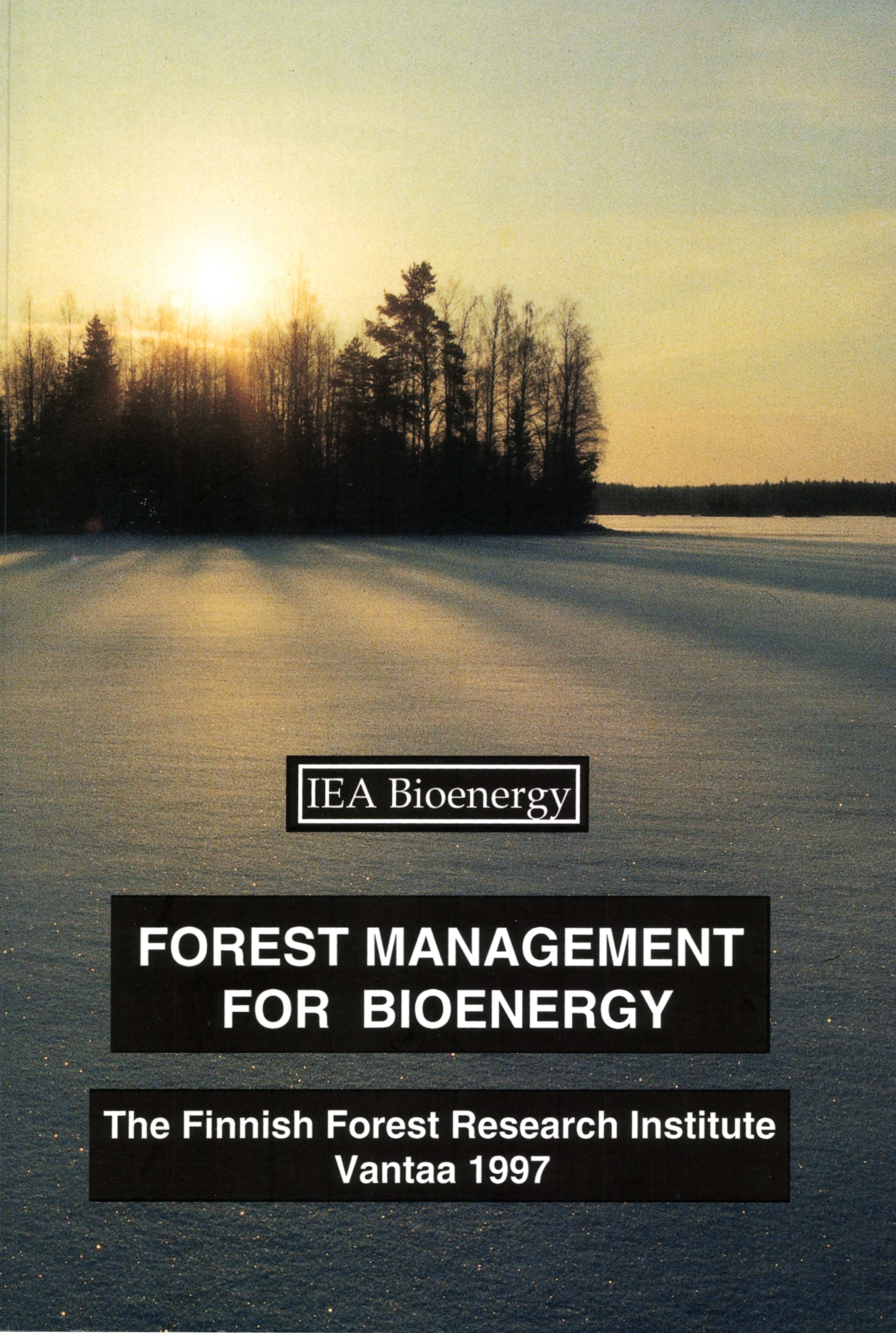

IEA Bioenergy

FOREST MANAGEMENT FOR BIOENERGY

The Finnish Forest Research Institute
Vantaa 1997

IEA Bioenergy

FOREST MANAGEMENT FOR BIOENERGY

Proceedings of a joint meeting of Activities
1.1, 1.2 and 4.2 of Task XII in Jyväskylä, Finland,
September 9 and 10, 1996

Edited by
Pentti Hakkila, Maija Heino and Essi Puranen

The Finnish Forest Research Institute
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237 p. 5

Activities A1.1 (Forest Management), A1.2 (Harvesting) and A4.2 (Environmental Issues) of Task XII/IEA Bioenergy arranged in September 1996 in Finland a joint meeting on Forest Management for Bioenergy: Silviculture, Harvesting and Environment. This Proceedings of the four scientific sessions of the meeting is composed of 26 papers dealing with the production of biomass for energy as a by-product of conventional forestry. Central topics are forest management for integrated production of industrial raw material and energy, harvesting small-sized trees and logging residue for energy, and role of models in developing environmental guidelines for sustainable energy output from forests.

Keywords: IEA, bioenergy, fuelwood, forest management, harvesting, environment, environmental guidelines

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Cover photo: Pentti Hakkila

PREFACE

The International Energy Agency is the energy forum for 23 industrialized nations, and the forefront of world efforts to advance the development and deployment of sustainable energy technologies. As one element of this effort, the IEA has established a collaborative Implementing Agreement on Bioenergy. The Agreement has presently three annexes, each of them forming the basis for a specific Task. During 1995—1997, the cooperation program includes the following Tasks:

— Task XII: Biomass production, harvesting and supply
— Task XIII: Biomass utilization
— Task XIV: Energy recovery from municipal solid waste

Task XII consists of four areas. Three of them deal with a specific source of biomass as a raw material of renewable energy, while the fourth area is concerned with problems such as feedstock preparation, systems studies and environmental issues which are basically independent of the source of biomass:

— Area 1: Conventional forestry
— Area 2: Short rotation forestry
— Area 3: Agricultural energy crops and residues
— Area 4: Interfacing and systems studies

Each area has two or more Activities, which are the operative units of the cooperation program. An important part of the program of the Activities is an annual meeting in one of the participating countries. The IEA Bioenergy Executive Committee encourages cooperation between the Activities. In 1996 three Activities interested in the energy production from conventional forestry hold a joint annual meeting on Forest Management for Bioenergy: Silviculture, Harvesting and Environment. The following Activities were involved:

— Activity 1.1: Forest Management (Leader Jim Richardson, Canadian Forest Service, 580 Booth Street, Ottawa, Ontario K1A 0E4, Canada)
— Activity 1.2: Harvesting (Leader Pentti Hakkila, Vantaa Research Centre, Finnish Forest Research Institute, Box 18, 01301 Vantaa, Finland)
— Activity 4.2: Environmental Issues (Leader Tat Smith, New Zealand Forest Research Institute, Private Bag 3020, Rotorua, New Zealand)

The meeting was arranged in September 1996 in Jyväskylä, Central Finland, which is the center of bioenergy research in Finland. The leaders of the three Activities were responsible for the scientific program, and the Finnish Forest Research Institute was responsible for the practical arrangements. A three-day study tour was organized jointly by the Finnish Forest Research Institute, VTT Energy, Forestry Centre of Central Finland, Metsäliitto Company and UPM-Kymmene Company. Sixtyseven scientists and practitioners from 14 countries participated in the joint meeting. Altogether 28 scientific papers were presented, 26 of which are published in this Proceedings. The publication is available from the Leaders of the Activities.

I express my warmest thanks to all persons and institutions who kindly contributed to the meeting and the subsequent study tour.

Pentti Hakkila

The Finnish Bioenergy research programme

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Abstract

The aim of the Finnish Bioenergy research programme for the years 1993 - 1998 is to increase the use of economically profitable and environmentally sound bioenergy by improving the competitiveness of solid biofuels. The main research fields concern production methods of wood fuels, peat production, use of bioenergy, and conversion of biomass to bio-oils. Some agrobiomass projects are also included. This presentation concentrates on wood fuels production research.

Integrated harvesting methods which produce both wood raw material for pulp mills and wood fuel for energy production have been developed further and partly demonstrated. Three new methods of final felling and two new methods for first thinning are demonstrated.

Keywords: bioenergy, wood fuels, research, development, demonstration

1 Introduction

Finland is a leading country in the use of bioenergy and has excellent opportunities for increasing bioenergy use from the level of 20 % of today up to 25 - 30 %. The Finnish Government has set as an objective for the promotion of bioenergy a 25 % increase from the present level by 2005. This increment corresponds to 1.5 million tonnes of oil equivalent (toe) per year. R&D work has been considered to be the most important means to achieve this ambititious goal.

Energy research in Finland is organised into a series of research programmes. The object of the programmes is to enhance research activites and to group individual projects into larger packages. The common target of the Finnish energy research programmes is to proceed from basic and applied research to product development and pilot operation, and after that to the first commercial applications e.g. demonstrations. This paper presents results of wood fuel production research of the first three years of the Bioenergy research programme.

2 Research areas of the programme

The Bioenergy research programme is supported from the beginning of year 1995 mainly by the Technology Development Centre. Other important sponsors are the Ministry of Trade and Industry (MTI), the Ministry of Agriculture and Forestry (MAF) and Finnish companies. The coordination of the research programme is carried out by Jyväskylä Science Park Ltd.

The main research areas include the production of wood fuels and fuel peat, the use of bioenergy and conversion of biomass. In addition, the programme also includes special projects for producing biofuels from energy crops.

The Bioenergy research programme includes research projects connected with the biofuel handling and utilisation technology. The programme also involves schemes linked with the development of equipment and plant technology for small-scale combustion and small-scale power plants.

3 Organisation and funding

Public funding for the research programme during 1993—1998 is planned to be ECU 23 million and the funding from mainly industrial sources ECU 12 million: a total funding of ECU 35 million. The funding in 1993-95 has been about ECU 25 million, which exceeds the plans with 40 %. The share of the public financing remained below 50 % during 1995. In 1993—1995, nearly half of the funds were channelled to the area of production of wood fuels.

Industrial enterprises are represented at each level of the organisation of the research programme. The participants from industry, manufacturers, energy producers and users, form the leadership of the Executive Committee which is responsible for the long-term planning, international co-operation and the most important task - the allocation of financing to the research organisations. The Technology Development Centre allocates funds to the joint development projects, while the Ministry of Trade and Industry funds demonstration projects in industry.

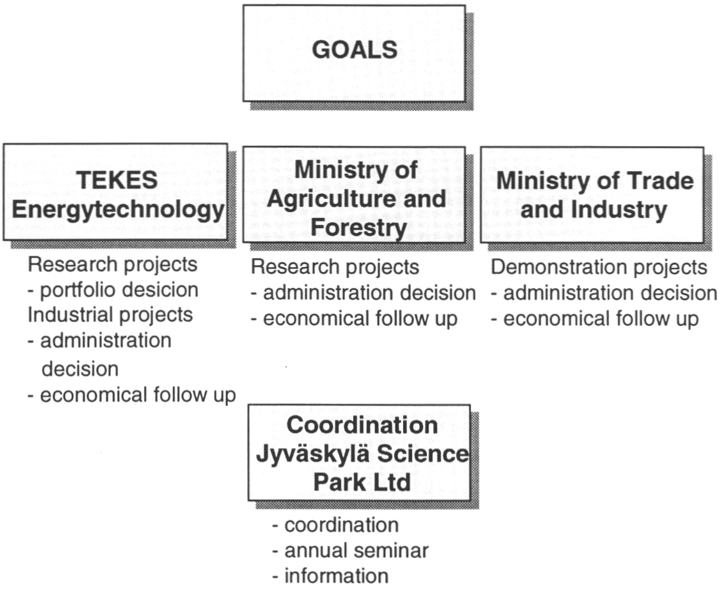

Figure 1. Organisation.

Table 1. Funding of the programme.

Financier	Plan		Realization		
	Per year	1993-98	1993	1994	1995
		Million Finnish marks			
TEKES	16	96	27	20	19,4
• research			8	8	8
• industrial			8	7	5,2
• demonstr. (MTI)			11	5	6,2
MAF	7	42	1,5	2,8	2,7
industry, others	12	72	22	23	29,4
Total, mill. FIM	35	210	50,5	45,8	51,5
Total, mill. ECU	6	36	8,6	7,8	8,7

4 Bioenergy resources

The annual total primary energy consumption in Finland was 31.6 million toe in 1995. The share of wood-derived fuels of the total primary energy consumption was about 14 % (ca. 4.3 million toe). At least 10 million m^3 (2 million toe) more wood could be harvested annually for energy purposes.

5 Operational principle

The aim of the research programme is to increase the use of economically profitable and environmentally sound bioenergy, by improving the competitiveness of present peat and wood fuels. Research and development projects will also develop new cost competitive biofuels and new equipment and methods for the production, handling and use of these fuels.

Increasing the use of bioenergy will limit the carbon dioxide emissions in energy production, improve the silvicultural state of forests, raise the level of self-sufficiency in energy production, and raise the productivity of forests. The creation of favourable conditions for entrepreneurial and business activity as well as new job opportunities are also important issues involved in bioenergy production. Finland has long exported forest industry and energy production equipment, and the development of demonstration projects will promote the development of new equipment especially for export.

6 Principal goals of wood fuel production research

The principal goals of the wood fuel production research are as follows:

- to develop new production methods for wood fuels in order to decrease the production costs to the level of imported fuels. The total increase in the use of wood fuel should be at least 1 million toe per year;

- to decrease the small scale production costs by 20 % compared with the 1992 level.

The most important area of the research on wood fuel production is the development of methods, machines and systems in order to produce cost competitive fuel. The integrated harvesting methods, which supply both raw material to wood products industries and wood fuel for energy production, have been chosen as the main area of research because they seem to be most promising. Increases in the area of young forests and their need for first thinnings have created a demand for new methods of harvesting. At the moment, high costs restrict the harvesting of small-sized trees either for industrial use or energy production.

7 Technology for the production of wood fuels

Production of wood fuels

Six commercial prototypes for small-scale production of wood fuels have been tested. For the production of wood chips a "so-called heat entrepreneur" system has been developed, in which the chips deliverer also attends to the operation of the heating plant. In this way, the difficult problem of determining the energy content of chips can be avoided.

As regards conventional firewood, new devices for firewood processing are being tested. A new delivery method has been developed for handling and distribution of firewood "from the forest to the customer".

Wood fuels from sapling stands and thinnings

Management principles for sapling stands have recently been changed. The precommercial thinnings are to be made later than recommended earlier, i. e., the trees should now be 4—7 m in height when thinned. The biomass yield per hectare will therefore increase to up to 40—50 m^3 (equal to 100 m^3 of chips). The annual area of sapling stands requiring silvicultural tending in Finland is about 200 000 ha. It has been estimated that about 2.5 million m^3/a of wood fuel (about 0.5 million toe) could be harvested from the sapling stands and precommercial thinnings of young forests.

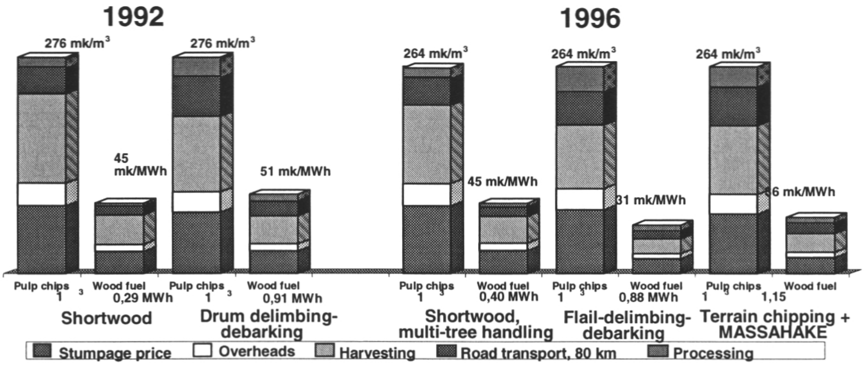

Figure 2. Cost of pulp chips and wood fuel (Finnish marks per m^3) from the first commercial thinning of Scots pine. Three alternative integrated technologies.

A central object of development has been the integrated production of chips for the pulp and paper industry and wood fuels. The integrated methods offer a competitive alternative for deliveries of first-thinning wood, provided that the raw material is suitable for pulping. The energy potential in Finland would be about 0.5 million toe/a. The development level of optional methods varies: some methods could be adopted immediately, while some require the development of machinery or demonstrations of the whole production chain.

Research is focused, in particular, on the thinning and production of wood fuel in pine stand, as the pine-dominant stands account for about 80 % of young forests. About 6 million m^3/a of stemwood could be logged from the first-thinning forests.

A chip harvester innovated by Oy Logset Ab has been developed to the demonstration level. It can chip the whole tree or tree parts at the site. A multi-tree harvester developed from a crane-mounted harvester head specificly for small-sized trees produces about 20 % more wood per hour than a single-tree harvester. This involves a cost reduction of about FIM 5 - 15/m^3. The machine is available commercially.

Different processing methods have been developed. The Massahake method classifies the whole tree chips into pulp chips and fuel. Studies of the Massahake method are continuing, the focus being on different parts of the system. The general technical feasibility has been verified in a demonstration plant that was commissioned in the town of Kankaanpää in 1995.

A chain delimbing-debarking method for small-sized wood shows good technical possibilities. However, the high bark content in winter conditions causes problems, and alternatives of eliminating these problems have been studied with the aid of a test machinery. A pilot plant that combines chain delimbing-debarking with small-drum debarking was constructed in 1995. Hooli Ltd. has developed a mobile truck-mounted plant to combine the delimbing-debarking technology and a hammer crusher for processing the fuel residue. The crushed fuel is blown direct to a lorry. The equipment was tested in 1995.

Wood fuels from final fellings

The present cost level of new production methods for harvesting logging residue from final fellings in spruce-dominant forests is shown in Fig. 3. It is possible to reach the level of FIM 45/MWh target. The biomass potential of final fellings in Finland is 1.0 million toe/a.

In a demonstration project in the region of Mikkeli in Central Finland, the cost of harvesting logging residue was less than FIM 43/MWh using a commercial technology for short transport distances. The cost was FIM 60/MWh in 1992.

A method based on the Chipset chipper has reached the demonstration stage. It chips the residue at the stump. The first harvester has been delivered for demonstration, and the exports are also beginning.

A unit consisting of a combined chipping and transport lorry and an exchangeable chip container is intended for producing fuel chips at the logging site all-year round.

The aim is to combine chipping and transport in the same vehicle. Long-distance transport can be carried out with two containers. The commercial testing of the method was initiated in 1995.

An integrated harvesting method based on whole-tree skidding of merchantable wood and energy wood has been tested in spruce-dominated final fellings. The harvesting cost of logging residue was less than FIM 10/m^3. This implies production costs of less than FIM 45/MWh for fuel given a transport distance of 80 km, provided that the development requirements concerning intermediate storage can be met. The method is ready for demonstration.

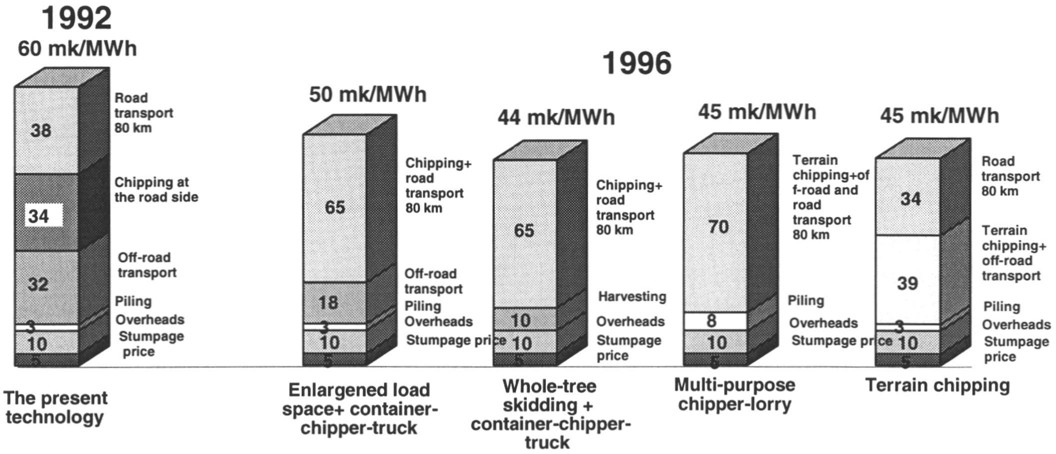

Figure 3.Cost comparison of production chains of logging residue chips. Hauling distance in the forest 250 m, truck transport 80 km.

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1 Forest management and integrated production

Photo Pentti Hakkila

Production of woody biomass for energy at different silvicultural systems

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Abstract

This paper examines different ways to increase the production of whole-tree chips for energy production. The influence of selected silvicultural factors: tree species, thinning programme and especially plant density and nurse trees on the production of wood chips, are examined. Calculations based on Danish yield tables and results from field trials on plant density and thinning programmes in Denmark show an increase in volume production when the plant density is increased. Using intolerant tree species, such as common alder or hybrid larch as a nurse tree in Norway spruce or beech stands can substantially increase the whole-tree chips yield, if the nurse trees are chipped in the early thinnings. It is stressed that the production of whole-tree chips must not jeopardise the general forest management objectives.

Keywords: Biomass, bioenergy, chips, forest management, spruce

1 Introduction

Biomass is a renewable energy source. For the last 25 years whole-tree chips have been produced in the Danish coniferous forests in the early thinnings. The purchasers are district calorific plants. The present total consumption of fuelwood in Denmark is 553 000 m³ solid volume per year, of which 220 000 m³ solid volume is whole-tree chips (Lind, 1994). This corresponds to 3.7 percent of the renewable energy sources in Denmark. Eight percent of the total Danish energy consumption is based on renewable energy sources. The Danish government plans to increase this percentage to 30 percent in the next thirty years. One of the means in reaching this objective is to use whole-tree chips from existing forests and planned afforestration. The objective of the Danish government is to double the total forest area in a period of 100 years.

Wood for energy purposes can be produced in two principal ways: firewood and whole-tree chips from conventional forestry or whole-tree chips from short rotation forestry, e.g. osier in 20 years rotations. This paper investigates ways to increase the production of whole-tree chips at different silvicultural systems by using different species, thinning programmes, plant densities and nurse trees.

It must be stressed that Danish forestry is a multiple-use forestry where some of the main forestry ‘products’ are: high-quality timber, conservation of the natural environment, protection of the cultural history and provision of opportunities for recreation.

The suggested silvicultural measures to increase whole-tree chips production in the Danish forests are selected on the basis that they should present a realistic option for current forestry practice. The production of fuelwood must not jeopardise the general forest management objectives, e.g. the production of high-quality timber, and nature protection.

The early thinnings in conifer stands can only be carried out without cost to the forest owner if he can sell the chips. Quite often, costs and revenues from these early thinnings barely balance, or even result in an economic loss (Suadicani, 1993). If no market for whole-tree chips exists, thinnings are often postponed until the trees in the stand reach a size where thinning costs and revenues are better balanced. But in order to ensure the production of high-quality timber, production and selling of whole-tree chips for energy, are imperative. Hence, production of fuelwood has to be seen as an integrated part of the multiple-use forestry.

2 Methods

The production of whole-tree chips in Norway spruce stands on a richer soil ("East Denmark") and a poorer soil ("West Denmark"), with and without nurse trees is calculated based on mathematically formulated thinnings programmes (e.g. Skovsgaard, 1995), yield tables and results from field trials.

The same is done for beech on a medium quality soil. It is reasonable to assume that a similar pattern to that of Norway spruce, where the production increases with increasing plant density until approximately 10 000 plants per hectare, applies to beech. But empirical evidence of this relation for beech has not been established. Hence, this paper does not discuss chips optimisation in beech in regard to the optimal plant density, but to using nurse trees.

Empirical material which illustrates the variation of volume production in relation to plant density in West Denmark (mainly forest on heath and dune land) is somewhat limited. Based on the plant density experiment in Gludsted Plantation which is the only existing measured and computed plant density experiment on heath land, and a felling experiment from the same location, the total volume production per hectare with variable plant densities is estimated.

The examples are based on the assumption that by increasing the number of plants per hectare, stand closing is accelerated, eventually leading to a higher chips production. An increased plant density can be imperative if the objective is to raise the production of fuelwood in the early thinnings, otherwise the quality of the remaining stand might be substantially lowered.

Another assumption is that the chip harvest can increase if fast-growing nurse trees are used. The idea is to harvest the nurse trees in the early thinnings as whole-tree chips, and thereby speed up the fuelwood production.

The choice of principal tree species in the examples are Norway spruce (*Picea abies* (L.) Karst.) and beech (*Fagus sylvatica* L.). Norway spruce and beech represent the vast majority of conifer and deciduous stands in Denmark. Furthermore, it is expected that Norway spruce and beech also in future will be the principal tree species in Danish forestry. Presumably, in future they will be grown in mixed stands to a higher extent than is the case today.

For Norway spruce, examples which represent the plant density in present forestry are presented as well as higher plant densities. Volume production and hence the potential fuelwood yield will to a certain degree increase with increasing plant density in the period, until the stand is closed (Heding, 1969; Handler and Jakobsen, 1986). A corresponding correlation has not been demonstrated for beech (Henriksen, 1988). Therefore, the plant density does not vary in the beech example. However, in the example of natural regeneration of beech, the influence of the number of seedlings on the chips production is examined.

The thinning regimes are based on technical, biological and economical considerations. Optimisation of the chips production has to be carried out within the frames of the silvicultural possibilities in a given area and without decreasing the future sustainability of the site.

Choice of thinning intensity and thinning interval is determined by many diverging considerations such as: stem diameter development, age of final felling, storm stability, wood quality, risk of disease or insect attacks, and the stability of the adjacent stands. The thinning programmes which are used in the examples in this report are based on results from thinning and plant density experiments as well as experience gained from present forestry in Denmark.

The use of nurse trees is studied separately for Norway spruce as well as beech. Hybrid larch (*Larix x eurolepis* Henry), Common alder (*Alnus glutinosa* (L.) Gaertn.), and poplar (*Populus* spp.) are chosen as examples of nurse trees. Presumably, hybrid larch and common alder are the most frequently used nurse trees in Denmark today (Henriksen, 1988).

The result of using the examples is to specify how to manipulate the two main factors: plant density and nurse trees. The task is to analyse at which plant densities, with or without nurse trees, the whole-tree chips production is optimised in relation to a sustainable, multiple-use forestry.

3 Results

3.1 Norway spruce

The chips optimisation example for Norway spruce, East Denmark, is an attempt to establish thinning programmes for different plant densities. The example shows at what plant densities the maximum amount of chips can be harvested and also when to start the thinnings.

The example covers the interval 1 500 to 10 500 plants per hectare. Recent plant density experiments in Norway spruce stands (Handler and Jakobsen, 1986) show a correlation between increasing plant density and increasing volume production. A precondition for the establishment of the example is a previous study of stem-number reduction and diameter development in not-thinned Norway spruce stands (Heding, 1969).

The underlying principle of the example is that the due to the differences in the original plant density and subsequent natural thinning produces different amounts of volume until a certain stand height (11.7 m), where a harmonisation takes place in regard to stem number, height, and diameter.

A graphic illustration of the chips production per hectare distributed to the first and additional thinnings, until a height of 11.7 m for Norway spruce, East Denmark, at variable plant density is shown in Fig. 1. Please note that the separate data are connected with a straight line. These lines do not represent a mathematical correlation. This applies to all the following figures in this paper.

At 6 500 plants and more per hectare the relative increase in chips production stagnates. Consequently, a relatively small chips production gain is obtained through the use of very high plant densities (7 500 to 10 500 plant per hectare) in relation to a moderate plant density (6 500 plants per hectare). Thus the production gain is highest at lower plant density.

At a density of 6 500 plants per hectare, a chips production of approximately 137 m³ solid volume (371 m³ loose volume) per hectare is achieved for Norway spruce, East Denmark. This is a chips production of approximately 34 to 88 m³ solid volume per hectare (corresponding to 91 to 237 m³ loose volume per hectare) more than chips production at the common plant densities of 4 500 to 2 500 plants per hectare today.

The same type of calculations are made for a poorer locality in the Western part of Denmark. Currently, 3 500 to 4 000 plants per hectare are used. The production of chips at variable plant densities, distributed to thinnings, is shown in Fig. 2.

In West Denmark, according to the example, 6 400 plants per hectare yield a chips production in Norway spruce until a height of 11.7 metres of approximately 155 m³ solid volume (419 m³ loose volume) per hectare. That is approximately 56 to 87 m³ solid volume (152 to 235 m³ loose volume) per hectare more than a corresponding plant density of 2 500 and 4 500 plants per hectare respectively.

If the chips production in West Denmark with 6 400 plants per hectare (approximately 179 m³ solid volume per hectare) is compared with the production of chips in East Denmark with a plant density of 6 500 plants per hectare (approximately 137 m³ solid volume per hectare), it can be observed that the chips production is a bit higher in West Denmark. However, a significant difference is that the duration of the production in West Denmark is 20 years longer compared to East Denmark.

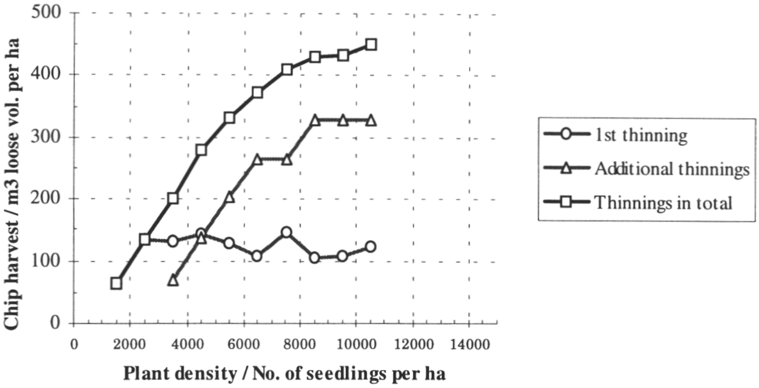

Figure 1. Chips harvest in m³ loose volume distributed to first and additional thinnings for Norway spruce in East Denmark at variable plant densities.

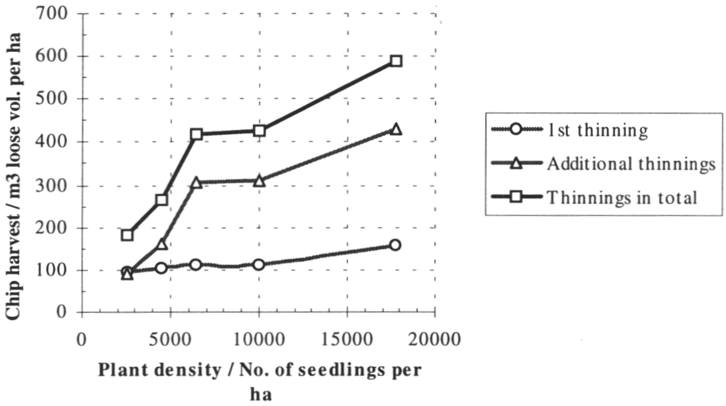

Figure 2. Chips harvest in m³ loose volume distributed to first and additional thinnings for Norway spruce in West Denmark at variable plant densities.

3.2 Norway spruce with nurse trees

Nurse trees are trees that are planted simultaneously with the principal tree species. The general uses of nurse trees are:

- Protection of other and more sensitive tree species
- Increased production
- Improvement of biological diversity
- Aesthetic considerations

Nurse trees can protect the main tree species against e.g. frost, competing herbaceous layer and damages caused by game. Furthermore, the nurse trees will often through shelter and shadow favour the development of the tree form. Protection is often the main motive to plant nurse trees. Using nurse trees creates a greater variety of woody species at a given area, potentially improving the biological diversity (flora and fauna) in the initial phase of the stand development. Some of the species used as nurse tree can also meliorate the soil conditions.

The use of nurse trees is a solution, where the total production is increased considerably without reducing the biodiversity or the opportunities for recreation.

In the example for optimisation of the chips production through the use of nurse trees, hybrid larch is used as nurse tree. Larch is the most commonly used nurse tree in conifer stands. Fig. 3 shows the production gain using nurse trees for whole-tree chips production in East Denmark.

There is a gradual increase in the chips production in Norway spruce and Norway spruce with nurse trees at increased plant density. Based on the results in Fig. 3 it seems reasonable to use between 5 500 and 7 500 plants per hectare in order to increase chips production by means of nurse trees in a Norway spruce stand with larch as nurse tree. This corresponds to an increase of the chips production of approximately 40 percent compared to Norway spruce without nurse trees. Obviously, in relation to optimisation of chips production, a significant increase is gained when using the intolerant tree species larch as nurse tree in Norway spruce stands in East Denmark. The results of using nurse trees on the poorer locality is shown in Fig. 4.

Fig. 4 shows a gradual increase in the chips yield when larch is used as nurse tree until a density of 6,400 plants per hectare. At 6 400 plants per hectare the excess production is approximately 52 m³ solid volume (140 m³ loose volume) per hectare. At higher plant densities the increase in excess chips production is reduced. If the plant density is increased with approximately 50 percent, from 6 400 to 10 000 plants per hectare, the excess production is only 57 m³ solid volume (154 m³ loose volume), which is an increase of only 5 percent compared to the excess production at 6 400 plants per hectare.

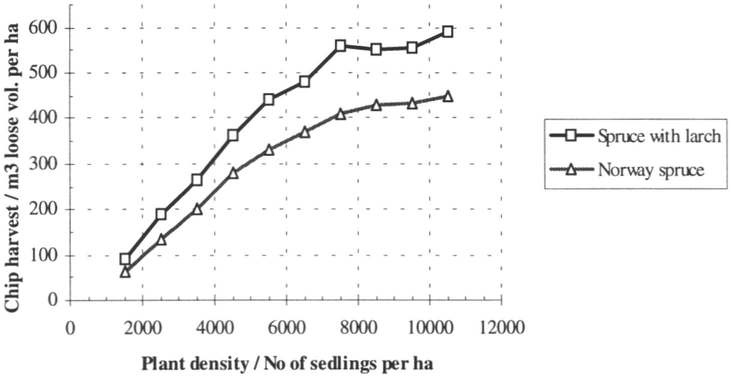

Figure 3. Total chips harvest in m³ loose volume for Norway spruce and Norway spruce with nurse tree in East Denmark at variable plant densities.

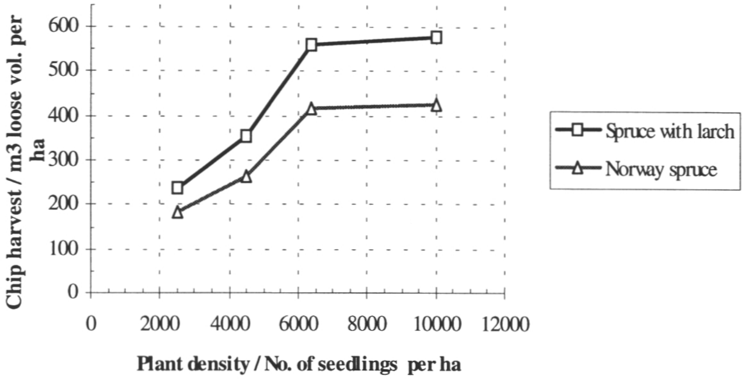

Figure 4. Total chips harvest in m³ loose volume for Norway spruce, and Norway spruce with larch as nurse tree in West Denmark at variable plant densities.

It seems reasonable to use 6 400 plants per hectare in Norway spruce stands with larch as nurse tree, distributed on 4 200 Norway spruces and 2 200 larches, corresponding to an increase in chip harvest of 35 percent compared to Norway spruce without nurse trees.

3.3 Beech with nurse trees

Normally in Denmark, beech is planted with an interval of approximately 1.5 metres between the rows and 0.6—1.0 metres between the plants in the row. This corresponds to 6 000 to 10 000 plants per hectare. The chips yield until the age 15 in a pure beech stand and in a beech stand with various nurse tree species mixed in rows, in East Denmark is calculated. At the age of 15, the first thinning is carried out. It is assumed that the nurse trees in all of the three cases are felled, dried, and chipped at an age of 15 years. The chip harvestes in beech stands with and without nurse trees are shown in Fig. 5.

Fig. 5 shows that the beech stands with larch or poplar nurse trees have a chips production that is three times as large as that in the pure beech stand. Common alder produces a little less than poplar and larch. Pure beech stands produce according to the example about 22 m³ solid volume (58 m³ loose volume) chips per hectare until year 15, while beech with larch as nurse tree produces 68 m³ solid volume (184 m³ loose volume) chips per hectare.

It can be concluded that if the whole-tree chips production is to be increased in beech stands, a considerable gain can be obtained using nurse trees. In addition, it is concluded that hybrid larch is to be preferred as a nurse tree in beech stands in regard to increased chips production. This is confirmed by existing practical experience.

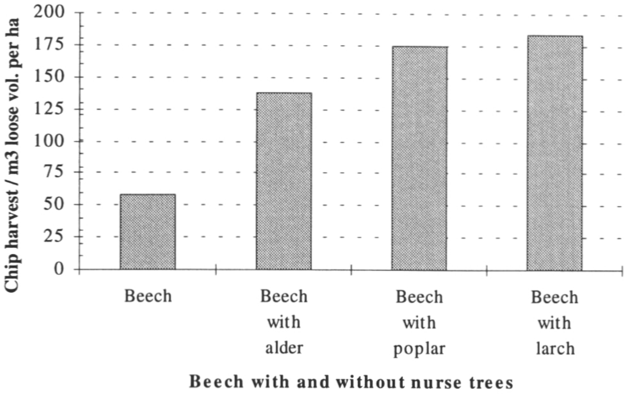

Figure 5. Chips harvest in m³ loose volume for beech with and without nurse trees until the age of 15 years in East Denmark.

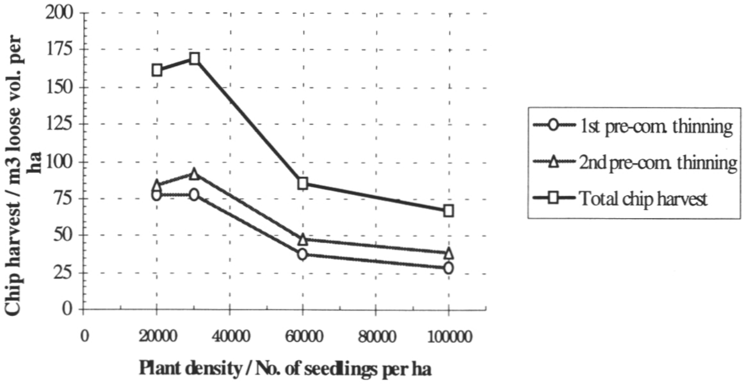

Figure 6. Chips harvest in m³ loose volume per hectare for 1st and 2nd pre-commercial thinning in beech, natural regeneration at variable plant densities.

3.4 Natural regeneration of beech

It is quite common in Denmark to make relatively heavy but few pre-commercial thinnings in natural regeneration of beech. Pre-commercial thinning means thinning of young trees when no, or very few, marketable assortments are produced. Typically, a brush cutter which cuts the plants by rows (and sometimes in perpendicular patches) is used at the first pre-commercial thinnings. The felled volume is left at the forest floor. Hereby no nutrients leak the stand, but at the same time the opportunity to use the produced biomass for energy purposes is lost. Alternatively, brush cutting can be replaced with chipping in the pre-commercial thinnings.

Fig. 6 shows the total chips yield for the first and the second pre-commercial thinning in beech stands with natural regeneration for low and high plant densities.

The conclusion of the chips production in beech stands with natural regeneration from the first and the second pre-commercial thinning is that high plant densities of 60 000 and 100 000 plants per hectare produce too small a chips yield to justify sending a chipper into the stand. On the other hand, at heavy pre-commercial thinnings of 50 percent reduction of the stem number, at low plant densities of 20 000 to 30 000 plant per hectare, sending a chipper in the stand should be considered. The chips yield is approximately 60 m³ solid volume (162 m³ loose volume) per hectare.

4 Discussion

The chips harvests for the different silvicultural systems are calculated on the basis of data from yield tables and field trials in Denmark. Actual measurements of whole-tree chips harvests in stands with high plant densities and with nurse trees have not been done, since these kind of stands are not currently general practice in Denmark. The calculations of the chips yield in the early thinnings in West Denmark are based on a limited empirical material, and the results must only be taken as indicative. However, these calculations can form the basis for the establishment of field trials with stands with higher plant densities where nurse trees are used. It must be stressed though that increases in plant density are unlikely to occur without other benefits arising such as increased timber quality and stand stability.

5 Conclusion

From the foregoing analysis it is evident that whole-tree chips yield from Norway spruce and beech stands can be increased, compared to the current practice by manipulating the plant density and the thinning programme. Greater plant densities, up to approximately 6 500 plants per hectare in Norway spruce stands compared to usual number of plants of 2 500 to 4 500 per hectare, seems to optimise the chips yield. It depends, however, on the premise that there is a market for the chips harvest, and that income and expenses related to the whole-tree chips production balance. Furthermore, the chips harvest must not jeopardise the general forest management objectives.

If the removal of nutrients from the forest ecosystem exceeds the supply of nutrients, on a continuing basis, a sustained yield cannot be obtained. Thus, it is important to make an assessment of the nutrient status in the different forest stands where production of whole-tree chips are planned to take place. On richer soils, the withering of parent material and recycling of nutrients within the ecosystem may be sufficient to cover the loss of nutrients, removed by whole-tree chipping.

The application of nurse trees, using intolerant species such as common alder and especially hybrid larch can substantially increase the chips yield in both beech and Norway spruce stands, taking advantage the fast juvenile growth of the intolerant tree species. The greatest chips yield in absolute terms is achieved in Norway spruce stands, particularly with larch as nurse tree. An increase in chips harvest, compared with spruce without larch as a nurse tree, of between 30 and 40 percent can be expected.

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Yield of biomass in young mixed forests of birches (*Betula pendula* Ehrh & *Betula pubescens* Roth) and Norway spruce (*Picea abies* (L.) Karst.)

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Biomass production in seven experimental plots with 25-year old mixed stands of Norway spruce and broad-leaves (mainly birch) were analysed. The trials are on good forest sites in south-eastern Norway. The experiment had been established and designed with five different precommercial thinning regimes when the mean height of birch was 2-5 m. All trees had been measured at five years' intervals. The data has been used to calculate tree heights, stem volumes and total dry matter yield of stems, bark and branches as a function of age and stand density. In mixed stands on good sites the dry matter production from a birch shelter can be 75 - 90 tons/ha at a total age of 25 years, if the density is approximately 2400 or more broadleaved stems per ha. On an annual basis it would be 3.0 to 3.6 tons.

If the density of the birch shelter is reduced to approx. 2500 stems per ha in a precommercial thinning (when the birches are 3-4 m high), the result will eventually be a pure, high yielding spruce stand when the birches are removed in the first commercial thinning. Leaving 2500 birch stems in the precommercial thinning also gives us the possibility to treat the stand as a pure birch stand in the first commercial thinning. This variety of silvicultural choices is reduced if a dense birch-Norway spruce regeneration is managed for very short rotations without precommercial thinning, or if the first commercial thinning is delayed.

Key words: *Betula pendula, Betula pubescens, Picea abies*, growth and yield, mixed stands, spacing

1 Introduction

The birches - silver birch and downy birch (*Betula pendula* Ehrh & *Betula pubescens* Roth) - are the dominating broadleaves in Scandinavia. Both species are very valuable for timber and bioenergy. Dense, pure stands of birch can be very productive for bioenergy when grown in short rotations (Ferm 1993, Johansson 1996). The birch species regenerate both from seeds and stump sprouts. They are often recognised as pioneer trees in the natural succession following clearcutting of the climax species Norway spruce (*Picea abies* L. Karst.). Birches and other broadleaves have until recently normally been considered as a problem in young stands of Norway spruce. However, a large portion of the birch timber being produced in Scandinavia comes from mixed birch and Norway spruce stands. (Ferm 1993).

Today's focus on bio-diversity has led to an increased interest towards silvicultural systems which mimic natural succession in forest ecosystems. In practical forestry, the two birch species and Norway spruce can be grown in mixtures using different thinning regimes with the purpose to grow both bioenergy and timber. An increased use of mixed stands of birch and Norway spruce raises several questions about choice of harvesting technology, harvesting time and the size of biomass production of both birch and spruce in such stands, as well as the influence of broadleaves on wood quality of spruce.

2 Material

In 1975-78, Peder Braathe established a nation-wide experiment in Norway at 14 locations where Norway spruce, birches and some other broadleaved species had regenerated after clear-cut. The regeneration was 7-15 years old at the establishment, with mean height of broadleaves ranging between two and five metres. After the previous clear-cutting, all 14 locations had been planted with spruce, but at varying spacing and with varying results (Braathe 1988). The experiment was not primarily designed in order to study the highest possible biomass production. The main purpose was to study height growth and competition within and between trees of the two species at different density regimes, with revisions every five years. However, the experiment is well suited for being analysed also from a bioenergy point of view.

Only broadleaves that had reached 2.5 cm DBH were considered as competitors to the spruce, and trees of smaller dimensions were therefore not measured. The study has involved detailed measurements of height and diameter development of both Norway spruce and broadleaves, and their position in the plots compared to their neighbours. The results after five and ten years have been published by Braathe (1984, 1988). In the following, measurements made 15 years after establishment have been analysed to calculate the volume of stem mass including bark of broadleaves and spruce, as well as the total dry matter of stemwood including bark and branches of the broadleaves.

The present study is limited to seven trials in South-east Norway. The five different treatments given at the time of establishment were:

0 - No pre-commercial thinning
1 - Pre-commercial thinning favouring birches and other broadleaves by spacing them 1.5- 2.0 metres apart. Spruce was not removed
2 - Pre-commercial thinning by leaving fill-in trees of birch in openings of the Norway spruce stand
3 - Treatments as in 2 or intermediate between 1 and 2. Beating up with birch in openings without any regeneration
4 - Pre-commercial thinning by removing all broadleaves, creating a monoculture of Norway spruce

The plots used were either 20 x 30 metres (0.06 ha) or 25 x 25 metres (0.0625 ha). Treatment 3 is excluded from this study because beating up with birch is of little practical interest from a bioenergy point of view.

Already at the establishment of the trials, large variations in site index and spacing were observed within and between plots in some trials. In treatment 1, the aim to get 2500 broadleaved stems per hectare was only obtained in two of the seven trials (Trial No. 06 and 08).

Table 1 gives an overview of the trials, with number (Trial No), name, number of replications, latitude (Lat. N), altitude (Alt (m)), and site index defined as the arithmetic mean height of the 100 largest trees per hectare (largest by diameter) at age 40 in breast height. The mean site index is shown in the last column, with the site index variation within each trial in parenthesis. All trials have mean site indices ranging from high medium (G17) to very high (G25), with a corresponding yield potential ranging from 7.5 to more than 12.0 m^3/ha/year for Norway spruce. The climatic timberline in this part of Norway is approximately at 1000 m above sea level.

The numbers of Norway spruce and broadleaved trees (all species) are listed for all trials and treatments in Figs. 1—7. Braathe (1988) has classified silver birch as the dominating species in trials 01, 03, 05, 06 and 07, and downy birch as the dominating in trials 02 and 08. Both species can, however, be seen in all seven trials. In addition to the birch species, grey alder (*Alnus incana*), aspen *(Populus tremula*), hazel (*Corylus avellana*), and rowan (*Sorbus aucuparia*) occur.

After five years some broadleaves were removed in treatments 1 and 2. Their numbers and total volume are shown in Table 2. The proportion of birch (both species) 15 years after establishment is given in per cent of the total number of broadleaved stems (N%), and in per cent of the total volume (V%) of all broadleaved trees (Table 2).

A few trees of Scots pine (*Pinus sylvestris*) were found in some of the locations. They became subjects to moose-browsing at an early age (Braathe 1988). Since these pine trees contribute very little to the total yield, they are excluded from the study.

Table 1. Number of replications, latitude (Lat. N), altitude (Alt (m)), and site index on the trials.

Trial No.	Name	Replications	Lat. N	Alt. (m)	Site index (H40)
01	Nittedal	2	60° 4'	150	G21 (+/-1)
02	Sørkedal	2	60° 2'	330	G18 (+/-2)
03	Notodden	2	59° 37'	220	G22 (+/-2)
05	Hof	1	59° 35'	40	G17 (+/-5)
06	Skiptvet	2	59° 33'	100	G25 (+/-1)
07	Gjerstad	2 1)	58° 57'	140	G21 (+/-3)
08	Grue	2	60° 23'	330	G20 (+/-4)

1) Treatment 0 & 1 in trial No. 07 has only one remaining replication (beaver damage)

Table 2. Broadleaved stems felled five years after establishment (treatment 1 & 2), in stems per ha (N/ha), cubic metres per ha (m^3/ha), and percentage of birch stems (N%) and birch volume (V%) of all broadleaved trees, 15 years after establishment (treatment 0, 1 & 2).

Trial	Felled, Trm. 1		Felled, Trm. 2		% Birch, Trm. 0		% Birch, Trm. 1		% Birch, Trm. 2	
No.	N/ha	m^3/ha	N/ha	m^3/ha	N%	V%	N%	V%	N%	V%
01	110	1,3	20	0,1	49	74	60	71	84	96
02	380	4,9	80	1,8	74	89	100	100	100	100
03	390	5,4			50$^{1)}$	89	94	94	92	98
05	80	0,7	240	3,0	17	33	67	88	54	75
06	1380	15,0	220	3,2	88	88	100	100	100	100
07	340	5,2	300	1,6	52	66	79	79	75	76
08	690	4,4	300	1,1	99	98	99	99	100	100

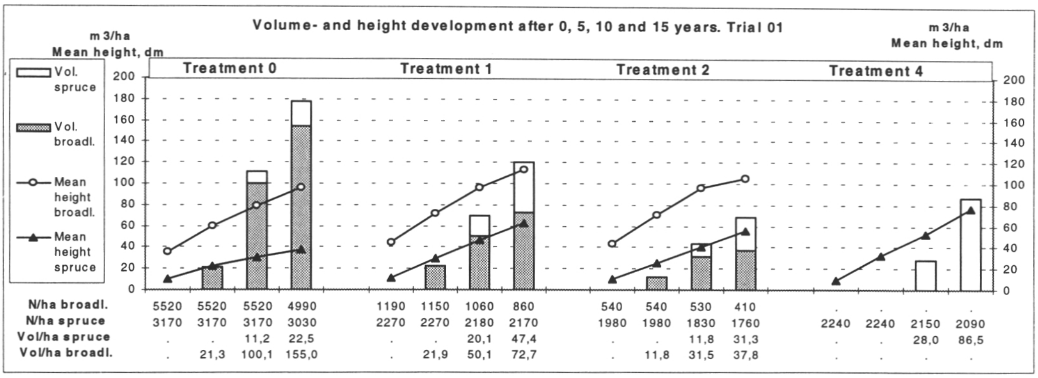
1) Some understorey trees in trial No. 03 were not measured at the establishment (mostly rowan and hazel). As a consequence, the real percentage of birch is somewhat lower than shown in table 2, both in stems/ha and volume/ha. For the same reason, the real, total volume of broadleaves is approximately 10 % higher than shown in Fig. 3.

3 Calculations

The stem volume of birches, other broadleaves and Norway spruce has been calculated by current Norwegian volume functions (Braastad 1966, Vestjordet 1967). Standing volume including bark for Norway spruce and the broadleaves, number of stems/ha, and mean heights 15 years after the establishment of the trials have been calculated for treatments 0, 1, 2, and 4. Corresponding figures for the various treatments at the ages zero, five and ten years after establishment are taken from Braathe (1984, 1988).

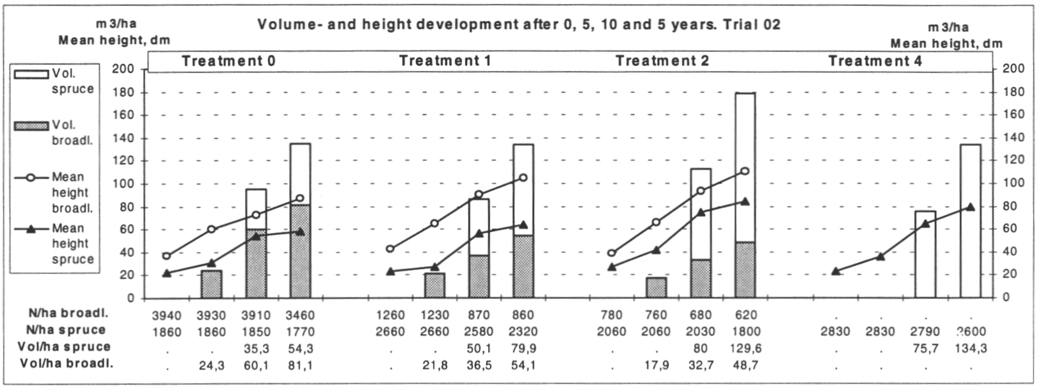
The dry matter content from broadleaves was calculated in tons/ha at various stand ages, using functions for single trees from Marklund (1988). The values include stemwood with bark, and living and dead branches, but not foliage. The dry matter content is presented at a total age of 15, 20 and 25 years, derived from the values at 5, 10 and 15 years after treatment.

All trials were not laid out at the same age after stand establishment. Therefore, the trials are sorted in age intervals of five years. This means that if the total stand age is within a range of 7 to 12 years, the stand is given a total age of 10 years etc. As a consequence, the results must be seen as approximations of the true values.



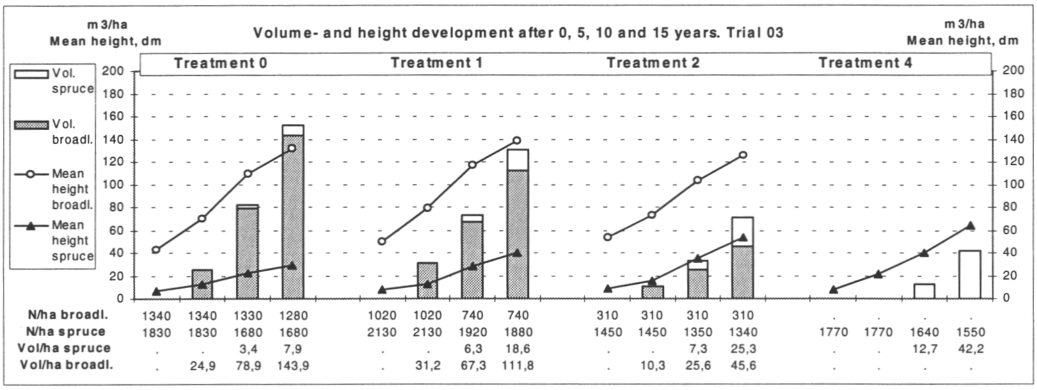
	Treatment 0				Treatment 1				Treatment 2				Treatment 4			
N/ha broadl.	5520	5520	5520	4990	1190	1150	1060	860	540	540	530	410	.	.	.	.
N/ha spruce	3170	3170	3170	3030	2270	2270	2180	2170	1980	1980	1830	1760	2240	2240	2150	2090
Vol/ha spruce	.	.	11,2	22,5	.	.	20,1	47,4	.	.	11,8	31,3	.	.	28,0	86,5
Vol/ha broadl.	.	21,3	100,1	155,0	.	21,9	50,1	72,7	.	11,8	31,5	37,8	.	.	.	.

Figure 1. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 01.



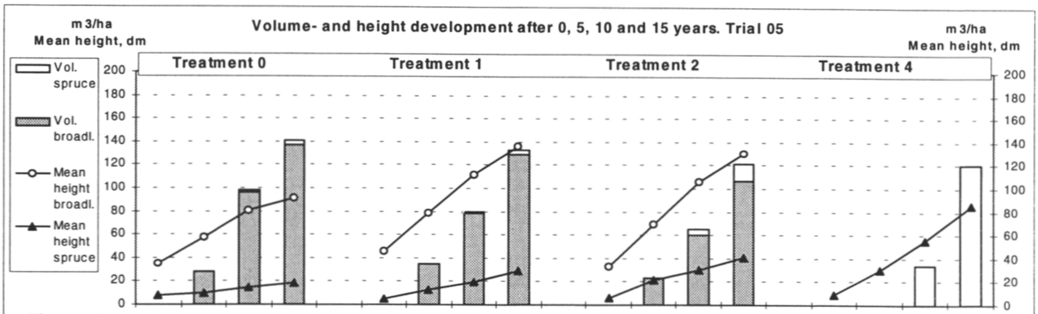
	Treatment 0				Treatment 1				Treatment 2				Treatment 4			
N/ha broadl.	3940	3930	3910	3460	1260	1230	870	860	780	760	680	620	.	.	.	.
N/ha spruce	1860	1860	1850	1770	2660	2660	2580	2320	2060	2060	2030	1800	2830	2830	2790	2600
Vol/ha spruce	.	.	35,3	54,3	.	.	50,1	79,9	.	.	80	129,6	.	.	75,7	134,3
Vol/ha broadl.	.	24,3	60,1	81,1	.	21,8	36,5	54,1	.	17,9	32,7	48,7	.	.	.	.

Figure 2. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 02.



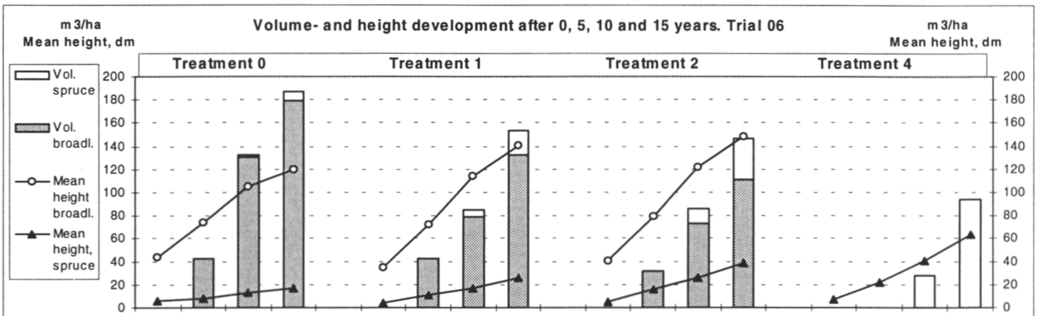
	Treatment 0				Treatment 1				Treatment 2				Treatment 4			
N/ha broadl.	1340	1340	1330	1280	1020	1020	740	740	310	310	310	310	.	.	.	.
N/ha spruce	1830	1830	1680	1680	2130	2130	1920	1880	1450	1450	1350	1340	1770	1770	1640	1550
Vol/ha spruce	.	.	3,4	7,9	.	.	6,3	18,6	.	.	7,3	25,3	.	.	12,7	42,2
Vol/ha broadl.	.	24,9	78,9	143,9	.	31,2	67,3	111,8	.	10,3	25,6	45,6	.	.	.	.

Figure 3. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 03.



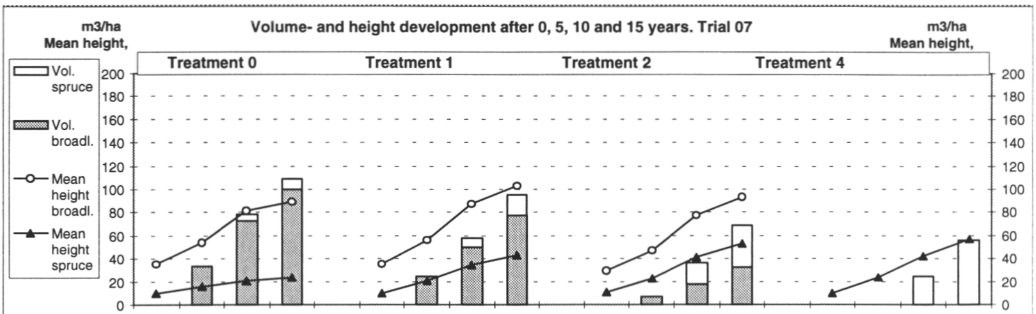
N/ha broadl.	8530	8340	8150	6980	1170	1170	1050	920	1300	1350	1060	980	.	.	.	.
N/ha spruce	1870	1870	1870	1780	1170	1170	1170	1170	2170	2170	2080	1970	2080	2080	2050	1950
Vol/ha spruce	.	.	1,8	3,5	.	.	1,1	4,1	.	.	5,2	14,3	.	.	34,4	120,5
Vol/ha broadl.	.	28,3	96,3	136,9	.	34,5	78,7	128,9	.	23	60,2	107,1	.	.	.	.

Figure 4. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 05.



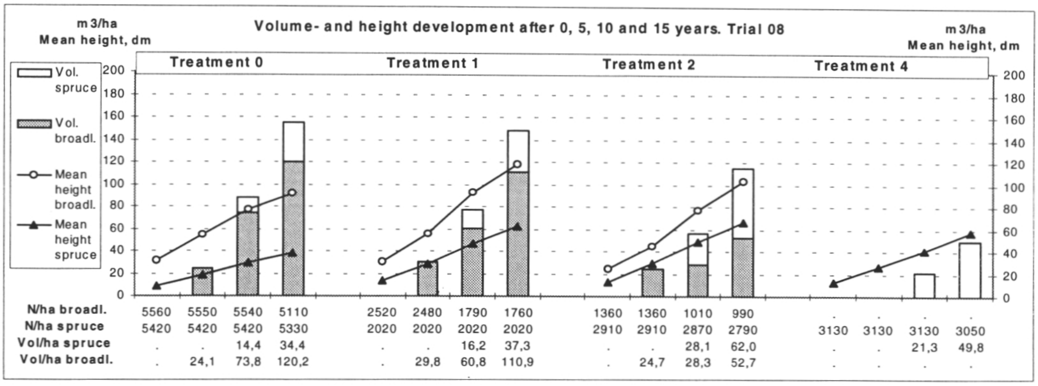
N/ha broadl.	6670	6660	6650	5450	3000	2990	1620	1470	1230	1230	960	810	.	.	.	.
N/ha spruce	16670	16670	13360	13000	7770	7770	7560	7420	5090	5090	4990	4930	4550	4550	4290	4240
Vol/ha spruce	0	0	2,1	8,0	0	0	6,2	20,8	0	0	12	35,57	0	0	27,9	93,91
Vol/ha broadl.	0	42,8	130,5	179,0	.	42,2	79,1	132,7	.	31,9	73,7	110,8	0	0	0	0

Figure 5. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 06.



N/ha broadl.	6400	6180	5250	4210	1550	1470	1200	115	850	840	540	540	.	.	.	.
N/ha	3420	3420	3360	3310	1310	1310	1310	1280	3300	3300	3070	2510	2940	2940	2700	2410
Vol/ha	.	.	5,8	9,0	.	.	7,9	17,6	.	.	17,8	36,3	.	.	24,1	56,0
Vol/ha broadl.	.	33,5	73	100,	.	24,4	49,9	77,0	.	7	18,	32,5	.	.	.	.

Figure 6. Volume in m³/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 07.



N/ha broadl.	5560	5550	5540	5110	2520	2480	1790	1760	1360	1360	1010	990	.	.	.	.
N/ha spruce	5420	5420	5420	5330	2020	2020	2020	2020	2910	2910	2870	2790	3130	3130	3130	3050
Vol/ha spruce	.	.	14,4	34,4	.	.	16,2	37,3	.	.	28,1	62,0	.	.	21,3	49,8
Vol/ha broadl.	.	24,1	73,8	120,2	.	29,8	60,8	110,9	.	24,7	28,3	52,7	.	.	.	.

Figure 7. Volume in m^3/ha (stemwood including bark) and mean height in dm at 0, 5, 10 and 15 years after establishment. Trial 08.

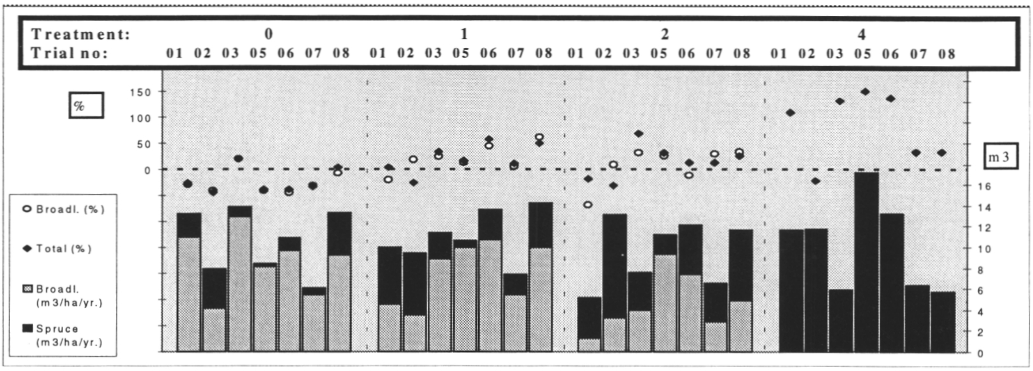


Figure 8. Mean annual increment in the last five-year period (10—15 years after establishment), for both broadleaves and Norway spruce (bars). The bars are corresponding to the right hand Y-axis (cubic metres per ha/year, including bark). The average stemwood volume increment in this period, is shown in per cent of the average volume increment in the previous five year period (points, corresponding to the left Y-axis).

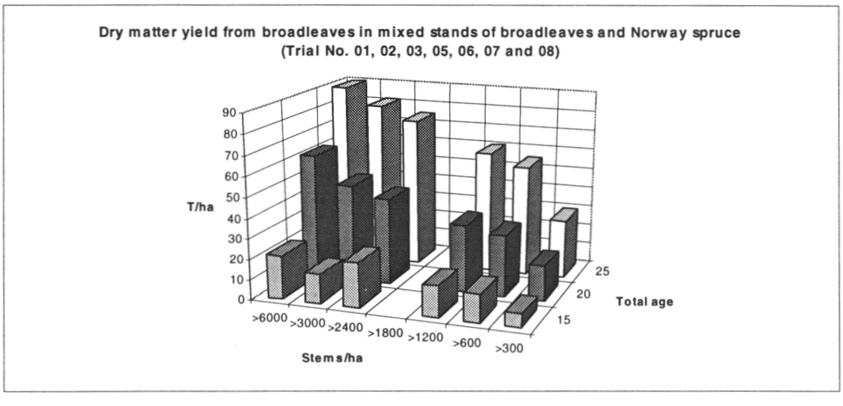


Figure 9. Dry matter yield from broadleaves (tons/ha), as a function of total age and stand density. The different classes of stemnumber/ha has a range fram 300—599 (>300), 600—1199 (>600), 1200—1799 (>1200) etc.

4 Results

The development of volume (stemwood including bark) and height, all as mean values, in seven different trials, and for the four different treatments from establishment (0), and 5, 10, and 15 years thereafter, are presented in Figs. 1—7. The mean annual increment in the last five-year period (10—15 years after the establishment of the experiment, total age approx. 20—25 years) is presented in Fig. 8, comparing the average stemwood volume increment in this period with the average increment in the previous five years (in per cent). This is calculated for broadleaves and Norway spruce separately. Fig. 9 summarises the average total dry matter yield for broadleaves (stemwood, bark and branches) for the seven trials considering total age and number of stems/ha. (In Fig. 9 the different plots are sorted independent of treatment, as a function of stand density and age only.)

5 Discussion

The graphical presentation of the results (Figs. 1—7) shows clearly that the plots without any pre-commercial thinning (treatment 0) in all seven trials have given the highest yield until 10 years after establishment (total age approx. 20 years). But the superiority of the untreated plots is about to be reduced in the last five-year period. In this period, the wider spacing in treatments one, two and four has already lead to a somewhat larger increment than in the previous period in all trials except trials 01 and 02 (stable growth in trial 06). In treatment zero, the volume growth has declined compared to the previous period in all trials except trials 03 and 08. This trend is likely to continue in the next period, 15—20 years from establishment. However, in the majority of the trials, the volume growth in treatment zero is still as high, or even somewhat higher, than in the other treatments. In treatment zero, current annual increment by volume is also still well above mean annual increment for the same treatment up to a total age of approximately 25 years. Comparing the yield data between treatments within each trial is, however, difficult as a result of site differences within each trial. The volume growth figures for the last five-year period are also affected by snow damage in some of the treatments.

The amount of dry matter of stemwood, bark and branches from broadleaves which can be harvested from both untreated and precommercially thinned, mixed stands with spruce about 20—25 years after establishment is a question of particular interest. In treatment 0, the mean yield of total biomass was 84.5 tons/ha (53.7—114.8) 15 years after establishment (at an approximate total age of 25 years). In trial 02, which had the lowest yield (53.7 tons/ha), the results are clearly influenced by heavy snow damage during the last five year period. The average yield in treatment 1 was, as can be expected due to the lower densities, somewhat less than in treatment 0 (67.5 tons/ha). The results in Fig. 9, where the plots were sorted according to their stand density and age (the treatments were not considered), indicate that if about 2400 stems/ha or more of broadleaved trees are left in a pre-commercial thinning, the average yield could be as high as 75—90 tons/ha 25 years after the clear-cut, when the biomass from spruce is not counted. The mean annual increment for such a regeneration would, when the yield from spruce is not counted, be approximately 3.0—3.6 tons, or a little less than half of what could be produced in a Danish short rotation salix orchard (Heding 1992), and one third of what could be produced in a corresponding Swedish orchard on farmland (Willebrand 1992). The volume production from the broadleaved shelter in this study is comparable with the yield from several swedish experiments with young mixtures of birch and Norway spruce (Anderson 1984).

In several of the plots in this experiment, the stand density of broadleaves at the time of establishment was too low to achieve a maximum yield. According to this study an early high production can only be reached if the stand density is rather high already from the stand establishment. The results from this experiment probably give a fairly good impression of the amount of biomass which can be produced from broadleaves at an early stage in mixed stands on fertile sites, when the broadleaves are regenerated naturally without any soil preparation.

From a maximum yield point of view, the choice of silvicultural method in such stands (mixed stands vs. a monoculture of Norway spruce) can not be judged without concerning the loss of spruce growth in the mixed stands in the same period. There is a good correlation between loss of spruce growth and the density of broadleaves in the different plots in this experiment (Braathe 1988). In well managed monocultures at the average site indices on the different trials, the spruce is capable of producing from 7.5 to more than 12.0 cubic metres of stemwood including bark per ha/year as an average for the whole rotation period, equal to an annual biomass production including branches of approximately 3.75—6.0 tons/ha. When compared to treatment 4, the loss of height growth in spruce in treatment 0 fifteen years after establishment (at a total age of approximately 25 years) is varying from -13 to -6 years, with -8.5 years as mean value. The corresponding mean loss in treatments 1 and 2 is 5.25 (-10 to +1 year) and 2.15 (-8 to + 2) years, respectively.

The results from this experiment indicate that the loss of spruce growth during the first 25 years after establishment is more than compensated for by the biomass growth of broadleaves in the mixed stands. Such a conclusion is, however, depending on the assumption that the loss of spruce growth is almost exclusively caused by the sheltering broadleaves in the same period. On the other hand, if the upper storey of broadleaves were to be suddenly removed 20 or 25 years after stand establishment, the spruce would for certain need some time to build up a crown mass which is capable to utilise the increased growing space. Therefore, when compared to a monoculture of spruce, the total loss of spruce growth in the sheltered stands will probably increase in the following years even if the broadleaved shelter is removed. In the most dense stands, it is even possible that a sudden removal of the shelter might cause heavy mortality among the spruces. As a result of the variation in site index within the trials (Braathe 1988), and the questions connected with the future growth of spruce after a removal of the broadleaved shelter, it must be regarded as uncertain whether an admixture of broadleaves in the first 20—25 years of the rotation period can compensate for the loss of spruce growth in the long term.

When tending young, mixed stands of birch and Norway spruce on good site indices, we are facing several silvicultural options which involve production for bioenergy. In the precommercial thinning, such stands could be made into pure stands of either spruce or birch. Another choice could be to leave a birch shelter with the same stand density as recommended for pure stands of birch (approx. 2500 stems per hectare according to Braastad et al. (1993)), and later harvest all or some of the birches for bioenergy or pulp in the first thinning, finally ending up with a high yielding spruce stand or a thinned birch stand (with or without a spruce understorey). The first commercial thinning should take place no later than 20—25 years after stand establishment, at a dominant height of about 12 metres.

If a dense mixed stand is not precommercially thinned, or if the number of birch stems for other reasons is significantly higher than 2500 stems per hectare, creating a pure stand of spruce through the first commercial thinning will probably cause problems related to felling damage and the change in light condition for the understorey spruces. Also, at this late stage, the possibility to create a high quality birch stand on the basis of a over-dense mixed stand will be limited.

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Silviculture systems for the production of energy biomass in conventional operations in Atlantic Canada

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1 Introduction

This paper is a much reduced version of a report of the same title. It is available on the World Wide Web at:http://www.unb.ca/web/forestry/centers/asdsl.htm.

The International Energy Agency Bioenergy Agreement (IEA), in its Task XII group (Activity 1.1), aims to "improve the economies of biomass production of forests, increase the understanding of the silvicultural processes involved and develop the means to bring forward increased quantities of forest biomass to the market place as cost effectively as possible". One of the activities undertaken toward this aim is to carry out a study of silviculture systems that can be used to produce both energy biomass and traditional products in conventional forestry operations. The study presented in this report would serve as a companion to a similar study being carried out in Denmark. This report presents the results of the Atlantic Canada study.

Case studies were chosen to reflect the rich variety of possibilities found in Atlantic Canada. The aim of each case study is to present one stand type and one silviculture system combination representative of the biological or socio-economic conditions in each of the different parts of the Atlantic region. Stand types were therefore chosen that are either typical of the region or demonstrate how conventional forestry could be modified to produce more biomass. The silvicultural, financial and energy yield implications of each system are presented and the potential use and contribution to the region's energy supply is described. The results of the three case studies are then synthesized to identify broader findings that would help guide future studies.

In addition to regional case studies, a number of issues affecting the potential of forest biomass production are discussed. These include the appropriate scale at which to analyze energy biomass issues and the impact of market and policy issues.

2 Study methods

The central focus of the study is the individual silviculture system case studies designed to produce biomass energy from conventional forestry operations. Case study development involved four main activities: 1) Stand type and operational context selection; 2) Silviculture system design for the stand types selected; 3) Parameter selection for evaluating each silviculture system and stand type combination; 4) Synthesis of case study results to draw conclusions about the various silviculture system and stand type combinations and their potential to increase biomass production. The principles guiding activies 1 and 2 above are summarized below (activies 3 and 4 are left out for the sake of brevity, but are contained in the full report).

A secondary part of the study deals with policy changes and incentives that could increase energy biomass production. This part of the project involved three main activities: 1)Definition of the advantages and disadvantages of energy biomass production in terms of its economic, social and environmental sustainability; 2)Summarization of key issues; 3)Suggestion of some policy changes or incentives that might help make biomass energy production from conventional operations more attractive. A brief summary of the results of these activities is given here and readers are referred to the full report for more detail.

Principles in stand type and operational context selection

Selection of the stand type and operational context (geographic location, demographics, industry structure) was largely guided by three principles:

- capture the range of stand types found in the Atlantic Region;
- deal with stand types likely to be important in conventional operations over the analysis period;
- focus on stand types for which there is little information about appropriate silviculture for energy biomass production (e.g., partial cutting in hardwoods).

Principles in silviculture system design

Silviculture system design was driven by five main principles. The silviculture systems must:

- be indicative of the practices likely to be commonly used over the analysis period (5—10 years);
- capitalize on equipment types already available in the area (to foster implementability);
- compensate for the undesirable characteristics of energy biomass such as dispersion and low bulk density;
- recognize the key silviculture issues involved (nutrient demand, reforestation success, intervention objectives such as wildlife, stand improvement, regeneration);
- recognize financial issues associated with integrated production of energy biomass and conventional products (machine productivity, low value of biomass, high costs of handling biomass).

General assumptions used in case studies

Four general assumptions have been made for all three case studies presented in this report. They were made to facilitate calculations and comparisons and have been used consistently across the three case studies.

1) *Silviculture prescriptions* — It was assumed that the silviculture prescriptions suggested by the foresters we contacted in each of the case study areas were an

acceptable basis for our design of silviculture systems for biomass recovery. No attempt was made to determine whether specific elements in each silviculture prescription were optimal. All three cooperators are experienced foresters.

2) *Incremental costing* — This study focusses on the recovery of biomass from conventional forest operations. As a result, any costs over those that would have been incurred in conventional operations if energy biomass had not been recovered should be charged against the biomass.

3) *Adjustments for inflation* — Recent historical information has been used to estimate costs in certain case studies and have been adjusted using the forest industry *Machinery and Equipment Price Indices* published by Statistics Canada (Catalogue 62—007).

4) *Biomass moisture content* — For the purpose of this report, tree component moisture content has been assumed to be 45% on a wet basis (i.e., 45% of the green weight of trees is water).

Methods for yield and cost estimates

The average yields of the three stand types studied were calculated from detailed forest inventory data supplied by cooperating agencies in the three case studies. The total above-ground mass (ovendried tonnes or odt) of the entire tree and the mass of the merchantable stem of each harvested tree were estimated based on biomass equations from Lavigne (1982), Freedman *et al.* (1982) and merchantability fractions from Honer (1967) combined with the inventory data. The mass of unmerchantable tree components was then multiplied by a biomass recovery rate used to account for branch and top loss during skidding to determine the net biomass obtained from harvested species. Biomass recovery rates were estimated at 70% for softwoods (Routhier, 1982) and 95% for hardwoods. The merchantable volume for each stem was determined by dividing the merchantable mass by each species' specific gravity (Panshin and DeZeeuw, 1980).

Costs for each intervention were based on a combination of actual piecework rates paid to local contractors (provided by cooperating agencies) and from machine production functions and rental rates from published sources (e.g., Zundel, 1992).

3 Case study descriptions

New Brunswick — Tolerant hardwood partial cutting

The Edmundston and Plaster Rock crown license and freehold limits of the Fraser Paper Inc. company contains a large area of hardwood forests in northwestern New Brunswick. The stand type studied comprises 60% of the hardwood forest area, is composed of hardwood stands or mixedwood stands with a preponderance of tolerant hardwoods that do not have a history of hygrading. They typically contain a mix of good and poor quality material with a diverse age class distribution. These high quality even-aged hardwood and mixedwood sites are the focus of the New Brunswick case study for four reasons: 1) they represent most of the hardwood forested area; 2) to grow and capture the high value, high quality wood producing potential of these stands requires management of abundant low value material within the stands that is well suited to the production of biomass; 3) Fraser Inc. is preparing to bring its own 45—megawatt wood-fired electrical generation plant on-line in Edmundston in 1997 and these stands will supply the bulk of Fraser Inc.'s biomass fuel; and 4) they represent a particular challenge to foresters since they will be managed on an uneven-aged basis.

The stands on Fraser Inc.'s land are to be treated with a partial cutting system on a 15—18 year cycle (Ouellet, pers. comm., 1996). At each intervention, the basal area will be reduced by approximately one third of the original amount by harvesting trees with undesirable characteristics such as excessive size ("wolf trees" greater than 45 cm in diameter), poor form, animal damage, decay and species according to a priority list.

This type of intervention will help promote growth in the high quality residual trees (yellow birch and sugar maple) for future harvest of high value conventional products (i.e. veneer, clearwood, sawlogs, etc.). The removal of wolf trees will allow for more rapid growth of co-dominant trees and for the establishment of natural regeneration in the gaps created. They are targeted for removal because they also typically have little potential for value growth and occupy a large stand area. Crop and other residual trees help establish regeneration while providing sufficient shade to avoid excessive competition from undesirable species of trees and ground vegetation. Sugar maple is favoured as a leave tree due to its high value and its ability to respond to thinning. Beech is priorized for removal since much of it is decadent due to disease.

Most of the harvesting is done as a full-tree harvest with feller-bunchers and grapple skidders. However, wolf trees are harvested by woodsworkers with powersaws. These trees are taken out as tree-lengths to avoid damage to residual trees from abrasion with the large crowns of wolf trees during skidding. Trees with commercial value are mechanically delimbed at roadside. All other trees, and unmerchantable portions of delimbed trees, will be chipped into hogged fuel using a Morbark 23 chipper and shipped to the 45-megawatt electrical generating station in Edmundston.

Newfoundland — Clearcut harvesting in black spruce and balsam fir

The Newfoundland case study is based in the Corner Brook area of western Newfoundland on the operations of the Corner Brook Pulp and Paper Ltd. company. The pulp mill in Corner Brook is fed largely from a crown timber license typified by softwood dominated sites of medium to good fertility. The stand type chosen for this study is dominated by balsam fir with small components of black spruce, white spruce and white birch. Stands in this type are typically in the 90 year age group and have good pre-established spruce and fir regeneration due to incomplete crown closure (approximately 51—75%). The poor windfirmness of balsam fir and spruce grown in stands that have never been thinned requires the use of clearcut harvesting.

Corner Brook Pulp and Paper, Ltd. aims to maintain the softwood composition of the stands it harvests and to achieve high yields of pulpwood in future rotations. The company tries to use natural regeneration rather than planting to reduce reforestation costs. As a result, its reforestation strategy tends to focus on protection of advanced regeneration. One of the key elements in the protection of small seedlings is the shade afforded by slash distributed on the site after harvest and, in areas where seedlings are prone to burning off (e.g., where thin soils cover bedrock), the use of full-tree harvesting is considered to be undesirable. The consequences of windrowing harvesting residues in shortwood harvesting is not yet fully understood. In this study we assume that sufficient regeneration is available to successfully restock the forest after a full-tree harvest with feller-bunchers.

Nova Scotia — Shelterwood harvesting in red spruce

The Nova Scotia case study is based on red spruce (*Picea rubens* Sarg.) stands found in the Mooseland area of Nova Scotia (Halifax County). These stands are highly fertile and by age 80—90 years can contain 350—500 cubic metres of wood per hectare. These stands should, according to silviculturists in Nova Scotia, be harvested at 80—90 years either by clearcutting or through partial harvesting leaving a large number of stems per hectare designed to provide shelter for establishing regeneration. Ten to fifteen years after harvest, the stands may contain up to 30,000 stems per hectare of red spruce regeneration. Once seedlings attain a height of 30 cm and are no longer in danger of burning off through exposure to full sunlight, the remaining trees will be removed, preferably in winter when the seedlings are protected by the cover of snow. The protection afforded by the snow is necessary as the residual trees being removed can have crown diameters of 5—7 metres which pose a significant threat to seedlings from the sweeping action resulting from skidding operations (Prest, pers. Comm., 1996). Harvesting methods tend to be either manual or mechanized shortwood although there is a significant productivity capacity available in cable skidders used in full-tree or tree-length harvest systems.

The fundamental strategy on these highly productive sites is to develop a high stocking of red spruce based on natural regeneration. Red spruce grows best initially under partial shade. For this reason, and to protect the spruce trees from excessive competition, this stand type will be managed under a two-stage shelterwood cutting system.

The initial intervention will be full-tree harvesting using manual felling and cable skidders. This harvesting system replaces the tree-length or shortwood systems that would normally be used in this stand type. In this first entry, harvesting will occur without snow cover in order to provide good germination sites for regenerating red spruce. Forty percent of the basal area is the targeted removal goal: ten percent coming from the trees in the largest diameter at breast height (dbh) classes, and the remaining thirty percent coming from the lower dbh classes. In addition, intolerant hardwoods such as white birch are harvested to capture potential mortality losses in these short-lived, shade intolerant species. Trees will be delimbed at roadside using a stroke delimber and the merchantable stems cut into log lengths and pulpwood using a roadside slasher. Residual biomass is to be chipped at roadside using a Bruks 1001CT residue chipper and shipped 50 km to its end-use facility.

Ten years following the initial harvest, a second removal cut will be performed, with manual full-tree harvesting using cable skidders. This operation will be done under snow cover to minimize damage to seedlings and regeneration. Fifty percent of the basal area of the remaining trees of the original stand will be targeted for removal, applied evenly across all of the diameter classes. Roadside processing will be as described for the initial harvest. Fifteen years after the initial entry, a final removal of the original stand will be scheduled. In this instance a mechanized shortwood harvest will be used to a) protect stocking of the natural regeneration and b) maintain as much nutrient potential as possible on the site for the established regeneration. At this stage, regeneration will be in a rapid growth phase with large nutrient demands.

4 Synthesis of case studies

This section brings together the results of the three case studies with respect to the primary parameters used to evaluate them, i.e. biomass yield, biomass cost, and silvicultural and environmental consequences. Forest level consequences of energy biomass harvesting are described and the applicability of the silviculture systems proposed is briefly discussed.

Biomass Yield

Table 1 summarizes the yield and cost estimates from the three studies. The per hectare yields for the three case studies had a wide range. The shelterwood harvests in Nova Scotia yielded from 10—16 odt/ha while the Newfoundland clearcuts yielded 43.6 odt/ha. The New Brunswick partial cuts yielded 48.3 odt/ha. The high values for Newfoundland and New Brunswick yields are due to the fact that they were recovering biomass from the stems of unmerchantable tree species (white birch in Newfoundland, beech in New Brunswick). The Nova Scotia energy biomass was produced only from the tops and branches of merchantable trees. In the New Brunswick case, the yield was brought down somewhat by the need to harvest wolf trees with a tree-length system. If the cutting cycle is such that most trees are below this 45 cm diameter threshold in future interventions, the energy biomass yield may increase, although this depends on which species are harvested.

Table 1. Summary of cost (Canadian dollars), yield and environmental issues associated with each case study.

Case Study	Biomass		Environmental Issues
	Yield[1] (odt[2]/ha)	Cost[3] ($/odt)	
New Brunswick (tolerant hardwood partial cut)	48.3	35.58	• nutrient depletion
Newfoundland (softwood clearcut)	43.5	22.16	• natural regeneration • wildlife • nutrient depletion
Nova Scotia (softwood progressive shelterwood cut)	10—16	23.69—25.41	• nutrient depletion

[1]) assumes 70% energy biomass recovery of softwood and 95% for hardwood

[2]) odt = oven-dry tonne (1000kg)

[3]) Delivered cost to an energy facility 50km from the harvesting area, including the cost of compensatory fertilization with wood ash

Merchantability standards play a key role in determining biomass yield. This is particularly true for the cases where non-merchantable species are converted to energy biomass. In the Newfoundland study the impact of changing white birch from unmerchantable to merchantable would be a 22% reduction in energy biomass yield. In New Brunswick, the impact would have been a 75% reduction in the yield in the first intervention. Since the pressure on the hardwood resource is increasing in the Atlantic region as pulp mills are modified to accept a proportion of their furnish in the form of hardwood chips, there is a significant potential for currently unmerchantable species to become merchantable.

The effect of changing the minimum top diameter on biomass yield is much less pronounced. Yields were affected by a only few percentage points by lowering the minimum top diameter from 7.6 to 5.1 cm in the Newfoundland case. The pressure to lower top diameters is likely to be much less pronounced in the Atlantic region than that to accept hardwoods, given the much smaller contribution it could make to wood supply.

Biomass cost

The three cases studies indicate that energy biomass could be produced for between \$20.39/odt and \$35.58/odt at 50 km distance from an end-use facility. The cost was highest in New Brunswick because the full-tree harvest of beech recovered no merchantable volume that could bear some of the harvesting cost. The narrowness of the range between Nova Scotia and Newfoundland is a function primarily of the fact that, in both cases, energy biomass is produced in a full-tree harvesting system. The cost of full-tree harvesting (\$/m^3 of conventional products) was lower than or only slightly above the cost of the cheapest alternative (usually tree-length harvesting). As a result, there was very little incremental biomass harvesting cost and the cost of the biomass is essentially equivalent to the cost of chipping, hauling and compensatory fertilization.

The reasons for the low absolute cost of biomass processing is that the unmerchantable material from which energy biomass is made is concentrated at roadside by the full-tree harvesting system, raising the productivity of the Bruks 1001CT chipper to, in our assumptions, 14 Gt/hour (9.1 odt/hour). The Bruks chipper cost (used in New Brunswick and Newfoundland) was \$9.34/odt. The Morbark chipper used in the New Brunswick case study cost \$14/odt. If the chipper were to treat stump-area debris following shortwood harvesting, the chipping cost would rise (assuming a \$85/hour machine rental rate) to between \$17—28/odt since production would drop to between 3—5 odt/hour (Mitchell et.al.,1988).

Environmental impacts

The environmental impacts of biomass energy recovery are more difficult to generalize. One of them is the potential reduction in long-term yield of conventional products due to nutrient removal during harvesting. This problem can be partially addressed by spreading wood ash in sufficient quantities in areas harvested. This activity has a relatively low cost (\$0.50—3.91/odt) since the ash applied is assumed to be essentially free. It does not, however, compensate for the removal of nitrogen. Should this need to be replaced as well (e.g., where nitrogen is the limiting nutrient), it would cost in the range of $457/tonne applied (at 45% nitrogen content). This could add another $6—20/odt of biomass based on the yields and nutrient removals presented above. It should be noted, however, that the case study sites have inherently high fertility and may well not need compensatory fertilization.

Another environmental issue related to energy biomass harvesting is the role that coarse woody debris (CWD) plays as wildlife habitat. Specific recommendations have been developed to maintain CWD in managed forests to provide wildlife habitat. In the Newfoundland example, a systematic practice of leaving 5 stems per hectare of average dbh 30 cm would lead to a reduction of 1.0 odt (-1.5%) of merchantable material per hectare and 0.4 odt (-1.0%) of energy biomass. This implies that this kind of wildlife management prescription would have a small effect on biomass yield.

Silviculture impacts

Another potential impact is the effect of biomass removal on germination, survival and growth of regeneration. This is unlikely to be a major factor in either the New Brunswick or Nova Scotia cases where the post-harvest environment is likely to favour regeneration by desired species. In Newfoundland, there is widespread concern over the use of full-tree harvesting on exposed, nutrient poor and short growing season sites. Existing literature indicates that over the long term, full-tree harvesting does not result in significantly different stocking of regeneration from tree-length or shortwood systems in Newfoundland. The range of sites dealt with by the studies on which this conclusion is based is limited and it would be prudent to evaluate the impacts on the poorer sites.

If full-tree harvesting resulted in insufficient regeneration stocking, while both shortwood and tree-length harvesting did not (as is currently the popular view), the cost of artificial regeneration would have to be added to the biomass price. If we assume replanting costs to be $550/ha, the cost of biomass could be increased by as much as $13/odt in the Newfoundland case (based on current biomass yields). It should be noted, however, that plantations of desirable species have better long-term yields and potentially lower costs of protection and tending (e.g., pre-commercial thinning) than do partially stocked stands of natural regeneration with highly variable density. This can have significant effects on sustainable harvests that could, to some extent, compensate higher planting costs.

Forest level implications

Studies of silviculture practices are an important component in helping to increase biomass production. They deal with stand level issues related to harvesting and reforestation costs and revenues. For most Canadian forestry situations, however, the stand level issues are integrated in management planning at the forest level. The silviculture practices carried out in any given stand type on large crown land licences or industrial freehold from coast to coast are decided as a result of forest level concerns. The need for forest-wide sustainability of timber supply, environmental quality and social values is what drives the choices of where to apply the various silviculture systems available to foresters. If we treat the impacts only at the stand level, we may reach conclusions that are inappropriate when we evaluate their broader implications at the forest level. The same may be true of energy biomass production.

Some of the forest level effects of energy biomass harvesting may be felt through the "allowable cut effect" (ACE) phenomenon. An ACE occurs when, in forests constrained to produce even flows of timber, forest managers are allowed to liquidate old growth stands more rapidly in the short term by putting in place young stands that grow more quickly than the old stands they replace. An ACE may also occur when the productive landbase is expanded. Energy biomass harvesting can create ACE through at least three mechanisms: by increasing yield in harvested stands by forcing the use of planting over natural regeneration; by reducing site productivity through nutrient removal; and by increasing the productive land base area. Since nearly all Crown land in Canada (90% of productive forest land) is under non-declining timber flow constraints, there is a need to analyze biomass production at the forest level.

Potential applicability of the silviculture systems described

While the silviculture systems described and their respective stand types are province-specific, they were selected because they represent situations that exist broadly throughout Atlantic Canada. In general, all of the systems presented in the case studies are conventional silviculture practices. What distinguishes them is that they use full-tree rather than tree-length or shortwood harvesting. In other words, where a shelterwood harvest is being carried out with a shortwood harvesting system, the full-tree equivalent could be used and biomass recovered at roadside. As a result, the general guideline for applicability would be that the proposed silviculture systems could be used wherever their conventional analogues are used so long as there is a market for the biomass produced. A further caveat is that they should not be used where harvesting residues and unmerchantable species must be used for purposes other than energy production (e.g., as a nutrient source, wildlife habitat or to help ensure survival of seedlings). It should, therefore, be clear that the systems proposed could find widespread applicability.

5 Policy changes and incentives to make energy biomass production more attractive

Biomass energy production is currently constrained by two main forces: the lack of markets and the perceived balance between its advantages and disadvantages. The following sections discuss these two forces and propose action that might be taken to make energy biomass production from conventional operations more attractive.

Markets for energy biomass

Where a market exists for energy biomass, the private sector finds effective and efficient methods of resolving silvicultural and operational problems that would otherwise limit exploitation of that market. Technical issues involved in biomass production do not seem to be limiting. Instead, the existence of a market seems to be one of the main impediments restricting growth in biomass use. Some of the factors affecting market development include:

- *Fear of competition* — The forest industry has long resisted independent development of biomass energy facilities for fear of competition for forest fibre. Competition could increase prices, reduce fibre supply or both.

- *Fear of independent electrical production* — Many public electrical utilities have maintained energy pricing structures that inhibit development of independent production facilities. There is some concern by officials of the state monopolies on power generation that independent production of electricity in wood-fired co-generation plants would result in a loss of control over the reliability and quality of power production.

- *Clean air legislation* — One of the advantages of biomass as a fuel is that it contains very little sulphur. As a result, it can be burned without the use of sulphur dioxide scrubbers. This is an advantage over most fossil fuels, which contain greater amounts of sulphur. The lack of clean air legislation that clearly provides incentives to reduce air pollution in power generation facilities in many jurisdiction makes fossil-fuelled production comparatively attractive by reducing the air pollution advantage of biomass energy plants.

Advantages and disadvantages of biomass energy

Production of energy from forest biomass is not an end in itself, rather, it has been proposed as an alternative or complement to conventional sources of energy such as fossil fuels and nuclear power. In a society increasingly concerned with sustainable development, proponents of biomass energy address their arguments to the main components of sustainable development, namely environmental, economic and social (WCED 1987). Opponents of biomass harvesting routinely cite environmental issues focussing on the spectre of over-harvesting and denuding of the landscape and the attendant rise in air pollution from the combustion of wood products. The current perception held by industry and government is that while there is merit to both sides of the argument, the advantages and disadvantages cancel each other out and, as a result of this, there is no incentive to pursue commercial production of biomass energy. If policy changes and incentives aimed at encouraging energy production from forest biomass are to be effective they need to concentrate on strengthening its advantages and weakening its disadvantages.

Fears of nutrient depletion can be calmed by a combination of information about the likely impacts, by judicious use of existing ecological site classification information to limit biomass harvesting to sites with low susceptibility to productivity losses and by use of compensatory fertilization where appropriate. Concerns about negative silviculture impacts and financial unattractiveness have little basis as general rules and can only be addressed by local analyses, some of which will need a forest level perspective.

Biomass energy has significant advantages in the area of socio-economic impacts. However, these are only revealed if analyses are carried out at the socio-economic level rather than the single firm financial level. Socio-economic analysis considers such issues as net national value-added, employment, public sector debt, shifting use of forest resources, wildlife and other environmental effects. Comparative analysis of biomass energy production from conventional forestry operations with alternative energy sources is needed to provide a more comprehensive evaluation and is likely to identify more opportunities for biomass production than now exist.

6 Conclusions

Applicability of energy biomass harvesting in conventional operations

- The silviculture systems described have wide applicability. Wherever their shortwood or tree-length analogues are used and residues are not needed for other purposes, the full-tree systems proposed are likely to provide good results.
- A large proportion of the land base can be managed by one of the three systems described, although the specifics of the prescription might change (e.g., basal area removed, harvest priority, shape of clearcut).
- Harvesting systems that leave the biomass attached to the stem until it reaches roadside are likely to have the lowest costs of energy biomass harvesting and chipping.

Environmental consequences

- Compensatory fertilization with wood ash would cost little relative to the cost of harvesting and chipping and could replace all nutrients except nitrogen.
- Prescriptions currently in use to provide coarse woody debris and snag trees for wildlife can be accommodated without significant biomass yield reduction.

Point of view and scale of analysis

- There are a number of implications of energy biomass harvesting that will be felt mainly at the forest level rather than at the stand level, including: allowable cut effects in forests constrained to produce non-declining yields, expansion or shrinkage of the operable land base and net value-added from energy biomass production.

Policy changes and incentives required to encourage energy biomass production

- Biomass energy projects need to be evaluated at a socio-economic level from environmental, social and economic perspectives to show the full range of their positive impacts
- A simple protocol for analyzing biomass energy projects at the socio-economic level (including forest level impacts analysis) needs to be developed and documented
- Effective and efficient techonological approaches to compensatory fertilization need to be documented and/or developed to calm the main fears about biomass energy.

7 Recommendations

1) A socio-economic study of biomass energy production should be carried out in some location in Canada as a model for this kind of analysis. It should deal with social, environmental and economic impacts of biomass harvesting and utilization for a specific project. The forestry component of this analysis should contain a forest-level, long term biomass supply analysis that specifically considers the implications of potential yield reductions and of changes in the cost or effectiveness of reforestation interventions.

2) Literature on the long term growth effects of biomass harvesting with and without compensatory fertilization should be analyzed and summarized in an IEA report. Biomass energy harvesting should also be compared to natural disturbances in this report.

3) A study of the state of the art in compensatory forest fertilization with wood ash and other fertilizers should be carried out. It should deal with technologies available to work in stands at a range of different development stages such as: recent cutover; high-density regenerating stand; immature and early-mature stands.

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Wood fuel from precommercial thinning and plantation cleaning in Canada

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Abstract

Precommercial thinning and plantation cleaning offer opportunities for increasing the availability of wood fuel in Canada. In 1992, approximately 130,000 ha were treated with precommercial thinning or stand cleaning. Motor-manual methods predominate these silvicultural activities. However, at stand densities greater than 10,000—15,000 stems/ha, mechanized systems are more economical. Recovering this biomass for wood fuel would require changes to silvicultural systems and harvesting technology.

Keywords: biomass, precommercial thinning, tending, weeding, wood fuel

1 Introduction

Early thinning in juvenile stands and cleaning in plantations to remove competing vegetation from around crop trees are proven and effective methods to stimulate tree growth, maximize residual stand value, and reduce future harvesting costs. Although thinning has been carried out in Canada for more than 65 years (Schenstrom 1931), it is only recently that precommercial thinning (PCT) in juvenile stands (5—15 years of age) has become a well-established practice. For example, in 1975, approximately 22,000 ha were thinned (Fig. 1). Since then, PCT has increased steadily to present levels of approximately 90,000 ha annually (Canadian Council of Forest Ministers 1996). As well, environmental concerns have prompted forest managers to consider non-chemical methods of controlling undesirable woody vegetation in plantations. Motor-manual and mechanical cleaning to remove competing deciduous tree species in conifer plantations are gaining acceptance as alternatives to aerial herbicide spraying. In 1992, approximately 40,000 ha were cleaned using motor manual or mechanical methods (Fig. 1).

The amount of potential biomass from PCT and plantation cleaning varies depending on the species, origin of the stand, and stand age. However, pre-treatment densities of 10,000 to 50,000 stems/ha at 10 to 15 years of age are common (Hosick 1991; Nicks 1991; Brown 1991) and in some cases, densities as high as 214,000 stems/ha have been reported (Smith 1987; Hedin 1988; Ryans 1995). Tree diameters range from 2 to 10 cm and typical tree height is 1.5—2 m. Target post-treatment densities vary from 1500 to 3500 stems/ha (Hosick 1991). Thus, up to 70 to 100 tonnes/ha (dry basis) of biomass might be available for recovery following PCT and plantation cleaning (MacLean and Wein 1976; Singh 1982). In most cases, the biomass which is felled during PCT and cleaning is either macerated by the cutting action or is left on site because of inherently high handling costs associated with small timber and the low recovery value of such wood for pulp furnish (Brenoe and Kofman 1990).

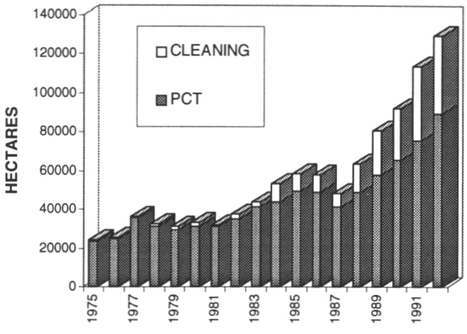

Figure 1. Precommercial thinning and cleaning in Canada.

PCT and cleaning of early successional stands and juvenile conifer plantations respectively offer opportunities for increasing the availability of wood for fuel in Canada. Recovering the biomass from PCT and cleaning would, in many cases, require changes in current silvicultural practices and tending and thinning systems, and would have implications for reforestation, growth and yield, nutrient levels, and environmental quality (Hakkila 1989; Richardson 1991; Mard and Tham 1991; Sabourin et al. 1992). Felling, extraction, and comminution systems might also require modification (Verkasalo 1994).

2 Biological considerations in thinning and cleaning

The physiological basis for thinning has been well documented (Oliver and Larson 1990). The early successional stage of stand development after clearfelling or fire is characterized by a short but often dense and patchy growth of saplings and shrubs.It is beneficial for most commercial tree species to experience competition early during stand development to achieve the desired tree form and quality. However the optimal tree density required to achieve maximum crop harvest is lower than that required to get the desired form and quality and at some point in a stand's development thinning is therefore desirable. The primary consideration in thinning for timber production is to make light, water, and nutrients more readily available to the crop trees. The response of a stand to thinning depends on the stand's density, age, crown condition, site quality, stem vigour, and resource competitors including competing vegetation, micro-organisms, and wildlife.

The early successional stage of stand development provides abundant forage for ungulates, and many species of small mammals, furbearing animals, and songbirds are also particularly adapted to the early successional stage of development (Brunell and Eastman 1976; Telfer 1976). Spacing changes the structure of the stand, thereby changing the habitat conditions for wildlife. Studies suggest that species such as snowshoe hare (*Lepus americanus*) which depend upon dense juvenile conifer stands for winter cover are negatively affected by increased spacing (Waterhouse et al. 1988). However, the impact on most wildlife is minimal unless stand density is reduced from 'dense' (> 50% crown cover) to 'open' (< 50% crown cover) (Telfer 1990).

Precommercial thinning also provides an opportunity to sanitize the stand. However certain pathogens such as Annosus root rot (*Heterobasidion annosum*) can cause considerable damage in thinned stands (Gross 1991). The fungus commonly infects surfaces of cut stumps and logging wounds. Treatment of such surfaces with borax or sodium nitrate has been prescribed (Myren and Punter 1972) after harvesting pine in southern Ontario.

The possibility of increased insect defoliation in thinned stands has generated considerable interest as thinning assumes greater prominence. Studies in unmanaged forest defoliated by the spruce budworm (*Choristoneura fumiferana*) indicate that host susceptibility increases with increasing crown closure and proportion of host species (Fauss and Pierce 1969). Opening up stands by spacing and thinning therefore has the potential to reduce stand susceptibility to spruce budworm defoliation (Crook et al. 1979). Studies with other insect species indicate that thinned lodgepole pine (*Pinus contorta*) attacked by the lodgepole terminal weevil (*Pissodes terminalis*) and more open stands of Sitka spruce (*Picea sitchensis*) damaged by the sitka spruce weevil (*Pissodes strobi*) exhibited increased incidence of attack compared to unthinned stands (Bella 1985; Alfaro and Omule 1990). However, thinned stands of lodgepole pine were less susceptible to attack by the mountain pine beetle (*Dendroctonus ponderosae*) (Mitchell et al. 1983).

The most problematic aspect of the removal of biomass for wood fuel from PCT and plantation cleaning is the risk of excessive losses of nutrients and the effect this has on future stand growth (Van Hook et al. 1982; Hakkila 1989). The risks are exacerbated with PCT and plantation cleaning because nutrients are concentrated in the tissues of plants of smaller diameters such as those harvested in PCT and plantation cleaning (Van Hook et al. 1982) and because nutrient demand is usually at its greatest soon after the first thinning (Mälkönen 1977 *in* Hakkila 1989).

3 Methods

Motor-Manual

Presently motor-manual methods using either conventional chainsaws or more commonly, purpose built brush saws predominate precommercial thinning and plantation cleaning operations. However, high costs are incurred with motor-manual methods because of low productivity. Average productivity in motor-manual PCT

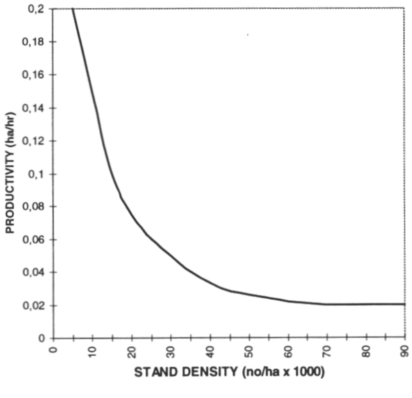

Figure 2. Productivity of motor-manual precommercial thinning.

ranges from 0.02 to 0.15 ha/hr. The productivity in motor-manual cleaning operations also tends to be at the low end of this range of productivity (Holmsen 1988). Variations in productivity are due to many factors, including operator experience, training and motivation, work organization, weather, various site and stand factors, particularly stand density (Smith 1987). Data from one PCT operation in Nova Scotia shows that productivity declines sharply over the range of 5,000 to 30,000 stems/ha and levels off at more than 40,000 stems/ha (Fig. 2). Payment schemes for silvicultural workers generally include production incentives that are tied to stand densities.

Mechanized

Although not suitable to low-density stands, mechanical treatments offer the most practical alternative to motor-manual operations because machinery is less affected by increasing stand density (Berg et al. 1975). Row or strip thinning, combined with selective motor-manual release is considered the most effective approach for achieving desired biological and economic objectives (Smith 1987; Hedin 1988).

Interest in mechanized PCT began in the late 1940's in Canada. During the late 1940's to the middle 1960's most mechanized PCT was experimental. Strip thinning was accomplished with mixed results using a variety of equipment included brushland discs, uprooting with a winch, and straight and V-blades on tracked tractors (Ryans 1988; Ryans and Cormier 1994). The first operational-scale PCT projects in Canada were undertaken in Manitoba from 1963—1965 using drum choppers to strip thin in eight- to nine year old jackpine (Pinus banksiana) stands with an average density of 47,000 stems/ha (Bella 1966).

Since the early 1970's most mechanized PCT has been carried out using a variety of powered cutting heads. Because these cutting heads are carrier-mounted, there is little flexibility for selective felling and most of the thinnings are macerated by the cutting action making recovery for wood fuel impossible (Ryans 1988; Ryans and Cormier 1994; Ryans 1995).

Development of an operational PCT system is concentrating on mechanized row thinning systems. To meet the spacing prescriptions for much of the boreal forest, the width of the cut strip should ideally be 1.83 to 2.44 m. Most off-the-shelf brush cutters were designed for brush cutting applications where a narrow width of cut is a detriment to productivity. Other constraints include potential damage to residual crop trees, incomplete mortality within cut strips, and difficult site conditions (Ryans and Cormier 1994). PCT machines must be capable of working in stands with densities greater than 20,000 stems/ha and trees 2—4 m high. Units must be capable of manoeuvring around up to 200 trees/ha larger than 15 cm in diameter (Smith 1987). At the present, little consideration is given to developing mechanized PCT systems capable of felling and recovering early thinnings for wood fuel. An exception was the Valley Forest Products Strip Thinner, which was designed and tested in New Brunswick in the late 1970's, consisting of two circular felling saws and a chipper mounted of the front of a wheeled skidder. The thinnings were felled, chipped, and then fed into a hopper. However, the machine did not progress beyond the prototype stage.

Equipment designed specifically for plantation cleaning was developed in the 1980's in Sweden, where mechanized systems are currently in widespread use (Hellstrom 1992). The first mechanical cleaning machine in Canada, a Swedish FMG 0450 equipped with an FMG cleaning head, was tested in Nova Scotia in 1990 (Ryans and St-Amour 1994). In 1991, a Silvana Selective cleaning head was mounted on a Ford Versatile Model 9030 bidirectional tractor and tested across Canada (St-Amour and Ryans 1992; Hunt 1993; Mitchell and St-Amour 1995). Currently there are two Silvana Selective (FMG 700) cleaning heads mounted on Ford Versatile Model 9030 bidirectional tractors working in eastern Canada. Key features of these and other plantation cleaning equipment include precise control of the boom offering selective cleaning capability and carriers with high ground clearance.

The normal mode of operation consists of straddling the centre row of trees and cleaning the plantation in a semicircle in front and to the sides of the machine in one pass — cleaning 9.5—11 m wide swath. On most operations, the felled trees remain on site in whole tree form and could potentially be recovered for wood fuel. Productivity is greatly affected by the density of stems to be removed, the number of crop trees to be released, tree heights, and operator experience. Productivity ranges from 0.09—0.35 ha/hr (St-Amour and Ryans 1992; Mitchell and St-Amour 1995). Comparisons with motor-manual cleaning methods suggest that the break-even point for mechanized cleaning is 10,000 to 15,000 trees removed per ha (Ryans and St-Amour 1994). This is consistent with the Swedish experience.

3 Conclusions

PCT and plantation cleaning are gaining operational acceptance in Canada. Presently motor-manual methods predominate, however work is ongoing to develop viable strip thinning systems. Recent developments in mechanized plantation cleaning systems also appear promising. In addition to the many biological benefits from early spacing and cleaning, PCT and plantation cleaning offer opportunities for increasing the availability of wood fuel in Canada. Recovery of biomass would require changes in current silvicultural practices and tending and thinning systems, as well as modifications to felling, extraction, and comminution systems.

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The impact of fuelwood harvesting on forest management in Finland

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Abstract

At the price level of 45 FIM per MWh, the economically harvestable amount of fuelwood in the study area of about 1 Mha in western part of Finland accounts for 570 000 m^3 annually without competition from industrial wood. This price level corresponds to the price of the competing energy forms, which are peat, coal and oil.

Wood prices paid by the forest industry for small-diameter stemwood are superior compared to the prices paid for energy wood. In the competition situation the harvestable energy wood of 120 000 m^3 consists almost totally of logging residues from final cuts of spruce-dominated stands. At the price level of 85 FIM per MWh energy production will be a profitable alternative to pulping.

The effect of utilisation of energy wood on employment depends greatly on the harvesting method used. Collecting logging residues using highly mechanized methods needs only 10—25 workers. At higher wood prices, the higher proportion of manual stemwood harvesting offers work for 50—100 people annually. Chipping, road transport, combustion and harvesting work done by private landowners represent significant additions to these figures.

The harvesting of fuelwood adds to the landowner's revenues when compared to the most intensive management programs for producing industrial wood. At the price level of FIM 65 per MWh the increase is 3 %; at the level of FIM 85 per MWh 22 %. At low prices the economic impacts come in the form of wages paid to employees; at higher prices the net income (stumpage price) becomes significant.

The discounted (3 %) net revenues show that harvesting energy wood always increases future net incomes, no matter what the demand for industrial wood is, high or low.

Keywords: Bioenergy, fuelwood, silviculture, forest management

1 Introduction

1.1 The history of utilisation of Finnish forests

For several centuries, the use of wood for heating was the main form of use for Finnish forests. As recently as in the middle of the 19th century, the annual drain of wood amounting to ca. 50 Mm^3 was accounted for by wood consumed in heating, tar distillation, and slash-and-burn agriculture (Fig. 1). The share of industrial wood consumption was almost zero.

The advent and rapid development of industrial sawmilling and pulping in the 1870s did not threaten the use of wood as fuel. This was possible because there were huge reserves of small-diameter hardwood stands, which regenerated naturally on clear-felled and burnt-over areas. All the trees felled could be used for heating following the end of the era of slash-and-burn cultivation and prior to the era of industrial use of birch in paper-making.

After World War II, wood found increasing use by the country's forest industry. The problems of sustainable wood production and the increasing demand for birch by the paper industry resulted in the substitution of wood by other energy sources. The proportion of wood in the total energy consumption of Finland dropped below 50% for the first time at the end of the 1950s. At the same time, for a period of a couple of years, total removals from Finnish forests exceeded the estimated sustainable drain.

After four decades of intensified silviculture, the total growth of Finnish forests has increased by more than 40% to 80 Mm^3a^{-1}. Concurrently with this development, the total drain has remained at less than 60 Mm^3. The rapid increase in the total production capacity of Finnish forest industries is due to the more meticulous utilisation of the wood raw material, the decrease in fuelwood consumption, and the increased imports of raw wood from abroad, mainly from Russia and the Baltic countries.

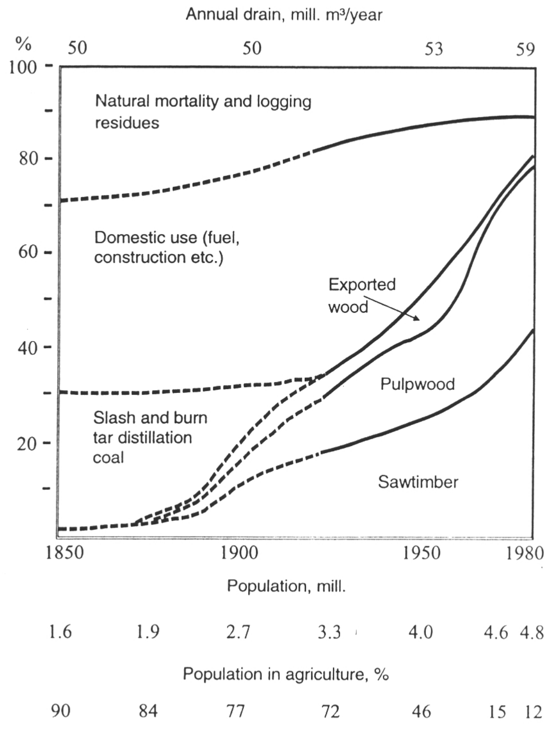

Figure 1. Wood consumption in Finland 1850—1980 (according to Kuusela 1984).

Given such a situation, the sustainability of wood production is no longer threatened. In spite of the pressure to establish new nature conservation areas, there is still room for increasing use of wood for energy generation.

1.2 The utilisation of energy sources

In 1993, ca. 32% of the total energy (30 Mtoe) consumed in Finland was generated using domestic energy sources; wood, peat, and hydropower. The proportion of biofuels, 17%, was the highest among the world's industrialised nations. Only Sweden and Austria were close to this level. More than 2/3 of the bioenergy generated in Finland was based on using wood. Up until now, the growing of short-rotation energy crops has been of minor practical importance. The over-production in agriculture, however, gives us good opportunities to produce biofuels on an area of one million hectares in the future.

Wood-based energy generation, 14% of the total energy consumed in Finland, corresponds to an annual amount of 25 Mm^3. Most of this energy is generated in pulp mills, and only 5.5 Mm^3 are consumed by heating plants and in heating on farms. Finnish sulphate pulp mills, in fact, generate more energy than they need. Consequently these mills are in a position to sell wood-based electrical power to the surrounding communities. The target of the Finnish Parliament is to increase the annual generation of wood-based energy by an amount corresponding to 10 Mm^3 wood.

The biggest problem in using wood for energy purposes is the high costs of harvesting, transportation, and combustion. To be a profitable alternative to competing energy forms (peat, coal, oil), the price of fuelwood should not exceed FIM 45 per MWh when at the place of consumption. This price must include harvesting, forest haulage, long-distance transportation, chipping, and the stumpage paid to the forest owner. The collecting of logging residues on clear-fell areas, mainly of spruce, has been the closest to this target. The "second best" method is what may be called "integrated harvesting", where industrial stemwood and logging residues are harvested simultaneously and used at the pulp mill in paper-making and energy generation. The harvesting costs for small-diameter stemwood for energy generation clearly exceeds the target level of FIM 45 per MWh.

1.3 The aim of the study

The current total growth of Finnish forests clearly exceeds the annual drain, thanks to the silvicultural measures applied during the last few decades. The high level of wood production is positive from the point of view of forest industry, nature conservation, and wood-energy generation.

High wood harvesting costs are the main obstacle in the endeavour towards profitable utilisation of fuelwood in Finland. A factor of uncertainty is the long-term sufficiency of wood in the vicinity of bigger heating plants. This is an important point to be aware of because we know from experience that the radius of profitable wood procurement around each heating plant is only twenty or so kilometres.

Up until now, economic calculations demonstrating the low profitability of fuelwood harvesting have been partly misleading. The positive effects of cleaning and thinning young stands on long-term stand development have only very seldom been included in such calculations. This is, at the moment, of particular importance due to the decreased demand for small-diameter industrial wood. The effects on employment, and on the national economy, of utilising indigenous raw material instead of imported energy are positive, too.

The aims of this study were as follows:

a) To determine the amount of fuelwood that can be sustainably and profitably harvested (over a period of 40 years) and over a large area (1 Mha).

The harvesting potential will be estimated on the basis of data provided by national forest inventories conducted in Finland and using alternative maximum wood prices with and without the competition of the forest industry. In these calculations, the purpose will also be to find the relatively most profitable harvesting methods for different stand types.

b) To determine the effects of harvesting fuelwood on the future development of the forests.

The development of the forests will be simulated using alternative production strategies for fuelwood and industrial wood. The long-term effects on the forest resources, stand structure, future wood production, and employment can be seen at the end of the simulation period of 40 years.

c) To determine guidelines for silvicultural measures in integrated wood production for energy generation and forest industry.

The harvesting of fuelwood will be studied in these calculations as part of the most profitable growing programme. The aim is to determine the kind of stands where fuelwood harvesting is most profitable and the most appropriate harvesting methods in each case.

2 Material and methods

2.1 Study material

The data consists of 3577 study plots measured in the course of the 8th national forest inventory (NFI8) in 1991—1992. The total study area of about 1 Mha is situated in the western part of Central Finland (64° N, 24° E). An abundance of young stands on drained peatlands is a typical feature of this geographical region. The proportion of peatlands is 52% of the total forest area. The main tree species are Scots pine (52%), Norway spruce (24%), and broadleaved species (mainly birch, 24%).

Objectively selected inventory plots guarantee unbiased estimates of forest resources for the whole area. All the data are measured and the calculations made by individual trees.

2.2 Simulation of stand development

MELA is the name of a computer software product developed at the Finnish Forest Research Institute for making long-term forecasts of stand development over large areas (Siitonen 1983). The system consists of a stand simulator based on single trees and an optimisation part using linear programming. Initially, this program was used in dealing with calculations covering large areas and based on NFI data. Recently it has found increasing use in forest management planning for smaller farm holdings.

In the simulation part of the program, the development of each plot or forest stand is simulated over a selected period of time for all possible kinds of silvicultural measures. The intensity and timing of tending and thinning, alternative ways of harvesting (e.g. industrial versus energy), rotation length, and wood prices are some of these alternatives. This results in tens or even hundreds of possible development alternatives for each stand. In whole-area optimisation, only one "path" is selected so that the final solution fulfils the goals and constraints of the whole area. In this study, more than 200 000 stand level alternatives existed at the final optimisation stage.

The goal in optimisation in most cases is to maximise profits without forgetting constraints. The constraints are usually connected with the long-term sustainability of forest management, with nature conservation, with labour, or money that can be invested in forestry.

The present study required some additional options to be included in the MELA system. New management practices were added because of harvesting wood for energy generation. As regards all final-felling operations in spruce-dominated stands, also the harvesting of logging residues was simulated. Stands ready for first thinning got an alternative of integrated whole-tree harvesting in addition to the traditional shortwood method directed to utilise only stemwood in forest industry. The inclusion of new alternatives also required some research work in developing biomass functions and cost models for the new harvesting methods.

2.3 Alternative management programs

The goal in optimisation was net revenues discounted to the beginning of the 40-year simulation period. The discounting interest rate applied was 3%, which is commonly used in this kind of long-term economical calculations in Finland. Six different felling programs were studied. These programs differ from each other mainly in regard to wood prices (=harvesting costs) and the intensity of utilisation of forest resources. The prognoses have also been done with and without price competition between industrial wood and energy-generation wood.

The following six management programs were compared in the final analyses:

A. Programs assuming full, sustainable utilisation of forest resources
  Program #1 (full industrial utilisation)
    Maximisation of the discounted net revenues (3%). Annual drain and net revenues were not allowed to decrease during the period of 40 years. The harvesting methods were directed to the industrial use of wood and excluded energy wood.

Program #2 (full utilisation)

In addition to what was done in Program #1, energy wood was also harvested. The maximum price of fuelwood brought to the place of utilisation was FIM 45 per MWh. The extent and methods of energy-wood harvesting in the competition situation with industrial wood will be studied.

Program #3

The only difference with respect to Program #2 was that the maximum price of energy wood was FIM 65 per MWh.

Program #4

As Program #2, but with the maximum price now FIM 85 per MWh.

B. Programs with below-maximum utilisation (1990 level)

Program #5

Maximisation of discounted net revenues (3%) to the beginning of the 40-year period. Only industrial wood was harvested. Annual drain was restricted to the level of the years 1991-1992 (low utilisation level).

Program #6

In addition to what was done in Program #5, energy wood was also harvested. The maximum price of fuelwood at the place of utilisation was FIM 65 per MWh.

3 Results

3.1 Harvesting potential of energy wood without competition from industrial wood

The maximum amount of harvestable energy wood in the study area of 1 Mha was estimated by maximising the outturn of energy wood without any constraints and without competition. The results showed the energy wood resources of the area to be high. With maximum prices FIM 45, FIM 65 and FIM 85 per MWh, the annual harvesting potentials during the next 10 years were 0.8, 1.8, and 2.0 Mm^3 respectively assuming no competition from the forest industry. The corresponding energy generation varied from 1.6 to 3.9 TWh annually. These amounts are high enough to supply 20—50 heating plants, each of which could deliver enough heat to keep several thousand detached houses warm.

At the price level of FIM 45 per MWh, the only profitable harvesting method was the collecting of logging residues in clearcut areas formerly dominated by spruce. Another possible method was that of integrated harvesting of fuelwood and industrial wood, if all the harvesting costs in the forest (excl. road transportation costs) could be focused on the pulp fraction.

Increasing the price to FIM 65 per MWh made it possible to also harvest stemwood for energy generation. At this energy price level a stumpage price of only ca. FIM 10 per m^3 could be paid for fuelwood, and thus it could by no means compete with the prices paid by industry for pulpwood. At the price level of FIM 85 per MWh, the stumpage price of FIM 30—40 per m^3 made fuelwood somehow competitive with the industrial use of first-thinning wood.

3.2 Harvesting potential and harvesting methods in alternative management programs

In practice, energy wood must compete with the demand by forest industry for pulpwood. Logging residues are the only wood raw material that can be harvested for energy generation without competition. The results of four management programs are shown in Table 1. Programs #2, #3 and #4 maximise the discounted (3%) net revenues in the combined production of industrial and energy wood. In all programs, the long-term sustainability of wood production was guaranteed by restricting fellings in such a way that the total wood volume remained stable or increasing during the 40-year simulation period. In Program #6, the annual drain is at a clearly lower level than is suggested by the sustainability requirement. In fact, felling in Program #6 is at the level of the years of economic recession in the early 1990s.

The felling potential of energy wood under competition from the demand for industrial wood is only 14—26% of the maximum potential without competition. Wood prices paid by the forest industry for small-diameter stemwood are superior compared to the prices paid for energy wood. Only at the highest price of FIM 85 per MWh does energy wood begin to be a realistic alternative to pulpwood. This price is far above the price of competing energy sources, e.g. oil, coal, peat.

At the lowest price of FIM 45 mainly logging residues can be collected to fulfil the energy-wood demand of three medium-sized heating plants (10—20 MW corresponding annual consumption of 100 000 m^3 of wood chips); at the highest price, 9—10 plants could be kept supplied with chips.

Table 1. The amount of harvestable wood for energy generation using different maximum prices (harvesting costs) for wood. Programs #2—#4 represent full sustainable utilisation; Program #6 represents low utilisation.

Period	1991— 2000	2001— 2010	2011— 2020	2021— 2030
	Energy wood, 1000 m³/year			
Prog. 2 (45 FIM per MWh)				
Total amount harvested	120	120	120	120
stemwood, %	7	19	29	48
crown biomass, %	93	81	71	52
Prog. 3 (65 FIM per MWh)				
Total amount harvested	187	187	187	187
stemwood, %	21	22	31	54
crown biomass, %	79	78	69	46
Prog. 4 (85 FIM per MWh)				
Total amount harvested	365	365	365	366
stemwood, %	40	49	47	69
crown biomass, %	60	51	53	31
Prog. 6				
Total amount harvested	226	216	211	208
stemwood, %	44	36	37	41
crown biomass, %	56	64	63	59

3.3 Effects of energy wood harvesting on employment

The effect of utilisation of energy wood on employment depends greatly on the harvesting methods used. Collecting logging residues from final-felling areas in former spruce-dominated stands and integrated harvesting in pine-dominated first-thinning stands use highly mechanised methods and thus need very little labour. This becomes evident from the employment figures presented in Programs #2 and #3 (Table 2). The annual labour needed to harvest 100 000—200 000 m^3 of solid wood is only 10—30 people. In Programs #4 and #5, the higher proportion of manual stemwood harvesting offers work for 50—100 people annually in the forest. For the whole of Finland, this figure could be 10 to 20 times higher.

The aforementioned employment figures include only the work in the forest and they are valid for efficient, highly mechanised harvesting systems. Chipping, road transport, combustion, and the work done in building heating plants and harvesting machines represent significant additions to these figures. The lower mechanisation rate in the harvesting work done by private landowners means that the employment effect of energy wood is even higher in practice.

3.4 The future production potential of the forests

The relative net revenues under different management programs are presented in Fig. 2. The results show that the harvesting of fuelwood adds to the landowner's revenues when compared to the most intensive management programs (Programs #1—#4). At the price level of FIM 65 per MWh the increase is 3%; at the level of FIM 85 per MWh the increase is 22%. At low prices the economic impacts come in the form of wages paid to employees; at higher prices the net income (stumpage price) becomes significant. In the later decades the net revenues markedly increase under all the intensive programs. This is mainly due to the larger dimensions that the growing stock in young peatland forests attains.

Programs #5 and #6 (under-utilisation) result in clearly lower revenue levels than the more intensive programs. The use of energy wood in a situation of low demand by forest industry increases net incomes by 10% (price FIM 65 per MWh) when compared to the program directed only to the production of industrial wood.

Table 2. Annual harvesting areas and employment under different management programs (only energy wood).

Period	1991— 2000		2001— 2010		2010— 2020	
	Area	Years	Area	Years	Area	Years
Prog. 2	1500	10	4200	15	2500	20
Prog. 3	4300	25	5400	25	5300	35
Prog. 4	8700	80	9200	90	10500	95
Prog. 6	6900	60	7500	45	7100	45

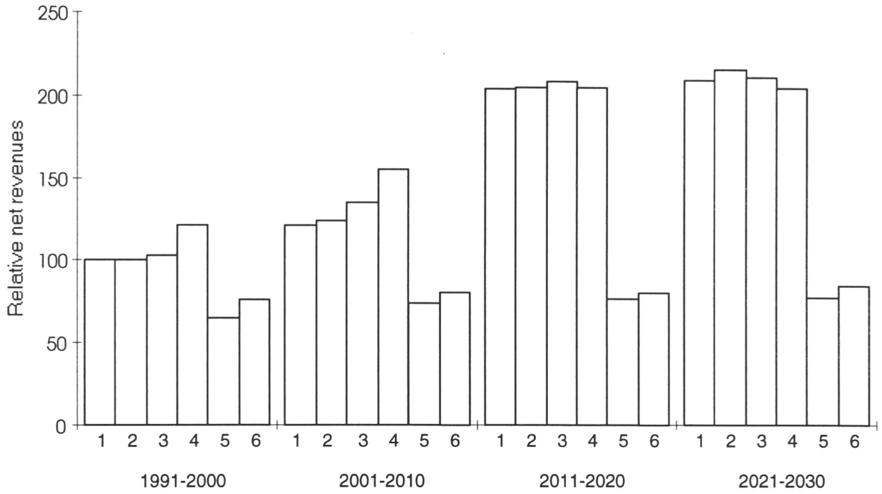

Figure 2. Relative net revenues per decade under six different management programs.

The discounted (3%) net revenues make it possible to compare all the future revenues to each other under different management programs. The calculations show that harvesting energy wood always increases future net incomes, no matter what the demand for industrial wood is, high or low. This increase is 1.0% to 4.4 % depending on the prices paid for energy wood. Analyses also reveal that it is not possible to substitute economic felling losses, caused by under-utilisation of forest resources, by heavier felling in the future.

4 Discussion and conclusions

The potential of harvesting wood for energy in the studied region of one million hectares is high, if there is no competition with the forest industry for small-diameter wood. The maximum price of FIM 45 per MWh (the price of alternative energy sources like peat, coal and oil) resulted in a harvestable volume of 0.8 Mm^3 of solid wood for energy generation annually during the next 10 years. Were the price FIM 20 higher per MWh, or were the harvesting systems developed to be much more competitive, the amount would double. In the long run of 40 years, these amounts would fall by ca. 30%.

The aforementioned wood quantities are high enough to keep 15—30 heating plants of 10—20 MW capacity supplied with raw material. Each of these power plants could deliver heat for the needs of several thousand houses.

In practice, energy wood must compete with pulpwood. In addition, the harvestable amounts of logging residues and energy wood in integrated harvesting depend on the harvested industrial wood. If the maximum price for energy wood is as low as FIM 45 per MWh, all small-diameter stemwood is most profitable when utilised by forest industries. At the price level of FIM 85 per MWh, energy wood becomes competitive with industrial wood. Low demand by forest industry for small-diameter wood results in a profitable harvesting at the price level of FIM 65 per MWh.

The most profitable methods in large-scale utilisation of wood energy are the collecting of logging residues in formerly spruce-dominated final-felling areas and the integrated harvesting of pulpwood and energy wood in conjunction with the first commercial thinning of young stands. Energy generation in pulp mills or local power plants is profitable because of the savings achieved in logging and long-distance transportation.

The decentralised utilisation of energy wood by households living on farms and in detached houses was not addressed in this study. This does not mean that the small-scale use of wood for heating houses is unprofitable. On the contrary, by using wood for energy generation, the forest owner can save money, employ himself, and improve the silvicultural state of his forests. Thinning of young stands for energy wood results in faster stand development, better wood quality, decreased risk for snow and wind damage, and more profitable logging operations in later thinnings.

The positive effects of harvesting wood for energy generation are worth promoting among forest owners, local authorities, states and international communities. The globally most important fact is that the utilisation of wood energy does not increase the amount of CO_2 in the atmosphere because the new tree generations fix the carbon released in combustion. Even if combustion by man does not occur, the same amount of carbon will, in the long run, be released as wood decomposes — but without mankind benefiting from its thermal potential.

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2 Harvesting of biomass for energy

Photo Jaakko Miettinen

New techniques for small-tree harvesting

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Abstract

The objective of developing new harvesting technology is the efficient processing of small-diameter trees at all stages of harvesting and transportation. Emphasis is also placed on the quality of the raw material produced, and on the quality of the harvesting work.

Developing a single partial stage independently of the rest of the chain can easily result in the loss of some of the potential benefits offered by development work. As many of the partial stages as possible should be considered simultaneously when new technology is developed.

Harvesting is the most important cost factor in the conversion chain of wood from thinning. Consequently this area of development requires special effort. The foremost demand imposed on the new, developing harvesting technology is that its productivity in relation to its costs should be clearly greater than that of the current solutions. This can be achieved through the development of new technical solutions and efficient working methods, and through their appropriate application.

Keywords: thinning, small trees, harvesting technology, multi-tree harvesting

1 Introduction

Were all the forest industry investment projects currently envisaged in Finland to be implemented, the consumption of wood would increase by 6—8 million m³ per year for the next few years. This would bring the consumption of industrial roundwood in Finland to over 60 million m³ per year. The envisaged expansion focuses primarily on pulp production. It is likely that the Finnish forest industry sector will face some difficulties in satisfying its wood requirements even if imports of roundwood were to continue at the current rate of c. 8 million m³ per year. The increase in wood consumption also means that the merchantable wood from thinning stands must be made available to industry. The primary condition for the utilisation of wood from thinning stands is that the use of this wood must be profitable.

Thinning operations have to be carried out not only to satisfy the increasing industry demands but also as a means of ensuring future wood production. Currently, an annual volume of 4—6 million m³ of first-thinning wood is harvested, and another c. 8 million m³ is harvested from later thinnings. Close to 80 % of the first-thinning stands are pine-dominated. Thinning operations are of great importance for the supply of raw material for the pulp industry. First thinnings represent c. 30% of the allowable pine pulpwood harvest. All in all, thinnings amount to c. 50 % of the total allowable pine harvest. The respective figures for birch pulpwood are 25 % and 46 %.

First-thinnings have been carried out at a rate clearly below that required by sound silviculture. The harvesting conditions in thinning operations are disadvantageous, and productivity of work is clearly below that achieved in final cuttings. The costs of harvesting wood from thinnings are 2—3 times those of harvesting wood from final cuttings. Whatever the intended use, the competitiveness of the small-diameter wood from first thinnings is inferior to that of pulpwood obtained in conjunction with finalcuttings.

2 Development

The development of wood procurement techniques in thinning stands presupposes that these techniques are adapted to the management goals and requirements of the conversion stage. The procurement technique must be efficient in order for the economic requirements to be fulfilled. The objective in the development of harvesting technology is the efficient processing of small-diameter trees throughout the various stages of harvesting and transportation.

The aim is to produce a technology based on efficient multi-tree processing in both the harvesting and forest haulage stages. A further aim is to keep the prices of the machines as low as possible in relation to their productivity. Attention must also be paid to the quality of the raw material produced, and to the quality of the harvesting work.

3 Implementation

The principle in implementation is to develop the chain of conversion of wood from thinnings in order to include as many of the partial stages as possible. Developing a single partial stage independently of the rest of the chain can easily result in loss of some of the potential benefits offered by development work. In order to obtain the best possible overall result, the effects on the chain of conversion of wood from thinnings in all of the projects have to be taken into consideration. For example, a manufacturer of forestry machines may co-operate with a wood procurement organisation and an industrial plant in the development of a “tailor-made” first-thinnings wood conversion chain based on innovative wood harvesting technology to serve the needs of the plant.

4 Areas for development

4.1 Harvesting technology applied in thinning operations

Harvesting is the principal cost factor in the conversion chain of wood from thinnings. Consequently, the development of this particular partial area requires special effort. The most significant economic returns can be expected here. The foremost demand imposed on new, developing harvesting technology is that its productivity in relation to its costs should be clearly greater than that of current solutions. This can be achieved through the development of new technical solutions and efficient working methods, and through their appropriate application.

Not only must the new technology be efficient — it must also be ecologically sound. Wood harvesting must be implemented with due consideration of the environment. The development of the new technology must be linked to environment and nature conservation. A precondition for the implementation of new technology is that its impact on the harvesting trace be studied by assessing the harvesting technology's impact on the stand and the soil.

4.1.1 New techniques in shortwood and tree-section methods

The methods based on the processing of industrial wood from thinnings aim at achieving non-delimbed or delimbed material cut to the optimal transportation length. The felling-delimbing-crosscutting-bunching stage accounts for most of the costs. The following means of improving productivity have been identified:

— developing the multi-tree processing features of single-grip harvesters
— expanding a machine's operating range by means of combimachine solutions
— extensive application of multi-tree processing at different work stages

Multi-tree harvester

Multi-tree processing techniques aim to achieve higher efficiency through simultaneous processing of several trees. Multi-tree processing may be applied either to some or all of the work stages. Wood quality parameters, e.g. length and minimum top diameter, must be clearly specified when applying multi-tree processing. Preliminary tests in 1993 have shown that the working technique is operational and enables a remarkable improvement in the profitability of the work. The productivity has been 20—30 % higher in multi-tree harvesting than in the single-tree cutting. The bundle, processed simultaneously, can consist of 2—5 trees, and the number of small-diameter trees can be even higher. Multi-tree processing can be applied to stems of varying diameter. The quality of delimbing has been good, and it can be regulated depending on the end use of wood.

Further developments of the multi-tree harvester are to improve the handling of the trees during the cross-cutting, increase automation, and improve the mounting/dismounting mechanisms of the multi-tree harvesters. The working techniques and methods are still under development. The aim is to improve the suitability of multi-tree processing for integrated harvesting of wood for fiber and energy.

Combi-machine

In the case of the combi-machine, the one and the same machine performs several work stages, e.g. felling-, crosscutting and off-road transportation, and in some cases even intermediate transportation. Delimbing can be an optional function to be used when transportation distances are long, when energy wood is not utilized or when the mill's wood handling equipment is not able to process wood with branches.

The target in the existing project is to develop an equipment combination capable of single-tree and multi-tree handling, as well as load compaction. Combi-machine will be able to use the whole-tree, tree-section and shortwood methods in the harvesting of small wood.

Preliminary results have shown that the working technique functions and enables a considerable increase in the productivity in small wood harvesting. Further development work will consist of testing new types of combi-machines (cutting equipment, load compaction equipment, accumulating grapple), improving the operational properties by developing the control and driving systems, and developing the working techniques and methods applied in energy wood and integrated harvesting.

Off-road transportation

The most significant productivity factor influencing the economics of off-road transportation is load size. On the other hand, increasing the load size results in higher surface pressures and may lead to problems with the harvesting trace (rutting and damage to tree roots). There is a need to develop an off-road transportation vehicle capable of payload gross weight ratios and especially payload surface pressure ratios which are clearly superior to current ratios. Compacting devices also require further development as their use as ancillary equipment greatly improves the productivity of hauling non-delimbed wood.

Possible development targets with regard to off-road transportation are summarised as follows:

- increasing payload share
- reducing surface pressure exerted by machines
- automation of crane movements when loading and unloading
- development of load compacting devices for non-delimbed material.
- testing of new base machine constructions

Another area of development in off-road transportation is loading and unloading. The automation of crane movements is one means of improving productivity and also of reducing damage to trees.

4.1.2 New techniques in chipping

Methods based on chipping in the forest or at the roadside continue to be developed. Forest-located technology for producing chips for the pulp industry is technically demanding, and there is no commercially viable solution available at present.

The fundamental problems of chipping in the forest include the low productivity and high costs of the harvesting and off-road transportation stages. Chip quality is another challenge associated with forest-based chipping. The requirements set down for pulp chips must be met, and productivity must be clearly higher than at present (in relation to the costs). Viable solutions for the use of chipping waste and the possible environmental problems must also be found.

Procurement methods based on chipping in the forest or at the roadside include the following development challenges:

- felling and processing of non-delimbed wood raw material
- off-road transportation of non-delimbed wood raw material
- chipping in the forest, forest haulage of chips and delivery to the mill
- technology for chipping at the roadside
- transportation of chips to the mill
- chipping at a central processing plant or in the mill yard
- improving chip quality
- logistics involved in procurement based on chipping.

There is also a need to develop logistic support for the functioning of the chain of operations in the chipping process.

4.2 Developing measurement methods for small-tree harvesting

The measurement of wood quantities is of great importance in wood harvesting, transportation and trade. The basic requirement is that measurement must not be an obstacle to the application of new techniques in the conversion chain. The measurement of wood from thinnings must be developed so that it can be performed reliably when using advanced, efficient harvesting and transportation techniques.

To take an example: an obstacle to the widespread application of multi-tree processing is that accurate volume measurement is not possible with the currently available mechanised measurement methods. Another related problem is that volume cannot be used as the sole basis for measurement. Alongside volume measurement, there must be the possibility of applying weight scaling. Especially when measuring small-sized timber, there is considerable room for improvement in the application of weight scaling. From the point of view of conversion of wood from thinnings, knowledge of the dry mass of pulpwood is more important than knowing its volume. The advantage in developing weight scaling is in its accuracy and the low associated costs. The cost of weighing is ca. FIM 2 per m^3 whereas manual measurement in the forest by chainsaw operators costs FIM 6—8 per m^3.

Weight scaling can be integrated in off-road transportation, in truck transportation and at mill reception. The development of crane-mounted weighing instruments is of great interest. Weighing can occur in conjunction with unloading using crane-mounted weighing instruments. The introduction of weight-based measurement methods presupposes not only technical development work but a significant production of basic information necessary for the implementation of measurement and its application in information systems.

Providing volume weight (density) coefficients for small-diameter wood is a primary goal. The application of weight-based measurement systems requires the development of predictive models for varying conditions and different parts of the country.

5 Conclusions

The problems associated with small-tree harvesting from thinnings are the same in the Nordic countries, the rest of Europe, and in North America. A fundamental challenge is to develop a chain of conversion for wood from thinnings, a chain that is efficient, economic and ecologically acceptable. Since the wood obtained from thinnings is small in size, and since the harvesting conditions are similar in different parts of the world, the possibilities for applying uniform harvesting technology are significantly greater in thinnings than in final fellings. The long-term trend in forestry throughout the world is leading to the expansion of various thinning systems. The basis for this development lies in the need to maintain forest biodiversity.

There is an immense global demand for environmentally friendly, economical technology for harvesting small-sized wood. Solutions based on the shortwood system are gaining increasing popularity especially in thinning stands. This is bound to promote exports of Scandinavian wood harvesting technology throughout the world. Forest machine manufacturers, to be able to offer competitive alternatives in this market segment, need to invest in comprehensive development work focusing on the conversion chain of small-sized wood from thinnings.

Finnish applications of chain flail techniques

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Abstract

The first commercial thinning at the age of 25—40 years is a critical link of the Finnish forest management system. Good silviculture presupposes that at least 200 000 ha of young forests be thinned annually, yielding 9,7 million m³ of stemwood and an additional 3,0 million m³ of crown mass. Only a fraction of the target is achieved.

Whole-tree harvesting, multi-tree handling and integrated recovery of fiber and energy are being studied to improve the efficiency of small-tree operations. Chain flail technology is one of the most promising among new technical solutions. The paper reviews recent progress in Finland using this technique. The following applications are described:

- Modification of a mobile American chain flail delimber-debarker-chipper
- A stationary chipping plant based on successive use of chain flails and a small-diameter drum for delimbing and debarking tree sections
- A mobile truck-mounted small-tree processor for chain flail delimbing and debarking of tree sections and crushing the process residue for fuel
- A farm tractor-driven chain flail processor for small scale operations
- Chain flail simulator of VTT Energy for further development of the technology

Keywords: chain flail techniques, small-sized wood, early thinnings

1 The task of early thinnings

The first commercial thinning of a young Scots pine or Norway spruce stand is carried out at the age of between 25 and 40 years. If this treatment is omitted or seriously delayed, the trees start deteriorating and the stems become slim and vulnerable to snow breakage. Consequently, well-timed thinning is crucial for the later development and production of a young stand.

The results of the national forest inventories show that each year at least 200 000 ha of young forests should be commercially thinned for the first time. With an average drain of 45 m³/ha in the south and 35 m³/ha in the north, the annual cutting potential of these first thinnings is 9.7 million m³ of stemwood, bark included. In addition, the removal would include 3.0 million m³ of crown mass with foliage (Hakkila et al. 1995).

From the point of view of the national economy, it is important to use as large a proportion of the biomass as possible for the production of pulp and paper. The remaining part of the removal is classified as a source of renewable energy. However, since the nutrient balance of forest soil must be maintained, a part of the biomass should be left in the forest. Consequently, it is recommended that the trees are topped at the 5 cm diameter and only stem portions thicker than 5 cm are recovered, branches included. The optimal use of biomass removal from the first thinnings is then as follows:

	Removal from early thinnings	
	Mill. m^3/a	%
Suitable for fiber	7.7	61
Suitable for energy only	3.1	24
To be left in the forest	1.9	15
Total biomass	12.7	100

2 The problem of early thinnings

Although timely realization of early thinnings is of utmost importance for the future development of a stand, only a fraction of the necessary thinnings is carried out. This is a result of a number of technical and economic problems:

- The cost of harvesting is high due to the small size of the trees and low yield of timber per hectare. Since the introduction of one-grip harvesters the cost of harvesting has decreased in all types of stands, but for small-sized trees the reduction has not been sufficient. In 1994 the average cost of harvesting from stump to road side was as follows:

	Cost of harvesting	
	FIM/m^3	\$ US/m^3
First thinnings, motor-manual cutting	100—150	22—33
First thinnings, mechanized cutting	75—90	17—20
Later thinnings, mechanized cutting	50—65	11—14
Regeneration cuttings, mechanized cutting	29—35	6— 8

- The loss of wood is high in various phases of harvesting and processing, particularly in debarking drums where thin logs tend to break when mixed with thicker raw material from later thinnings and regeneration cuttings. This increases further the cost of small-sized wood.
- Juvenile wood from early thinnings has different technical properties to those of mature wood. Uncontrolled variation of the proportion of juvenile wood in the raw material flow results in an uneven quality of pulp.

Solving the problems of early thinnings is presently one of the priority topics in the forest technology research in Finland. The Bioenergy Research Program is funding a large number of research and machine development projects such as multi-tree handling with one-grip harvesters, off-road and on-road transport of small-tree rawmaterial, separation and segregation of the energy component from the fiber component, assessment of the variation of the technical properties of the raw material when used for fiber or fuel, etc.

Separation and segregation of the energy component from the fiber component can be done with ring debarkers, drum debarkers or chain flail delimber-debarkers prior to the reduction of the biomass to chips, or by upgrading the chips after the size reduction. All these alternatives have been tested and demonstrated on a practical scale during the last two years in Finland (Hakkila et al. 1995).

The chain flail principle was studied by several machine manufacturers in the USA, Canada, New Zealand, Sweden and Finland in the 1970s, but the results were then not satisfactory. The breakthrough took place in the late 1980s in the USA and Canada (Wattson & Twaddle 1990, Watson 1992). Although the technique was designed for American conditions, interest was soon aroused in Finland as well, primarily to process small-sized trees from early thinnings in conjunction with the integrated harvesting of fiber and fuel.

The American chain flail technique was introduced to Finland and modified for local conditions in 1991. Since then, several new technical solutions have been developed. This paper summarizes the most important experiments and results of chain flail technique in Finland during the first half of the 1990s.

3 Mobile delimber-debarker-chipper

Pertti Szepaniak Oy, a forest machine enterprise, imported a Peterson Pacific DDC 5000 delimber-debarker-chipper from USA to Finland in fall 1991. Since the machine was originally designed to process long trees in conjunction with whole-tree skidding, it had to be adjusted to the Finnish log-length or cut-to-length system, i.e. to the processing of 4—7 m tree sections from early thinnings.

Pertti Szepaniak Oy carried out an extensive research, development, demonstration and commercialization project in cooperation with Enso Oy as the user of the raw-material, Metsäteho Oy and the Finnish Forest Research Institute (Hakkila & Kalaja 1993, Kuitto & Rieppo 1993, Rieppo et al. 1996b). Among the major technical changes were an additional feeding table for tree-sections, a more efficient crane and modifying the chip discharge chute to load the truck and its trailer from above instead of from the rear.

The total operating time was 7000 hours during the first three years, resulting in 235 000 m^3 solid of pulpwood chips mainly from small-diameter tree-sections of Scots pine. The average productivity was thus 34 m^3 solid of chips per operating hour.

The capacity of the DDC processor is actually unnecessarily high in view of the small size of the private forest holdings in Finland. Furthermore, in the private forests, the landing areas tend to be too small and crowded for simultaneous operation of the DDC processor, truck with trailer and front loader for residue removal. The DDC processor is therefore often stationed at a timber terminal or mill yard, depending on the transport distance and the size of the timber sale, instead of at a roadside landing. Fig. 1 shows that at typical transport distances the volumes of pulpwood chips produced at a roadside landing have to be rather large to make the option profitable, otherwise it pays to centralize the DDC processing.

Fig. 1 is a product of Metsäteho's decision support system for the DDC processing of small trees. The computer model can be used to compare the profitability of the technique under various conditions. Another example is Fig. 2, which shows the effect of the price of fuel chips on the cost of pulpwood chips in four different cases.

The efficiency of a logging system is not determined by the productivity of labour and cost of production alone. Efficiency is a broader concept, so that the result depends also on the recovery of fiber and fuel and the quality of the products. Since wood has a high stumpage price in Finland, and since the quality requirements of pulp and paper products are especially strict, these aspects have been given great emphasis in the Bioenergy Research Program. The primary tree species studied is pine, which is generally easier to process than spruce or birch.

In DDC processing of undelimbed tree-sections, the primary product is pulpwood chips and the by-product is process residue, which is subsequently reduced to fuel chips in a separate operation with a crusher. Table 1 shows the biomass distribution of tree-sections of pine into fiber and fuel components after DDC processing. In a typical case, 77 % of pine biomass is recovered as pulpwood chips and the remaining 23 % as process residue from below the feeding table, chain flails and dirt separator of the chipper disc. The loss of potential pulpwood is 3.3 %, and content of bark in the fiber component 2.2 %.

Regarding the loss of potential pulpwood, the result is fully satisfactory. On the other hand, the content of bark in pulpwood chips remains high. The maximum allowable amount of bark is 1 % of the dry mass in the raw material of sulfate pulp, but this limit is achieved only in favorable conditions. Typically the content of bark in pine chips produced by the DDC processor is 1—2 % in the summer time and up to 3—4 in the winter time in a temperature of -20°C. For tree-sections of spruce and birch the percentages are even higher.

The Finnish experiences of DDC processing of tree-sections from early thinnings have many positive aspects. Nonetheless, the content of bark in the pulpwood chips should still be reduced, and the recovery of process residue for fuel from roadside landings should be improved. These aspects affect the goal setting in the ongoing development of chain flail techniques in Finland.

Recent tests by the Enocell Company demonstrate that a debarking drum can also be employed for small-sized pulpwood without causing excessive wood loss, if thin logs are processed separately from conventional thicker logs. However, an acceptable result is achieved only with the most modern drums, and even then the treatment of undelimbed tree sections is problematic and reduces the capacity. On the other hand, the chain flail technique is readily applicable to tree-sections, but the content of bark in the pulpwood chips remains high, especially in the winter time.

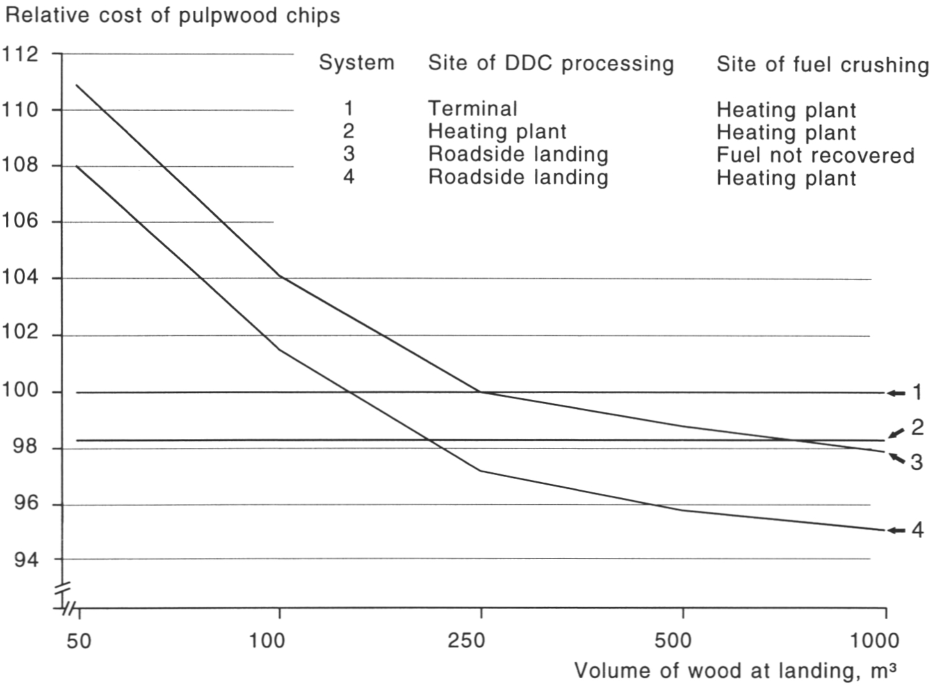

Figure 1. Relative cost of pulpwood chips processed from tree sections of pine from early thinnings, as a function of timber volume at a road side landing. Manual cutting and average off-road and on-road distances (Rieppo et al. 1996a). Four alternative procurement schedules.

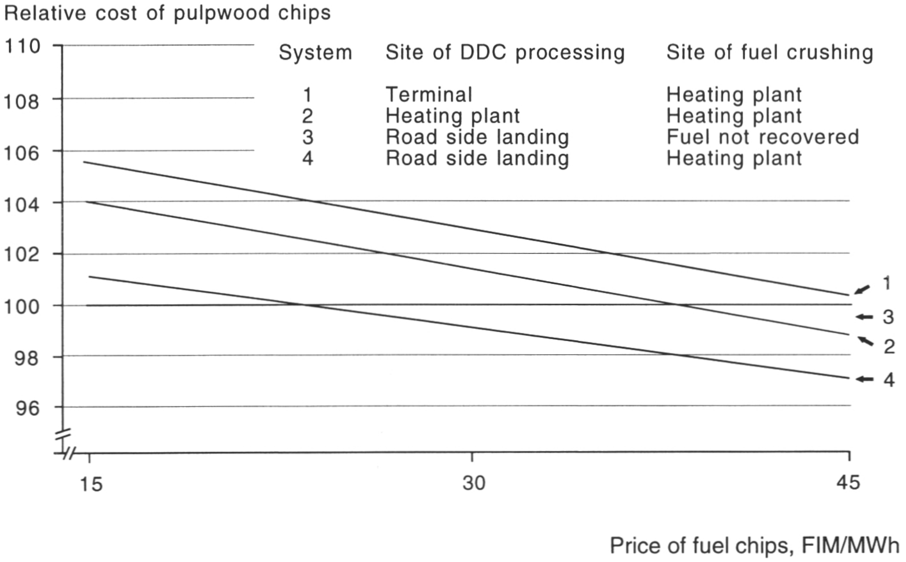

Figure 2. The effect of the price paid for fuel chips on the cost of pulpwood chips at the plant (Rieppo et al. 1996a).

Table 1. Distribution of biomass from tree-sections of pine into fiber and fuel components after DDC processing.

Component	Proportion of biomass	Content of stemwood %	Proportion of stemwood
Residue from feeding table	3.2	0.0	0.0
Residue from chain flail	15.9	3.2	0.5
Residue from chipper separator	3.6	79.9	2.8
Fuel component, total	22.7	14.5	3.3
Pulpwood chips	77.3	97.8	96.7
Total biomass	100.0	100.0	100.0

4 Stationary chain flail/drum debarking plant

Pertti Szepaniak Oy has designed and built a stationary delimbing-debarking-chipping plant which combines the advantages of both the techniques in a unique way. Processing begins with chain flail treatment to remove all branches and a part of the bark. The remaining bark mantle is partly broken and can therefore be removed in the subsequent phase by a relatively short 10 metre long rotating dry drum. A small drum diameter (210 cm, bark openings 40—43 mm) is designed to force the logs through in parallel, thus reducing log breakages.

Table 2 shows how the delimbing and debarking of pine proceed in the combined process. The recovery of fuel is more than doubled when pulpwood is harvested with branches.

Wood loss is affected by the diameter and freshness of logs, temperature and the roughness of the treatment. In the combined process, both treatments are more gentle than in sole flailing or sole drumming. This reduces the loss of wood and wear of chains. Wood loss occurs mainly in the flailing phase. Table 3 represents an early test of the first prototype plant.

After these preliminary trials of the first prototype plant in cooperation with Enso Oy, Metsäteho Oy and the Finnish Forest Research Institute, in 1996 Pertti Szepaniak Oy built a full-scale processing station at Enso's Kaukopää Mills in Imatra. The station is composed of a two-drum chain flail, a 10 m long dry drum, a disc chipper and a screen for the removal of over-sized particles and under 7 mm fines. The station is already in daily operation. Studies on the productivity, raw material flow, debarking result and particle size distribution of the chips continue. Enso's unpublished test results suggest that with correct adjustments the bark content target of 1 % can be achieved with pine and birch.

Table 2. Process residue from tree sections of Scots pine in Pertti Szepaniak Oy's stationary chain flail drum debarking plant (Hakkila et al. 1995).

	Flail residue		Drum residue	Fuel residue
	Branches	Bark+wood	Bark+wood	Total
	Percent of infeed			
Conventional pulpwood	0.0	7.6	3.0	10.6
Undelimbed tree sections	11.3	10.4	2.9	24.6

Table 3. Wood loss from tree sections of pine in Pertti Szepaniak Oy's stationary chain flail/drum debarking plant (Hakkila et al. 1995).

	Flailing	Drumming	Total	Bark content of pulpwood chips
	Wood loss, %			
Conventional pulpwood	1.3	0.2	1.5	0.9
Undelimbed tree sections	3.2	0.3	3.5	0.4

5 Mobile delimber-debarker-residue crusher

The American DDC processor is designed to produce clean pulpwood chips, while the utilization of process residue is of little importance. Indeed, process residue is often a nuisance and is given no value. Experience also shows, that the recovery of DDC residue from stony roadside landings is difficult and costly. Only when processing takes place in a terminal or mill yard, preferably on paved ground, can the residue be readily recovered for energy.

Hooli Oy, a northern Finnish forest machine and truck enterprise, has developed a new truck-mounted DDC processor, which after delimbing and debarking crushes and recovers residue instead of chipping the clean pulpwood logs. Tree sections are fed with the truck's crane into the chain flail from one side of the truck, and clean pulpwood logs are discharged on the other side of the truck. The crane has to be used to pile the pulpwood. The flail residue is conveyed into a hammer mill-type crusher, and the crushed fuel is blown into a truck or trailer for direct transport to a heating plant.

In the normal DDC system, pulpwood is chipped and blown into a truck, and the process residue is left at the work site. In Hooli's system, however, pulpwood logs are left at the landing site, and process residue is crushed and loaded into a truck. Pulpwood can be chipped later at the landing site with a truck-mounted disk chipper, or transported to the mill in log form. The advantage is that the fuel component can be recovered cleanly and almost completely, and transported quickly to its destination. The system is feasible only if the demand and price of forest fuels are high enough to cover the costs of fuel production.

The equipment was developed in 1993—1995 by Hooli Oy in cooperation with Finntech Ltd Oy, Enso Oy, VTT Energy and the Finnish Forest Research Institute. The first field tests were carried out in late 1995 and early 1996. In both cases, the temperature was below zero, ranging from -2°C to -22°C.

The productivity ranged between 12—20 m^3 of solid clean pine pulpwood logs and 6—8 loose m^3 of crushed fuel chips per operating hour, depending on the properties of tree sections and conditions at the landing. In these preliminary tests, the proportion of bark in the pulpwood logs was about 2 % and the loss of stemwood 2—4 % (Hooli et al. 1996).

The Hooli method is an attractive solution especially for northern Finland, where the trucking distances are long and the segregation of fiber from fuel should therefore be done at the road side landing before trucking of pulpwood to the forest industry and fuel chips to heating plants. The results of the tests encourage the further development of the equipment and system. The development program may include (Hooli et al. 1996):

— An additional flail drum to improve the debarking result,
— The addition of a bark brush to reduce the bark content after flailing,
— Improvement of the work organization and landing arrangements to increase the productivity,
— Refining the logistics of the system from stump to mill to reduce the overall cost of operation.

6 Farm tractor-mounted delimber

Eskon Paja Company at Kinnula has developed a light farm tractor-mounted flail delimber for small-sized trees. The 400 kg device is mounted on the three-point linkage of a tractor and driven either solely mechanically, or partly mechanically (flail) and partly hydraulically (feeding rolls). Auxiliary equipment includes a chainsaw slasher, a length measuring device and a hydraulic winch. About 20 delimbers have been sold so far. The Work Efficiency Institute has carried out preliminary studies of the delimber.

One or several small trees of less than 15 cm in diameter are fed manually, by tractor winch or by tractor crane into the delimber from the left-hand side of the tractor. Two infeed rolls force the trees to pass two horizontal rotating axles, both of which are equipped with four steel chains. The delimbing results from the impacts of the rotating chains. The delimbed stems fall onto the ground on the right-hand side of the tractor. Process residue accumulates below the delimber. If the stems are very branchy, accumulating residue tends to cause problems.

The delimber is designed for small-scale operations and small-sized trees. Parts of branches may remain, especially in the case of birch, but the delimbing result is sufficient for the production of conventional firewood and high-quality fuel chips. The chains partly break the surface of the bark and thus facilitate the drying of the treated fuelwood stems.

7 Chain flail simulator

In the flail process, the delimbing and debarking result is affected by many factors: the properties of the raw material (diameter and length of logs, branchiness, bark thickness, freshness), temperature, the type of chains (thickness, length, positioning), the rotation speed of the flail drum, the feeding arrangement and impact angle of the chains, the number of logs treated simultaneously, etc. The effects of each factor are only approximately understood, and there is a paucity of scientific literature on the delimbing-debarking process.

Since the bark content continues to remain above the target limit of 1 %, a wider acceptance of the chain flail technique presupposes further improvements in this respect. In order to study the chain flail process scientifically, so as to improve the result and meet the strict requirements of industry, VTT Energy built a full-scale chain flail simulator. It is composed of exchangeable modules, such as an in-feed device, flail delimber-debarker and brush for refinement of the debarking result. The equipment is covered by shock-proof glass which makes it possible to observe the process and to record it with a high-speed video camera (Aho 1996).

The simulator is expected to produce new and better knowledge on factors such as the effects of the length, positioning, impact angle and rotation speed of the chains on the bark content of chips, wood loss, the productivity of the work and chain wear. This understanding will help to further develop the technic.

8 Summary

The modern chain flail technique was introduced into Finland in 1991 from the USA. The role of the IEA Bioenergy Research Cooperation speeded up the information exchange and technology transfer. Regarding the raw material source, and timber procurement and utilization technology, conditions in Finland differ greatly from those in America. Consequently, it was necessary to adjust the technology to meet the local requirements.

The present paper reviews the research, development, demonstration and commercialization work carried out during the last five years in Finland concerning the chain flail technique. New innovations have been introduced and studied with promising results. Although the chain flail technique is not used widely yet, its potential in the integrated utilization of small-sized trees from early thinnings is recognized by researchers, machine entrepreneurs, forest industries and the state-supported national Bioenergy Research Program. There is a full reason to believe that this concept will play a more important role in the Finnish small-tree utilization in the future.

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Chain-flail simulator

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Abstract

Planning the chain-flail simulator was started in 1994, and its construction was completed by the end of 1995. Test runs were started in November 1995. In the initial phase the test runs concentrated on testing larger entities. More precise test runs will be carried out in 1996.

The goals are to develop the chain-flail delimbing-debarking method so that it is possible to reduce the bark content of wood to below 1.0 %, to reduce the amount of sticks and impurities going into the chipper, and to utilize the bark and branch residue for energy. The objective in 1995 was to carry out preliminary fundamental and applied research on the operability of different chain and brush combinations.

The laboratory simulator is composed of modules. The equipment includes a feeder, chain-flail delimber, chain-flail debarker, brush unit, and a collection pocket. Initially, only the feeder, the chain-flail delimber and the pocket were constructed. Collection trays are located under the delimber-debarker for residues. In addition, there is a control center, equipped with sensors for collecting the data.

Keywords: chain flail, simulator, debarking, delimbing, bark content, wood loss

1 Background

In Finland, pulpwood is mainly harvested using the cut-to-length method. Pulpwood is also harvested using integrated methods which produce both pulpwood and firewood. This approach has been developed intensively during recent years.

One of the integrated options is the chain-flail delimbing method. The stems are cut, delimbed and debarked at the roadside or at the terminal by flaying with steel chains. The delimbed puplwood, passed through the process, can be chipped directly onto the truck. The process residue such as branches, needles and bark, can be used as fuel. The method is in wide commercial use in the USA. There are some chain-flail debarking units in use in Finland as well.

The percentage of bark in the wood after processing of pine wood with a chain-flail delimbing-debarking unit varies between 0.5 and 2.5 % in summer. The percentage of fines and over-sized in the chips is 5—8 %. In winter the corresponding values are higher.

The maximum allowable bark content of chips is 1.0 %. As the bark content increases, the price of the chips decreases.

The chain-flail delimbers used in the USA are not directly applicable to Finnish conditions. It is therefore important to study and develop the method for applications in the Finnish forest sector. The research and development work is intended to serve both new equipment as well as that already in use.

Planning the test equipment began in 1994. Construction work was completed by the end of 1995. Testing and operability measurements of the equipment were carried out in 1995, and the actual testing started in November 1995. Initially, the test runs concentrated on testing larger entities. More precise test runs will be carried out in 1996.

The project aims to develop the chain-flail delimbing-debarking method so as to maintian the residual bark content of wood below 1.0 %, to reduce the portion of the sticks and impurities going into the chipper, and to utilise the residual stick and branch material directly for energy production.

2 The implementation

A laboratory simulator, consisting of different kinds of modules was developed in 1994. The equipment consists of a feeder, chain-flail delimber, chain-flail debarker and brush debarker units, and of a collection pocket. The feeder and the chain-flail units, as well as the pocket were constructed at the beginning of the project. It is possible to replace the chains with a brush-roll to study the operability of both the chains and the brushes when debarking single trees.

The side panels of the unit consist of thick inspection glass for viewing the behaviour of the chains and brushes as they strike the wood. The striking action of the chains is recorded using a high-speed video-camera, the images from which are used for analysing the debarking process in detail. The test runs concentrate on testing the equipment, and improving the testing and measurement practices. Actual test runs started in November 1995. Debarking tests with small-sized pine wood have been carried out using chains of varying length, diameter and siting, and different brush constructions.

The effects of the chain and brush lengths, and their positions, striking angles and speeds on the bark removal will be studied with the simulator. The individual effects of different constructions on both the unaffected wood and variously pretreated stems will be studied. The detachment of the bark in different stages will also be studied.

Information on the shapes of the chains and brushes, and the feeding and rotation speeds leading to the best results, will be obtained from the laboratory tests.

3 The equipment

3.1 Designing the equipment

Designing was started in 1994, when the feeder and the chain-flail delimber units and the collection pocket were constructed (Fig. 1). The chain-flail delimbing unit can be replaced by a brush-roll. It is thus possible to study the operability of both the chains and brushes in debarking of individual trees.

3.2 The properties of the equipment

The delimber-debarker (Fig. 2) consists of three operational modules; a feeding table, a delimber-debarker and a collection pocket. Under the delimber-debarker there are collection trays for process residues. In additon to these devices the equipment consists of a control center, from which the equipment will be controlled. The control center uses computers to collect the measuring data. The dimensions of the equipment are: length 23.4 m, height 5.2 m and width 3.3 m. The width of the control center is 3.0 m. The width of the feeder conveyor is 1.2 m, and the height of the inlet opening 0.7 m. The total weight of the equipment is about 30 tons.

The delimbing-debarking unit consists of two delimbing drums. They are adjustable up and down with hydraulic cylinders. The rotation speed is 0—1400 rpm. The striking angle is adjustable from normal 90 ° angle towards the stem to ± 45 °. The maximum timber feeding speed is 40 m/min.

A data collection system make it possible to measure the tree feeding speed (the rotation speed of the chain of the feeding rolls and feeding table), rotation speed and the elevation of the chain rolls, as well as the electric power demand of the rolls. Different types of graphs of the measuring results can be produced on screen using different time-axis for the measuring targets.

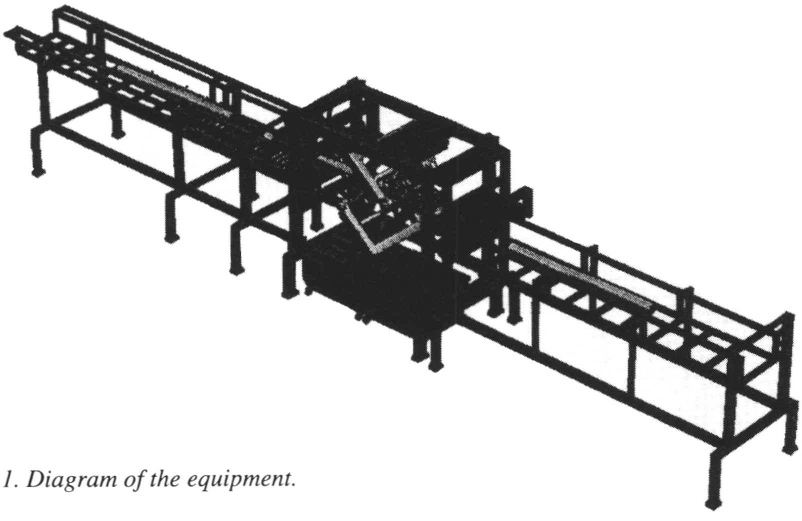

Figure 1. Diagram of the equipment.

Figure 2. The present equipment.

4 Measurements

Delimber-debarker test-runs were made using several different chain types. Over 300 tests were made. A part of the tests consisted of single through-put tests of the stems. During other tests a single tree or several trees were put through the system several times due to scale limitations of the equipment (one delimber-debarker pair).

The best possible delimbing and debarking efficiency and the smallest wood losses from damage of the timber were studied by changing the length and the diameter of the chain, and by changing the position of the chains in the chain-drum.

Different tree species, single trees or bundles of trees, the feeding speed, the rotation speed of the delimber, the types of chains and their positioning, and the settings of the delimber with respect to the timber (the striking distance and the angle with respect to the stem) were used as test parameters.

It is possible to process either single trees or bundles of trees. The bundles can consist of up to 8 small trees from early thinnings. When processing bundles, trees often escape. Speeded up by the chains, through the debarking section, very little debarking of the escaped trees actually takes place. The phenomenon occurs because the feeding rolls of the equipment cannot hold fast all the trees in the bundle. Further development is required in order to avoid escapes.

The timber feeding speed can vary from 0 to 40 m/min. Only the speeds 10, 20, 30 and 40 m/min were used in the tests. The rotation speed of the chain/brush rolls can vary between 0—1400 rpm. The rotation speeds used in the chain tests were 250—600 rpm, and those used in the brush tests 600—1200 rpm.

The first test runs were made using 16 mm standardised delimber chains manufactured by Ofa Oy. The number of links used was 6, 7 or 8, and the link lengths used 28, 33 and 38 cm. eleven mm chains were used in later experiments, and 5 and 3 mm surface hardened spring steel brushes were used in the brush under-chain delimber experiments.

Different chain arrays were used. Delimbing and debarking depths, the lengths and the thicknesses of the chains, and the relationship of the chains to each other in axial, longitudinal and radial directions, were tested.

5 The possible testruns

5.1 Delimbing/debarking of unfrozen timber

Delimbing/debarking tests of unfrozen timber were carried out using 16 mm standardized chains and settings of chain arrangement no. 2 (09.11.95 app.). According to the tests it is possible to obtain a bark content of 1.0 % or less using slow feeding speed (10 m/min) even with rather low rotation speeds (400 rpm). At this speed the chains did not break the timber. As the feeding speed was increased to 30 m/min it was still possible to obtain a bark content less than 1.0 % at higher chain-roll rotation speeds. The target bark content could not be obtained using a feeding speed of 40 m/min (Fig. 3). No debarking tests were made with unfrozen timber using thinner chains. These tests will be carried out in 1996.

Fig. 4 shows the bark content as a function of the chain striking density. Ready linear, polynomial and exponential curves were fitted in the curve obtained using the curve fitting operation of the Excel -spreadsheet calculation program. The exponential curve is, on the basis of theoretical inspections, closest to the experimentally determined curve, because it approaches zero asymptotically as occurred also in the debarking process.

5.2 Bark removal in different parts of a log

The accuracy of the tests and the effectiveness of the equipment with respect to different parts of the trees were studied by making several cascaded test-runs with same driving parameters. The tests were carried out using the same chain arrangement and the test procedure. The maximum deviation in the middle of the log was nearly 2 %, which might be partially due to -23 °C frost during the tests. However, tests runs 323—328 (Fig. 5) show that the larger variation of the bark content occurs at the base and the top ends of the trees. This might be due to the nature of the equipment, required by the research (to achieve visibility to the process required), in which the distance between feeding and receiving rolls is longer than in an actual production machine. This means that only one roll holds the base and top ends of the trees, and the debarking is therefore less controlled.

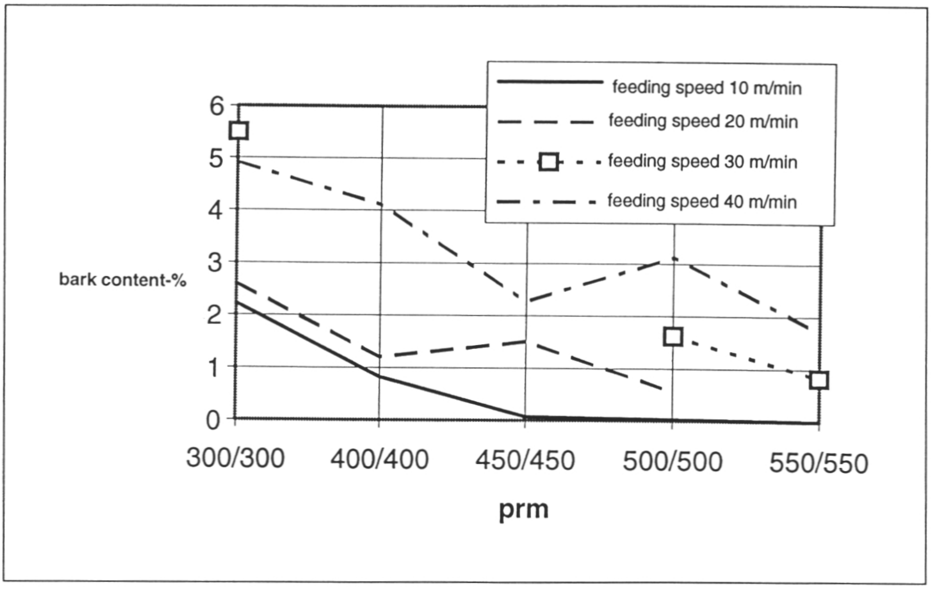

Figure 3. Bark content of unfrozen pine from first thinning as a function of feeding speed and rotation speed of chain drums.

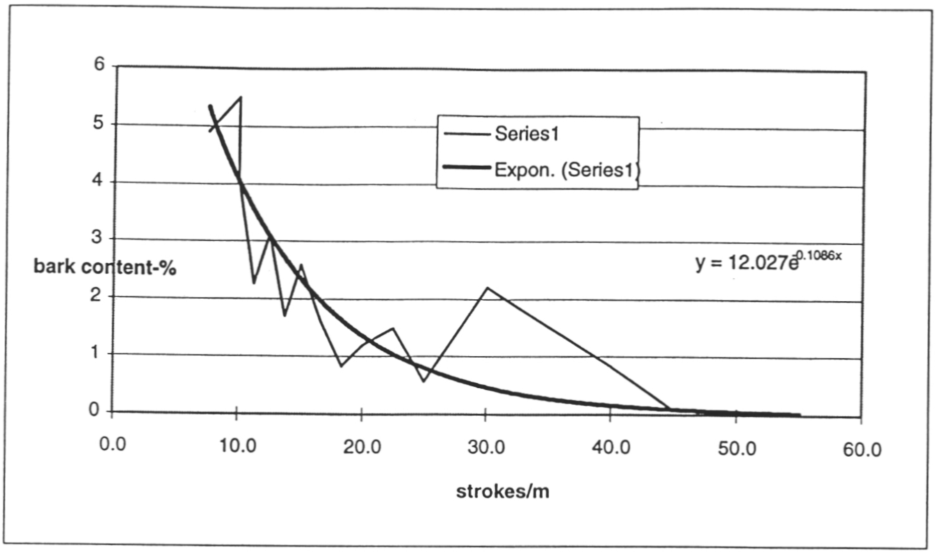

Figure 4. Bark content of unfrozen pine from first thinning as a function of the number of strokes per minute.

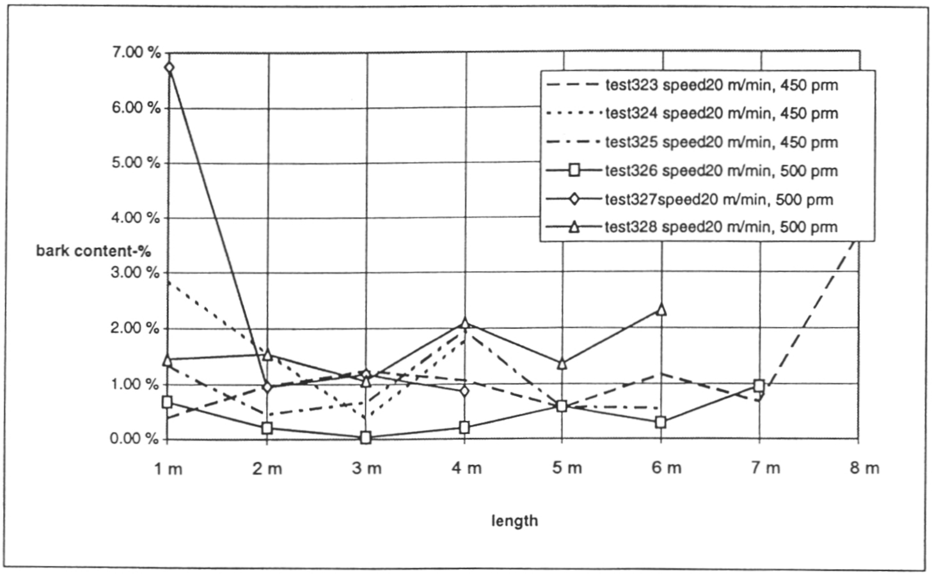

Figure 5. Deviation of the test runs showing the poor controllability of the ends of the trees.

5.3 Damage to the timber

The goal is to obtain less than 1.0 % bark content with as little wood loss as possible. To obtain a low bark content with only one pair of thick chains, it is often necessary to maintain a relatively high rotation speed so that the chains strike the log surface sufficiently densely to remove the bark. Under such conditions the chain may break the timber causing, in addition to actual wood losses, the splintering and breakage of the log.

Different test runs are presented in Fig. 6. In these tests, the feeding speed was constant, but the rotation speed of the chain drum varied from 300 rpm to 500 rpm. The timber was not broken at the lower rotation speed, but the bark content remained high. The bark content decreased at the higher rotation speed, but the timber was broken and splintered.

5.4 Differences between chain and brush test runs

The brushes do not break the wood at high rotation speeds, whereas chains do. On the other hand, plain brushes can not sufficiently loosen the bark from frozen timber. Therefore, the timber has to be pretreated with chains, and brushes can only be used for final purification.

Figure 6. Test runs using different chain rotation speeds: 300 rpm in test 148 (left), and 500 rpm in test 155 (right).

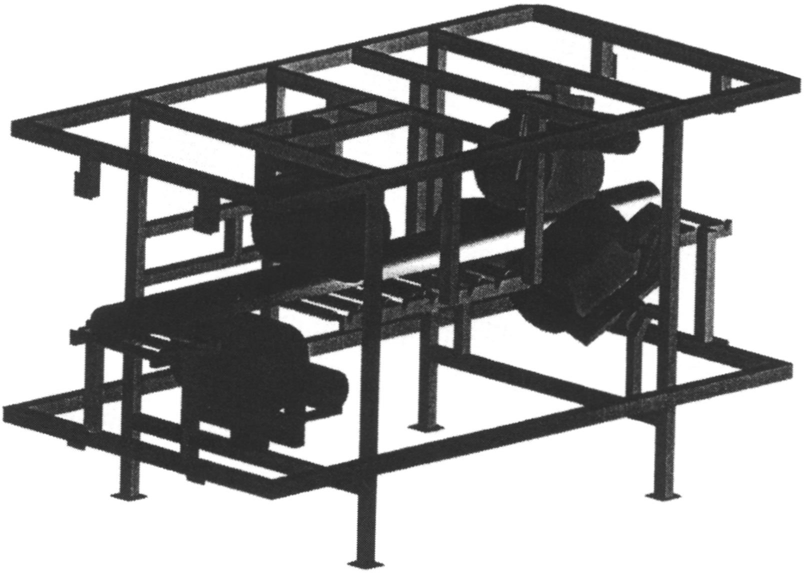

Figure 7. Layout of the vertical and longitudinal debarking equipment.

6 Continuation

A new module will be constructed in 1996 to study the debarking effect of the chain and brush packs (Fig. 7). In these tests, the packs will be mounted vertically and/or longitudinally. The results will be applied to the second generation prototype, which will also be tested. The main target is to study the technical development requirements and the possibilities and equipment solutions for delimbing and debarking. The aim is to obtain as low bark content as possible with low wood losses using the most common tree species growing in the Nordic countries under all possible conditions. Studying the actual method in practice, and the other parts of the delivery chain (felling, transportation, processing) are not included in the testing schedule, even though they closely support this project.

Logging residue as a source of energy in Finland

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Abstract

Logging residue from regeneration cuttings is a major reserve available for the production of renewable energy in Finland. The technically harvestable annual reserve is estimated to consist of 8.6 million m³ biomass needles included, or 5.6 million m³ needles excluded, corresponding 18.1 or 12.3 TWh/a respectively. The present technology is based on the mechanized harvesting of stemwood with single-grip harvesters, off-road transport of residues to road sides with forwarders, chipping at the road side and truck transport of chips. The cost of chips produced from logging residues, 46 FIM/MWh at the plant, is essentially cheaper than the cost of any other kind of forest chips. Nevertheless, the amount used by heating plants in 1995 was only 50 000 m³ solid or less than 1 % of the harvestable reserve, since profitable harvesting presupposes large users. It is obvious that the use of fuel chips from logging residue will grow considerably during the next few years.

Keywords: logging residue, regeneration cuttings, harvesting, drying, cost, energy potential

1 The energy potential of logging residue

The growth of stemwood in Finnish forests is about 80 million m^3 per year. The growth of all above-ground biomass of the growing stock, including branches, is 110 million m^3 per year. The removal of stemwood in 1994 was 62 million m^3, which consisted of 55 million m^3 of commercial timber, 1—2 million m^3 of natural mortality, and 5 million m^3 of waste stemwood, which was left as logging residue.

Finnish forests contain substantial biomass reserves. The most important resources of energy wood are trees removed during the precommercial and early commercial thinnings of young stands, residual stemwood and crown mass from regeneration cuttings and poor quality, small-sized deciduous trees from under-productive stands.

Logging residue in this instance refers to stems and branches — not stump or root wood — that remain in the forest after harvesting timber. The more industry uses indigenous stemwood, the more logging residue is created. With a stemwood drain of 62 million m^3 per year, approximately 24 million m^3 of crown mass and 5 million m^3 of low-quality stemwood including bark are left as residue. The gross energy value of this residue is 55 TWh, which is equivalent to almost 5 million tons of oil (Fig. 1).

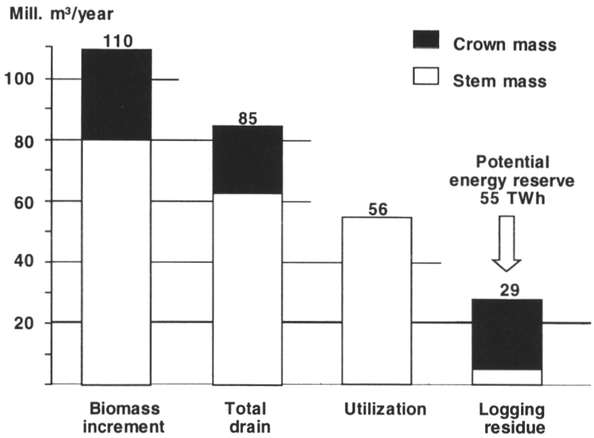

Figure. 1. The growth, drain and utilization of biomass in Finnish forests in 1994. Growth = drain + surplus; and drain = utilization + waste + natural mortality (1—2 million m^3/year).

Opportunities using logging residues for energy are created especially in conjunction with regeneration cuttings. Residues are then most abundantly available both per unit of area and per stand. With reference to stemwood, the crown mass of a managed mature stand contains 21 % extra biomass for pine, 54% for spruce and 16 % for birch (Hakkila 1991). Depending on the previous management, state of health and size of a stand, between 2 — 5 % of the stemwood is also logging residue. On a typical clear-cutting area in southern Finland, the volume of residue, needles included, is about 50 m^3/ha in pine stands and about 120 m^3/ha in spruce stands, that is a gross energy content of 95 MWh/ha and 230 MWh/ha respectively (Fig. 2).

The profitability of residue recovery depends of course on the price ratio of fuels. Nonetheless, even if demand and price for fuel chips should increase substantially, only a part of the potential reserve can be exploited. In calculating the volume of harvestable logging residue on a national basis, the following restrictions have been made:

- Thinning areas are not taken into consideration, which decreases the harvestable reserve by 25%.
- The minimum accumulation in a clear-cut must be 200 m^3 for spruce and 400 m^3 for pine stemwood, which decreases the reserve by a further 20 %.
- Logging residue should not be harvested from clear-cutting areas on land that is low in nutrients or otherwise has a delicate ecological balance. This limitation decreases the reserve by 15%.
- Unnecessarily scrupulous recovery of logging residue results in the impoverishment of the soil, increases the unit costs of harvesting and increases the amount of impurities in the residue. How great a portion of residue can be harvested and is worthwhile depends on the abundance of residue, conditions, the formation of costs and the development of harvesting techniques. According to field experiments, the recovery from fresh residue piles left by a single-grip harvester is 70 %.

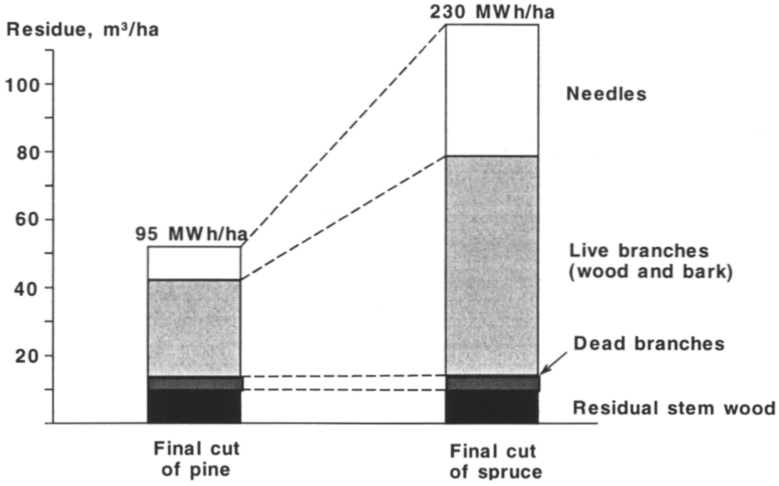

Figure 2. The volume of logging residue in the final cuttings of managed pine and spruce stands, when the drain of stemwood is 200 m^3/ha.

— If the residue is left to dry and drop its needles for nutrient balance or other reasons, the amount of biomass available is 30 % less. Only 65 % of seasoned residue can be recovered.

Despite these deductions, logging residue from final cuttings is the most abundant source of forest energy in Finland. It is also the most attractive from the standpoint of harvesting techniques, harvesting logistics, and harvesting costs. Needles are of great significance from the point of view of the recovery:

	Harvestable residue in clear-cutting areas	
	Mill. m³/a	TWh/a
Green, including needles	8,6	18,1
Seasoned, excluding needles	5,6	12,3

The estimate includes a number of ecological and technical uncertainty factors, because research knowledge and experience continue to be insufficient. Neither do we know to what extent and at what stumpage price forest owners are willing to make logging residue available for energy use. While the removal of residue makes site preparation and regeneration easier, and it also has landscape management and recreation benefits, concerns over edaphic nutrient losses may limit the supply.

A summary of harvestable forest energy reserves in Finland, Fig. 3, demonstrates that the most important component by far is residue from clear-cutting areas even when needles are allowed to fall off before recovery. Logging residue chips make up for 50—60 % of the whole gross energy value of the reserve:

- If the minimum diameter of pulpwood is 5 cm in the first commercial thinning stands, and the residue of the clear-cutting areas is left to season and drop needles before recovery, the total harvestable reserve is 10.4 million m^3, or 21.8 TWh per year.
- If the minimum diameter of pulpwood is 7 cm in the first commercial thinning stands and the residue from the clear-cutting areas is recovered when green, including needles, the harvestable energy reserve is 15.4 million m^3, or 31.6 TWh per year.

The Finnish calculations are conservative. The Swedish University of Agricultural Sciences in its own estimates takes into consideration only reductions that originate from ecological limitations and presumes that ash is returned in full to the forest. Thus a relatively higher estimate is arrived at in Sweden. According to the Swedish estimates the potential reserve of energy wood in the year 2005 will be, including present use, a total of 74—92 TWh, of which logging residue comprises 54—59 TWh /year (Hector et al. 1995).

The Swedish estimate is much bolder than the Finnish one, three times higher in fact. It reflects substantial support given to renewable sources of energy on the part of official energy policies, a belief in the possibilities of forest energy, as well as the ability of energy wood to compete as an alternative with fossil fuels and pulpwood. Nevertheless, logging residue has a central position in both countries.

Logging residue has received less attention than biomass from early thinnings in Finnish development plans and the Bioenergy Research Program. As the capacity of the pulp and paper industry grows, it is worthwhile directing wood from the early thinnings to the forest industry. Attention is therefore turning towards a use for logging residues.

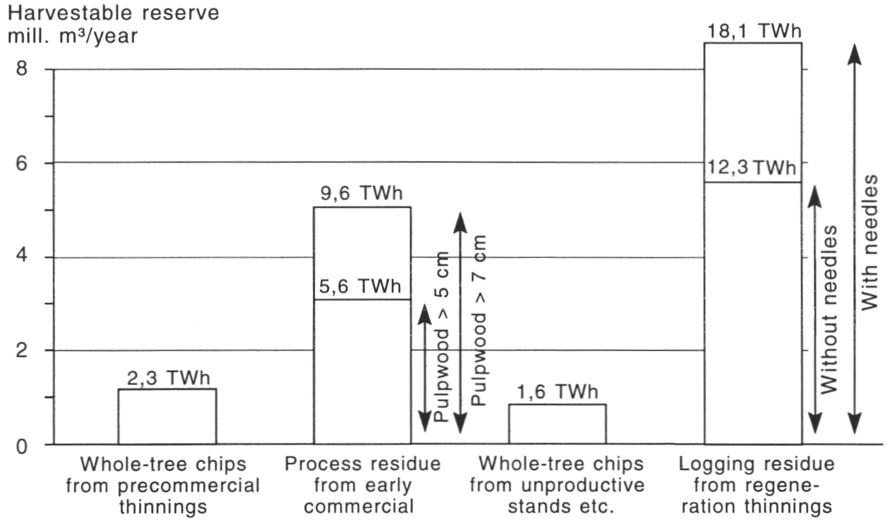

Figure 3. The harvestable forest energy reserve. The minimum diameter requirement for pulpwood in precommercial thinnings is either 5 cm or 7 cm.

2 Planning of residue harvesting

Great demands are placed on the effectiveness of a procurement organization. The question is not so much a matter of the suitability of certain machinery as the efficiency of the whole procurement organization from stump to plant.

In order for the fixed costs of machinery and organization to be kept under control, it is necessary to strive for year-round full employment, even though an achievement specifically in energy wood procurement is very difficult. Underemployment, irregular use, and unforeseen fluctuations always increase costs and eat away at the profitability of logging contractors. In 1994 harvesters were employed for an average 2400 hours and forwarders 1820 hours (Jaakkola 1994), but the employment of the special machinery used to harvest energy wood is more seasonable and remains clearly under this level. The upkeep, investment in machinery and full employment of a procurement organization will only be possible when really large wood-fired cogeneration plants are founded in Finland.

The production of energy wood is not separate from the rest of the forestry, rather it should be fully integrated with the general planning of the forest management and the harvesting of industrial timber. For example, marketable energy wood sites can be produced by postponing the precommercial thinning, or the working techniques of a harvester can be modified to better serve residue recovery on clear cut areas. A forest energy stand register is needed to assist planning. Information on available stands would be gathered in such a register. The register would provide information on the amount of residue remaining in the stand, when the harvesting of timber will take place, transport distances, road network, description of the landing, carrying capacity of the land, etc. Local forest management associations could play a central role in compiling the register.

The mechanization of timber harvesting has created good conditions for the recovery of logging residues, as the collection of the biomass is faster and more effective than if it is not spread throughout the area. The efficiency may further be enhanced when the working technique of the harvester is modified to serve residue recovery.

3 Technology of harvesting

All the mechanized regeneration cuttings in Finland are done with a single-grip harvester. If the residue is to be salvaged for energy, the trees should be delimbed by the side of the harvester instead in front of it. The residue would then accumulate in high heaps beside the strip road for easy recovery instead of being run over by forwarders on the strip road. Whereas in a conventional harvesting operation the harvester leaves only one third of the residue mass in heaps greater than 50 cm high, in modified methods the proportion would be two thirds (Nurmi 1994).

The modified harvesting technique may lower the productivity of stemwood cutting until the operator has adjusted to it. However, this would not be true in every case (Nurmi 1994, Elonen & Korpilahti 1996). If the stemwood harvest would lower efficiency by 3 %, this would increase residue harvesting costs by 2 FIM/m^3 (1

FIM/MWh) in spruce stands and by 4 FIM/m^3 (2 FIM/MWh) in pine stands. In spite of this added expense, the switch to the modified technique would pay off, since the forwarder's productivity would increase, recovery would increase and the amount of impurities in the fuel would decrease.

The off-road transport of the residue is carried out with a standard forwarder. Hence the productivity can be increased simply by increasing the load space and modifying the grapple. With this type of modified forwarder, the productivity ranges between 10—13 m^3/h when the distance to the landing is 250 meters and the single-grip harvester uses a conventional work technique. However, when the harvester has piled the residue along the strip road, the forwarding productivity ranges between 12—17 m^3/h. Simultaneously the degree of recovery also increases (Fig. 4). When the harvest of both round wood and residue is carried out as one entity, the benefits are inevitable as summarised below:

	Normal harvester operation	Modified harvester operation
Forwarder productivity, m^3/h	10—13	12—17
Residue recovery, %	55—60	65—80

Additional machine movements are avoided if logging residue is forwarded with the same tractor as round wood, although forwarding of different assortments is done in different loads. However, if residue recovery is done with separate equipment it is possible to make modifications such as the enlargement of the load space for the forwarder. The use of a different machine would also make it possible to season the residue on the clear cut over a summer period. But, the profitability of each alternative is greatly affected by the current employment of machines and operators (Asikainen 1995).

Forwarding can also be done with a farm tractor with a modified load space and grapple. A farmer may deliver the residue from his own and other forest owners holdings to a road side landing and sell it to a procurement organization or a chipping contractor.

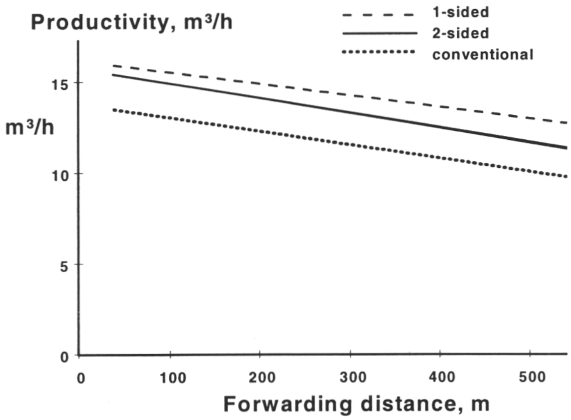

Figure 4. The productivity (m^3/h) of residue forwarding as a function of distance (m).

In Finland the comminution usually takes place at a landing whereas in Sweden chipping is done at the stump. The productivity of large chippers at the landing site is almost as high with residue as with whole trees. A completely new alternative has been a chipper and an exchangeable chip container installed on the same terrain truck chassis. This MOHA chipper truck comminutes residue either on the clear cut or on the landing depending on the carrying capacity of the site. MOHA is equipped with a trailer and is capable of road transportation as well. In this way the wasteful waiting times between the chipper and the truck can be avoided (M. Hämäläinen & P. Pankakari 1995). Other alternatives for residue recovery, such as whole-tree skidding, baling and new comminution technology are also being studied within the Bioenergy Research Programme.

4 Drying and storage

Ensuring the quality of the fuel is an important part of the harvesting schedule. This requires the right timing of the harvest and storage. It is essential to know when, where and for how long to store logging residue.

The seasoning of residue can take place on a clear cut area in heaps created by the single-grip harvester or at the landing in large piles. Better drying is accomplished at the landing, as seen in Table 1. Branches do become defoliated when drying takes place. This means that the amount of recoverable material is significantly diminished. The greatest recovery is accomplished when residue recovery occurs straight after logging. However, in this case half of the forwarded material is water, which leads to higher hauling costs and a lower energy value.

When considering residue harvesting it is essential to establish the priorities. If the goal is to return nutrients into the growth cycle, then seasoning should take place on the clear cut site. On the other hand, if the nutrient status of the site is rich then the residues may be removed needles intact and seasoned at a landing.

Table 1. Moisture content of the residual biomass in different storage environments at different times. Clearcutting in September 1994.

Storage environment	Date of measurement		
	September -94	June -95	September-95
		Moisture content, %	
Clearcut area	56.0	46.7	28.5
Landing site	56.0	..	42.2
		Needle content, %	
Clearcut area	27.7	20.4	6.9
Landing site	27.7	..	18.9

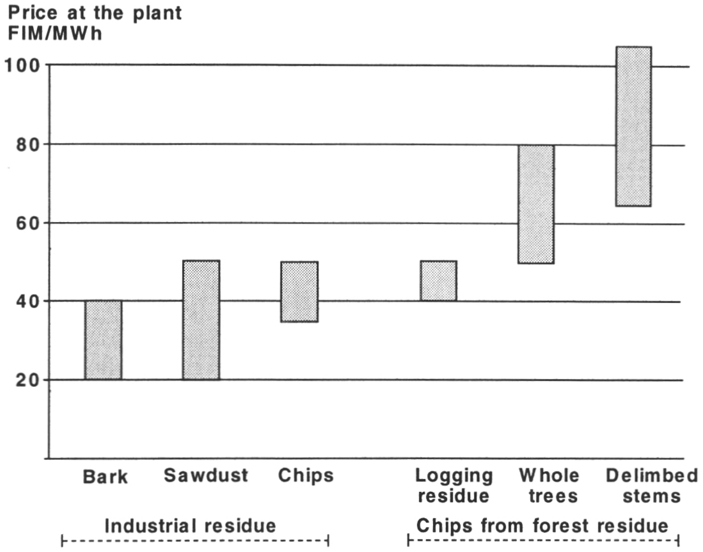

Figure 5. The price of wood fuels (excluding VAT) paid by heating plants in 1995 according to the user questionnaire (Hakkila & Fredriksson 1996).

5 The cost of fuel chips

A recent questionnaire revealed the average fuel wood prices of 50 plants using forestry chips in 1995. The results of the questionnaire are presented in Fig. 5. The differences are very significant. The variation within a certain wood fuel type is also great.

Industrial wood residues are a less expensive fuel than forest chips. The least expensive are bark and sawdust. The cost of chips from small-sized trees is considerably higher, especially chips from delimbed stems. The average costs — weighted by amounts consumed, were as follows:

	Average cost at the plant in 1995, FIM/MWh
Industrial process residue:	
Bark	32
Saw dust	33
Chips	44
Forest chips:	
Chips from logging residue	46
Chips from small-sized whole trees	62
Chips from small-sized delimbed trees	89
Forest chips, average	58

In 1982 the Finnish Forest Research Institute surveyed the use of forest chips as a source of fuel in district heating plants. Since then the cost of forest chips has decreased. This has been partly due to the development of machinery and methods, but also due to developments in the organization and logistics of procurement. Competitive bidding has resulted in the general decrease of forest machinery rates, and this has an effect on the procurement costs of energy wood, even though logging equipment is underemployed. Only the cost of chips from delimbed small-sized stems has slightly increased, since it has not been possible to mechanize the work.

	Year 1982	Year 1995	Change, %
	Cost at the plant, FIM/MWh		
Chips from logging residue	52	46	-12
Chips from small whole trees	75	62	-17
Chips from small delimbed trees	85	89	+ 5

That the relative cost competitiveness of wood fuels is clearly better in Sweden than it is in Finland is a result of differing fuel taxation policies, not because production costs are less expensive. The table based on NUTEK'S quarter-annual price statistics shows that the average price (not including VAT) of forest chips paid by Swedish heating plants in 1995 was 24% higher than the average price of forest chips in Finland (exchange rate in May 1996: SEK=0,70 FIM). Heating plants paid slightly more for wood fuel than industrial plants (Prisblad...1996).

	Sweden 1995	
	Heating plants	Industrial plants
	Price of fuel, FIM/MWh	
Chips from industrial residue	64	55
Chips from forest residue	76	72
Pellets and briquettes	102	..

The largest single item contributing to the cost of small-sized trees is felling, piling and delimbing. Chips from logging residue from clear-cutting areas have very low costs in the felling and piling phase, because when a single-grip harvester is employed, the residue is ready to be recovered just as it is.

The largest single item contributing to the cost of logging residue chips is chipping. The cost of road transport varies greatly from case to case depending on the hauling distance, and as procurement areas expand the cost of truck transport grows proportionally. In Finland, it is hardly possible at present to earn stumpage from energy wood, any advantage the forest owner gains is silvicultural (Table 2).

From the point of view of employment and the local income formation however, it is to be hoped that as large a share as possible of the procurement costs is made up of wages for forest workers, machine operators, and supervision. Unfortunately, the high manual input also means high total costs. Consequently, cost competitiveness is best for those types of chips that are produced with a small manual labor input. The share of labor costs is 70—80 % for chips from delimbed small-sized stems, 45—50 % for whole-tree chips, and 25—30% for logging residue chips.

Table 2. The average cost structure of chips from whole trees and logging residue without stumpage price.

Cost factor	Chips from whole trees	Chips from logging residue
	Cost structure, %	
Cutting	29	2
Off-road transport	19	23
Cost at the road side	48	25
Chipping	22	38
Trucking of chips	19	27
Interest	3	2
Overheads	8	8
Cost at the plant	100	100

6 Present use of fuel chips from logging residue

In 1994, the total consumption of primary energy was 31.6 million toe in Finland. Wood-based fuels accounted for 15 % of the total consumption and 7% of the electricity production. Of industrialized countries, only Sweden reaches the same relative level as a user of wood-based fuels.

The main utilization of wood-based fuels is in the forest industry, which uses a substantial amount of wood rawmaterial for the production of energy. The volume share of energy raw material is 15—25% for the saw-milling industry, 40—50% for the plywood/ veneer industry, 10—15% in the mechanical pulp industry and 50—60 % in the sulfate pulp industry of all rawmaterial, bark included. In all cases, the fuel component is processed from industrial residue, so that the use of wood-based fuels in the forest industry is essentially passive. The forest industry does not actually procure timber specifically for energy purposes because forest chips are considerably more expensive than residue produced at the site.

Great emphasis has been placed on wood-fired heating and cogeneration plants in the prevailing discussion on the use of wood-based fuels. The reason is by no means the present level of utilization, but rather the expectations placed on the plants especially by the rural municipalities.

In the latter half of the 1950s, numerous wood-fired heating plants were built in Finland. However, because the prices of fossil fuels decreased and the use of birch for pulpwood increased, most of these plants gradually converted to oil. When interest in the use of indigenous fuels was kindled again as a result of the first and second world-wide energy crises in the 1970s, only a few plants still burnt wood chips, but the know-how existed. The government began to subsidize investments made by wood-fired plants, and in the years 1979—1982 the number of wood-fired heating plants increased considerably.

By the end of 1982, there were a total of 115 forest chip-fired heating plants producing greater than 0.5 MW. The plants included 60 district heating plants, 17 garrisons, 9 educational institutions, 8 industrial plants, 5 hospitals and 4 dairies. In 1982, these heating plants consumed 393 000m^3 forest chips. In addition, the forest industry burned 84 000 m^3 and farms 120 000 m^3 of forest chips.

After a sharp decline in the early 1990s, in the last few years the consumption of chips as a fuel has again increased. There are now 102 users each burning more than 250 m^3/a. Sixty of these are municipal district heating plants. The location and the size are shown in Fig. 6.

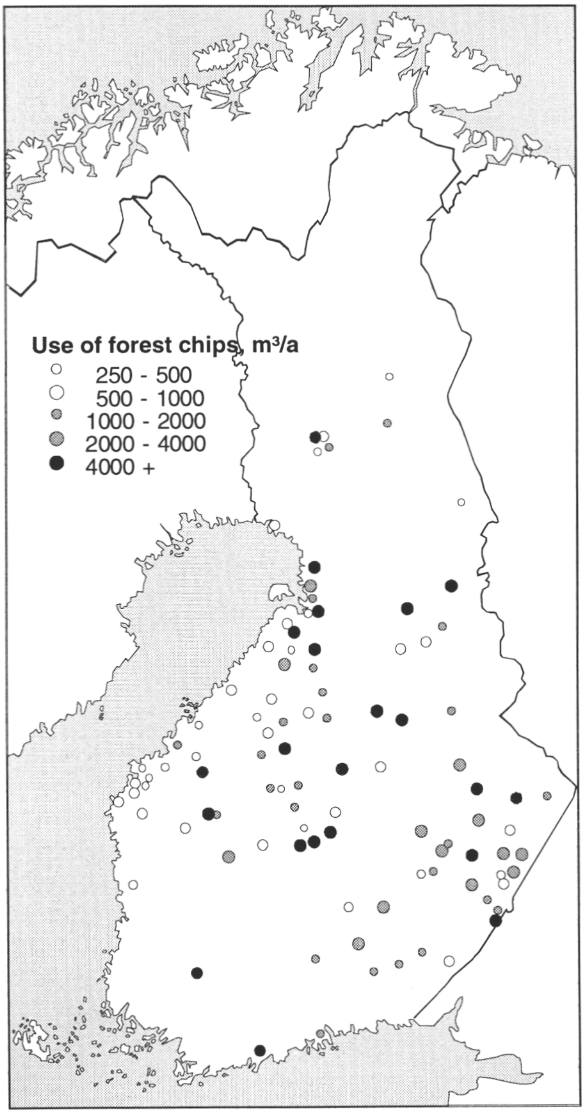

Figure 6. Heating plants using forest chips in 1995. Plants using more than 250 m^3/a (625 m^3-loose/a).

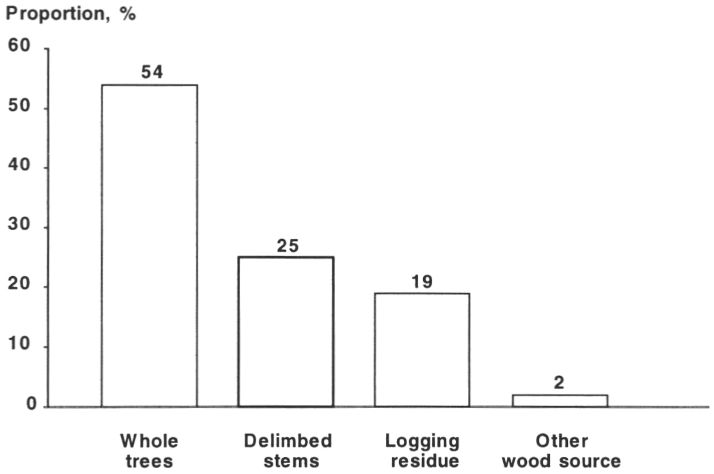

Figure 7. The sources of forest chips in 1995.

In 1995, the total use of forest chips was 258 000 m^3 which equals to 644 000 m^3 loose. Fig. 7 shows that the most important source of fuel wood was whole-tree chips made from small-sized trees. In spite of the high cost, the use of chips made from delimbed stems is still quite common. The reason for this is the outdated conveyer mechanisms at the small plants which require stick-free chips to function properly. On the other hand, forest owners lack experience in the handling and transportation of non-delimbed trees and logging residue.

In comparison, the consumption of logging residue is still modest when considering its availability and low cost. In 1995, the figure was only 50 000 m^3, which amounts to less than 1% of the harvestable reserve. Demand for logging residue is nonetheless increasing as new plants will be inaugurated in 1996.

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Baling of forest residues — a system analysis

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1 Introduction

The compression of logging residues makes it possible to increase handling efficiency along the whole chain from harvest until arrival at the end-user. This increase can be ascribed mainly to increased payloads on the forwarder, truck, and train, possibilities for efficient long-distance transport by train, lower chipping costs through centralised conversion, and finally, simplified logistics, since the compressed unit can be stored at several points along the path from clear-cutting to the heating plant.

A fully functional technique for compressing logging residues should offer interesting possibilities for a system transition, new ways of thinking, and associated opportunities for increasing efficiency in the development of a system for delivering logging residues. In the Autumn of 1994, the Swedish companies Trädenergi Väst AB and Bala Press AB began co-operating in the development of a mobile machine for compressing logging residues. The method of compacting logging residues was originally based on agricultural technology used to compress hay and straw into round bales. Bala Press AB developed the round-bale technology and constructed equipment for compressing various types of products. The company currently manufactures around 20 types of presses, most of which are used for handling waste.

A first prototype for compressing logging residues was tested in Nossebro, Sweden, during Spring 1995, and in September of the same year a second test run was carried out under terrain conditions. In Summer 1996, the baler was used in the UK to establish the feasibility of baling residues from whole tree harvesting operations.

A system analysis has been used to compare costs of operating a baling system with the costs incurred in a conventional chip and chip transport system. It is based on the bales being transported either directly from the forest to the heating plant by truck, or transported by truck from the forest to the railway station and the rest of the way by rail. Fuel chips are transported by truck directly from the forest to the heating plant.

2 System Description

In the analysis which is applicable to Swedish conditions, a baling system and a conventional chip transport system have been compared. For the baling system, costs for both transport by truck+rail and truck-only transport have been calculated. For the chipping system, costs were calculated only for the truck-only transport alternative.

For UK conditions, information from the 1996 trials of baling and transport has been provided and compared with the Swedish results where possible.

2.1 Baling

In Sweden, Trädenergi Väst AB initially plans to bale the logging residues during the summer half of the year, i.e. April through to September. It is assumed that most of the baling will be carried out on the clear-cut area. During felling, the harvester operators will create piles of slash (branches and tops) in order to facilitate subsequent fuel handling procedures, referred to as "fuel-tailored felling". The slash then dries in the piles, and most of the needles fall off and remain on the clear-cutting. This is important since a large proportion of the nutrients in the material is bound in the needles. Desiccation is also important since it increases the amount of energy produced per unit of fuel consumed while reducing the rate of decomposition during storage. Baling can also be carried out year round. In this case, part of the baling during the autumn and winter seasons will take place at roadside stacks or directly after felling on the clear-cut. Baling immediately after felling results in material with a higher moisture content, and nutrient-rich needles are removed from the area.

Given the adoption of the baling system in the UK, it is most likely that the system would only be adopted in whole tree harvesting systems where the residues are available at the forest road or landing. Ground conditions over much of the UK are unsuitable for terrain baling which is advocated for Swedish conditions where winter frost improves ground bearing pressure considerably. The economics of wood fuel harvesting in the UK is such that the uptake of baling systems is only likely where the residues have been accumulated at zero cost to the wood fuel element, as part of a whole tree operation for example.

2.2 Technical Description

The bale press consists of a hollow cylinder with hydraulically driven gables, an infeed opening, and a separate motor (prototype version). The logging residues are compressed into 120 x 120 cm cylindrical bales. The machine weighs 10—11 tonnes and can be mounted on a medium-sized forwarder, or a small lorry. The bale press is fed using an integral crane and grapple mounted on the base unit.

By reading a control unit in the cabin, the operator can determine the chamber pressure in the baler. Once a bale is ready, it is enclosed in netting before the drum is opened, and the bale is lifted out using the forwarder crane and grapple.

The work cycle is divided up as follows:

1. Infeeding of logging residues and continuous compression.
2. Compression, netting, and opening of the chamber. This sequence is started by the operator, whereupon it proceeds automatically. This makes it possible to move between landings, or adjust the shape of the slash pile while the sequence is being carried out.
3. Lifting of the bale to the ground using the forwarder crane.

4. The sequence in which the chamber is closed and put into operation is started by the operator, and proceeds automatically once the bale has been lifted out of the chamber.

2.3 Study of the bale press

In October 1995, the Forestry Research Institute of Sweden carried out a small study on baling. The highest performance levels attained were about 15 bales per G^0 hour. The consensus was that baling performance could be increased to at least 15 bales per G^{15} hour by making planned improvements on the bale press and by allowing the operator to improve his working procedures. In this limited study, the mean weight of the bales was 620 kg at a moisture content of 45%. It was not possible to find any reliable relationship between conversion time and bale weight.

The baling trials in the UK, carried out during the Summer of 1996, were more extensive, and 164 bales were produced over 4 working days of the trial which was carried out over three forest sites in 2 locations. Bale weights, productivity and baling costs for both locations are summarised in Table 1.

2.4 Forwarding of bales

In Sweden, terrain baling necessitates transport of bales over the terrain from the clear-cut to the road. Conventional forwarders with an expanded cargo space are used. Expansion of the cargo space requires a widening of the bunks, extra stakes and possibly an extension of the entire cargo space. It should be possible to transport at least 15 bales on the forwarder, which gives a payload of 9.3 tonnes at a bale weight of 620 kg. Practical trials will show how many bales can be transported and how forwarding costs can be minimised. In the system analysis, the payload has been estimated at 15 bales per load.

Table 1. UK trials — Results summary. G° zero rest allowance, G^{15} 15% rest allowance.

	No of bales in trial	Av. Bale weight (kg)	Moisture content (%) wet	Energy content (MWh)	Productivity at G^0		* Costs based on G^{15}		
					(gt/hr)	(bale/hr)	(£/gt)	(£/bale)	(£/MWh)
Location 1 — Baling at landing									
Lodgepole pine "wet"	70	569	35	1.77	11.40	20.00	6.94	3.95	2.23
Lodgepole pine "dry"	25	391	23	1.56	7.40	18.90	10.69	4.18	2.68
Willow "dry"	20	265	12	1.18	4.82	18.20	16.71	4.43	3.75
Location 1 — Baling at stump									
Lodgepole pine "dry"	15	435	23	1.56	7.3	16.80	10.91	4.75	3.04
Location 2 — Baling at stump									
Sitka spruce "wet"	31	484	28	1.71	8.69	17.95	9.06	4.39	2.57

2.5 Transport

The fact that the bale is a well-defined unit with a relatively high density, makes it possible to use standard equipment and simplify transport handling.

Truck Transport

Truck transport regulations vary considerably between Sweden and the UK. In Sweden, load platform lengths up to 24 metres are permissible with a maximum payload of 35 tonnes. The maximum gross vehicle weight in Sweden is 60 tonnes. In the UK, load platform length is restricted to 13.6 metres with a maximum payload (determined by vehicle tare) of approximately 24 tonnes. The maximum gross vehicle weight in the UK is 38 tonnes.

In Sweden, for the first bale transport trial, a conventional vehicle for general cargo was used. Up to 60 bales, corresponding to a payload of 37.2 tonnes at a bale weight of 620 kg, were loaded on a 24 m long vehicle. In the analysis, transport costs are estimated for a conventional logging residues vehicle with a maximum payload of 35 tonnes. There are several conceivable vehicle configurations that could be used for truck transport. For example, the cargo space can have full-width decks and sideboards. A used trailer that is custom built can be cheap enough to be put out of service during the times of the year when it is not used. The truck's cargo space could be retrofitted so that it can be used the year round. The vehicle is equipped with a conventional logging crane. The payload for this type of vehicle in Sweden should be able to reach as high as 37 tonnes.

In the UK, bales were moved from the 2 trial sites on a conventional 15 metre “flat bed” trailer using an articulated tractor/trailer unit. Loading was carried out by a forwarder on site and off loading at the storage site by mobile crane. The bales were loaded on their sides with the last two bales loaded on their ends. A total of 38 bales were carried on each load. The highest percentage of maximum permitted load was achieved with the wet lodgepole pine bales, with individual bale weights of 569 kg giving a total load of 21,622 kg out of 23,000 permitted (94%). Maximising the load could be obtained with careful loading to achieve 40 bales per load. Payload comparisons for Swedish and UK truck transport are compared in Table 2.

Table 2. Comparison of payload and energy content in connection with truck transport, 45% moisture content.

	Sweden Volume (m³/no bales)	Payload (tonnes)	Energy content (MWh)	UK Volume (m³/no bales)	Payload (tonnes)	Energy content (MWh)
Fuel chips	105 m³	33	84	75 m³	25	64
Logging residues	135 m³	20	51	90 m³	13	34
Logging residues compressed into bales	60 bales	37	95	40 bales	24	62

Rail Transport

Rail transport has only been considered for this paper for Sweden where simple freight cars of an older model can be used for transporting bales via rail. However, either sideboards have to be used to meet railroad safety standards, or the bales can be transported in containers that are placed permanently on the cars. The containers also enable the train to be efficiently unloaded upon arrival at the heating plant. To transport the bales to the heating plant at Gothenburg, a train with 39 cars is run daily from four different stations. The amount of time available for loading varies from 2.5 to 8 hours. Payload comparison between chip and bale transport is given in Table 3.

Table 3. Comparison between fuel chips in a container and non-chipped logging residues compressed into bales with a 45% moisture content in terms of payload and energy content per freight car.

Materials	Volume (m³/no bales)	Payload (tonnes)	Energy content (MWh)
Fuel chips in container	70 m³	22	57
Logging residues compressed into bales	40 bales	25	64

2.6 Reception and chipping of bales

The reception and chipping of bales at the heating plant is treated in a general way in the system analysis. To be able to compare the baling system with the conventional chipping system, costs incurred up until the time of bale chipping are compared with those incurred in connection with delivery of the fuel chips to the chip bin, plus associated costs for investments in operating the chip bin.

The freight cars can be unloaded with a gantry crane and conveyors, with the bales being fed directly into the chipper or stored prior to chipping. If the bales are in the containers on the freight car, the containers themselves can be lifted up and emptied onto a conveyor belt. Costs for unloading, transport, and temporary storage of the chips as well as the chipping costs, are based on preliminary data on investment and operating costs. A Bruks AB chipper has an estimated capacity of 200 MWh of fuel chips per G^{15} hour.

2.7 Conventional chipping system

The costs for a bale system are compared with those of a conventional system. In the latter, logging residues are collected in piles on the clear-cut site, using "fuel-tailored felling", forwarded to the logging road with a slash forwarder (payload 4.5 tonnes), and chipped in stacks along the logging road with a 400 kW mobile chipper immediately before transport. They are then transported on a cargo-exchange vehicle in three containers each with a volume of 35 m³ solid. The combination truck+rail is not considered to be a realistic alternative since the material is to be transported directly from the forest to the heating plant without any terminals in between.

2.8 Bale storage

In Sweden, Raida Jirjis at the Department of Forest Products, Swedish University of Agricultural Sciences, conducted a trial where changes in moisture content and dry-matter losses were studied in stored bales. The bales were stored outdoors in both covered and uncovered stacks, as well as indoors in a barn. Every treatment consisted of 39 — 51 bales, which were produced at the first Swedish trials site at Nossebro. The baling was carried out in December 1994, at which time the moisture content was measured. The following April and October, the moisture content in the bales was measured again, and dry-matter losses were determined

At the time of baling, logging residues used in the trial had a moisture content between 31% and 38%. The material consisted of residues produced in connection with felling during 1994 which were then stored in covered stacks prior to baling. Bales in the study weighed between 400 and 600 kg. They thus weighed less than the bales produced later which had a mean weight of over 600 kg.

Preliminary results indicate that changes in bale moisture content in the various treatments agree well with previous measured values for logging residues in covered and uncovered stacks. A tentative conclusion is that storage of the bales has not reduced the ability to maintain a low moisture content and, to a certain degree, has even contributed to drying the logging residues. Nor did covering the bales appear to hinder drying. If the residues are sufficiently dry at the time of baling, an increase in bale weight should not influence the pattern of change in moisture content. On the other hand, the moisture content dynamics occurring during the storage of bales with a very high moisture content are still uncertain. Even dry-matter losses for bales are of the same order of magnitude as those determined previously for covered and uncovered stacks. Raida Jiris reported that the material was very dry and dusty at the time of the last inspection in October 1995. Visible fungal growth was minimal in most of the bales.

In the UK, a similar trial of bale storage is ongoing, having started after baling in late summer 1996 and scheduled to continue to Summer 1997. Some 135 bales have been stored in 3 stacks 3 bales high in a former quarry site in North East Scotland. Each bale will be weighed at intervals of 3 months throughout the trial with destructive sampling to determine moisture content changes. No results are yet available.

Given the tentative results of the Swedish storage trials it would appear that bales are less sensitive to storage than chips and can be stored temporarily at several places along the chain from the clear-cut to industrial plant. Bales can be stored on the clear-cut, along roadsides, at roads or terminals free from spring thaw, and at the railway station or with the end-user.

3 System Comparisons

In Table 4, the costs of supplying the heating plant in Gothenburg with baled logging residues up to and including chipping is compared with delivery of fuel chips.

In Fig. 1, the break points between three systems for supplying forest fuels are given for various transport distances. Note that transport costs are only calculated for truck transport. In addition to calculating the costs for the chipping system and the baling system, the costs for a conventional system based on unchipped and uncompressed logging residues have also been calculated.

Costs for chipping the bales were set at £1.00/MWh. This cost is based on the use of large-scale chipping technique with high utilisation. Smaller studies of the larger mobile chipper now being built (Bruks 1004CT) show that it has the capacity to chip both bales and logging residues. Performance and cost relations between the chipping of bales and the chipping of logging residues have yet to be studied; thus the comparison presented below should be considered to be a preliminary estimate. Other costs are taken from the earlier table.

Table 4. Costs for supplying a heating plant with raw materials that have to be transported a mean distance of 160 km. Comparison between a baling system and a conventional chipping system. The baling system can reduce costs by approximately 10 — 25% when the transport distance is this long. Storage costs not included.

	Baling		Chipping in stacks
	(£/MWh) Truck 25 km + train 160 km	(£/MWh) Truck 160 km	(£/MWh) Truck 160 km
Purchase Costs	2	2	2
Baling	2.5 — 3-5	2.5 — 3.5	-
Forwarding 300 m	1	1	2.4
Truck Transport	1.3	4.5	5
Loading at railway station	0.2	-	-
Rail transport, simple freight car set up	2	-	-
Unloading and internal transport at Heating plant	0.4	0.3	0.2
Chipping	1	1	3.8
Total	10.4 — 11.4	11.3 — 12.3	13.4

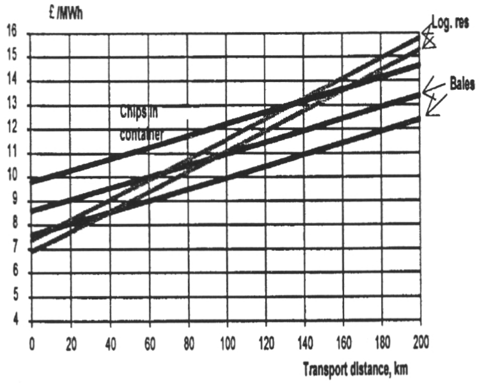

Figure 1. Break points between three systems for supplying forest fuels. Transport costs only calculated for truck transport. Storage costs not included.

4 Discussion

In both the Swedish and UK trials, there were few technical problems associated with the baling of forest residues. In both trials the costs of baling were similar and confined to a range of costs between £2.23 to £3.75/MWh. Bale density allowed maximum transport payloads to be achieved in both Swedish and UK trials.
The system analysis on the Swedish system is based on short studies on the first prototype of the baler (but the outputs and costs are close to the extended trials in the UK), and calculated values for various sub-operations in a baling system. The analysis shows that a supply system where logging residues are compacted on the clear-cut and then chipped at the end-user's factory or at the terminal holds great promise.

Baling and the associated supply system should be studied further in order to obtain more detailed information on performance levels and technical solutions for various sub-operations as well as to optimise the overall logistics of the system.

The analysis is based on baling in Sweden during the summer half of the year, from April to September. During this period, baling should be carried out mainly on the clear-cut, utilising dried logging residues that have dropped their needles. However, summertime baling will almost certainly, to some extent, also be carried out at roadside stacks when the carrying capacity is reduced on the clear-cut, or in cases where the residues on the clear-cut are too moist while material in the stacks is dry.

To extend the period of use of the machine, baling could be carried out at the stacks during wintertime. In this case one cannot take advantage of the much lower forwarding costs of the baling system. Direct baling on the clear-cut following harvest during winter could also be a way to extend the work season. However, this requires that the receiver be willing to accept a higher moisture content in the material and that the removal of green material from the clear-cut is acceptable to the forest owner.

Chipping of the bales requires a chipper or crusher with a very large feeding device. Obviously, for production on a large scale, specially constructed machines can be built by the end-user. The large, mobile chipper built today, the Bruks 1004CT, is an interesting alternative for supplying smaller production plants or for chipping at the terminal. Pilot studies carried out in Spring 1996 showed that this can be an interesting technique.

For further transport, it should be possible to use both trucks and freight cars with only minor modifications. Full payloads on both trucks and freight cars, as well as possibilities for making efficient transfers between truck and train, enable the long-distance transport of compressed logging residues. The environmental impacts of transport, eg emissions of oxides of nitrogen and carbon, can be reduced dramatically by using electric trains. This alternative is, naturally, of special interest in cases where shipments are destined for densely populated areas.

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Use of simulation for the development of fuelwood-harvesting systems

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Abstract

In many cases, fuelwood-harvesting systems consist of machines that interact. The performance of systems with interactions can not be studied with analytic operations research methods. Instead, numeric methods such as simulation should be applied. Simulation enables the modelling of interactions and the effect of random factors in the performance of the whole system. Furthermore, if GIS is applied, the effect of work conditions can be studied. In this paper, system simulation is introduced as a tool for the analysis of fuelwood-harvesting systems. In addition, linking of GIS and simulation is discussed.

Keywords: simulation, fuelwood harvesting system, modelling

1 Introduction

Wood-harvesting system consists of several machines which are used for different harvesting and transport activities. If these machines work separately the estimation of system level performance and harvesting cost is rather simple: the cost of each activity is estimated and costs are summarized to obtain the total costs of harvesting. This approach works if activities at each stage are conducted separately but it can lead to heavily biased cost estimates when applied for systems with interdependencies (Asikainen 1995).

The development of a machine in a system does not necessarily promote the system performance. If there is a bottleneck on the next step of a system, any improvements at the previous stages don't always effect on the system level. In fuelwood-harvesting systems this effect is very common, if the chipping, forwarding and trucking take place simultaneously.

Systems with interactions can not be modelled with analytic OR techniques. In these methods it is usually assumed, that decision variables are independent and their values do not change over time. In a system with interdependences, decision variables are often interrelated and their values change dynamically over time. Simulation models can handle also interrelated systems, and they have been applied also in the field of wood harvesting (Seppälä 1971, Asikainen 1995).

This paper describes the simulation techniques generally and gives some examples how it can be applied in modelling of fuelwood-harvesting systems.

2 Simulation vs. analytic methods

As a means of operations research, simulation has been compared with other OR procedures. Simulation can be used to analyse complex situations that cannot be solved by analytic OR models. Simulation is a relatively straightforward method, and simulation methods are usually easier to apply than analytic ones. Simulation can be the only method that can be used to experiment with new policies, ideas or organisation of the work. It does not disturb the real system, as does for instance time studies with new machines. Various decision-making scenarios can be tested without stopping the production lines, hospital or chipping terminal. Experimental conditions can be better controlled in a simulation than in an experiment with the system itself (Law & Kelton 1982). Simulation allows the testing of several alternative scenarios or decisions in a short period of time because time compressing is possible in a model. Therefore, it is cheaper to collect the data in a simulation model than in a real system.

Simulation has some negative aspects too. Good and detailed simulation models can be very expensive (Render & Stair 1992). The model construction and gathering input data and iformation about performance of the model elements are often time consuming. The quality and reliability of the analysis depend on the quality of the model. The large volume of numbers produced by a simulation study often creates a tendency to rely on the study's results more than is justified (Law & Kelton 1982). Analytic methods for OR provide general problem-solving algorithms, which are applicable for numerous problems. Contrary to analytic models, each simulation model is unique: It is tailored for a specified problem and to answer specific questions. Its solutions are not usually transferable to other decision making situations (Render & Stair 1992).

3 Simulation project

An OR study can be divided into five phases (Taha 1992):

1. Definition of the problem,
2. Construction of the model,
3. Solution of the model,
4. Validation of the model, and
5. Implementation of the results.

These phases are also found in a simulation project, but it has a few specific characteristics. The steps of a general simulation project are described below and the examples are taken in the field of energy-wood harvesting.

Identification of the objectives includes description of the goal or objectives of the study, identification of the decision alternatives of the system, and recognition of the limitations, restrictions and requirements of the system. This is the most important phase of any OR (simulation) project (Render & Stair 1992, Thesen & Travis 1992, Witness 1994). The list of questions to be asked from the model helps the modeller in the following stages. For instance, the goal of a chipping contractor is to minimize the harvesting costs. He wants to know an optimal combination of machines in each situation.

The scope of the model refers to where the model begins and where it ends, i.e. what is the system boundary. For instance, a chipping-process model may begin at a logging site and end in the fuel storage of a heating plant. Definition of the system and the model boundary refers to the objectives of the model. The level of details contained within a model should be kept to a minimum: "Model the minimum necessary to achieve the model's objective" (Witness 1994). Nevertheless, all essential elements and processes must be included in the model.

Simulation calls for *information about the variables and processes contained in the model*. This information may be readily available from previous statistics or studies. For instance, production functions for a chipper and a chip truck are available. Information may not be available directly, but it can be derived from existing reports by combining information. The delay pattern of harvesting machines falls into this category: The total proportion of delays is known but the shapes of the delay distributions are not readily available. Field studies can be conducted to gather data on the modules of the model. Estimates and educated guesses must be used if the data are neither available nor collectable. If such estimates are used, they must be clearly declared as assumptions upon which the model is based. New machines, such as the latest model of a chipper, have not been studied in the conditions in which it will operate. In this case, the manufacturer may give some information about the performance level or at least about modifications made in the machine. If the operation of comparable older machines is known, it can be used as a basic situation and the effect of modifications can be evaluated by experts.

The *input data* for harvesting system simulation includes essentially the description of working conditions. Harvesting system works in a large geographic area, where the conditions vary remarkably. The work-site factors must be identified. This can be done by using existing data on work-site factors. At least average values of work conditions and rough estimates of their deviation must be given in the model. One possibility is to feed a simulation model with existing stand data site by site.

Existing geographic information systems offer a versatile tool for input data generation. It is recommended, that the key variables are described in terms of random distributions. The field data is compressed into a random distribution. For instance, the forwarding distance can be described by an exponential distribution and the volume of logging residues/ha by Erlang distribution. The use of distributions as input data enables faster sensitivity analysis and experimentation in the simulation project: only the parameters of distributions are varied before each experiment. If the input data are given in form of files, the content of files must be edited before each experiment.

Before the actual *model building*, the most difficult areas for the model-building and additional data requirements must be identified. In the structuring phase the facility to be modelled is sketched. It is recommended that the model be built incrementally: first a simple model is constructed and tested (Law & Kelton 1982, Banks & Carson 1984). Necessary details are then included into the model until the level of details satisfies the requirements set by the objectives of the modeller.

The modeller has to choose an appropriate tool for model building. Until 1960, simulations were performed using such general purpose programming languages as Fortran, Pascal etc. This activity, however, was complex and slow. Use of general purpose simulation language for building of a model requires fluency in the use of the language. Although this approach is time-consuming, it offers the most flexible tool for model construction (Ojala 1992). Simulation languages (GPSS, SIMULA, SLAM etc.) are designed to support the mechanics of modelling. The use of simulation language diminishes the programming effort, gives a concept apparatus for model construction and simplifies implementation of the simulation (Andersin & Sulonen 1974). Although the use of simulation languages diminishes the programming effort considerably, learning of the language and constructing the model can be time-consuming.

A simulator is a parameter-driven simulation that requires a little or no programming. Simulator provides an interface that enables the user to call up preprogrammed statements in the simulation language (Banks et al. 1991). When appropriate, the simulator offers a rapid way to model a process. Although simulators were developed in the beginning of the 1980's to model manufacturing processes, several kinds of systems and processes such as hospitals, airports and organizations etc. can be modelled with them. A simulator strives to substitute for programming by providing an interface that enables the user to call up preprogrammed simulation language statements. The model is constructed of objects which have their counterpart in the real world. The contents of the object library depend on the area of application for which the simulator has been built. For instance, a manufacturing simulator has objects related to manufacturing processes, such as welding robots, conveyors and vehicles. The robust features of simulators include programming, conditional routing, part attributes, global variables and interfacing to other software (Banks et al. 1991). These features give the simulator greater flexibility to model complicated systems and build up complex logic for interactions between the elements in the system.

Wood-harvesting systems fit well in the framework of manufacturing simulator (Asikainen 1995). Chippers can be described as production machines, trucks as vehicles and chip storages as buffers. Chips or raw material can be represented as part in a manufacturing system. Other elements in a simulator such as random number generators with different random distribution can be utilized to describe the random effects found in a harvesting system.

One of the most important problems facing a modeller is that of trying to determine whether a (simulation) model is an accurate representation of the actual system being studied (Law & Kelton 1982). A valid model gives a good representation of reality (Kleijnen & Groenendaal 1992). *Validation* is determining whether a simulation model is an accurate representation of the real world system under study.

In the *verification* phase the computer program is debugged to ascertain whether any mistakes have been made in programming (Law & Kelton 1982, Kleijnen & Groenendaal 1992). The results can be calculated manually and then compared with the program outputs. Certain modules of the simulation program can also be verified. Law and Kelton (1982) give some practical hints to help the modeller verify the simulation program. It is better to start with a simple model, which is gradually made as complex as needed, than to develop a complex model immediately. The model can also be run under simplified conditions, where the outputs are known or can easily be calculated. Many simulation packages also offer also a graphical presentation of how the simulation actually progresses. It is very helpful in the construction phase of the model to check the logic of system elements or interactions between entities.

The first step of in validation is to attempt to develop a model with high face validity, i.e. a model that on the surface seems reasonable to people who are specialists on the system under study (Law & Kelton 1982, Banks & Carson 1984). To develop such a model, the modeller should make use of all existing knowledge. This means discussions with experts, finding out the existing theory or studies, and observations of the system. Conversation with experts familiar with the system ensures that the model will not be developed into an abstraction that is far from the real world (Ojala 1992). One should seek out and use relevant results from similar models and also suggest intuitively how certain components of a complex system operate.

The second step is to test quantitatively the assumptions made during the initial stages of model development. One useful tool during the second step of validation is sensitivity analysis. This technique can be used to determine, how much the model output varies if the value of an input parameter is varied.

Finally, a simulation model is fed with real life input data and the results are then compared with those from the real system. This is possible if the real system or research results for the system exist. Usually, however, the modules of the model can be tested this way but not the model as a whole.

Experimentation means execution of the computer simulation model. When the model approximates closely enough the behaviour of the real-life situation, several what-if scenarios may be investigated. These scenarios should have been defined within the original objectives of the simulation study. Successful experimentation typically involves using a warmup period or starting conditions, suitable run length and running the model with more than one random number stream (Witness 1994). In experimentation, input parameter (factor) values are varied and output measures (response) are investigated (Law & Kelton 1982). Factors can be either qualitative or quantitative. Quantitative factors can be expressed numerically, for instance, the number of trucks in a transport system, whereas qualitative factors refer to structural assumptions in the model, such as chipping at the landing or at the terminal. Controllable factors represent policy options available to the managers of the real world system being modelled, for example, the number of workers working in a chipping yard. Uncontrollable factors cannot be controlled in the real world system by the managers: the number of chip users in a certain district cannot be decided by the chipping entrepreneur.

There are several possibilities for gathering observations from a simulation model (Taha 1992). The model can be run several times from the beginning to the end with different initial data, and output values are recorded at the end of each run. In the subinterval method, a single run is divided into batches, each of which represents a statistical observation. In the replication method, the model is started from the beginning before each observation. The transient (warmup) period can be omitted, if desired. Another alternative is to give the model relevant starting conditions.

Simulated data can be *analysed* in the same manner as a data gathered in the real system. It must be kept in mind, that in simulation the modeller decides which sources of random variation are included in the model. Furthermore, the amount of random variation is also controlled. Therefore a careful sensitivity analysis is needed to check the effect of assumption made in the experimentation phase.

4 Discussion

Simulation offers a flexible tool for analysis of fuel-wood harvesting systems. It greatest advantage is the ability to model in details a great variety of systems with machine interactions. The effects of these interactions in the machine and system performance can be quantified. The waiting times and delays caused by other components in the system are illustrated and also their effects on harvesting costs can be estimated. Simulation can be used in iterative optimisation of the system: various alternatives are tested and decision variables are evaluated.

In fuelwood harvesting simulation has been applied in the comparison of different systems such as chipping at the landing, chipping in the forest, and chipping at the terminal (Asikainen 1995). Different chip-trucking systems have been compared (Asikainen 1995).

It must be kept in mind that spreadsheet-based calculations can often be used for analysis of the system. If the system under study does not contain real interactions and system elements work independently, simulation does not give any additional information compared to spreadsheet calculations.

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Practical experiences of small-scale heating enterprises in Finland

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Abstract

Heating entrepreneurship (i.e. supplying customers with heat energy generated from wood raw material) is a new form of rural enterprise in Finland. The action model is such that the entrepreneur is mainly responsible for supplying heating energy to municipal real estates in the form of chipped wood. The heating entrepreneur procures the fuel and attends to the supervision of the heating plant. The entrepreneur is paid on the basis of the amount of heat generated. The price of heat supplied is usually bound to the price of fuel oil. There are twenty to thirty examples of heating enterprises in Finland, and several new enterprises are being planned.

Heating entrepreneurship provides extra income, especially for farmers, who have otherwise unmarketable potential fuelwood in their woodlot, under-utilised timber harvesting equipment, experience of using fuel chips, and lack of supplementary income opportunities. However, this form of entrepreneurship can seldom provide the primary livelihood.

The Work Efficiency Institute has been engaged in developing small-scale heating enterprises (based on heating plants with capacities of 50—500 kW) within the context of the national Bioenergy research programme. Among other things, the Work Efficiency Institute has produced a booklet aimed at potential entrepreneurs. Finland also has a number of 500—1500 kW heating plants that are run on a co-operative basis.

Keywords: fuelwood, bioenergy, heat entrepreneurship

1 Background

Heating entrepreneurship is a new form of rural enterprise in Finland. The action model is such that the entrepreneur mainly has responsibility for supplying heat to municipal real estates using indigenous fuels. The heating entrepreneur procures the fuel and carries out the supervision of the heating plant. The entrepreneur is paid for services rendered on the basis of the amount of heat generated. The price of heat is usually bound to the price of fuel oil. There are twenty to thirty examples of heating enterprises in Finland, and several new enterprises are being planned.

Heating enterprises offer extra income especially for farmers who have otherwise unmarketable potential fuelwood in their woodlots, under-utilised timber harvesting equipment, experience of heating using wood chips, and lack of supplementary income opportunities. Heating entrepreneurship can seldom provide the primary livelihood.

When establishing a heating enterprise, the factors to be considered include the size of the site to be heated and the required investments. The commonest form is one in which 1—3 entrepreneurs are responsible for heating local premises. Such heating plants are usually 50—500 kW. Heating entrepreneurs are usually forest-owning farmers. In small heating sites managed by heating entrepreneurs, the main fuel is usually chips from small-diameter wood, with light fuel oil as the reserve fuel.

In a heating co-operative, the action model is such that forest owners collaborate in the procurement and the delivery of the fuel chips to the customer's premises. The co-operative's members are also in a position to earn revenues in the form of interest paid on the invested capital and dividends paid out by the co-operative. A heating co-operative must have at least five members. The co-operative solution is appropriate when dealing with heating entities larger than single building, e.g. district heating plants. In these cases the plant size is between 0.5 MW and 5.0 MW. A more limited action model is that of a fuelwood co-operative responsible merely for procuring and delivering wood chips to the plant.

There are several other forms of heating enterprise in which the heating entrepreneur's tasks vary according to the stage of work in the chain of events between procurement of the fuel raw material and heating. If the entrepreneur is unable to procure enough fuelwood from his own woodlot, he can supplement his stock of fuelwood through purchasing standing wood. In some cases it may be more economical to use the services of another entrepreneur to carry out the chipping. Chip transportation can also be contracted to another entrepreneur.

The action model varies depending on the harvesting and chipping equipment, and also according to the ownership of the heating equipment. Chip-fired heating plants are usually owned by the purchaser of the fuel, usually the local municipality. In the case of larger entities, the energy co-operative may also own the district heating plant and the energy distribution network belonging to it. Yet another model has the heating entrepreneur investing in chip-fired heating plant, but the purchaser then redeems the equipment within an appointed time.

2 Case studies in Finland

Even though heating enterprises are still a new form of activity in Finland, some research data are already available. The Work Efficiency Institute has examined chip heating managed by heating entrepreneurs in connection with a project conducted under the auspices of the national Bioenergy research programme. The objective was to develop heating enterprises and to determine possibilities for reducing the associated costs.

A follow-up study examined five chip-fired buildings with 50—400 kW solid-fuel-fired boilers. Heating entrepreneurs were asked to record the time given daily to the various work stages, the amounts of fuel, and the amounts of heat generated by the district heating station. The data were also acquired by familiarization with the heating sites and by interviewing heating entrepreneurs and municipality representatives. The study resulted in a booklet to assist people who are considering becoming heating entrepreneur.

Table 1 shows the background data concerning the follow-up cases included in the study. The volume of the properties heated varied between 1 800 and 13 200 m^3; they consisted of schools and homes for the elderly. Previously these buildings had been heated using light fuel oil. The initiative for launching heating enterprises came from the heating entrepreneurs in four cases and from the purchaser of the heating service in one case.

In three cases the municipality made the investment in the heating plant and the heating entrepreneur in two cases. Those heating entrepreneurs that had invested in the heating equipment were paid an extra sum by the municipalities in proportion to the cost of the basic investment. The energy supply contracts between the heating entrepreneurs and municipalities were for periods of two to ten years. The compensation paid for the heat energy without the investment cost varied between FIM 92 and FIM 204 per MWh in the follow-up cases. Differences in the calculation criteria etc. of the energy supply contracts resulted in wide variation in the price of heat energy.

In two of the heating sites there were three heating entrepreneurs but only one in the other sites. One of the entrepreneurs had a forestry background while the others were farmers. The entrepreneurs lived at distances of two to twelve kilometres from the heating sites.

The consumption of chips delivered varied between 1.48 and 1.81 loose cubic metres per MWh (Table 2). The moisture of the chips varied between 20 and 40%, depending on the site. The aim was to use dry (over a year old) chips or dried chips in the winter. In other seasons of the year, particularly in the summer, moister fuel was often used. Problems caused by excessive chip moisture were not encountered at the follow-up. Chips reduced from delimbed wood were generally used at small heating sites because their chip silos and discharging devices did not operate reliably with whole-tree chips. At larger heating sites attempts were made to use chips made of either partly delimbed or whole trees.

Light fuel oil was used during short breaks caused by maintenance of the heating equipment. The share of light fuel oil in the generation of heat energy varied between 0% and 3% at four of the sites. Light fuel oil was used as a secondary fuel during consumption peaks at one site. The share of light fuel oil at this site was about a third of the generated heat.

Table 1. The chip-fired sites in the study.

Site	1	2	3	4	5
Site to be heated	School	School	School	Old people's home	Old people's home
Investor in heating plant	Municipality	Municipality	Entrepreneur	Municipality	Entrepreneur
Size of plant, kW	50	120	150	300	400
Number of entrepreneurs	3	1	1	3	1

Table 2. Consumption of chips and amount of generated heat supplied by heating entrepreneurs in the follow-up study.

Site	1	2	3[1)]	4	5
Plant size, kW	50	120	150	300	400
Length of follow-up period, months	9	8	4	12	12
Chip consumption, m^3 (loose)	193	194	159	921	1325
Heat generated, MWh	117	107	96	624	750
Chip consumption, m^3 (loose)/MWh generated	1.64	1.81	1.66	1.48	1.77

[1)] Not full heating season

3 Use of work time

The work performed by heating entrepreneurs during the follow-up period varied between 14 and 220 hours in heating work and between 65 and 830 hours with respect to the entire work chain. The follow-up period was shorter on two sites because heating of the sites with indigenous fuels was begun after the start of the heating season.

The productivity of harvesting (felling and forest haulage) varied between 0.4 and 0.8 m^3/ha. The productivity of chipping was between 3.8 and 7.5 loose cubic metres per hour when heating entrepreneurs chipped into trailers at the intermediate storage point. Felling was mainly by chainsaw. Forest haulage employed an agriculture tractor equipped with a hydraulic crane and a forestry trailer.

Table 3 shows the work input in supplying fuel to and heating of district heating plants per unit of heat generated. In the case of the site where no outside labour force was used, the total work input was 2.6 h/MWh. On the other sites, the heating entrepreneurs also used the services of outsiders in the procurement of fuelwood.

Table 3. Total work input by heating entrepreneurs in the procurement of chips and heating work per unit of heat generated (h/MWh), follow-up cases.

Work stage	Site				
	1	2	3	4	5
	Work hours per unit of heat generated, h/MWh				
Harvesting of fuelwood	0.64[1]	1.16	0.15[2]	0.71[3]	0.56[4]
Chipping and transportation of chips to intermediate storage	0.23[5]	0.40	0.43	-	-
Chip transport to plant, and heating	1.12	1.08	0.87	0.47	0.54[6]
Total	1.99	2.64	1.45	1.18	1.10

[1] 34% of fuelwood consisting of sawing waste.

[2] Forest haulage only. Felling work done by outside labour.

[3] 40% of forest haulage done by forest machine contractor. 13% of fuel sawdust and 5% sawing waste.

[4] Forest haulage done by forest machine contractor. 40% of felling work done by outside labour.

[5] 46% of chips produced by chipping contractor.

[6] Fuelwood transported to heating plant by chipping contractor.

Table 4. Distribution of heating entrepreneurs' work time, follow-up cases monitored in the Work Efficiency Institute study.

Work stage	Site				
	1	2	3	4	5
	Proportion of work time, %				
Transportation of chips to plant and topping up of chip silo	28	30	64	51	-[1]
Heating	46	38	27	30	63[2]
Travel to the heating plant	26	32	9	19	
Total	100	100	100	100	100
Total, h/MWh	1.12	1.08	0.87	0.47	(0.46)

[1] Fuelwood transported by chipping contractor.

[2] Heating entrepreneur did 60% of heating work.

Transportation of chips to district heating plant and heating consumed 0.47—1.12 h/MWh, of which 0.14 — 0.51 h/MWh consisted of heating. Supervision of heating was the major component on all sites. The number of visits to the plant required per heating day varied between 0.43 and 1.12. In the winter, visits had to be made almost daily to district heating plant but in other seasons of the year less often. The fewest visits were required by sites with automatic alarm systems. The formation of cavities within the chips in storage silos caused alarms and increased the number of visits, especially in the case of site #5.

Fuelwood was transported to district heating plants by agricultural tractor and trailer. The transport distances varied between 2 and 11 kms. The chip loads varied between 2.5 and 10 loose cubic metres in size. The volume of the fuel silos had a considerable effect on the work hours required for chip transportation. In the case of site #3, the chips were often brought to the district heating plant in small lots because the volume of the chip silo at the plant was only 3 m^3. This increased the amount of work required even though the distance was only 2 km (Table 4).

4 Profitability of operation from the entrepreneur's point of view

The remuneration for supplying heating energy (excl. investment-compensating) varied between FIM 92 and FIM 204 per MWh on the follow-up sites. Differences in the calculation premises and other such differences in energy supply contracts resulted in wide variation in the price of heat energy. The price per energy unit was determined on three sites using a calculation formula based merely on the price of light fuel oil. On two of the sites, payments were based on the price of heat energy sold by the municipal district heating plant. The price of heat energy at these sites was more advantageous to the heating entrepreneurs than at the other sites. The subsidy paid from forest improvement funds increased the profitability of operation at four sites, where the share of the forest improvement subsidy in the heating entrepreneurs' incomes was between 8% and 16%.

The margin for the work done by the heating entrepreneurs at four of the sites was between FIM 40 and FIM 77 per hour when the interest on the investments in harvesting equipment, insurance costs, and storage costs were excluded (Table 5). The margin varied between FIM 36 and FIM 71 per hour when these were included. The margin has to cover the entrepreneur's earnings with the associated social security costs and the entrepreneur's risk. At these sites, the entrepreneurs had previous experience of using chips as fuel on their own farms.

One entrepreneur's operation was unprofitable. The payments to this entrepreneur for energy produced were distinctly smaller than those paid to others. Also, the entrepreneur had no previous experience of chip-fired heating. The site of his operation was also characterised by technical disturbances, which increased costs and contributed to the unprofitable operation.

The productivity of operation of the different stages, the cost of equipment, the use of external services, and the material costs of fuel all influenced the economic outcome. When assessing profitability, it is also necessary to take into account the fact that harvesting work in entrepreneurs' own woodlots is tax-free up to 125 m^3 solid per year. The wood obtained from entrepreneurs' own woodlots therefore gives a competitive advantage over other fuels. Also, the taxation of incomes from

Table 5. Computation of margins for heating entrepreneurship. Margin A ignores interest on capital invested in equipment and insurance and storage costs. Margin B includes them. VAT is not included. Margins include work earnings and entrepreneur's risk.

	Site				
	1	2	3[1]	4	5
Plant size, kW	50	120	150	300	400
Incomes, FIM	25 440	19 950	17 870	92 590	67 480
Expenses, FIM	7 440	7 580	7 530	46 010	81 220
Margin A, FIM	18 000	12 370	10 340	46 580	13 740
Margin A, FIM/h	77	40	74	61	-
Margin B, FIM/h	71	36	69	57	-

[1] Not a full heating period.

heating enterprises is supportive. Fuelwood harvested from entrepreneurs' own woodlots ignored stumpage price as the benefit was considered to have been obtained via the enhanced silvicultural state of the woodlots in question.

For the entrepreneurs involved in this study, the heating season under examination was either their first or second, and problems were still being experienced with the heating plants. As the entrepreneurs' experience and skills improve, their operations should become more efficient, and their profitability should therefore improve.

Some of the factors affecting the profitability of heating entrepreneurship are summarized as follows:

- ability to negotiate a good heating energy supply contract
- ability to avoid investments
- possibility to purchase services from outsiders
- ability to use equipment at minimum hourly costs with respect to productivity
- ability to use seasoned material instead of having to dry chips
- ability to minimise the number of supervision visits to the heating plants through meticulous care of plant equipment and through an automatic alarm system at the plant.

5 Discussion

Some the advantages of heating enterprises from the point of view of municipalities are: increased use of local labour, supply of local raw materials, reliability of heat supply, and savings in costs. Furthermore, the money previously spent on purchasing oil now circulates locally promoting local livelihoods, and also increases the amount of locally taxable incomes.

Finland has a significant fuelwood reserve in the small-diameter trees and felling residues that do not fulfil the quality requirements imposed on industrial wood. A farm woodlot often contains more fuelwood than can be consumed on the farm. This surplus wood can be used as raw material by heating enterprises. Considering the under-utilisation of forests in Finland, harvesting this material does not pose a problem for the supply of the raw material to industry. The use of small-diameter trees for energy generation promotes forestry and enhances opportunities for practising multi-purpose forestry.

The mechanisation of timber harvesting enables an increase in first-thinnings work by forest owners. The recovery of wood material of below pulpwood diameter for energy generation improves the profitability of this work. Society encourages the silvicultural management of young stands in Finland by, for instance, subsidising rehabilitation felling and tending, and also by paying a subsidy when energy wood fulfilling certain requirements is collected from young stands.

Farms have equipment which is often under-utilised. This applies especially to equipment used in timber harvesting and making fuelwood. Generally speaking, Finnish farms are technically well-equipped for engaging in wood fuel harvesting. The equipment used in the production of fuelwood for household consumption is usually a suitable basis for heating entrepreneurship, and little other special equipment is required.

Modern heating devices are already so advanced that wood-based heating no longer requires 24-hours-a-day supervision, as may have been the case earlier. Also, modern heating devices do not essentially differ from those used on farms. Thus, supervising such equipment is not an obstacle if the entrepreneur is accustomed to wood heating.

Buildings owned by municipalities and especially those owned by other public organisations and lying outside larger district heating networks represent a major potential for heating entrepreneurs. Some of these sites are oil-fired schools, day-care centres, old people's homes, and residential buildings owned by municipalities. Sites within district heating networks have yielded good experiences as regards the co-operative operation model. Another future category of clientele is that of private housing corporations.

6 Further studies

Heating enterprises in Finland are a new form of activity which still needs further development. The Work Efficiency Institute will continue with the development of heating entrepreneurship by concentrating on studies to improve the profitability of operation. Profitability is definitely a precondition for the stability of operation from the viewpoints of both the entrepreneurs and customers. In the assessment of profitability, consideration will be afforded to both the business effects and the indirect effects on society, as well as effects from the tending of forests.

The functioning of the production chains and of the heating plants in connection with heating entrepreneurship also require further development. Efforts must also be made to sell this operation model to potential entrepreneurs and municipalities.

Harvesting low-grade stands for biomass and timber in Prince Edward Island Canada

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1 Introduction

Prince Edward Island is Canada's smallest province. It is a 578 000 hectare island in the gulf of St. Lawrence, off the coast of Nova Scotia and new Brunswick. It has a population of 133 000. The economy is based on agriculture, fisheries and tourism. PEI has a small, but growing forest industry.

PEI has no fossil fuel or hydro resources. As oil prices rose steeply in the 1970s, there was grave concern about the possible impact on the economy. The Provincial Government began to look at PEI's woodlands as a future source of energy for businesses and institutions.

Woodland covers 48 % (276 000 hectares) of the area of PEI. The Crown owns only 10 % of the woodland. About 90% of the woodland area is privately owned, consisting of 16 000 existing or former farm woodlots which belong to 12 000 private owners. The average size of woodlots is 16 hectares, but some are as large as 80 hectares.

Historically the woodlots of PEI were the forest lands that did not get cleared for agriculture. They were heavily logged for shipbuilding and other timber purposes. Until recently these woodlands were completely unmanaged and of very poor quality. There is also currently 32 000 hectares of woodland that was in agriculture and was abandoned at various times throughout this century as people left the farms and migrated to jobs in other parts of Canada. This land became woodland dominated by white spruce (*Picea glauca*). This woodland has been the focus of vigorous harvesting in the last decade, as timber prices have risen.

The rise in interest in forest bioenergy coincided with a growing commitment by the Federal Canadian Forest Service and the provincial Department of Forestry in the renewal and management of PEI's woodlands. They saw the whole tree chipping of low-grade stands as a means of removing stands of low economic value and preparing sites for replanting with genetically superior trees.

2 Woodchip production

Trials on the use of woodchips began in 1979. They were initially focused on residential heating systems since there was concern that the growing demand for roundwood hardwood for home heating was going to outstrip the sustainable supply. The limited success of residential chip burners led to a shift in focus toward larger chip plants to heat the many buildings owned by the Province in 1984. In the ensuing ten years about 20 chip burning plants were installed in schools and hospitals across PEI. There were also two district heating systems constructed in Charlottetown, the capital of PEI. They are presently being expanded into one large district heating system. In addition, about 75 small commercial biomass systems have been constructed mainly on farms. They burn both woodschips and sawdust.

Initially, the provincial Department of Forestry directed the harvesting contractors to chip entire stands of low-grade trees. They actually located the chip harvest sites for the principal chip contractor. *Bulk Carriers Inc.* started the first large chipping operation in PEI in 1985. They employed an ÖSA feller-buncher and a Bruks 800 CT terrain chipper mounted on a 10 tonne Rottne forwarder and Multi-Lift-type container truck with 6 containers. This was strictly a whole tree energy chipping operation. It was not integrated with timber harvesting and this likely hurt the profitability of the operation. The company was frequently criticized for chipping saw material which they were not set up to sort out. This contractor operated between 1985 and 1990. Average annual production was 10 000—11 000 green tonnes per year. This operation employed 4 people.

Arsenault's Sawmill won the major woodchip supply contract in 1989 and they are currently PEI's largest woodchip contractor. Arsenaults run an integrated harvesting operation that produces both woodchips and high quality saw material. Ideal harvest sites for them are stands that have high volume, but only a small percentage of quality saw material. These are often mixed wood sites that other conventional contractors would not find economic to harvest. They are unwilling to pay much for stumpage on such sites, if indeed, they are willing to harvest them at all.

Typical chip production is 130—150 tonnes per hectare as well as varying quantities of saw material. Some very good sites with a high percentage of poplar (*Populus tremuloides*) have generated volumes up to 260 tonnes per hectare. The percentage of saw material sorted out depends on the species mix in the stand and the strength of the demand for lumber. In a strong lumber market, a lot of balsam fir (*Abies balsamea*) sawlogs are sorted out for timber. In a weak lumber market most balsam fir will be chipped.

Arsenaults practice hot logging. Each day in winter two or three chainsaw operators fell the amount of wood that they need as chipping material. All the felled wood is chipped the same day. They do not want chipping material to get buried under snow.

Sawlogs are processed at the stump. The remaining chipping wood is forwarded to a roadside landing with an 8 tonne 230 Timberjack forwarder. Chipping is carried out at roadside landings with a Finnish TT97R drum chipper, powered by a 300 kW Cat engine. Trucking is carried out with one 10 wheel dump truck that hauls 15 tonnes and two 18 wheel dump trucks that haul about 30 tonnes.

This operation employs about 9 people who are all from the same family. This is made up of up to 3 cutters, a forwarder operator, a chipper operator, 3 truck drivers and a foreman. The average daily production in a 10 hour day is 180 tonnes. In the low demand shoulder seasons, the crew numbers go down to 4 or 5 depending on the number of trucks hauling. The surplus workers shift to conventional timber operations.

Arsenaults major customer has been the two biomass-fired Charlottetown district heating systems as well as four smaller institutions. They also supply some of the small commercial biomass systems. Annual production is about 21 000 green tonnes per year. In recent years they have also done quite a lot of land clearing for agriculture due the expansion of the potato industry in PEI.

The price of Arsenault's whole tree chips delivered to the Charlottetown area in 1996 is $ 27.00 per tonne (Cdn.). This is down from a high of $35.50 per tonne in 1994. The principal buyer, the district heating company (Trigen), offered these lower prices on a "take it or leave it" basis. The company also sells a 50:50 mixture of slab chips and sawdust at $25 per tonne delivered. The price of chips is lower when the trucking distances are relatively short.

John Acorn is the second commercial PEI woodchip contractor. He produces about 4 000 green tonnes of woodchips per year. He employs a feller-buncher to fell and windrow the wood. Sawlogs are processed by the cutter. Chipping is performed by a Bruks 1001 CT terrain chipper. The chipper travels to the chipping material at the stump. Chips are transported in a 10 wheel truck equipped with a Multi-lift-type container system that the contractor built himself at relatively low cost. The containers haul about 11 green tonnes of woodchips. This is a two person operation. The woodchips are sold to 3 schools and 2 hospitals in eastern PEI. John Acorn's equipment is underutilized. His business is constrained by a small market.

3 Woodchip consumption

The consumption of woodchips in Prince Edward Island has grown slowly from about 2 000 in the early 1980s, to 23 000 green tonnes in 1989. It peaked at about 30 000 tonnes in 1995. Whole tree chips constitute about 75 % of the total, with sawmill chips making up the other 25 %. There has been a strong preference for woodchips among biomass plant operators, but sawmill waste has begun to be used in recent years, particularly in the small commercial systems which are all in the private sector.

4 Sawmill waste suppliers

Two relatively small sawmills in central and western PEI sell barky chips for energy. Sawmill waste basically means sawdust in PEI. The consumption of sawdust amounts to about 6 000 green tonnes per year, although usage is growing steadily.

Most small sawmills also sell the limited volumes of sawdust that they have available, although most of it is used for farm animal bedding. PEI's largest sawmill, Georgetown Timber Ltd., produces about 50 000 green tonnes of sawmill waste per year. The company supplies many of the small commercial biomass systems with sawmill waste. Some people truck their own fuel and pay only a $25 loading charge. Georgetown Timber also delivers fuel with a 15 metre van that is equipped with a walking floor unloading system. The van hauls about 30 tonnes. The sawmill waste costs an average of $15 per tonne delivered, but the cost varies according to the haul distance.

Prepared hog fuel, including bark, has not been available, although Georgetown Timber is gearing up to produce hog fuel for the expanded Charlottetown district heating system.

5 What is the future for biomass in PEI?

PEI has long been the most active province for bioenergy development in Canada due largely to the strong support from the provincial and federal governments. However, significant changes have been taking place in recent years. The PEI Government has been cutting back on expenditures in order to control its deficit. The PEI Energy Corporation which owned the Charlottetown district heating plants was running a deficit, largely because of losses at a garbage burning plant. The corporation has been wound down and the two district heating systems were sold to an American company called Trigen. Trigen is expanding the district heating system and creating one larger system. A new heating plant is under construction at the site of the old garbage plant located on the Hillsborough River. This will be 25 MW heating plant. Approximately 50 % of the heat load will be generated from garbage, 40 % will come from hog fuel from PEI's largest sawmill in Georgetown. Bunker C oil will make up the remaining 10 %.

Woodchips will no longer be a fuel source for the district heating system in Charlottetown after the 1996—97 heating season. Thus, the Arsenault's have lost their major woodchip customer. They will be left with only a number of smaller institutions that use perhaps 5 000 tones of chips.

The privatization of the two district systems and its consolidation into one larger system, created an opportunity to switch to no cost garbage and lower cost sawmill waste. It is not surprising that a private company would opt to use the cheapest source of energy that is available to it.

The two existing woodchip contractors are likely to continue to produce woodchips for the existing plants. There could be some small growth in woodchip usage in small commercial biomass plants, but most new plants will use sawmill waste if it is available.

New larger woodchip heating plants are unlikely in PEI. The price of light oil in bulk is about 22 cents per litre which is too low to provide a reasonable payback on new woodchip plants. For larger users, bunker oil is available at 12—13 cents per litre which is roughly equivalent to the price of whole tree woodchips. For any significant growth to occur in woodchip usage, it would require a rise in the cost of crude oil or a change in the taxation policy regarding heating fuels. Heating fuels are not heavily taxed in Canada as they are in Europe. Canada, regrettably, does not have carbon taxes. Carbon taxes is not popular with the oil, gas and coal interests based in Western Canada.

The Arsenault's wood chipping operation is efficient. They get relatively high production from a minimum of equipment. It basically consists of only a forwarder, a chipper and chip transport vehicles. It is easy to sort out and handle merchantable saw material. The operation is flexible. Output can be varied from 45 to 180 tonnes per day without having to park a lot of expensive machines and leave them idle. This type of operation could serve as a model for new chipping operations that will hopefully supply woodchips for heating plants in remote communities in Northern Canada.

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Storage trials with willow from short rotation

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Abstract

A large storage trial of Willow from short rotation was conducted, including six different sizes of material and six ways of covering. In total about 700 tonnes of fresh material were divided over fourteen piles, of which ten were located outside and four indoors. The trial is not yet concluded. Prelimenary results on the development of the moisture contents, temperature in the piles and loss of dry matter and heating value are presented.

Keywords: Storage, short rotation forestry, willow, temperature, dry matter loss, moisture contents

1 Background

Storage of wood fuels is still a large problem, where the major factors are size of the chip, moisture contents and method of storage. Willow from SRF is harvested during the worst time of the year in the period December to April, so that it is not possible to dry the material before comminution. The resulting fuel is very wet (50—60 % of fresh weight).

Several projects in Europe suppose that the fuel from SRF plantations can be delivered around the year: this makes it necessary to store large amounts of SRF crops for prolonged periods of time. It is therefore imperative to do research in the storage properties of SRF crops, where the influence of size and storage method is investigated, preferably in one large trial under similar conditions.

The trial is part of two projects. The first one is an international project supported by the EU called: "Development of harvesting and storage technologies essential for the establishment of short rotation forestry as an economic source of fuel in Europe" (AIR3 CT94-1102). The emphasis in this project is on harvesting. This project is being carried out in co-operation between institutions in Great Britain, Sweden, Germany, France, Italy and Denmark.

The other project is a national project called "Systems analysis of the supply chain when supplying a central gasification co-generation plant with willow from SRF around the year" (EFP 1383/95-0007). The institute's role in this project is mainly on the storage aspects of willow SRF. This project is a co-operation between the Agricultural Advisory Center, Elsam Projekt A/S and the Danish Forest and Landscape Research Institute.

2 Purpose

The trial is conducted to see the influence of piece size and the method of covering on storage losses of willow from short rotation in one large trial.

3 Materials

Six different materials are included in the trial:

- whole shoots (harvested with Dansalix wholeshoot harvester)
- 20 cm long chunk (produced with Silvatec firewood chunker after harvesting with Dansalix)
- 10 cm chunk (harvested with Austoft sugarcane harvester)
- 5 cm chip (harvested with Austoft sugarcane harvester)
- 2.8 cm long chip (harvested with Claas forage harvester with SRF header)
- 2.5 cm long chip (harvested with Bender II SRF harvester)

4 Storage methods

The storage trial encompasses several storage methods, both indoors and outside. The following storage methods are used:

- in the free, no cover (Claas, Austoft 5cm, whole shoot, Silvatec)
- in the free, plastic cover (Claas, Austoft 5 and 10 cm, Bender)
- in the free, airtight as silage (Claas, Austoft 5cm)
- in the free, paper cover on top (whole shoot, Silvatec)
- under roof, unventilated (Claas, Austoft 5cm)
- under roof, ventilated (Claas, Austoft 5cm)

All outside piles are located on tarpaulins to facilitate removal. The covered piles have been closed with black plastic, with a ventilation pipe on the top of the pile, which protruded at both ends of the stack and had several chimneys. The plastic is held in place with a fishing net, which in turn is weighed down with lengths of pulpwood. The plastic is allowed to move somewhat, so that air can get in. The purpose of the plastic is more to keep rainfall out, rather then to keep moisture in.

With the silage piles greater care was taken: first a layer of tarpaulins was laid down, then a layer of plastic. The chips were dumped on the plastic. The top of the pile was covered with a tarpaulin and then the plastic from the bottom was closed to the top. The whole pile was then covered with a second layer of plastic, which was weighed down at the edges with sand. In this way the piles were made airtight. During the storage period the piles were inspected at intervals and any holes that might have occurred were mended with tape.

In all fourteen piles of approximately 50 tons fresh material each have been established. Ten piles are located in Vejle (outdoor storage) and four in Horsens (storage under roof). Establishment took place in December 1995-January 1996. The piles are to be removed in two tempi: May 1996 and September 1996.

All piles are followed with temperature measurements during the whole storage period. In the ventilated piles, also the number of active hours of the fan, the energy consumption and the volume of air passing through the piles are measured. The purpose of the ventilation is not to dry the material, but to cool the piles in order to keep fungal growth within bounds. The ventilator only works when the temperature in the pile exceeds the ambient temperature by 5 °C. All piles have netbags in the centre, situated around the temperature sensors. All piles will be weighed at the beginning of the storage period and at the end. Moisture contents at those times will be measured. In this way the total dry matter loss can be calculated.

Samples will be taken at the start, and at the two removal times to count the number of fungal spores. This part will be carried out in co-operation with “Institutionen för Virkeslära” of the Swedish Agricultural University in Uppsala (Raida Jirjiz). The results are not yet available.

Besides the two large piles of silage of Claas and Austoft 5cm chip, also a mini trial in 25 litre drums has been included. The contents of these drums and samples of the large piles will be analysed at Foulum Research Center (Erik Møller) for their contents of alcohol, and lactic and butyric acid. The results are not yet available.

Another aspect of the trial is that the chips and chunk are also used after storage to measure their bridging properties. This part is being carried out in co-operation with the Swedish Agricultural University in Alnarp (Jan Erik Mattson). The results are not yet available.

3 Results from the revision in May

In two weeks in May 1996 half of each of the piles 2—9 (Vejle) and 11—14 (Horsens) were loaded in containers and delivered to two heating plants. Half of pile 1 (whole shoots) was chipped with a mobile chipper and delivered in containers to the heating plant. Pile 10 (silage of Claas chips) was left undisturbed until the second revision at the end of September 1996.

Visually it could be noted that the smaller the size of the chips, the larger the degradation. There was also a marked difference between the covered piles and the open piles, where the covered piles had suffered more than the open. This is contrary the experiences so far and is the result of very little precipitation in the storage period, where less than half the normal rainfall was noted. Especially the covered piles of the finer material (Austoft 5cm, Bender and Claas) showed fungal growth on the surface of the piles with fruiting bodies.

Tabel 1. Changes in moisture contents, dry matter and energy losses in all piles.

Nr.	Pile	Start Wet kg	Diff. MC %	Diff. DM %	Diff. GJ %
1a	Whole shoots, uncovered	14 280	15.4	10.42	3.76
1b	Whole shoots, paper cover	18 970	17.3	5.14	-2.55
2	Austoft 5, silage airtight	31 000	-4.8	9.43	12.02
3	Austoft 5, covered	25 220	-2.1	19.11	20.15
4	Austoft 5, open	19 200	-1.1	17.49	18.03
5	Austoft 10, covered	26 640	1.8	11.26	10.32
6	Bender II, covered	26 020	0.0	17.37	17.37
7a	Silvatec 20, open	12 220	13.5	9.07	3.16
7b	Silvatec 20, paper cover	14 180	7.9	12.30	8.64
8	Claas, open	25 540	1.3	23.05	22.45
9	Claas, covered	23 620	1.3	16.46	15.69
11	Claas unventilated	19 555	11.0	13.45	8.57
12	Claas ventilated	23 290	11.2	12.68	7.88
13	Austoft 5, unventilated	25 045	14.1	16.42	11.01
14	Austoft 5, ventilated	28 854	14.3	10.26	4.49
10	Claas silage	41 620	na	na	na

Moisture contents

In Table 1 an overview is given over the changes in moisture contents and losses in dry matter and energy contents.

As can be seen from Table 1, the larger the particles of the outside stored material, the greater the loss in moisture contents. There is a difference of 15 to 17 % between the initial moisture contents and the one in May for the whole shoots. Likewise the 20 cm chunk dropped between 8 and 13 %. Several of the covered piles even increased in moisture contents, probably due to respiration of the very much alive material.

The four indoor piles also had a considerably lower moisture content after storage. Surprisingly the moisture contents of the ventilated and the unventilated pile did not differ very much. This can be attributed to the fact that the ventilation is restricted to cooling of the piles. The fans only operate while the stack temperature is 5 °C above ambient temperature.

Dry matter

Seen over all the piles, the loss of dry matter varied from 5 % to 23 %. In the dry matter losses the conclusions are not that simple: not always did the piles behave as expected.

The two sections of the whole shoots and 20 cm chunk had been expected to show a very small loss. Instead the whole shoots lost from 5.1 to 10.4 % dry matter and the 20 cm chunk from 9.1 to 12.3 %. Some of this loss can be explained by respiration of the live material. Especially the whole shoots lost dry matter because of the flowering. That the outside section of the whole shoots pile lost double so much as the inner section is hard to explain. May be the extra loss is due to outside interference. Some of the dry matter loss in the whole shoots can also be attributed to soil that had been brought to the trial by the log truck that delivered the shoots at the storage site. This soil dropped uncontrolled from the shoots during the chipping operation. At the next removal measures will be taken to assess the amount of loss through soil.

Still a tendency can be seen that the smaller chip sizes loose more dry matter than the larger chips or chunk. This is illustrated in Fig. 1. It can also be seen that the inside piles in general have smaller losses than the outside piles. This is probably due to the fact that no moisture at all is added to the piles through precipitation and that evaporation can happen without hindrance.

Losses in heating value

The loss in heating value shows a slightly different picture than the losses in moisture contents and dry matter, since there is a close link between the heating value and the moisture contents. This is illustrated in Fig. 2, which depicts the loss of heating value of all the assortments. One pile (whole shoots, paper cover) gained heating value, because the dry matter loss was modest and the moisture contents dropped considerably. Again there is a group of the large sized assortments (whole shoots and 20 cm chunk) and the inside piles that show lower losses than the other outside piles. The loss has a direct connection to the size of the material also.

A comparison between the loss of dry matter and the loss of heating value is given in the three dimensional Fig. 3. The columns are ordered by their loss of heating value.

In all but one case is the loss in dry matter larger than the loss in heating value. Only the silage pile of Austoft 5cm chips has larger loss in heating value than in dry matter. The total moisture content in this pile increased by 4.8 % during the first 6 months of the storage trial. The storage loss in this pile can be attributed to two factors: a modest one of respiration, where during the first few days the remaining oxygen was used to form water and CO_2 and then a silage process where alcohol is formed also with water as a by-product. That is the reason why this pile increased in moisture content.

The calculation in heating value loss has only been based on the dry matter loss. When the results of the alcohol contents analysis become known, the heating value loss will be corrected for this fact.

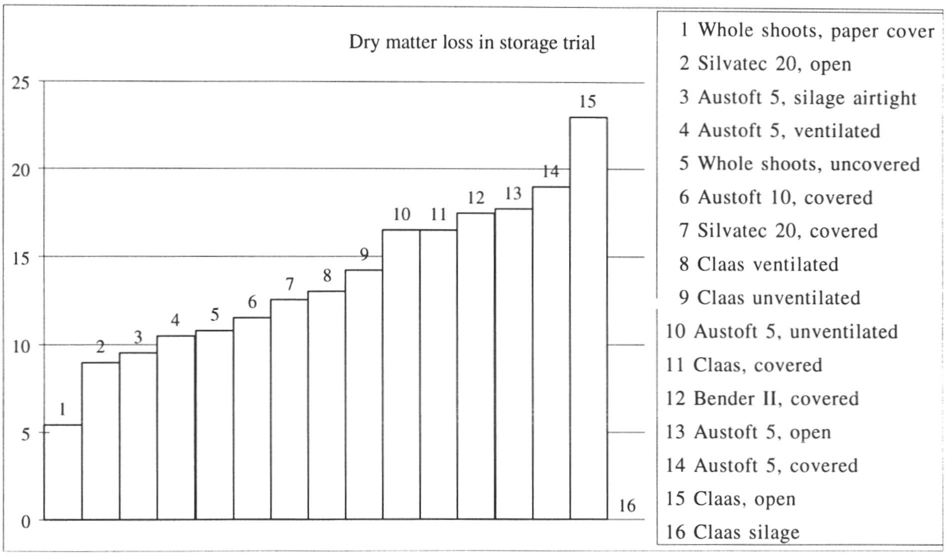

Figure 1. Dry matter losses (%) of all assortments in sequence of losses.

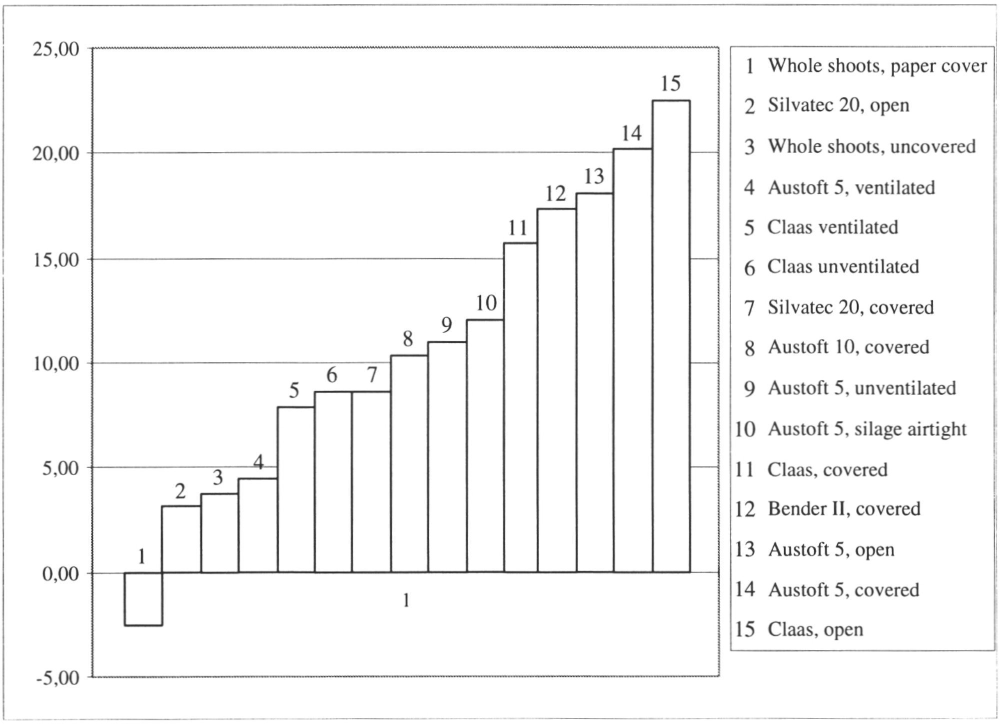

Figure 2. Changes (%) in heating value.

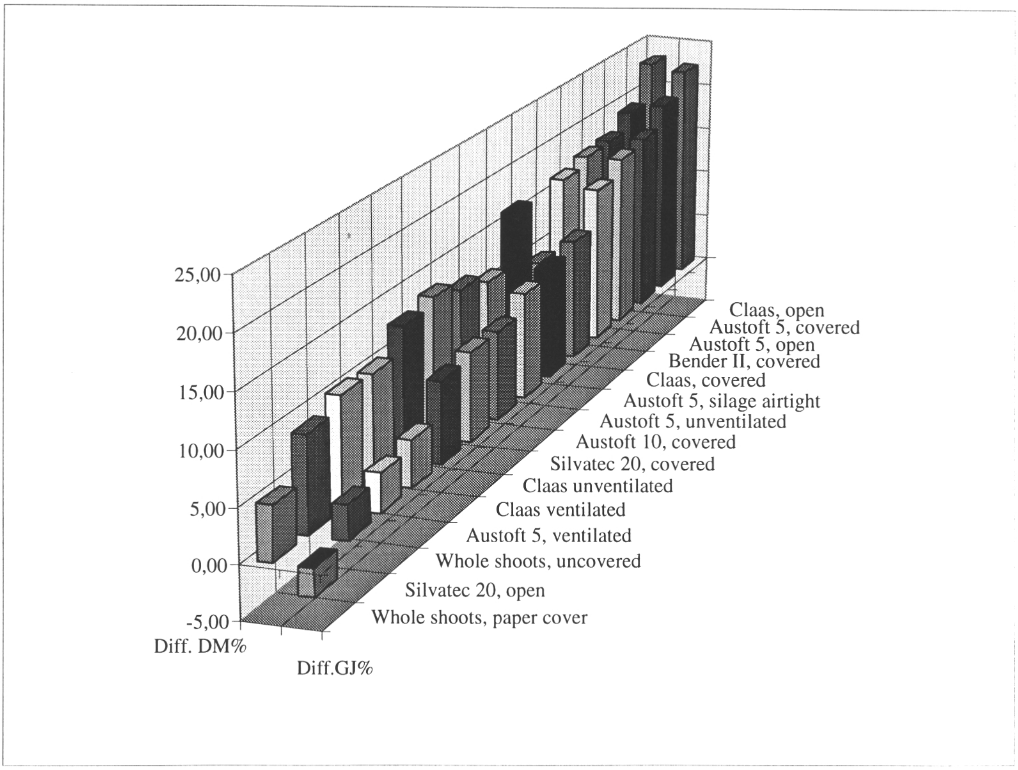

Figure 3. Comparison of changes in dry matter (DM) and energy value (GJ).

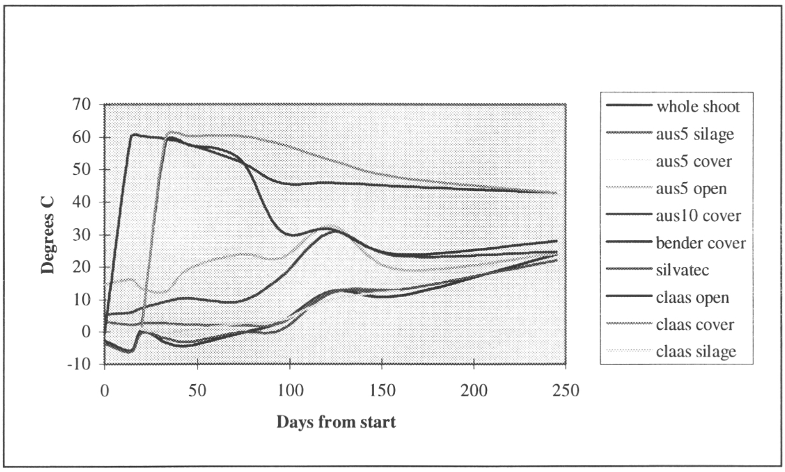

Figure 4. Temperature development in the outside piles.

Temperature development

In all the piles, the temperature development has been monitored. In Fig. 4 it can be seen how the temperature developed in the outside piles. The results from the inside piles have not been received yet from the subcontractor.

It is clear that the finer the material, the higher the temperature in the piles. The temperature in the whole shoots and the Silvatec chunk largely follow the ambient temperature with a certain delay. Remarkable is the temperature of the silage piles, which remain low even though the material is rather fine, especially in the Claas silage pile.

The covered piles have in general a higher temperature than the open piles. The plastic cover, even though it is loose and there is a ventilation pipe in the top, hinders the natural ventilation of the piles.

4 Conclusions

Even though the storage trial has not been finished yet, some conclusions can be drawn:

- Storage of large size particles, such as whole shoots and large chunk shows a lower storage loss than the other assortments
- Storage indoors of chips shows a lower loss than outside
- Storage under tarpaulin showed this year larger losses than in years with "normal" rainfall
- Storage of chips in airtight conditions is promising but should be investigated further, also with other types of chips that are not as fresh as willow
- The temperature in chips piles depends directly on the size of the chips. The highest temperatures were found in the piles with the smallest chips.
- The covered piles had in general higher temperatures than the uncovered, because the natural ventilation of the pile is restricted by the tarpaulin.
- The silage piles showed hardly any raise in temperature.

A report on the whole storage trial will be available at the end of the year, including dry matter loss, development of moisture contents, heating value, bridging properties, fungal spores analysis and analysis of the silage (alcohol, lactic and butyric acid contents).

Employment effects of wood fuel harvesting

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Abstract

Increased use of wood fuels can create new permanent jobs that are economically and socially useful. This paper summarizes several studies, mainly northern European, of the current or estimated labor requirement for heat production based on wood fuels. Differences in conditions, assumptions and methods complicates a comparison and the results shall be regarded as approximations.

The current labor requirement is around 200 man-years/TWh or 425 man-years/ million m^3. There is a considerable variation depending on the supply system. The input of labor can be reduced by using the most efficient methods. Most jobs are in mechanized harvesting.

The total employment effect from wood fuels, including indirect jobs, is estimated to be 400—450 man-years/TWh.

In order to be economically competitive also wood fuel systems have to be mechanized and efficient with low input of labor.

Keywords: wood fuels, harvesting, employment, jobs, manpower

1 Introduction

The increasing use and interest in wood fuels and bioenergy is mainly based on environmental reasons, partly economical, agricultural and other additional advantages. One of these additional benefits which has gained attraction is the opportunity to create new, local jobs. It is of course the high rate of unemployment in most parts of Europe and associated high costs, which has led to increased interest for creating new permanent jobs that are economically and socially useful. According to Grassi (1996) the expenditure for the unemployment in the European Union's 12 member states in 1993 was about 210 billion ECU (11.700 ECU/person).

There are however few studies of employment or manpower requirement in wood fuel systems. In an early Swedish study from 1984 the National Energy Administration (1984:5) estimated the labor requirement for procurement of biofuels to approx. 300 man-years per TWh and an additional 40 man-years/TWh in heating plants. Some years later the labor requirement for procurement of wood fuels is calculated to be only half as high, 100—150 man-years/TWh (Danielsson, 1991).

There are many difficulties in summarizing or comparing studies depending on differences in wood fuel supply systems, ways of calculation, definitions of limits, technology, etc.. To calculate the manpower requirement in a new rapidly developing branch of business is no exact science, but rather a qualified estimate. Instead of summarizing different studies I have chosen to present one previous study and make comparisons with other studies.

One of the more recent and extensive studies of employment effects is a Swedish study (Danielsson and Hektor, 1992) made for the ”Biofuel Commission”, which was appointed by the Department of Industry to analyze the long term possibilities for an increased use of biofuels.

That study is based on both reported results from studies of harvesting systems and statistics and experiences from wood fuel companies. The latter was possible because Sweden has a fairly large commercial market for wood fuels, due to high environmental taxes on fossil fuels. The objective was not to describe the actual situation, but to make a forward looking estimate which would refer to the coming years (which means around mid/late1990s).
To achieve that, the study is based on a conservative calculation of the man-power requirement in the most efficient supply systems.

The employment effects only include direct jobs for harvesting, transportation, administration and combustion. Indirect jobs in manufacturing, construction, service, etc. are not included, neither are multiplying effects from an improved local economy.

For conversion of energy and forestry units the following general factors have been used.

— 1 m^3 (solid wood) = 0,425 ton dry substance
— 1 ton d.s. = 5 MWh (fuel)

2 A Swedish study of manpower requirement

In 1991 when the use of biofuels in Sweden were 32 TWh per year, the actual employment was calculated to be slightly over 200 man-years/TWh in the district heating sector. This corresponds to about 430 jobs per million m^3 of wood. In the forest industry where byproducts such as bark and sawdust are used for energy production the employment was about 35 man-years/TWh (Danielsson and Hektor, 1992).

The labor requirement for additional volumes of wood fuels have been calculated for some different types of fuels and supply systems (Table 1). Roughly three levels of employment can be noticed, depending on systems.

- Internal use of byproducts in the forest industry generates few new jobs.
- Harvesting of fuels from conventional forests and short rotation forestry (SRF) with highly mechanized methods require about 100 additional man-years/TWh (215 man-years/ million m^3).
- Effective methods for private forest owners require about 250 additional man-years/TWh (550 man-years/ million m^3).
- As many as 400 man-years/TWh are required for small scale heat contracting, producing and selling heat from a small plant.

It is obvious that the employment effects depend on the structure in both forestry and the energy sector, and can vary between countries and regions.

The jobs generated by wood fuels from slash and whole trees are mainly mechanized operations in forestry, harvesting and chipping, while the additional jobs at heating plants and the energy sector are few (Table 2).

Table 1. Estimated future additional labor requirement, man-years per TWh of wood fuel.

	Production	Harvesting	Terrain-transport	Chipping	Road-transport	Heating plants	Adm.	Total
By-products	-	-	-	-	17	5	6	28
Slash for fuel	-	-	48	30	18	5	14	115
Whole trees for fuel								
- large scale	-	19	53	17	17	5	14	125
- forest owners	-	135	73	17	17	5	14	261
SRF								
- large scale	31	→	16	←	22	5	15	89
- small scale heat contracting	31	24	30	83	90	133	15	406

Table 2.Estimated future additional employment for use of wood fuels distributed on different types of jobs. Based on large scale harvesting of slash and small trees in Table 1.

Type of jobs	Share of employment
Harvesting	71 %
Road transport	14 %
Heating plants	4 %
Administration	11 %
Total	100 %

3 Present employment levels

Some factors indicate that the study by Danielsson and Hektor underestimates the job potential, or that the development and introduction of new technology has not been as rapid as anticipated.

The need for road transportation is higher. Upgrading of wood fuels to pellets or briquettes adds jobs for the production, which is not offset by fewer jobs at the heating plants. The number of additional jobs at the heating plants are higher.

A summary of the present employment level in two common supply systems is shown in Table 3. It is based on information from fuel companies and heating plants as well as statistics and studies (Brunberg et.al., 1994). It is further assumed that 2/3 of the volume comes from harvesting of logging residues and 1/3 from harvesting of whole trees for fuel.

If by-products are used instead of harvested wood the labor requirement will be reduced by about 100 man-years, while small scale manual harvesting will add approximately 100 man-years. Both alternatives are less likely. Almost all by-products are already used and small scale methods are not common for commercial use of wood fuels. Their relative competitiveness is less in handling of bulky fuel assortments than in conventional harvesting.

Table 3. Present employment effect in Sweden, man-years/TWh.

Operation	Fuel chips to heating plant	Pellets to heating plant
Harvesting	105	105
Transport	40	40
Pellets production	-	45
Distribution	-	15
Heating plants	20000	10
Administration, miscell.	15	15
Total	180	220

4 Other studies

A summary of different studies of employment effects of wood fuels is made in Table 4. It is made without consideration to differences in conditions and assumptions. All data refers only to the number of direct jobs needed for the systems. It is more uncertain whether displaced jobs are taken into account. If not, it will not have any considerable effect, while according to Grassi the displaced jobs account for less than 10% of the new ones.

Even though there is a fairly wide variation, most figures point at a level of around 200 man-years per TWh of wood fuels. The only exceptions are the calculations by

Table 4. Different estimates of employment effects.

Study	Man-years/TWh
Procurement only	
Danielsson,1991	100—150
Hakkila,1996	182
Total systems	
Danielsson and Hektor,1992	
- actual heating plants	~200
- near future	160—170
This paper	
- fuel chips	180
- pellets	220
Hakkila,1996	225
SVEBIO,1996	300
(Swedish Bioenergy Association)	
Grassi,1996	~500
(European Biomass Industry Association)	

the business associations, which are considerably higher. But, it should be noted that Grassi's estimate refers to Central and Southern Europe, with quite different conditions than in the northern parts.

One way of checking the calculations is to compare total labor costs in relation to the value of the fuel. In Sweden the price (value) on fuel chips delivered to a heating plant is approximately 13 million ECU/TWh and the labor costs about 30.000 ECU/man-year. If the need for labor for harvesting and transport only is 150 man-years, the labor costs will account for about 35% of the fuel value. And if 200 man-years are needed, 46% of the value. As a comparison the total labor input in Swedish forestry (harvesting and silviculture) 1993 corresponds to 133 man-years per TWh harvested wood (Skogsstyrelsen, 1995).

In this type of large scale mechanized forestry labor costs should not be close to half of the costs, but rather around 1/3 for a system to be economically competitive. However, in small scale systems it is possible to substitute some input of machines with human labor. The numbers in Table 4 shows that the input of labor is at a reasonable level, but should not be higher. If the use of wood fuels shall generate more jobs it must be by upgrading to pellets, liquid fuels or other high value products.

5 Indirect jobs

Indirect jobs are for example manufacturing and service of machines and equipment, building of heating plants and other jobs generated by the wood fuel system, but not directly involved in the handling. Grassi (1996) has estimated the number of indirect jobs to be approximately at the same as the direct jobs and Hakkila (1996) refers to an estimate at 1,3 times the direct jobs.

The total employment effect, direct and indirect jobs, would then be in the magnitude of 400—450 man-years per TWh or in the region of 900 jobs per million m^3.

6 Conclusions

It is important to notice that estimates of the employment effects shall only be regarded as examples based on certain assumptions. They can give good information about the need for labor in general, but not exact numbers. The labor requirement can vary considerably depending on the supply system. The choice of system, or mixture of systems, depends on the local structure in forestry and the energy sector. Some operations can be done, at the same costs, with more or less labor intensive methods.

Other conclusions are:

- If the main objective is to study the employment effects it is necessary to take displaced job into account.
- Current labor requirement is around 200 man-years per TWh, corresponding to 425 man-years per million m^3.
- Current labor requirement can be reduced by using the most efficient methods.
- Labor requirement is reduced to about 100 man-years/TWh when using by-products and can be about 300 man-years/TWh for manual, small scale methods.
- Most jobs are in mechanized harvesting.
- The total employment effect, including indirect jobs, can be in the magnitude of 400—450 man-years/TWh.

An increased use of wood fuels can create many new jobs, but in order to be economically competitive also the wood fuel systems have to be efficient, highly mechanized and have low input of labor. The number of jobs generated by wood fuels is higher than in traditional forestry, but the difference is not remarkable.

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3 Role of models in developing environmental guidelines for sustainable energy output from forests

Photo Pentti Hakkila

Conceptual framework for monitoring the impacts of intensive forest management on sustainable forestry

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Abstract

There is global consensus among industrialized nations of the world that forest resources should be managed sustainably. Criteria for the conservation and sustainable management of temperate and boreal forests have been developed by the Helsinki and Montreal Processes. Work is underway in participating countries to identify, test, and apply indicators for judging sustainable forest management. Bioenergy forests include managed natural forests, plantation forests, and woody crops. These systems are very different biologically and physically; therefore, system-specific indicators of sustainable management are required, because the biodiversity, productivity, and other values conferred are very different among forest types. It is critical that meaningful, science-based indicators be developed and properly applied to ensure the protection of forests and a bioenergy supply.

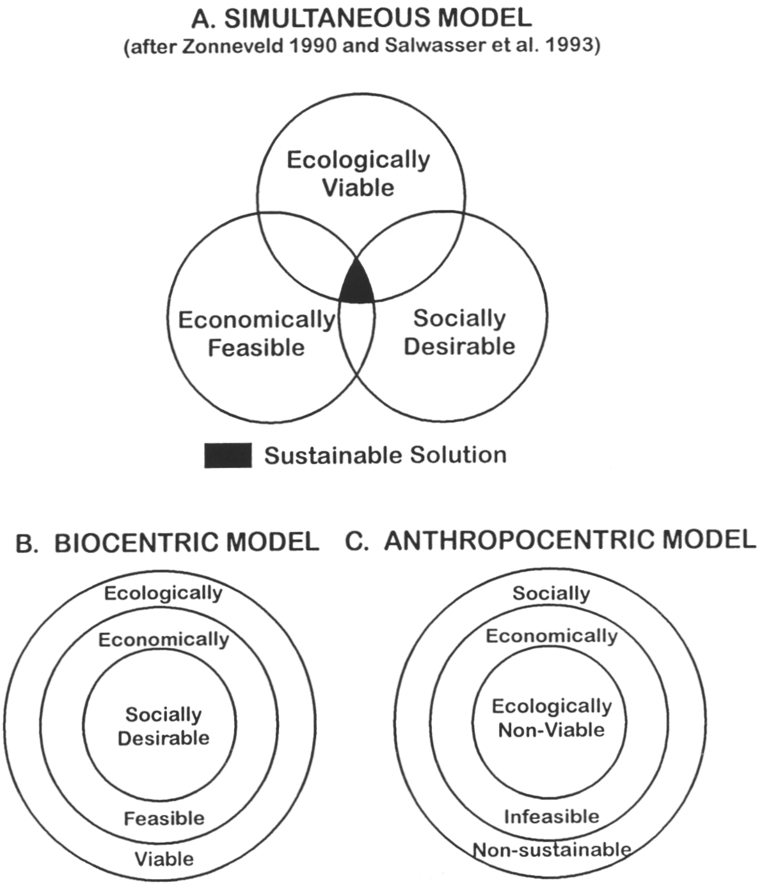
Keywords: Bioenergy, sustainability, soil productivity, biodiversity

1 Introduction

During the past 10 years, the Environmental Issues Activity Group (IEA Bioenergy Task XII, Activity 4.2) concerned itself with forestry practices effects on soil productivity, forest function, water quality, biodiversity, and waste application. These issues remain very much in the forefront of concern in forestry communities throughout the world, and they are the forest environment issues at the root of the sustainable forest management and green certification movements. As we strive towards increasing bioenergy production, we must understand how intensive harvesting and forest management affect soil productivity, forest function and biodiversity so that these values can be sustained in the process. A science-based understanding of management effects is important, because in many places in the world, codes of practice are being written and enacted into law that have little basis in science, but are rather politically motivated and not necessarily good ecologically or economically. Our IEA activity groups should encourage good science in this area, and influence the development of guidelines for the management of forests for bioenergy through information exchange, education, and social and political persuasion. With that in mind, the purpose of this paper is to present a conceptual framework for achieving biological and physical sustainability of forests managed for bioenergy.

2 Sustainable forests versus sustainable forestry

The conservation ethic that has underpinned natural resource management for half of the century is giving way to a sustainability ethic that explicitly contains the notion of intergenerational equity. Whether reference is made to forests, forestry, or human communities that depend on forests, sustainability is usually defined as the potential to produce the same amount and quality of goods and services in perpetuity. The World Commission on Environment and Development (1987) defined sustainability as it pertains to human communities: "development which secures the needs of today's population without destroying the ability of future generations to secure their needs," has been extrapolated to forestry and other resource management systems. For example, member companies of the American Forest and Paper Association (AFPA) have adopted in principle "to practice sustainable forestry to meet the needs of the present without compromising the ability of future generations to meet their own needs" (AFPA 1994).



A. SIMULTANEOUS MODEL
(after Zonneveld 1990 and Salwasser et al. 1993)

B. BIOCENTRIC MODEL

C. ANTHROPOCENTRIC MODEL

Figure 1. Alternative models depicting components of sustainable forestry.

AFPA member companies committed themselves to practicing sustainable forestry, but have not clearly defined it. For whom and for how long is implicit in the notion of intergenerational equity, but precisely "what" should be sustained has been discussed for a decade without complete resolution. Today there is a fair amount of agreement that the forest, the business of forestry, and human communities that depend on forests all need to be sustained and should be part of the definition. Therefore, forest management for bioenergy or other products must be ecologically viable, economically feasible, and socially desirable. Zonneveld (1990), and Salwasser et al. (1993) suggest that sustainability occurs when management is simultaneously viable, feasible, and desirable (the shaded area of Fig. 1A). Perhaps, but this model overlooks a necessary biocentric hierarchical order of the three components (Fig. 1B). A biocentric model recognizes that social structure and function (human communities) are constrained by economic feasibility (business of forestry), and economic feasibility is constrained by (nested within) the ecological system (forest) on which both the economy and society depend. The simultaneous model suggests a need for interactive feedback among components to achieve sustainability, but forests do just fine without human economies and societies. On the other hand, a sustainable forest-based economy requires a sustained forest, and a sustainable forest-based society requires a sustained economy, a nested association depicted by the biocentric model (Fig. 1B). Unfortunately, forest management in many countries of the world can be characterized by the anthropocentric model (Fig. 1C): forest-based human communities enjoying a non-sustainable standard of living on deficit economics based on dwindling forest resources. This is reminiscent of the entire USA society currently enjoying a non-sustainable standard of living on a national economy $6 trillion in debt, while species extinctions accelerate and soil productivity declines.

Sustaining forests, forestry, and forest-based human communities as goals of sustainable forest management are being addressed by the Helsinki Process guidelines for the management of forests in Europe (1994). The Process began with a 31-nation Ministerial Conference in 1990. During a second meeting in 1993, sustainable forestry was defined as "management and use of forests and forest land in a manner and at rate which preserves their biological diversity, productivity, capacity for regeneration, vitality, and potential now and in the future for meeting definite ecological, economic, and social functions at local, national, and global levels without causing damage to other ecosystems." During a follow-up meeting in 1994, a set of criteria and indicators was adopted for assessing whether sustainable forest management is achieved. The criteria are listed in Table 1 next to a list developed via the Montreal Process (1995), a parallel initiative begun by Canada and joined by non-European countries with boreal and temperate forests. The two separate and independent processes came up with surprisingly similar criteria as measures of sustainable forest management, which lends confidence to their value.

Forest management that conserves, maintains, and enhances these six criteria should result, then, in healthy forests for the use of multiple human generations. However, there is concern that biological viability of forests and other environmental resources may not be compatible with the reality of economic development and the improvement of human living standards (Arrow et al. 1996), and there are arguments pointing out that sustainability may not even be an issue because humankind has so far

Table 1. Criteria for the conservation and sustainable management of temperate and boreal forests developed by the Helsinki and Montreal Processes.

Helsinki Process	Montreal Process
1. Maintain forest resources and their participation in the global carbon cycle.	1. Conserve biological diversity.
2. Maintain the health and vitality of forest ecosystems.	2. Maintain the productive capacity of forest ecosystems.
3. Maintain and develop the ability of forests to produce timber and other products and services.	3. Maintain forest ecosystem health and vitality.
4. Preserve and develop the biological diversity of forests.	4. Conserve and maintain soil and water resources.
5. Maintain and develop the role of forests in water supply and protection against erosion.	5. Maintain the forest contribution to global carbon cycles.
6. Maintain other socioeconomic roles and functions of forests.	6. Maintain and enhance the long-term multiple socio-economic benefits to meet the needs of societies.

been able to avoid scarcity through resource substitution and technical ingenuity (Toman 1993), substituting human knowledge, technique, social organization, and capital accumulation for natural resources. How much human knowledge must this generation trade for 10% less biodiversity? How much capital accumulation should be transferred to the next generation to substitute for degraded soils and polluted water? Can we substitute technical ingenuity in harvesting and bioenergy systems for loss in vitality and health of forest ecosystems? Whose economists would make these equity decisions? Certainly not the next generation's.

If and when substitutions are made, irreversibility of some criteria and the reversibility of others should be considered. If this generation trades social organization for higher CO_2 levels in the atmosphere and higher levels of pollutants in waterways, CO_2 concentrations and water quality can conceivably be reversed by future generations. However, for all intents and purposes, at least two criteria, less biodiversity (fewer species) and degraded soil systems are irreversible within generational lifespans and should be considered non-substitutable. These two criteria are fundamental to a biocentric approach to sustainable forestry, and will be used to illustrate a framework for applying sustainability criteria to bioenergy systems.

3 Applying sustainability criteria to bioenergy systems

Forest-based bioenergy is harvested from managed natural forests, long-rotation plantation forests, and short-rotation woody crops. Among these systems there exists a large gradient in system complexity. We attempt to manage natural forests sustainably by encouraging natural processes. To manage woody crops sustainably, we apply many techniques used in agriculture. Plantation forests are managed with a combination of techniques (Fig. 2). Most natural forests have high levels of biodiversity, while woody crops, especially clonal stocks, have low biodiversity. The amount of cultural input and soil manipulation also varies greatly among forest management systems. The sustainability criteria may be the same, but the indicators that measure the success in applying the criteria will often be different because the systems are very different. An integrative approach using functional performance indicators (e.g., forest processes) is best suited for managed natural forests, while a more reductionist approach using structural condition indicators (e.g., soil quality characteristics) is best suited for woody crop systems. In any case, our expectations (and society's) for biodiversity, productivity, and other values contained in the Helsinki and Montreal Process criteria must be different among these bioenergy systems, and sustainability judgments must be system-specific.

Some indicators for structural and functional components of biodiversity and soil productivity are listed in Table 2. Judging the sustainability of management will probably be based on a number of indicators, but they should be chosen, and their response to management should be judged, based on the nature and capabilities of the forest type.

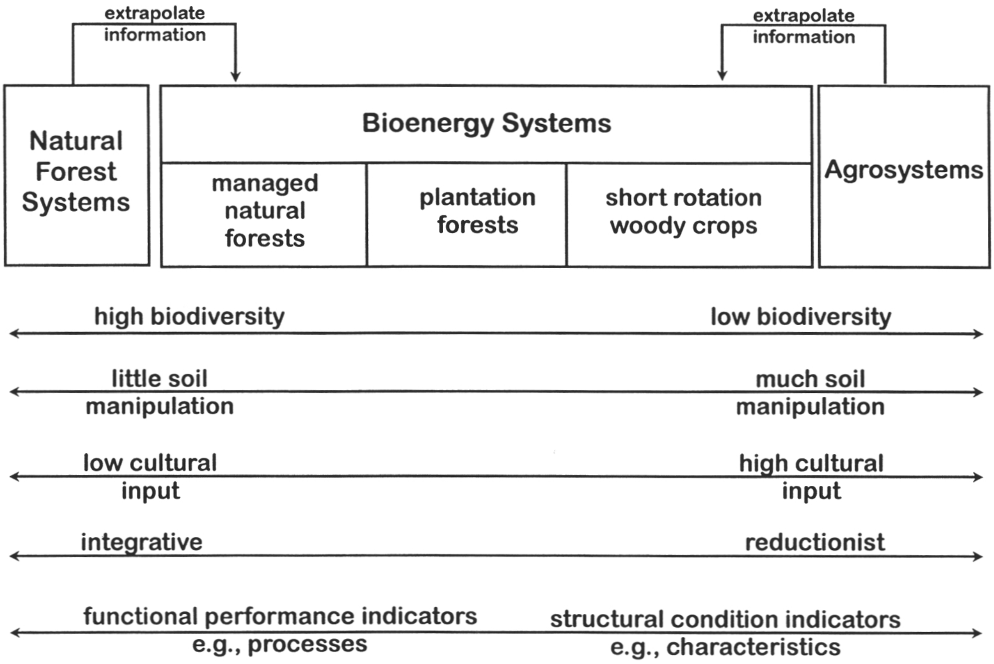


Figure 2. Relative contrast of the nature of natural forest systems, bioenergy systems, and agrosystems.

Table 2. Some proposed indicators of sustainable forest management.

Biodiversity	
Structural: • genetic information • populations • physiognomy • landscape pattern • others	Functional: • genetic processes • life histories • interspecific interactions • land-use trends • others
Soil Productivity	
Structural: • aggregate stability • soil porosity • OM content • available water holding capacity • soil horizonation • others	Functional: • OM decomposition • N mineralization • O_2 diffusion • oxidation/reduction • flora/fauna interaction • others

The effects of harvesting and management are conceptualized in Fig. 3. At some low level of combined structural and functional attributes, a forest system will become non-sustainable. A given forest or forest site has a measurable starting point (e.g., stars in Fig. 3) and its function and structure can be changed by harvesting and management. For example, harvesting and managing forest A for biomass may cause a sustainable impact shown by the vector. The return vector depicts recovery of the functional and structural properties by either natural or human-applied mitigation. Management of forest B is non-sustainable, while forest C shows management-induced recovery of a previously degraded site. The short length of the forest A impact vector depicts high resistance to change, and the complete return of the recovery vector shows high resilience. The opposite is shown for impact and recovery effects on forest B, i.e., low resistance and resilience.

Fig. 4 shows where each of the bioenergy forest types resides on a function/structure response surface for gauging management impacts on biodiversity. Managed natural forests have relatively higher functional and structural biodiversity compared to woody crops. Long-rotation plantation forests fall between the other two forest types.

The forest A example depicts a non-sustainable response to management given that biodiversity did not return to a functional/structural limit defined for managed natural forests. After recovery, management of forest B is sustainable, and the woody crop example depicts sustainability throughout a management scenario.

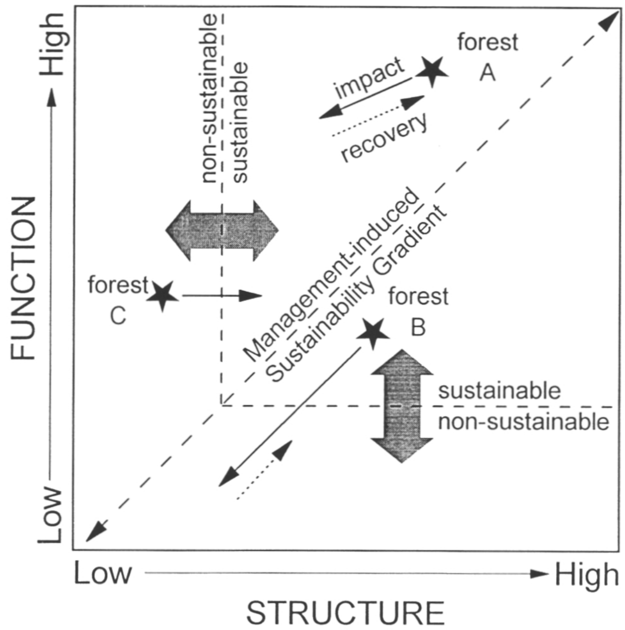


Figure 3. Conceptualization of harvesting and management effects on forest function and structure.

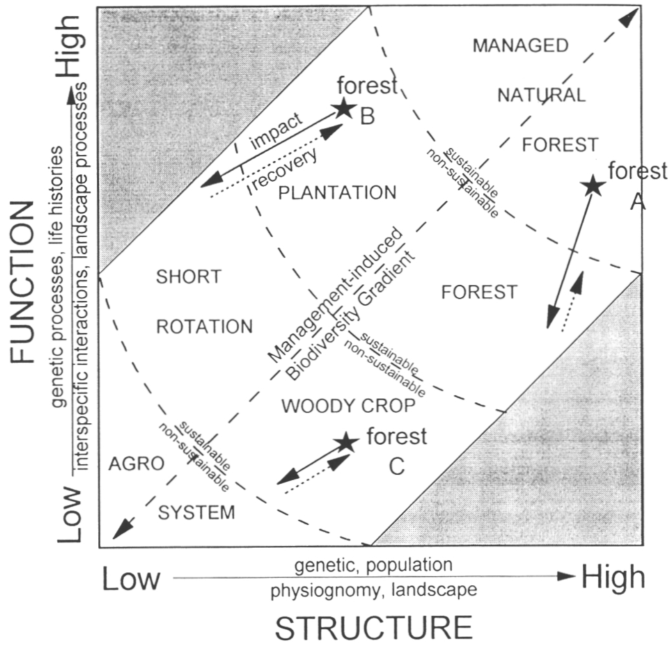


Figure 4. Conceptualized management effects on functional and structural components of biodiversity for three bioenergy forest types. Stars depict pre-harvest biodiversity for hypothetical forests within each type.

All biological and physical criteria identified by the Helsinki and Montreal Processes could be depicted using some version of Fig. 3. It suggests that (i) both functional and structural indicators should be used to judge management impacts on sustainability (an argument might also be made for compositional indicators [Noss 1990], especially for biodiversity); (ii) it shows that sustainable/non-sustainable limits must be identified for each indicator; (iii) that sustainability judgments must be forest-type specific; that forests have different starting points (position of star), some are more resistant to impacts than others (length of vector), and some are more resilient than others (magnitude of recovery vector); and that management can both decrease and increase sustainability.

A final example, Fig. 5, conceptualizes management-induced changes in soil productivity. Instead of plotting indicators by functional and structural attributes, fertility and soil-water/air balance indicators may be more useful for judging sustainability of this criterion. Just as it was argued that biodiversity indicators must be forest-type specific, soil productivity indicators must be soil-type specific. In the southeastern United States, harvesting and management will have a greater effect on fertility indicators than soil-water/air indicators for Entisols. The opposite will be true for Alfisols, which are often poorly drained and susceptible to disturbance from wet-weather logging. The relative importance of fertility and soil water/air balance for each soil order is shown by their placement on the two-way matrix. Some overlap should be assumed, just as soils overlap spatially in nature.

Research is currently under way on forests B and C depicted in Fig. 5. Forest C, located on the coastal plain of South Carolina, is a one-year-old loblolly pine plantation planted after harvesting a 20-year-old plantation of the same species. Wet-weather harvesting severely disturbed the soil and changed the water table level and rate of soil drainage. Logging slash, litter, and surface soil was also redistributed on site. The trajectory and extent of recovery are unknown, but indicators are being used to measure recovery response, and changes in soil productivity indicators will be correlated with stand response (Burger and Kelting 1996).

Forest B, located in a river bottom in southern Alabama, is a tupelo-baldcypress type that also experienced severe soil disturbance during clearcut harvesting of skidder-logged plots. Although soil water/air properties were modified after harvest (Aust 1989), no soil changes were evident after seven years, and naturally-regenerated productivity was greater than that on adjacent helicopter-logged plots (Aust et al. 1996). Forest A depicts slash pine plantations established via mechanical site preparation on sites in the sandhills region of northwestern Florida. Fire and mechanized site preparation that removed significant amounts of organic matter and topsoil from excessively-well drained Entisols was non-sustainable management based on poor growth and yield of the stands (Brendemuehl 1967).

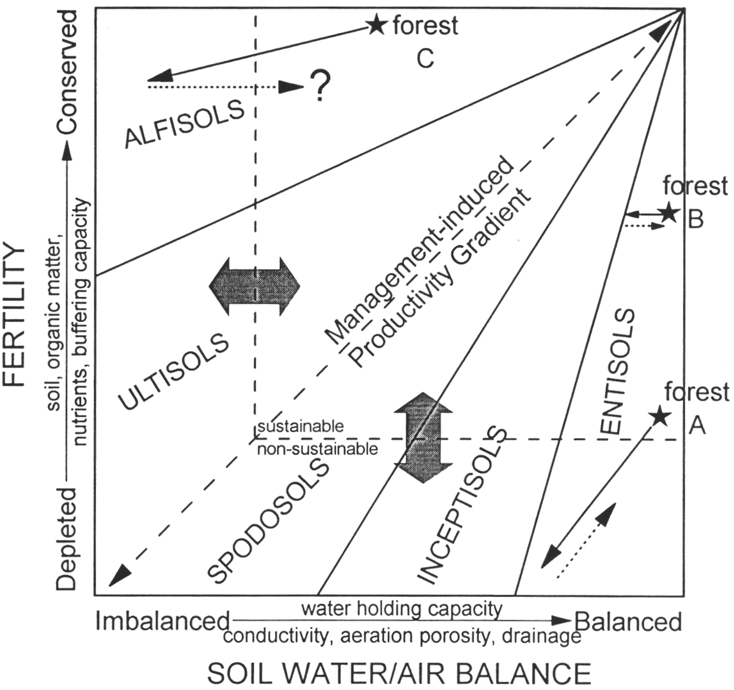


Figure 5. Conceptualized management effects on soil fertility and water/air balance by soil orders. Forest examples are for studies in the southeastern USA. Impact and recovery vectors are described in the text.

4 Conclusion

Sustainable forest management is the stated goal of most public and corporate forest landholders as well as many private landowners. Sustainable forest management has been defined, at least in terms of what it should accomplish, and criteria and guidelines for achieving it have been developed and executed to varying degrees. Biomass forests will be subject to the same sustainability goals as other forests. Many of the same criteria will be used to accomplish sustainability, and levels of success will be scrutinized and judged. A biocentric approach towards sustainability is recommended that recognizes the need to first maintain the ecological viability of forests before imposing economic and social expectations. Sustainability criteria have been identified by local, regional, and world groups; all criteria lists contain the maintenance of biodiversity and land productivity, but not everyone appreciates that loss of either due to management can be irreversible, which by definition is non-sustainable. Indicators of biodiversity and soil productivity, as well as other sustainability criteria, are being researched and developed by a variety of individuals and groups in the global forest community. Forest-, site-, and soil-specific indicators are needed for all biological and physical criteria that are sufficiently sensitive to show important change, easy and cost-effective to measure, collect, or calculate, and calibrated against system change. This process will be more difficult and lengthy than the one needed to define "sustainable forestry." However, it is critical that meaningful, science-based indicators and standards be developed and used to ensure the protection of forests, property-owner rights, and the public's energy supply.

5 Acknowledgements

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Template for developing guidelines for sustainable forest management for bioenergy production

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Abstract

Guidelines for sustainable bioenergy production systems must have both local and global applicability, conceptual relevance to the major issues, and be realistic in recognising ongoing decision support system developments supported by industry and government departments internationally. In addition, guidelines should allow for incorporation of gains in our knowledge and understanding.

The proposed framework for guidelines discussed in this paper includes six components: (1) setting management goals; (2) planning; (3) implementation and operation; (4) monitoring; (5) review; and (6) a research programme. The template is based on the stated intentions of forestry companies to manage their forests sustainably; builds on the philosophy of ISO 14001 environmental management systems and a "plan-do-check-review" cycle; and will eventually produce the information required for management decisions. This approach requires incorporation of local information to be applicable in managing forests for bioenergy production.

As the guideline is developed for local applicability, uncertainty about selecting management practices with the ability to achieve stated goals for bioenergy production and environmental quality should be identified explicitly in the decision making framework (e.g. code of practice). This will enable managers to plan for information acquisition to close gaps in their knowledge base, and to reduce the risks associated with making decisions without adequate information.

Keywords: Bioenergy, sustainability, forest management, guideline template

1 Background

Increasing environmental pressure, particularly on natural resource-based industries, has led to increased legislative control and a move towards global environmental performance standards. This pressure is reflected in international agreements, national, regional- and local-authority policies, and in forest company management goals.

The outcome of this pressure is the ongoing definition and development of environmental performance standards or desirable outcomes. The Montreal Process criteria and indicators (Anon. 1995a and 1995b) are an example of a global standard, and in New Zealand, the Resource Management Act (RMA) (1991) and the "Principles for Commercial Plantation Forest Management in New

Zealand" (signed in Wellington 6 December 1995 by six groups representing the forestry sector and environmental organisations) are two examples. Although slightly different in focus, each of these takes a holistic approach to defining sustainability by seeking to sustain or enhance ecological, social, or economic performance of land use activities. Achievement of environmental goals provides a focus for forest management, and thus provides the focus of decision support systems developed to aid forest industry. Without a stated goal, environmental management can be perceived as an end of its own, and can evolve to be exclusive of other forest management goals.

International concern for the environmental effects of agriculture and forest management has stimulated debate about the sustainability of land use management practices, especially those with the potential to have adverse impacts on a wide range of environmental, social, and economic values. The debate about sustainable land use practices has created the need for relatively precise definitions of sustainability; stimulated research to provide the technical information to underpin the definitions; and created a need for environmental management systems that provide a framework for making sustainable land use management decisions based on elements of planning, implementation, and review.

The International Energy Agency Bioenergy Agreement (IEA Bioenergy) was established for increasing our understanding of the potential for substantial bioenergy production (Brown 1992). The IEA Bioenergy programme has focussed on sustainable land use, and has made significant contributions to developing the technical understanding to underpin definitions of sustainable forest management (e.g. Dyck *et al.* 1994, Smith 1995). These efforts have continued into the present work programme, and the targets to be completed in the three year period for the IEA Bioenergy Task XII Activity 4.2 "Environmental Issues" include: refining the conceptual framework for defining sustainable bioenergy production systems; and developing guidelines for sustainable production systems, which includes guideline review, testing and validation.

The objectives of this paper are to discuss the contextual requirements of guidelines for sustainable bioenergy production systems; and to present the components of a generic template or framework for guideline development, which could be applied internationally to meet local requirements. Where necessary, examples of guideline components will be drawn from New Zealand and elsewhere.

2 Guideline requirements

Guidelines developed in the context of the IEA Bioenergy programme should ideally have global and local applicability; conceptual relevance for forestry, bioenergy production systems, and sustainability; and be realistic, in the sense of recognising ongoing efforts of industry and governmental departments to develop codes of practice and recommendations for best management practices (BMPs). In addition, guidelines must account for limitations in our technical knowledge about sustainable forest management systems, and provide a mechanism for continual improvement as new information becomes available.

One problem associated with guideline development is to take into account regional variation in forestry due to climate, physiography, soils, species (flora and fauna), and socio-economic conditions. Recommendations for BMPs are required before functional relationships are quantified for either forest productivity or sustainable forest management. The relationship between forest productivity and such factors as site quality, genotype, and silvicultural practices is not well established for most tree species and forest types. The problem is even greater for developing BMPs for sustainable forest management, as the current definitions are a mixture of quantitative and qualitative factors. Therefore, for the purposes of the IEA Bioenergy programme, we are not proposing BMPs which are considered prescribed, acceptable practices. Rather, as part of the IEA Bioenergy programme, we are proposing a means of aiding the decision-making process in the context of site-specific conditions and values.

These problems associated with guideline development suggest the need for a "generic template". As such, the guideline template would be a framework of essential components, and would require incorporation of region- and site-specific details for operational application at the local level.

In summary, a framework for guidelines for sustainable bioenergy production systems should:

- aid the achievement of environmental goals;
- be relatively static to aid implementation, but allow revision of component parts as new knowledge or environmental expectations change;
- comply with or be complementary to existing standards (e.g. ISO 14001);
- recognise local, national, and international goals to eliminate duplication of management and ensure consistency;
- involve all levels of forest management and operational staff; and
- provide clear structure to enable performance audits.

3 Guideline template

Forest industry in New Zealand and elsewhere seems to have accepted the importance of environmental management systems (EMS) to their international market competitiveness, since it allows them to demonstrate a commitment to good environmental stewardship. As a result, at least two New Zealand forest products companies have gained certification under the ISO 14001 standards in 1996 (personal communication, Telarc NZ). The proposed guideline template incorporates the philosophy behind ISO 14001 EMS to help managers achieve their stated goals and continually improve using a "plan-do-check-review" cycle. The proposed guideline is a framework for developing adaptive management systems for sustainable bioenergy production. Fig. 1 shows the major components of the proposed framework, which was adapted from elements of the International Standards Organisation ISO 14001 standards for Environmental Management Systems (EMS) (Telarc NZ 1995).

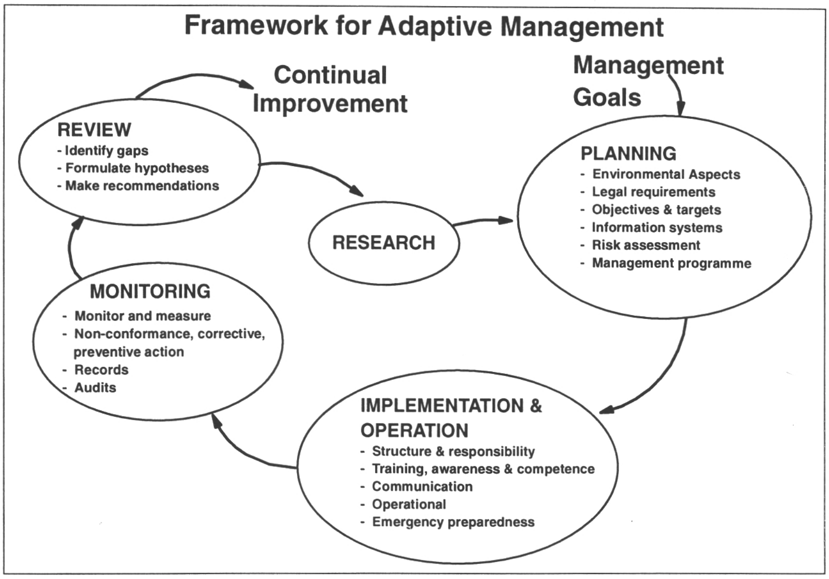

Figure 1. Proposed framework for developing adaptive management systems for sustainable bioenergy production. The framework is adapted from steps involved in the 1995 ISO 14001 Environmental Management System which incorporates elements of a "plan-do-check-review" cycle (adapted from Telarc NZ 1995).

The six major components of the proposed guideline template involve: (1) setting management goals; (2) planning; (3) implementation and operation; (4) monitoring; (5) review; and (6) a research programme. Aspects of planning, monitoring systems, and research will be discussed below, with diagrams used to expand on components of Fig. 1, as necessary.

3.1 Planning

Three essential elements of planning include: definition of environmental values; risk assessment and identification of potential effects of forestry operations on values; and selecting BMPs to protect values. For example, the New Zealand Forest Code of Practice (NZ FCOP) incorporates these elements into an environmental planning process (Fig. 2) (LIRO 1993). The NZ FCOP was developed to guide decision making for all forestry operations, from crop establishment and site preparation to tending and harvesting. The code focuses on identifying appropriate low cost techniques to fulfil environmental and safety objectives. The code addresses a range of environmental issues beyond sustaining forest productivity. However, since most forestry operations have the potential to affect the environment, the holistic approach presented in the NZ FCOP helps management achieve sustainability while considering other criteria.

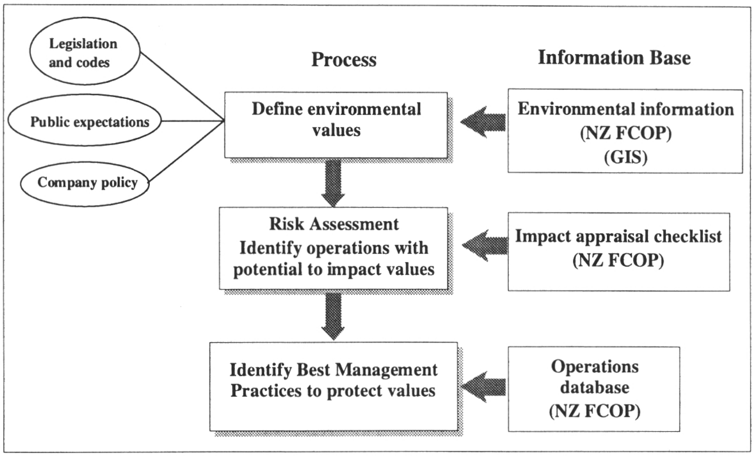

Figure 2. New Zealand Forest Code of Practice (NZ FCOP) environmental planning process.

Environmental values. In this planning step, environmental values are defined by review of relevant legislation and legal codes, public expectations, and company policy. In New Zealand, the RMA promotes sustainable environmental, social and economic values by avoiding, mitigating, or avoiding adverse effects of land use operations. On an international level, agreements similar to the Santiago Declaration (referred to as the Montreal Process) (Anon. 1995a, Anon. 1995b) have proposed criteria and indicators of sustainable forest management based on seven criteria (Table 1). The RMA and Montreal Process are sufficiently broad to cover public expectations for sustainable forest management. One difficulty to overcome in implementing either the RMA or Montreal Process is providing the technical information to underpin such subjective terms contained in each as "significant impacts". Forestry companies depend on global competitiveness for long-term survival; and therefore, are keen to adopt environmental management systems that satisfy internationally established environmental goals.

Table 1. Criteria of sustainable forest management in temperate and boreal forests proposed in the Montreal Process (Anon. 1995a).

Criteria 1—6. These characterise the conservation and sustainable management of temperate and boreal forests, and relate specifically to forest conditions, attributes, or functions.

1. Conservation of biological diversity of ecosystems, between species, and within species
2. Maintenance of productive capacity of forest ecosystems
3. Maintenance of forest ecosystem health and vitality
4. Conservation and maintenance of soil and water resources
5. Maintenance of forest contribution to global cycles
6. Maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies

Criterion 7. Requires that legal, institutional, and economic infrastructures be developed to achieve criteria 1—6.

This component of the proposed guideline template would develop local utility as values specific to the region are incorporated. In New Zealand, common values for forest sites include: soil stability; site productivity; water quality and quantity; healthy aquatic ecosystems; important cultural and archaeological sites; recreation; amenity; safety; and financial yield. A consultative process is generally required so the values of all stakeholders can be identified before operations proceed.

McMahon and Kilvert (1996) used a geographic information systems (GIS) overlay approach to characterise the spatial pattern and sensitivity of a range of values. Values pertaining to a forest near Rotorua, New Zealand were mapped individually, and GIS-type techniques used to produce a composite map which defined the critical values and value sensitivity throughout the forest.

Risk assessment. Forestry companies must develop procedures to identify the potential for their management practices to have an adverse impact on environmental values, and to assess the significance of these impacts. The emphasis here is on adverse effects because of an interest in mitigating negative effects. However, forest managers also select silvicultural practices which maximise positive benefits for the least cost. Identifying the potential for operations to negatively affect values is necessary for choosing among operational alternatives to achieve a specific environmental goal. In the NZ FCOP, this step is accomplished through the "impact appraisal checklist" (Fig. 2). The checklist allows managers to identify forest operations which have the potential to impact values. It is a matrix of operations and values in which the extent and severity of potential effects are rated.

In many cases, our current understanding of the effects of operations on the environment is poor. For example, the effects of slash removal on site productivity are only known for a few sites up to about mid-rotation ages and generally unknown for most types of sites in all major forest regions (see Morris and Miller 1994). However, forest managers are accustomed to making decisions with imperfect information, and must make a decision regarding potential adverse environmental impacts of their operations on the basis of the best information available. It is expected that the regionally applicable "impact appraisal checklists" could be updated as new information becomes available.

Identify BMPs to protect values. Protection of environmental values can be accomplished by selecting operations which avoid or minimise adverse impacts. As mentioned above, the quantitative impacts of many operations on environmental values are not well known, so it is expected that this aspect of the planning process would be improved with research, as, for example, with updates to the "impact appraisal checklist". The operations database used to select cost effective, low impact techniques (BMPs) to protect values should document the source and reliability of the information used to identify adverse impacts and BMPs. Awareness of the reliability of information is important for assessing the risks associated with decisions made on the basis of that information.

Information systems. Information systems are required for forest managers to achieve sustainable management across a generally diverse forest estate. Among other applications, information storage and retrieval methodology is required for spatially based data and for operational databases. Information is increasingly stored in electronic form, and replacing or supplementing hard copy based systems. Geographic information systems are increasingly essential for digitally mapping landscape attributes, environmental values and risks (e.g. McMahon and Kilvert 1996). Operational databases and additional information storage and retrieval can be based on Hypertext software (e.g. Nielsen 1989) or expert systems (see Proe *et al.* 1994). Fig. 2 identifies the ways in which information aids the environmental planning process in the NZ FCOP.

3.2 Monitoring systems

Monitoring is an essential component of an environmental management system to determine if goals are being met, and if not, how to do better in the future. In the proposed framework for guidelines, monitoring and management review are essential elements to identify the adequacy of the operational phase of management; to identify gaps in knowledge or the planning process; and make recommendations for improved management or research, where knowledge is inadequate (Fig. 1).

In bioenergy production systems, monitoring is required for silvicultural and operational performance measures, and may be required for research reasons. Silvicultural monitoring includes repeated measures of tree nutrition and growth

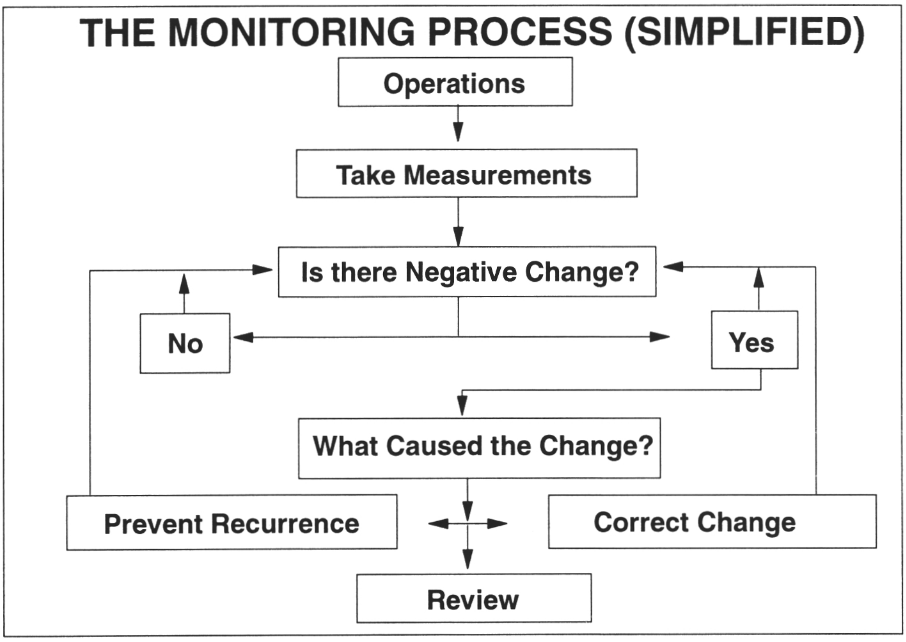

Figure 3. The monitoring process (after Platt 1992).

rates on permanent sample plots (PSPs), and is conducted routinely by most forest managers. Operational monitoring is required to audit compliance with performance standards for operational outputs and environmental impact analysis, and is an essential step in the "plan-do-check-review" cycle of ISO 14001 and other EMS approaches.

Research monitoring can only be conducted within the framework of an experimental design. However, it is important to recognise that the monitoring process involves taking measurements and making management decisions based on analysis of the results (see Fig. 3). If the knowledge base is insufficient to make recommendations on the basis of the monitoring, then research must be conducted to enable better decision-making in the future. We propose the incorporation of research into the ISO 14001 framework for adaptive management systems for bioenergy production (see Fig. 1) to enhance the potential for continual improvement in the information underpinning management decision making.

3.3 Research programme

An important component of the proposed framework is the means of improving management performance through the process of evaluating and monitoring performance, identifying gaps in knowledge, formulating hypotheses, and conducting research to develop new knowledge for improving BMPs (see Fig. 1). These components provide a system where research and adaptive management are linked to increase the forestry knowledge base and improve BMPs for sustainable bioenergy production systems. Such an approach is based on concepts developed by forest industry and should meet their requirements for practicing sustainable forest management (Heninger *et al.* 1995).

The sustainability of bioenergy production systems based on either short rotation or conventional forestry has yet to be demonstrated. Ongoing research is required to identify sustainable production systems for all major forest regions of the world, and to provide forest managers with adequate decision support tools. For example, research results are needed to improve the "impact appraisal checklist" and to ensure BMPs have the potential to achieve the stated environmental goals for bioenergy production systems. A paper presented by Smith *et al.* (1996) indicated how New Zealand research was designed to improve risk assessment for harvest residue management to sustain site fertility for *Pinus radiata* production. These recommendations could eventually be incorporated into the NZ FCOP impact appraisal process.

4 Summary

Guidelines for sustainable bioenergy production systems must have both local and global applicability, conceptual relevance to the major issues, and be realistic in recognising ongoing decision support system developments supported by industry and government departments internationally. In addition, guidelines should allow for incorporation of gains in our knowledge and understanding.

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Empirical models and the use of databases in developing decision support tools for the sustainable removal of biomass from forests

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Abstract

This paper examines some of the issues regarding the practical definition of sustainable forest management and explores how far current information, based largely upon empirical models, can take us in producing guidelines for sustainable bioenergy production from forests.

Sustainable systems of production must be environmentally acceptable, ecologically sound and economically viable. People who use a decision support system (DSS) may be involved in policy development, forest management or energy production. It is important, therefore, to provide sufficient information to meet the needs of a wide range of potential users.

An approach is described by which the risk to sustainable forest management may be incorporated within a DSS in such a way that the user can set acceptable risk levels. Examples from Scotland are used to illustrate several components of a potential DSS. The stages necessary to develop and implement a DSS for assessing the likely consequences of bioenergy production from forests are outlined and potential limitations of such an approach are discussed.

Keywords: Decision support system, DSS, risk assessment, sustainable management, forest bioenergy, site and yield modelling, soil classification, site classification, indicators of sustainability.

1 Introduction

There have been a plethora of initiatives to promote sustainable development following the publication of Agenda 21 from the Rio Summit (UNCED 1992). In many of these, emphasis has been placed upon the use of renewable energy sources and a reduction in consumption and reliance upon fossil fuels. Forests have, for many centuries, been a source of fuel in many regions of the world. There is concern, however, that the use of forest products for fossil fuel substitution in industrialised countries may lead to more intensive silviculture. This could occur through the use of short rotation production systems or the intensification of harvesting from conventional forests to include nutrient rich crown components such as twigs and foliage. Whether or not such systems of production will prove to be sustainable remains a controversial issue because there is presently no consensus on the methodology to be adopted in the assessment of sustainable forest management (Heinen 1994; Zinck and Farshad 1995). The purpose of this paper is to examine some of the issues regarding the practical definition of sustainable management and to explore how far current information, based largely upon empirical data, can take us in developing decision support tools to assist in producing environmental guidelines for sustainable energy output from forests.

2 Considerations in the development of a Decision Support System

A decision support system is a *tool* which provides *information* to *assist* in the making of *decisions*, where a decision is a *judgement*. Thus, in considering our current understanding and sources of information available for the development and implementation of a DSS, it is necessary to clarify:

— What decision is to be made?
— By whom is the decision to be made?
— Upon what is the decision to be based?

What Decision is to be made?

In the context of the present paper, there are two decisions, or "judgements" that may be required:

— How can bioenergy be produced on a sustainable basis from a given site?
— Where can a given bioenergy production system be practised on a sustainable basis?

In the present context, the term "sustainable" implies that the system of production must be environmentally acceptable, ecologically sound and economically viable. The exact criteria used to define these components of sustainability have been discussed elsewhere (Toman and Ashton, 1996; Burger 1997; Smith 1997) and must, to some extent, be case sensitive and defined by the user of the DSS.

By whom is a decision to be made?

There are a number of "key players" who may be involved in making judgements regarding the sustainable production of energy from forests:

— Policy makers developing a regulatory framework
— Forest managers producing the biomass
— Managers of industry involved in the utilisation of biomass for energy

Factors which influence the judgement of each key player may be similar but the weighting associated with each factor may differ according to individual priorities (Table 1). If we consider the three components of sustainability to be environmental, ecological and economic then there are three possible scenarios for the three types of decision makers:

a) all agree that each factor is of paramount importance;
b) the importance of each factor differs but all agree on the ranking;
c) the importance of each factor is ranked differently by each decision maker.

Table 1. Potential scenarios for the prioritisation of components of sustainability (environment, ecology and economics) by different users (policy makers, forest managers and industrial energy producers) of a decision support system. 3 = most important; 2 = intermediate importance; 1 = least important.

	Environment	Ecology	Economics
a) All components of paramount importance			
Policy	3	3	3
Management	3	3	3
Industry	3	3	3
b) Priorities of each user coincide			
Policy	2	1	3
Management	2	1	3
Industry	2	1	3
c) Priorities of each user differ			
Policy	3	2	1
Management	2	1	3
Industry	1	3	2

The third scenario is the most likely and, as such, a wide range of information may be needed to assist each decision maker with the judgements they may wish to make.

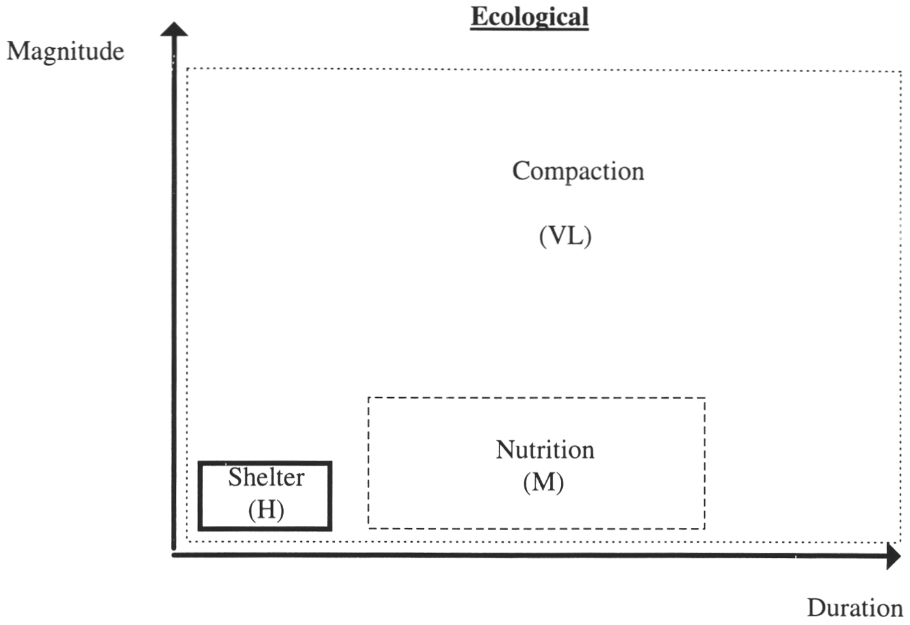
This situation becomes increasingly complex when one considers that all decisions, or judgements, are based either explicitly or implicitly upon *risks*. In addition to the ranking of each factor being different between decision makers, their perception of acceptable risk may also differ (Table 2). Several factors may influence the perception of risk and its acceptance by decision makers. First, the components of sustainability may be ranked differently as illustrated in Table 1. Secondly, the level of acceptable risk may be influenced by the number of potential outcomes to which the risk applies. A policy maker may accept a consequence of 10 per cent economic failures in business if the returns from the remaining 90% increase sufficiently. A single enterprise may have an acceptable risk level of 1 in 1000 compared to the 1 in 10 which may be accepted by policy makers. Finally, the consequences of a given action may affect the perception of risk. The risk associated with tossing a coin to decide who starts a football match may be perceived quite differently to the risk associated with gambling your house on the toss of a coin even though the probability of each is 50%.

Table 2. Quantitative and qualitative perceptions of risk by different decision makers.

Econ = economic component of sustainability
Environ = environmental component of sustainability
Ecol = ecological component of sustainability

RISK		Decision Maker		
Quantitative	Qualitative	Policy	Manager	User
1 in 1000	Very Low		Econ	
1 in 100	Low	Environ	Environ	
1 in 20	Moderate	Ecol	Ecol	Ecol
1 in 10	High	Econ		Econ
1 in 5	Very High			Environ
1 in 2	Ex. High			
1 in 1	Certain			

Fig. 1 illustrates the factors which may affect the perception of acceptable risk with respect to the potential impact of whole-tree harvesting on the ecological elements of sustainable production. It is known that removal of harvest residues will change the microclimate of the forest floor (Proe et al 1994). This effect is relatively small compared to seasonal and annual variations in climate and will only persist for a short time until vegetation regrowth occurs. There are few options that managers have in ameliorating the possible consequences of altered microclimate. However, although the effect is fairly certain and there may be very limited scope for amelioration, a *high probability* for such an impact may be tolerated because the *effect* is perceived to be small and transient and the *risk* (represented by the area of the rectangle in Fig. 1) is therefore low. The nutritional consequences of whole-tree harvesting are less clear (Aber et al 1979; Carey 1980; Lundkvist 1988; Proe and Dutch 1994). It is likely that on some sites, increased removal of nutrients at harvest may have an impact on the ecology of a site for a considerable period and the magnitude of that impact may be substantial. There may, however, be a range of ameliorative options available if the ecology of a site is adversely affected, such as fertiliser application or wood-ash recycling. Under these circumstances a *moderate probability* of damage may be deemed acceptable as the *risk* is difficult to predict and there is some scope to ameliorate any adverse consequences that may be observed. It has been hypothesised that whole-tree harvesting may increase soil compaction where the brash mat is removed and ground-based harvesting is practised. Soil compaction can have a large and prolonged effect upon ecological processes, and ameliorative measures, where possible, may be very expensive (Donnelly and Shane 1986; Skinner et al 1989). For these reasons, the *risk* associated with soil compaction may be perceived as *high* and the probability of occurrence must be minimised by appropriate harvesting practices.



Risk = f (Magnitude, Duration, Probability)

± f (Ameliorative Options)

Figure 1. Factors contributing to the ecological risk associated with whole-tree harvesting. H indicates high probability of occurrence, M indicates moderate probability of occurrence, VL indicates very low probability of occurrence. Areas of rectangles represent degree of risk with respect to shelter, nutrition and soil compaction.

Upon what is a decision to be made?

Whilst issues of sustainability have been the focus of much discussion following the Bruntland Report (WCED 1987) and Rio Summit, the concept of sustainable yield is well rooted in forest management and silviculture (Maini 1992; Wiersum 1995). Although this is only a subset of "deep" sustainability (Heinen 1994) it is, perhaps, a starting point in considering how the production of energy from our forests may impact upon sustainability with respect to the long-term yield of biomass from tree crops. Given that decisions are having to be made now with respect to the sustainable management of our forest resources it is important to consider and, where appropriate, use sources of information currently available whilst recognising the limitations of that information.

3 Applicability of Decision Support Tools and assessment of risk

There are two important issues when considering the development of DST's based upon currently available information and our present understanding of ecosystem function:

- How to generalise results?
- How to quantify risk?

Generalisation of Results

Results may be generalised by three procedures:

- First Principles
- Extrapolation
- Interpolation

If our understanding of processes is sufficient then it may be possible to generalise results from first principles using known physical or chemical laws. Such a level of understanding has yet to be achieved with respect to the functioning of forest ecosystems and we still rely heavily upon empirical information to guide management decisions. Extrapolation from one system to another or from the present to the future may be the only option available in the absence of other information. However, such an approach necessitates making assumptions regarding the stability of relationships through space or time which cannot be tested and which may well prove unfounded. Given our current level of understanding and the type of information available for the development of DSS's, the most effective approach is that of interpolation. Our aim must be to produce response surfaces for key indicators for each component of sustainability. A surface is required because many responses may be non linear and several indicators may interact.

Smyth and Dumanski (1995) recognised the following attributes as being important for the choice of suitable indicators:

- They should show steady, reasonably predictable responses to change without significant fluctuation over short periods or short distances
- They should represent a clear measure of a cause having a well understood effect
- They should be able to be measured and expressed in numerical terms

However, Mitchell et al (1995) identified a number of causes of uncertainty in the use of indicators:

- little or no knowledge of critical system limits
- incomplete or poor quality of data
- unpredictable system behaviour

They concluded that a likely range of indicator values may be preferable to a single value, especially if a probability distribution could be attached to the values.

Quantification of risk

In crop production, risk has been defined as the probability of not meeting one's targets and is a function of average yield, yield target and the variance in yield (van Noordwijk et al 1994). It is therefore necessary to have models in which crop growth is sensitive to *yield determining variables* and *major management factors* together with an expected probability distribution for environmental variables for annual crops (van Noordwijk et al 1994). Forest yield models have often focused upon yield determining variables but ignored management factors which may affect yield because "good management practices" are assumed to be an inherent component of forest management.

4 Information sources

Site and yield studies

One avenue of potential information with respect to long-term production is to examine the large number of site and yield studies that have been conducted over many years. Such studies comprise the development of empirical yield models relating site variables to production using regression techniques. There are, of course, severe limitations in such models, not least of which is the lack of explicit representation of cause and effect relations. This may, however, be less of an issue than it may seem. Many of these models have been developed by "experts" working in forest research or forest management. As such, the selection of candidate variables for inclusion in site and yield models represents a compromise between variables that "experts" consider likely to be important in determining forest yield and those that are readily obtainable and quantifiable, at a reasonable cost and used by practising foresters. In research, the latter constraint may be relaxed.

In a review of forest site quality evaluation in the US, Carmean (1975) listed a wide range of topographic, climatic and soil features that had been used in regression analyses. Many have been summarised in Table 3. It should be remembered that site and yield models are usually confined to a given region and are species specific. Although there may be no explicit representation of cause and effect relations within such models it is possible to produce response curves for individual soil features. For example, Alban (1974) expressed site index (SI) as:

$$SI = bo + b_1 X + b_2 \mathrm{Ln}\, X$$

for each X variable which included several determinants related to soil chemistry. Such equations produce curvi-linear relations of the form illustrated in Fig. 2. A similar response was obtained by Haig (1929 cited in Coile 1952) for the relationship between site index and the soil physical attribute of the proportion of "fines" (silt and clay) in the surface horizon (Fig. 3).

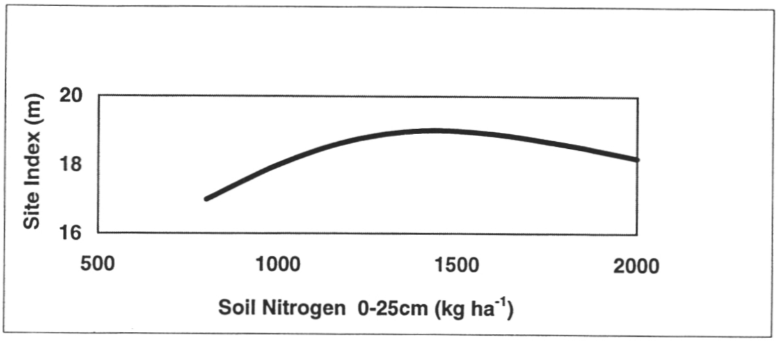


Figure 2 a. Effect of soil nitrogen content on site index for red pine.

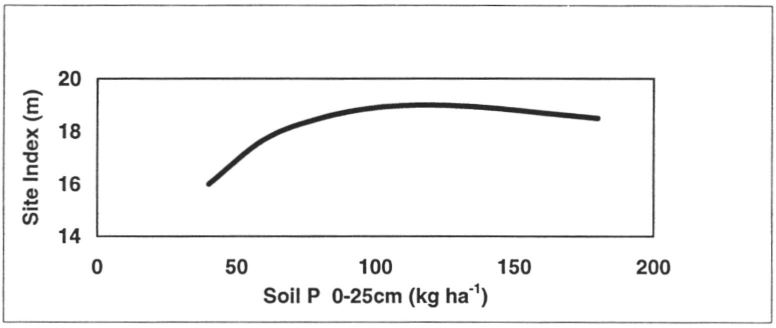


Figure 2 b. Effect of soil phosphorus content on site index for red pine.

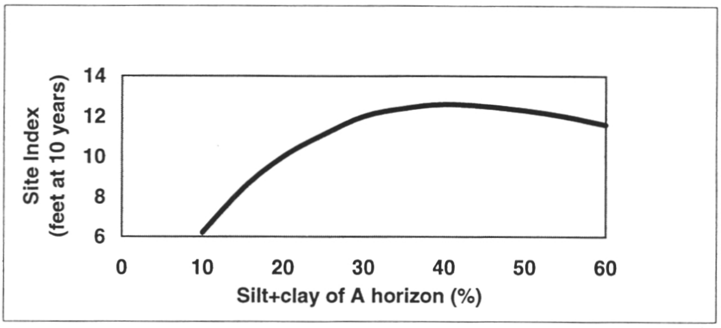


Figure 3. Effect of silt and clay content of soil on site index of red pine.

Many studies have used regression techniques to predict tree growth from a broad range of site factors, many of which may be influenced very little by management. For example, volume growth of Sitka spruce in Scotland was predicted from data held within a geographic information system which comprised temperature and rainfall data (corrected to a measured site elevation) and a differentiation between organic and mineral soils (Allison et al 1994). This model was able to account for 59 per cent of the variation in general yield class (Hamilton and Christie 1971) of Sitka spruce in Scotland. A number of data sets were included in the study by Allison et al (1994).

Table 3. Topographic, climatic and soil features used in forest site quality evaluation in the U.S. (Carmean 1975).

Topography / climate	Soil
Latitude	Surface soil depth
Rainfall	Surface soil organic content
Temperature	Surface soil N
Aspect	Depth of surface peat
Elevation	
Slope position	Subsoil texture
Slope steepness	Thickness of B2 horizon
Surface drainage	Subsoil imbibitional water value
	Subsoil stone content
	Subsoil density
	Drainage class
	Depth to least permeable horizon
	Depth to mottling
	Soil Group
	Soil pH
	Depth to fine textured horizon
	Depth of rooting
	Soil K
	Depth of A and B horizons
	Available moisture
	Available P and K
	Water table depth
	CEC

Two earlier studies had examined site and yield relations for Sitka spruce in the upland areas of Scotland and Northern England (Worrell and Malcolm 1990a, 1990b) and on better quality land in Scotland (Macmillan 1991). Variables used in the regression equations and the performance of these models are summarised in Table 4. Climatic factors dominated the growth of Sitka spruce in Upland areas, explaining 78 per cent of the variation in general yield class with a further 2 to 4 per cent being explained by local topography and soil factors. On the better land, however, only 37 per cent of the variation could be explained by the selected variables with climate being far less dominant and local site factors likely to have been more important. It is clear that the response of tree growth to climatic and edaphic factors is site specific with attributes varying in importance from site to site. For each of these studies it was also observed that the error of prediction for a single site was large (typically around 25 to 40 per cent) whereas errors of prediction for groups of similar sites were much less (around 5 to 10 per cent). Thus, the precision of such models may be sufficient for strategic use at a national or regional level but of little value to forest managers at an operational level.

Table 4. Variables used in regression analysis of Sitka spruce growth in the uplands and lowlands of northern Britain.

Uplands	Lowlands
Elevation	Elevation
	Slope
Temperature	Yield Class Zone
Wind	
Rain	
Topex	Topex
Aspect	Aspect
Major Soil Sub Group	Major Soil Group
Total Soil Depth	
Rooting Depth	
	Site Drainage
	Soil Drainage
Crop Age	Crop Age
$r^2 = 86\%$	$r^2 = 37\%$
n = 187	n = 121
$r^2 = 78\%$ (elevation, temperature, wind)	
Worrell & Malcolm (1990a and 1990b)	Macmillan (1991)

In a study of relationships between the growth of Sitka spruce and soil attributes in north east Scotland, Blyth and MacLeod (1978) obtained the strongest correlations with rooting depth, thickness of organic layer, soil pH and total phosphorus content of the surface horizon. The same authors examined the variability of soil characteristics in terms of the number of samples required to estimate plot means (0.01 ha) to within ± 10 per cent (Blyth and MacLeod 1978). They required 6 samples for total nitrogen content, 9 samples for total phosphorus content and 29 samples for acetic acid extractable nutrients.

From their work, Blyth and MacLeod (1981) recognised the following properties of site variables as being desirable for yield prediction:

— well-correlated with growth
— regular pattern of variation across the landscape
— good precision of measurement
— low variability across management units

To this list could also be added that they should, as far as possible, be independent of one another if they are to be used in the assessment of sustainable forest management. There is, to some extent, a conflict in attempting to identify indicators of sustainability that respond to forest management and yet are reasonably uniform across the landscape and can be measured with sufficient precision to recognise change.

Soil and site classification

Many countries have their own soil classification system used for mapping and site classification. The soil classification system used in Scotland is based largely upon morphological features that could be recognised easily in the field by soil surveyors, and takes little direct account of soil chemical properties (Butler 1980). However, a large database now exists with information on soil physical and chemical attributes for the units used in mapping. Such information may be of use in the development of Decision Support Systems if they can be linked to site and yield modelling and risk assessment.

Fig. 4 shows a generalised hypothetical growth response to a site or soil attribute. The response curve can be divided into six regions, or classes, based upon the growth response to an increasing value of the attribute:

I	Insensitive due to attribute value being too low
II	Gradual positive response
III	Rapid, positive response
IV	Little response which may be positive or negative
V	Gradual negative response
VI	Insensitive due to attribute value being too high

By characterising the growth response to attributes held within a soils database, it may be possible to identify key attributes. Frequency distributions for each attribute can then be produced. For example, Fig. 5 shows the frequency distribution of soil pH for the uppermost soil horizon in over 3100 of the soil profiles held within the Scottish Soils Database located at the Macaulay Land Use Research Institute in Aberdeen. If the soils are then limited to histo-placic podzols that have developed over acidic parent material the frequency distribution becomes much narrower (Fig. 6). These distributions will depend upon the specific attribute being examined and the individual soil groups being extracted from the database. There is a much wider distribution of soil pH for brown earths (cambisols) developed on near-neutral (Skokloster values between 0.5 and 1.0 keq H^+ ha^{-1} y^{-1} according to Langan et al. 1995) parent material (Fig. 7) but such a frequency distribution can still be of use in

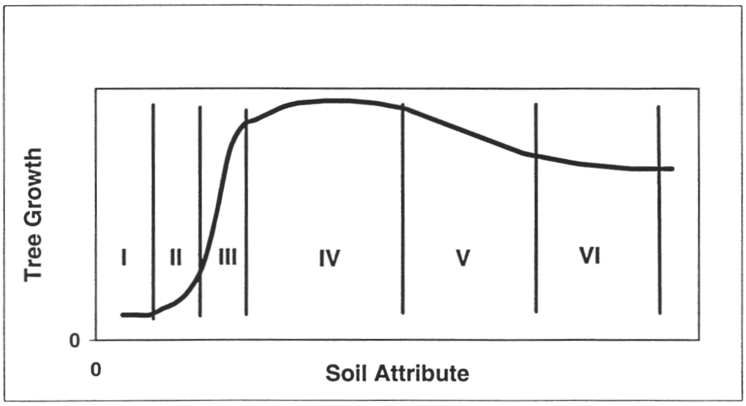


Figure 4. Hypothetical growth response of trees to a given soil attribute (categories explained in text).

risk assessment. By superimposing such frequency distributions upon growth response curves for each soil attribute, the likely sensitivity to that attribute on a given site (for which the soil type is known) could be assessed (Fig. 8). Table 5 illustrates the type of output which may be possible from such Decision Support Systems. Such information could then be used to decide if a more precise value of the attribute is needed and knowledge of the variability of that attribute could aid the decision of sampling strategy to be used in the field. For more strategic evaluations, soil maps could be employed and the frequency distribution of soils within mapping units could be used to assess risks associated with intensive harvesting on different site types.

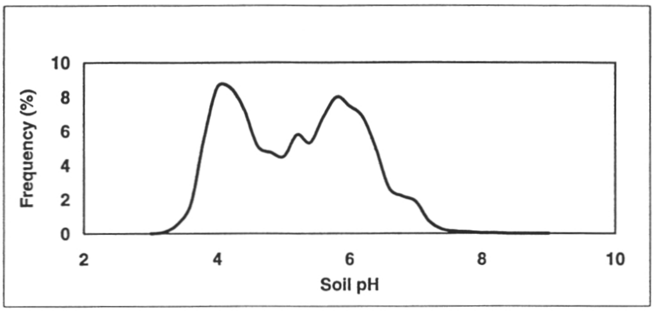


Figure 5. Frequency distribution of soil pH in water for uppermost horizons of 3116 soil profiles (data extracted from the Macaulay Land Use Research Institute's soils database for Scotland).

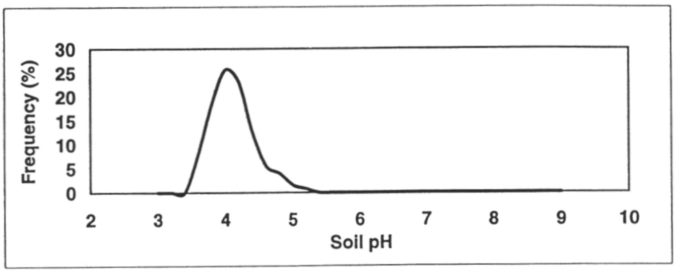


Figure 6. Frequency distribution of soil pH in water for uppermost horizons of 125 histoplacic podzols developed on acid parent material (data extracted from the Macaulay Land Use Research Institute's soils database for Scotland).

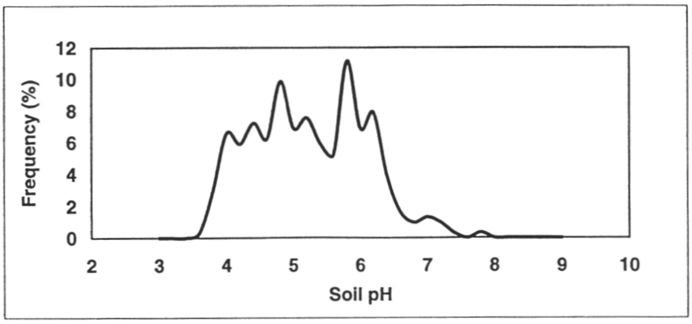


Figure 7. Frequency distribution of soil pH in water for uppermost horizons of 305 cambisols developed on near-neutral parent material (data extracted from the Macaulay Land Use Research Institute's soils database for Scotland).

Table 5. Potential form of output from a component of a decision support system for evaluating the sustainability of bioenergy production from forests

pH class	Growth Response	Acidic PM* histo-placic podzol probability	Neutral PM* eutric cambisol probability
I	none	0	0
II	+	0.5	0.1
III	+ + +	++ 0.5	0.3
IV	none	0	+ 0.3
V	- -	0	- 0.2
VI	-	0	0.1

* PM = Parent Material
\+ = positive growth response (number of +'s indicate strength of response)
\- = negative growth response (number of -'s indicate strength of response)
shaded areas represent majority of distribution for each soil grouping

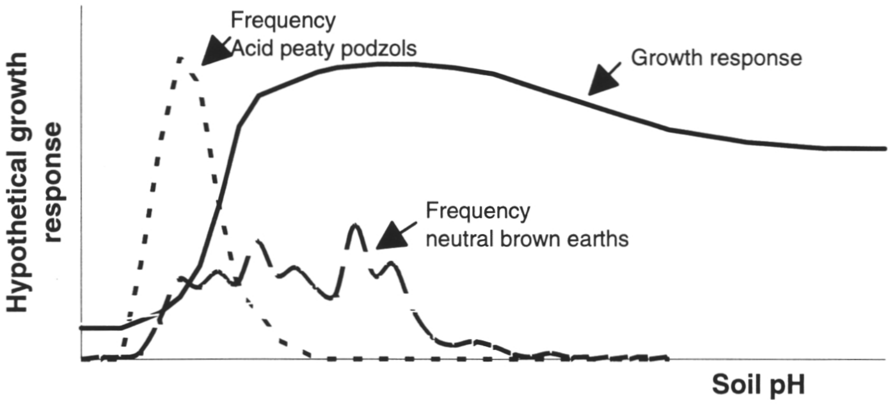


Figure 8. Frequency distributions of soil pH in uppermost soil horizons from contrasting soil types superimposed upon a hypothetical growth response of trees to soil pH.

It is clear that a key component of such a system is to characterise the impact of management, for example intensive harvesting, upon key soil attributes. This must be done by carefully designed, long-term field experiments and by using the understanding we do have to impose boundaries around the likely magnitude and direction of change on different site types. Such an approach can ensure that appropriate measurements are taken on existing experiments and that sampling protocols are appropriate given the variability associated with each attribute. If these attributes can be linked directly to vegetation communities, as has occurred in a number of site classification systems which use indicator species, then it may be possible to assess management impacts upon economic and ecological components of sustainability with a *user-defined* level of risk.

A major issue in this approach is a breach of the assumption that each key indicator is independent. It is well known that human assessments and heuristics are susceptible to ignoring key interactions. Where such interactions occur, it is necessary to develop response surfaces linking such attributes and to examine site characteristics and potential management impacts within such surfaces. This would need a more sophisticated statistical approach beyond the scope of this paper, but the principles should remain the same.

5 Conclusion

It is clear that we have to make judgements within constraints of time, money and existing knowledge (Andrews 1988) but, as stated long ago by Ortega y Gasset (1944 cited in Miller and Wali 1995) “we cannot put off living until we are ready”.

The following actions may lead to the development of DSS’s, based upon current information, to aid in assessing the potential consequences of bioenergy production from forest products:

- Full characterisation of growth response to a range of soil indicators
- Define key soil indicators for sustainable forest management
- Determine probability distribution of each indicator for a given site or soil type
- Assessment of sensitivity of growth to likely range for indicators
- Ranking of indicators by importance for each site or site type
- Decision to determine if sampling is necessary and appropriate intensity
- Assessment of management impacts upon indicators
- Assessment of potential amelioration options and likely effectiveness

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Components of a geographic forest ecosystem model used for potential management of interior Alaska's forests

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Abstract

A description of a theoretical model based on forest ecosystem growth dynamics (GAFED) and potential regeneration dynamics (ABFEM) is presented for white spruce ecosystems in interior Alaska. The model has been written based on the GRID commands which are part of the ARC/INFO Geographic Information System. The model has a strict geographic representation of the individual site or landscape. The GAFED model was able to accurately predict the growth, decomposition, and carbon dynamics of an old growth white spruce ecosystem on the floodplain in interior Alaska. The ABFEM model was able to realistically simulate seed crops, seed dispersal and seedling establishment for a burnt white spruce ecosystem. The next set of major work for the models is to move to a large landscape level to predict the effects of management of forest for the interior ecosystems of Alaska.

Keywords: growth dynamics, regeneration dynamics, modelling, ecosystem, white spruce, Alaska

1 Introduction

The management of forests in an area the size of interior Alaska needs to be considered from the standpoint of the individual site to be managed and the affects of management across the landscape. Spatial interactions of ecosystem processes can occur when considering the individual tree structure of the ecosystem and the ecosystem structure of the landscape. From a spatial perspective potentially important factors like; topography, soils, climate, variation in vegetation community types, and ecosystem age structure within a region need to be considered. These represent the primary state factors (Jenny 1941) that occur across a region. They are important at both the site and landscape levels of spatial distribution in maintaining the quality of the ecosystem function during management activities.

A geographically referenced group of data sets that can be used to define the primary state factors that control ecosystem function across Alaska are being developed. Topography is one of the easiest and can be developed from the DEM data that is currently available. A detailed climate classification has been developed (Hammond and Yarie, in press). A preliminary version of a vegetation classification for the state has been developed (Flemming, pers comm), and work is currently in progress to develop an age structure map of forest types within the state. These data sets can be used to parameterize a Geographic Alaskan Forest Ecosystem Dynamics model (GAFED) and an Alaskan Boreal Forest Establishment Model (ABFEM). The models can then be used to investigate the dynamics of forest management at both the individual site (individual tree) and landscape levels of spatial resolution.

Simulation of early post-disturbance forest establishment patterns is an important tool for understanding the structure and function of the boreal forest landscape. Mechanistic or process-oriented models allow for increased knowledge of important processes, identification of knowledge gaps, and applied use for planning and evaluating management actions. This involves reasoning from known or hypothesized principles to deduce an unknown factor using a series of progressively more specific concepts (Karplus 1977). These principles govern the nature of the equations used to characterize the structure and function of a given system (Proe et. al. 1994).

Providing a geographic component to a process-oriented model allows for simulation of biological processes upon a defined landscape. Such a model could prove valuable to the land manager, offering assistance in planning and evaluating management actions. A Geographic Information System (GIS) framework allows simulation of system dynamics at various spatial scales which are geographically referenced.

The models will be designed to work at all levels of spatial resolution. Primary analysis will be developed at the individual tree within a stand level of landscape resolution (one square meter grid cell resolution). In the future a biogeoclimatic classification for the state of Alaska will then be used to summarize stand level results at the landscape level (one hectare or greater grid cell resolution).

2 Model Structure

2.1 GAFED Model

The GAFED model is primarily a process model that will use the important limiting factors to drive forest growth, forest floor, and mineral soil dynamic routines. The model was developed as an AML within ARC/INFO GRID. The routines necessary for the model have been developed so that grid cell size is not a strict limitation (Table 1). The majority of routines can be applied at either an individual tree (1 m grid cell size) or landscape representation (1 ha or above grid cell size). There are a group of routines that require a greater level of modeling detail if used at a small grid cell size (1 m) (Table 1).

Table 1. Relationship between model routines and grid cell size.

Model Components valid across all grid cell sizes	Model Components with cell size dependencies
Vegetation Production	Litterfall
Decomposition	Regeneration
Climate	Tree Mortality
Disturbance by Fire	

2.1.1 Vegetation production

The nitrogen productivity concept (Ågren 1983, 1985; Ingestad 1977, 1980, 1981) is used to model the tree growth at both the individual tree and forest stand level of spatial resolution (Yarie, in review). The nitrogen productivity can be defined as the amount of annual production per unit of foliar nitrogen:

$$\frac{dW}{dt} = Pn \bullet N - f \bullet W_f \tag{1}$$

where W is plant or stand biomass, t is time, Pn is the nitrogen productivity (unit production/unit nitrogen), and N is the foliar nitrogen content, f is the rate of foliage tissue mortality, and W_f is foliage biomass.

At steady state nutrition ($\frac{\mathrm{d(N / W}}{\mathrm{dt}} = 0$) the plants (or forest stands) growth rate is proportional to the amount of foliar nitrogen in the plant (N) and the nitrogen productivity (Pn). The nitrogen productivity is at a maximum during the exponential growth phase and depends on a number of plant properties including genotypic properties, weather conditions, self-shading and ageing. There is a decrease in the nitrogen productivity due to self shading and plant ageing (Ågren 1983) such that:

$$Pn = Pn_{max} - b \bullet W \tag{2}$$

where $\mathrm{Pn}_{\mathrm{max}}$ is the maximum nitrogen productivity, b is considered an ageing and/or light extinction parameter, the other parameters have been defined for equation 1.

Equation 2 has been used to calculate the nitrogen productivity of individual seedlings (Ingestad 1979a, 1979b; Ingestad and Kahr 1985) and stands of trees (Ågren 1983). It is also being used to calculate productivity of trees and stands within interior Alaska (Yarie, in review). Both equations 1 and 2 were developed for a specific geographic unit size as opposed to the unit size of a specific biological component (tree). It should be possible to develop a simple equation (equation 2) for calculation of the nitrogen productivity for a single tree to a stand of trees (Yarie, in review).

2.1.2 Litterfall

Foliage, root, and twig litterfall is spread equally within an 81, 81 or 121 m^2, respectively, area around the tree for the 1 m^2 grid cell size. Tree death and stemwood litterfall is positioned in a random direction chosen from eight (0°, 45°, 90°, · · ·, 315°) potential angles from the tree base. In stands of trees with individual grid cell sizes larger than the height of the tallest tree, litterfall occurs within the grid cell.

2.1.3 Decomposition

The carbon and nitrogen content of litter cohorts are modeled using the litter quality, microbial growth rate and microbial efficiency of the individual litter cohort. The cohort is combined with the humus layer when a predetermined amount of decomposition has occurred. The humus layer is then decomposed using the same procedures as in the L and F layers. Decomposition dynamics are modeled using the theoretical representation presented by Bosatta and Ågren (1985) and Ågren and Bosatta (1987).

2.1.4 Model validation

Model validation will be carried out using tree growth, forest floor and mineral soil dynamic variables that have been measured in the Fairbanks area as part of the Bonanza Creek Long-Term Ecological Research (LTER) Program (see the BNZ-LTER World Wide Web home page; http://www.lter.alaska.edu). There is sufficient information available on tree growth and forest floor dynamics from the Bonanza Creek LTER site to evaluate the model behavior for soil temperature, moisture dynamics, carbon and nitrogen turnover, and tree growth across both upland and floodplain successional sequences.

2.2 ABFEM Model

ABFEM was created within the GRID package of ARC/INFO using ARC Macro Language (AML's) and Menus. Each model routine runs entirely within ARC/INFO, utilizing a complex set of AML's and interactive Menus. Menus allow the user to set initial variables and parameters and provide the user with various choices. All model routines utilize grids and scalars, whose cell values represent various parameter values. This allows all model parameters (input and output) to be geographically referenced and provides for realistic simulation of interactions among processes within a defined landscape unit.

ABFEM simulates early post-disturbance seedling establishment patterns within the boreal forest of interior Alaska. The model simulates seed production, seed dispersal, and seedling establishment of tree species upon a disturbed landscape. The model has been developed to handle several tree species and various spatial scales with a minimum of change to the modeling code. Currently the model simulates only white spruce establishment patterns and is being modeled at a grid cell size of 10 meters (100 m^2).

The model involves four main processes represented by AML routines; seed production, seed dispersal, seedling establishment, and disturbance. Several process variables are initialized by the user through menus.

The site menu choice allows the user to choose from a list of site coverages that already exist or input a new area coverage. This coverage is used to create a site grid that identifies between seed sources and disturbed areas for use by the routine DISPERSE. The display output menu choice allows the user to choose various forms of simulation results, including seedfall and seedling maps, seed production tables, and statistical output of seedfall and seedling patterns.

2.2.1 Seed production

The routine SEEDS simulates the annual cone crop and associated seed crop for each year of the simulation period. The routine is a Monte Carlo simulation of the probabilistic nature of white spruce cone crops, which follows the work of Fox et. al. (1984). The routine uses a random number generator and scalars to simulate the cone crop. The cone crop is classified as either good-excellent or poor-moderate. Successive good-excellent cone crops can not occur. The user is queried for the probability of a good-excellent crop and the rating of the crop prior to simulation. Following cone crop simulation an associated seed crop is simulated. The seed crop (# seeds/grid cell falling within the source stand) is projected from a normal distribution with mean and standard deviation of the cone crop rating.

2.2.2 Seed dispersal

The routine DISPERSE disperses seeds from the source(s) onto the disturbed landscape. This routine provides the user with choices that allow for the potential effects of wind upon dispersal patterns and the inclusion of a long distance dispersal component (distance greater than 300 meters). The shape of the curve relating the number of dispersed seeds to distance from source will vary depending upon such factors as the settling velocity, height of release, wind speed and turbulence, and specific morphological adaptations (Augspurger and Franson 1987). The most widely used forms for the dispersal curve are the inverse power law and the negative exponential (Okubo and Levin 1989). This routine uses the negative exponential equation derived by Youngblood and Max (1992) for floodplain white spruce in interior Alaska.

DISPERSE calculates the Euclidean distance of each cell within the disturbed area to the closest source cell. This distance grid is input into the dispersal equation along with the seed crop parameter and a grid of dispersed seed is created. This seedfall grid may be altered if the user chooses one or both of the dispersal options. The user has the option of adding a wind component. The WINDS sub-routine calculates the direction of each cell within the disturbed area to the closest source cell. This parameter reduces both the distance and density of seed which can be dispersed in non-windward directions.

The user may also choose a long distance dispersal component. The LONG sub-routine simulates the potential long distance dispersal of a defined proportion of the within stand seedfall onto a defined percentage of disturbed grid cells, within a given distance interval (i.e. 300 m to 1200 m). A random number grid is created which is used to stochastically define which cells may receive long distance seeds (i.e. 5 percent).

2.2.3 Seedling establishment

The ESTABLISH routine simulates the early post-disturbance establishment patterns of white spruce seedlings upon the landscape. The routine uses a dynamic seed:seedling index and seedbed substrate information in conjunction with the seed dispersal input grid to determine successfully established seedlings on a cell by cell basis. The seedbed substrate information is obtained from the output grid of the DISTURB routine. The user can define a seed:seedling index interactively with menus or choose a default index.

The seed:seedling index determines the number of viable seeds needed to produce an established seedling. Requirements which a seedbed must provide for germination and seedling establishment are adequate moisture, sublethal seedbed temperatures, and reduced competition (Zasada 1971). Therefore, this ratio will be influenced by the severity of forest floor disturbance (i.e. scorched versus completely consumed), time since disturbance (influence of competing vegetation), and topography (specifically aspect). Differences in suitability lead to patch-dependent differences in seed survival, germination, establishment and/or subsequent growth and survival, and consequently to the conversion of an initial landscape pattern of seedfall into a final landscape pattern of adults (Schupp 1995). By creating a dynamic seed:seedling index that considers time since disturbance, forest floor conditions at the individual cell level, and topographic aspect of each cell; the requirements and processes of successful seedling establishment are implicitly modeled. The ESTABLISH routine outputs a grid of established seedlings produced by the dispersed seed crop.

2.2.4 Disturbance effects

The DISTURB routine simulates the effects of disturbance upon the forest floor. Currently, the routine simulates only the effects of wildfire. Future model versions will also allow for simulation of flooding, insects, and anthropogenic disturbances (i.e. forest harvesting activities). The frequency of fires in the last 200 year have resulted in a mosaic of vegetation in the interior of Alaska that is closely related to past fire history (Viereck 1973). The heterogeneous nature of a fire results in this mosaic and can be seen at various spatial scales. DISTURB simulates this pattern of heterogeneity across the landscape by burning the forest floor to varying degrees of intensity. A random number generator is used to create a disturbance grid which is then classified into 1 of 5 burn classes, following Dyrness and Norum (1983). The user can then choose from several random burn patterns. These patterns are created with various focal functions within GRID. The disturbance grid is used by the ESTABLISH routine for determining proper seed:seedling ratios to be used on individual cells.

3 Model Run Results

3.1 Basic ecosystem function

The nitrogen productivity concept represents one approach for development of algorithms for expansion from individual tree to stand or landscape levels of estimation of primary production. A simple nitrogen productivity equation for trees and stands of trees on a unit area basis within interior Alaska was estimated (Yarie, in review). This relationship can be applied to the major species within interior Alaska as a single equation at this time. The equation is:

$$Pn_{max} = 133.191 - 0.0394 * (\text{foliage biomass/unit area})$$

The model was able to accurately predict the growth of white spruce and birch trees in an old-growth white spruce forest on the floodplain in interior Alaska. Measured diameter growth for white spruce between 1989 and 1993 averaged 0.9 cm at breast height. The model predicted an average of 0.86 cm for the same time period. Total biomass growth for the modeled tree species in this site was approximately 4,380 gms / tree or 290 gms / m^2. The above ground portion was then approximately 145 gms / m^2. These values are typical for mature white spruce forest stands found in interior Alaska (Yarie and Van Cleve 1983).

The model was able to predict litter decomposition for the tree foliage when compared to litterbag decomposition for the mature white spruce site. The model and litterbag field data, were a mixture of the tree foliage litterfall found on the validation site. The exact mixture of the litterfall in the modeled version was dependent on the movement of foliage litterfall around the tree. The model also calculated the decomposition of moss and tree twig litter.

Sugar and sawdust treatments were applied to the site to raise the C/N ratio to that close to black spruce ecosystems. The C/N ratio was measured at the end of each year in the field plots. In general the model was able to simulate the carbon and nitrogen dynamics. The modeled C/N ratio and the carbon and nitrogen dynamics followed that measured in the field for the sugar treatment (Table 2). The C/N values within the sawdust treatment plots were predicted to be higher in the model but their dynamics were similar to that measured in the field (Table 2). One additional point with regards to the modeled system was that the treatments were added to the system at the same time; a single 15 year run was made with all three treatments (sugar, sawdust, and fertilizer) within the modeled site.

The carbon respiration (Table 3) measured in the field includes the root respiration, while that predicted from the model is only the carbon respiration resulting from forest floor decomposition. In general the model follows the expected results due to the treatments. The actual respiration measurements during 1990 were started during the summer (late June) so the actual measurements are lower than the amount of respiration due to the sugar treatment (was applied during late May). Differences between modeled and actual measurements could be attributed to root respiration (Ruess et. al. 1996).

The last set of results that is important to present at this time is the carbon flux, either capture or release, from the individual grid cells and the average for the entire control plot. The average carbon capture for this stand was between 12 and 44 grams per square meter each year. Total annual carbon capture was 8.4 kg for the entire plot (15 m x 15 m). Carbon capture was found scattered throughout the entire plot but only in the cells that contained a tree. Carbon release was found in cells in which trees were not present. Release was due to decomposition of the forest floor and mineral soil organic matter. For a mature stand this represents one of the best estimates of carbon capture for the boreal forest because of the inclusion of moss in the understory and the inclusion of root growth for the trees present in the model.

The estimates for ecosystem carbon uptake were less than those reported by Bonan (1992). He estimated that the trees captured about 1580 gms /m^2 in a year and that including moss and microbial respiration the net capture was also about 1580 gms/ m^2 per year. That value was significantly higher than the estimate in the GAFED model. The GAFED model is estimating carbon release from the forest floor and mineral soil combined with carbon uptake by the moss layer at about 115 gms/m^2 per year while Bonan (1992) estimated about 200 gms/m^2 per year. The indication from this analysis is that both of the estimates are reasonably correct. The need to move to the landscape with the differences in vegetation types accurately portrayed should be obvious.

Table 2. Comparison of the C/N ratio between field treated plots and modeled plots.

Treatment	Year	Measured	Modeled
		C/N	C/N
Control	1990	39.8	38.5
	1991	36.7	38.5
	1993	39.2	39.0
	1994	34.0	39.1
	1995	34.2	39.1
Sugar	1990	45.7	51.4
	1991	35.4	36.6
	1993	36.0	35.9
	1994	31.8	35.7
	1995	33.0	35.6
Sawdust	1990	49.4	69.5
	1991	44.7	67.2
	1993	42.1	65.1
	1994	34.1	63.2
	1995	32.9	61.6
Fertilizer	1995	32.4	38.7

Table 3. A comparison of the C respiration in the FP4A treatment plots and the GAFED model predictions.

Treatment	Year	Measured C Respiration (Kg/m²)	Modeled C Respiration (Kg/m²)
Control	1990	0.310	0.134
	1991	0.364	0.130
	1992	0.296	0.111
Sugar	1990	0.418	1.601
	1991	0.369	0.766
	1992	0.303	0.526
Sawdust	1990	0.378	0.228
	1991	0.369	0.224
	1992	0.326	0.214
Fertilizer	1990	0.345	0.163
	1991	0.372	0.159
	1992	0.321	0.136

3.2 Seed dispersal - Rosie Creek Burn Simulation Example

The next set of work for the GAFED model will be to verify the dynamics for a number of additional sites within the Taiga LTER program. In addition a verification effort for the landscape level with the data sets that are available for the area surrounding the Bonanza Creek Experimental Forest will be put together. The final result will be the ability to start to develop accurate estimates of the carbon flux across the forested landscape of interior Alaska.

3.2.1 Simulation methods

The model was applied to the Rosie Creek burn, about 20 km southwest of Fairbanks. The simulation represents a potential scenario of post-disturbance white spruce seedling establishment and is not an historical simulation. In the future the model will be run, following the historical records of seedfall in the burn area. Currently, establishment patterns are being collected to test observed establishment patterns versus the simulated patterns.

In this example, a 12 year simulation period was run. The probability of a good-excellent seed crop was set at 20 percent, with the seed crop rating of the year previous to the simulation being rated as poor-moderate. The default seed:seedling index was used and a focal majority burn pattern was chosen. Wind effects and long distance dispersal options were not chosen.

3.2.2 ABFEM Results

The routine SEEDS initiated a 12 year Monte Carlo simulation of white spruce cone and seed crops. A good-excellent cone crop was not produced until the final year of the simulation period. Within stand seedfall density varied from year to year, ranging from 179 seeds/m^2 to 990 seeds/m^2 for poor-moderate crops and the good-excellent crop had a density of 2688 seeds/m^2. The routine DISPERSE then dispersed the seed crops upon the landscape. Maximum dispersal distances for an individual seed crop year ranged from 474 m in year 10 to 617 m in year 12.

The routine ESTABLISH simulated seedling establishment patterns for each year, as a function of the seed crop, the seedbed substrate condition, and the seed:seedling index. Using the default seed:seedling index, establishment patterns resulting from each seed crop are shown. Maximum establishment distances, for white spruce seedlings, ranged from 140 m in year 10 to 380 m in year 1.

The effects of variable cone crops, wind, long distance dispersal, and seedbed characteristics can provide insight into the potential outcome of various management activities.

3.2.3 Future modeling work

This modeling project has identified numerous future projects. These projects include development of a harvesting simulator, simulating treeline movement, investigation of landscape-level seed dispersal patterns, and development of dynamic seed:seedling indexes.

Inclusion of topographic effects upon seed dispersal is needed. This will allow for simulation of the effect landscape topography has upon dispersal patterns. Another development area involves the issue of seedling growth and competitive interactions. A rather simplistic representation might be development of an annual growth algorithm for both established seedlings and the competing vegetation. This algorithm would take into account such information as seedbed conditions, aspect, years since disturbance, and species specific information.

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Nutrition and productivity of radiata pine following harvesting: testing a working model of site classification in New Zealand

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Abstract

An atlas was developed in the 1980's to classify both the existing nutritional status (N, P, K, Mg, and B) of radiata pine plantations in New Zealand and the susceptibility of these plantations to nutrient deficiency in subsequent rotations. Three trials, aged from 4 to 9 years within a series established to examine the effect of biomass removal at harvest on subsequent productivity, were used to test the classification system. The sites chosen covered a range of soil types and climatic conditions. The working model of site classification accurately predicted nutritional differences among the three sites for N, P, B, and Mg, and also indicated the likelihood of Upper Mid Crown Yellowing (UMCY) risk, which is due to Mg deficiency in older *Pinus radiata*. The nitrogen status in unfertilised stands was found to be useful for predicting productivity levels. The nutritional classification model also indicated the likelihood of productivity losses associated with organic matter removals.

Keywords: Sustainable, classification, harvesting, radiata, nutrition

1 Introduction

An atlas was developed in the 1980's to classify both the existing nutritional status of radiata pine plantations in New Zealand and the susceptibility of these plantations to nutrient deficiency in subsequent rotations. Intensive harvesting trials at three locations encompassing a range of fertility and probability of deficiency were chosen to test the classification system as a working model.

The objectives of this work were to test the following hypotheses:

1. Foliar nutrient concentrations can be predicted by the "probability of deficiency" according to the site classification working model
2. Foliar nutrient concentrations are related to tree productivity
3. Harvesting intensity is negatively correlated with succeeding forest growth, and inadequate nutrition is the reason for the negative correlation
4. Harvesting impacts due to nutrient removals can also be predicted by the working model's "probability of deficiency".

2 Methods

2.1 Working model for site classification

An atlas of radiata pine nutrition in New Zealand was constructed by extracting nutritional data (analytical methods from Nicholson, 1984) from 40 000 *Pinus radiata* (D.Don) samples from the Forest Research Institute plantation nutrition database, and relating these to New Zealand Soil Bureau soil maps (Hunter *et al.* 1991). From deficient and marginal sites, many of the samples in the nutrition database will include a history of added fertiliser. Nutrition was classified as either deficient, marginal, or satisfactory for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and boron (B). Associated with each classification was either a low, medium, or high probability of encountering a nutrient deficiency in the future (Hunter *et al.* 1991).

Intensive harvesting trials at three locations encompassing a range of fertility levels and probability of deficiency levels (Table 1), were chosen to test the nutritional atlas as a working model.

2.2 Intensive harvesting studies

The three trials used to test the classification system are located in second rotation plantations at Woodhill, Tarawera, and Kinleith Forests. Site characteristics are detailed in Table 2 (Anon, 1954; Anon, 1983). Soil and forest floor characteristics are given in Table 3 (Smith et al. 1994; Lowe and Thorn, FRI unpublished data; Nicholson, 1984). The pre harvest organic matter and nitrogen components were determined as described by Dyck et al. (1991), and are summarised in Table 4 (Smith et al. 1994; Lowe and Thorn, FRI unpublished data; Nicholson, 1984).

Table 1. Current nutritional status (Current) and probability of deficiency in future rotations (Prob.) at Woodhill, Tarawera and Kinleith forests as predicted by the nutritional atlas.

	Woodhill		Tarawera		Kinleith	
	Current	Prob.	Current	Prob.	Current	Prob.
N	Marginal	High	Marginal	Low	Satisfactory	Low
P	Satisfactory	Low	Satisfactory	Low	Satisfactory	Low
B	Satisfactory	Low	Marginal	High	Marginal	Medium
Mg	Satisfactory	Low	Satisfactory	Low	Marginal	Medium

Table 2. Site characteristics.

	Woodhill	Tarawera	Kinleith
Soil type	Pinaki sand	Tarawera gravel	Taupo sandy loam
Distance from coast (km)	2	37	60
Elevation (m)	30	90	490
Mean monthly temp (C)			
February	18.9	19.3	18.4
July	10.3	8.9	7.4
Precipitation (mm)	1330	1820	1420
First rotation stand age	42	27	26

Table 3. Soil (0 to 10 cm) and forest floor characteristics at the end of the first rotation.

	Woodhill	Tarawera	Kinleith
Soil			
N (g 100g^{-1})	0.015	0.12	0.32
Organic C*:N	24	18	18
Bray-P (mg kg^{-1})	30.4	13.8	9.3
Exch K (cmol kg^{-1})	0.14	0.4	0.37
Exch Ca (cmol kg^{-1})	0.89	3.3	1.73
Exch Mg (cmol kg^{-1})	0.89	1.2	0.36
Exch K:Mg	0.16	0.33	1.03
pH	5.6	5.4	4.9
Forest floor (<10 cm diameter)			
N (g 100g^{-1})	1.29	0.94	1.32
Organic C*:N	29	33	29

* modified Walkley-Black (Metson, 1956)

Table 4. Organic matter and nitrogen content on each site prior to harvesting first rotation (OM = Mg ha^{-1}; N = kg ha^{-1}). Standard deviations (where available) are given in parentheses.

	Woodhill		Tarawera		Kinleith	
Component	OM	N	OM	N	OM	N
Foliage	7	68	8	120	9 (1)	122 (1)
Branches	34	78	23	46	61 (6)	160 (7)
Stem	463	130	343	189	205 (7)	132 (7)
Forest Floor	36	465	24 (5)	360 (45)	25 (4)	437 (26)
Soil (1m depth)	96	914	97 (27)	1935 (667)	373(41)	5058(1206)
Total		1655		2650		5909

The harvesting treatments were designed to simulate the effect of nutrient removal alone. Machinery was kept off-site during harvesting, to avoid the confounding effect of soil compaction. The harvesting treatments common to the three trials that were examined to test the classification system are:

FF Whole-tree harvest, forest floor removed;
WT Whole-tree harvest;
SO Stem only harvest, single layer of slash.

Organic matter and nitrogen pools following trial establishment are shown in Table 5 (Smith et al. 1994; Lowe and Thorn, FRI unpublished data).

The treatments were installed in a randomised block split-plot design (with and without fertiliser). At Woodhill and Tarawera the treatments were replicated in 3 blocks, with split-plots being 30 m X 30 m. At Kinleith treatments were replicated in 4 blocks with split-plots being 40 m X 40 m. Details of fertiliser nutrients applied to the three sites are shown in Table 6.

Table 5. Organic matter and nitrogen pools (1m depth, excluding roots) following trial establishment (OM = Mg ha^{-1}; N = kg ha^{-1}).

	Woodhill		Tarawera		Kinleith	
Treatment	OM	N	OM	N	OM	N
FF	96	914	97	1935	373	5058
WT	132	1379	121	2295	399	5495
SO	173	1525	153	2461	470	5777

Table 6. Sum of fertiliser nutrients applied to the three sites (kg element ha^{-1}).

Fertiliser additions as of age	Woodhill* 9 yr	Tarawera** 6 yr	Kinleith*** 4 yr
N as Urea-N (quarterly applications)	1750	500	600
P as LLSuper (single application)	100	50	50
B as Ulexite (single application)	6	8	6
Mg as CalMag (single application)	100	100	100

* initial application of N at age 1;
followed by quarterly applications of 50 kg N ha^{-1};
initial application of P, B and Mg at age 5

** initial application of all elements at age 3;
then quarterly applications of 50 kg N ha^{-1} since age 4;

*** initial application of all elements at age 2,
followed by quarterly applications of 50 kg N ha^{-1};

Silvicultural treatments:

Bare root seedlings were planted at 2 x 2 m spacing (2500 stem ha^{-1}) at all 3 sites. TheWoodhill and Tarawera sites were thinned at years 7 and 5 respectively to 1250 stem ha^{-1}. The data sets used for this paper from the Woodhill, Tarawera and Kinleith sites are up to and including years 9, 6 and 4 respectively. The sites have been maintained weed-free.

2.3 Testing the site classification as a working model for predicting both nutrition, and harvesting impacts on site productivity

Although productivity comparisons will be made across sites, it must be borne in mind that differences in climatic factors also exist. The following describes how each of the following hypotheses were tested.

1. Foliar nutrient concentration classes can be predicted by the "probability of deficiency" according to the site classification working model. This was tested by examining contrasts and trends over time in foliar N, P, B, and Mg concentrations across harvesting treatments for the 3 sites. Foliage was collected annually from each site, and the concentration of nutrients determined (Nicholson, 1984).

2. Foliar nutrient concentrations are related to tree productivity. This was tested by relating a productivity index (diameter at 1.4 m, DBH) as an estimate of the productivity at each site over time to foliar nutrient concentrations. Tree diameters and heights were measured annually.

3. Harvesting intensity is negatively correlated with succeeding forest growth and that inadequate nutrition is the reason for the negative correlation. This was tested by examining diameter growth with increasing biomass removal, and by examining the ameliorative effect of fertiliser on productivity.

4. Harvesting impacts due to nutrient removals can also be predicted by the working model. This was tested by examining the effect of biomass removal on subsequent foliar nutrition.

3 Results and Discussion

3.1 Foliar nutrient concentrations are predicted by the "probability of deficiency" according to the site classification working model

The working model predicts a marginal level for average N fertility at Woodhill forest with a high probability of N deficiency, and marginal and satisfactory average N fertility at Tarawera and Kinleith forests respectively. At both Tarawera and Kinleith forests the probability of N deficiency is low. The data presented in Fig. 1 supports the prediction. At Woodhill forest, unfertilised trees were well below the current fertiliser intervention level of 1.2% for N; at Tarawera and Kinleith, unfertilised trees were above the current fertiliser intervention level, at about 1.3 % for Tarawera, and 1.8% for Kinleith. At Tarawera by age 6, foliar N concentrations had fallen to 1.2% with the expectation of recovery for later years. The decline in foliar N concentration as a result of soil supply in relation to increased demand in the period leading up to canopy closure has been clearly demonstrated in plantation radiata pine by Hunter and Skinner (1986).

At each of the 3 sites foliar P values (Fig. 2) for the unfertilised trees are > 0.11% supporting the prediction of satisfactory average P fertility with a low probability of some deficiency.

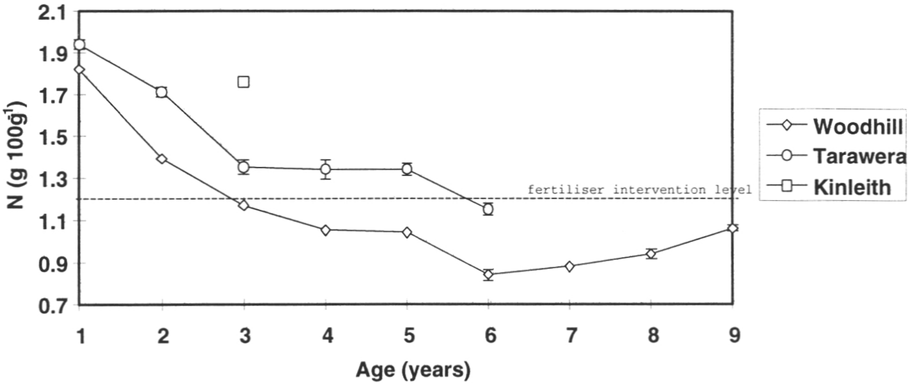

Figure 1. Foliar N in unfertilised treatments at the three sites. Where available, the standard errors about means are indicated by confidence intervals.

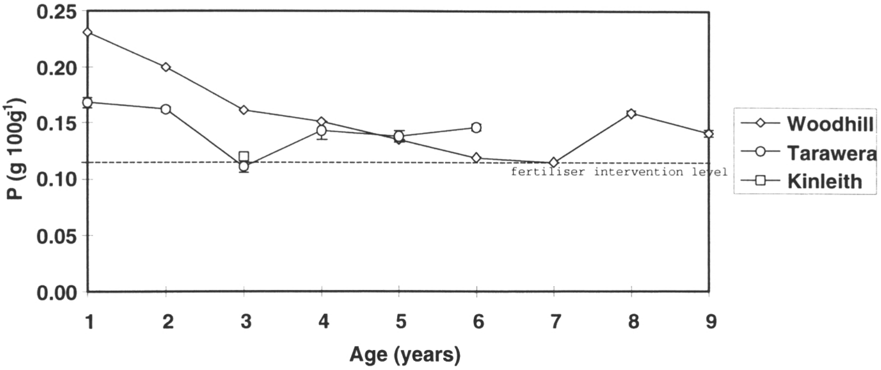

Figure 2. Foliar P in unfertilised treatments at the three sites. Where available, the standard errors about means are indicated by confidence intervals.

Foliar Mg concentrations at both Tarawera and Woodhill forests were well above 0.08% (Fig. 3) and therefore supported the working model prediction of both satisfactory average fertility with low probability of deficiency. At Kinleith forest, foliar Mg values were low at 0.07% (marginal fertility) with a medium probability of deficiency as predicted by the working model.

Foliar B concentrations at Tarawera forest were predicted to be marginal with a high probability of deficiency and this is reflected in the crop's B nutrition which by age 6 has decreased to 6 ppm (Fig. 4), well below the current intervention level of 8 ppm. At Kinleith, the prediction is for marginal B levels with a medium probability of deficiency. The crop concentrations are 10 ppm at age 3, marginal for radiata pine. At Woodhill foliar B levels were above the deficiency threshold, where the prediction was for a satisfactory average fertility with a low probability of deficiency.

The results at the end of the monitoring period for the 3 sites are summarised in Table 7.

Table 7. Second rotation nutritional status at Woodhill, Tarawera and Kinleith forests.

	Woodhill	Tarawera	Kinleith
N	Deficient	Satisfactory	Satisfactory
P	Satisfactory	Satisfactory	Satisfactory
B	Satisfactory	Deficient	Marginal
Mg	Satisfactory	Satisfactory	Deficient

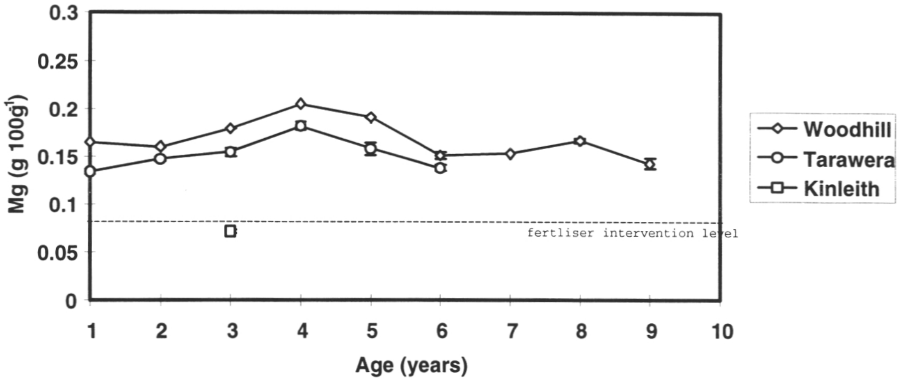

Figure 3. Foliar Mg in unfertilised treatments at the three sites. Where available, the standard errors about means are indicated by confidence intervals.

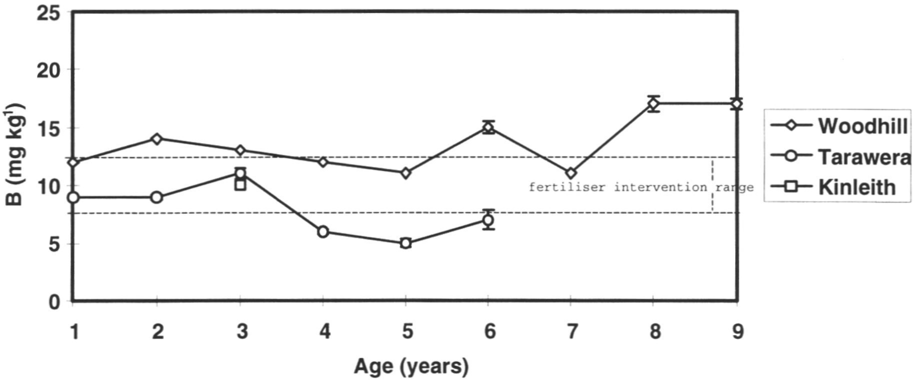

Figure 4. Foliar B in unfertilised treatments at the three sites. Where available, the standard errors about means are indicated by confidence intervals.

3.2 Foliar nutrient concentrations are related to tree productivity

Differences in site productivity (DBH) in relation to variation in foliar nitrogen are indicated in Fig. 5 and show that foliar N is related to growth. The data is for nitrogen at age 6 at which time all other nutrients are non-limiting. Between the two sites there are major differences in total N pools (Table 4).

Leading up to and beyond canopy closure, productivity at the Tarawera site is higher than at the Woodhill site (Fig. 6). This reflects differences in the current crop's ongoing nutrient status. Foliar concentrations (see Figs. 1—4) for N P Mg and B are satisfactory for Tarawera. For the Woodhill site the major nutrient limitation is N; with P, Mg and B concentrations being satisfactory. Little can be concluded for the Kinleith site since the available data is for age 3, and several years behind the period of canopy closure when possible differences between harvesting treatments will be observed.

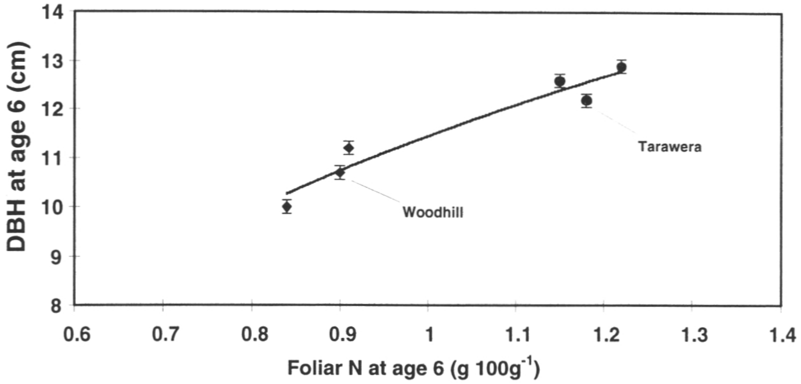

Figure 5. Foliar N versus DBH at age 6 in unfertilised treatments at Woodhill and Tarawera. Where available, the standard errors about means are indicated by confidence intervals.

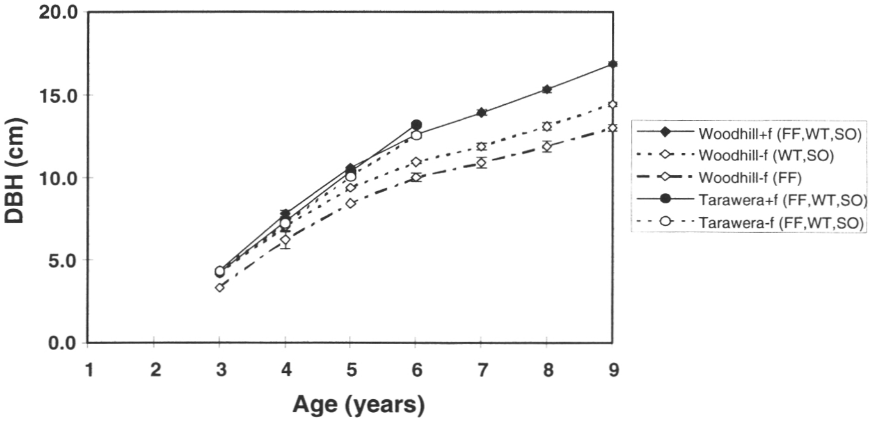

Figure 6. The effects of fertiliser additions and harvesting treatment on productivity at the Woodhill and Tarawera sites. Where available, the standard errors about means are indicated by confidence intervals.

3.3 Harvesting intensity is negatively correlated with succeeding forest growth and that inadequate nutrition is the reason for the negative correlation

At Woodhill forest diameter growth was in the order WT=SO>FF (P=0.05); the addition of fertiliser enhanced growth on all harvest treatments (Fig. 6). A comparison between the Woodhill and Tarawera site is difficult. At Tarawera the trees are younger (stress on the site for nutrients is less), and diameter growth is in the order FF=WT>SO. Although productivity in the SO treatment is significantly lower (P=0.05), the difference is small, and average values across harvesting treatments have been plotted (Fig. 6). At this age it is likely that the decomposition of the slash is restricting productivity in the SO treatment by immobilising N. It is not expected that this trend will continue. The applied fertiliser, although high by management standards, has had little effect on improving productivity in the presence of adequate nutrition. At Kinleith, there was no difference in productivity as a result of harvest intensity, and fertiliser had no effect on productivity up to age 4 (data not presented).

3.4 Harvesting impacts due to nutrient removals can also be predicted by the working model

At Woodhill forest, the site N fertility is marginal, and the working model predicts the probability of N deficiency to be high. Following harvest, the subsequent crop's N nutrition had become deficient as demonstrated by both foliar N concentrations, and the positive response to the addition of N fertiliser. The effect of increasing harvest intensity on subsequent productivity was therefore predicted by the working model. At the Tarawera site, the probability of N deficiency was low. There was little effect of increasing harvest intensity on subsequent growth and there was an absence of a fertiliser effect. The working model predicted the experimental outcome. At the Kinleith site the data for age 3 is insufficiently advanced to examine the relationship between the medium probability of Mg deficiency and harvesting impacts. The nature of the prediction of harvest intensity on Mg nutrition has yet to be determined through forest growth.

The Atlas of Radiata Pine Nutrition in New Zealand was found to accurately predict the observed nutritional status of the unfertilised crop at the 3 intensive harvesting study sites. The effect of increasing biomass removal on subsequent crop productivity was also able to be predicted where data was available to canopy closure. However, additional research is needed to determine: how to "measure" potential site nutrient availability; the value of logging residues; functional relationships between nutrient pools and productivity; thresholds between sites of low, medium, and high risk, and the point in time for threshold to be measured. However, the Atlas does not consider the effects of site disturbance (compaction) on site productivity. The working model also indicated the likelihood of Upper Mid Crown Yellowing (UMCY) risk, which is due to Mg deficiency in older *Pinus radiata*.

4 Conclusions

The Atlas of Radiata Pine Nutrition in New Zealand was found to accurately predict both the observed nutritional status of the unfertilised crop at the 3 intensive harvesting study sites as well as the effect of increasing biomass removal on subsequent productivity. The Atlas accurately predicted differences between sites for N, P, B, and Mg fertility. Nitrogen appears to be a key determinant for productivity.

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Long term site productivity research for developing and validating computer models that contribute to scientifically based codes of practice

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Abstract

This paper illustrates how steady-state and dynamic computer models can be used for the development of scientifically based codes of sustainable forestry practice, with emphasis on assessing sustainability and long-term effects of intensive forest harvesting on forest biomass productivity, and with emphasis on model calibration and model performance testing. Dynamic models that rely on a mixture of generalized empirical, semi-empirical, and theoretical (mechanistic) stand level growth and yield functions will likely become a key research tool in this respect, by integrating results from biogeochemical process studies, field experiments, and monitoring into a generalized nutrient cycling framework. Steady-state mass balance models (SMB) can be used for similar purposes, and become important when practical needs and/or lack of comprehensive data limit the use of dynamic models. A study is presented that shows the application of the two modelling approaches to the impact evaluation of whole-tree harvesting on jack pine (Pinus banksiana Lamb.).

Keywords: Computer simulation modelling, whole-tree harvesting, sustainability, site quality, jack pine.

1 Introduction

The need for developing scientifically based codes for sustainable forest practices requires sound yet practical methods for evaluating, monitoring, and predicting the biophysical functioning and sustainability of highly complex forest systems. Special considerations need be given to potential effects of forest harvesting on species shifts, forest productivity, and cycling of water, energy, nutrients, and carbon. In this paper, we focus on simulation models as a framework to advance results from process studies, field experiments, monitoring, and hypothesis testing in the context of quantifying forest ecosystem functioning. Doing so is essential for integrated model formulation, calibration, modification, and validation (Fig. 1), as enunciated earlier by the IEA Harvesting Impacts Working Group (Rolff and Dyck 1986, Dyck and Mees 1991, Dyck et al. 1994).

At this time, much progress can be made in terms of conceptualizing and modelling ecosystem processes and functioning for various forest types and sites. It should be undersood, however, that the resulting models capture, not mimic, the basic functioning of natural forest systems. Progress towards this aim is obtained by formulating understandable simplifications, approximations, and assumptions about ecosystem functioning. In turn, such formulations needs to be defensible in terms of scientific and practical use, and need to be appropriate towards meeting particular forest management objectives. Not surprisingly, such objectives will vary considerably in terms of scale (space and time), and need for detail. The following questions need to be addressed before model building:

(1) What are the precise modelling objectives?
(2) What are the pertinent time and space scales (scope)?
(3) What are the essential components of the ecosystem that need explicit, quantitative expressions?
(4) How are the components related to each other; what are their functions?
(5) What are the processes and inputs that affect these functions, by component?
(6) What level of detail and information (data) is actually required to achieve a functional, objective-driven, efficient, realistic and insightful representation of the ecosystem?
(7) By which means can the existing complexities be best simplified, and expressed as such in terms of program organization, transparency, and documentation?
(8) What modelling uncertainties arise by lack of definition (information) about salient ecosystem processes and ecosystem conditions, and how can they be addressed effectively and efficiently?
(9) What is the sensitivity of model output to lack of parameter, process, or component definition?

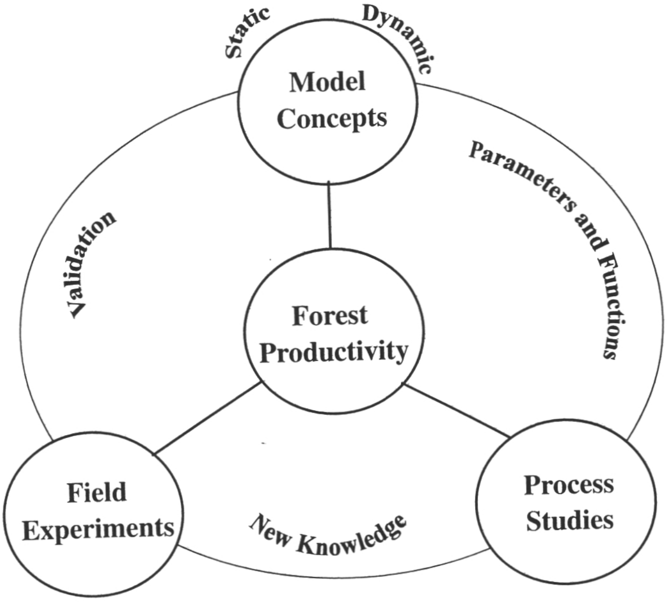

Figure 1. Linkages between field experiments, computer simulation models, and process studies.

(10) How do model parameters vary by site, by tree species, assuming that the same modelling framework can be applied to all species of interest?

(11) What is the predictive accuracy (or bias) of the model output for species and sites that were not part of model calibration?

(12) How can the model be formulated and calibrated such that cumulation of errors (error propagation) can be avoided or minimized?

Experience has shown that many of these questions can be addressed by considering forest ecosystems (stands) as an interconnected set of functionally important biomass and nutrient storage compartments (foliage, wood, fine roots, forest flow, mineral soil, atmosphere), with each compartment influencing the other through processes that involve the transfer of energy (radiation, heat) and matter (net photosynthate production, litter, water, nutrients). For productivity and site quality assessments, one needs to consider, e.g., solar radiation (and reflection), heat (thermal flux), deposition (wet and dry), soil weathering, erosion, leaching, litterfall, organic matter accumulation, decomposition and mineralization, within-tree allocation of photosynthate, nutrient uptake, and within-tree allocation of nutrients to within-tree compartments such as wood, fine roots, foliage, and bark, etc. Formulating processes that affect forest growth and nutrient cycling in terms of field measurable parameters allows one to calibrate the resulting model by direct comparing the process formulation with field measurements or observations. In this way, process-based models become fairly robust per species, and across site class; i.e., there are no error accumulations. Robustness is increased by process calibration across the spectrum of natural variability (e.g., poor vs. rich sites, wet vs. dry sites), thereby confining model inaccuracies to input and interpolation-type errors. Robustness is further increased by checking model performance at sites not previously used for model calibration.

Model functions and related growth simulations can be defined for various levels of time resolution. For long-term simulations (centuries), annual input and process formulations are convenient and efficient. Mid-range calculations (decades) should be based on monthly input and process formulations, to account for seasonal and within-season growth variations. Short-range calculations are best done with daily input and process formulations, to account, e.g., for the effects of weather on forest net photosynthesis.

At present, there are two model types that are useful for addressing forest productivity: those that are dynamic, by attempting to trace the functioning of stand development through several rotations, and those that are static, by addressing forest growth at presumed steady-state conditions. Both deal with basic requirements for tree growth (light, water, nutrients), and apply the principles of energy and mass conservation in the context of tree growth and related stand functioning.

In all of this, model utility is severely limited if the model has to be calibrated or re-calibrated for each individual stand and species combination. Model utility is further restricted when the model structure and organization of modelling detail lacks clarity. Much improvement can be made in this direction by utilizing high-level programming languages that appeal to both forest scientists and forest managers as an effective communication, documentation and calculation medium. For example, STELLA II (1994) allows one to approach the overall modelling task by way of developing visual and therefore fairly self-explanatory computer modules that are also fully documentable within the program, piece by piece.

2 Dynamic models

Dynamic models contain a mixture of empirical, semi-empirical, and theoretical (mechanistic) process formulations. One example is the FORECAST model, which is a continuation of the ENFOR (Canadian Energy from the Forest) sponsored FORCYTE modelling series. This modelling series addresses nutrient cycling and forest growth from an empirical perspective,. The scientific underpinning of this series has evolved by a gradual reformulation about key processes and driving functions (Kimmins, pers comm., Proe et al. 1994). Other models and modelling series have come along since. Such models differ by type and extent of detail considered, i.e., number of processes, number of stand compartrments, number of parameters, and extent of mechanistic formulation.

For forest management purposes, reliable projections of atmosphere-, soil-, and harvest-induced changes on future forest biomass growth and sustainability are critical. For example, atmosphere-induced changes in soil moisture, temperature, and nutrient availability (NO_3-N) explain about 83% of the year-to-year tree ring variation in sugar maple (Yin et al. 1994). Similarly, changes in nitrogen, sulphur and base cations in precipitation have been observed to affect soil nutrient availability in Europe and North America (MacDonald et al. 1992). Consequently, efforts have to be made to simulate effects of climate, hydrology, nutrient loss, and soil nutrient replenishment on forest biomass growth. Doing so involves considering processes such as soil organic matter mineralization, soil weathering, and atmospheric ion deposition (e.g., Liu et al. 1992, Arp and Oja 1996). Other factors that need to be become part of dynamic model formulations are site-specific nutrient removals and additions as affected by, e.g., harvesting, and by topographic position (Band et al. 1995).

3 Steady-state models

Steady-state models are built on simple assumptions and simple mass balance statements about nutrient inputs, uptake, cycling, and leaching. The formulation of these assumptions and statements constitutes the steady-state mass balance approach (SMB). This approach, by way of its inherent simplicity and transparency, lends itself for cooperative model development among various research agencies, and has already been used as an effective tool for evaluating acid precipitation impacts on soil acidification (deVries et al., 1996). Typically, model input requirements per site are small, thereby facilitating simultaneous evaluations and mapping of the results across various forest types and site conditions. As well, SMB models provide a general framework for dynamic model input, thus enabling one-on-one comparisons between dynamic and steady-state model formulations. In contrast, data requirements for site calibration and initializion are large for dynamic models, thereby keeping the application of the latter in the realm of research for the most part.

4 Examples

The ForSVA model is an example of a dynamic model that quantifies photosynthate (biomass) production and nutrient transfers among all major stand components, i.e., foliage, wood (including bark and coarse roots, fine roots), forest floor, mineral soil, and soil solution. Processes addressed in ForSVA are net primary production, biomass respiration, litterfall (including throughfall), litter decay (including translocation of nutrients and of photosynthate before foliage fall), soil weathering, nutrient uptake from available nutrient pools, and atmospheric deposition (Fig. 2). Air temperature and precipitation are used as driving variables to simulate soil moisture, rate of soil organic matter decomposition, nutrient mineralization and transformation rates, and weathering rates of soil minerals. Air temperature and precipitation are further used to simulate the evapotranspirative water loss per leaf area. Such losses are directly and positively related to the leaf-area dependent calculations of productivity (net C assimilation). The latter calculations are further influenced by atmospheric CO_2 concentrations, and by nutrient availabilities and related foliar nutrient concentrations.

The ForCrit model is an example of the SMB approach. This model can be used to calculate sustainable forest harvest levels according to harvest method, dominant tree type, soil conditions, and atmospheric inputs. Model inputs are limited to annual summaries for precipitation, AET, atmospheric deposition (S, N, Ca, Mg, K), soil conditions (depth, clay content, soil parent material type by base content, Ca, Mg, K

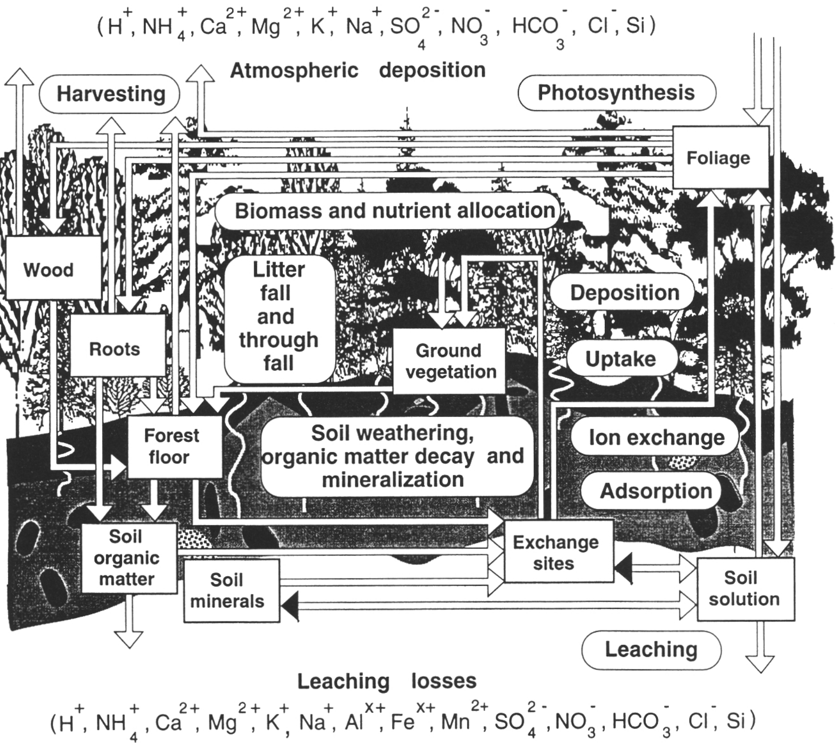

Figure 2. Processes and stand compartments addressed with the ForSVA model.

availabilities), drainage condition, and nutrient content of harvest stand components. Using ForCrit shows how severe (or beneficial) the consequences of a particular management scenario might be for the growth and sustainability of particular forest types. For example, applying ForCrit to the analysis of whole-tree harvesting impacts on sustainable forest productivity shows a general agreement between calculated and observed mean annual biomass increments (MAI) (Fig. 3) for 24 forest stands in New Brunswick (Maliondo et al, 1990), and 2 jack pine sites in Northern Ontario. The figure also suggests that plots with mean annual growth (MAG) (projected) ≥ MAG (observed) are sites that have a potential for sustainable whole-tree harvesting. Plots with MAG (projected) ≤ MAG (observed), however, should not be used for whole-tree harvesting. In all MAI calculations, careful consideration needs to be given to topographic position: seepage as well as poor aeration affect productivity, and hence MAI.

A comparison was done for ForCrit and ForSVA calculations for a moderately productive jack pine stand in Ontario, Canada. ForCrit calculations suggest a borderline case for whole-tree harvesting. ForSVA calculations suggest the same, and predict a gradual loss of forest productivity over time (Fig. 4). As well, For SVA estimates the magnitude and timing of productivity loss that might be associated with whole-tree harvesting.

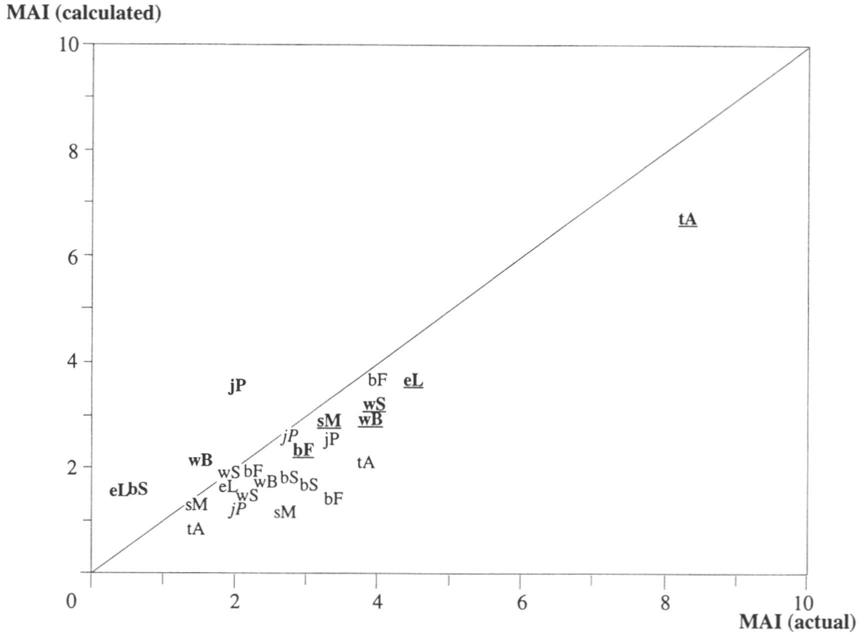

Figure 3. Comparison of actual mean annual biomass increment [MAI, tons/(ha year)] and ForCrit-calculated sustainable MAI (whole-tree), for 24 mature forest stands in New Brunswick, and 2 (italics) in Northern Ontario, Canada. Line shows 1:1 correspondence. Bold entries are affected by topographic position: ForCrit-MAI for bold entries without underline is overpredicted, when actual drainage situation (poor to imperfect) is not considered in the calculation. Bold entries with underline are adjusted upward to account for seepage.jP: jack pine; wS: white spruce; bS: black spruce, wB: white birch; sM: sugar maple; tA: trembling aspen; eL: eastern larch; bF: balsam fir.

The ForHyM2 model (Meng et al. 1995) is a dynamic forest hydrology model that can be used to evaluate pre-and post-harvest water and heat flow through forest stands and forest watersheds, based on local weather records, and basic descriptors for forest conditions, summer through winter. An example of a ForHyM2 application is shown in Fig. 5 for the Nashwaak Experimental Watershed Project in central New Brunswick, Canada. This figure illustrates that the effects of harvesting on total stream discharge is relatively small for a predominantly tolerant hardwood forest. The lack of a strong hydrological response in this situation is due to rapid forest regrowth after cutting, and a partial compensation among several water input and output processes such as reduced snow and fog catch and reduced evapotranspiration. A satisfactory agreement between pre- and post-harvest observations and simulations regarding cumulative streamflow was observed (Meng et al. 1995).

Estimating the amount of water and heat flowing through forests and forested watersheds is essential for estimating soil moisture and soil temperature as affected by, e.g., harvesting and climate change. Soil moisture and temperature, in turn, affect forest growth, nutrient flows, and nutrient cycling. For example, ForHyM2-simulated values for soil moisture and temperature were used to evaluate the above-mentioned year-to-year variation in maple growth, through regressions (Yin et al. 1994). In this way, experimental trials, process studies, and simulation modelling became fully integrated.

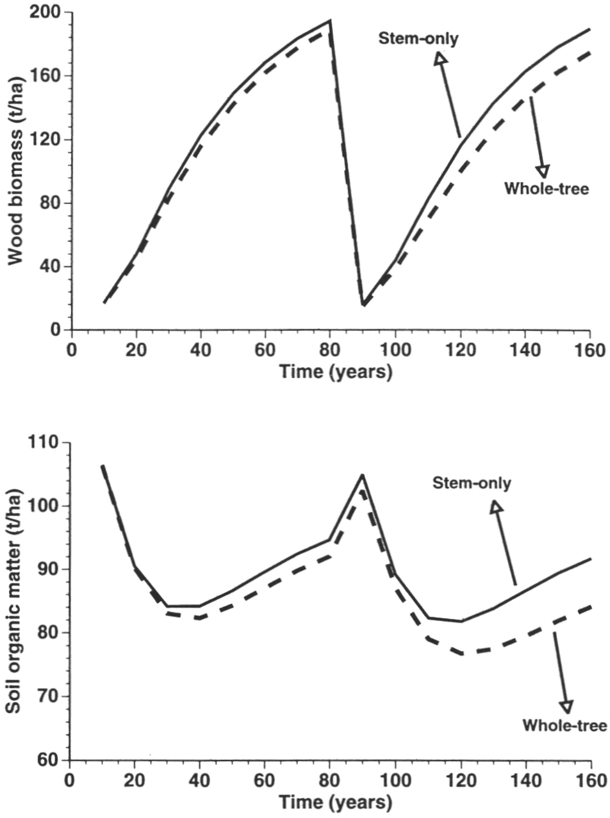

Figure 4. Comparison of ForSVA simulated stand biomass for a jack pine stand in Ontario after stem-only (solid line) and whole-tree harvest.

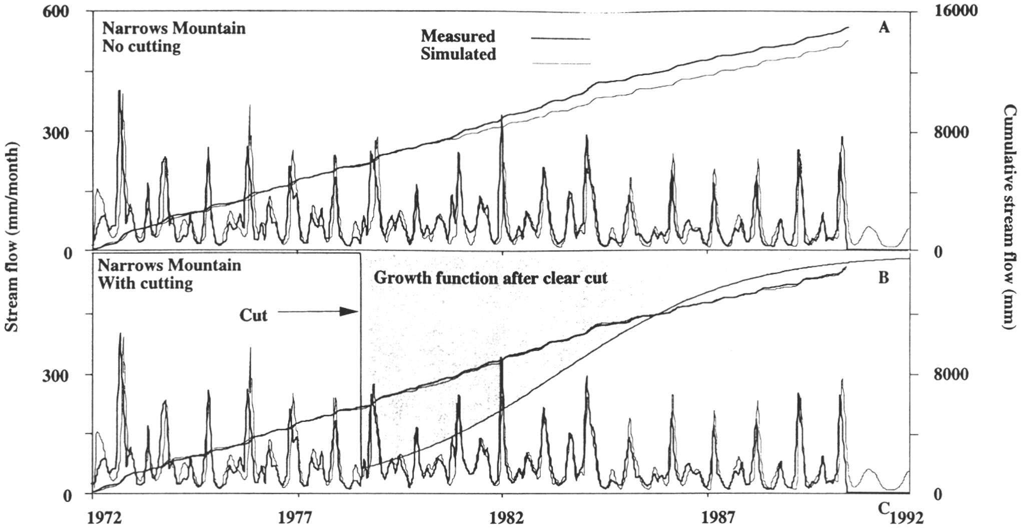

Figure 5. Comparison of monitored stream discharge at Hayden Brook and Narrows Mountain, New Brunswick, and corresponding ForHyM2 simulations.

5 Long-term experiments

In order to be reliable, long-term experimental field studies must have the treatments applied factorially, and treatments must be adequately replicated, so that small changes in growth can be detected. Such studies, furthermore, should help in identifying those species/site combinations that are at risk to loss of production. Results from such studies afford opportunities to test whether organic matter and nutrient removals from a site affect tree growth, and generate information for model calibration and model performance testing.

The Long-Term Soil Productivity Study (LTSP) of the United States Forest Service is an example (Powers et al. 1990). This study consists of three levels of organic matter removed, and three levels of compaction for a suite of sites with differ by tree species and soil quality. Remedial treatments (fertilization, herbicides, deep plowing) are included in the design. From related experiments, number of observations referring to post-harvest plantation growth and changes in soil properties (six to fifteen years) are already available (Cole 1995, Smith et al. 1994). For example, post-harvest depressed growth of Douglas-fir plantations was restored by the addition of nitrogen in amounts equivalent to that removed by logging (Cole 1995).

Another important study is the Integrated Forest Studies (IFS) program (Johnson and Lindberg 1992). This study generated comprehensive data sets for various forest conditions and nutrient flows in North America, with one additional forest site in Norway. Conditions and flows addressed were: atmospheric deposition, throughfall, soil percolation, soil weathering, and nutrient contents for foliage, wood (various compartments), roots, forest floor, and mineral soil layers. The studies also included analytical overviews and special case studies, such as the comparison of Douglas fir and red alder growth on a previous Douglas fir site, and a general overview of the impact of soil acidification on forest growth.

Further important contributions to discerning relationships between forest productivity and site conditions are being made through long-term field studies that deal with changes in organic matter and nutrient pools. This is done for undisturbed forest conditions, often at the watershed level (e.g., Foster et al. 1994), and for forest plantations (e.g., Richter et al. 1995).

6 Conclusions

This paper presents opportunities and examples by which the effects of intensive harvesting on long-term forest biomass productivity can be examined by integrating field experiments and process studies into a dynamic and steady-state simulation modelling context. For this purpose, model calculations need to be based on fairly simple assumptions about net primary production, allocation patterns of nutrient and photosynthate within the vegetation, and nutrient cycling. Furthermore, models must be generalized across various species/site combinations, in order to reach their full potential as a research tool for the development and evaluation of forestry practice codes. In principle, production predictions need to be validated using the results of long-term field experiments that examine the impact of harvesting and site preparation scenarios on site productivity.

For the jack pine case study, dynamic and steady-state modelling results were found to be in general agreement with each other and with field observations on forest biomass growth, although the former provided more details about the changes that follow periods of forest disturbance. We regard the model illustrations presented here as a first approximation for site-specific simulations regarding forest biomass and nutrient cycling under changing harvesting scenarios. Both steady-state and dynamic models require input (1) for driving models (e.g., weather, atmospheric deposition, and soil and site descriptors), (2) for calibrating individual model processes, and (3) for validating model performance with data other than the input used for calibration.

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Role of process models in developing environmental guidelines for sustainable energy output from forests

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Introduction

Concern over the long-term effects of forest management combined with the lack of long-term data sets with which to evaluate such effects has naturally led to the use of simulation modeling. The need for modeling seems obvious, given the lack of long-term data sets or other alternatives with which to evaluate these effects, and the wherewithal for the construction and utilization of models is clearly available. However, once outputs are produced, questions rapidly begin to arise as to what such outputs are really good for. Can they be used as predictions? If so, how can one judge their accuracy? Do the dangers of inaccurate predictions outweigh the benefits of making them?

Arguments are often made that simulation models can be used to gain insight into ecosystem fuctioning (Kimmins et al 1979; Aber et al 1982; Orestes et al 1992; Johnson et al., 1995a and b; Rastetter 1996). But if model portrayals are inaccurate or imcomplete, how much insight is really gained by modeling? What gain is there in observing the behavior of a system that does not exist in nature? How can we judge how close models actually portrayal those aspects of the system that we are interested in?

These are serious questions which are seldom addressed by modelers; all too often, modelers show only the best of their results and discard failures. The scienfitic community senses this, seeing a suspiciously frequent match between simulated and measured results, and harbors deep suspicion about both models and modelers which they feel ought to be shared by policy makers.

The charge of this paper is to evaluate the potential of process models for developing environmental guidelines for sustainable energy output from forests. In conducting such an evaluation, I will first review the general features and some of the predictions of some of the models which have been applied to intensive forestry over the last two decades. Following this, I will discuss the potential applicability of these models to the development of environmental guidelines. Finally, I will review some of the general philosophies governing the validation, verification, and confirmation of models, using insights provided by two recent articles on that subject (Orestes et al 1994; Rastetter 1996).

2 Models used to evaluate the effects of intensive harvesting

Several models were developed during the late 1970's and early 1980's to address the effects of intensive forest harvesting (Kimmins et al., 1979, 1984; Aber et al 1980, 1982; Rauscher et al 1983). These models and their predictions have been reviewed by

Johnson and Dale (1986) and Binkley (1989), and only brief synopses will be provided here. In general, the early models (FORCYTE, FORTNITE, LINKAGES, NITCOMP) focussed upon N cycling processes and their effects upon stand growth over several rotations. The early models did not explicitly simulate nitrate leaching, thus severely limiting their applicability to environmental guidelines for water quality. The later models (NuCM, SOILN-FORESTSR) do explicitly simulate nitrate leaching, but, as will be described below, the accuracy of these simulations leaves open questions as to their applicability for environmental guidelines.

3 Forcyte

The FORCYTE model has been described as a hybrid between a process model and an empirical model (Kimmins et at. 1984). FORCYTE assumes N is the major factor limiting tree growth. The structure of the model is to balance supply against demand of nutrients. If demand exceeds supply resulting in reduced growth for three consecutive years, site quality is reduced. Conversely, if supply exceeds demand, then growth increases and site quality can be improved. The growth equations are either from the Chapman-Richards relation (Pienaar and Turnbull 1973) or from site specific volume-age data. In either case, the relationship between stem-wood volume and age is meant to reflect soil moisture and climate conditions. The model is meant to be applicable to even-aged plantations. Therefore, only average trees are represented, and there is no variation possible in tree growth response to nutrient conditions. Input parameters define the average N concentration and decomposition rates for each age class of each biomass component (foliage, bark, branches, fine roots, and stem—wood and large roots). The large amount of data necessary to parameterize the model makes transfer from site to site difficult. The FORCYTE model is unique in that it includes a cost/benefit ratio of harvesting as one of the outputs (Kimmins et al. 1984).

4 Fortnite/Linkages

FORTNITE (Aber and Melillo 1980) and its offspring LINKAGES (Pastor and Post 1985) are process models. Both FORTNITE and LINKAGES treat nitrogen availability as one factor limiting tree growth in addition to soil moisture, light, and temperature. These models are based upon the JABOWA model of forest development (Botkin et al. 1972). They are process models in the sense that the major processes and feedbacks affecting tree birth, growth, and death are included so that sources of variation in forest development can be examined. A major advantage of process models is the ease with which assumptions can be relaxed. The effects of new factors (e.g., N fixation) upon tree birth, growth, or death can be expressed as mathematically, and the changes in forest development can be simulated rather than determined by collecting a new data set. In the models, nutrient decomposition affects available N which, in turn, can limit the annual growth of each tree. The rate of nutrient decomposition is tracked using annual decay compartments. The models treat on-leaf decay in great detail but model dead-wood and root decay only by individual species. The species-specific data required for the decomposition routine Includes the N-immobilization rate, lignin decay rate, and initial percentage of N and lignin in litter.

This information is currently available for 12 species groups (Pastor and Post 1985). N leaching and denitrification are not explicitly simulated.

Aber et al (1982) simulated the effects of harvest intensity, species, rotation length, and N fertilization on biomass yield in northern hardwood forests in New England using the FORTNITE model after it had been validated by comparing its outputs with measured values for basal area, species composition, leaf production, forest floor biomass, and dead wood mass after clearcutting. The FORNITE simulations indicated that short rotations would cause a reduction in yield by as much as two-thirds which could be partially offset by fertilization. Simulations also indicated that whole-tree harvesting on a 90-year rotation increased yield compared to clearcutting.

5 NuCM

The NuCM model was designed primarily for simulating the effects of atmospheric deposition on nutrient cycling proceses, and thus has a heavy emphasis on factors affecting solution chemistry. NuCM depicts the cycling of N, P, K, Ca, and Mg at a stand level, but also includes the fluxes of major cations (H^+, NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Na^+) anions (NO_3^-, SO_4^{2-}, ortho-phosphate, Cl^-, HCO_3^-, organic anion) and Si in precipitation, throughfall, and soil solution. In the NuCM model, the ecosystem is represented as a series of vegetation and soil components. Allows for an overstory consisting of one generic conifer and one generic deciduous species of specified biomass and nutrient concentration (foliage, branch, bole, roots). NuCM also allows an understory which can be divided into canopy, bole, and roots. Maximum growth in the model is defined by the user (e.g., from yield tables) and is constrained by the availability of nutrients and moisture. The soil includes multiple layers (up to ten), and each layer can have different physical and chemical characteristics. The movement of water through the system is simulated using the continuity equation, Darcy's equation for permeable media flow, and Manning's equation for free surface flow (Munsen et al., 1992). Percolation occurs between layers as a function of layer permeabilities and differences in moisture content. Nutrient pools and fluxes associated with soil solution, the ion exchange complex, minerals, and soil organic matter are all tracked explicitly. The processes which govern interactions among these pools include user-specified rates for decay, nitrification, anion adsorption, cation exchange and mineral weathering. Non-competative adsorption and desorption of sulfate, phosphate, and organic acid are simulated in NuCM using either linear or Langmuir adsorption isotherms. Cation exchange is represented by the Gapon equation. Mineral weathering reactions in the model use rate expressions that depend upon the mass of mineral present and solution-phase hydrogen-ion concentration raised to a fractional power.

NuCM has been applied to a variety of manipulations in recent years, including atmospheric deposition (Johnson et al 1993 and in press), Al mobilization by nitrate pulsing (Johnson 1995), liming (Johnson et al 1995b), harvesting, and species change (Johnson et al 1995a). Model outputs have successfully matched field data quite well in some cases (liming, harvesting effects on Ca; Johnson et al 1995a and b), and very poorly in other cases (Al mobilization by nitrate pulsing Johnson 1995). For the purposes of this discussion, the results of the harvesting and species change simulations are most relevant.

We simulated the effects harvest and species change (from loblolly pine [*Pinus taeda* L.] to mixed oak) on nutrient cycling for Duke Forest, North Carolina using the Nutrient Cycling Model (NuCM) (Johnson et al 1995a). The results of this simulation were very similar to those obtained in field studies comparing these species near Oak Ridge, Tennessee: high Ca uptake in the mixed mixed oak stand caused depletion of exchangeable Ca^{2+} and reduced Ca^{2+} leaching compared to loblolly pine (Fig. 1). In both field and model results, the effects of mixed oak on Mg^{2+} were superficially counter-intuitive but chemical consistent: mixed oak caused reduced exchangeable Mg^{2+} but increased Mg^{2+} leaching relative to the loblolly pine stand because of changes in the Ca^{2+}/Mg^{2+} ratio on the exchanger (Johnson et al 1995a).

The field results, which were based upon three years data collection of water data, suggested that total Ca^{2+} export via leaching and whole-tree harvesting in the hardwood and loblolly pine stands were similar: lower Ca removal in harvest in the loblolly pine stand was offset by greater Ca^{2+} leaching (Johnson and Todd, 1987). The simulations results also showed this pattern in the final years of the rotation, but also showed that cumulative Ca^{2+} leaching in the hardwood stand was only slightly (16%) less than in the loblolly stand, and total Ca export via leaching and whole-tree harvesting was therefore considerably greater in the hardwood stand than in the loblolly pine stand over the full rotation (Fig. 2). Thus, the simulation results suggested that nutrient budget analysis using only a few years of leaching data extrapolated over a full rotation could be very misleading because of changes in leaching rate with time.

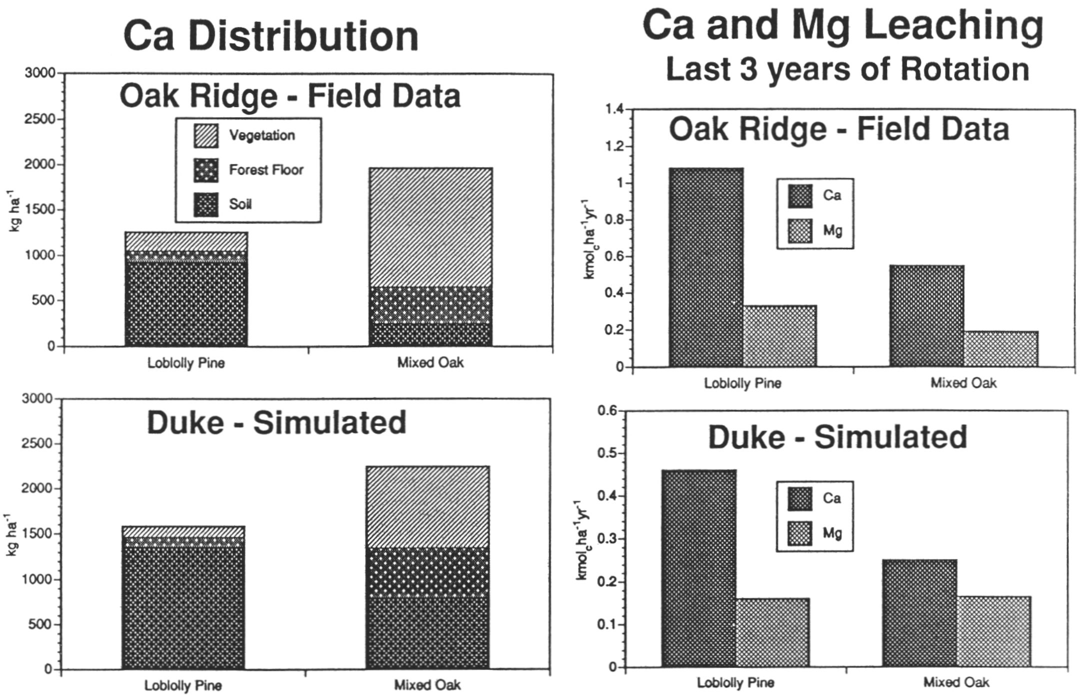

Figure 1, left: Ca distribution in loblolly pine and mixed oak stands near Oak Ridge, TN (upper panel) and simulated for the Duke site (lower panel). Right: Ca and Mg leaching in loblolly pine and mixed oak stands near Oak Ridge, TN (upper panel) and simulated for the Duke site (lower panel).

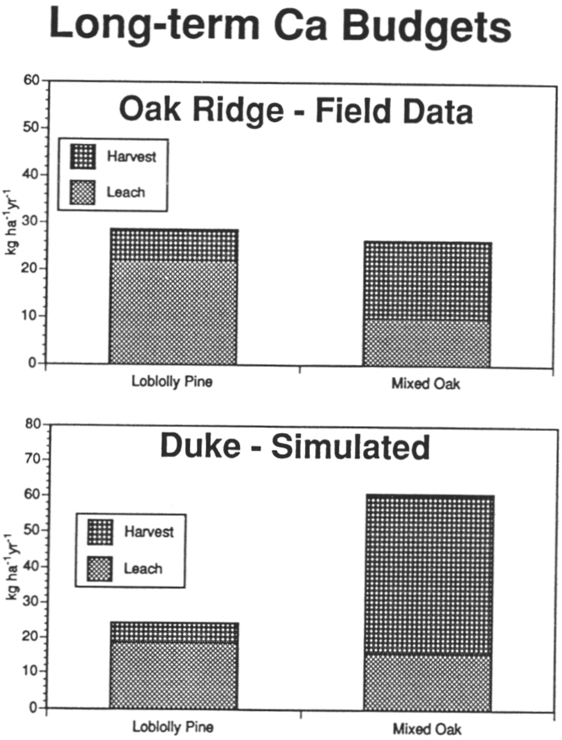

Figure 2. Calculated long-term Ca losses over a full rotation from field data at Oak Ridge, TN (upper panel) and from simulations for the Duke site (lower panel). (From Johnson and Todd, 1987; and Johnson et al. 1995a).

6 Soiln-forestsr

The SOILN-FORESTSR model was designed specifically for simulating growth and nitrogen cycling in a short-rotation Salix plantations in Sweden (Eckersten 1994). The model consists of a plant submodel (FORESTSR) which was links a photosynthesis-based growth with N uptake and multi-layered soil N model (SOILN) developed for agricultural soils. Both leaching and denitrification are specifically simulated in the model. The model was validated against data from a short-rotation *Salix viminalis* stand near Uppsala, Sweden. Growth-related outputs from the model matched field data quite closely, but correlations between model output and field values for soil mineral N were “very poor”. The model predicted high rates of nitrate leaching, but these results were not compared with field data.

7 What should these models be used for?

In their excellent overview on the uses and limits of numerical modeling in the earth sciences, Orestes et al (1994) rein in models and modelers with strict definitions of commonly-used terms like verification and validation. They assert that a model can never be verified because verification implies a demonstration of the absolute truth. Validation is defined as demonstration that the model "does not contain known or detectable flaws and is internally consistent" (Orestes et al 1994, p. 642), but it implies nothing as to the accuracy with which the model portrays the real world. They take especially strong issue with the common practice of splitting a data set, using the first half for calibration and the second half for "verification." They suggest terms like "forced empirical adequacy" to describe a "successful" model, and assert that it is encumbant on the modeler to not only demonstrate the reliability of the model but also delineate the limits of its applicability. These authors contend that " the primary value of models is heuristic" and that they are most useful when used to challenge existing formulations rather than to validate or verify them" (p. 644). Thus, taken at face value, the arguments presented by Orestes et al (1994) would preclude us from using models for developing environmental guidelines for sustainable energy production or for any other purpose.

In his review and analysis of models of ecosystem response to global change, Rastetter (1996) argues that "the unequivical tests required by modern scientific methods cannot be used to evaluate models of ecosystems response to changes in climate and carbon dioxide concentration" because rigorous tests of this nature are either irrelevant and impossible within reasonable time frames. He asserts that questions such as those addressed by these models are "trans-scientific": questions of fact that can be stated, but cannot be answered by scientific investigation. The question then becomes, do we leave such trans-scientific questions alone, no matter what their importance, or attempt to address them by synthesizing "indirect scientific information from diverse sources", as Rastetter suggests the global models accomplish.

It is the opinion of this author that process models should not be directly used to develop environmental quidelines for sustainable energy output from forests, the admonitions of Rastetter notwithstanding. There are both technical and philosophical reasons for this opinion. From a technical viewpoint, some of the process models seem to perform adequately in terms of predicting biomass yield and nutrient export; however, one must ask what is gained by using these models instead of much simpler yield tables and nutrient drain calculations? Also from a technical viewpoint, the process models do not adequately simulate two important processes: 1) soil weathering, and 2) nitrate leaching. Soil weathering remains an elusive quantity to measure, let alone simulate, yet is it vital to the long-term changes in soils. Nitrate leaching is a fuction of so many variables that change over such short duration that it simply cannot be accurately simulated with today's knowledge of the processes and controls involved. The general patterns of nitrate leaching can be mimicked, as is illustrated from NuCM simulations for the highly-calibrated red spruce site in the Smoky Mountains (Fig. 3).

However, it is readily apparent that even the relatively sophisticated NuCM model cannot accurately portray the detailed temporal patterns in soil solution nitrate that are observed in the field. Given the importance of groundwater nitrate concentrations in developing environmental standards, it is clear that the process models have a long way to go before they can be used to develop any but the most broad of guidelines.

From a philosophical point of view, it is clear that these process models have heuristic value and should be used to help guide the research and the simple, probably empirical models needed for ennvironmental guidelines. However, by their very nature, process models have "too many knobs": there are usually far more parameters needing values

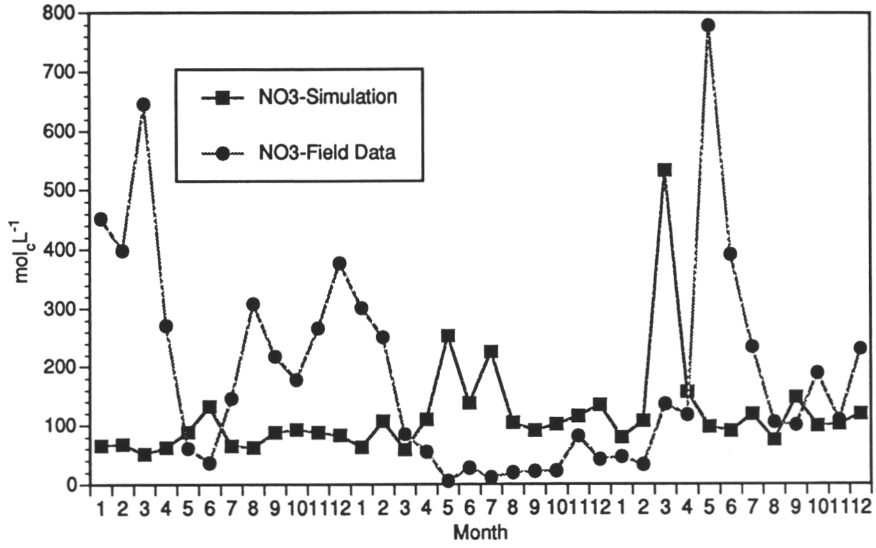

Figure 3. Measured and simulated soil solution nitrate for a red spruce stand in the Great Smoky Mountains, North Carolina, USA. (From Johnson et al. 1991 and 1996).

than there are values to apply to them. Thus, users of the process models must use educated guesses in many cases, leaving open the possibility of getting any result desired by simply manipulating unknown parameter values or ranges. Such manipulation can very easily be incorportated into calibration or validation exercises. In short, the results of process modeling usually cannot be unique for a given set of site conditions, and thus they are useless for direct application to environmental guidelines.

8 Conclusions

Simple empirical models - like yield curves - are seldom questioned because they are not subject to manipulation based upon the user and users know the bounds of their applicability quite well. Process models can certainly be used to understand what might underly such simple empirical models, but, because they are too complex to yield consistent results from one user to another and because they do not adequately simulate some important nutrient cycling processes, they should not, in my opinion, be directly used to develop environmental guidelines. These models have considerable heuristic value, however, and should be used to guide our research and explore the collective implications of our current understanding of ecosystem processes.

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Modelling forest management effects on organic matter decomposition in British Columbia

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Abstract

A suite of empirical field trials are underway to examine the influence of climate and litter chemistry, and the effects of management practices such as forest removal, opening size, species mixtures, fertilization and soil disturbance on rates of decomposition in British Columbia, Canada. Results will be used to estimate rates of decomposition of litters in each biogeoclimatic zone in B.C., and to develop equations that predict rates of decomposition with modifiers for the effects of management practices. This information will be incorporated into the ecosystem model FORCEE, to reduce the input data needed to predict rates of decomposition. Results to date suggest that moisture and lignin concentrations are key variables influencing decomposition rate, and that decomposition in slower in clearcuts and N-fertilized forests.

Keywords: organic matter decomposition, modelling, British Columbia

1 Introduction

Nitrogen limits the productivity of most north temperate forests, and the availability of N to trees is dependent on it being recycled through decomposition of organic matter. Predicting the effects of forest management practices on long-term site productivity therefore requires that we understand their effects on rates of decomposition and N release from organic matter. Presently, questions about long-term productivity and sustainability can only be addressed using simulation models. Estimates of decomposition rates are critical for predicting productivity with these models. In the series of models (FORCYTE, FORCAST, FORCEE) developed by J.P. Kimmins and colleagues at U.B.C., productivity is driven by N availability, which in turn is driven by estimates of rates of litter decomposition and N release in the ecosystem. These data must be provided by the user, and therefore require that empirical data be derived either from field experiments or from literature values. Simulations have shown productivity estimates to be very sensitive to estimated rates of litter decomposition. To increase the ease and accuracy of the model for use in forests of British Columbia, I am modifying the decomposition subroutine of the model, based on results from a series of field trials. The results will provide input data for rates of decomposition of most litter types in most types of forest ecosystems in B.C., as well as modifiers to account for the effects of management practices such as forest removal, mixtures, fertilization, and soil disturbance. In addition, results of these experiments will be used to develop equations that will predict rates of decomposition, given information on litter chemistry and climate. Users will be able to choose the approach that best suits their situation. Following is an overview of the strategy to improve our ability to predict and model rates of decomposition in B.C. forests under different management regimes.

2 Approach

Model development is proceeding through three major steps:

1. a series of field experiments to measure rates of decomposition in B.C. forests and determine their relationship to climate and litter chemistry, and the influence of common management practices such as openings, species mixtures, fertilization and soil disturbance,
2. development of a set of equations that predict rates of decomposition based on climate and litter chemistry, with modifiers for the effects of management practices,
3. incorporation of results into FORCEE to provide users with:
    - a) estimates of decomposition rates of each litter in each biogeoclimatic zone with modifiers particular to that zone
    - b) equations to predict rates of decomposition of any litter in any zone

3 Experiments

The litterbag technique is used in all experiments, in which litter is incubated on site in mesh bags and the weight of material remaining is periodically measured. Concentrations of C and N in litter are measured at each collection, to estimate rates of release of these elements. A description of each of the experiments and some of the results to date follow.

3.1 Influence of climate on decomposition rates

The overriding influence of temperature and moisture on rates of decomposition has been demonstrated (Bunnell et al. 1976), and differences in decomposition rates among biomes are related to general climatic conditions (Kimmins 1987). Relationships between decomposition rate and climatic variables such as actual evapotranspiration (AET) across a wide range of climatic conditions have been developed (Meentemeyer 1978), and are used in models to predict decay rates in different ecosystems (Kimmins 1993, Pastor and Post 1986). This experiment will determine the best relationships for B.C. British Columbia has a diversity of climates, due to its size (49°— 60°N), maritime influence, and mountainous topography. The result is a diversity of forest types, which have been used to divide the province into 14 biogeoclimatic zones (Meidinger and Pojar 1991). Representative climatic data for each zone studied are in Table 1.

Rates of decompositon of standard litter substrates are being measured in 9 forested biogeoclimatic zones within B.C. There are currently 26 installations, at least 2 in each zone. At each installation, rates of mass loss of pine needle litter, forest floor material and aspen leaf litter are being measured for 5, 4 and 3 years, respectively. Rates of mass loss will be compared with climate measurements at each site or from the nearest climate station, to determine the best relationships for predicting rates of decomposition. Site fertility parameters such as soil texture and C:N ratios of forest floor and soil will also be measured to determine if they have an additional influence on decomposition rates.

Table 1. Climatic characteristics for biogeoclimatic zones of British Columbia studied in Experiment 1.

Zone	Annual precipitation (mm)	Annual snowfall (cm)	Annual temperature (°C)	Number of frost-free days
BWBS	452	187	-1.4	146
CDF	873	50	9.5	305
CWH	2140	82	9.2	291
ESSF	1177	782	1.1	140
ICH	1063	422	6.9	221
IDF	414	145	4.2	163
MH	2954	820	5.0	198
PP	332	97	8.6	226
SBS	628	242	3.3	170

BWBS = Boreal Black and White Spruce
CDF = Coastal Douglas Fir
CWH = Coastal Western Hemlock
ESSF = Engelmann Spruce Subalpine Fir
ICH = Interior Cedar Hemlock
IDF = Interior Douglas Fir
MH = Mountain Hemlock
PP = Ponderosa Pine
SBS = Sub-boreal Spruce

Table 2. Weight of lodgepole pine needle litter remaining after decomposing for 3 years at sites in each biogeoclimatic zone. Initial litter weight was 2.0 g. Mean (and standard deviation in brackets) of 7 samples per site.

Zone*	Site	Weight remaining (g)
BWBS	Inga Lake	1.07 (.06)
	Bear Mt	0.83 (.17)
	Fairbanks	1.41 (.04)
CDF	Shawnigan S	0.88 (.06)
	Shawnigan N	0.77 (.11)
CWH	Blaney Lake	0.86 (.21)
	Pt McNeill	0.69 (.12)
ESSF	Otter Creek	0.77 (.11)
	Spanish Lake	1.05 (.20)
ICH	Adams Lake	1.01 (.16)
	Malakwa	0.63 (.10)
	Hidden Lake	0.87 (.10)
IDF	Valentine Lake	1.07 (.11)
	Boston Bar	1.06 (.17)
MH	Strachan	0.89 (.15)
	Garibaldi	0.88 (.15)
PP	Skihist	1.55 (.08)
	Trout Creek	1.24 (.19)
SBS	Beedy Creek	0.66 (.11)
	Topley	0.88 (.14)

* abbreviations as in Table 1

Average values for the weight of pine needles remaining after decomposing for 3 years at each site were generally fastest in forests on the coast (CWH, CDF and MH zones) and in the interior wet-belt (ICH), and slowest in dry interior forests (PP) (Table 2). This suggests that moisture is more influential than temperature on rates of litter decomposition in B.C.

3.2 Influence of litter chemistry on decomposition rates

Chemical characteristics of litter such as concentrations of lignin, N, C:N, and lignin:N have correlated with the relative rates of decay of different litter types in many studies (Berg 1986, Taylor et al. 1989a), and lignin:N ratios of litter are used to predict decay rates in several models (Kimmins 1993, Kurz et al. 1992, Pastor and Post 1986). Rates of decomposition of 12 substrates, including needles, leaves, moss, roots, cones and wood were measured in an earlier study (Taylor et al. 1991) and will be used to estimate relative decay rates for different litter types. Rates of decompositon of foliar litter of 10 species of trees in B.C. are being measured at two locations, in the boreal forest and in the coastal forest. Rates of decay of each species will be correlated with litter chemistry parameters, to determine the best relationships for predicting rates of decay of these litter types. The same suite of litter chemistry parameters has been measured in other species, so the relationships will be used to predict relative rates of decay of litter of all tree species in B.C.

The initial chemistry of the litters are shown in Table 3. Weight loss during the first 2 years is shown in Table 4. Western red cedar, firs and western hemlock decomposed more slowly than other species. The strongest relationship was with % lignin (r^2=0.409), which ranged from 18% in Engelmann spruce to 38% in cedar (Fig. 1).

Table 3. Initial chemistry of foliar litter of 10 species of B.C. conifers in Experiment 2.

Species	%C	%N	% Lignin	C:N	Lignin: N
Lodgepole pine	49.03	0.47	33.32	104.3	70.9
White pine	50.62	0.55	23.28	92.0	42.3
Ponderosa pine	48.38	0.60	28.62	80.6	47.7
Western hemlock	50.32	0.76	33.16	66.2	43.6
Western larch	45.68	0.39	19.66	117.1	50.4
Engelmann spruce	47.37	0.58	18.29	81.7	31.5
Subalpine fir	50.29	0.44	21.91	114.3	49.9
Western red cedar	47.16	0.54	38.78	87.3	71.8
Douglas-fir	47.65	0.50	23.81	95.3	47.6
Amabilis fir	55.88	0.39	24.29	143.3	62.3

Table 4. Percent weight loss of foliar litter of 10 species of conifers during 2-year incubation at sites in boreal and coastal B.C. Values followed by the same letter are not significantly different based on oneway ANOVA and Bonferroni's multiple range test.

Species	Boreal			Coast		
Lodgepole pine	27.0	a	(2.6)	52.9	a	(6.4)
White pine	27.6	a	(4.8)	52.5	a	(3.9)
Ponderosa pine	31.2	a	(4.2)	51.6	a	(4.7)
Western hemlock	22.5	ab	(2.7)	46.0	ab	(7.2)
Western larch	29.7	a	(3.0)	55.3	a	(7.2)
Engelmann spruce	32.3	a	(10.8)	53.7	a	(6.0)
Subalpine fir	28.3	a	(6.8)	46.4	ab	(6.6)
Western red cedar	16.1	b	(3.7)	41.3	b	(5.1)
Douglas-fir	29.8	a	(4.4)	53.5	a	(8.1)
Amabilis fir	15.3	b	(2.8)	47.7	ab	(9.9)

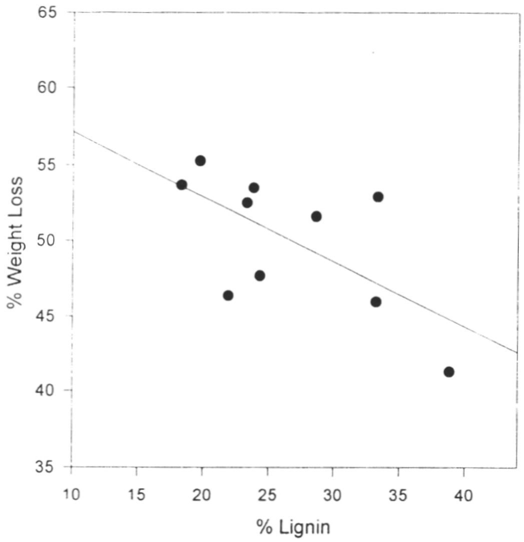

Figure 1. Relationship between inital lignin concentrations in foliar litter of 10 species and rates of weight loss during two years incubation in coastal B.C.

3.3 Influence of forest removal on decomposition rates

The influence of clearcutting on decomposition rates has been studied extensively, and although there is a general perception that decomposition is faster in clearcuts, the evidence does not support this generalization. As Yin et al. (1989) and Keenan and Kimmins (1993) discuss, clearcutting may increase or decrease decomposition rates, depending on the regional climate. Clearcutting may also have different effects on decomposition in different forest floor layers (Binkley 1984). Experiments to determine the effects of forest removal on rates of decomposition of litter and forest floors have been established in several forest types in B.C. At 22 of the 26

Table 5. Weight of pine needle litter remaining after 3 years decomposition in adjacent forest and clearcut sites. Original weight was 2.0 g.

Zone[1]	Site	Forest	Clearcut
BWBS	Bear Mt	0.83 (.17)	0.93 (.19)
CDF	Shawnigan S	0.88 (.06)	1.00 (.12)*
	Shawnigan N	0.77 (.11)	0.85 (.08)
CWH	Pt McNeill	0.69 (.12)	0.98 (.14)*
	Blaney Lake	0.86 (.21)	1.22 (.03)*
ESSF	Otter Creek	0.77 (.11)	0.79 (.09)
	Spanish Lake	1.05 (.20)	1.06 (.19)
	Lucille Mt[2]	1.04 (.23)	1.00 (.11)
ICH	Adams Lake	1.01 (.16)	1.16 (.14)
	Malakwa	0.63 (.10)	1.12 (.14)*
	Hidden Lake	0.87 (.10)	1.23 (.16)*
	Date Creek[2]	1.06 (.11)	1.11 (.02)
IDF	Valentine Lake	1.07 (.11)	1.16 (.16)
	Boston Bar	1.06 (.17)	1.09 (.07)
SBS	Topley	0.88 (.14)	1.26 (.06)*
	Aleza Lake[2]	1.01 (.13)	1.26 (.07)*

[1] abbreviations as in Table 1; [2] 2-year data

* clearcut significantly different from forest based on oneway ANOVA

forests studied in Experiment 1, litterbags containing the same standard substrates have also been installed in adjacent clearcuts. Eleven of the sites are silvicultural systems trials, in which there are openings of different sizes, in patch or partial cuts. Comparisons of rates of decay in each of the treatments will be used to predict the impacts of clearcutting and alternative silvicultural systems on rates of decomposition. Changes in decomposition rates will be related to the changes in climate induced by each harvesting system, using on-site microclimate data.

After 3 years, rates of decomposition of pine needle litter were slower in clearcuts than in adjacent forests at almost all sites, and significantly so at 7 of the 16 sites (Table 5).

3.4 Influence of species mixtures on decomposition rates

Several studies have demonstrated that litter decay rates can be influenced by the presence of other kinds of litter (Fyles and Fyles 1993, Taylor et al. 1989b), particularly when broadleaf and needle litter are mixed. Experiments have been established to determine the effects of mixing litter in the three major mixedwood forest types in B.C.: boreal (spruce/aspen), interior wet-belt (Douglas-fir/birch/pine) and coast (Douglas-fir/alder). Rates of decay of pure and mixed litter of each species is compared during incubation in pure and mixed forests.

Table 6. Percent of original weight of pure and mixed foliar litter of trembling aspen and interior spruce remaining after decomposing for 3 years at four sites.

Site	Aspen litter		Spruce litter	
	Pure	Mixed	Pure	Mixed
Aspen	24.8 (2.0)	28.4 (2.3)*	39.0 (2.9)	35.8 (6.0)
Spruce	27.5 (2.5)	26.8 (2.6)	49.9 (2.1)	48.2 (4.6)
Mixedwood	21.5 (4.4)	22.4 (3.6)	38.3 (2.5)	36.4 (2.4)
Clearcut	21.3 (3.7)	26.8 (2.6)*	53.0 (5.0)	51.8 (8.5)

* mixed litter significantly different from pure litter based on oneway ANOVA

After decomposing for three years at four sites in the boreal forest, differences between pure and mixed litter of spruce and aspen were small (Table 6). There was a tendency for aspen litter to decompose more slowly and spruce litter to decompose more quickly when mixed with litter of the other species.

3.5 Influence of fertilization on decomposition rates

It is generally assumed, and implicit in some models, that increasing N availability through fertilization will increase the rates of litter decomposition. However, direct studies of the effects of N fertilization on decomposition rates have had variable results, and indicate that external N supply has little effect on decay rate (Hunt et al. 1988, Prescott 1994). The effect of higher N concentrations in litter of a single species on decay rates is also unclear. Berg et al. (1987) found that greater N availability in pine needles stimulated decay in the early stages but inhibited decay during the later lignin decay phase, but Prescott (1994) found no influence. Prescott et al. (1992) suggested that decay of litter with low lignin and high labile C contents may be stimulated by fertilization, whereas litter with high lignin and low labile C contents will not.

Two experiments have been established, in a trembling aspen stand in northern B.C. fertilized once with N, and in a Douglas-fir stand in coastal Washington fertilized repeatedly with N. At each site, litter from control and fertilized plots is decomposing in both control and fertilized plots. Litter from fertilized (sewage-sludge-amended in Washington) plots had initally higher concentrations of N than litter from control plots. Comparison of rates of decay in each treatment will determine if improved N availability, either in the forest floor or in the litter, increases rates of decay. The current hypothesis is that greater N availability will increase the decay rate of the high quality litter (aspen), but not of the low quality litter (Douglas-fir).

After two years, Douglas-fir litter was decomposing more slowly in fertilized plots than in control plots (Table 7). There was no apparent influence of needle source (*i.e.* endogenous N concentration).

Table 7. Weight of Douglas-fir needle litter from control and sewage sludge-amended plots remaining after decomposing for 2 years on control and N-fertilized plots. Original weight was 2.0 g. Values followed by the same letter are not significantly different based on oneway ANOVA and Bonferroni's multiple range test.

Needle source	Incubation site	Weight remaining (g)
control	control	0.85 (0.10) a
sludge	control	0.94 (0.11) a
control	fertilized	1.21 (0.07) b
sludge	fertilized	1.21 (0.10) b

3.6 Influence of soil disturbance on decomposition rates

It is generally considered that mixing organic and mineral horizons hastens decomposition of organic material. Johansson (1994) showed faster decomposition of needles on scarified compared to non-scarified sites. Effects of exposure of mineral soil on decomposition rates will be examined in one silvicultural systems trial which included pushover logging, to reduce root disease. In the pushover treatments, litterbags were placed on the exposed mineral soil; in the conventional treatments, bags were placed on organic material. This experiment was recently installed, and results are not yet available.

4 Modelling strategy

In the existing FORECAST model, decomposition is simulated on the basis of empirical input data for annual weight loss of each litter type. Mineralization and immobilization are calculated based on a combination of: 1) input data for nutrient concentrations in fresh litterfall and in humus; 2) data on the shape of the curve describing the pattern of change in nutrient concentration during decomposition from litter to humus; and 3) simulated weight loss in decomposing litter. With these data the model simulates changes in the nutrient contents of litter cohorts over time; decreases are a measure of nutrient release by mineralization, and increases are a measure of immoblization from the available soil nutrient pool. It is planned to retain this simulation approach as an option in the model, but to add an alternative in the form of predictive equations that relate weight loss and mineralization to input variables for climate and litter quality.

The best equations for predicting rates of decomposition in B.C. forests will be determined from the studies of the influence of climate and litter quality. The required data must be simple to obtain, so standard climate data and conventional chemical analyses will be used. The equations will be tested with data from four additional decomposition experiments in B.C. that were not used in developing the equations. If the influences of site fertility or management practices prove significant, these will be built in as modifiers to the equations.

The results of the experiments will also be used to generate a database that will provide users with estimates of decomposition rates of any litter type in any biogeoclimatic zone, which will be built into the model in its current format. The user will only need to enter the zone and the species present, and the model will generate esimates of decomposition.

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The role of logging residues in site productivity after first thinning of Scots pine and Norway spruce stands

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Abstract

The aim of this study was to quantify the growth response of first-thinning stands of Scots pine and Norway spruce to whole-tree harvesting and to estimate the need for nutrient compensation on the basis of seven long-term field experiments. The thinning grade of the experiments was on an average 35 % of the stand basal area. The amount of logging residues in spruce stands was about double compared to pine stands, and the spruce stands were rethinned ten years after the establishment of the experiments. The harvesting of logging residues in pine stands had only minor negative effect on the tree growth during the 15 years following harvesting. The growth of whole-tree harvested plots in spruce stands was decreased by 10 % compared to that of stemwood-harvested plots during the following 10-year period after thinning. Needle analyses did not indicate any significant differences in the nutrient status of trees between the harvesting intensities. Owing to the larger biomass and nutrient removal, the negative consequences are more obvious in spruce stands than in pine stands.

Keywords: Pinus sylvestris, Picea abies, whole-tree harvesting, fertilization, nutrient losses, growth response

1 Introduction

Interest in logging residues as a source of raw material and energy has increased during recent decades. For example, in the mid-1970's in Scandinavia, attention focused on the utilization of logging residues as an energy source (Hakkila 1985). The possibility of utilizing small-diameter trees and logging residues from early thinnings is of special interest as these could make thinning operations more profitable (Hakkila 1989).

However, at an early stage in the discussion, theoretic conclusions were made about the possible harmful effects of intensified forest biomass utilisation (Tamm 1969). The canopy of thinning stands contains about one third of the total biomass of the above-ground parts of such tree stand, and as much as two thirds of the nutrients. So it was concluded that whole-tree harvesting could impoverish the supply of nutrients to the soil and consequently promote soil acidification. As a result, stand increment would also be impaired. Especially this was seen to constitute a problem on dry and nutrient-poor sites (Lundmark 1983). From the viewpoint of maintenance of the site productivity it is of decisive importance to know whether or not the immediate nutrient losses resulting from the harvesting of biomass could be replaced sufficiently through the mineralisation of the soil organic matter, weathering of minerals, and atmospheric deposition. A precondition for the maintenance of the biological nutrient cycling is that the nutrient reserve formed by the soil organic matter is not endangered by the harvesting of logging residues, and that decomposition by soil microbes continues without any major disruptions. In addition to the type of organic matter, the nutrient cycle is influenced by soil temperature and moisture regime. When assessing the impacts of harvesting logging residues, the mutual relations of the site fertility factors on different site types should be borne in mind.

2 Material and methods

Long-term field experiments were established in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stands in 1977–80 (Fig.1). The experimental stands were due for first thinning, which was then carried out on every sample plot. The experiments have yielded results over a period of fifteen years. The same problem is also being investigated in a Nordic joint study based on a series of experiments depicting different growing conditions (Jacobson et al. 1996). The principal results of the Nordic project are not, however, available yet.

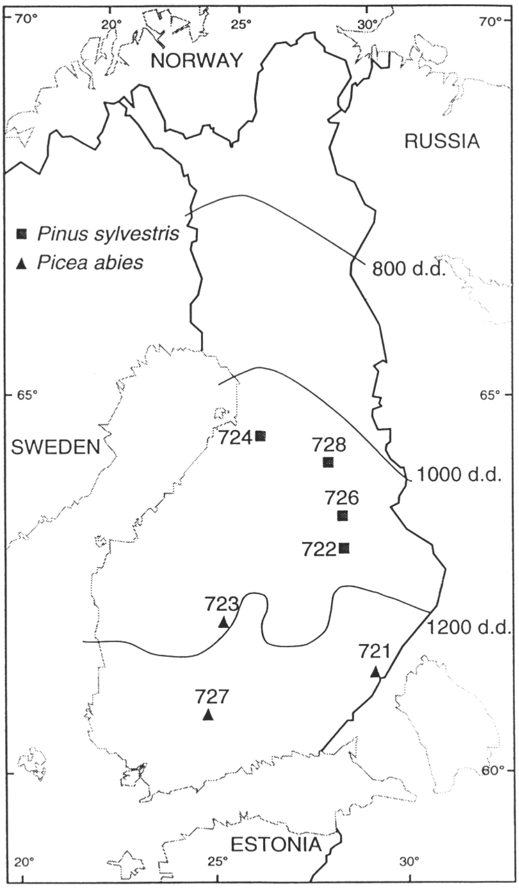

Figure 1. Location of field experiments and isotherms of the effective temperature sum (degree days, > +5 °C). Annual precipitation decreases from the southern (700 mm) to the northern (600 mm) experiments.

Table 1. The general site and stand characteristics of the experiments after thinning.

	Site			Tree stand after thinning			
Exp. No.	Soil org. matter [1] t/ha	Soil texture	H_{100} m	Age a	Stems No./ha	H_{dom} m	Volume m^3/ha
Pine stands							
722	19.6	Cs [2]	21	55	693	15.2	99
724	16.5	Fs [3]	18	58	903	13.1	69
726	14.8	Fs	27	24	1261	9.1	57
728	15.6	Fs	20	56	648	14.4	83
Spruce stands							
721	23.3	Fs	31	39	1106	16.9	189
723	24.8	Fs	28	40	1115	14.7	134
727	27.3	Fs	28	57	721	20.5	221

[1] In humus layer, [2] Cs = Coarse sand, [3] Fs = Fine sand

The site types of the Scots pine stands included dry, dryish or moist, i.e. the typical pine sites. The spruce experiments represent most fertile spruce sites (Table 1). The field experiments also include fertilization treatments to study the possibilities to compensate the nutrient losses due to whole-tree harvesting:

1. Whole-tree harvesting (WTH),
2. Merchantable stem harvesting (MSH),
3. MSH with doubled amount of logging residues,
4. WTH and compensatory fertilization with equal amounts of N, P and K removed in logging residues,
5. WTH and normal NPK fertilization (180 kg N/ha, 36 kg P/ha, 72 kg K/ha) and
6. MSH and normal NPK fertilization.

The treatments in each of the experiments were grouped into two to four randomised blocks minimising the variation of soil conditions, site, and tree stand volume within the block.

In the spruce stands, the second thinning took place ten years after the first. The logging residues and fertilization treatments were repeated in the same way as at the establishment stage. The pine stands have not been rethinned yet.

Different methods were used for the estimation of biomass and nutrient removals. At the establishment stage, logging residues were collected from the whole-tree harvesting plots and chipped. The total chip yield per plot was weighed green, and the chip samples were taken for dry-matter and nutrient determinations. In the second thinning in spruce stands, sample trees representing different size categories of trees to be removed were selected at random on each plot for biomass measurements. The living crowns of these trees were divided into four equal sections and a sample branch was taken from each section. One sample branch was taken at random from the dead branches below the living crown limit. All the dead and living branches on the sample trees were weighed green. The living sample branches were divided into different fractions and the dry-matter percentage of all the samples was then determined. The total dry-mass of the logging residues on the plots was determined by means of regression estimation.

3 Assessing effects of nutrient loss

3.1 Nutrient content of logging residues

Typically, 35 % of the basal area was removed in thinning. The amount of logging residues produced in spruce stands was about twice that in pine stands. This difference was even greater as regards the nutrient content of the residues (Table 2). This is partly explained by the fact that spruce stands grow on more fertile sites than those of pine. Expressed per volume unit of stemwood removed in thinning, the logging residues in pine stands amount to ca. 270 kg/m^3 while in spruce stands the figure is ca. 190 kg/m^3. The stands of spruce in this study were composed of clearly larger stems than those of pine.

In the case of the experimental stands of this study, the total recovery of logging residues would increase the volume of harvested biomass by a factor of 1.5–1.7 and the removal of nutrients by a factor of 1.9–3.6 when compared to conventional harvesting of merchantable stem. Considering the nutrient cycling, the biomass of logging residues correspond to ca. 5 years' litterfall, but the amount of nutrients bound into logging residues is more than twice that contained in the equivalent amount of litter.

Table 2. The biomass amounts and nutrient contents of the logging residues at the time of establishing of the experiments.

Exp.	Stemwood removed		Logging residues					
No.	Volume	% of basal area	Biomass	N	P	K	Ca	Mg
	m^3/ha		t/ha	kg/ha				
Pine stands								
722	43.7	33.6	8.3	23.3	2.9	11.1	16.9	3.9
724	13.7	20.0	8.0	21.2	2.7	10.7	18.4	4.2
726	25.9	33.1	9.7	43.6	4.7	17.1	20.0	4.7
728	35.1	32.7	7.7	34.1	3.3	12.7	15.7	3.5
Spruce stands								
721	90.1	34.5	17.3	75.6	9.5	25.6	83.9	7.8
723	61.7	34.4	15.3	56.7	8.2	19.9	51.8	6.9
727	110.5	35.3	18.3	95.5	7.7	32.4	83.0	8.4

3.2 Growth response

The amount of logging residues in first-thinning stands on pine sites remained small and their removal has had only a minor negative effect on tree growth during the 10–15 years' monitoring period (Fig. 2). Removal of logging residues appears to have a greater impact in spruce stands than in pine stands. The growth of whole-tree harvested plots in spruce stands was 10 % smaller than that of stemwood-harvested plots during the following 10-year period after thinning. Accordingly, the plots with double amount of logging residues grew 7 % better than the stemwood harvested plots. However, the response to the logging residues was statistically significant ($p < 0.05$) only in one of the experiments (723).

One obvious reason to the different response of pine and spruce stands is the greater logging residue biomass in spruce stands. Also, the superficial root system of spruce may explain this outcome.

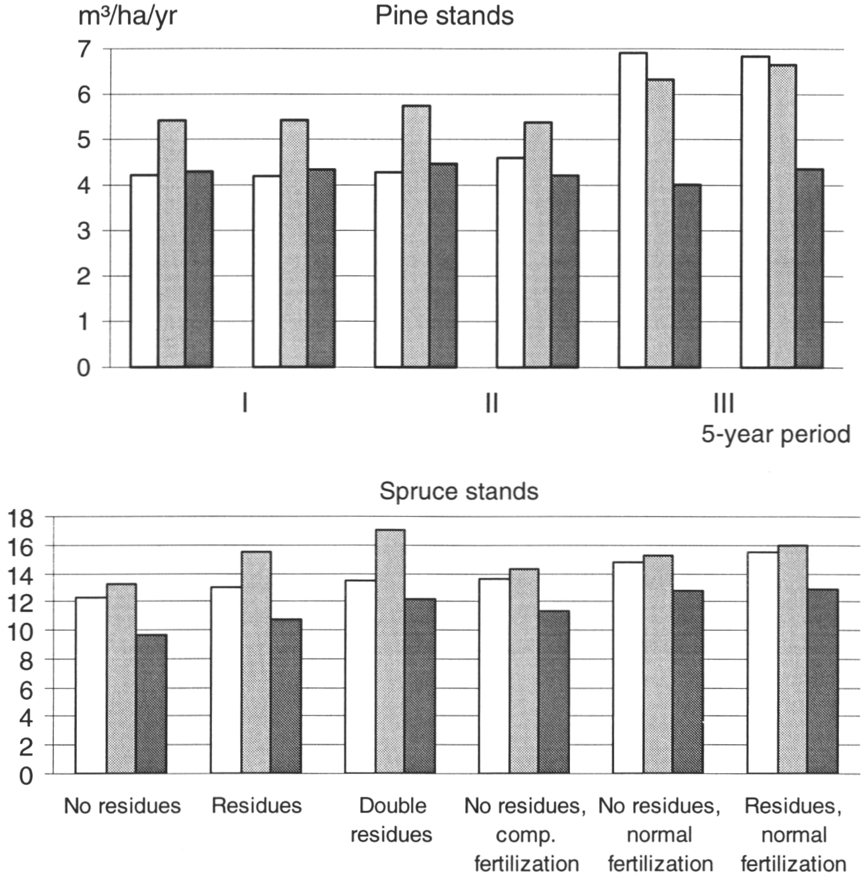

Figure 2. Volume growth by treatment during three 5-year periods.

The absolute growth response to fertilization was about equal in pine and spruce stands, in spite of differences in the amount of standing volume and site type. In pine stands the differences between normally fertilized and corresponding unfertilized plots were 2.7, 1.1 and –0.1 m^3/ha/yr during the consecutive 5-year periods. In spruce stands these responses were 2.5, 1.3 and (because of the refertilization) 2.7 m^3/ha/yr. The relative response to fertilization was thus much higher in pine stands (Fig. 3). The responses were statistically significant ($p < 0.01$) in all of the pine experiments during the first 5-year period and in one of them (724) also during the second period. The within stand variation of growth was much greater in spruce stands than in pine stands. Because of it the growth response to fertilization was statistically significant only in one of the spruce stands (723) during the first 5-year period.

In a Swedish study, forest growth has been observed to decrease by 7–12 % in two pine stands following whole-tree harvesting (Andersson 1983). In Norway, first thinning conducted as whole-tree harvesting has impaired growth in spruce stands on fertile sites by 1.5 m^3/ha/a over a monitoring period of 5–6 years; this corresponds to 11 % of the growth following stemwood harvesting (Tveite 1983). In pine stands, the corresponding loss was 7 %. However, the duration of growth recession on these experiments is not known. Lundkvist (1993) reported results from an extensive series of experiments by Leijon, which indicate constantly greater volume increment for treatments where logging residues were left on the site.

3.3 Soil effects

The conclusion made is that the harvesting of logging residues accelerates soil acidification. The harvesting of logging residues after clear-cutting results in acidification of the organic horizon in acid forest soils (Staaf & Olsson 1991, Lundkvist 1993). In the present study material, no statistically significant differences were observed in the pH of the humus layer. However, logging residues appear to have some effect on the acidity of the humus layer, because the pH of this layer was 0.1–0.2 pH-units higher than on the whole-tree-harvested plots.

Ten years after thinning, despite the considerable amounts of nutrients removed in whole-tree harvesting, the method applied had no significant effect on the nutrient resource of the humus layer. Neither did needle analyses indicate any statistically significant differences between the harvesting intensities regarding the nutrient status of trees.

Harvesting of logging residues affects the growth of conifer stands rather slowly. Obviously this depends on the slow decomposition of organic matter and the delay in the release of nutrients to trees. The various fractions of logging residues mineralise at different rates. The nutrients of the needle fraction are almost entirely released during the first decade, while the decomposition of thicker branches takes a considerably longer time (Staaf 1984).

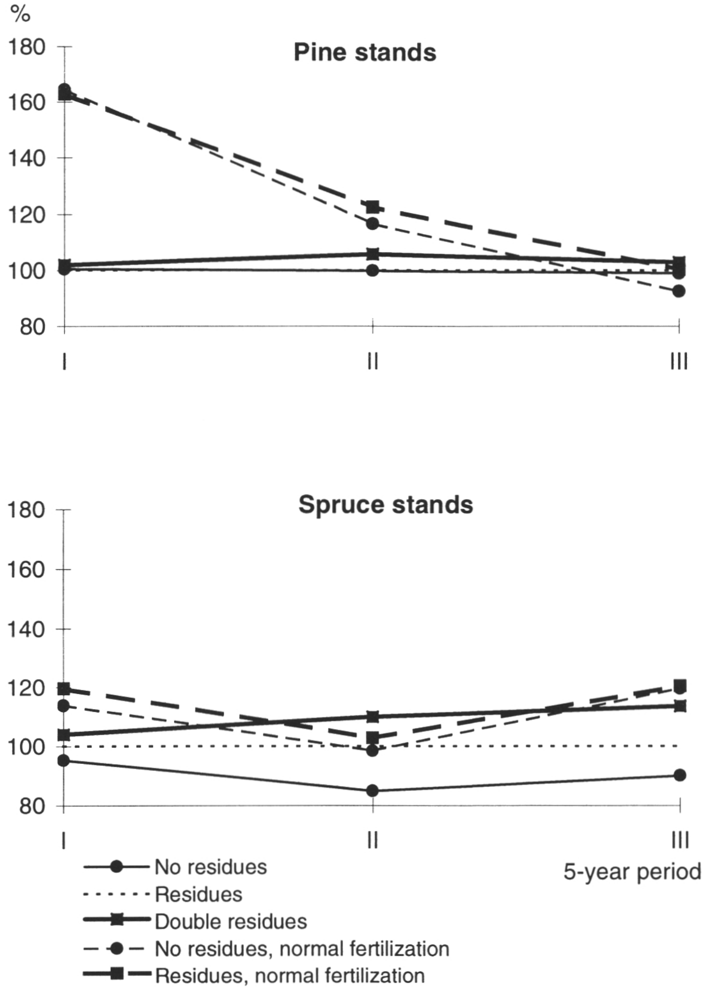

Figure 3. Volume growth by treatment compared to that induced by harvesting of merchantable stemwood with logging residues being left on the site (= 100).

4 Conclusion

The effect of whole-tree harvesting on the growth of stands depends on site conditions and tree species. Obviously, the harmful consequences of whole-tree harvesting on site productivity are dependent on the nutrient amounts removed. Owing to the larger biomass and nutrient removal, the negative consequences are more obvious in spruce stands than in pine stands. Because of the slow net mineralisation of nutrients in logging residues, it is understandable that the stands studied responded more rapidly to readily soluble fertilizers than to equivalent amounts of nutrients in logging residues.

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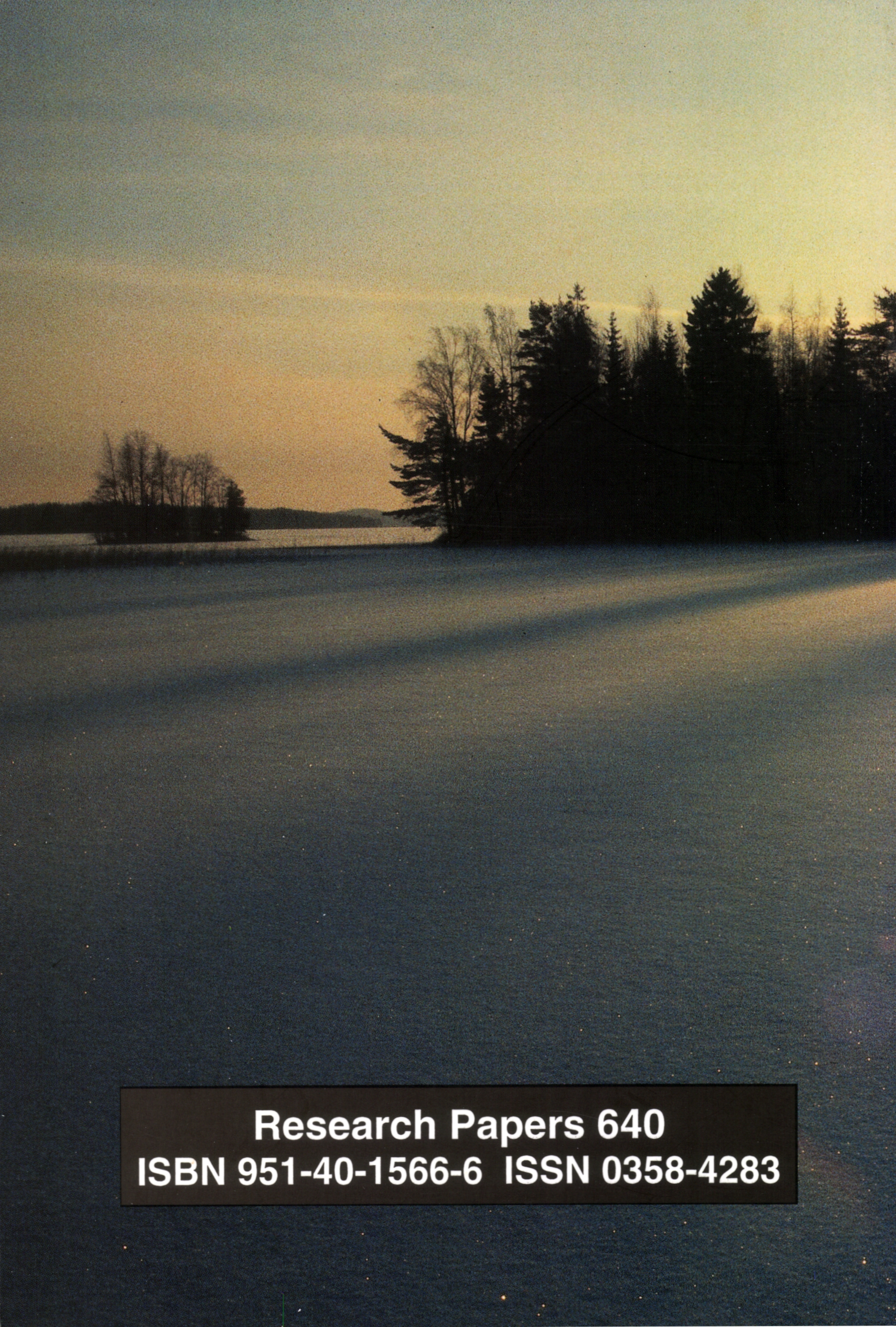

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