal 050, 8 Venture, 9 Lara, 10 VåSr 8401.

		Harvest dates				Cultivars
Site	Location	1996	1997	1998	1999	included
Jokioinen	60°49'N,23°28'E	20 May	16 May	19 May	19 May	1–10
Laukaa	62°25'N,26°15'E	13 May	11 May	13 May	–	1–10
Tohmajärvi	62°11'N,30°23'E	22 May	–	–	–	1–4, 6–10
Ylistaro	62°57'N,22°31'E	26 April	16 May	25 May	–	1–4, 6–10
Ruukki	64°42'N,25°00'E	20 May	20 May	20 May	5 May	1–10
Sotkamo	64°60'N,28°20'E	16 May	22 May	22 May	12 May	1–4, 6–10
Rovaniemi	66°34'N,26°10'E	27 May	25 May	11 May	–	1–10

Table 17. Soil type and nutrition level in the reed canary grass variety trials.

Site	Soil type	pH	Electrical conductivity siemens m^{-1}	Ca mg/l	K mg/l	Mg mg/l	P mg/l	Clay %	Humus %
Jokioinen	sandy clay	5.43	0.47	1018	180.0	280	7.4	29.4	4.2
Laukaa	silty clay	5.50	–	1110	68.0	147	6.0	–	–
Ylistaro	organic soil	5.31	0.82	1431	71.0	142	5.2	19.3	13.4
Tohmajärvi	sandy loam	5.70	0.80	1830	46.3	159	5.2	–	–
Ruukki	loamy sand	5.72	0.93	1213	108.0	113	21.5	7.3	6.8
Sotkamo	organic soil	5.40	1.52	1692	80.0	180	5.4	12.8	20.3
Rovaniemi	loamy sand	6.20	–	1860	238.0	603	20.0	rich in humus	

4.6 Statistical methods

Results of the field experiment were analysed using PROC MIXED of SAS Statistical Software (Littell et al. 1996) for Windows 6.12. All experimental designs, randomisations and statistical analyses, except those for repeated measurements, were performed according to Gomez and Gomez (1984). Statistical analyses with repeated measurements were performed according to Gumpertz and Brownie (1993). The covariance structure in the repeated measurements was chosen after comparing the structures using Akaike's information criterion (Wolfinger 1996). Assumptions of models were checked by graphical methods; box-plot for normality of errors and plots of residuals for constancy of error variance (Neter et al. 1996) or using PROC UNIVARIATE of SAS. The parameters of the models were estimated by the restricted maximum likelihood (REML) method. For comparing the fixed effects the CONTRAST statement of PROC MIXED was used to produce t-type contrasts. These data are not shown but are discussed in connection with the results.

Experiments for harvest timing, row spacing and fertilizer use

The field experiments for reed canary grass and tall fescue were set up in a split-split-plot design in Jokioinen and in strip-split-plot design in Vihti. Results were analysed using corresponding mixed models. DM yield, number and proportion of stems, DM content, crude fibre, ash, SiO_2, N, P and K content were analysed separately for each year on clay (Jokioinen) and on organic (Vihti) soil, for both species, to test differences among harvest timings, row spacing and fertilizer application levels and their interactions. In 1995, the DM yield data for reed canary grass for Jokioinen and the data for DM content of tall fescue for Vihti were logarithmically transformed to give homogeneity of variance and normal distribution. The significant yield differences caused by harvest timing, row spacing and fertilizer rate were examined using the contrast statement in PROC MIXED.

Experiment on age of the reed canary grass ley

The field experiment comprised two fertilizer application rates that were completely randomised into blocks. Commercial NPK fertilizer was used. The fertilizer treatments were combined with two harvest timings in a split-plot design with 3 replicates. To establish differences, analysis of variance was done for DM yield, stem proportion and number of stems m^{-2}, content of crude fibre, ash and silica as well as for pulping characteristics. Harvest year was used as a repeated factor when analysing the variables. The year of harvest had a correlated effect when used as a repeated factor. After testing different possibilities for analysing the DM yield and stem yield the covariance structure chosen was ARH(1). The heterogeneous first-order autoregressive ARH(1) structure assumes exponentially declining correlations (Wolfinger 1996) accepting random variation among the years. The covariance structure chosen for the quality variables was that for compound symmetry (CS) where the covariances in the model remain constant.

Experiment on sowing time and cover crop of reed canary grass

The five sowing times were completely randomised across four blocks. The data for DM yield, DM content, number of stems and proportion of stem fraction years were analysed for three years using the mixed procedure. Harvest year was used as a repeated factor when analysing the variables. The covariance structure of the repeated measurements best fitted ARH(1).

Experiment on timing the delayed harvest

The effect of four successive harvests (subplots) of reed canary grass was studied at two cutting heights (main plots) in an experiment designed as a split-plot with four replicates. The five years were used as a repeated factor when analysing the variables DM yield and DM content, and the four years when analysing proportion of stem fraction, number of stems and the variables describing the development of plant stand measured in autumn. The covariance structure of the repeated measurements fitted best was CS.

Reed canary grass variety trials
Analysis of variance was done for DM yield at each experimental site separately. Year of harvest was used as a repeated factor when analysing the yield. The covariance structure of the repeated measurements fitted best was UN, which specifies a completely general (unstructured) covariance matrix. The structure does not include any assumptions of equality of variances or relations between covariances, and thus allows variation for each year (Wolfinger 1996). The proportion of plant parts and the mineral content of each plant part was studied in Jokioinen, Ruukki and Ylistaro from three cultivars. In stem proportion, significant differences among trial sites and varieties were tested using variance analyses. These were also used when testing pulping characteristics among the plant parts for cultivar Palaton. When testing the differences in mineral (ash, Si, K) and crude fibre content between plant parts from each trial site, the plant part was used as a repeated factor and the covariance structures used were UN or ARH(1).

4.7 Climate data

Climate data collected from Jokioinen in 1991–1999 and from seven research stations are given in Appendix I. The data from the years when the experiments were conducted are compared with the values from 1961–1990 (Finnish Meteorological Institute 1991).

5 Results

5.1 Selecting plant species

Mineral composition
The concentrations of undesirable minerals were higher in the non-wood species than in birch, and the concentrations in grasses and cereals differed from those in dicotyledons (Table 18). The ash content was lowest in straw of linseed and hemp (3.8–3.9% of DM) and highest in nettle and barley. The silica concentration in grasses ranged between 0.9 and 6.1% of DM and that in dicotyledons from 0.2 to 0.8%, being lowest in linseed straw (<0.1%). Plant mineral content was dependent on growth stage.

Pulping and fibre characteristics
Grass biomass and cereal straw were easy and fast to cook taking only 10 to 15 minutes, compared with processing wood, which took at least 90 minutes. Only small differences between the monocotyledons were found. Pulp yields were 33 to 40% of DM for grasses harvested during the growth period, and 42 to 48% for cereal straw (Table 19). Pulp yields for dicotyledons were much lower. The amount of screenings, which is insignificant in commercial birch sulphate pulp, was 0.1 to 1.2% for grasses, 11.8% for common reed, 0.6 to 2.6% for cereal straw and 13 to 41% for dicotyledons. Common reed gave a pulp yield nearly as high as cereal straw, but the amount of screenings showed that the cooking procedure was not appropriate for reed (Table 19).

Lower kappa numbers indicated that lignin content was lower for grass pulp than for wood pulp. Grasses harvested during the growing period were easily cooked to kappa number 9 to 14, which was lower than the kappa number for commercial birch sulphate pulp (17–20) (Table 19) and that for the other plants tested. Viscosity of the pulp made of grass, straw or hemp was similar to that of birch pulp. The amount of NaOH (16% of DM) used in trials was too low for dicotyledons. In the case of red clover and goat's rue the pulp yield, amount of screenings and kappa number, became more acceptable

Table 18. Mineral content in dry matter (DM) of crop samples taken in 1990.

Species	Growth stage	Ash %	SiO_2 %	Fe mg kg^{-1}	Mn mg kg^{-1}	Cu mg kg^{-1}	N %
Monocotyledons							
Reed canary grass	Culms 40 cm	8.76	2.63	56.7	24.0	7.05	1.73
	Panicles emerged	8.51	5.61	83.1	50.2	5.40	0.93
Tall fescue	20% panicles emerged	9.54	2.42	101.5	61.9	5.50	2.47
	Seed ripening	7.41	2.25	72.8	53.8	3.54	0.90
Meadow fescue	80% panicles emerged	7.62	1.52	100.3	42.4	5.03	1.28
	Seed ripening	6.99	2.04	78.8	52.3	4.11	0.97
Timothy	40% ears emerged	5.09	0.88	53.6	38.0	4.42	1.10
	Seed ripening	4.17	1.60	130.7	57.3	3.46	0.73
Rye	Seed ripened	5.31	3.61	131.3	18.8	3.26	0.52
Oat	"	9.10	3.68	159.0	46.2	4.95	0.96
Barley	"	10.03	6.13	48.6	15.3	3.29	0.33
Wheat	"	5.41	3.52	97.3	13.0	1.76	0.54
Common reed	Anthesis	7.79	3.30	51.3	13.4	3.58	1.06
	Senescence	4.17	3.82	72.7	13.4	2.78	0.31
Dicotyledons							
Goat's rue	Anthesis	8.94	0.19	98.7	21.4	10.60	2.87
	Seed ripening	6.93	0.27	109.0	17.6	7.95	1.96
Red clover	Anthesis	8.24	0.17	90.3	25.3	8.65	2.43
	Seed ripening	6.22	0.31	91.2	24.0	7.64	1.83
Lucerne	Anthesis	10.33	0.18	125.8	15.8	6.76	2.45
	Seed ripening	6.83	0.38	118.5	16.9	7.04	1.89
Linseed straw	Seed ripened	3.93	<0.10	54.6	87.3	6.09	0.99
Fibre hemp	Seed ripened	3.75	0.19	87.3	11.2	4.05	0.56
Nettle	Anthesis	12.13	0.78	100.7	102.7	6.92	2.70
Turnip rape	Seed ripened	6.10	0.14	74.5	14.0	3.27	0.96
Rape straw	Seed ripened	6.82	0.36	351.2	25.8	3.66	0.83
Birch, chipped		0.41	<0.10	22.3	114.0	0.90	0.11

when the dose of cooking chemical was increased to 20 or 24% of DM (Table 20).

5.2 Effect of crop management on raw material for non-wood pulp

5.2.1 Harvest timing, row spacing and fertilizer use

The aim of the study was to establish the combination of harvest timing and fertilizer application rate that resulted in the highest DM yield of the highest quality. To enhance straw production the doubled row spacing was compared with a 12.5 cm row spacing, which is more commonly used in Finland. Results for each year were analysed separately in reed canary grass and tall fescue. The interaction effects are presented in Tables 21, 24, 26, 29, 32, 36, 39, 41, 44 and 46, and were tested using contrast statements (data not shown in tables).

5.2.1.1 Reed canary grass

Dry matter yield

Harvest timing and fertilizer application rate affected markedly DM yield of reed canary grass, whereas the row spacing had only a minor ef-

Table 19. Screened pulp yield (% of dry matter), screenings (% of dry matter), kappa number, viscosity, fibre length (LW) and content of crude fibre (% of dry matter) for crop plant samples taken in 1990 compared to commercial birch sulphate pulp. Pulp process soda-anthraquinone.

Plant species	Growth stages	Pulp yield %	Screenings %	Kappa number	Viscosity	LW mm	Crude fibre %
Monocotyledons							
Reed canary grass	Culms 40 cm	36.9	0.3	9.1	1090	0.57	33.4
	Panicles emerged	35.6	1.3	12.1	1220	–	33.8
Tall fescue	20% panicles emerged	32.6	0.1	10.2	910	0.60	27.9
	Seed ripening	41.5	0.9	12.6	1070	–	36.8
Meadow fescue	80% panicles emerged	40.1	0.3	12.0	1080	0.72	33.6
	Seed ripening	45.5	0.6	13.0	1060	–	40.0
Timothy	40% ears emerged	33.7	1.2	13.5	1020	0.60	28.4
	Seed ripening	34.2	2.1	16.6	920	0.62	30.1
Rye	Seed ripened	48.2	2.6	12.5	1100	0.90	49.0
Oat	Seed ripened	42.3	0.6	14.4	1180	0.80	38.4
Barley	Seed ripened	48.3	2.0	19.9	–	–	45.7
Wheat	Seed ripened	43.4	2.1	10.0	–	–	45.3
Common reed	Anthesis	38.1	11.8	31.7	–	–	43.4
	Senescence	48.3	7.6	45.8	–	–	45.9
Dicotyledons							
Goat's rue	Anthesis	16.7	16.9	59.0	810	–	36.3
	Seed ripening	13.7	24.2	45.5	790	0.76	41.2
Red clover	Anthesis	29.5	6.6	76.8	810	–	27.8
	Seed ripening	23.9	13.4	63.4	850	0.70	40.6
Lucerne	Anthesis	19.5	11.8	77.3	680	–	30.9
	Seed ripening	20.9	17.2	65.0	810	1.08	43.8
Linseed straw	Seed ripened	13.0	35.7	80.2	760	–	57.2
Fibre hemp	Seed ripened	13.4	41.0	49.2	1100	–	61.4
Nettle	Anthesis	9.9	21.5	78.7	610	0.42	33.8
Turnip rape	Seed ripened	16.4	36.7	78.9	590	–	56.7
Rape	Seed ripened	12.3	38.5	74.7	690	0.83	51.1
Birch	Chipped	50.0	–	17–20	>1000	0.90	60.7

Table 20. Pulp yield (% of dry matter), screenings (% of dry matter), kappa number, viscosity and fibre length (LW) for goat's rue and red clover after pulping at different concentrations of NaOH (% of dry matter).

Crop species	NaOH-%	NaOH-residue g l^{-1}	Pulp %	Screenings %	Kappa number	Viscosity	LW mm
Goat's rue	16.0	2.6	13.7	24.2	45.5	790	–
"	20.0	6.5	18.3	15.7	38.2	970	1.01
"	24.0	11.7	22.5	11.6	34.7	920	0.92
Red clover	16.0	0	23.9	13.4	63.4	850	0.70
"	20.0	4.7	22.8	9.7	48.5	890	0.87
"	24.0	9.7	24.8	7.7	46.2	930	0.89

Table 21. Significance (P values) of difference among harvest time, row spacing and fertilizer application rate in dry matter yield of reed canary grass in 1994, 1995 and 1996 in Jokioinen and Vihti.

	Jokioinen			Vihti		
Source	1994	1995	1996	1994	1995	1996
Harvest (H)	0.0030	0.0054	0.1170	0.0001	0.0001	0.0001
Row (R)	0.0021	0.1073	0.2277	0.1935	0.9684	0.6792
HR	0.1468	0.3052	0.8931	0.1295	0.4701	0.5114
Fertilizer (F)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
HF	0.0382	0.4528	0.0043	0.0001	0.0001	0.0001
RF	0.0053	0.1087	0.3554	0.5662	0.0631	0.1162
HRF	0.2681	0.1227	0.4381	0.3927	0.7857	0.0137

Table 22. Effect of fertilizer application rate on total dry matter yield (kg ha^{-1}) of reed canary grass at different harvest timings in 1994, 1995 and 1996 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June+Oct	6380	7400	8050	9080	7810a
	Aug	7520	8800	9450	9080	8850a
	May	5340	6000	6320	6660	6050b
*Means for N rate		6380a	7400b	8050c	8450d	Means for row spacing*
*Means for	12.5 cm	6500a	8080b	8450b	8610b	7910a
	25.0 cm	6250a	6720a	7650b	8300c	7230b
1995	June+Oct	3870	4760	4890	5680	4760a
	Aug	5150	6720	7300	7300	6560b
	May	5990	7340	7750	8260	7280b
*Means for N rate		4930a	6170b	6520b	7000c	
1996	June+Oct	6850	7700	9030	9440	8260a
	Aug	4660	6670	8230	9760	7330b
	May	5320	7040	8140	8960	7360b
*Means for N rate		5610a	7140b	8470c	9390d	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

fect. In the first harvest year the row effect was pronounced in Jokioinen and in 1996 the harvest timing x row spacing x fertilizer application rate interaction was statistically significant in Vihti (Table 21). There were yield variations among years (Tables 22 and 23) caused by differences in weather conditions (Appendix I). Low precipitation during the growth period of 1995 (Appendix I) resulted in low DM yields, especially on sandy clay soil in Jokioinen (Table 22). In Vihti, the effect of the drought was recorded as retarded regrowth following harvesting in June 1995 (Table 25).

On sandy clay soil, the delayed harvest in May 1995 resulted in significantly lower yield when compared with harvest at seed stages (Aug) or earlier summer (June+Oct) in 1994 (Table 22). In 1995, yield at the seed stage did not differ from that of delayed harvest in Jokioinen. In 1996, there were no significant differences in

Table 23. Effect of fertilizer application rates on dry matter yield (kg ha^{-1}) of reed canary grass at different harvest timings in 1994, 1995 and 1996 on organic soil in Vihti.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June+Oct	8730	11450	13030	14320	11880a
	Aug	9730	11400	12630	13970	11930a
	May	6580	7910	7730	8330	7640b
*Means for N rate		8350a	10260b	11130c	12210d	
1995	June+Oct	7150	7800	9290	10480	8340a
	Aug	6560	12390	13150	14500	12400b
	May	6110	6140	6650	6000	6220c
*Means for N rate		7150a	8780b	9700c	10320d	
1996	June+Oct	6020	6990	9320	10260	8150a
	Aug	7250	11130	14010	14670	11760b
	May	6130	6140	6120	5970	6090c
*Means for N rate		6460a	8090b	9820c	10300c	

* Means within the column (harvest) and the row (N rate) followed by a different letter are significantly different (P<0.05).

DM yields for harvest times on clay soil. The wider row spacing (25 cm) resulted in lower yields in 1994 (Table 22), but subsequently there were no differences in yields attributable to different row spacing. Increasing fertilizer use resulted in an increase in total yield at the first harvest (June+Oct) of each year. However, the difference in DM yield between crops harvested at the seed stage (Aug) and the delayed harvest (May) at the two highest fertilizer application rates differed only in 1996 (Aug P = 0.0003, May P = 0.0432).

On organic soil, row spacing did not effect yield (Table 21) in any of the years or at any harvest times. Harvesting at the seed stage in August gave the highest yield in every year on organic soil (Table 23). Fertilizer application significantly affected the DM yield, but the effect depended on harvest timing and year. In 1994, increasing fertilizer application rates consistently increased the biomass at both harvest times (June+Oct and Aug) (P<0.01), but when harvested in the following May, only the non-fertilized plots differed from the fertilized plots (P<0.01). In the subsequent years, the fertilizer application rate had no effect on the biomass yield at delayed harvest May. In 1996, the yield difference attributable to applying100 and 150 kg N ha^{-1} was not significant in either earlier harvests indicating that 150 kg N ha^{-1} was unnecessarily high.

The plots harvested in June were also cut in October in order to measure the regrowth. Fertilizer application rate had the most significant effect on regrowth yield of reed canary grass (Table 24). On clay soil, the regrowth comprised, on average, 17% of the total yield of the plots in 1994, 32% in 1995 and 22% in 1996 and on organic soil 14%, 5% and 28%, respectively (Table 25). In 1994, the highest rate of fertilizer application increased the regrowth significantly (P<0.001) both on clay and organic soils. In 1995, the regrowth was very restricted in Vihti, being less than 500 kg ha^{-1}, due to low precipitation in late summer (Appendix I). In Jokioinen, the rainy June in 1995 favoured regrowth. In 1996, increase in the fertilizer application rate decreased the regrowth biomass in plots with 25 cm row spacing in Jokioinen (P<0.001). In Vihti, the highest rate increased the regrowth significantly (P<0.05), but the row spacing had no effect.

Table 24. Significance (P values) of difference between row spacing and fertilizer application rate for regrowth (measured in October) of reed canary grass harvested in June in Jokioinen and in Vihti.

	Jokioinen			Vihti		
Source	1994	1995	1996	1994	1995	1996
Row spacing (R)	0.2248	0.1693	0.1927	0.2949	0.5427	0.9681
Fertilizer (F)	0.0009	0.2057	0.0006	0.0001	0.0008	0.0693
RF	0.7704	0.5297	0.0001	0.2042	0.7582	0.5390

Table 25. Effect of fertilizer application rate on regrowth (measured in October) of reed canary grass (kg ha^{-1} dry matter) (harvested in June in 1994, 1995 and 1996 in Jokioinen and in Vihti.

		Jokioinen					Vihti				
		N rate kg ha^{-1}				Means	N rate kg ha^{-1}				Means
Year	Row	0	50	100	150	for year	0	50	100	150	for year
1994	Mean	1250	1200	1320	1510	1320	1470	1600	1720	2090	1720
1995	Mean	1520	1380	1540	1580	1510	270	300	350	430	340
1996	12.5 cm	1830	1810	1950	1910	1790	1590	1510	1960	2250	1830
	25.0 cm	1980	1640	1690	1500						

Table 26. Significance (P values) of difference in harvest timing, row spacing and fertilizer application rate effect on DM content of reed canary grass in 1994, 1995 and 1996 in Jokioinen and Vihti.

	Jokioinen			Vihti		
Source	1994	1995	1996	1994	1995	1996
Harvest (H)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Row (R)	0.2726	0.6805	0.7799	0.7000	0.1919	0.3795
HR	0.4398	0.6074	0.7111	0.5133	0.0333	0.9530
Fertilizer (F)	0.0001	0.0701	0.0001	0.0024	0.0001	0.1786
HF	0.0001	0.0177	0.0001	0.5131	0.2164	0.0003
RF	0.8846	0.5672	0.7458	0.9828	0.5902	0.8581
HRF	0.1853	0.3884	0.4039	0.9907	0.0537	0.0856

Dry matter content

The DM content of reed canary grass was not affected by row spacing in any of the years or at any harvest timings (Table 26). In Jokioinen and Vihti, time of harvest and fertilizer application rate had marked effects on DM content in each of the years studied. Fertilizer rate x harvest timing interaction for DM content was also recorded. On clay soil, the means of the DM content ranged from 23.9% to 29.9% when harvested in June, from 40.1% to 45.6% in August and from 86.3% to 93.2% in the following May (Table 27). The highest DM contents in June and August were obtained usually at the rate 0 or 50 kg N ha^{-1} (Table 27). However, in May the effect was no longer registered, and DM percentages varied greatly.

When grown on organic soil, the DM content of harvested reed canary grass ranged from 17.8% to 31.5% in June, from 31.7% to 42.1% in August and from 72.9% to 89.3% in May (Table 28). In 1994 and 1995, the highest DM con-

Table 27. Fertilizer application rate and row spacing effects on dry matter content (%) of reed canary grass at different harvest timings in 1994, 1995 and 1996 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for harvest*
Harvest		0	50	100	150	
1994	June	26.8	25.5	25.4	23.9	25.4a
	Aug	42.3	42.2	40.9	38.9	41.1b
	May	87.0	86.3	86.9	87.8	87.0c
*Means for N rate		52.1a	51.3b	51.1b	50.2c	
1995	June	29.9	30.0	29.1	28.6	29.4a
	Aug	42.2	45.6	44.6	43.9	44.1b
	May	93.2	93.0	92.6	93.1	93.0c
*Means for N rate		55.1a	56.2b	55.4a	55.2a	
1996	June	29.3	29.3	27.2	25.0	27.7a
	Aug	41.7	43.2	42.4	40.1	41.9b
	May	89.2	90.5	90.8	90.3	90.2c
*Means for N rate		53.4a	54.3b	53.5a	51.8c	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

Table 28. Effect of fertilizer application rate and row spacing on dry matter content (%) of reed canary grass at different harvest timings in 1994, 1995 and 1996 on organic soil in Vihti.

		N rate kg ha^{-1}				Means for harvest*
Harvest		0	50	100	150	
1994	June	30.3	27.6	26.7	26.6	27.8a
	Aug	39.0	38.5	37.6	37.1	38.0b
	May	74.5	75.1	73.5	72.9	74.0c
*Means for N rate		47.9a	47.1a	45.9ab	45.5b	
1995	June	31.5	30.9	29.9	28.9	30.3a
	Aug	40.8	42.1	40.2	38.7	40.5b
	May	89.3	88.4	87.9	85.7	87.8c
*Means for N rate		53.9a	53.8a	52.7b	51.0c	
1996	June	17.8	19.2	18.4	18.2	18.4a
	Aug	32.2	33.2	34.5	31.7	32.9b
	May	82.4	80.9	75.3	80.9	79.9c
*Means for N rate		44.1a	44.4ab	42.8ac	43.6a	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

tents were obtained in biomass harvested from plots that had received 0 or 50 kg N ha^{-1} (Table 28). The lowest DM contents on organic soil were recorded in biomass harvested from plots that had received the highest amount of fertilizer. In 1996, this effect was not recorded.

The DM content of regrowth biomass was affected by row spacing only in 1994 in Jokioinen (Table 29): the plots with wider row spacing gave higher DM content. The DM contents of regrowth harvested in October ranged from 33 to 40% on average in Jokioinen, and from 24

Table 29. Significance (P values) of difference between row spacing and fertilizer application rate effect on DM content of regrowth biomass (measured in October) of reed canary grass in Jokioinen and Vihti in 1994, 1995 and 1996.

	Jokioinen			Vihti		
Source	1994	1995	1996	1994	1995	1996
Row (R)	0.0343	0.9006	0.7616	0.5320	0.2027	0.5889
Fertilizer (F)	0.6399	0.0775	0.0001	0.0014	0.0106	0.2591
RF	0.7429	0.2523	0.0111	0.8367	0.7017	0.0138

to 35% in Vihti. These were higher than the respective DM percentages in June harvesting on clay soil and in two of the years on organic soil (Tables 30 and 31).

Table 30. Effect of fertilizer application rate on dry matter content (%) of regrowth biomass (measured in October) of reed canary grass in 1994 and 1995 in Jokioinen and Vihti.

	N rate kg ha^{-1}			
Harvest	0	50	100	150
1994 Jokioinen	33.1	33.1	32.6	32.9
1995 Jokioinen	39.3	39.3	40.0	40.1
1994 Vihti	35.4	34.5	33.6	33.7
1995 Vihti	24.7	25.3	25.5	24.6

Number of stems of reed canary grass

In Jokioinen, harvest timing, row spacing and fertilizer application rate had a significant effect on the number of stems m^{-2} (Table 32). Reed canary grass stands had the highest number of stems in August, averaging 816 m^{-2} (Table 33). Plants from the plots with 12.5 cm row spacing had more stems and tillers compared with the plots with 25 cm row spacing, when harvested in June (P = 0.0396) and August (P = 0.0011), whereas no significant differences attributable to row spacing were recorded when harvested in May. In June and August, the lowest numbers of stems were found in non-fertilized plots ($P<0.05$), whereas in May no differences resulting from application of different fertilizer rates were established.

On organic soil the numbers of stems m^{-2} were higher than on clay soil. The row spacing used had a modest effect at best on stem number (Table 35). Harvest timing and fertilizer application rate affected the number of stems m^{-2} (P = 0.0526 and P = 0.0301, respectively) (Table 32). The highest stem numbers per square metre were found in June (1008 stems m^{-2}) and in August (960 stems m^{-2}), whereas at delayed harvest the number of stems was less, 801 stems m^{-2} (P = 0.0590 Aug, P = 0.0234 June). In June and August the highest number of stems was found in plots fertilized at the highest rate, but in May the lowest rates were associated with the highest stem numbers.

Table 31. Effect of fertilizer application rate and row spacing on dry matter content (%) of regrowth biomass (measured in October) of reed canary grass in 1996 in Jokioinen and Vihti.

	Row	N rate kg ha^{-1}				Means for
Harvest	spacing	0	50	100	150	row spacing
1996 Jokioinen	12.5 cm	33.0	35.3	35.7	36.2	35.0
	25.0 cm	34.6	35.3	34.7	36.9	35.3
1996 Vihti	12.5 cm	25.9	24.2	24.4	26.5	25.2
	25.0 cm	23.8	27.3	25.4	25.7	25.5

Table 32. Significance (P values) of difference in harvest timing, row spacing and fertilizer application rate effect on number of stems m^{-2}, stem fraction, crude fibre, and mineral content (ash, SiO_2, N, P, K) of reed canary grass in 1994 in Jokioinen and Vihti.

Source	Number of stems	Stem fraction	Crude fibre	Ash	SiO_2	N	P	K
Jokioinen								
Harvest (H)	0.0064	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Row (R)	0.0032	0.0291	0.0067	0.2958	0.8821	0.5950	0.0828	0.6638
HR	0.0192	0.3777	0.0064	0.3752	0.5304	0.2159	0.0466	0.8398
Fertilizer (F)	0.0003	0.0001	0.5249	0.0001	0.0001	0.0001	0.0001	0.0001
HF	0.0408	0.1120	0.0164	0.0813	0.5439	0.0001	0.0106	0.0001
RF	0.6276	0.6141	0.3366	0.3309	0.3253	0.0723	0.4141	0.9235
HRF	0.1232	0.9329	0.3022	0.3575	0.1426	0.7666	0.0206	0.9681
Vihti								
Harvest (H)	0.0526	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001
Row (R)	0.0879	0.5307	0.8140	0.4839	0.5136	0.1301	0.1288	0.6682
HR	0.1789	0.6002	0.3466	0.5378	0.1604	0.9611	0.1337	0.0445
Fertilizer (F)	0.0301	0.0060	0.0365	0.0034	0.0001	0.0001	0.0001	0.0001
HF	0.0133	0.1618	0.4681	0.0001	0.8418	0.0001	0.0044	0.0001
RF	0.7918	0.2684	0.7616	0.1775	0.2819	0.7649	0.9258	0.7968
HRF	0.8720	0.1730	0.4921	0.1209	0.5262	0.3137	0.1612	0.7287

Table 33. Effect of fertilizer application rate and row spacing on number of stems m^{-2}, stem fraction (% of dry matter) and crude fibre of reed canary grass in June and August, 1994 and in May, 1995 on clay soil in Jokioinen.

	Row spacing 12.5 cm					Row spacing 25.0 cm					
	N rate kg ha^{-1}					N rate kg ha^{-1}					Means for
Harvest	0	50	100	150	Mean	0	50	100	150	Mean	harvest*
Number of stems m^{-2}											
June	546	656	796	706	676	562	410	746	552	568	622a
Aug	814	914	998	969	969	576	732	706	816	708	816b
May	572	578	608	500	565	488	596	580	644	577	571a
*Means for row spacing					721a					615b	
*Means for N rate	593a	648a	739b	698a							
Stem fraction % of DM											
June	48.0	48.8	45.3	44.6	46.7	46.5	46.5	44.5	43.1	45.2	45.8a
Aug	54.7	54.4	52.9	52.3	53.6	54.1	54.5	52.5	52.4	53.4	53.5b
May	64.5	63.9	62.8	64.1	63.8	61.5	63.9	61.3	62.7	62.4	63.1c
*Means for row spacing					54.6a					53.6b	
*Means for N rate	54.9a	55.2a	53.2b	53.2b							
Crude fibre % of DM											
June	37.6	39.3	39.3	38.3	38.6	38.7	38.7	39.3	38.5	38.8a	38.7a
Aug	37.4	36.5	36.1	37.0	36.7	39.2	38.5	38.8	37.9	38.6a	37.7b
May	45.6	46.7	45.8	45.8	46.0	45.5	45.9	46.1	46.4	46.0b	46.0c
*Means for row spacing					40.4a					41.1b	
*Means for N rate	40.7a	40.9a	40.9a	40.6a							

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

Stem proportion of reed canary grass
In both trials harvest timing and fertilizer application rate affected the proportion of stems in harvested biomass of reed canary grass (Table 32); the later the harvest, the higher the stem proportion in biomass (Tables 33 and 35). The highest stem proportion was recorded from plots that received the two lowest fertilizer application rates. Increasing fertilizer application decreased the relative amount of stem fraction in both trials. In Jokioinen (Table 33), the wider row spacing of 25 cm decreased the stem proportion compared with 12.5 cm ($P = 0.0291$), whereas in Vihti (Table 32), row spacing had no significant effect on stem proportion in harvested yield.

Crude fibre content of reed canary grass
In both reed canary grass trials (Table 33 and Table 35), crude fibre content of biomass was significantly higher at delayed harvest than when harvested in June or August ($P = 0.0001$). When biomass was harvested in May, fertilizer application rate had no significant effect on crude fibre content either on clay or organic soil. On clay soil, at the flowering stage, the highest crude fibre contents were obtained at 50 and 100 kg N ha^{-1}, and at the seed stage in non-fertilized plots ($P<0.05$). On organic soil, the fertilizer had very little influence on crude fibre content. However, when harvested at the seed stage, the highest rate resulted in the lowest crude fibre content ($P<0.05$). Row spacing affected crude fibre content only on clay soil when harvested at the seed stage, being higher at a row spacing of 25 cm ($P = 0.0004$) than at 12.5 cm.

Ash content of reed canary grass
Ash content of harvested biomass was, on average, lower on organic soil than on clay soil. In both Jokioinen and Vihti, the ash content of reed canary grass harvested in May (5.7% and 5.1%, respectively) was significantly lower than in plants harvested in August (8.3% and 7.5%, respectively) and June (8.7% and 7.8%, respectively) (Tables 34 and 35), but row spacing had no significant effect. At all harvests in Jokioinen and at spring harvest in Vihti, the highest ash contents were found in plants from non-fertilized plots.

Silica content of reed canary grass
Silica (SiO_2) content was lower in plants harvested on organic soil than from clay soil. At flowering, silica content on organic soil was 2.6% and on clay soil 3.0%, at the seed stage 2.7% and 3.5% respectively, and at delayed harvest 4.3% and 4.8%, respectively (Tables 35 and 34). Silica contents were strongly affected by harvest timing and fertilizer application rate for both soils ($P<0.001$), but row spacing had no significant effect on silica content of harvested biomass. Harvesting during the growing period resulted in significantly lower silica contents ($P<0.001$) than harvesting in May. Silica content was highest in non-fertilized plots and it decreased significantly ($P<0.001$) when fertilizer application rate was increased up to 100 kg N ha^{-1}. The decrease in silica content was smaller when the fertilizer rates were increased from 100 to 150 kg N ha^{-1} ($P = 0.0121$ on clay soil, $P = 0.087$ on organic soil).

Nitrogen, phosphorus and potassium content of reed canary grass
Harvest timing and fertilizer application rate had a significant effect ($P<0.001$) on N, P and K content of reed canary grass on both clay and organic soils (Tables 32, 34 and 35). The content of these minerals was lower the later the grass was harvested. The higher fertilizer application rates increased the N content of plants significantly in both trials at all harvests (Tables 34 and 35). However, at delayed harvesting the difference resulting from the application rates of 100 and 150 kg N ha^{-1} was not significant in either of the trials. The rates of 100 and 150 kg N ha^{-1} increased the P content in plants significantly on organic soil at all harvest times (Table 35). The effect of fertilizer was not as clear on clay soil: only 150 kg N ha^{-1} seemed to increase the P content in plants compared with other fertilizer application rates. On clay soil, the wider row spacing resulted in lower P content at both sum-

Table 34. Effect of fertilizer application rate on mineral content (ash, SiO_2, N, P, K) in dry matter of reed canary grass harvested in June and August, 1994 and in May, 1995 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
Ash %	June	9.1	8.7	8.5	8.6	8.7a
	Aug	8.7	8.3	7.9	8.1	8.3b
	May	6.5	5.7	5.3	5.2	5.7c
*Means for N rate		8.1a	7.6b	7.2c	7.3c	
SiO_2 %	June	3.9	3.1	2.6	2.3	3.0a
	Aug	4.6	3.6	3.0	2.8	3.5b
	May	5.7	4.8	4.4	4.3	4.8c
*Means for N rate		4.7a	3.9b	3.4c	3.1d	
N %	June	1.36	1.56	1.70	2.05	1.67a
	Aug	0.73	0.85	1.03	1.28	0.97b
	May	0.50	0.60	0.67	0.74	0.63c
*Means for N rate		0.87a	1.00b	1.14c	1.36d	
P g kg^{-1}	June	2.91	2.97	2.97	3.21	3.02a
	Aug	2.20	2.10	2.06	2.19	2.14b
	May	0.80	0.78	0.92	0.97	0.87c
*Means for N rate		1.97a	1.95a	1.98a	2.12b	
K g kg^{-1}	June	23.1	25.1	25.3	28.7	25.5a
	Aug	18.5	21.1	22.6	24.0	21.5b
	May	1.54	1.59	1.60	1.64	1.59c
*Means for N rate		14.4a	15.9b	16.5b	18.1c	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

mer harvests and the difference attributable to the row spacing was significant ($P = 0.0104$) solely at the seed stage (Table 34).

During the winter, the K content decreased from about 21 to 1.6 g kg^{-1} DM in both trials. All the fertilizer application rates increased the K content in plants significantly ($P<0.01$) on clay soil at harvests in June and August (Table 34). On organic soil, 150 kg N ha^{-1} did not result in increased K content compared with 100 kg N ha^{-1} at summer harvests. At delayed harvest, increasing fertilizer applications were not associated with altered K content of the biomass.

5.2.1.2 Tall fescue

Dry matter yield

On both clay (Jokioinen) and organic (Vihti) soil, harvest timing and fertilizer application rate had significant effect ($P<0.01$) on DM yield of tall fescue in 1994 and 1995, whereas row spacing had no marked effect (Table 36). In 1994, the first harvest in June, followed by an additional harvest in October, gave the highest total DM yield on both soil types. In 1995, the highest yields were obtained when the crop was harvested at the seed stage in August. Delayed harvest in May resulted in significantly less yield than harvest at the seed stage in both years and in both trials (in 1994 $P<0.001$, in 1995 $P<0.03$). The yield from delayed harvest of plots in Jokioinen averaged 54% and in Vihti 37% to 41% of those harvested during the growing period.

The effect of fertilizer application rate varied among trials. On clay soil, the increased fertilizer application rate did not result in increased DM yield when >50 kg N ha^{-1} was applied for the June+October harvest or for the seed stage

Table 35. Effect of fertilizer application rate on number of stems m^{-2} and proportion of stems, crude fibre and mineral content (ash, SiO_2, N, P, K) in dry matter of reed canary grass in June and August, 1994 and in May, 1995 on organic soil in Vihti.

Harvest	N rate kg ha^{-1}	Number of stems m^{-2}	Proportion of stems %	Crude fibre %	Ash %	SiO_2 %	N %	P g kg^{-1}	K g kg^{-1}
June	0	779	53.6	38.8	7.8	3.3	1.01	2.24	20.4
	50	1087	51.7	39.7	7.7	2.6	1.17	2.32	23.4
	100	1072	50.6	38.8	7.7	2.2	1.45	2.53	25.1
	150	1094	48.8	39.1	7.8	2.1	1.61	2.53	25.3
Means for harvest		1008a	51.2a	39.1a	7.8a	2.6a	1.31a	2.41a	23.5a
August	0	933	58.1	40.7	7.3	3.4	0.69	1.52	18.5
	50	946	57.9	40.8	7.3	2.7	0.83	1.59	21.2
	100	952	56.5	40.4	7.7	2.5	1.00	1.75	23.6
	150	1010	55.7	39.5	7.9	2.2	1.10	1.84	23.9
Means for harvest		960a	57.0b	40.3b	7.5a	2.7a	0.90b	1.68b	21.8b
May	0	779	63.2	45.8	5.9	5.0	0.52	0.92	1.70
	50	989	60.4	46.4	5.1	4.2	0.51	0.89	1.61
	100	809	62.2	46.2	4.8	3.9	0.64	0.95	1.53
	150	625	62.1	45.5	4.8	3.8	0.71	0.99	1.50
Means for harvest		801b	62.0c	46.0c	5.1b	4.3b	0.60c	0.94c	1.58c
*Means for N rate									
	0	830a	58.3a	41.8ab	7.0a	3.9a	0.74a	1.56a	13.5a
	50	1007b	56.7b	42.3a	6.7b	3.2b	0.84b	1.60a	15.4b
	100	944ab	56.4b	41.8ab	6.7b	2.9c	1.03c	1.74b	16.7c
	150	910ab	55.5b	41.4b	6.8b	2.8c	1.14d	1.79b	16.9c

* Means within the column and row followed by a different letter are significantly different ($P<0.05$).

harvest (Table 37). At delayed harvest in May 1995, 150 kg N ha^{-1} decreased yield significantly in comparison with 100 kg N ha^{-1} ($P<0.0462$). In 1995, all fertilizer treatments increased DM yield stepwise at the first harvest. At the seed stage, 50, 100 and 150 kg N ha^{-1} induced significantly higher yield than the zero rate control, and at delayed harvest in May 1996 100 and 150 kg N ha^{-1} were associated with yield increases above those associated with 0 and 50 kg N ha^{-1} ($P<0.01$). On organic soil, harvest in June plus regrowth in October resulted in the highest yield in the first year, but higher fertilizer rates did not result in significant increase in yield above that from an application of 100 kg N ha^{-1} (Table 38). At the seed stage, the non-fertilized plots gave the lowest yields ($P<0.05$), but no differences were recorded among the various treatments. In 1995, the highest yields were recorded when the crop was harvested at the seed stage in August. At delayed harvest in spring 1996, increasing fertilizer application did not affect DM yield.

The regrowth biomass of tall fescue was harvested during the beginning of October from the plots previously harvested in June at the flowering stage. The only source of yield variation of regrowth biomass in trials resulted from differences in fertilizer application rate (Table 39). In 1994, the regrowth comprised, on average, 13% of the total DM yield on both soil types (Table 40), and in 1995, 25% on clay soil and only 9% on organic soil. Fertilizer applied at 100 and 150 kg N ha^{-1} in particular increased the regrowth capacity both on clay and organic soils ($P<0.05$).

Table 36. Significance (*P* values) of differences in harvest timing, row spacing and fertilizer application rate for dry matter yield of tall fescue in 1994 and 1995 at Jokioinen and Vihti.

	Jokioinen		Vihti	
Source	1994	1995	1994	1995
Row (R)	0.3915	0.1003	0.8584	0.2224
HR	0.3511	0.3349	0.1184	0.9762
Fertilizer (F)	0.0008	0.0001	0.0001	0.0001
HF	0.0001	0.0001	0.0015	0.0002
RF	0.1899	0.2842	0.3269	0.5225
HRF	0.4059	0.9887	0.6242	0.8798

Table 37. Effect of fertilizer application rate on total dry matter yield (kg ha^{-1}) of tall fescue at different harvest timings in 1994 and 1995 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June+Oct	9360	11080	11470	11760	10920a
	Aug	8220	8670	8830	8650	8670b
	May	4710	4530	4310	3980	4380c
*Means for N rate		7430a	8190b	8200b	8130b	
1995	June+Oct	4010	5430	6280	7390	5780a
	Aug	6090	7090	7150	7200	6880a
	May	3220	3630	4230	4670	3960b
*Means for N rate		4440a	5380b	5920c	6420d	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

Table 38. Effect of fertilizer application rate on total dry matter yield (kg ha^{-1}) of tall fescue at different harvest timings in 1994 and 1995 on organic soil in Vihti.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June+Oct	12800	14120	15080	15760	14440a
	Aug	9190	10140	10780	11030	10280b
	May	3900	4090	3920	3980	3970c
*Means for N rate		8630a	9450b	9930bc	10250c	
1995	June+Oct	5880	8330	9260	9830	8320a
	Aug	8020	9170	10430	8950	9140b
	May	3740	3560	4130	4180	3900c
*Means for N rate		5880a	7020b	7940c	7650c	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

Dry matter content of tall fescue

Timing of harvest had the major effect on DM content of biomass on both soil types (Table 41). The biomass yields with highest DM content were harvested in spring (Tables 42 and 43). However, in spring 1996 the harvest was done as late as 30th of May in Vihti and the green shoots that had started to grow increased the

Table 39. Significance (P values) of differences attributable to row spacing and fertilizer application rate for regrowth biomass (measured in October) of tall fescue in Jokioinen and Vihti in 1994 and 1995.

	Jokioinen		Vihti	
Source	1994	1995	1994	1995
Row (R)	0.2216	0.9188	0.4702	0.2629
Fertilizer (F)	0.0001	0.0001	0.0001	0.0001
RF	0.3739	0.8064	0.5789	0.0545

Table 40. Effect of fertilizer application rate on regrowth biomass (kg ha^{-1} measured in October) of tall fescue in Jokioinen and Vihti in 1994 and 1995.

		N rate kg ha^{-1}				Means
Harvest		0	50	100	150	for year
1994	Jokioinen	1250	1310	1510	1570	1410
1995	"	1200	1340	1550	1790	1470
1994	Vihti	1550	1600	2000	2440	1900
1995	"	490	600	770	1110	735

Table 41. Significance (P values) of difference in harvest timing, row spacing and fertilizer application rate effect on DM content of tall fescue in Jokioinen and Vihti in 1994 and 1995.

	Jokioinen		Vihti	
Source	1994	1995	1994	1995
Harvest (H)	0.0001	0.0001	0.0001	0.0036
Row (R)	0.0916	0.3165	0.2709	0.3867
HR	0.1585	0.9419	0.6962	0.5949
Fertilizer (F)	0.0138	0.3560	0.1524	0.0111
HF	0.3595	0.0001	0.3196	0.1100
RF	0.3126	0.0213	0.4781	0.5473
HRF	0.2745	0.0129	0.0716	0.8206

water content in the biomass (Table 43). The biomass of tall fescue harvested from non-fertilized plots had the lowest water content ($P<0.05$) at the flowering stage and in Jokioinen also at the seed stage. At delayed harvest in spring, the differences in biomass following application of different rates of fertilizer application were inconsistent and non-significant.

Fertilizer application rate was the only source for variation in DM content of regrowth biomass in tall fescue harvested in October (Table 44). The DM content of regrowth yield (Table 45) was in most cases lower than that at June harvesting (Tables 42 and 43). Only in 1995 in Jokioinen was the DM content of regrowth biomass higher than that in June. More fertilizer resulted in lower DM contents in 1994 ($P<0.001$) in both trials, but in 1995 only on organic soil ($P<0.05$) (Table 45).

Number of stems of tall fescue

The data on the number of stems m^{-2} are only given for tall fescue from Jokioinen since no significant differences attributable to differences in harvest timing, row spacing, and fertilizer application rates were observed in Vihti (Table 46);

Table 42. Effect of fertilizer application rate and row spacing on dry matter content (%) of tall fescue in 1994 and 1995 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June	30.6	29.9	29.2	29.5	29.8a
	Aug	41.4	39.7	39.4	39.4	40.0b
	May	91.5	91.8	91.8	91.1	91.5c
*Means for N rate		54.5a	53.4b	53.4b	53.3b	
1995	June	29.4	28.9	27.2	27.8	28.4a
	Aug	35.3	34.9	32.1	32.1	33.6b
	May	59.5	63.0	64.8	65.6	63.2c
*Means for N rate		41.4a	42.3a	41.4a	41.3a	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

Table 43. Effect of fertilizer application rate on dry matter content (%) of tall fescue in 1994 and 1995 on organic soil in Vihti.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
1994	June	33.8	32.5	31.0	29.6	31.7a
	Aug	28.3	27.4	28.2	27.0	27.7a
	May	77.9	80.0	80.3	77.9	79.0b
*Means for N rate		46.7	46.6	46.5	44.8	
1995	June	33.5	32.1	30.9	30.2	31.6a
	Aug	37.7	36.7	37.3	38.4	37.5b
	May	42.9	41.7	38.2	39.2	40.4b
*Means for N rate		37.8a	36.6ab	35.3b	35.7b	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

where the number of stems ranged from 556 to 647 m^{-2}. In Jokioinen, harvesting in spring resulted in 574 stems m^{-2}, more than harvesting at the flowering stage (428 stems m^{-2}) ($P = 0.0374$) or seed stage (485 stems m^{-2}) (Table 47). Effects of fertilizer on the density of the tall fescue stand depended on the harvest time (Table 47). In June and August, the highest stem numbers were found when 50 kg N ha^{-1} was used, and in May in non-fertilized plots ($P<0.05$).

Stem proportion of tall fescue

In both trials, harvest timing and fertilizer application rate significantly affected the proportion of stems in tall fescue biomass. In Jokioinen, the row spacing effect was also significant (Table 46). In both trials, stem proportion increased in biomass when plant growth proceeded during the summer, being highest at delayed harvest the following May (Tables 47 and 49). The highest stem proportions were found in non-fertilized plots. Increased fertilizer use decreased the relative amount of stems in biomass as happened also with reed canary grass. In Jokioinen, the wider row spacing resulted in more stems in harvested yield ($P = 0.0052$) (Table 46).

Crude fibre content of tall fescue

In both trials (Tables 47 and 49), crude fibre content was significantly higher at delayed har-

Table 44. Significance (P values) of difference in row spacing and fertilizer application rate on dry matter content of regrowth biomass (measured in October) of tall fescue in 1994 and 1995 in Jokioinen and Vihti.

	Jokioinen		Vihti	
Source	1994	1995	1994	1995
Row (R)	0.7998	0.5336	0.3400	0.1193
Fertilizer (F)	0.0001	0.4277	0.0001	0.0156
RF	0.2837	0.2152	0.2027	0.6478

Table 45. Effect of fertilizer application rate on dry matter content (%) of regrowth biomass (measured in October) of tall fescue in 1994 and 1995 on organic soil in Jokioinen and in Vihti.

		N rate kg ha^{-1}				Means
Harvest		0	50	100	150	for year
1994	Jokioinen	28.7	28.2	27.4	27.3	27.9
1995	"	29.3	29.7	29.3	29.3	29.4
1994	Vihti	25.4	24.5	24.0	23.3	24.3
1995	"	26.5	26.4	25.6	25.3	25.9

Table 46. Significance (P values) of differences in harvest timing, row spacing and fertilizer application rate effect on number of stems, stem fraction, crude fibre, and mineral content (ash, SiO_2, N, P, K) of tall fescue in 1994 Jokioinen and Vihti.

Source	Number of stems	Stem fraction	Crude fibre	Ash	SiO_2	N	P	K
Jokioinen								
Harvest (H)	0.0938	0.0001	0.0001	0.0001	0.0102	0.0001	0.0001	0.0001
Row (R)	0.5831	0.0052	0.0013	0.0165	0.0021	0.0087	0.2041	0.4219
HR	0.0897	0.3906	0.6229	0.5633	0.5089	0.4534	0.3462	0.3792
Fertilizer (F)	0.0543	0.0001	0.0001	0.0002	0.0095	0.0001	0.0001	0.0001
HF	0.0073	0.0287	0.0007	0.2793	0.0049	0.2409	0.0797	0.0001
RF	0.0719	0.0694	0.7835	0.9265	0.3964	0.7096	0.0555	0.6645
HRF	0.2324	0.4238	0.0265	0.1878	0.0626	0.6825	0.8537	0.8450
Vihti								
Harvest (H)	0.4786	0.0040	0.0001	0.0001	0.0147	0.0123	0.0001	0.0001
Row (R)	0.3578	0.1854	0.6908	0.4020	0.5425	0.5272	0.9818	0.9722
HR	0.9792	0.8178	0.0984	0.5057	0.6438	0.9130	0.6072	0.4816
Fertilizer (F)	0.1105	0.0050	0.0001	0.0073	0.0349	0.0001	0.0001	0.0008
HF	0.1095	0.0852	0.0002	0.0372	0.0001	0.2077	0.0007	0.0273
RF	0.7935	0.7007	0.3866	0.7599	0.0759	0.0844	0.1618	0.6035
HRF	0.3104	0.7275	0.1406	0.4982	0.9330	0.7241	0.3720	0.5175

vest than in June or in August ($P<0.001$). At the flowering stage and at delayed harvest, the crude fibre content was highest in the non-fertilized and 50 kg N ha^{-1} plots, both on clay and on organic soil ($P<0.05$). At the seed stage the fertilizer had less effect on crude fibre content. Row spacing affected crude fibre content only in Jokioinen where the wider row spacing induced

Table 47. Effect of fertilizer application rate and row spacing on number of stems m^{-2}, stem fraction and crude fibre (% of dry matter) of tall fescue in June and August, 1994 and in May, 1995 on clay soil in Jokioinen.

	Row spacing 12.5 cm					Row spacing 25.0 cm					
	N rate kg ha^{-1}					N rate kg ha^{-1}					Means for
Harvest	0	50	100	150	Mean	0	50	100	150	Mean	harvest time
Number of stems											
June	538	568	386	454		288	424	442	324		428a
Aug	506	518	386	320		526	668	404	552		485ab
May	726	442	434	536		694	492	708	560		574b
*Means for row spacing					485a					507a	
*Means for N rate	546a	519a	460b	458b							
Stem fraction %											
June	30.6	27.8	25.2	25.4		32.3	32.0	30.4	21.6		28.2a
Aug	32.6	31.5	22.4	24.3		35.6	35.6	30.0	31.4		30.4a
May	51.1	47.2	42.7	48.1		53.2	51.2	51.7	51.4		49.6b
*Means for row spacing					34.1a					38.0b	
*Means for N rate	39.2a	37.5a	33.7b	33.7b							
Crude fibre %											
June	35.9	35.4	34.9	34.8		37.5	36.2	35.9	34.8		35.7a
Aug	39.1	36.7	37.9	36.6		40.6	38.2	37.6	38.3		38.1b
May	47.5	45.7	43.5	41.0		46.7	47.2	46.4	43.5		45.2c
*Means for row spacing					39.1a					40.2b	
*Means for N rate	41.2a	39.9b	39.4b	38.1c							

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

significantly higher crude fibre content ($P = 0.0013$).

Ash content of tall fescue

Unlike for reed canary grass, ash content of tall fescue was lower on clay than on organic soil. Harvest timing and fertilizer application rate affected ash content of tall fescue to a large degree, whereas row spacing had a significant effect only on clay soil (Table 46). In both Jokioinen (Table 48) and Vihti (Table 49) the ash contents of the plants harvested in May (4.4% and 5.2%, respectively) were significantly lower than in plants harvested in August (9.1% and 9.3%, respectively) or June (8.5% and 9.5%, respectively). On average, the lowest ash content was found in plants from non-fertilized plots and those from plots fertilized at 50 kg N ha^{-1}. However, in spring, the fertilizer had no clear effect on ash content in Jokioinen (Table 48). In Vihti, fertilizer application did not influence the ash content of biomass harvested at the seed ripening stage (Table 49). In Jokioinen the 25 cm row spacing was associated with significantly lower ash content ($P = 0.0165$) than a row spacing of 12.5 cm.

Silica content of tall fescue

Silica (SiO_2) content of tall fescue was affected by harvest timing and fertilizer application rate on both soils (Table 46). Silica content of tall fescue was lower in plants harvested on clay soil (Table 48) than on organic soil (Table 49), being respectively 2.4% and 3.2% at the flowering stage, 2.8% and 3.2% at the seed stage and 3.3% and 4.0% at delayed harvest. Harvesting during the 1994 growing period resulted in significantly lower silica content ($P<0.05$) than harvesting in May. Silica content was highest in non-fertilized plots and at 100 and 150 kg N ha^{-1} it de-

Table 48. Effect of fertilizer application rate on mineral content (ash, SiO_2, N, P, K) in dry matter of tall fescue in June and August, 1994 and in May, 1995 on clay soil in Jokioinen.

		N rate kg ha^{-1}				Means for
Harvest		0	50	100	150	harvest*
Ash %	June	7.9	8.4	8.8	8.8	8.5a
	Aug	8.6	9.2	9.2	9.3	9.1a
	May	4.3	4.2	4.4	4.8	4.4b
*Means for N rate		7.0a	7.3b	7.5bc	7.6c	
SiO_2 %	June	2.7	2.4	2.3	2.2	2.4a
	Aug	3.1	2.8	2.7	2.5	2.8a
	May	3.3	3.2	3.3	3.5	3.3b
*Means for N rate		3.0a	2.8b	2.8b	2.7b	
N %	June	1.01	1.23	1.40	1.53	1.29a
	Aug	0.67	0.84	1.03	1.23	0.94b
	May	0.60	0.65	0.80	1.05	0.77c
*Means for N rate		0.76a	0.91b	1.08c	1.26d	
P g kg^{-1}	June	1.71	1.88	2.02	1.96	1.89a
	Aug	1.39	1.48	1.61	1.80	1.57b
	May	0.83	0.79	0.85	1.08	0.89c
*Means for N rate		1.31a	1.38a	1.49b	1.62c	
K g kg^{-1}	June	24.0	27.8	30.1	29.7	27.9a
	Aug	25.8	28.6	29.7	30.4	28.6a
	May	1.03	0.94	1.11	1.46	1.13b
*Means for N rate		16.9a	19.1b	20.3c	20.5c	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

creased significantly ($P<0.05$). There were no differences in effect among the various fertilizer application rates. Row spacing had a significant effect on silica content only on clay soil where the plots with the wider row spacing (25 cm) were associated with significantly lower silica content ($P = 0.0021$).

Nitrogen, phosphorus and potassium content of tall fescue

Harvest timing and fertilizer rate had very significant effects ($P<0.001$) on the N, P and K content of plants on both clay and organic soils (Tables 46, 48 and 49). N content was lower the later the plants were harvested. Fertilizer application increased the N content in plants significantly at all rates and harvests in both trials. Row spacing had an effect on N content only on clay soil where the wider row spacing resulted in significantly lower N content ($P = 0.0087$).

P content was lower the later the plants were harvested ($P<0.01$) (Tables 48 and 49). The highest fertilizer application rate, 150 kg N ha^{-1}, increased the P content in plants significantly at every harvest compared with the controls (clay $P<0.01$, organic $P<0.001$). The differences between the effects of different fertilizer applications varied depending on the harvest timing. At spring harvest, the highest rate resulted in a higher P content compared with other treatments in both trials, but no significant differences between the other N rates were recorded.

K content decreased during the winter, from 28.6 to 1.13 g kg^{-1} on clay soil and from 27 to 1.71 g kg^{-1} on organic soil (Tables 48 and 49). The effect of fertilizer application was depend-

Table 49. Effect of fertilizer application rate and row spacing on stem fraction, crude fibre and mineral content (ash, SiO_2, N, P, K) in dry matter of tall fescue in June and August, 1994 and in May, 1995 on organic soil in Vihti.

Harvest		N rate kg ha^{-1}				Means for
		0	50	100	150	harvest*
Stem fraction %	June	35.5	32.3	29.6	26.3	30.9a
	Aug	36.6	38.1	38.8	36.3	37.4b
	May	45.6	40.1	39.4	39.6	41.2c
*Means for N rate		39.2a	36.8ab	35.9b	34.0b	
Crude fibre %	June	36.4	35.4	34.8	34.5	35.3a
	Aug	39.4	37.7	38.7	37.4	38.3b
	May	46.8	44.5	43.1	41.1	43.9c
*Means for N rate		40.9a	39.2b	38.8b	37.7c	
Ash %	June	8.9	9.3	10.0	9.8	9.5a
	Aug	9.2	9.4	9.0	9.5	9.3a
	May	4.9	5.1	5.1	5.7	5.2b
*Means for N rate		7.7a	7.9a	8.0ab	8.3b	
SiO_2 %	June	3.5	3.1	3.2	2.9	3.2a
	Aug	3.7	3.3	2.9	2.9	3.2a
	May	3.7	4.0	3.9	4.4	4.0b
*Means for N rate		3.6a	3.5ab	3.3b	3.4b	
N %	June	0.94	1.10	1.30	1.58	1.23a
	Aug	0.73	0.90	0.91	1.21	0.94b
	May	0.64	0.77	0.93	1.14	0.87b
*Means for N rate		0.77a	0.93b	1.05c	1.31d	
P g kg^{-1}	June	2.38	2.53	2.73	3.00	2.65a
	Aug	1.69	2.10	2.05	2.60	2.11b
	May	1.02	1.09	1.19	1.35	1.16c
*Means for N rate		1.70a	1.91b	1.99b	2.30c	
K g kg^{-1}	June	25.7	28.8	30.3	29.9	28.7a
	Aug	25.9	27.2	27.2	27.7	27.0a
	May	1.68	1.59	1.68	1.91	1.71b
*Means for N rate		17.8a	19.2b	19.7b	19.8b	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

ent on harvest timing in both trials (Table 46). In June and August, the K contents in non-fertilized plots were lower than in fertilized plots on clay soil ($P<0.001$). On organic soil, the difference between the non-fertilized and fertilized plots in K content was observed only at the flowering stage ($P<0.01$). At delayed harvest no significant differences in K content were recorded among the fertilizer application rates.

5.2.2 Age of reed canary grass ley

Dry matter yield

The effect of harvest timing on DM yields varied among years ($P = 0.0001$) (Table 50). The lowest DM yields (t ha^{-1}) were harvested at the beginning of the experiment in 1991 (spring) and 1992 (autumn) (Fig. 7a). Subsequently the yields were significantly higher, ranging from 6 to 8 t ha^{-1} on average. At the lower fertilizer rate, the age of the ley did not affect the spring harvested DM yield significantly, and the DM yields were relatively constant throughout the period 1992 to 1998. Among the autumn yields, only the yield in 1992 was significantly lower than the yields in the following years. The DM yields varied more at the higher fertilizer application rate and consequently the yield was more than 9 t ha^{-1} at both harvest times in 1997 (Fig. 7a). No significant decrease or increase in yield was recorded as the ley aged, either when measured in autumn or in spring.

Persistence of reed canary grass stand

The reed canary grass plots harvested in spring remained free of weeds for 8 years, i.e., until spring 1999 when a small number of *Elymus repens* L. seedlings was found in plots. At autumn harvest and especially at the lower fertilizer application rate, the weed infestation was greater and particularly in 1996 the total harvested biomass consisted of about 40% weeds including *Taraxacum officinale* L. and *E. repens* (Fig. 7b).

Number of stems

When number of stems and plant fractions were measured from the 25 x 50 cm sample taken in each plot before harvesting in 1992–1998, the results indicated that harvesting in spring resulted in more straw (644 stems m^{-2}) than harvesting at the seed stage (562 stems m^{-2}). The results were, however, highly dependent on the year of harvest (Table 51). The older the stand, the fewer stems per m^{-2}. At autumn harvest, the decrease was significant (3 first years vs. 3 last years) at both of the fertilizer application rates ($P = 0.0036$ and $P = 0.0013$). At spring harvest the decrease was smaller at the lower rate of 100 kg N ha^{-1} ($P = 0.0782$) and not significant at 200 kg N ha^{-1}.

Proportion of plant fractions

Plant fractions, such as stem, leaf sheath, leaf blade and panicle, were analysed from yields harvested in 1992–1998 (Fig. 8). The proportion of stems in reed canary grass biomass was sig-

Table 50. Significance (P values) of differences in fertilizer application rate, harvest timing and year effect on dry matter (DM) yield, number of stems and proportion of stem fraction of reed canary grass harvested in 1991–1999.

Source	DM yield	Number of stems	Stem fraction
Fertilizer (F)	0.0636	0.1983	0.6622
Harvest (H)	0.3103	0.1171	0.0001
FH	0.1160	0.9870	0.9713
Year (Y)	0.0023	0.0112	0.0001
FY	0.1365	0.5326	0.3242
HY	0.0001	0.0001	0.0171
FHY	0.0794	0.0110	0.8201

Table 51. Number of stems of reed canary grass in autumn and in spring yield at 100 and 200 kg N ha^{-1}.

	100 kg N ha^{-1}		200 kg N ha^{-1}		Means for
Year	Autumn	Spring	Autumn	Spring	year
1992	586	635	713	729	666a
1993	555	604	591	955	676a
1994	696	667	869	573	701a
1995	445	624	624	608	575ab
1996	344	549	464	853	553b
1997	472	425	530	512	485b
1998	456	629	523	653	565b

* Means within the column followed by a different letter are significantly different ($P<0.05$).

Table 52. Proportion of stem fraction (% of dry matter) in reed canary grass yield harvested in autumn and in spring as a mean of fertilizer rates of 100 and 200 kg N ha^{-1} in 1992–1998 in Jokioinen.

Year	Autumn	Spring	Means for year
1992	47.1a	48.4a	47.8a
1993	40.7b	54.1a	47.4a
1994	51.7a	58.6b	55.2b
1995	58.9c	70.5c	64.7c
1996	62.4c	75.1c	68.7c
1997	49.5a	61.9b	55.7b
1998	61.3c	64.0b	62.6bd
Means for harvest	53.1a	61.8b	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

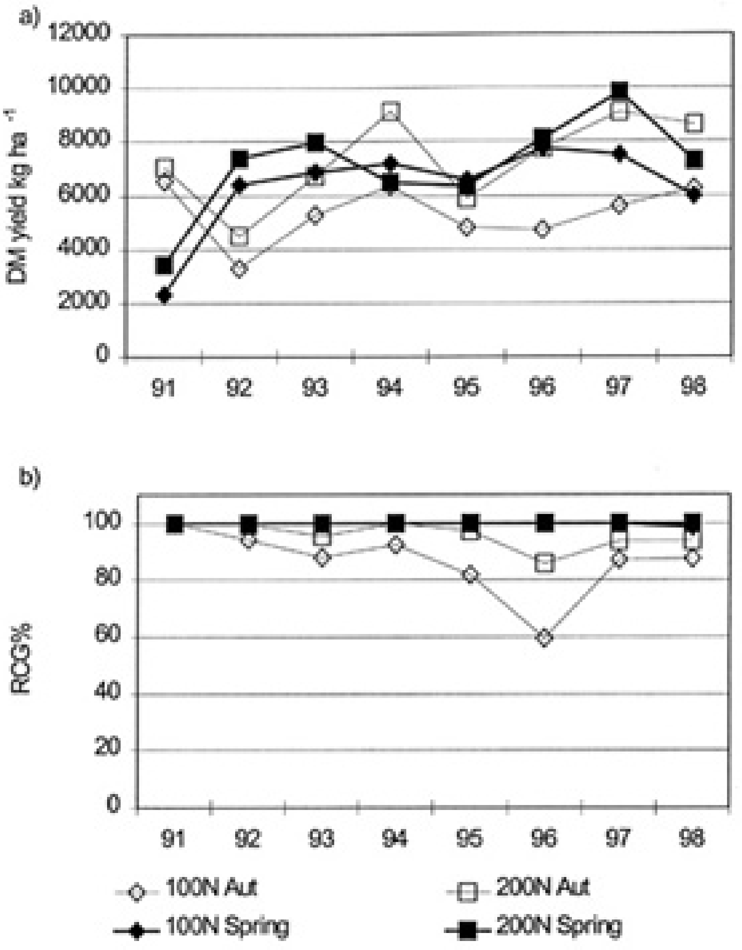


Fig. 7. a) Dry matter (DM) yield kg ha^{-1}, b) proportion of reed canary grass (RCG) % of dry matter in 1991–1998 on clay soil in Jokioinen. N fertilizer rates 100 and 200 kg ha^{-1}.

nificantly (P = 0.0001) higher at spring (61.8%) than at autumn harvest (53.1%) (Table 52). The proportion of stem varied greatly depending on the year (P = 0.0001), being lowest in spring yield of 1992 and in autumn yield of 1993, whereas fertilizer had only a minor effect on proportion of stem. The stem yield (kg ha^{-1}) varied depending on year (P = 0.0001), harvest timing (P = 0.0011) and fertilizer application rate (P = 0.0390) (Fig. 8). The stem yield harvested in spring (P = 0.0011) was on average 1200 kg ha^{-1} higher than that harvested in autumn. The proportion of leaf blades averaged 27.1% and 19.4%, and leaf sheaths 16.9% and 18.8% of the DM yield, from autumn and spring harvests, respectively. Panicles were present only at the seed stage in autumn when they contributed 2.9% to DM yield (Fig. 8).

Crude fibre content

The crude fibre content of reed canary grass was analysed in 1991–1994. Only the harvest time and the harvest year affected the fibre content (Table 53). The content was higher when biomass was harvested in spring rather than in autumn (P = 0.0001). The fibre content increased significantly as plant stand aged (P = 0.0001) at both fertilizer application rates and harvests (Table 54).

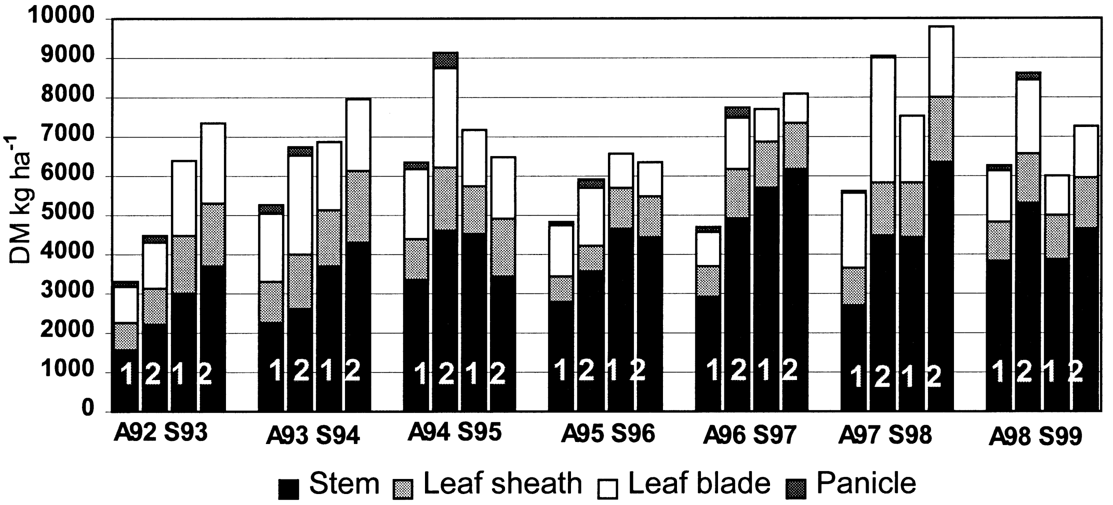


Fig. 8. Total dry matter (DM) yield of reed canary grass and proportion of plant fractions (1992–1999) harvested in August (A) and in spring (S) at 100 kg N ha^{-1} (1) and 200 kg N ha^{-1} (2) on clay soil in Jokioinen.

Ash content

The ash content of reed canary grass was measured only in the initial four years of the experiment (Fig. 9a). The ash content was 6.7% of DM when the crop was harvested in spring, and the content decreased when the higher fertilizer application rate was used and in plants of aged stands ($P<0.01$). In autumn, the percentage was significantly higher ($P = 0.0001$); 8.4% on average. Neither the fertilizer application rate nor the age of the grass stand affected ash content when harvested in autumn.

Silica

In addition to harvest timing and harvest year, fertilizer application rate affected the silica content of reed canary grass (Table 53). Silica content was significantly higher in material harvested in spring (5.3% of DM) than in that harvested in autumn (3.8% of DM) (Fig. 9b). Silica content decreased from 6.2% to 4.2% in spring yield during the four years, but this was not the case for autumn yields. The higher fertilizer application rate resulted in lower silica content in both autumn and spring yields.

Table 53. Significance (P values) of difference in fertilizer application rate, harvest timing and year effect on crude fibre, ash and SiO_2 content of reed canary grass in 1991–1994.

Source	Crude fibre	Ash	SiO_2
Fertilizer (F)	0.5158	0.0881	0.0271
Harvest (H)	0.0001	0.0001	0.0004
FH	0.1634	0.0270	0.8551
Year (Y)	0.0001	0.0053	0.0024
FY	0.2058	0.3260	0.4425
HY	0.6917	0.0001	0.0003
FHY	0.2153	0.5162	0.3640

Table 54. Content of crude fibre (% of dry matter) in harvested reed canary grass yield in autumn and in spring at 100 and 200 kg N ha^{-1} in 1991–1994.

Year	Autumn	Spring	Means for year
1991	30.5a	38.5a	34.5a
1992	28.6a	37.5a	33.0b
1993	32.8b	41.2b	37.0c
1994	36.1c	44.2c	40.1d
Means for harvest		32.0a	40.3b

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

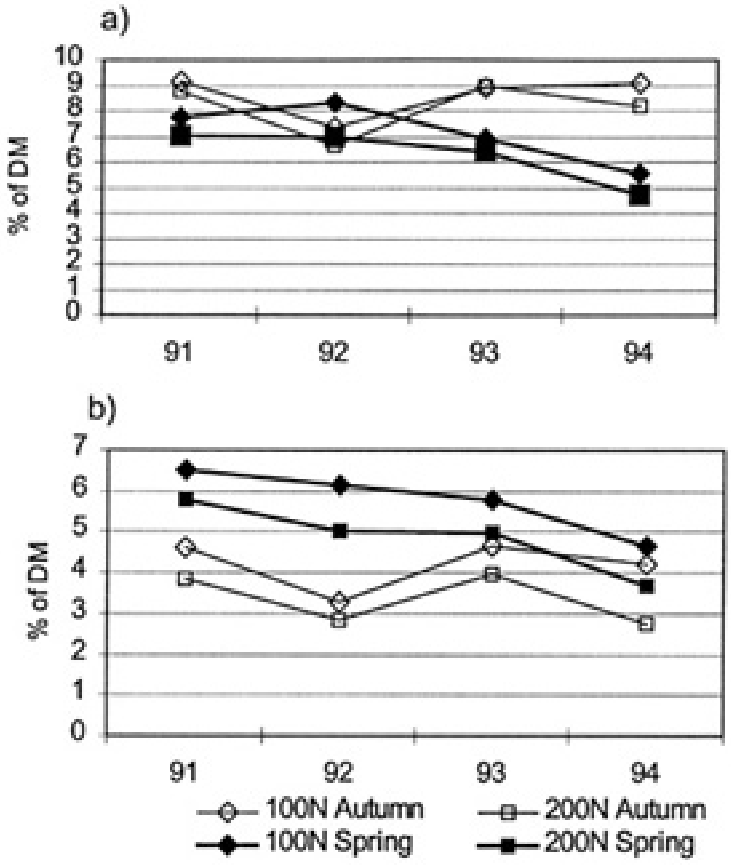


Fig. 9. a) Ash and b) silica (SiO_2) content % of dry matter (DM) of reed canary grass in August (autumn) and in May (spring) at 100 and 200 kg N ha^{-1} in 1991–1994 on clay soil in Jokioinen.

Pulping characteristics
Pulp yield, kappa number and screenings were measured only in the first and second years of harvest from two replicates. Harvest timing contributed most to the pulping characteristics (Table 55). Significantly higher pulp yield (P = 0.0010) and kappa number (P = 0.0045) were recorded from spring (41% of DM and 24.4, respectively) than from autumn harvests (35.1% and 18.5, respectively) (Fig. 10). Biomass harvested in autumn was easier to pulp than biomass harvested in spring, and less screenings was recorded (P = 0.0009). The screenings averaged from 1.1% to 1.6% of DM in autumn and from 1.7% to 2.9% in spring harvests (Fig. 10).

Table 55. Significance (P values) of difference in fertilizer application rate, harvest timing and year effect on screened pulp yields, kappa numbers and amount of screenings in pulping experiments of reed canary grass.

Source	Pulp	Kappa	Screenings
Fertilizer (F)	0.6924	0.5680	0.2528
Harvest (H)	0.0010	0.0045	0.0009
FH	0.0440	0.8682	0.0169
Year (Y)	0.3689	0.3100	0.4834
FY	0.3880	0.2033	0.8219
HY	0.0950	0.0414	0.0007
FHY	0.1893	0.0865	0.4227

5.2.3 Sowing time of reed canary grass

The crop was sown in May, June, July, August and September in 1995 in Jokioinen. In May reed canary grass was sown with and without cover crop. DM yield, DM content, number of stems

m^{-2} and proportion of stem fraction in the total above-ground biomass were studied at spring harvests in 1997, 1998 and 1999.

Dry matter yield and dry matter content
Sowing time influenced DM yield of reed canary grass (Table 56), being especially marked in the first year of harvest. In that case, sowing in May and June yielded more than sowing in July, August or September. In the following years, the yield differences were smaller. However, the sum of the yield from three years was double if the reed canary grass stand was sown in May and June instead of August and September (Table 57). DM yield was lowest in the first harvest year, independent of sowing times ($P<0.05$).

DM content of harvested biomass was 84% or more in all cases except in 1997, when the biomass harvested from the plant stand sown in September was only 79.2% (Table 58). In 1998 harvested biomass was very dry over the whole trial area (DM content more than 90%). In 1998 and 1999, no differences in DM content were recorded among stands sown at different times.

Number and proportion of stems
In 1997 the number of stems was very high (988 stems m^{-2}) in plots sown in May and low (356

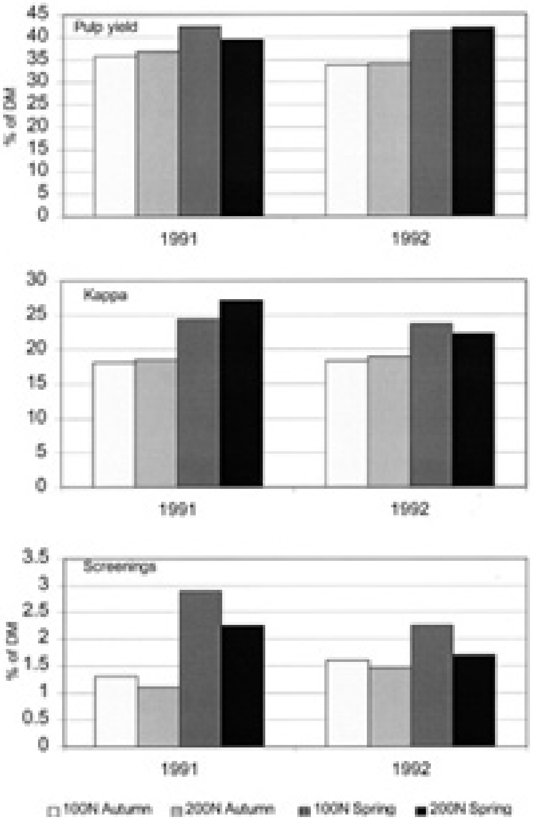


Fig. 10. Screened pulp yield, kappa number and screenings % of dry matter (DM) reed canary grass in 1991 and 1992 at 100 and 200 kg N ha^{-1} on clay soil in Jokioinen.

Table 56. Significance (P values) of differences in sowing time and harvesting year effect on dry matter (DM) yield, DM content, number of stems and proportion of stem fraction of reed canary grass harvested in spring 1997, 1998 and 1999.

Source	DM yield	DM content	Number of stems	Stem fraction
Sowing time (S)	0.0001	0.0114	0.0003	0.2733
Year (Y)	0.0002	0.0007	0.2075	0.0143
SY	0.0132	0.1617	0.0035	0.0298

Table 57. Dry matter yield (kg ha^{-1}) of reed canary grass sown on 30 May, 21 June, 22 July, 22 August and 20 September in 1995 and harvested in spring 1997, 1998 and 1999.

Harvest	Sowing time in 1995					
year	30 May	21 June	22 July	22 Aug	20 Sept	Means for year*
1997	5950a	5270b	2610c	1050d	960d	3170a
1998	7760ab	8370a	6040bc	5030c	4890c	6420b
1999	6670a	6650a	5780ab	4440b	4430b	5590b
*Sums for sowing	20380a	20290a	14430b	10520c	10280c	

* Means within the row or column followed by a different letter are significantly different ($P<0.05$).

Table 58. Dry matter content (%) of reed canary grass sown on on 30 May, 21 June, 22 July, 22 August and 20 September in 1995, and harvested in spring 1997, 1998 and 1999.

Harvest year	Sowing time in 1995 30 May	21 June	22 July	22 Aug	20 Sept	Means for year*
1997	89.8a	89.0a	88.8a	84.4a	79.2b	86.2a
1998	92.1a	92.2a	90.3a	92.1a	90.5a	91.4b
1999	87.0a	87.6a	85.5a	85.0a	85.1a	86.1a
*Means for sowing time	89.6a	89.6a	88.2a	87.2ab	84.9b	

* Means within the row followed by a different letter are significantly different (P<0.05).

stems m^{-2}) in plots sown in September (Table 59). On average, establishing the ley in August and in September resulted in the lowest number of stems in harvested biomass (P<0.05). High numbers of stems were not associated with high percentages of stem fraction in this experiment. The highest number of stems was recorded in the first harvest year, when the lowest proportion of stem fraction, on average 57.9% of DM, was detected (Table 59). In the following year the proportion of stem was higher (P = 0.0087). Sowing in August or September tended to result in lower stem fraction than earlier sowings, but no significant differences were attributable to sowing times. When the stem yields from three years were summed, the highest yields were recorded in stands sown in May and June (Fig. 11).

Effect of cover crop

When reed canary grass stands were established in May, using barley as a covering crop, DM yield decreased compared with the pure reed canary grass stand, when the yield was counted as a sum of the three recurrent harvesting years (Table 60). This was due to the lower yields in the first year associated with small proportions of stem fraction in harvested biomass. Of the two methods of harvesting the cover crop, cutting for

Table 59. Number of stems m^{-2} and proportion of stem fraction (% of DM) of reed canary grass stands sown in 30 May, 21 June, 22 July, 22 August and 20 September in 1995, and harvested in spring 1997, 1998 and 1999.

Harvest year	Sowing time in 1995 30 May	21 June	22 July	22 Aug	20 Sept	Means for year
Number of stems m^{-2}						
1997	988a	592b	690b	446b	356b	614a
1998	464a	648a	454a	296b	478a	468a
1999	598b	530b	792a	450b	614ab	596a
*Means for sowing time	683a	590a	645a	397b	482b	
Stem fraction % of DM						
1997	61.7ab	65.4a	55.4ab	49.7b	57.2ab	57.9a
1998	67.0a	70.9a	68.6a	67.2a	65.7a	67.9b
1999	64.8a	60.4ab	59.2ab	65.8a	57.9b	61.6a
*Means for sowing time	64.5a	65.6a	61.1a	60.9a	60.3a	

* Means within the row followed by a different letter are significantly different (P<0.05).

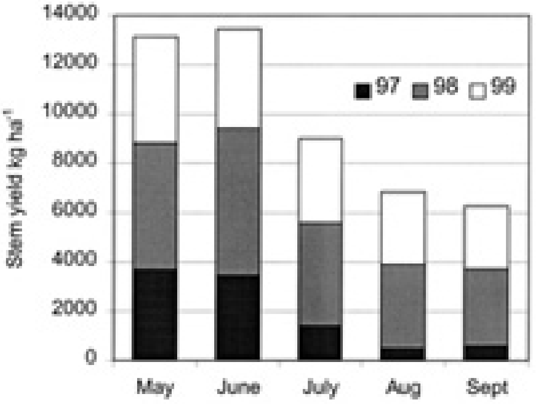


Fig. 11. Stem yield (kg ha^{-1}) in reed canary grass stands sown in 1995, and harvested in spring 1997, 1998 and 1999 on clay soil in Jokioinen.

silage at the end of August (Cover1) less advantageous for the development of the stand than threshing at the beginning of September.

Table 60. Dry matter (DM) yield (kg ha^{-1}) and stem fraction (% of DM) of reed canary grass sown on 30 May, with barley as a cover crop removed as silage on 28 August (Cover1), removed by threshing on 5 September (Cover2), and without cover crop as a pure stand, harvested in spring 1997, 1998 and 1999.

Harvest year	Cover1	Cover2	Pure stand	Means for year
DM yield kg ha^{-1}				
1997	3130	3430	5950	3200a
1998	5290	7320	7760	6390b
1999	5910	6660	6670	5790b
*Sums for sowing	14330b	17410a	20380a	
Stem fraction % of DM				
1997	58.2a	55.7a	61.1a	58.3a
1998	68.3b	70.7b	66.9a	68.6b
1999	61.4b	65.2b	64.8a	63.8ab
*Means for sowing	62.6a	63.8a	64.2a	

* Sums and means within the row followed by a different letter are significantly different (P<0.05).

5.2.4 Timing and stubble height of delayed harvested reed canary grass

Dry matter yield and dry matter content

Stubble height influenced significantly spring harvested DM yield of reed canary grass (Table 61). DM yield was on an average more than 30% higher (P = 0.0057) when the grass was harvested at a stubble height of 5 cm instead of 10 cm (Fig. 12) in five successive years (1994–1999). The stubble height of 10 cm resulted in higher harvest losses, which can be explained partly by the loss of DM yield in higher stubble, and partly by the loss caused by lodging (Table 63). When the harvests taken in four successive weeks were compared in each year, the effect of harvest time on DM yield was dependent on the

Table 61. Significance (P values) of difference in stubble height, harvest timing and harvest year effect on dry matter (DM) yield, content of stem fraction in DM yield, number of stems and stand height of reed canary grass harvested in spring. DM yield and stand height from the years 1994–1998, stem fraction and number of stems from 1995–1998.

Source	DM yield	Stem fraction	Number of stems	Stand height in spring
Stubble height (S)	0.0058	0.3953	0.8383	0.1737
Harvest (H)	0.0563	0.2063	0.7859	0.5744
SH	0.9172	0.7737	0.0539	0.3630
Year (Y)	0.0001	0.0001	0.0071	0.0001
SY	0.4800	0.6014	0.3290	0.2396
HY	0.0001	0.0046	0.0012	0.0001
SHY	0.0949	0.2081	0.0357	0.6072

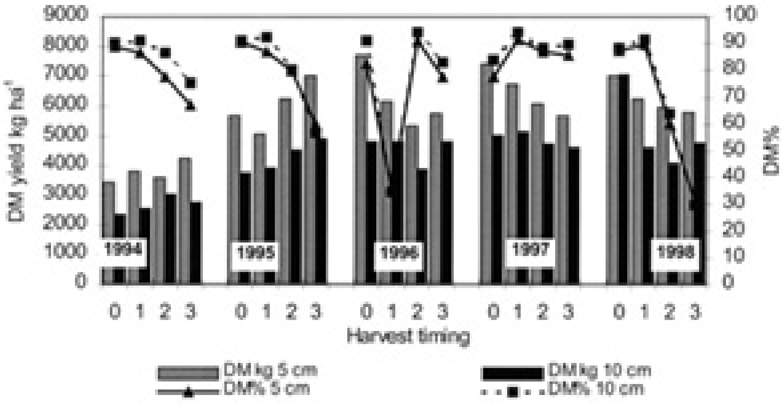


Fig. 12. Dry matter (DM) (kg ha^{-1}) and dry matter content (%) of reed canary grass harvested at stubble heights of 5 and 10 cm in 1994, 1995, 1996, 1997 and 1998 on clay soil, Jokioinen. Harvested DM yields are represented by columns and DM content by lines. Harvest timing: number of weeks after the first possible harvest date.

age of the stand ($P<0.01$). After the second year the highest yield was recorded when plants were cut at 5 cm stubble height on the first possible day after the soil was dry enough to support harvest machines in early spring (Fig. 12). The first possible harvest date varied yearly from 3rd to 11th May (Table 15).

The crop was dry enough for harvesting, having a DM content of about 85%, usually a week before the soil was dry enough to support the harvester and it was possible to take the first cut. The DM content of the crop harvested at 5 cm varied from 77.6 to 90.8% at the first harvest (Fig. 12), being even higher when the crop was cut at 10 cm. During the weeks following the first harvest the DM content was affected both by the weather conditions (Fig. 12) as in 1996, when the second cut was done too soon after rain, and by the increasing amount of green material. The moisture content of the biomass increased until the 4th harvest as a lodged plant stand maintained more moisture in harvested biomass and the amount of green material yield increased.

The proportion of stem fraction was measured in 1995–1998. On an average, the smallest stem proportion was found in biomass at the fourth harvest (Table 62), when it was delayed three weeks from the first harvest date. At the fourth harvest the variation of stem proportion was also smaller from year to year than at the earlier harvests. Also, the year was a significant source of variation. The highest stem proportions were measured in 1996 and 1997. The stubble height did not influence the proportion of stems significantly (Table 61).

Development of the plant stand

The first harvest date varied from 3rd to 11th May. The time between the first and the last harvests was three weeks. The field was under snow cover until mid-April every year. As a result of the pressure of snow, plants lodged and the height of the lodged crop stand ranged between 16 and 24 cm annually without differences between stubble heights monitored in previous years (Table 63).

In 1994, 1997 and 1998 the entire stand lodged independently of stubble height or harvest timing in previous years (Table 63). This prevented growth of green shoots, especially in 1997 (Fig. 13). In 1996 the stand was 72 cm high on average at the first harvest. Lodging of the crop increased during the subsequent weeks and at the last harvest the tops of green shoots were noted above the 20 cm high lodged crop stand. The new green shoots started to grow before the field was dry enough for harvesting and at the first cut the shoots were already 6–18 cm high. Three weeks later, the height of the shoots was 16–29 cm at the last harvest (Fig. 13). In 1997, the green shoot growth was delayed and shoots were found only sporadically among the harvested material. The proportion of green matter in the yield remained small (Fig. 13), but its influence on the moisture content of the yield was clearly seen in 1994 and 1995 (Fig. 12).

Table 62. Effect of the harvest timing and year on the proportion of stem fraction % of dry matter (DM) and number of stems m^{-2} at spring harvest of reed canary grass in 1994–1998. Harvest timing: number of weeks after the first possible harvest date.

Harvest timing	1995	1996	1997	1998	Means for harvest*
Stem fraction % of DM					
0	64.0a	70.6a	68.8a	59.6a	65.7ab
1	66.1a	69.6a	70.4a	60.4a	66.6ab
2	61.8a	75.1b	71.3a	60.6a	67.1a
3	62.6a	65.5c	65.9a	62.8a	64.1b
*Means for year	63.6a	70.2b	69.3b	60.9c	
Number of stems m^{-2}					
0	610a	686a	545a	333a	544a
1	577ab	633ab	640ab	437ab	572a
2	685a	496b	477a	493b	538a
3	440b	672a	604ab	544b	565a
*Means for year	578a	622a	566a	452b	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

Table 63. Effect of the harvest timing and the harvest year on lodged stand height (cm) at spring harvest of reed canary grass in 1994–1998. Harvest timing: number of weeks after the first possible harvest date.

Harvest timing	1994	1995	1996	1997	1998	Means for harvest*
0	18a	13a	72a	24a	17a	29a
1	21a	17a	54b	23a	14a	26a
2	26a	21a	45b	23a	15a	26a
3	29a	29b	25c	20a	17a	24a
*Means for year	24a	20ac	49b	23ac	16c	

* Means within the column or row followed by a different letter are significantly different ($P<0.05$).

The proportion of green material in biomass was measured from samples taken before each harvest. The proportion of green shoots increased as spring advanced, being 3.5 to 5% of DM at the last harvest. In 1997, the amount of green shoots was less than 0.1%, even at the latest spring harvest. As the harvest was delayed for more than one or two weeks from the first possible harvest date, the risk of excessive green matter in the harvested biomass increased substantially. This was especially the case when the height of the green shoots was more than 20 cm and the sample was cut by hand at less than 5 cm above soil level. When a harvester was used, some of the green tops fell and the proportion of green shoots in harvested biomass was consequently smaller than in the samples harvested by hand.

Because it was assumed that cutting the new plants at low stubble height may have had a restraining influence on the developing stand, the stand height, and number of plants and panicles were also measured in autumn, when the plants were fully mature. The results in Table 64 show that stubble height had no significant effect on plant height, number of stems and number of panicles and only a modest effect on the content of the stem fraction measured in autumn 1997 and 1998 (Table 66).

Harvest timing influenced plant height in

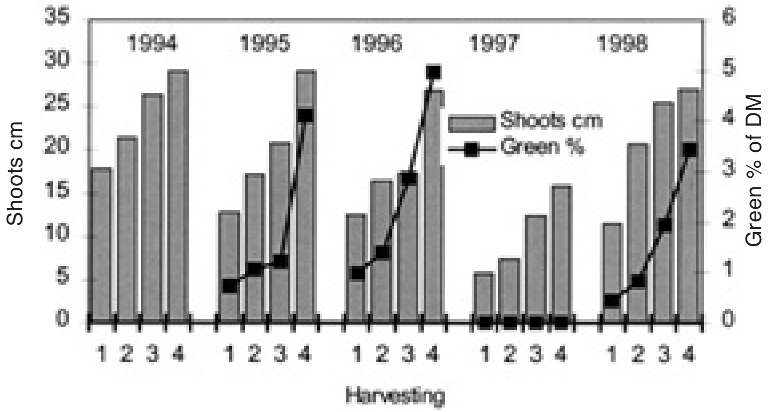


Fig. 13. The height of the green shoots (cm) and the amount of green material (% of dry matter) in spring 1994–1998. Harvest timing: number of weeks after the first possible harvest date.

1994 and 1995 when the late harvests resulted in shorter plants in autumn (Table 65). In 1996–1998 no differences between the harvest timings were observed. The number of stems m^{-2} was lowest in autumn 1998 (Table 65). The number of panicles m^{-2} decreased significantly in 1997 and 1998, especially in late harvests (Table 65).

In autumn, the content of stem fraction in biomass was affected significantly by harvest timing (P = 0.0014) and year (P = 0.0001) (Table 64). The proportion of stems decreased when the harvest was delayed more than one week (Table 66). The decrease from the first harvest to the fourth was significant in 1995 and 1997. In 1997 and in 1998, the stubble height also had an effect on proportion of stems, but the year effect was reversed. The stem fraction and the number of stems decreased significantly from 1995 to 1998.

Because of the large yield difference attributable to differences in stubble height, the weight proportion of different fractions of single straws was investigated. The section 5–10 cm from the soil surface was particularly interesting. The weight of the straw fractions of 5 cm length was higher when the fractions were taken closer to the soil surface (Table 67). However, the dry weight of the 5–10 cm section was only 5.8% of the total biomass and it was not the only reason for the yield difference resulting from cuts at two stubble heights. The weight cm^{-1} of the straw was higher at the base of the straw. DM content of straw fractions was 58% in fractions of 0–5 cm and 63% in fractions of 5–10 cm. In plant parts from 25 cm above soil level to the top of the canopy the DM content was 85%.

Table 64. Significance (P values) of differences in stubble height, harvest timing and harvest year effect on plant height, the number of stems and panicles, and content of stem fraction of reed canary grass in autumn 1995–1998.

Source	Plant height	Stems	Panicles	Stem fraction
Stubble height (S)	0.1122	0.6112	0.9723	0.4623
Harvest (H)	0.2321	0.2601	0.0363	0.0014
SH	0.9160	0.8499	0.4089	0.9314
Year (Y)	0.0001	0.0083	0.0001	0.0001
SY	0.8576	0.5425	0.6092	0.0065
HY	0.0005	0.5488	0.1590	0.0045
SHY	0.4312	0.5200	0.7425	0.7990

Table 65. Effect of the harvest timing and the harvest year on plant height (cm), number of stems m^{-2} and panicles in autumn 1994–1998. Harvest timing: number of weeks after the first possible harvest date.

Harvest timing	1994	1995	1996	1997	1998	Means for harvest*
Plant height in autumn cm						
0	155a	170a	181a	168a	163a	167a
1	152a	168a	179a	165a	165a	166a
2	148ab	159b	181a	168a	167a	164a
3	144b	155b	181a	169a	166a	163a
*Means for year	150a	163b	180c	167b	165b	
Number of stems in autumn m^{-2}						
*Means for year	553a	560a	668b	548a	450c	
Number of panicles in autumn m^{-2}						
0	174	326	242	73	108	185a
1	217	288	178	45	95	165ab
2	193	264	192	43	80	154bc
3	173	182	206	45	90	139bc
*Means for year	189a	265b	204a	52c	93d	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

Table 66. Effect of harvest timing and the harvest year on the content of stem fraction (% of dry matter) of reed canary grass measured in autumn in 1995–1998.

Harvest timing	1995	1996	1997	1998	Means for harvest*
0	69.0a	68.0a	61.1a	63.8a	65.5a
1	67.4a	67.9a	58.2b	64.4a	64.5ab
2	66.9a	66.3a	57.8b	63.5a	63.6bc
3	61.9b	65.7a	59.6b	62.6a	62.4c
*Means for stubble					
Stubble 5 cm	66.9a	66.8a	60.9a	62.4a	
Stubble 10 cm	65.7a	67.1a	57.5b	64.7b	
*Means for year	66.3a	67.0a	59.2b	63.5c	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

Table 67. Dry weight, proportion in dry matter (DM), density and DM content of fractions of single straws of reed canary grass.

Straw fraction	Weight g	Proportion %	Weight g cm^{-1}	DM content %
0–5cm	0.109	7.5	0.022	58.1
5–10cm	0.084	5.8	0.017	63.0
10–15cm	0.078	5.3	0.016	72.5
15–20cm	0.078	5.4	0.016	76.0
20–25cm	0.074	5.1	0.015	80.4
25–35cm	0.144	9.9	0.014	85.2
35cm→top	0.886	61.0	0.012	84.7

5.3 Research on reed canary grass varieties

5.3.1 Commercial cultivars of reed canary grass at delayed harvesting

The productivity of ten commercial cultivars or breeding lines of reed canary grass (R-90-7587, Palaton, Vantage, Rival, Jo 0510, Motterwitzer, Barphal 050, Venture, Lara and VåSr 8401) was

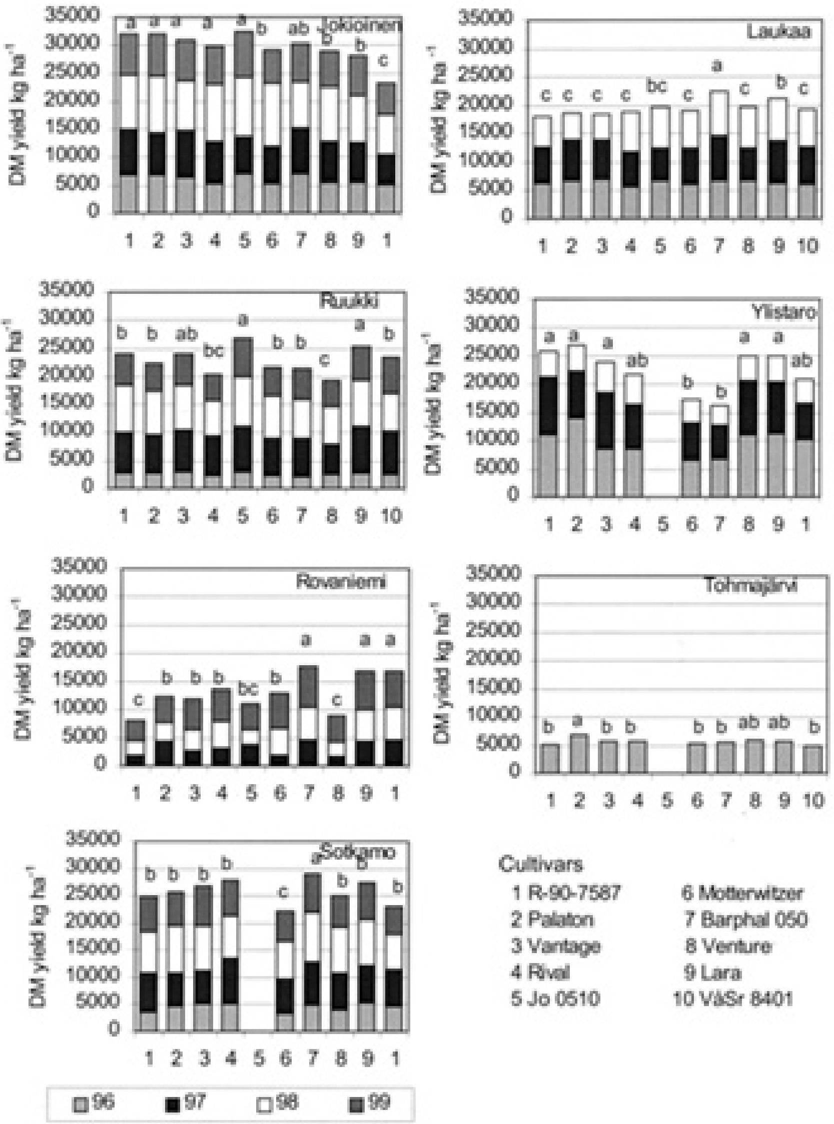


Fig. 14. Dry matter (DM) yield (kg ha^{-1}) of reed canary grass cultivars harvested in spring. A different letter above the column means that the harvested yields for cultivars are significantly different (P<0.05).

studied in seven Finnish locations. DM yield of the cultivars was compared at spring harvests in 1996–1999.

The cultivars studied grew well at all experimental sites (Tables 69, 70, 71, 72, 73, 74 and 75), even in Lapland (Table 74) (Fig. 14). However, variation between growing sites and harvest years were substantial. For this reason the results are presented separately for each experimental site. Significant differences between the cultivars were observed in each trial, but the differences were highly dependent on the year (Table 68). In Tohmajärvi (Table 75), the experiment was interrupted after the first spring har-

Table 68. Significance (P values) of differences in cultivar and harvesting year effect on dry matter yield of reed canary grass grown in Jokioinen, Laukaa, Ylistaro, Ruukki, Sotkamo, Rovaniemi, and Tohmajärvi.

Source	Jokioinen	Laukaa	Ylistaro	Ruukki	Sotkamo	Rovaniemi	Tohmajärvi
Cultivar (C)	0.0001	0.0001	0.0222	0.0227	0.0005	0.0001	0.0319
Year (Y)	0.0031	0.7540	0.0001	0.0001	0.0001	0.0001	–
YC	0.0001	0.0001	0.0334	0.0015	0.0001	0.0101	–

Table 69. Dry matter yields (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Jokioinen, 1996–1999.

Cultivar	1996	1997	1998	1999	Means for cultivar*
R-90-7587	6870a	8210a	9670a	7194a	7990a
Palaton	6940a	7470b	10100a	7393a	7970a
Vantage	6420a	8420a	8680a	7440a	7740a
Rival	5430b	7380b	10250a	6756a	7450a
Jo 0510	7040a	6700b	10550a	8235a	8130a
Motterwitzer	5270b	6780b	11170a	5942b	7290b
Barphal 050	7115a	8230a	7970a	6867a	7550ab
Venture	5530b	7380b	9600a	6397a	7230b
Lara	5680b	6980b	8390a	7107a	7040b
VåSr 8401	5050b	5430c	7100a	5587b	5790c
*Means for year	6130a	7300b	9350c	6890ab	

* Means within the column (cultivar) or row (year) followed by a different letter are significantly different (P<0.05).

Table 70. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Laukaa, 1996–1998.

Cultivar	1996	1997	1998	Means for cultivar*
R-90-7587	6340ab	6460ab	5200ab	6000a
Palaton	6880ab	7210a	4590a	6220a
Vantage	7100a	6930ab	4430a	6150a
Rival	5650b	6310ab	6930b	6300a
Jo 0510	6710ab	5830b	7130b	6560ac
Motterwitzer	6170ab	6370ab	6590b	6380a
Barphal 050	6890ab	7760a	7790b	7480b
Venture	6820ab	5630b	7340b	6600a
Lara	6380ab	7370a	7570b	7100c
VåSr 8401	6210ab	6530ab	6560b	6430a
*Means for year	6510a	6640a	6410a	

* Means within the column (cultivar) or row (year) followed by a different letter are significantly different (P<0.05).

vest in 1996 because the experimental station was closed. The cultivars Barphal 050 and Lara were productive, especially in the northern sites Rovaniemi (Table 74) and Sotkamo (Table 73) and also in Laukaa (Table 70) where the snow cover is moderately thick during winter. In the same locations Motterwitzer, Venture and line R-90-7578 were the most sensitive to the north-

Table 71. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Ylistaro, 1996–1998.

Cultivar	1996	1997	1998	Means for cultivar*
R-90-7587	11180a	10260a	4280ab	8570a
Palaton	13980a	8330ab	4660ab	8990a
Vantage	8470bc	10070a	5430a	7990a
Rival	8450bc	7970ab	5440a	7290ab
Motterwitzer	6660c	6580b	4040ab	5760b
Barphal 050	6870c	5870b	3510b	5420b
Venture	11080a	9550a	4310ab	8310a
Lara	11310a	9080a	4580ab	8320a
VåSr 8401	10250ab	6430b	4250ab	6980a
*Means for year	9810a	8240b	4500c	

* Means within the column (cultivar) or row (year) followed by a different letter are significantly different (P<0.05).

Table 72. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Ruukki, 1996–1999.

Cultivar	1996	1997	1998	1999	Means for cultivar*
R-90-7587	2710a	7420a	8370a	5460ab	5990a
Palaton	2730a	6920a	7630ab	5110ab	5600a
Vantage	3010a	7530a	7990ab	5570ab	6030ac
Rival	2420a	6960a	6370b	4650b	5100ab
Jo 0510	3020a	8210a	8830a	6800c	6710c
Motterwitzer	2420a	6660a	7480ab	5020ab	5400a
Barphal 050	2200a	6850a	6910ab	5570ab	5390ab
Venture	2490a	5440a	6710ab	4620b	4810ab
Lara	2770a	8320a	8140a	6020abc	6320c
VåSr 8401	2680a	7630a	6660ab	6470ac	5860a
*Means for year	2650a	7200b	7510b	5530c	

* Means within the column (cultivar) or row (year) followed by a different letter are significantly different (P<0.05).

Table 73. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Sotkamo, 1996–1998.

Cultivar	1996	1997	1998	1999	Means for cultivar*
R-90-7587	3650a	7110a	7740a	6330a	6210a
Palaton	4590b	6360a	8580a	6260a	6450a
Vantage	5010b	6270a	8260a	7370b	6730a
Rival	5120b	8470a	7660a	6700a	6990a
Motterwitzer	3230a	6480a	6830b	5710a	5560b
Barphal 050	4970b	7900a	9140a	7010b	7260c
Venture	3940a	7000a	8260a	5860c	6260a
Lara	5420c	6660a	8440a	6950b	6870a
VåSr 8401	4560b	6960a	6390b	5180d	5770b
*Means for year	4500a	7020b	7920c	6370b	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

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Table 74. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvests in Rovaniemi, 1997–1999.

Cultivar	1997	1998	1999	Means for cultivar*
R-90-7587	1990a	2390a	3730a	2710a
Palaton	4440b	3290a	4640a	4120b
Vantage	2770ac	3700a	5450ab	3980b
Rival	3170bc	4710ab	5830ab	4570b
Jo 0510	3800b	2630a	4740a	3720ab
Motterwitzer	1900a	4820b	6320b	4350b
Barphal 050	4620b	5850b	7180bc	5890c
Venture	1750a	2620a	4680a	3020a
Lara	4420b	5640b	6810bc	5620c
VåSr 8401	4630b	5890b	6300b	5610c
*Means for year	3350a	4150b	5570c	

* Means within the column or row followed by a different letter are significantly different (P<0.05).

Table 75. Dry matter yield (kg ha^{-1}) of reed canary grass cultivars at spring harvest in Tohmajärvi, 1996.

Cultivar	1996*
R-90-7587	5140ac
Palaton	6730b
Vantage	5740ac
Rival	5700ac
Motterwitzer	5330ac
Barphal 050	5490ac
Venture	6010ab
Lara	5820abc
VåSr 8401	4970c
Means for year	5660

* Means within the column followed by a different letter are significantly different (P<0.05).

ern conditions. Jo 0510, Palaton, Lara, and Vantage were productive in the trials situated in western Finland, Jokioinen (Table 69), Ylistaro (Table 71) and Ruukki (Table 72).

5.3.2 Mineral and fibre content of plant parts in reed canary grass cultivars

The proportion of different plant parts (stems, leaf sheaths, leaf blades and panicles) of three cultivars (Palaton, Venture and Lara) of reed canary grass from three locations (Jokioinen, Ylistaro and Ruukki) was analysed from samples collected in spring 1997. Mineral composition (ash, Si and K) and the amount of crude fibre were analysed in each plant fraction except panicles. The pulping characteristics, including pulp yield, amount of screenings, kappa number and fibre dimensions, were determined from the plant material harvested in spring 1998.

Proportion of plant fractions

The principal component of spring harvested biomass of reed canary grass was stem fraction (65–74% of DM) (Fig. 15). The proportion of leaf sheaths was 12–16%, and leaf blades 11–20% of DM. The number of panicles represented less than 0.5% of biomass harvested in spring. Lara had more leaves than other cultivars in Jokioinen and Ruukki. However, in Ylistaro the proportions of plant parts in different cultivars were almost equal. No significant trial site and cultivar effect was found on the proportion of stem fraction (Table 76).

Mineral and fibre content of plant parts

The contents of ash, silica, potassium and crude fibre of the plant parts are shown for each experimental site as there were large differences between the sites particularly for ash

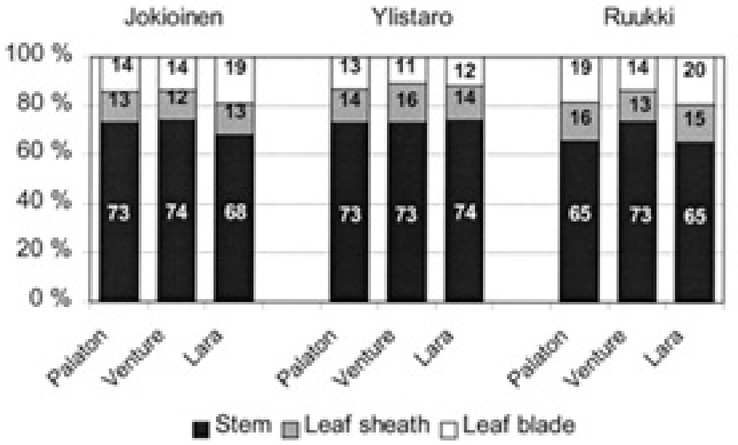

Fig. 15. The proportion (% of dry matter) of plant parts of reed canary grass cultivars harvested in spring 1996 in Jokioinen, Ylistaro and Ruukki.

Table 76. Significance (P values) of difference among trial sites, cultivars and their interactions on proportion of stem fraction in harvested biomass of reed canary grass grown in Jokioinen, Ylistaro and Ruukki.

Source	P-value
Trial site (T)	0.0704
Cultivar (C)	0.0977
TC	0.2674

(P = 0.0068), silica (P = 0.005) and potassium content (P = 0.0107) (data not shown). The highest amounts were found in Jokioinen and the lowest in Ruukki (in stem fraction) and Ylistaro (in leaf fractions). However, in Ruukki, a heavy wind caused soil contamination in winter 1997 resulting unusually high ash, silica and potassium content in both leaf blades and leaf sheaths. For crude fibre, the experimental site had a minor effect.

Significant differences in mineral and fibre content were found between different plant parts of the reed canary grass in every experimental site (P = 0.0001). In Jokioinen and Ylistaro, cultivars also differed significantly in ash and silica content (Table 77) and in Jokioinen, in crude fibre content in addition.

Table 77. Significance (P values) of differences among cultivars and plant parts in ash, silica, potassium and crude fibre content in dry matter of reed canary grass grown in Jokioinen, Ylistaro and Ruukki.

Source	Ash	SiO_2	K	Crude fibre
Jokioinen				
Cultivar (C)	0.0089	0.0091	0.1370	0.0156
Plant part (P)	0.0001	0.0001	0.0001	0.0001
CP	0.6635	0.0515	0.0039	0.0398
Ylistaro				
Cultivar (C)	0.0414	0.0256	0.3375	0.0942
Plant part (P)	0.0001	0.0001	0.0001	0.0001
CP	0.7009	0.8772	0.2843	0.8452
Ruukki				
Cultivar (C)	0.1070	0.1107	0.3813	0.4322
Plant part (P)	0.0001	0.0001	0.0001	0.0001
CP	0.0550	0.1698	0.7280	0.1441

Table 78. Ash content (% of dry matter) in stems, leaf sheaths and leaf blades of three reed canary grass cultivars grown in Jokioinen, Ylistaro and Ruukki.

Plant part	Palaton	Cultivar Venture	Lara	Means for plant part*
Jokioinen				
Stem	4.2	4.1	5.9	4.7a
Leaf sheath	7.0	6.8	9.1	7.6b
Leaf blade	10.4	10.3	12.5	11.1c
*Means for cultivar	7.2a	7.1a	9.2b	
Ylistaro				
Stem	3.2	3.0	4.3	3.5a
Leaf sheath	5.5	5.7	6.4	5.9b
Leaf blade	7.6	8.1	9.2	8.3c
*Means for cultivar	5.4a	5.6a	6.6b	
Ruukki				
Stem	2.8	2.6	3.1	2.8a
Leaf sheath	7.3$^{1)}$	5.5$^{1)}$	7.5$^{1)}$	6.7b
Leaf blade	15.9$^{1)}$	12.5$^{1)}$	16.1$^{1)}$	14.8c
*Means for cultivar	8.7a	6.8a	8.9a	

* Means within the column (plant part) and the row (cultivar) followed by a different letter are significantly different ($P<0.05$). $^{1)}$ soil contamination.

The significantly lowest ash, silica and potassium contents were found in stems and the highest in leaf blades (Tables 78, 79 and 80). The highest fibre contents were obtained also in stem fractions in every location (Table 81). The mineral and fibre contents of leaf sheaths were intermediate between stem and leaf blade fractions. In all locations, and in all plant parts, the highest ash, silica and potassium contents were recorded for Lara (Tables 78 and 79). In Jokioinen and Ylistaro the difference between Lara and the other two cultivars was significant ($P<0.05$) in ash and silica content.

The content of crude fibre in reed canary grass differed among plant parts ($P = 0.0001$). The stem fraction had the highest fibre content, from 48.0 to 52.1% of DM (Table 81). In Jokioinen and Ylistaro, Lara had a lower fibre content than Palaton and Venture in all plant parts. The difference between Lara and Venture was significant at both sites.

Table 79. SiO_2 content (% of dry matter) of stems, leaf sheaths and leaf blades of three reed canary grass cultivars grown in Jokioinen, Ylistaro and Ruukki.

Plant part	Palaton	Cultivar Venture	Lara	Means for plant part*
Jokioinen				
Stem	3.4	3.2	4.5	3.7a
Leaf sheath	5.2	5.0	6.8	5.7b
Leaf blade	7.2	7.7	9.4	8.1c
*Means for cultivar	5.3a	5.3a	6.9b	
Ylistaro				
Stem	2.1	2.1	3.1	2.5a
Leaf sheath	3.6	3.8	4.6	4.0b
Leaf blade	5.0	5.2	6.1	5.4c
*Means for cultivar	3.6a	3.7a	4.6b	
Ruukki				
Stem	1.8	1.7	1.8	1.8a
Leaf sheath	4.5$^{1)}$	3.3$^{1)}$	4.6$^{1)}$	4.1b
Leaf blade	9.4$^{1)}$	7.7$^{1)}$	9.1$^{1)}$	8.7c
*Means for cultivar	5.2a	4.3a	5.2a	

* Means within the column (plant part) and the row (cultivar) followed by a different letter are significantly different ($P<0.05$). $^{1)}$ soil contamination

Table 80. Content of K (g kg^{-1} of dry matter) of stems, leaf sheaths and leaf blades of three reed canary grass cultivars grown in Jokioinen, Ylistaro and Ruukki.

Plant part	Palaton	Cultivar Venture	Lara	Means for plant part*
Jokioinen				
Stem	0.6a	0.7a	0.9a	0.7a
Leaf sheath	1.1b	1.3b	1.8b	1.4b
Leaf blade	4.4c	2.3c	2.5b	3.1c
*Means for cultivar	2.0a	1.4a	1.7a	
Ylistaro				
Stem	1.1	1.3	1.4	1.2a
Leaf sheath	1.6	2.0	1.9	1.8b
Leaf blade	2.2	2.4	2.7	2.4c
*Means for cultivar	1.6a	1.9a	2.0a	
Ruukki				
Stem	1.6	1.4	2.6	1.9a
Leaf sheath	2.4$^{1)}$	2.4$^{1)}$	3.1$^{1)}$	2.6b
Leaf blade	4.3$^{1)}$	4.0$^{1)}$	4.9$^{1)}$	4.4c
*Means for cultivar	2.7a	2.6a	3.5a	

* Means within the column (plant part) and the row (cultivar) followed by a different letter are significantly different ($P<0.05$). $^{1)}$ soil contamination

Table 81. Crude fibre content (% of dry matter) of stems, leaf sheaths and leaf blades of three reed canary grass cultivars grown in Jokioinen, Ylistaro and Ruukki.

		Cultivar		Means for
Plant part	Palaton	Venture	Lara	plant part*
Jokioinen				
Stem	50.2	52.1	48.6	50.3a
Leaf sheath	39.4	39.8	37.2	38.8b
Leaf blade	28.2	30.1	27.6	28.7c
*Means for cultivar	39.3ab	40.7a	37.8b	
Ylistaro				
Stem	50.1	51.7	48.0	50.0a
Leaf sheath	41.4	42.3	39.3	41.0b
Leaf blade	29.1	29.2	26.7	28.4c
*Means for cultivar	40.2ab	41.1a	38.0b	
Ruukki				
Stem	50.3	49.8	50.0	50.1a
Leaf sheath	41.0	41.5	38.5	40.3b
Leaf blade	25.9	27.3	25.9	26.4c
*Means for cultivar	39.1a	39.5a	38.2a	

* Means within the column (plant part) and the row (cultivar) followed by a different letter are significantly different (P<0.05).

Pulping characteristics of plant fractions

Samples from different parts of reed canary grass showed significant variation in all their pulping characteristics (Table 82). Minor differences were found in the fibre and pulping properties of reed canary grass from different localities. The results are presented as means for the three experimental sites. The total pulp yield and the screened yield from stems was over 50% at kappa 10 (Table 82), whereas leaf sheaths gave yields of only about 42% and leaf blades 32% at higher kappa numbers. High pulp yield of the stem fraction was associated with high crude fibre content and kappa number (Fig. 16). Leaf blades also gave dark coloured pulps with low brightness and proved thus to be totally unsuitable for pulping. Because of the low quality of leaf blades and sheaths, pulps from entire plants cooked slower, gave significantly lower yield and pulp brightness than stems, but kappa numbers of same level as stem fractions. The black liquor pH after cooking whole plants was as high as after cooking the stems (pH 12.8) indicating the same delignification rate. The fibre length and dimensions of different plant parts varied greatly (Fig. 17).

Stem fibres were 0.86 mm long and they were longer than those in leaves. A coarseness of 0.09 to 0.10 mg m^{-1} showed stem, leaf sheaths and even the whole plants to be more suitable for papermaking than fibres from leaf blades. Fibre length in pulp from the whole plant was about 0.8 mm and coarseness 0.10 mg m^{-1}, which was significantly higher than the respective fibre properties in leaf sheaths and blades (Fig. 17).

Table 82. Results from the pulping experiments and crude fibre analyses of different plant parts of reed canary grass harvested in spring 1998. Significance (P value) of difference in plant part effect on the variables. DM = dry matter.

Variable	Whole plant	Stems	Leaf sheaths	Leaf blades	*P* value
Total pulp yield (% of DM)	46.6b	51.7a	41.7c	31.9d	0.0001
Screened pulp yield (% of DM)	46.2b	51.2a	41.6c	31.9d	0.0001
Kappa number	12.1c	10.0c	16.0b	21.3a	0.0016
Brightness (%)	30.0b	40.0a	23.3c	10.7d	0.0001
Black liquor pH	12.5ab	12.8a	12.2b	11.7c	0.0011
Fibre length (mm)	0.82a	0.86a	0.56b	0.48c	0.0001
Fibre width (µm)	16.6a	16.9a	16.1a	16.4a	0.6182
Fibre coarseness (mg m^{-1})	0.10b	0.09b	0.10b	0.20a	0.0001
Cwt index	4.5a	4.6a	4.8a	4.3a	0.2687
Crude fibre (% of DM)	44.5b	51.9a	42.5b	31.4c	0.0001

Means within the row (plant part) followed by a different letter are significantly different (*P*<0.05).

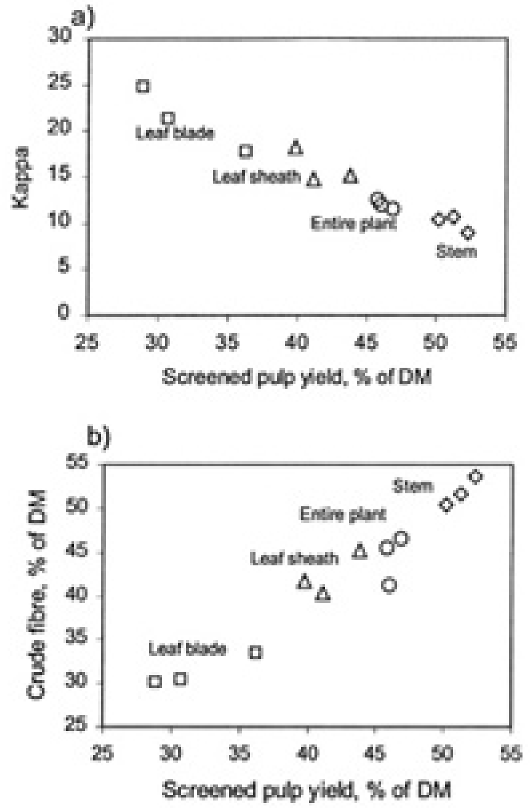

Fig. 16. Total pulp yield vs. a) kappa number and b) crude fibre content of dry matter (DM) in stems, leaf sheaths, leaf blades and entire plant of reed canary grass (cv. Palaton) harvested in spring 1998. Samples were collected from Jokioinen, Ylistaro and Ruukki.

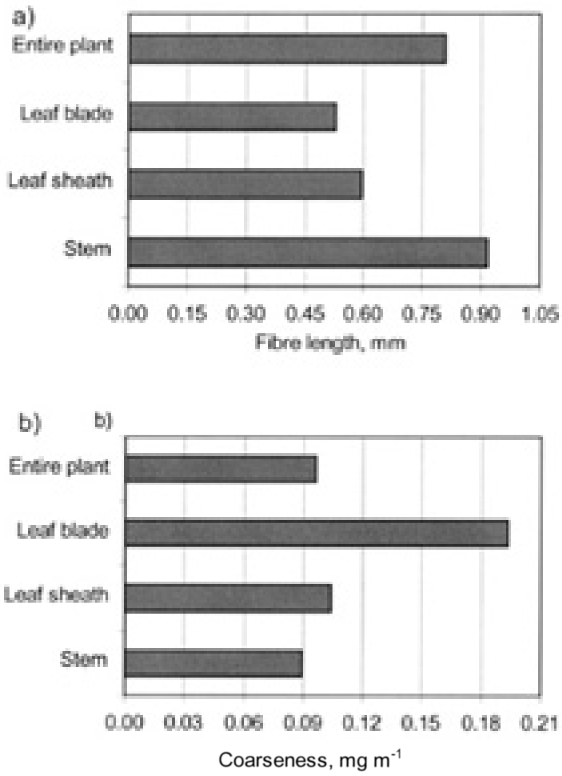

Fig. 17. Fibre properties of unbleached sulphate pulps made of stems, leaf sheaths, leaf blades and entire plants of reed canary grass (cv. Palaton) harvested in spring 1998. Samples from Jokioinen, Ylistaro and Ruukki.

Stems had the highest crude fibre content (52% of DM). Crude fibre content of whole plants was closer to that of leaf sheaths than of stems. Fibre width of reed canary grass was approximately 16.5 m, and plant part had no significant effect on it (Table 82). CWT index of the fibres of reed canary grass was 4.6 and was not dependent on plant part.

6 Discussion

When this study was started in 1990, the shortage of short fibre raw material for the pulp industry was, and still is, marked in Finland. The study aimed at finding a non-wood plant species that could be used as short fibre raw material for pulping and papermaking to substitute for the considerable importation of birch. The properties considered important for a fibre crop were high yielding ability, good pulping quality, good adaptation to the prevailing climatic conditions, possibilities for low cost production using existing farm machinery, possibilities for domestic seed production (Table 9), and availability throughout the year. Thus, our demands were similar to those voiced by Nieschlag et al. (1960): "A new fiber crop must fit the technical requirements for processing into pulp of acceptable quality in high yield and must also be adaptable to practical agricultural methods and economically produce high yield of usable dry matter per acre". A focus of this study was to find a species with the described properties above. An additional goal was to develop crop management to enhance formation of fibre yield from the most promising species. This discussion is dealing with the entire production chain with emphasis on crop management results.

6.1 Strategy used for selecting species for non-wood pulping

During the first stages of the study 17 species were chosen for preliminary pulping tests and mineral analysis. The species chosen were known to be high yielding crops and several species, e.g. common reed and straw of cereals had already been frequently used for pulping (Misra 1987, Hurter 1988). Hemp, nettle and linseed straw were studied, because their long bast fibres are known to be good raw material for papermaking (Kilpinen 1991, Ilvessalo-Pfäffli 1995). However, during the very early stages of the study the focus was on short fibre crops, for which monocotyledons, including four grasses and four cereal species, were of better quality in pulping tests, but had higher mineral content than the dicotyledons studied. The number of crop species evaluated in this study was much lower than that in experiments of Nelson et al. (1966). However, on the basis of the screening, only reed canary grass, tall fescue, meadow fescue, spring barley, goat's rue, red clover and lucerne were selected for further studies.

Results of additional studies showed that perennial grasses with good pulping quality and adaptability to Finnish growing conditions had an advantage over the dicot species in this study. Reed canary grass and tall fescue were especially promising species for pulping (Pahkala 1997) and hence, development of crop management began with these species in order to improve their yielding capacity and pulping quality. However, as a result of additional experience over two years it was evident that tall fescue was not competitive since its yielding capacity and number of stems decreased rapidly if harvested in spring. Therefore, subsequent studies focused solely on production of reed canary grass. The strategy and the criteria used for selection of the fibre plant are described in the flow-chart in Fig. 18.

6.2 The preconditions for production of acceptable raw material for non-wood pulping

6.2.1 Possibilities to enhance yielding ability

Harvesting time

The harvesting system greatly influenced yield capacity of the species. Tall fescue was favoured by a harvesting system of two cuts (first cut at flowering and second in October) to a greater extent than reed canary grass. The superiority of the two-cut system compared with three or one cut systems was reported in earlier studies (Nissinen and Hakkola 1994, Pahkala 1997). Two cuts of reed canary grass resulted in lower yields, especially on organic soil. In the years of experimentation, regrowth DM yield of reed canary grass comprised 5% to 32% and tall fescue 9% to 25 % of total harvested biomass. The regrowth ability was highly dependent on weather conditions during the post-harvest period. Precipitation after the first cut contributed markedly to the regrowth. In the studies of Mason and Lachance (1983), performed in Quebec, Cana-

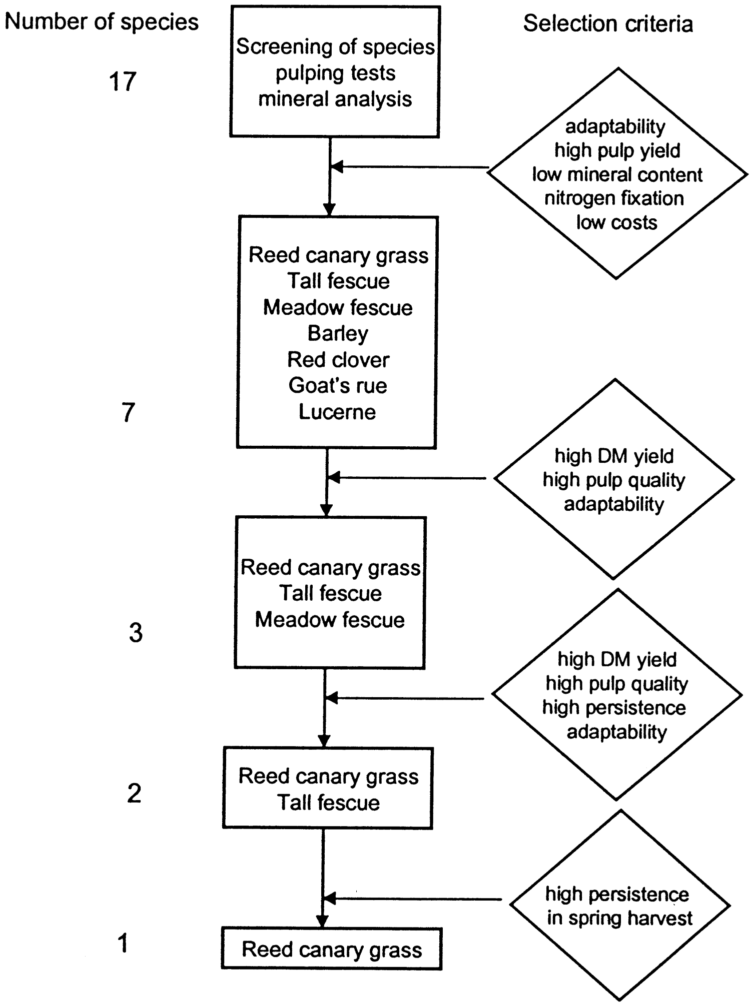

Fig. 18. Flow-chart for the selection of fibre plant.

da, 43% of total biomass of tall fescue was from regrowth and for reed canary grass it was 32%. The total DM yield of two cuts of reed canary grass and tall fescue however tended to decrease after the first year of harvest. Furthermore, for papermaking purposes the system of two harvests, combined with drying the biomass, is likely to be too expensive even when the combined biomass from two cuts would be high during the first harvest years.

High DM yields of reed canary grass and tall fescue were obtained when the crops were harvested in autumn at the seed ripening stage. However, the DM content was less than 45% for both species, and the harvested biomass needed to be dried to reach a DM content of 85% before storage (Hemming et al. 1996). Reed canary grass gave the highest yields when harvested only once either in autumn or the following spring. However, the annual variation in yield was greater when harvested in autumn. According to the studies of Mason and Lachance (1983), total annual yields of reed canary grass and tall fescue increased when the first harvest was delayed. In their study, reed canary grass was superior in yielding capacity to timothy (*Phleum* *pratense* L.), tall fescue and Kentucky bluegrass (*Poa pratensis* L.). Moreover, in Swedish studies reed canary grass had the highest yield potential when it was compared with brome grass (*Bromus inermis* Leyss.), tall fescue, cocksfoot (*Dactylis glomerata* L.) and timothy (Wisur et al. 1993).

Of the crop species studied, reed canary grass was favoured most by a spring harvest. The first spring harvest was done two years after sowing and it resulted in 4–7 t DM ha^{-1}. The following spring harvests gave yields of 6–8 t ha^{-1} in most years. DM yields increased with delayed harvest and increasing age of the ley compared with autumn harvests. This was also demonstrated in Swedish studies (Olsson 1993, Andersson 1994, Landström et al. 1996). Spring yields of reed canary grass were 6 to 10 t ha^{-1} annually and on organic soil even higher than 10 t: twice the annual yield of birch forest (4–7.5 t of DM ha^{-1}), the maximum annual growth of which is 8–15 m^3 (Ferm 1993). When reed canary grass was harvested in spring, the yield remained constant from the second year ley throughout eight years, but some variation caused by weather conditions was recorded in those years. The difference between the average yield at autumn and spring harvests was not significant during the eight years because of the first harvest year, which was associated with the lowest yields in every experiment. Reed canary grass would benefit from spring harvesting with good persistence of the stand and with small variation in yield. However, its productivity in the UK was 7–12% less than that of Miscanthus and switchgrass (Christian et al. 1999).

For tall fescue, delayed harvesting in spring resulted only in 37–54% of DM yields harvested during the previous growth period. Low spring yields of tall fescue were associated with the growth habit of the species: a plant stand of tall fescue consisted mostly of leaves, and the crop was flattened tightly along the ground under snow cover. In spring, it was impossible to lift the lodged biomass with harvesters, and the plants were partly rotten. After spring harvest, tall fescue produced much fewer stems and panicles than the plots harvested in summer or autumn. As a tussock grass, tall fescue may be more prone to damage during an early spring cut than reed canary grass. The reason for the enhanced formation of reproductive tillers could be also the lack of light in late summer of the previous year, when the tillers of tall fescue were initiated or when the tillers were too young in autumn to respond to low temperature induction (Hare 1993). The enhanced effect of shading on tiller formation was reported for cocksfoot (Hare 1994). Because of poor biomass and straw yield, tall fescue was considered not to be suitable for spring harvesting.

The spring harvest duration of the present studies was about 10–15 days, when the moisture content of the grass was between 10% and 15%. The moisture content decreased to this level even before ice had disappeared from soil, i.e. in south Finland in late April. High moisture content of the soil or rain showers occasionally delayed harvesting for weeks. Hemming et al. (1996) estimated that during the harvest period of two weeks in spring there would be 6–9 days when the weather conditions favour harvesting in Finland. It was also obvious that the harvesting has to be done before the new tillers are 15–20 cm high. If the emerging shoots are taller at harvest, they may drastically reduce quality of the harvested biomass because of increasing moisture and mineral content of the biomass. In literature this is called the “harvest window” problem. It is described for Miscanthus in the Netherlands (Huisman 1994, Venturi and Huisman 1997). It is the period between the possible start of the harvest, defined by the decreasing moisture content of soil and biomass in spring time, and the end of the harvest period when the tillers grow too long.

Effect of nutrients

Increase in the supply of mineral nutrients from the deficiency range increases the growth of crop plants. The positive yield response to nitrogen application is well known for grasses (MacLeod 1969, Hiivola et al. 1974, Allinson et al. 1992, Gastal and Bélanger 1993). In this study, the increased fertilizer application rates usually resulted in increased total yield of reed canary grass, when the biomass was harvested at the green stage in summer or in autumn. However, on a clay soil the yield increase with increasing fertilizer application rates was obvious also in spring up to 150 kg N ha^{-1}. A rate of 200 kg N ha^{-1} did not improve yield beyond that promoted by 100 kg N ha^{-1}. On organic soil, the spring yield response to increasing fertilizer rates was smaller than on clay soil and applications in excess of 50 kg N ha^{-1} did not result in higher DM yields. The results show that growing reed canary grass on clay soil requires more N fertilizer to reach the same DM yield as growing the crop on organic soil. Overuse of fertilizers may be uneconomic and cause environmental problems for farmers. Fertilizers represent the principal cost in cultivating reed canary grass when the rate of 70 kg N ha^{-1} is exceeded (Maunu and Järvenpää 1995). When reed canary grass was grown on clay soil and harvested in spring the economic optimum for the fertilizer application rates is likely to range from 50 to 100 kg N ha^{-1}. Growing reed canary grass on organic soil for papermaking might be advantageous as less fertilizer is required. However, more research is needed to have further long-term information on development and yield formation of reed canary grass on organic soil.

Yield of tall fescue was not enhanced at the highest fertilizer application rate of 150 kg N ha^{-1} during the two first years of harvest. On clay soil there were hardly any differences among the various treatments beyond 50 kg N ha^{-1} when tall fescue was harvested at the green stage. On organic soil, the yield response for the highest rate was recorded only at the seed stage in 1995. However, the results of Moyer et al. (1995) from young tall fescue swards showed yield increase by 53% as N application rate increased from 13 to 112 kg N ha^{-1}, and by 69% as the rate increased from 13 to 168 kg N ha^{-1}. At delayed harvesting in spring the differences in yield among the treatments seemed to be inconsistent and not statistically significant. If tall fescue is used as raw material for papermaking, fertilizer application rates higher than 100 kg N ha^{-1} are not likely to improve yield.

Harvest losses

Stubble height markedly affected the harvested DM yield of reed canary grass. When grass was harvested at 5 cm instead of 10 cm, the DM yield was on an average more than 30% higher. The reasons for such a high yield difference may be several. When cut at the height of 10 cm versus 5 cm, the loss of the total biomass measured as the weight loss of 5 cm straw was 5.8%. The higher harvest losses at a stubble height of 10 cm caused by lodging were also evident, but were not measured in this study. In the study of Horrocks and Washko (1971), plants cut in spring leaving 10 cm stubble instead of 4 cm produced the same number of tillers, but the weight per tiller after a 4 cm cut was about 60% higher than that after a 10 cm cut. In the present study, the number of stems counted in autumn and spring was not affected by stubble height. However, the weight of individual tillers was not measured and the high yield, when cut at 5 cm, remained partly unexplained. Harvesting losses resulting from the harvester and baling would be high, but under favourable conditions were less than 15% (Hemming et al. 1996). The summary of the factors affecting harvested DM yield of reed canary grass is presented in Fig. 19.

6.2.2 Development of crop management practices targeting high quality

Fibre content

High fibre content in raw material is desirable for fibre production. In this study, the crude fibre content of reed canary grass and tall fescue was always higher the later the crops were harvested, being thereby highest at spring harvest. Reed canary grass and tall fescue crude fibre contents were highly correlated with pulp yield (Hemming et al. 1996, Pahkala et al. 1999). An increase of fibre content with delayed harvest is explained by ageing of the plant, and is associ-

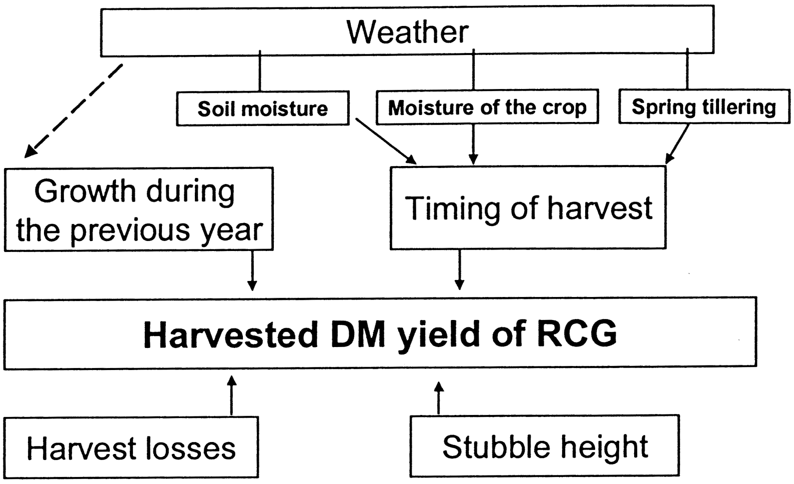

Fig. 19. Factors affecting spring yield of reed canary grass (RCG).

ated with increase in the relative amount of plant cell walls (cellulose and lignin content in particular). This takes place at the expense of other cell constituents as described for several forage crops (Buxton and Hornstein 1986, Albrecht et al. 1987, Buxton and Russel 1988, Gill et al. 1989). Another possible reason for fibre increase at delayed harvesting would be the different weight distribution of the plant parts in harvested biomass. The cell wall concentration, and thus the fibre content, is highest in stems (Buxton and Hornstein 1986), and the proportion of stems increased with plant age at the expense of the leaf fraction (Olsson et al. 1991, Pahkala and Pihala 2000). In this study, the highest pulp yield and crude fibre content was measured for stems and the lowest for leaf blades. Thus, the proportion of stems is likely to be a determining factor contributing to fibre content of the total biomass. However, even more than a half of the biomass of reed canary grass consisted of stems, whereas the corresponding proportion in tall fescue was 30–45%. In spite of this difference, the crude fibre content of total biomass, as well as the pulping results from earlier studies (Pahkala 1997), was almost the same. The result indicates that the leaf fraction of tall fescue, unlike that of reed canary grass, contains fibres suitable for pulping. The fertilizer application rate had rather a small effect on crude fibre content of reed canary grass and tall fescue especially in spring harvested biomass. However, the lowest content of crude fibre was often found in plants that had received the most fertilizer. Increased fertilizer use decreased the relative amount of stems in biomass and concomitantly fibre content. It increased the proportion of leaves more than that of stems. The highest stem proportion of reed canary grass and tall fescue was found in plots where the total DM yield was lowest, in most cases in non-fertilized plots or in those that had received 50 kg N ha^{-1}.

Mineral content

The quality of paper pulp is dependent on quality and homogeneity of the biomass used as raw material, as well as the impurities that often originate from soil. When entire plants are used for pulping, heterogeneity in fibre and mineral content of the raw material can result in variation in the quality of the pulp (Ilvessalo-Pfäffli 1995). In fibre production, mineral elements such as silicon can complicate the recovery of chemicals and energy in pulp mills and cause thereby extra costs (Ranua 1977, Keitaanniemi and

Virkola 1982, Rexen and Munck 1984, Jeyasingam 1985, Ulmgren et al. 1990). Other harmful elements for the pulping process include potassium, chlorine, aluminium, iron, manganese, magnesium, sodium, sulphur, calcium and nitrogen (Keitaanniemi and Virkola 1982). In the present study, the concentrations of undesirable minerals were higher in non-wood species than in birch, and the concentrations in grasses and cereals were generally higher than those in dicotyledons. The total mineral content, indicated as ash content, was lowest in straw of linseed and hemp and highest in nettle and barley. High silica concentrations are known to be typical of grass species (Ilvessalo-Pfäffli 1995, Marschner 1995), because grasses accumulate silica in epidermal cells, where it protects the crop against herbivores and fungi (Jones and Handreck 1965). If grass biomass is used as a fibre source for paper manufacturing evidently more silica and other minerals enter the process than when wood is used. However, results from this study showed that it is possible to decrease the mineral content of the raw material by modifying crop management practices such as harvesting time, fertilizer application rate, soil type and by using the plant parts with the lowest mineral content as raw material. The chemical composition of a plant part varies depending on the stage of development when the mobile elements move from organ to organ as growth proceeds (Jeffrey 1988). The ash content decreased as plants aged, being lowest in spring yield, as Landström et al. (1996) also showed. The potassium and nitrogen content was clearly lower in spring than in autumn. This was probably due to leaching during winter. The trend was the same for both plant species and occurred irrespective of plant part (Pahkala and Pihala 2000). Contrary to this, silica content clearly increased as harvesting was delayed, being highest in spring yield of reed canary grass and tall fescue. In several earlier studies, the concentration of silicon was found to increase as a plant aged (Tyler 1971) and was highest in dried material at delayed harvest (Landström et al. 1996, Burvall 1997). Silicon is deposited as silica crystals mostly in the epidermis of plants (Ilvessalo-Pfäffli 1995) and it is not exposed to leaching. When studying mineral content of each plant part, ash and silica content were lowest in stems irrespective of the harvest time. In leaf sheaths and especially in leaf blades, the content of minerals was clearly higher than in stems. Petersen (1989) reported high ash and silica content in leaves of cereals and Theander (1991) in leaves of reed canary grass.

In addition to a yield response, mineral nutrition can influence the mineral composition of a plant. Increase in fertilizer application rate elevated potassium, nitrogen and phosphorus content, whereas ash and silica content decreased. The highest contents of ash and silica were found in plants from non-fertilized plots. When harvested during the growing period, silica content decreased when fertilizer application rate increased for both species, but in reed canary grass the stepwise decrease was seen also in spring yield. Soil type affected mineral content of biomass. The lowest ash and silica content was found in plants grown in sandy and organic soil and highest in those from clay soil. Thus, our results indicated that it is possible to produce high quality raw material for pulping, i.e. high fibre content and low mineral content, by combining moderate fertilizer application to a grass crop with spring harvesting. When the increase in the stem fraction of biomass is realized by this means, it also results in improved quality of raw material.

The density of grass stands is often an important measure in regulating canopy structure. Using the wider row spacing of 25 cm, rather than the more standard 12.5 cm, did not result in a yield or quality advantage for reed canary grass. In tall fescue, the effect of row spacing was more obvious than for reed canary grass, especially on clay soil. In Jokioinen, the wider row spacing resulted in more stems in biomass of tall fescue, lower ash and silica content and higher crude fibre content. The increased stem proportion following the use of wider rows possibly contributed to improved quality of tall fescue.

6.2.3 Possibilities for reducing production costs

When grasses are grown for paper pulp, their crop management differs from that used in conventional grassland farming. As short fibre raw material the price for grass at the mill gate cannot be much higher than that for birch. According to calculations of Paavilainen et al. (1996b) and Hemming et al. (1996) the price for a ton of dry reed canary grass should be 389 to 421 FIM (65–71 euros) at maximum, whereas the corresponding price for birch or pine was 472 to 479 FIM (79–81euros) at a reference mill. High biomass yield and high pulp yield are the most important factors contributing to profitability when raw material is produced for the fibre industry.

6.2.4 Requirements and possibilities for domestic seed production

Except for lucerne, nettle, fibre hemp and common reed, the species screened at the first stage of this study seed can be produced on a commercial basis in Finland, or it has at least been shown to be possible. Results from the study of Sahramaa and Hömmö (2000b) showed that seed production for reed canary grass is possible in Finland, but seed yield and vigour, i.e. germination ability and seed weight, varied greatly depending on year and harvesting time. At the optimum harvest time, 15 days after completion of anthesis, the seed yield of reed canary grass was 100 to 369 kg ha^{-1}, i.e., close to the level reported in Sweden (280–361 kg ha^{-1}, Cedell 1994). The yield was highest in one- and two-year old plant stands and the high seed yield was associated with high 1000 -seed weight and high seed germination ability. Commercial seed production of reed canary grass has started on 400 hectares, but stability problems exist, i.e. yield decrease already at the second harvest year has been recorded (Myllylä and Myllylä 2000). A possible solution would be to harvest the seed once and then use the crop in the following years for fibre or energy or harvest the seed only every other year, as recommended by Myllylä and Myllylä (2000) for the commercial seed growers.

Tall fescue is not commonly grown in Finland. However, a new cultivar, Retu, was released in 1995. It is a highly persistent, winter hardy cultivar and following its release the area sown to tall fescue has increased from zero to 1000 ha within the last five years. In the official variety trials, the average seed yield for tall fescue has only been 395 kg ha^{-1} as a result of poor panicle production (Niemeläinen 1994). However, seeds of tall fescue did not shatter as easily as those of reed canary grass, and thus, seed production would be easier. The low seed yields will keep the price high, as is also the case with reed canary grass.

6.2.5 Enhanced adaptability of reed canary grass to Finnish growing conditions

Selecting an appropriate cultivar or breeding a new one are principal means for optimising adaptability and thus, high yielding capacity and quality for the prevailing growing conditions. The ten cultivars included in the study were all bred for feed. Thus, their growth habit and productivity were rather similar. The quality traits for a biomass crop differ from those for fodder crop. For example, decreasing alkaloid content of the biomass by breeding may increase attack by insect pests or herbivores (Coulman et al. 1977, Østrem 1987). The ideotype of reed canary grass for fibre use has high stem to leaf ratio, high fibre content and low mineral content (Andersson and Lindvall 1999), and is in these respects dissimilar to a fodder type. In this study, it was not possible to identify the highest yielding cultivar for each location because of large genotype x harvest year interactions for DM yield. The spring yield was often highest in the second or third year of spring harvest. In Rovaniemi, the most northern trial site, the development a sufficiently dense stand took a year longer than elsewhere. The annual average DM yields were 6 to 7 t ha^{-1}. However, the highest yields, 11 t ha^{-1} in Jokioinen and 14 t ha^{-1} in Ylistaro, indicated the high yield potential of the crop. Yields could have been even higher if the trials had been harvested in spring following the first harvest; spring harvest of the variety trials started after two years of autumn harvest.

Large DM yield is one of the main goals in breeding agrofibre crops (Lindvall 1992, Sahramaa and Hömmö 2000a). However, the variation among growing sites and among harvesting years was more substantial than variation among cultivars. The cultivars Barphal 050 and Lara tended to be most productive at the northernmost sites, Rovaniemi and Sotkamo, whereas Motterwitzer and Venture were the most sensitive ones in the extreme growing conditions. Barphal 050 and Lara were productive also in Laukaa, where the snow cover is thick in winter. Jo 0510, Palaton, Lara, and Vantage were more productive in the trials in western Finland, Jokioinen, Ylistaro and Ruukki. The variation in quantitative traits including yield capacity is controlled polygenically, the relative effect of which is smaller than that arising from environmental factors such as climate, nutrition and crop management (Baltensperger and Kalton 1958, Sachs and Coulman 1983, Østrem 1988a, Falconer and Mackay 1996).

Studies on the morphology and quality of three cultivars (Palaton, Venture and Lara) indicated only modest variation in proportion of plant parts. The cultivars were bred for feed purposes and thus their growth habits were rather similar. There were no significant differences between growth at the three locations (Jokioinen, Ylistaro and Ruukki), which indicates that the growth habit of each genotype was independent of the location and prevailing soil type. However, when the fibre and mineral content of each plant part was studied, all plant parts of cultivar Lara contained lower fibre but higher mineral content than those of Venture and Palaton. Thus, Lara was concluded to be less suitable for fibre production. When testing the reed canary grass breeding material, variation in stem proportion and mineral and fibre content were recorded (Sahramaa and Hömmö 2000a). The reason for the variation in mineral content has been studied in Miscanthus populations collected from Japan. The large variation in nitrogen and potassium contents in the spring harvested Miscanthus were related to degree of crop senescence in autumn (Jørgensen 1997). The first severe frost in the autumn increased the rate of mineral loss from plant material. If the effect of autumn frost on the mineral content in spring yield is evident, as Jørgensen (1997) suggested, early senescence of the plant stand is very important when producing raw material for pulping due to less minerals in harvested biomass.

Since the quality of the current cultivars bred and grown for feeding purposes was not satisfactory for fibre use, a new type of grass cultivar adapted to northern growing conditions is evidently needed. Breeding programs aimed at developing such cultivars for non-food purposes began in 1993 in Finland and in 1989 in Sweden (Lindvall 1997, Andersson and Lindvall 1999, Sahramaa and Hömmö 2000a). In contrast to cultivars bred for feeding purposes, substantial morphological variation has been found within the breeding material collected from different locations in Finland and in Sweden (Lindvall 1999, Sahramaa and Hömmö 2000a). As some variation in chemical components of interest has also been found in the breeding material, it is likely that new cultivars, targeted for fibre production purposes, can be released in the future. The interest in producing reed canary grass for non-food purposes has therefore not ceased.

6.3 Feasibility of non-wood pulping

Pulping grass biomass and cereal straw was easy and fast. It took only 10 to 15 minutes, when the soda-anthraquinone process was used for pulping at the first screening of species. Processing wood took at least 90 minutes. Only modest differences between the monocotyledons were found. Pulp yields were 33 to 40% of DM for grasses harvested during the green stage, and 42 to 48% for cereal straw. Pulp yields for dicotyledons were much lower and the amount of uncooked screenings, which is insignificant in commercial birch sulphate pulp and less than 3% for grasses and cereal straw, was up to 41% for dicotyledons. The cooking procedure was the same for all species, which is likely to explain the unsatisfactory pulping result for dicotyledons. Probably short cooking time was more suitable for the monocots. Also the amount of NaOH (16% of DM) used in trials was too low for dicotyledons. In the case of red clover and goat's rue the pulp yield, the amount of screenings and kappa number became more acceptable when the dose of cooking chemical was increased to 20% or 24% of DM.

In the present study, delayed harvesting greatly affected pulping characteristics of reed canary grass by increasing both kappa number and pulp yield. Biomass harvested in autumn was easier to pulp than that harvested in spring, and less screenings were recorded. The screenings averaged from 1.1% to 1.6% of DM in autumn and from 1.7% to 2.9% in spring harvest. The kappa numbers, indicating lignin content (Håkansson et al. 1996), were lower for grass pulp than for wood pulp or for pulp made from legumes and other dicots. In grasses and legumes, lignins are predominantly formed from coniferyl and sinapyl alcohols with only small amounts of p-coumaryl alcohol (Buxton and Russel 1988). However, large variation in lignin structure and content exists among the major crop groups and among species (Sarkanen and Hergert 1971, Gross 1980). During maturation of grass, syringyl lignin increases in proportion relative to guaiacyl and *p*-hydroxyphenyl lignins (Carpita 1996). The increased lignin content and especially syringyl lignin would explain higher kappa number and screenings in biomass harvested in spring.

Samples from different parts of reed canary grass showed significant variation in all their pulping characteristics. Only fibre width or CWT index (indexed value of cell wall thickness) of reed canary grass did not differ among plant parts. Stems are the most useful plant part, giving the highest yield, lowest kappa number under constant cooking conditions, and the brightest pulp. The stem fraction was the most suitable for fibre production since it contained the lowest mineral content and the highest content of crude fibre. This resulted in the highest pulp yield. Spring harvesting and fractionation of the raw material, especially removal of the leaf blades, reduced the mineral content and improved the pulpability and papermaking potential of reed canary grass (Paavilainen et al. 1996b). Stem fibres with a fibre length of about 0.9 mm and a coarseness of about 0.09 mg m^{-1} were best suited for papermaking. Large amounts of fine material originated from epidermal and parenchymal cells of leaf blades, which also made the sheets more difficult to dewater as reported also by Wisur et al. (1993). Stems had the highest crude fibre content, being 52% of DM. Crude fibre content of whole plants was closer to that of leaf sheaths than that of stems. Leaf blades also gave dark coloured pulps of low brightness and thus proved to be completely unsuitable for pulping. Because of the low quality of leaf blades and sheaths, the pulps from whole plants cooked slower and gave significantly lower yield and pulp brightness than stems alone. Kappa number was about the same as for stem fraction. Removing the undesirable minerals along with the leaf blades would reduce the mineral content considerably and, simultaneously the relative proportion of stem, the most fibre-rich part of the crop, would increase. Using a higher proportion of stem fraction would increase the pulp yield and improve the pulp quality as shown by Petersen (1989) and Paavilainen et al. (1996b). When a crop was harvested in spring, the total pulp yield correlated with crude fibre content of the plant part (Pahkala et al. 1999). Crude fibre, measured using the Weende analytical system, has been a standard method for more than a century for determining fibre in animal and human foods (van Soest 1985). From cell wall constituents, the crude fibre determination yields cellulose, and a small fraction of hemicellulose and lignin. The remaining hemicellulose and lignin, and even a fraction of cellulose, is dissolved using a combination of acid and alkali. Pulp yield determined by chemical pulping and measures the same fibre fractions: cellulose, some hemicellulose and a part of the lignin. Thus, the crude fibre content of grass may serve as an indicator of pulp yield.

At the pulp mill, leaves, dust and dirt can be removed by air fractionation before cooking (Paavilainen et al. 1996b). However, in grasses the leaf sheath is usually tightly rolled around the stem, being thereby more difficult to remove than leaf blades. Mechanical pretreatment improves the quality of the pulp by increasing bleachability and decreasing the fines and silica particles in the raw material. Removing 40% of the silica through pretreatment of the grass (Paavilainen et al. 1996b) can decrease the amount of silicon entering the process. The dewatering and drying ability of pure grass pulps can be improved by mechanical fractionation and blending the grass pulp with long-fibre softwood pulp (Wisur et al. 1993. Paavilainen et al. 1996a, Paavilainen et al. 1996b). Based on the result of a pilot test, reed canary grass pulp is a potential short fibre component for fine papers in blends with long fibres from soft wood pulp. No runnability problems were found in the pilot process when the amount of reed canary grass sulphate pulp was increased to 70% of the pulp blend (Paavilainen and Tulppala 1996). Dewatering and drying characteristics also stayed constant. This result differed from that obtained in Sweden (Wisur et al. 1993), where unfractionated, short-chopped green reed canary grass was difficult to dewater. Increased grass pulp affected some of the paper properties important for runnability on the paper machine and for printability of the paper. Tear strength was decreased, but optical properties and paper surface properties including smoothness and gloss were improved (Paavilainen and Tulppala 1996). Pulp yield and quality have been improved through crop management and pulping processes suited to the raw material. The development stage of the crop at harvesting greatly affected the amount and quality of the pulp. When late summer harvested reed canary grass was delignified using ethanol as the pulping chemical, kappa number stayed high (50–65) using an even cooking time of two to five hours (Håkansson et al. 1996). The pulping method may also influence paper properties such as tear strength and the light scattering coefficient (Thykesson et al. 1998).

7 Conclusions

This thesis describes a strategy and a process to locate, select and introduce a crop for a new purpose. The steps taken along the process overlapped during the ten years of research, but the goal, to have a new fibre crop for domestic short fibre production, remained clear throughout the study. In conclusion, the concept of large-scale cultivation of a new fibre crop, reed canary grass, is described as a result of crop management research conducted in 1990–2000. Baling, storage and transport were described by Hemming et al. (1996).

Crop management practices for reed canary grass as a forage crop were well established even though the grass was not commonly grown in Finland. In growing reed canary grass for fibre, the best time for sowing was spring or early summer, although the slowly emerging seedlings became subject to weed competition and drought. Small seeds, with a 1000 seed weight of about 0.9 g, were sown at 800 to 1000 viable seeds m^{-2} (i.e., 7–10 kg ha^{-1}). This gave a dense stand if sown without a cover crop at a depth of 1 cm and using rows spaced at 12.5 cm. A double row spacing resulted in more weeds, and lower biomass yield with less stems. Even though the natural habitat of reed canary grass is wet and flooded areas, it grows on almost any soil type. It was relatively drought tolerant after the seedling stage, but on heavy clay soils establishment was uneven. Using more seed may ensure establishment on clay soil. However, reed canary grass established well and produced high biomass on humus-rich wet soils and sandy soils. It tolerated flooding well, and grew even in an area inundated with seawater at low salt concentration.

The amount of nutrients removed from the field with the harvested crop varied considerably and depended on harvest time. At spring harvest, only half of the supplied N and P were removed with the crop. The supplied K was in balance with that removed, 6 t ha^{-1}. On organic soil, which is very suitable for reed canary grass, lower fertilizer application rates can be successfully used. Nitrogen fertilizer was applied to stands of reed canary grass at 40 to 70 kg ha^{-1} at establishment and in the first harvest year and during subsequent seasons at 70 to 100 kg ha^{-1}, depending on the desired yield and soil type.

Reed canary grass typically yielded 7–8 t ha^{-1} within three years of sowing on clay soil and exceeded 10 t ha^{-1} on organic soil after the second harvest year. The optimum harvest time for reed canary grass for pulp production was spring. The harvest period allowed by weather conditions ranged from 10 to 15 days in Finland. At that time the moisture content of the non-viable grass biomass was between 10% and 15% and the maximum height of the new, green tillers 15 to 20 cm. The stubble height strongly influenced harvested yield. If the plant stand was cut to 10 cm from the soil surface, the DM yield was 30% lower than when cut to 5 cm. Harvesting can be performed by mowing followed by baling. Under favourable conditions, harvest losses were less than 15%. Storage of round bales was cost-effective in simple outdoor stacks covered by plastic. The economical transport distance of the bales to a pulp mill was estimated to be about 50 km (Hemming et al. 1996). When cut in the spring, reed canary grass was very persistent and grew well for at least 10 years. The stem was the most valuable part of the plant from the perspective of pulping performance, containing more fibre than other plant parts. The content of undesirable minerals was also lowest in the stem, and especially in spring harvests, in which the stem content was often 60 to 70% of the DM yield, increasing with plant stands age.

The cultivars of reed canary grass currently grown in Finland were solely bred for forage. One of the most important properties of a cultivar for pulping is a high proportion of stem fraction in the yield, in contrast to cultivars used for feed. Other useful properties for a cultivar are abundant biomass and adaptability to the prevailing climate. The variety experiments performed in this study showed modest differences in yielding capacity and in the proportion of stem fraction. However, when harvested in spring, the cultivars Barphal 050 and Lara were superior in northern Finland, and also in Laukaa, in mid-Finland, where the snow cover is moderately deep in winter. Jo 0510, Palaton, Lara, and Vantage were more productive in the trials in western Finland, Jokioinen, Ylistaro and Ruukki. However, Lara was less suitable for fibre production because of its lower fibre content, associated with higher mineral content compared with Palaton. Breeding reed canary grass for non-food purposes continues in Finland and Sweden and new cultivars are to be released close towards the end of this decade. Cultivation of reed canary grass has started in Finland, and it is now sown on more than 500 hectares.

Introducing a crop for a new purpose requires a large research effort, and it is possible only with co-operation of several research institutes. Furthermore, as the crop was not commonly grown in Finland, the work required was even greater than would have otherwise been the case. The success of this new crop for Finland, for domestic short fibre production, ultimately depends on the interest shown by the pulping industry.

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SELOSTUS

Peltokasvit sellun ja paperin raaka-aineena

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Suomessa viljelystä poistettavan peltoalan määrästä esitettiin 1990-luvun alussa arvioita, joiden suuruus vaihteli 0,5 miljoonasta hehtaarista 1 miljoonaan hehtaariin. Samoihin aikoihin hienopaperin kulutus kasvoi ja lehtipuuta jouduttiin tuomaan yhä enemmän maahan. Näihin lähtökohtiin perustuen aloitettiin vuonna 1990 tutkimus, jonka tarkoituksena oli kehittää menetelmä, jolla saataisiin tuotettua suomalaisista peltokasveista koivun veroista lyhytkuituista raaka-ainetta mahdollisimman edullisesti hienopaperin raaka-aineeksi. Samalla oli tarkoitus saada elintarviketuotannosta vapautuville pelloille uutta käyttöä. Tässä väitöskirjassa esitetyt tulokset ovat Agrokuitututkimuksen kasvintuotanto-osasta vuosilta 1990 ja 1993–1999. Koska nämä tulokset ovat osa suuremmasta kokonaisuudesta, väitöskirjassa on tarkasteltu myös projektin muiden osatutkimusten sekä ruokohelven kuitukäyttöön läheisesti liittyvien muiden tutkimusten tuloksia suhteessa kasvintuotantotukimuksista saatuihin tuloksiin.

Tämän tutkimuksen tarkoituksena oli selvittää, voidaanko Suomen peltokasveista löytää sellun raaka-aineeksi soveltuvia lajeja, joita voitaisiin tuottaa kilpailukykyiseen hintaan ja onko tuotantotekniikalla mahdollista vaikuttaa suotuisalla tavalla sellun raaka-ainekasvien biomassan tuottoon ja kemialliseen koostumukseen. Tutkimuksen tarkoituksena oli myös laatia kuvaus suurille viljelyaloille tarkoitetusta viljelymenetelmästä, joka tuottaisi tarkoitukseen valitusta kasvilajista teollisuuden käyttöön mahdollisimman laadukasta, lyhytkuituista raaka-ainetta.

Alustava tutkimus käynnistyi vuonna 1990, jolloin mukana oli 17 kasvilajia. Näistä valittiin edelleen sellu- ja kivennäisanalyysien perusteella seitsemän kasvilajia viljelyteknisiin tutkimuksiin, joissa selvitettiin kasvien biomassan tuottoa sekä viljelytoimenpiteiden vaikutusta sellun ja paperin valmistuksen kannalta tärkeisiin laatutekijöihin. Vuonna 1993, jolloin vakavasti otettavia ehdokkaita lyhytkuituiseksi sellukasviksi oli enää ruokonata (*Festuca arundinacea* Schreb.) ja ruokohelpi (*Phalaris arundinacea* L.), perustettiin laajoja kenttäkokeita molemmista kasvilajeista. Samaan aikaan tutkimusta laajennettiin käsittämään koko tuotantoketju viljelystä paperin valmistukseen saakka.

Tuotantotekniikan vaikutuksia ruokohelven ja ruokonadan biomassasadon määrään, sellun valmistuksen kannalta tärkeiden kivennäisaineiden pitoisuuksiin sekä sellusaantoon ja laatuun tutkittiin eri korjuuaikoina ja käyttäen erilaisia lannoitusmääriä. Kasvilajeista vain ruokohelpi soveltui monivuotisessa viljelyssä korjattavaksi keväällä kuloheinänä, mikä kokeilluista korjuutavoista tuotti sellun valmistukseen parhaiten soveltuvaa raaka-ainetta. Ruokohelpi osoittautui myös kestävimmäksi kasvilajiksi, jonka kuiva-ainesadot vakiintuivat ensimmäisen korjuuvuoden jälkeen noin 7–8 tonniksi hehtaarilta. Kun ruokohelpi korjataan keväällä, kylvöjen väli voi olla jopa kymmenen vuotta. Ruokohelven vuotuiset typpilannoitusmäärät vaihtelevat 50–100 kg N hehtaarilla. Markkinoilla olevia ruokohelven rehulajikkeita voidaan käyttää kuidun raaka-aineena ja ne menestyvät aina Pohjois-Suomea myöten. Parhaiten kevätkorjuuseen soveltuivat Palaton, Lara, Vantage ja Venture lajikkeet. Viljelyn lopettamisen jälkeen ruokohelpi ei jää pellolle rikkakasviksi, jos kasvusto hävitetään glyfosaatilla ja kynnetään syksyllä, ja parina seuraavana vuonna viljellään yksivuotisia kasveja esim. kevätviljaa.

Heinäkasvien kivennäisaineiden pitoisuudet olivat suurempia kuin puuraaka-aineessa, mutta kuitupitoisuudet lähes samanlaisia. Ruokohelpiraaka-aineen laatuominaisuuksia voitiin parantaa korjaamalla kasvusto keväällä kuivana kuloheinänä, jolloin sadon vesipitoisuus on ainoastaan 10–15 %. Sellun valmistuksessa haitallisten kivennäisaineiden määrää voitiin vähentää käyttämällä ruokohelven keväällä kuloheinänä korjattua satoa, ja edelleen poistamalla kevätkorjatusta materiaalista lehtilavat, jotka sisälsivät eniten kivennäisaineita ja vähiten kuitua. Ruokohelven kasvinosista korsi sisälsi eniten kuitua ja vähiten kivennäisaineita ja se soveltuu siten parhaiten sellun valmistukseen.

Kun uusi kasvilaji otetaan lyhyessä ajassa laajamittaiseen tuotantoon, se vaatii onnistuakseen laajoja tutkimuksia, jotka etenevät samaan aikaan koko tuotantoketjussa. Tämän tutkimuksen tulosten käyttökelpoisuus ja siten myös tutkimuksen onnistuminen punnitaan tulosten soveltamistilanteessa, kun ruokohelpeä viljellään suurilla pinta-aloilla ja saatu raaka-aine käytetään sellun valmistukseen.

Appendix I a

Climate data (mean temperature and precipitation for month and year, effective temperature sum, the date for the start and the end of growth period) from Jokioinen, Vihti, Tohmajärvi, Laukaa, Ylistaro, Ruukki, Sotkamo and Rovaniemi is provided by the Finnish Meteorological Institute (online from Intranet http://mttinfo.mtt.fi/saa) compared with the values from 1961-1990 (Climatological statistics in Finland 1991).

Jokioinen

	1991		1992		1993		1994		1995		1996		1997		1998		1999		1961-1990	
Month	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm
January	-3.6	69	-2.1	50	-2.3	56	-4.8	52	-3.6	46	-6.2	8	-4.6	41	-2.2	53	-6.3	61	-7.5	36
February	-7.5	16	-2.7	31	-3.4	16	-14.0	1	-1.0	58	-11.3	35	-4.3	56	-4.7	42	-7.7	48	-7.4	24
March	0	31	0.4	43	-0.9	2	-3.2	54	-0.3	45	-4.5	29	-1.1	31	-4.6	28	-1.8	28	-3.5	25
April	3.4	14	1.3	48	3.3	29	5.0	33	2.7	47	2.6	24	1.2	45	3.1	15	5.0	42	2.4	31
May	7.2	29	11.4	7	13.6	1	7.8	34	8.7	87	8.8	65	7.7	16	9.2	65	7.5	13	9.4	35
June	12.1	69	15.7	25	11.4	56	12.1	66	16.7	121	13.1	52	16.1	101	13.7	99	17.4	30	14.3	47
July	16.6	55	16.0	47	15.6	107	19.0	1	15.3	53	13.9	136	17.8	141	15.2	70	17.5	49	15.8	80
August	16.2	92	14.3	107	12.9	136	15.1	54	15.1	65	17.0	14	17.8	44	13.0	83	14.1	55	14.2	83
September	9.1	80	11.3	59	5.7	13	10.0	105	10.3	45	8.3	20	10.0	78	10.5	29	11.6	34	9.4	65
October	5.4	49	-0.6	64	3.0	51	4.4	75	7.6	66	6.4	56	2.4	47	4.9	82	5.8	109	4.7	58
November	2.6	81	-1.8	63	-3.6	3	-1.0	24	-2.8	47	2.5	128	-0.4	43	-3.9	15	1.6	36	-0.5	55
December	1.6	34	0.1	33	-3.5	61	-0.4	51	-8.5	19	-6.1	28	-3.5	30	-3.3	46	-3.7	84	-4.9	42
Year	5.0	619	5.3	577	4.4	558	4.3	551	5.0	699	3.7	595	4.9	673	4.2	627	5.1	589	3.9	581
Effective temperature sum ºC																				
	1185		1343		1139		1271		1396		1159		1381		1209		1435		1241	
Growth period																				
start	10.5.		27.4.		22.4.		22.4.		20.4.		8.5.		28.4.		19.4.		18.4.		-	
end	19.10.		9.10.		20.10.		30.10.		29.10.		31.10.		20.10.		28.10.		14.11.		-	

Appendix I b

Vihti (Maasoja) Tohmajärvi

	Vihti (Maasoja)										Tohmajärvi					
	1993		1994		1995		1996		1961-1990		1995		1996		1961-1990	
Month	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm
January	-1.9	71	-4.4	66	-3.5	62	-6.6	8	-7.7	39.4	-5.5	45	-9.1	14	-11.7	41.0
February	-3.1	17	-15.2	1	-0.8	78	-12.0	25	-7.6	30.4	-3.2	73	-13.6	38	-10.5	31.9
March	-0.8	27	-3.3	59	-0.1	56	-5.4	36	-3.7	33.3	-1.0	55	-6.1	26	-5.2	34.6
April	3.2	16	4.9	56	2.5	26	1.9	23	2.5	34.1	1.5	53	1.2	27	1.1	36.0
May	12.8	5	7.8	65	8.9	84	8.9	65	9.6	32.9	8.6	38	7.4	67	8.6	36.0
June	11.6	54	12.4	47	17	28	13.1	76	14.5	38.8	16.4	31	13.3	43	14.0	56.7
July	15.6	101	18.6	0	15.4	36	14.2	131	16.0	71.8	14.4	49	13.8	78	15.9	69.7
August	12.8	133	14.5	87	14.7	60	15.7	8	14.2	82.3	14.2	85	15.2	30	13.5	80.2
September	5.5	13	10.5	110	10.1	88	7.6	22	9.5	69.7	9.1	41	6.7	28	8.3	65.1
October	2.8	62	4.2	93	7.5	65	6.4	57	5.0	70.5	6.0	71	4.4	51	3.2	64.7
November	-3.4	5	-0.8	20	-3.2	63	3.1	164	-0.1	64.3	-5.2	61	2.1	108	-2.5	60.9
December	-3.2	74	-0.5	70	-10.7	29	-6.1	32	-4.7	51.2	-12.2	27	-8.8	77	-8.1	54.0
Year	4.4	577	4.2	673	4.8	676	3.5	645	3.9	619	3.6	628	2.3	584	2.2	631
Effective temperature sum °C																
	1125		1263		1380		1124		-		1276		1018		-	
Growth period																
start	22.4.		22.4.		3.5.		3.5.		-		-		-		-	
end	20.10.		29.10.		28.10.		28.10.		-		-		-		-	

Appendix 1

Appendix I c

Laukaa Ylistaro

	1995		1996		1997		1998		1961-1990		1995		1996		1997		1998		1961-1990	
Month	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm	ºC	mm
January	-5.4	42	-7.5	14	-8.1	26	-4.7	62	-10.0	43	3.8	19	-5.1	9	-6.5	21	-3.7	43	-8.6	31
February	-3.2	57	-13.3	28	-6.5	29	-9.5	53	-9.5	30	2.3	39	-12.5	19	-5.4	25	-6.6	48	-8.4	21
March	-1.3	31	-4.9	27	-3.2	39	-7.4	31	-4.7	35	-0.1	52	-4.4	16	-1.4	16	-5.7	30	-4.1	23
April	1.2	46	1.5	36	-0.7	63	0.3	12	1.3	37	2.1	22	2.2	13	0.2	35	2.3	4	2.0	29
May	7.8	66	7.7	68	6.5	43	7.7	26	8.7	40	7.7	44	7.4	52	6.7	27	7.7	50	8.8	38
June	16.5	42	13.0	73	15.4	49	13.1	96	14.1	56	16.4	75	13.0	55	15.6	48	13.0	93	14.0	42
July	14.7	35	13.8	113	18.1	55	15.6	112	15.7	78	14.9	45	13.7	115	18.0	56	15.6	144	15.5	68
August	14.2	95	16.1	39	16.6	34	12.4	110	13.6	91	14.1	34	16.0	25	16.5	23	12.8	83	13.6	70
September	9.0	70	7.1	31	9.2	90	9.7	33	8.3	67	9.6	48	7.3	24	10.0	119	9.9	35	8.8	61
October	6.2	57	4.9	57	1.0	49	4.1	87	3.4	56	6.8	42	5.6	34	1.6	60	4.8	76	4.1	50
November	-4.5	45	1.0	114	-2.3	48	-4.4	17	-2.2	59	-3.7	25	-0.1	96	-1.2	41	-4.3	14	-1.4	45
December	-11.0	14	-8.5	42	-5.8	32	-5.6	40	-7.2	47	-9.8	12	-7.1	61	-3.4	14	-4.4	43	-6.2	35
Year	3.7	599	2.6	643	3.4	556	2.7	679	2.6	639	4.3	458	3.1	518	4.3	486	3.5	668	3.2	513
Effective temperature sum ºC																				
	1241		1054		1275		1084		1144		1252		1052		1300		1124		1161	
Growth period																				
start	17.5.		9.5.		7.5.		27.4.		-		20.4.		8.5.		6.5.		23.4.		-	
end	29.10.		31.10.		20.10.		28.10.		-		29.10.		31.10.		20.10.		28.10.		-	

Appendix I d

	Ruukki												Sotkamo											
Month	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm	^{o}C	mm
January	-5.8	46	-5.3	13	-8.6	25	-6.9	54	-12.7	40	-10.7	32	6.7	16	-7.1	12	-11.1	23	-7.4	34	-13.7	25	-12.4	30.2
February	-4.4	55	-12.7	30	-8.2	44	-11.1	39	-10.4	37	-9.8	24	4.9	33	-14.6	18	-9.2	41	-14.1	41	-11.2	25	-11.4	23.0
March	-1.1	27	-5.0	9	-3.5	38	-7.2	21	-3.7	29	-5.3	27	2.1	23	-5.5	10	-5.0	23	-8.4	16	-3.8	21	-6.4	25.2
April	1.0	23	0.8	24	-2.2	51	-0.4	8	3.2	13	0.8	25	0.4	16	0.1	18	-2.8	28	-1.7	9	3.3	22	0.0	27.4
May	6.8	52	6.0	33	5.2	42	6.2	50	5.4	35	7.7	36	6.9	50	5.7	45	5.1	36	6.2	53	4.9	47	7.5	38.4
June	15.6	40	12.3	38	14.3	37	12.7	92	15.5	40	13.2	49	15.4	49	12.2	100	14.3	50	12.8	54	16.6	28	13.3	55.5
July	13.9	44	14.1	75	17.9	39	15.5	191	15.8	64	15.4	61	13.8	45	13.4	94	17.5	69	15.8	67	16.0	75	15.6	67.8
August	13.4	33	15.5	25	14.8	58	12.0	107	11.7	44	13.1	71	13.2	47	15.3	25	15.2	39	12.0	105	12.1	39	13.1	88.5
September	8.3	38	6.9	21	8.8	94	8.7	31	9.6	26	8.0	57	8.3	40	6.8	10	9.1	33	8.8	33	9.8	52	7.8	63.5
October	5.0	53	4.3	55	0.5	32	3.4	94	4.2	43	2.9	50	4.6	63	3.8	37	0.3	39	3.4	97	4.6	41	4.4	45.2
November	-6.6	37	-1.0	95	-3.0	37	-5.2	28	-0.3	72	-3.0	50	7.4	20	-0.2	74	-4.0	27	-5.6	19	-1.7	47	-3.8	42.0
December	-11.2	13	-10.0	50	-5.8	17	-6.8	47	-8.1	48	-8.0	37	12.2	16	-11.6	47	-7.6	24	-7.7	36	-8.0	52	-9.4	33.3
Year	2.9	460	2.2	470	2.6	516	1.8	762	2.6	490	2.0	519	2.5	418	1.6	488	1.9	431	1.3	565	2.5	472	1.4	540
Effective temperature sum ^{o}C																								
	1118		961		1146		996		1113		1032		1115		930		1156		993		1180		1055	
Growth period																								
start	18.5.		21.5.		9.5.		24.4.		18.4.		-		18.5.		9.5.		9.5.		27.4		18.4.		-	
end	29.10.		13.10.		3.10.		27.10.		16.10.		-		29.10.		13.10.		3.10.		26..9.		17.10.		-	

Appendix I e

Rovaniemi

	1996		1997		1998		1999		1961-1990	
Month	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm
January	-8.5	17	-12.9	36	11.5	70	-16.2	40	-12.8	37
February	-14.7	22	-11.2	39	-17.0	56	-13.3	32	-11.7	30
March	-6.9	11	-6.3	50	-10.5	29	-6.2	33	-7.0	30
April	-1.6	36	-4.6	57	-3.1	22	1.0	26	-1.1	27
May	3.6	30	3.9	14	5.0	47	4.4	33	5.8	33
June	11.0	85	13.2	12	11.3	75	14.9	44	12.3	51
July	13.4	104	17.1	45	15.9	97	15.0	132	14.6	61
August	14.7	29	14.0	44	11.3	115	10.2	47	12.1	70
September	5.7	8	7.8	59	7.0	38	8.8	30	6.6	60
October	2.6	76	-1.0	20	1.3	73	2.4	43	0.4	55
November	-3.1	72	-5.8	33	-8.1	37	-2.4	83	-5.9	45
December	-11.7	30	-9.2	41	-12.1	48	-13.4	35	-10.6	36
Year	0.4	518	0.5	449	-0.8	707	0.5	576	0.2	535
Effective temperature sum °C										
	811		1007		841		955		794	
Growth period										
start	23.5.		31.5.		13.5.		19.5.		-	
end	13.10.		27.9.		11.10.		6.10.		-	