Norwegian Journal of Agricultural Sciences

Supplement No. 24 1996

Silvicūltūre for Fuelwood

Ås Science Park Ltd., Norway

NORWEGIAN JOURNAL OF AGRICULTURAL SCIENCES

Norwegian Journal of Agricultural Sciences is a forum for publishing Norwegian research with international interest within the following areas: Aquaculture, Animal Science, Soil and Water Science, Agricultural Engineering and Technology, Natural Resources and Environment, Food Technology, Crop Science, Forestry, Economics and Society Planning.

PUBLISHER

The journal is published by the Ås Science Park Ltd., Sagabygget, N-1432 Ås, Norway. Norwegian Journal of Agricultural Sciences (ISSN 0801-5341) is published four times a year, each issue containing approximately 100 pages. Four issues comprise one volume. Annual subscription NOK 500,-. Supplement issues can be ordered separately through the publisher.

REFEREE

All papers submitted for publication will be sent to competent international referees.

CORRESPONDENCE

All correspondence, editorial or otherwise, should be adressed to Ås Science Park Ltd., Sagabygget, N-1432 Ås, Norway

The drawing on the cover: Kjell Aukrust

ISSN 0802-1600

Norwegian Journal of Agricultural Sciences

Supplement No. 24 1996

Silviculture for Fuelwood

Proceeding from IEA
Bioenergy
Task XII Activity on
«Forest Management»
Asker, Norway, Sept. 4-6,1995

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Preface

Conventional forestry operations are a significant source of biomass for energy purposes. By removing this biomass in the form of pre-commercial thinnings, harvesting residues or otherwise underutilized species, benefits to silviculture may also be produced. Exploring and developing this potential is the motivation behind the IEA Bioenergy Task XII Activity on "Forest Management" under whose auspices a workshop on the theme of "Silviculture for Fuelwood" was held at Asker, Norway September 4-6, 1995. The workshop was organized by the Agricultural University of Norway, Department of Forest Sciences. Eleven papers were contributed to the workshop by participants from five of the six countries (Canada, Denmark, Finland, Norway, Sweden, United Kingdom) collaborating in the Activity. Seven of the papers are included in these proceedings, following scientific peer review and revision.

The editor of these proceedings expresses his sincere appreciation to the authors of the papers for their contributions and to the reviewers for their diligent efforts.

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Editor
Ås, Norway

Management of birch forest

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Johansson, T., 1996. Management of birch forest. Norwegian Journal of Agricultural Sciences. Supplement No.24: 41-54. ISSN 0802-1600.

Management of birch forest growing in Nordic countries is presented. Biological characteristics of the two birch species: silver birch (*Betula pendula* Roth) and pubescent birch (*Betula pubescens* Ehrh.) are described. Natural regeneration of birch on forest land is the common way to establish birch forest. Planting is too risky as moose, roe deer and hare very frequently browse the plants.Birch is a light demanding species and strong competition causes the plant to react. If the competition is too strong, the percentage green crown decreases below 50 % of the tree height. Then the growth rate is decreased and a cleaning or thinning operation later on does not repair the damage. Therefore birch forest must be intensively managed from the young stand stage. Two to three thinning operations are necessary to maintain the growth rate and to manage an even-aged stand containing large-diameter stems with high wood quality. On a fertile forest site silver birch has a total yield production of 270 m^3 ha^{-1} and pubescent birch 150 m^3 ha^{-1} based on a rotation period of 50-70 years. Some recommendations about management of sprout forest stands are given. Recommendations are given on silvicultural methods for afforestation on abandoned farmland. Total yield production for silver birch forest growing on farmland is 350 m^3 ha^{-1} and 200 m^3 ha^{-1} for pubescent birch based on a rotation period of 40-60 years. Fuelwood production of naturally regenerated birch on abandoned farmland is discussed. An annual mean yield of biomass production of at least 5-6 ton d.w. ha^{-1} is possible.

Key words: *Betula pendula* Roth, *Betula pubescens* Ehrh., birch forest, biomass, competition, farmland, fuelwood, management, sprouts, yield.

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In this paper management of birch forest is discussed. The subject is limited to native birch species in Nordic countries.

The genus *Betula* belongs to the family *Betulaceae,* as does the genus *Alnus*. According to Raulo (1987) there are about 50 species of *Betula* in the world cf. Fig. 1. In Nordic countries there are two main birch species: silver birch (*Betula pendula* Roth) and pubescent birch (*Betula pubescens* Ehrh.). A third species, dwarf birch (*Betula nana* L.), mostly growing on peatland areas, but also on mineral soils in mountains, normally has no economic value for forestry. The two birch species are spread over northern and middle (southern) Europe and in the east to Asia cf. Fig. 2. Note that pubescent birch has the same range as silver birch but farther to the south and to the east. Northern Norway (Lebesby) Lat 70° 57' N., Long 27° 05' E. has the most northern birch

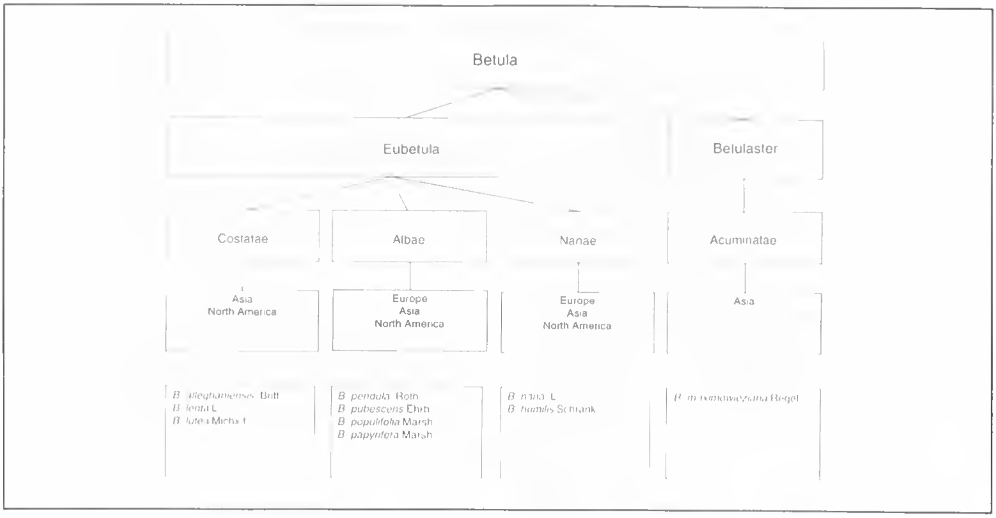

Fig. 1. The genus Betula *and examples of species.*

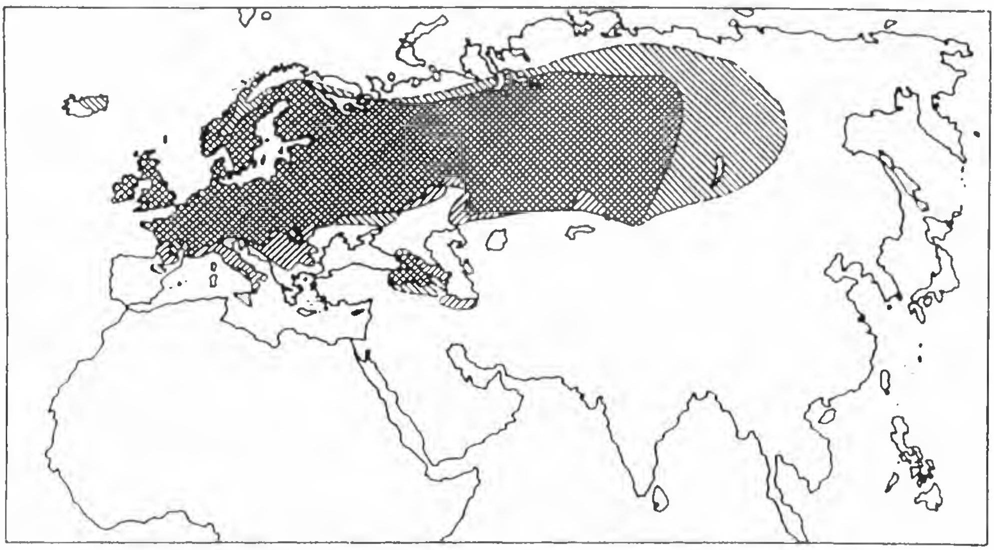

*Fig. 2. Extension of silver birch (*Betula pendula *Roth) and pubescent birch (*Betula pubescens *Ehrh.) (Thomasius 1975).*

forest (pubescent birch) in the world. Birch has been widely used by the Nordic people as fuelwood during the centuries. Birch wood is important as a raw material for handcraft work. Today, birch timber and pulpwood are a very important economical outcome in Nordic forestry especially in Finland, Norway and Sweden. In Finland birch for veneer production has been common since the 1970s.

There are some characteristics of the

two species which make it possible to classify them: young individuals (< 15 years) of pubescent birch have hairy shoots and silver birch shoots have warts. These characteristics are a very significant way to classify the two species when the plants are young (< 15 years). But the older the trees are, the more difficult it is to classify them correctly. On older trees the main distinguisthing characteristics are as follows. Pubescent birches typically have single-tooth leaves and silver birch double-tooth leaves. The bark on the lower part of a silver birch stem is more or less black and furrowed. The seed wings of silver birch are 3-4 times wider than the seed. Seed wings for pubescent birch are 1.5-2 times wider than the seed.

Recent genetic research reveals that there can be exchange of genetic material between birches of different species cf. Kennedy and Brown (1983), Anamthawat-Jónsson and Tómasson (1990) and Anamthawat et al. (1993). This can explain intermediate forms. However, a test by Lundgren et al. (1995) showed that 20-30% of the birches classified according to the above-men-tioned method based on visual character-istics were wrongly classified. This was most pronounced in mixed stands of silver and pubescent birches. A chemical "percipitation test" has been introduced (Lundgren et al. 1995). In the chemical method the bark from birches are dissolved in 2,4 dinitrophenylhydroazine. If the solution is still yellow after half to one hour the tested species is pubescent birch; if the solution changes colour to orange, the species is silver birch. The test indicates if it is silver birch or another birch species. In other parts of the world with a lot of birch species the test method is not usable for a general classification in specific species.

Pubescent birch grows best on fertile and moist sites. On the other hand, peatland areas are covered by the species. In Finland, natural regeneration on peatland of pubescent birch has been practised for a long time. These areas are mostly wet and have a low oxygen level which pubescent birch tolerates. In recent years finnish farmers have become more interested in testing pubescent birch on the most problematic farmlands (wet peat origin). Silver birch grows best on deep fresh-moist fertile sites but also reasonably well on fairly dry soils. On soils with a fine mineral structure such as clay or silt and on peatlands, silver birch grows slowly. Pubescent birch is less light-demanding than silver birch although both are light-demanding especially in the adult period. They start seed production at 15-20 years of age, sometimes earlier (10-12 years old).

In Sweden 5 % of the forest area is covered by pure broadleaved forests and 7 % by mixed soft and hardwood forests cf. Kempe et al. (1992). Mostly, birches grow in mixed stands both with hardwood species (alder, beech, maple and oak) and softwood (Norway spruce and Scots pine), Fig. 3. Mixed stands of birch and Norway spruce were studied by Frivold (1982a), Braathe (1984,1988), Agestam (1985) Mielikäinen (1985) and Tham (1988). An overview is reported by Frivold (1982b), Bergman (1982) and Johansson and Lundh (1991). Methods for managing mixed stands of birch and Norway spruce are discussed by Braathe in these proceedings and therefore are only mentioned here.

Generally, birch is not planted on forest land areas in Nordic countries. Game species such as moose (*Alces alces* Lin.), roe deer (*Capreoulus capreoulus capreoulus* Lin.), hare (*Lepus capensis* Lin., *Lepus timidus* Lin.) and rabbits (*Oryctolagus cuniculus* Pallas) severely

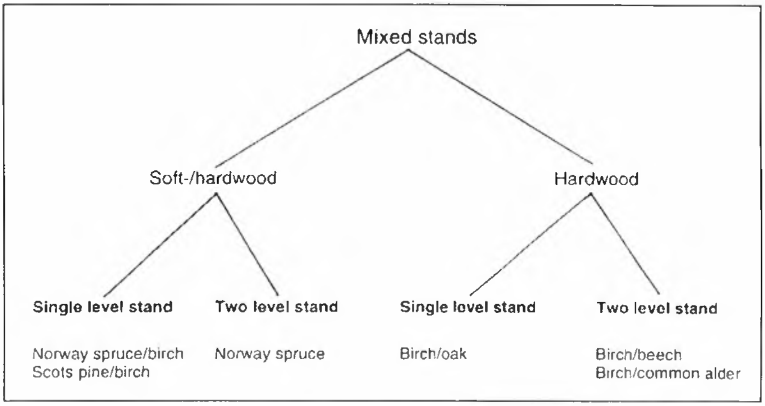

Fig. 3. Examples of mixed forest combinations.

browse the stands. However, in Finland planting of silver birch on forest land has been common from the beginning of the 1970s. In general, in Nordic countries pure birch plantations are managed on farmland or on pasture land areas.

Establishment

Generally, birch stands on forest land are created by natural regeneration (seeds or sprouts). On abandoned farmland, birch is one of the most popular species for plantation. Mostly, those plantations are fenced or the plants are sheltered by plastic tubes. Otherwise, the plants are browsed by moose, roe deer and hare. However, in Finland until nowadays, plantations on farmland have very seldom been fenced due to high costs and a low population of moose and roe deer. Moose damages have been avoided by planting only close to roads or houses.

Natural regeneration from seed is common on forest land after clear felling especially when the ground is scarified. Sarvas (1948) has made a lot of studies of seeding by birch. Fries (1984) reported that an older birch tree produces 1 million seeds per year. He studied the seedfall on a clear felled area of 1.5 ha and found that 800 seeds per m^2 fell in the middle of the area. The seeds were spread from the forest around the cut area. The number of birch in the forest was low and the trees were scattered, with few birch growing near the clear cut area.

Generally, there are seed trees of birch in the forest near the clear cut area. Seedlings of birch have a growth rate similar to Scots pine for the first five years cf. Fig. 4. At that age, there will not be any serious competition in height or light between birch and pine. Mostly, the plants grow in the scarified spots or furrows. Root competition and water deficit might cause a decrease in the growth rate and a lower vitality in the Scots pine.

Birch also regenerates by sprouts. Most of the buds are localised on stumps 1-5 cm above to 1-5 cm below ground level (Johansson 1992a). When the birch is cut, the sprouts develop. The number of sprouts per stump decreases from > 5 to < 2 during a period of five years (Johansson 1991). Most of the stumps, 80-90 %, are still alive the year after cutting

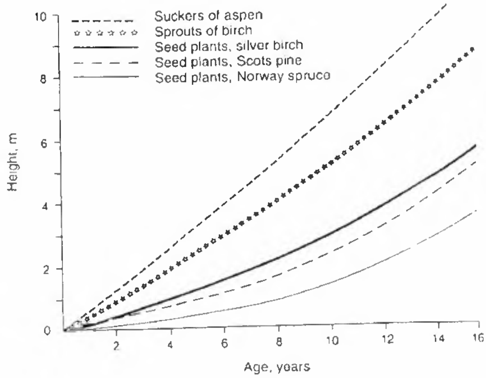

*Fig. 4. Height increment of aspen (*Populus tremula *L.) suckers, birch (*Betula pendula *Roth and* Betula pubescens *Ehrh.) sprouts and seedlings of silver birch, Scots pine (*Pinus sylvestris *L.) and Norway spruce (*Picea abies *(L.) Karst.). After Haveraaen (1985) and added by Johansson.*

(Johansson 1992b, c). In practice, most foresters are of the opinion that felling time (month) increases or decreases the number of sprouting stumps. Johansson (1992b) studied the sprouting mechanism of young (2-5 year-old) silver and pubescent birches. He reported lower sprout heights for birch cut in June-October than for other periods of the year. The number of living stumps varied, but not in a significant way. The stump height and the number of sprouts have also been discussed. Kvaalen (1989) and Johansson (1991) concluded that there was no correlation between stump height and number of sprouts per stump. The growth of sprouts was 21 % higher on 0 cm high stumps than on 60 cm high stumps in Kvaalen's study. But six years later there were no height differences. In Johansson's study there were small differences in sprout heights beween the studied stump heights (0, 10, 20, 40 and 80 cm).

Sprouts grow faster than seedlings, Fig. 4. In the study by Johansson (1992b) tree height for 5-year-old silver birch sprouts was 2.5-3.0 m compared with 1.0-1.5 m for 5-year-old seedlings (Palo 1986).

Pre-commercial thinning (cleaning)

Depending on the future management of the young stand, pre-commercial thinning or cleaning is necessary. A dense birch stand in which no cleaning has been done will be severely damaged by snow or wind. The percentage of green crown of birch decreases in a dense stand and the growth rate is then decreased. Cleaning or pre-commercial thinning is generally recommended to be done, either when the birch is 2-3 m high, or, if the risk of browsing by moose is high, when the birch is 4-6 m. Braastad et al. (1993) generally recommend precommercial thinning or cleaning in birch when the trees are 4 m high. Normally, the stem number after cleaning is 1 600-2 000 ha^{-1}. A light pre-commercial thinning with 3 000-5 000 stems ha^{-1} left will produce a high total yield. The wood quality will then be high, but the diameter of the logs is small compared with the log diameter from a normal cleaning. Some experience indicates that height growth is stimulated in a dense stand, but a cleaning is important at least when the birches are 6-7 m high. The last mentioned is not relevant if the production aim is maximum yield for chips only. Then the price for chips for energy is the main question for the harvesting method together with the most practical way to harvest the stand.

Pre-commercial thinning has mostly been carried out using brush saws. Since the 1980s cleaning has been mechanized cf. Wästerlund (1988). A machine developed for cleaning operations has been commonly used in Swedish forestry for the last decade, Fig. 5. The machine cost about 1.5 to 2 million SEK and is mostly used both for cleaning and for thinning operations. The steepest terrain and terrain covered with a lot of boulders is not suitable for the machine. When using a machine for cleaning, about 1 ha per hour is cleaned compared with 1 ha per day for the conventional motor-manual cleaning with a brushsaw. Studies on the sprouting ability of hardwood stumps cut by the machine and by brush saw showed no differences in number of living stumps and number of sprouts per stump (Johansson 1992d). No severe damage on residual hardwood and softwood plants was observed. The machine method is used when the number of broad-leaved trees is very high (> 10 000 stems ha^{-1}) and/or the stem diameter is high (> 5 cm DBH). The common brushsaw method used in these types of stands will be expensive for the owner and laborious and dangerous for the worker.

Thinning

A general rule when managing birch stands is that the spacing must be wide enough so the birch does not suffer for lack of light. Otherwise the percentage green crown is too low (< 50 %). A low percentage causes a yield decrease which cannot be made up later on. In addition, the stems will be weak and the risk for wind breakage increased. A birch forest must be thinned two or three times to produce timber and pulpwood. Schemes for thinning operations have been publish-

Fig. 5. Vehicle for mechanized pre-commercial thinning. Photo: Jonas Palm.

ed by, among others, Oikarinen (1983) cf. App. 1 and Vuokila (1983). The number of thinning operations depends among other things on the aim of birch production. In Finland especially most of the birch produced are used for veneer production and pulpwood. If the production aim is maximum yield for chips only, no thinning operation is necessary. The trees are harvested when the most economically suitable age occurs. If high timber quality is the main task then three operations might be necessary. Birches growing on very fertile sites also demand three thinning operations. Mostly the schemes are based on the relation between basal area and dominant height:

If two thinning operations are sufficient, the first should be done when the dominant birch is 12-14 m high. Then the stem number is reduced to 700-900 stems ha^{-1}. The second has to be done when the dominant trees are 18 m, after which 400-500 stems ha^{-1} are left. The lower number is used when the aim for production is veneer.

When a thinning programme contains three thinning operations, cf. Haveraaen (1985), the first is done when the dominant birch is 10-12 m high. The number of stems per hectare after thinning might be 900-1 100. The second thinning must be done when the dominant birch is 18 m. The number of stems per hectare after thinning might be 800. At a dominant height of 24 m, the third thinning in a birch stand could be done. Then 400-600 stems ha^{-1} are left.

In Norway (Braastad et al.1993) the recommedations for thinnings are:

First thinning when the dominant height of silver birch is 12 m. The number of stems is reduced to 1 200 stems ha^{1}. Pubescent birch is thinned when it is 14-18 m high. Then the stem number is reduced to 800 stems ha^{-1}.

Second thinning occurs when the dominant birch are 15 m and then 600 stems ha^{-1} is left. Pubescent birch is not thinned a second time.

Clear cutting and yield production

Silver birch growing on fertile soils is clear cut at 40-50 years of age (Frivold and Mielikäinen 1991). Mostly silver birch is clear cut when it is 60-70 years old. Pubescent birch might be cut at a greater age, 60-80 years, according to Braastad et al. (1993). When the aim is to manage a future stand of birch stand, 50-100 mature birches are left on the clear felled area as seedtrees.

Annual mean yield production of birch varies depending on species and site index. On the most fertile sites in Nordic countries silver birch has an annual mean growth of 8-9 m^3 ha^{-1} $year^{-1}$. Braastad (1967) published yield tables for silver and pubescent birches, Table 1. Silver birch produces more than pubescent birch and grows on more fertile sites. Braastad (1985) reported 1.5 m^3 ha^{-1} $year^{-1}$ higher potential yield of silver birch than pubescent birch. In a study by Oikarinen (1983), silver birch annual mean growth during the rotation period varied from 8.9 m^3 ha^{1} $year^{-1}$ for $H_{50} = 30$ m to 5.9 m^3 ha^{-1} $year^{-1}$ for $H_{50} = 22$ m. The total yield production for birch is lower than for Norway spruce. As a general rule, birch forest produces 85-90 % of the yield production (m^3 ha^{-1}) in a Norway spruce forest. On the most fertile sites the difference is higher than that mentioned above.

Table 1. Mean and total yield production of silver (*Betula pendula* Roth) and pubescent (*Betula pubescens* Ehrh.) birches. (Braastad, 1967)

	Silver birch			Pubescent birch		
Site index, H_{40}	23	20	17	14	11	8
Rotation period, year	40	50	60	65	85	110
Mean yield production, $m^3ha^{-1}year^{-1}$	8.5	6.5	5.0	3.5	2.5	1.5
Total yield production, m^3ha^{-1}	340	325	300	228	213	165

Afforestation on abandoned farmland

In Nordic countries the over-production on farmland of both cereals and meat has been discussed during the last decade. At the end of the 1980s most of the Nordic countries had started programmes for afforestation on abandoned farmland. Public opinion and governments demanded more hardwood trees than softwoods. Subsidies for plants, planting and fencing were given if the farmer planted hardwoods. The most common tree species planted on farmland in these areas is birch. When planting birch on former farmland, there are at least three main factors to be ensidered:

- Vegetation control
- Soil type - plant species
- Fencing.

Today, chemical treatment with glyphosate (Roundup) the year before planting is commonly used. Another method is to harrow or plough the area before planting. To get an acceptable vegetation control with this method, one or two treatments are sufficient. In some cases spot scarification is sufficient. Normally, 2 000-3 000 plants ha^{-1} are recommended. Silver birch is the most common species on farmland. However, if the soil type contains a high proportion of fine materials such as fine sand or silt, pubescent birch is a more common species. If the soil type is classified as heavy clay, only pubescent birch should be planted. The plantation area must be fenced by net both for moose and roe deer and for smaller animals such as hare and rabbits. Also plastic tubes to protect individual plants have been used. The tubes protect the plants against browsing for the first years after planting and from vegetation competition. The plants grow faster in a tube than without because of the protection against wind and the warmer and more stable climate in the tube. The tubes must be fastened carefully as hard winds might destroy the tubes or blow them away.

As a general rule for Nordic conditions pubescent birch produce 75-80 % of the diameter or height increment of silver birch. Growth of birch is more rapid and higher on farmland than on forest land. The rotation period for birch growing on farmland is 40-50 years compared with 60-80 years on forest land. The yield production of birch plantations on farmland has been studied by, among others, Raulo (1977) and Oikarinen (1983). Raulo concluded that silver birch produced 366 m^3 on farmland and 269 m^3 on forest land. Figures for pubescent birch were lower: 200 and 148 m^3 respectively. These are only examples. The yield level is dependent on the site conditions.

Managing sprout forest stands

In studies of sprouting ability of birch, single sprouts on stumps grow faster than the fastest growing sprout on stumps with a group of sprouts (Johansson 1992b, c). On a forest area with a fresh birch stand growing on a fertile site it is possible to manage the sprouts to produce a high-quality stand. Studies on birch stems, initially sprouts, of different ages does not reveal higher frequency of root rot than for sown or planted birch.

A clear-felled area is invaded among others by birch sprouts from cleaned birch understory. All but one sprout per stump are cut using pruning shears, two or three years after emergence. The remaining sprout ought to be the most vital and the highest sprout on the stump. This sprout grows fastest and has the best stability if it emerged close to the ground level i.e. the base of the stump. Initially, the sprouts will grow very fast as they already have a functioning root system which has a large area compared with the small root system for a seedplant or a planted birch.

The reduction of sprouts per stump must be done at an early stage if the stem is to be straight from ground level. Otherwise, competition between sprouts forces the stems to grow as far as possible from each other. This results in bent stems with a low timber quality.

Fuelwood production

On abandoned farmland areas, naturally regenerated alder, aspen and birch invade the area soon or later. According to Kalela (1961) they invade rather slowly. But in a study by Johansson (1992e) the birches invaded the area during a five-year period since the area was taken out of arable production. Johansson´s results indicate that the biomass production of birch varied between 2 and 10 ton d.w. ha^{-1} $year^{-1}$, Fig. 6. As a mean 5-6 ton d.w. ha^{-1} $year^{-1}$ is a realistic prognosis for short-rotation forestry based on naturally regenerated birches without irrigation, fertilization or fencing. These figures are based on a rotation period of 15 years. On fertile sites the rotation period is shorter, about 10 years.

The studied farmland areas were chosen only for an initial discussion about the yield production potential. A conventional short-rotation forest of *Salix*-species

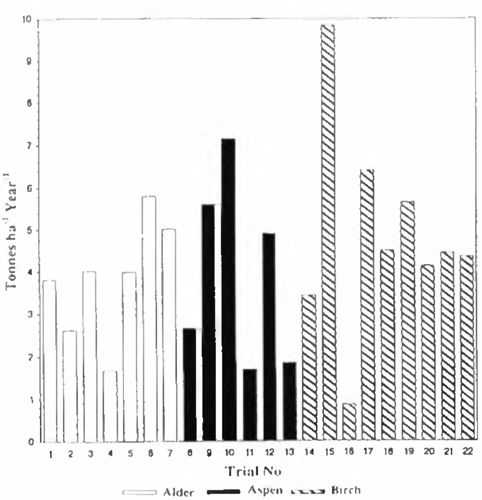

Fig. 6. Biomass production d.w. ha^{-1} $year^{-1}$ *for alder (*Alnus incana *(L.) Moench. and* Alnus glutinosa *(L.) Gaertn.), aspen and birch growing on farmland (Johansson 1992e).*

produces 10-12 ton d.w. ha^{-1} $year^{-1}$. In an ongoing study of methods to improve the growth conditions and the rate of invasion of seedlings, the most suitable soil types for short rotation forestry and the occurence and duration of sprouting periods are studied.

Conclusion

Today, birch and other broadleaved species are important for forest production. In many countries the pulpwood price is as high as for Norway spruce. Mixed stands of birch and Norway spruce are created and not only managed by the forester in the case that such stands are created by the "Nature" on his forest areas. In the discussion about biodiversity in forests, birch and other hardwoods are important species to take account of. In the future, the number of species for maintaining a sustainable forest is at least as important as managing the established conifer stands.

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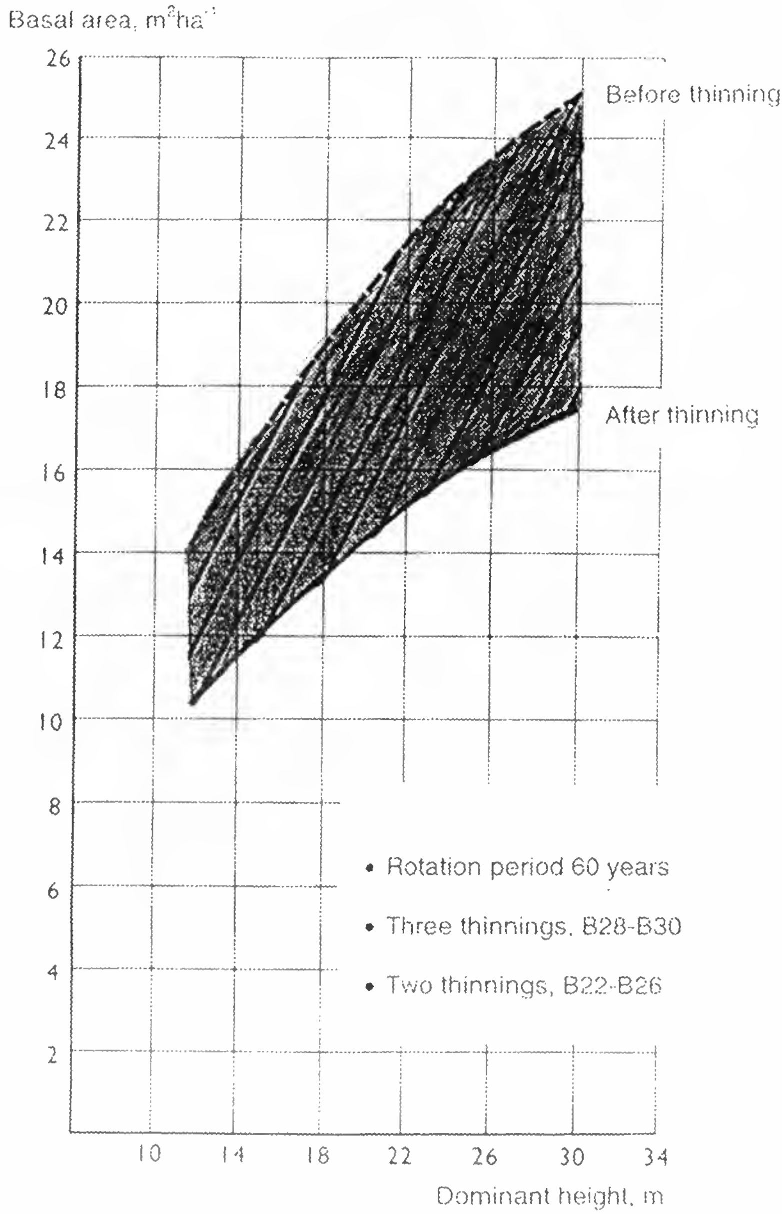
Appendix 1.



Finnish thinning scheme for silver birch (Oikarinen 1983)

Yield and management of mixed stands of spruce, birch and aspen.

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Frivold, L.H & R.Groven 1996. Yield and management of mixed stands of spruce, birch and aspen. Norwegian Journal of Agricultural Sciences. Supplement No. 24:17-24. ISSN 0802-1600.

A review study is made to compare yield of mixed stands of spruce and birch with yield of pure stands of the same species. If results from pure stands in South East Norway are combined with results from managed, single-storied mixed stands in Finland and Sweden, mixed stands appear to yield more by volume than pure birch stands. The difference from volume yield of pure spruce stands appears to be small. Yield of non-managed mixed stands seems to be closer to that of pure birch. Published studies of aspen-spruce mixtures are few. With all-species biodiversity in mind, thinning of hardwoods by dispatching them on root and leaving them in the stand without felling is proposed as an alternative to conventional thinning.

Key words: *Betula pendula, Betula pubescens*, fuelwood, mixed stands (forest trees), *Picea abies, Populus tremula*, production data, species diversity, wood

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Forest stands with birch or aspen mixed with Norway spruce are important elements of natural ecosystem dynamics in Fennoscandian boreal forest landscapes. Birches - downy birch (*Betula pubescens* Ehrh.) and silver birch (*Betula pendula* Roth.) - and aspen (*Populus tremula* L.) are light-demanding pioneer species emerging after forest fires or other large-scale disturbances. Norway spruce (*Picea abies* (L.) Karst) is a rather shade-tolerant climax species which, if the forest is left undisturbed, mixes in and eventually takes over as the main tree species on suitable sites.

A close-to-nature forest management in our parts of the world thus cannot avoid the questions of managing mixed stands with spruce and birch or aspen.

Research on mixed stands in Fennoscandia has concentrated on birch-spruce and birch-pine mixtures; very few studies have been published about aspen-spruce stands. This presentation concentrates on birch-spruce studies, and is based on previous reviews by the same authors (Groven & Frivold 1994, Frivold & Groven 1994). We shall compare the yield of pure stands with the yield of mixed stands, and give some consideration to future trends in silviculture.

Yield of pure stands

While studies of mixed stands in Fennoscandia took off only during the last two decades, yield of pure and even-aged stands has been thoroughly studied since the 1920's. The yield patterns of the commercially most important tree species in pure, regular stands are thus rather well known in Scandinavia.

The current Norwegian site index system is using the top height at an age of 40 years at breast height as index value for each species. Top height is the arithmetic mean height of the 100 largest trees, according to diameter, per hectare. Age at breast height is the average age, at 1.3 m height above ground, of the same trees (Tveite 1976). This site index system is based on pure, even-aged stands where top height trees have not been suppressed at early stages. Modern yield tables and growth models based on this site class system have been produced in Norway for birch (Braastad 1977), aspen (Opdahl 1992), Norway spruce (Braastad 1975) and Scots pine *(Pinus sylvestris)* (Braastad 1980).

A set of conversion functions between site indices and between potential yields on the same site for four main tree species in South East Norway has been made by Braastad (1985). They are based on a small amount of data collected from individual trees at various altitudes in South East Norway. It is not clear whether the trees were planted, but we can assume that at least the birches were natural. Braastad concludes that the potential yield of silver birch is lower than the potential yield of Norway spruce. The difference increases with increasing site index. Where the potential yield of Norway spruce is 10 m^3/ha/year the potential yield of silver birch will be about 7 - 8 m^3/ha/year.
The potential yield of downy birch is lower than the potential yield of Norway spruce. The difference is small when the site index is low (G 8). However, on sites where potential yield of Norway spruce is 7.5 m^3/ha/year (G 17), the difference is over 3 m^3/ha/year.

Birch wood has a higher density than wood from pine or spruce. Thus, yield differences would be less conspicous if production of dry matter were concerned.

Yield of mixed stands

3.1 Effect of species mixture

Ecological theory suggests that there is a potential productivity advantage to be gained from growing trees in mixed stands. Such an advantage is especially likely if the species in question use different niches of the stand ecosystem. This was put forward by classical German authors long before the term ecology was used (e.g. Cotta 1849: 97f), and we find it again in modern works (e.g. Kelty 1992: 125).

In Scandinavia, Laitakari (1927, 1935) showed that birch, spruce and pine roots tend to penetrate the soil at different depths, provided that the soil is sufficiently deep and well-drained. This supports the theory of productivity advantages from mixture.

The effect of species mixture (Johnsson 1962) can be found by comparing the yield of mixed stands with the yield of corresponding pure stands. Yield might be measured in volume, dry matter or value. There are two alternative criteria for assuming a positive mixed forest effect:

1. If the mixed stand yields more than the highest yielding species of the mixture can do in a corresponding pure stand, then there is a positive effect of species mixture.
2. If the mixed stand yields more than

the mean value of what all the species of the mixture can perform in corresponding pure stands, then there is a positive effect of species mixture.

In most studies, criterion 1 has been used.

3.2 Yield studies in mixed stands

In his classical text-book «Waldertragskunde», Assmann (1961) says that if the laws of forest growth are difficult to find in pure stands, the difficulties of finding them in mixed stands appear almost invincible. A major obstacle is the great range of tree species composition and stand structure in mixed forests.

In the three decades that have elapsed since Assmann wrote this, quite a few Scandinavian researchers have ventured into the subject, aided by modern information technology. The bulk of these investigations are dealing with mixed stands of birch and spruce or pine. In most of them the objects of research are largely temporary plots in stands which were never designed as experimental fields. Analyses of single trees by increment cores still make it possible to make model studies (e.g. Mielikäinen 1980, 1985, Agestam 1985, Ekö 1985).

While birch and pine are light-demanding species, spruce is rather tolerant to shade. Spruce is well able to survive and grow in mixtures with birch, except on very dry sites. Pine, however, more often succumbs if overgrown by broadleaves (Kalela 1961, Frivold 1982).

Silver birch is a stronger competitor than spruce in young and middle-aged stands. In the first decades after stand establishment the height growth of silver birch is greater than that of spruce, giving rise to a two-storied phase during the development of even-aged stands. Downy birch is a more equal, or even weaker competitor than spruce. Its height growth is closer to that of spruce. In even-aged stands, the two-storied phase can be less pronounced than with silver birch (Frivold & Mielikäinen 1990). Downy birch can on the other hand also make an undergrowth in conifer stands (Laiho et.al. 1995), but if the canopy is dense it will remain as an undergrowth.

The life span of birch is normally shorter than that of pine or spruce. Except for dry and poor sites, mixed stands of birch and conifers are mostly temporary stages in a development towards climax spruce forests (Lappi-Seppälä 1930, Kielland-Lund 1981).

In young, two-storied stands with spruce under birch, spruce has a considerably lower height increment if grown under a dense canopy of birch than if it is grown alone or with a few, scattered birches (Braathe 1984, 1988). Another study indicates that when birches are removed, e.g. at an age of 25 - 30 years (which might be a suitable fuelwood size), an understorey of spruce can regain the loss of height development and may even grow better than spruce which was never sheltered by birch (Tham 1988).

Yield in temporary plots of mature and semi-mature mixed stands of birch and spruce in South East Norway has been compared with yield table data for pure, well-managed stands of the same tree species (Frivold 1982). The mixed stands in the survey were partly irregularly managed (apparently for fuelwood) partly non-managed, and many of them were multi-storied. As a mean, they contained 66 % birch by volume. The comparison showed that the volume production of those mixed stands was closer to pure birch stands than to that of pure spruce stands.

Swedish and Finnish model studies of managed mixed stands of birch and conifers, however indicate that the yield of such stands does not differ very much from the growth of pure spruce or pine stands of a corresponding site (Mielikäinen 1980, 1985,Agestam 1985). See Tables 1 and 2.

We recall that according to Braastad (1985), pure stands of any of the two birch species yield less by volume than pure stands of spruce can do on corresponding sites. Now, if this is valid, and the results from Sweden and Finland shown in Table 1 and 2 are valid for South East Norway too, then it is a better alternative for timber production to grow birch and conifers in mixed stands than growing them separately in pure stands. In other words, there is a positive effect of species mixture by criterion 2 above.

If production of dry matter is considered rather than volume production, the mixed stand alternatives turn out even better, yielding up to 15 % more than pure conifer stands (Mielikäinen 1980, 1985).

For practical forestry, a maximum pro-

Table 1. Relative volume and dry weight increment of mixed stands of Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) versus pure stands of Norway spruce. The figures result from simulations and apply to one rotation period (80-90 years) of natural stands in South Finland, managed for high-quality timber production. After Mielikäinen (1985). Site is given by the Norwegian H_{40} system.

Stand type	Relative volume increment	Relative dry weight increment
Site G14 (medium)		
100% *P.abies*	100	100
75% *P.abies* + 25% *B.pendula*	103	109
50% *P.abies* + 50% *B.pendula*	102	111
30% *P.abies* + 70% *B.pendula*	103	114
Site G19 (high)		
100% *P.abies*	100	100
75% *P.abies* + 25% *B.pendula*	105	111
50% *P.abies* + 50% *B.pendula*	103	115
30% *P.abies* + 70% *B.pendula*	104	117

Table 2. Relative volume production of mixed stands of Norway spruce (*Picea abies*) and birch (*Betula pendula* and/or *B. pubescens*) versus pure stands of Norway spruce. The figures result from simulations and apply to one rotation period (90-100 years) of managed natural stands in Sweden. After Agestam (1985). Site is given by the Norwegian H_{40} system.

Site/Treatment	Pure stand	Mixture 75-25	Mixture 50-50
Site G13(lower medium)	Spruce	Spruce-Birch	Spruce-Birch
Birch kept throughout rotation	100	97	92
Birch gradually removed	100	98	97
Site G17 (upper medium)	Spruce	Spruce-Birch	Spruce-Birch
Birch kept throughout rotation	100	96	88
Birch gradually removed	100	99	96

portion of 50 % birch by volume has been recommended, gradually reducing it to zero when the stand reaches an age of 50 years (Frivold & Mielikäinen 1990). This recommendation however applies to silviculture for timber of top quality of birch and spruce, in good birch districts.

Studies of a few single stands with aspen-spruce mixtures suggest that spruce has a similar influence on aspen as it has on birch (Hegre & Langhammer 1967, Langhammer & Opdahl 1990). Later revisions seem to support that conclusion.

Mixed stands and fuelwood in future silviculture

Wood for energy is by no means a new invention to Norway. Wood was the major source for energy until the last half of the 19th century, and fuelwood played an important part in private households until the 1950's. With the ample supply of oil and hydroelectricity, silviculture for fuelwood is not a big issue in our forestry nowadays. The situation is in sharp contrast to most developing countries.

The lack of interest in fuelwood, together with changes in animal husbandry towards less use of pastures, have caused profound changes in rural landscapes. Borders between farmland and forest have become sharper.

While the standing volume of spruce was about 25 % higher in the 1980's than in the 1940-50's, that of hardwoods was turned 50 % higher in the same period (Tomter 1989). A return to fuelwood as an important source of energy at a national level is not likely in the near future in Norway. The last boom was during the German occupation 1940-45, when the amount of fuelwood cut for sale in East Norway increased by almost 600 % compared to just before the war (Opsahl 1953: 27). From the point of view of percieved welfare, such a return would not even be desirable, as it would be a result of a breakdown in our present luxury supply of energy and oil money. Nowadays, most fuelwood qualities are used for pulp or chipboards or not used at all.

Silviculture for fuelwood <u>only</u> can still be of local interest. Mixed softwood-hardwood production where stands stay mixed until the birches reach timber dimensions does not neccessarily fit into that concept.

Mixed softwood-hardwood stands however do have a potential in (post)-modern multiple-use silviculture. It has been said that the classical world of thought in German forestry, with large, uniform, single-species stands for the greatest rate of interest, finally collapsed during the storm on the night of 1 March, 1990 (Hatzfeldt 1994). Fennoscandia has been spared from such a catastrophe. Still, there are strong trends here towards a more close-to-nature silviculture (Frivold 1993)

Mimicking nature is a way to preserve and enhance biodiversity: an important part of sustainable forestry in its present sense. To mimic the natural fire dynamics in boreal forests, some rather large areas should follow the natural succession from birch and aspen through mixed stands. It is believed that old, dying and dead hardwood trees are crucial as habitats for many threatened and endangered species, and that there is a lack of such trees in our present forests. A solution is to leave some standing hardwood trees in the forest to die, or dispatch them standing without felling. Such «habitat trees» should be selected among low timber quality trees if timber of higher qualities is the aim of production. Here we might see a conflict between silviculture for fuelwood and multiple-use silviculture in a future mixed-stand management. However, there will always be parts of a sawlog tree which cannot be used as sawlogs, and there will always be someone who wants wood for fuel.

Acknowledgements

We would like to thank our peer reviewers, Dr. Eric Agestam and Dr. Kari Mielikäinen, for valuable comments. We are also indebted to colleagues at the Department of Forest Sciences for useful discussions and help.

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Aspen-mixedwood silviculture in the boreal forest of Ontario, Canada

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Jeglum , John K.1996 . Aspen-mixeswood silviculture in the boreal forest of Ontario, Canada. Norwegian Journal of Agricultural Sciences. Supplement No. 24: 25-40. ISSN 0802-1600.

A review concerning aspen and mixedwood silviculture and research in Ontario is presented. Definitions for mixedwoods are given, and the magnitude of the mixedwood resource and importance to the industry is clarified. The silvics and ecology of the five main species of boreal mixedwood are provided. The mixedwood research programs of the Canadian Forest Service, Ontario Region are presented, and operational and experimental silvicultural systems are described.

Keywords: aspen, boreal, ecology, mixedwoods, Ontario, research, silvics, silviculture

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There is currently much interest in Canada about the utilization and management of trembling aspen (*Populus tremuloides* Michx.), and mixedwoods containing aspen. The provincial and federal research organizations have developed programs of aspen and mixed-woods research, and industry is developing new technologies to more fully utilize this resource. Several recent mixedwood conferences have been published (Samoil 1988; Adams 1989; Shortreid 1991), a number of workshops held (Edmonton, Alberta 1994, Richmond, B.C. 1995, and Sault Ste. Marie 1995), and numerous silvicultural trials and experiments put in place (e.g. Navratil 1994; Scarratt 1996). Recently, an article has been published making a case for proactive, intentional management for mixedwoods on appropriate sites in Ontario (MacDonald 1995).

In Canada, there are several main centres of research activity in aspen and mixedwood silviculture, in Alberta, British Columbia, New Brunswick, Ontario, and Quebec. It is quite beyond the scope of this paper to cover this topic for the whole of Canada. Consequently, in this paper I focus on the situation in Ontario. I present a brief overview of the silviculture of trembling aspen and mixedwoods, focusing on the situation in the boreal forest of Ontario.

Background

Historically, industrial forestry in Canada has been based on the utilization of a single species or product type, exploited primarily for export markets. In the late 1800's and early 1900's it was «hurling down the pines», based on the large white and red pine *(Pinus strobus* L. and *P. resinosa* Ait.) for squared timber and lumber. When this resource started to become limited, interest shifted to other products such as sawn lumber from white spruce (*Picea glauca* [Moench]Voss) and jack pine (*Pinus banksiana* Lamb.). Then the superior fibres of black spruce (*Picea mariana* [Mill.]B.S.P.) were exploited for paper, and as this species-product became limited, trembling aspen became utilized for paper, plywood and chipboard. Owing to the conversion of previously conifer-dominated stands to mixedwoods or hardwoods after clearcutting (e.g. Kabzems 1952; Yang & Fry 1981; Jeglum 1983; Hearnden et al. 1992), the hardwoods will continue to furnish high proportions of fiber to Ontario's forest industry.

Historically, most of the forest research effort in Ontario has been devoted to the conifers, owing to their abundance and importance in the pulp and lumber industry, and also the general view that the broadleaved species were unwanted competition to be purged from conifer plantations. However, it has been recognized for a long time that the intolerant, boreal hardwood species are important pioneer species that could be better utilized. Consequently, there has always been interest in how the intolerant hardwoods (trembling aspen and white birch *Betula papyrifera* Marsh.) could be managed in relation to the coniferous softwood species.

One of the earliest studies of mixed-wood in Ontario dealt with spruce and fir *(Abies balsamea* [L.] Mill.) reproduction in a mixedwood stand (Hughes 1967). Several harvesting-regeneration options were used, including 1) clearcutting, 2) deferred 'softwoods only' cutting, 3) 'softwoods only, cutting, and 4) hardwoods poisoned, followed by deferred 'softwoods only' cutting. Recently, a graduate thesis was devoted to assessing this study area after 37 years (Robertson 1994). The strongest phytosociological trend was the gradient in canopy composition from hardwood to mixedwood to softwood types. Results were not conclusive that any of the harvest methods, or hardwood poisoning, had improved the content of spruce and softwoods.

In 1981, a boreal mixedwood symposium was held in Thunder Bay, Ontario (Whitney & McClain 1981). This symposium highlighted mixedwoods as a forest type whose importance could only increase in the future, owing to its relatively southerly location, the inherent fertility of most sites that support mixedwood forest cover, and the tendency for conifer-dominated stands to convert to mixedwoods after clearcutting. At the conference, a broad range of topics were covered -- definition, site types, dynamics and succession, fibre utilization, impacts of harvesting, forest management practices, vegetation management, and damages owing to insects and diseases. In addition, a summary of management and research needs was provided (Weingartner 1981). This has been followed by a number of literature reviews (We-ingartner & Basham 1979 (1); Sutton, R.F. (2); Wedeles et al. 1995), problem analyses (MacDonald & Weingartner 1994; Weingartner & MacDonald 1994), and a major review of the ecology, management, and use of the aspen and balsam poplar in the prairie provinces of Canada (Peter-

son & Peterson 1992).
Two major research programs have recently been initiated in the mixedwoods in Ontario, spearheaded by the Canadian Forest Service (Scarratt 1996) and the Ontario Ministry of Natural Resources (MacDonald & Weingartner 1994).

Definition

It is difficult to define boreal mixedwood, owing to the diversity of species and site types which it can encompass. Kabzems (1952) noted that the cover type and composition of boreal forests depend on soil texture and moisture regime, as well as the biological characteristics of each species. "Generally on poorer sites there are pure stands of simple structure, while on better ones [sites] mixed and more differentiated ones [stands]." (ibid., p. 15). Kabzems listed the main tree species of the type as white spruce, trembling aspen, black spruce and white birch, and the minor species as balsam fir and balsam poplar. Jack pine is sometimes present.

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(1) Weingartner, D.H. & Basham, J.T. (eds.) Forest management and research needs in the boreal mixedwood forest of Ontario. The Spruce-Fir-Aspen Research Committee, Unpubl. Rep., 1979. 90 pp.
(2) Sutton, R.F. Unpublished literature review. Can. For. Service, Sault Ste. Marie, Ontario.

The definition of mixedwoods based upon composition ranges from narrower to broader. Some prefer to focus on the two main species that are most frequent associates in mixedwoods across the whole of Canada and into Alaska -- trembling aspen and white spruce (A.G. Gordon, Pers.Comm.(3)). Others define mixedwoods so broadly as to include sites that are capable of supporting both hardwood and softwood tree species (e.g. Weingartner & MacDonald 1994; MacDonald 1995). This concept would extend the mixedwoods concept to include the majority of upland forest sites in Ontario.

Recently, MacDonald has clarified the concept of boreal mixedwood site: "..an area with climatic, topographic and edaphic conditions that favour the production of closed canopies dominated by trembling aspen or white birch in early successional stages, black spruce or white spruce in mid successional stages and balsam fir in late successional stages." MacDonald goes on to characterize the site conditions: " ... typically [they] have well-drained, fertile soils on mid-slope positions, and exclude wet lowlands, dry sand plains and shallow soils on bedrock outcrop (McClain 1981). These sites are among the most productive because they support good growth of all boreal species, including nutrient demanding hardwoods."

The mixedwood forest changes compositionally from west to east, owing to increasing humidy. In the west aspen and white spruce dominate with lesser components of the other species. In Ontario and eastwards, the other species are more prevalent, balsam fir and black spruce increasing relative to white spruce, and white birch relative to trembling aspen.-

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footnote (3) A.G. Gordon, Ont. For. Res. Inst., Min. Natur. Resour., Sault Ste. Marie, Ont.

From the viewpoint of inventory it is necessary to set some limit of minimum composition in the stand for both hardwood and softwood components. For example, MacDonald defines boreal mixedwood stand as "..a tree community on a boreal mixedwood site in which no single species exceeds 80% of the basal area. Any defining or associated tree species qualifies as a canopy component."

It must be realized that stands can, from one rotation to the next, shift into or out of mixedwood, given different histories of disturbances or stages of succession. There is a natural successional trend of mixedwood towards progressively more conifer content (Kabzems 1952; Gordon 1985). This successional trend is influenced and modified by natural disturbances such as wildfire, blowdown and insect outbreaks that selectively reduce one or a few species. Spruce budworm *(Choristoneura fumiferana* Clem.) acts selectively to reduce balsam fir and white spruce, while forest tent caterpillar (*Malacosoma disstria* Hbn.) acts selectively on trembling aspen and white birch. Gordon (1985) has shown how the influence of a spruce budworm outbreak has shifted the composition toward more hardwood. In addition, disturbance by man can shift composition in the mixedwood. For example, harvesting selectively for conifers, combined with the naturally higher regeneration potential of the hardwoods, shifts the composition of previously softwood-dominated stands towards hardwoods (e.g. Kabzems 1952; Yang & Fry 1981; Jeglum 1983; Hearnden et al. 1992).

The Aspen and mixedwood resource

In Ontario conifer-dominated stands occupy 27.9 M ha of productive forest land area, while hardwood dominated stands occupy 11.8 M ha. In terms of areal extent, spruce (white and black combined) and jack pine are the predominant working groups of conifers, accounting for 17.2 and 8.4 M ha, while poplar (including aspen) and white birch are the main working groups of hardwoods, with 5.1 and 3.1 M ha, respectively (Ketcheson & Jeglum 1972). Volumes of wood harvested in 1989 for the spruce, jack pine, poplar, and white birch working groups were 8.5, 6.1, 2.8 and 0.2 M m^3 (Ghebremichael 1993). It is clear that white birch is highly underutilized.

It is difficult to make an estimate of how much of the forest belongs to mixedwood. The forest inventory in Ontario has always been based on single species or species group working groups, and a mixedwood category has not been recognized. An estimate could be drawn out of the existing Ontario Forest Resource Inventory, but this exercise has not yet been done. An inventory based on remotelysensed data revealed that 52% of the total dense forest in northeastern Ontario consisted of mixed species (Spectranalysis, Inc. 1994).

The aspen and poplar resource have recently been the focus of increased utilization in the province of Ontario. Two years ago, the province looked into the feasibility of using more of the underutilized birch and poplar resource. A call for proposals was made for the development of mills to produce "oriented strand board"(OSB) mills. OSB is a construction board in which the flakes of aspen and poplar are alternated in different directions, and then glued together. This increases the strength and stability of the board, and has the advantage that low grade stems can be used. The board is in high demand and is a replacement for wafer board and plywood.

Five or six new or expanded OSB mills are being developed in northern Ontario. The preferred species for OSB is aspen, but a little balsam poplar will also be used. Up to 25% of other species, primarily white birch, can go into the product. This material will come largely from mixedwood stands, but also from pure stands of aspen, balsam poplar (*Populus balsamifera* L.), and white birch.

Presently most or all of the aspen resource has been allocated. When the OSB plants are completed, the proportional use of the aspen and poplar resource will be about 45% for OSB, 45% for pulp, and 10% for veneer plywood of structural grade.

Silvics and ecology

Boreal mixedwood cover types occur on a broad range of soil conditions, from fresh to moist, and from clayey to sandy loams. These sites are usually the more fertile and productive sites in the boreal zone, both in terms of timber yields and their ability to sustain high wildlife populations.

Ecological management of the mixedwoods requires understanding the silvics and ecology of the main tree species that occur on the mixedwood sites. In the following, I provide encapsulations of the main ecological features of the five main boreal mixedwood tree species. Most emphasis will be given to aspen, owing to its current economic importance and relevance to this workshop.

Trembling Aspen

Trembling aspen silviculture has been dealt with thoroughly in several proceedings and silvicultural guides (e.g. Davidson et al. 1989; Adams 1989; Sims et al. 1990; Bell 1991; Peterson & Peterson 1992).

Aspen is the main hardwood species of the mixedwood. It is nutrient-demanding, growing best on clay, clay loam, and sandy loam soils, with fresh to moist moisture regimes. It is a shade intolerant, pioneer species that regenerates prolifically after disturbance.

Reproduction is both sexual and vegetative. Abundant crops of very light seed are produced annually, and dispersed by wind many kilometres. Vegetative reproduction is by prolific suckering from roots. Most virgin stands have arisen after wildfire, either from suckering or seed.

Cutting stimulates sucker production in proportion to the degree of cutting. Increased temperature and light stimulate suckering, and clearcutting in winter to early June induces more suckering than cutting later in the summer. Mechanical site preparation stimulates suckering when the organic mat is not completely removed and roots remain intact. Most suckers arise in the first year and may grow over 2 m in height. After this, height growth tapers off to 30 to 60 cm per year. Seedlings also grow rapidly, achieving 1-1.3 m in 3 years.

Owing to its fast growth aspen can become serious competition to conifers in 5 to 10 years after cutting. Several chemicals are effective in killing or setting back aspen -- 2,4-D; hexazinone, and glyphosate. Girdling before a harvest is a technique to kill the aspen and reduce the amount of root suckering. «Whipping» damage can be severe to conifers at 55 to 75 years when the conifers begin to pass through the hardwood canopy.

Stands reach maturity at 80 to 120 years, but usually begin to break up at 55 to 90 years, owing to extensive decay and loss in vigour. When stands open up, shrub vegetation, particularly mountain maple (*Acer spicatum*), beaked hazel (*Corylus cornuta*) and alder (*Alnus rugosa* [DuRoi] Spring. and *A. crispa* [Ait.] Pursh.), commonly increase and inhibit aspen suckering.

Aspen responds well to fertilization,

and thinning/spacing (e.g.Weingartner 1991). A density management diagram is being developed for aspen by Weingartner (OMNR-OFRI, Sault Ste. Marie). The main damaging agents to aspen are the forest tent caterpillar, which occurs in 30 to 40 year cycles in the boreal forest (Webb 1967), and stem and root decay and stain (Whitney 1988; Hiratsuk 1995). Browsing by moose (*Alces alces* L.) and deer (*Odocoileus virginianus* Zimmerman), and felling close to streams by beavers (*Castor canadensis* Kuhl), are other hazards to the species.

White Birch

White birch has had the least amount of utilization and active management of any of the mixedwood species in Ontario. However, its silviculture is well known (e.g. Ohmann et al.1978; Perala and Alm 1990; Sims et al. 1990; Bell 1991).

The species occurs broadly on many soil textures, but it is most common on dry to fresh and intermediate nutrient regimes. It is shade intolerant, and a pioneer species, but can occur in openings in mixedwood that is breaking up.

Reproduction is both sexual and vegetative. Abundant, light, winged seeds are produced yearly, and are blown long distances. There is prolific stump sprouting after cutting or burning.

Seedlings establish best on mineral seedbeds, and growth of seedlings is moderately fast. Stands develop rapidly, maturing at age 60 to 90 when dieback and root and stem rot occur. It is replaced by spruce and fir. After clearcutting, there can be dieback of the tops of trees and rapid decadence. Braathe (1995) suggests that birch dieback of both white birch and yellow birch (*Betula alleghaniensis* Britton) in eastern Canada and northeastern USA has been caused by early spring thaws and subsequent frost.

The main damaging agents to white birch are insects (forest tent caterpillar *Malacosoma disstria* Hbn.,and the bronze birch borer *Agrillis anxius* Gory), heart rots, post-logging dieback, frost induced diebacks, and wildlife browsing.

White Spruce

White spruce silviculture has been dealt with in several proceedings and silvicultural guides (e.g. Arnup et al. 1988; Sutton 1969; Gordon 1981, 1985, 1995; Sims et al. 1990; Bell 1991).

White spruce is an important conifer species in mixedwoods. It is nutrient-demanding, growing best on medium-textured (sandy clay, sandy clay loams) and fine-textured clay loam; it is infrequent on coarse-textured and shallow soils, and all but the richest shallow peats. It does best on intermediate moisture conditions, moist to fresh, and is intermediate in shade tolerance. It can establish directly after wildfire and wind throw, but also can develop as a secondary stand beneath hardwoods.

Reproduction is mostly sexual with cone crops every 2 to 6 years. Layering is rare. Cones open in the fall and winter of the first year, and seed can be dispersed on the order of 60 m. Seedlings establish best on mineral soil or rotting wood, and seedlings initially grow slowly. Planted seedlings may go into growth "check" for some years before showing rapid juvenile growth. In natural stands, spruce remains beneath the canopies of faster-growing hardwoods until about 80-100 years when it begins to pass through the canopy.

Spruce can live for over 200 years, and because of the competition mortality and thinning by insects and disease, the surviving, large, old spruce tend to occur as rather widely-spaced individuals. These spaced stands develop understories of smaller trees of the mixedwood group, especially balsam fir and younger white spruce, and several tall shrubs, particularly mountain maple, beaked hazel, and alder. Sometimes the cover by the shrubs, especially the maple, is so dense that only maple seedlings can survive in the understorey. Here one could interpret the final successional stage or "climax" of the mixedwood to be the maple-dominated tall shrub layer.

A number of damaging agents can be listed -- vegetative competition, frost damage, pine shoot weevil (*Pissodes strobi* [Peck]), spruce budworm (*Choristoneura fumiferana* [Clem.]), whipping by hardwood when passing through the canopy, red squirrel (*Tamiasciurus* hudsonicus Erxleben) cone clipping, and root and butt rots (Whitney 199_)*. Because of the harvesting method of product selection, white spruce is being "cleansed" from the mixedwood, leaving little or no seed sources for genetic variability. Gordon (1985, 1995) has been calling for preservation of genetic diversity of spruce and other boreal species.

Black Spruce

Black spruce silviculture has been described in several proceedings and silvicultural guides (e.g. Great Lakes Forest Research Centre 1975; Arnup et al. 1988; Haavisto et al. 1988; Robinson 1974; Vincent 1965; Kennington & Jeglum 1995; Gordon 1995; Crook & Cameron 1995).

Black spruce can achieve high cover in some mixedwood stands. Even though it can be in mixedwoods,and grows best on medium- to fine-textured loams, it is more common in monodominant stands on poor sites -- organic, peat soils and shallow soils over bedrock. It is intermediate in shade tolerance.

Reproduction is both sexual and vegetative. Good cone crops occur every 2 to 6 years. The cones are semiserotinous, opening with the heat from fire, but otherwise with tight scales that release the seed slowly over several years. Thus there is a seedbank in the canopy that provides a continuous seedfall. Seed is dispersed 60 to 200 m, and for even longer distances in winter on crusty snow surfaces. Layering is important in wetter sites and peatlands.

Seedlings arise on *Sphagnum*, mineral soil and other moist seedbeds. Early growth is very slow. Stands can arise following wildfire, in which case they are even-aged. They also can convert to uneven-aged stands naturally, or after partial harvest and harvesting which preserves the advance growth. Black spruce can also persist beneath canopies of other species, such as in mixedwood, and occupy gaps as hardwoods die or are blown down. Breakup may begin at 70 to 100 years, but much depends on the depth and stability of the soil. On peatland sites with slower growth trees achieve ages of 150 to 200 or more years.

A number of damaging agents can be listed -- vegetative competition, *Sphagnum* moss smoothering, spruce needle rust (*Chrysomyxa* spp.), root and butt rots, cone insects, and red squirrel cone clipping. However, generally these are not serious, and the species also has the favorable attributes of low susceptibility to spruce budworm and late spring frosts.

Balsam Fir

Balsam fir silviculture has been considered in several proceedings and silvicultural guides (e.g. Bakuzis & Hanson 1965; Sims et al. 1990; Bell 1991).

Balsam fir occurs widely in the landscape, although it is not as common on poorer peatlands or coarse-textured soils. It does best on the moderate to rich sites, and is found across the moisture spectrum from wet to dry. It is the most shade tolerant of any boreal species.

Reproduction is mostly sexual with cone crops every 2 to 4 years. Layering occurs but is not important. Seeds disperse up to 60 m.

Seedlings establish abundantly on a variety of seedbeds, even on raw duff and feathermoss. Seedlings grow very slowly initially, and can exist beneath canopies for 50 years or more. The saplings come up beneath both hardwood and conifer, and tend to be abundant understorey in overmature stands of mixedwood. They often remain after commercial clear-cutting, and provide the food for spruce budworm outbreaks.

Balsam is highly susceptable to spruce budworm outbreaks, to root and butt rots, and to stem breakage by wind. Build ups of budworm killed fir in older dense stands, are highly susceptable to wildfire owing to the highly incendiary nature of the resinous needles, bark and wood.

Silvicultural systems

Currently in Ontario there is no clear policy or set of silvicultural options for mixedwoods. However, a special provincial working group is in the process of developing guidelines, in response to the directives from the recent decision of Class Environmental Assessment for timber management (Koven & Martell 1994).

The main silvicultural systems being used operationally in Ontario are:

1. <u>Unassisted natural</u> - conventional commercial clearcutting, no further treatment. This is done when the content of aspen is equal or greater than 30%, which is thought enough to ensure filling in of the area by aspen suckering. The method promotes more hardwood content than in the original stand.
2. <u>Assisted natural of spruce</u> - modified clearcutting, leaving seed trees, with understory site preparation, tending, sometimes with fill-planting. It might be possible to girdle aspen prior to cutting to reduce suckering. Herbicide or manual tending are usually required.
3. <u>Artificial regeneration</u> - commercial clearcut, site prepare, plant spruce, tend-tend-tend. Vegetative competition is high, and treatment expensive.

Other partial cutting systems have been proposed, and are currently being experimented with (e.g.Ohman et al. 1978; Scarratt 1996; Navratil et al. 1994). Weddeles et al. (1995) give a summary of silvicultural systems, adapted from Day (1993), which would be appropriate for boreal mixedwoods. These systems include clearcut, stripcut, seed tree, two-stage, shelterwood, and selection.

The two-stage harvesting and tending model is one that has much potential for use in Alberta mixedwoods (Brace & Bella 1988; Navratil et al.1994). In this system one begins with the situation of a evenaged, two-tiered mixed stand of aspen and white spruce, in which the aspen is above the spruce owing to its faster growth. The aspen is harvested at age 60, then the spruce is allowed to grow to around 120 years or until it is mature. It is cautioned that this system may not work in Ontario and eastern Canada, where there is often abundant balsam fir in the understory.

Windthrow is a problem with the two-stage harvest system. Navratil et al. (1994) gave some innovative suggestions for how to reduce windthrow. For example, one might use alternate strip thinning (similar to alternate strip clearcutting) of the aspen, in order to give the remaining spruce in the first-thinned strips protection and time to strengthen their root systems before the second cut strips are thinned of their aspen content.

Research activities

In Ontario, much of the current research is guided by the recent environmental assessment (Koven & Martel 1994). There are two main forest research programs in the mixedwoods. These are centered at the Canadian Forest Service (CFS-Ontario Region, Sault Ste. Marie), and the Ontario Forest Research Institute (OFRI-Sault Ste. Marie, part of the Ontario Ministry of Natural Resources, OMNR). Both of these programs include contributions from other organizations such as universities, Canadian Wildlife Service, and others. In this review I shall emphasize the CFS programs.

Black Sturgeon Lake Program

This program is a large, multidisciplinary, multiagency and based on long-term ecosystem studies (Scarratt 1996). An experimental area has been established near Black Sturgeon Lake, north of Nipigon, Ontario. In it there are four main experiments: partial cutting, a site preparation, prescribed burning, and conifer regeneration under aspen shelterwood. Numerous other component studies are included, usually superimposed upon the aformentioned experimental layouts, namely; site impacts, logging damage to residual trees and advance growth, pathological and entomological responses, seedbank dynamics, postharvest vegetation sucession, stand dynamics, growth and yield, soil nutrient dynamics, soil fauna, and wildlife relationships.

Partial cutting

This study is intended to compare the impacts of a number of cutting regimes associated with different harvesting and extraction systems -- clearcutting with full-tree and tree-length methods; high intensity shelterwood cutting with full-tree extraction, partial delimbed full-tree extraction, and cut-to-length harvesting methods; and patch cutting (ca. 20% removal). The shelterwood cuts removed about two thirds of the merchantable volume including all merchantable balsam fir, while retaining a uniform canopy of good quality aspen and a few potential white spruce seed trees (2-3 per hectare). Several kinds of impacts are being studied related to the harvesting -- slash differences, site disturbances, shrub and vegetation regrowth, damage to residual trees and differences in canopy structure.

The harvesting operations were monitored by staff of the Forest Engineering Research Institute. Gingras (1995) reported that owing to considerable operator turnover during the trials, the data collected on productivity, costs and damage to residual stems did not reflect well-conducted operational work. Some of his qualitative observations were as follows: 1) Manual felling and cable skidding was not very successful owing to operator difficulties. Worker motivation is a critical requirement for success. 2) Feller-buncher/grapple skidding worked reasonably well, but caused fairly high levels of damage to residual trees, a problem which could be resolved with better equipment. Slightly higher levels of mineral soil exposure could be a positive feature favoring natural regeneration. 3) The cut-to-length system provided good productivity and caused the least amount of damage to residual stems. However, it did not expose much mineral soil, and hence was not as favorable in creating receptive seedbed for further natural seeding.

Site preparation
This study is focused on the impacts of site preparation. Several site preparations were tested, including high speed mixing, rototiller and screefing.Variables being studied are vegetation regrowth, seedling survival and growth, organic matter decomposition and element mobilization, biodiversity of soil fauna, and biodiversity of soil microflora and spread of root decay fungi. Early results showed considerable impacts of the different treatments on soil fauna and incidence of the common decay fungus, *Armillaria*.

Prescribed burning
The studies are intended to document the impacts of prescribed burning on vegetation succession and nutrient cycling. Burning treatments included: 1) burn in standing mixedwood, 2) partial trampling (50%) of balsam fir, followed by prescribed burning, 3) tree-length harvest followed by prescribed burning, and 4) full tree harvest to roadside followed by prescribed burning.

Conifer Regeneration
This phase, begun in 1995, aims to determine conditions required to successfully regenerate white and black spruce from seed or planting stock beneath an aspen shelterwood and in patch cuts. A number of site preparations are included soil mixing, surface organic matter removal, mounding, and herbicide application.

Biodiversity
Mixedwoods with aspen are notable for their higher biodiversity in comparison with pure conifer stands. In addition to higher diversity of trees, shrubs, understory plants, invertebrates and microorganisms, mixedwoods provide food, cover and habitat for numerous wildlife species. They also provide other non-timber orientated uses -- i.e.for berry and mushroom gatherers, hunters and naturalists. Aspects of biodiversity included in the Sturgeon Lake research are vegetational succession, forest floor invertebrates, soil micro-organisms, forest-dwelling song birds and salamanders.

Rinker Lake Program
Another research area has been established in boreal forest and includes some aspects of mixedwood research, often at the landscape level of study (Sims & Mackey 1994). Some of the studies associated with this program are: 1) forest-dwelling birds, 2) terrain, hydrology and climate modelling, 3) remote sensing and GIS-based ecosystem mapping, 4) forest successional pathways, and 5) wetland ecosystem surveys.

Small Opening Studies
Researchers with the Canadian Forest Serviceault Ste. Marie have set up an experiment in a mixedwood dominated by trembling aspen, with scattered white spruce, in which openings have been created in the canopy as circles or strips (Carlson & Groot In press). Hand scalping was done to the organic-mineral interface to provide planting spots for white spruce, and spots for seeding. Herbicide was applied as one treatment for competition control.

Tentative conclusions are: 1) on rich sites, aspen can only be controlled by shading with very small openings that are always shaded, 2) both 9m and 18m diameter circles reduce frost damage, 3) herbicide reduces competition for light and soil moisture, and 4) the use of small openings to control aspen may be impractical in terms of harvesting.

Productivity

There is increasing interest in the proactive management of mixedwoods, owing to its resilience, diversity of trees with overlapping functions, and potential for maximizing biological activity per unit area (MacDonald 1995). Hardwoods such as aspen and white birch may provide benefits to site fertility by providing soil stability and increasing the pH by adding Ca, Mg and other nutrients to the soil. Gordon (1981, 1983) has suggested that mixedwood sites have a more active forest floor horizon than under conifers with faster nutrient cycling, owing to the improved nutrient status from the hardwood litter.

A working group on Long-term Sustainable Productivity consisting of scientists from the CFS and OMNR-OFRI, has been studying the impacts of nutrient removals by full-tree logging, and other impacts such as compaction (Gordon et al. 1993; Tenhagen & Jeglum (4)). The group has been emphasizing the black spruce and jack pine working groups, but has recently broadened its scope to mixedwoods because of the background it possesses in nutrient cycling in this forest site type (e.g. Gordon 1981, 1983). Gordon (1983) has reported that nutrient replacement times following disturbances such as harvesting are more rapid in mixedwood stands than in spruce monocultures.

Hardwoods may also provide protection to the conifers of mixedwoods by reducing insect and disease impacts, for example by reducing damage by white pine weevil, reducing damage from spruce budworm during budworm outbreaks, and by reducing the impact of frost.

Research needs

The needs for research in mixedwoods have been assessed by Weingartner & MacDonald (1994). These authors listed the following issues:

1) Enhanced utilization and market development
2) Site preparation and regeneration,
3) Tending
4) Mixedwood management planning
5) Forest measurement
6) Mixedwood harvesting
7) Forest protection
8) Basic research
9) Linkages to other issues and mixedwood stakeholders, and
10) Mechanisms for transferring infor mation and technology.

Many of the needs listed above are being addressed already in the research programs described in this review.

Summary

Boreal mixedwoods represent a broad range of well-drained, fertile upland sites, often highly productive, rich in biodiversity, and characterized by five upland conifer and hardwood tree species in various combinations and stages of succession. Because boreal mixedwoods tend to occupy the most fertile sites, they are potentially the most productive forests, not only in terms of timber yields but also in biodiversity, wildlife populations, and other forest uses. The potentially high productivity and range of options for mixed forest silviculture presents the forest manager with a challenge to manage optimally for a wide range of uses, not only forest production but also non-timber benefits rich in biodiversity. Current research in Ontario is providing valuable information that is ecosystem and process orientated on the long-term consequences of forestry impacts.

Acknowledgements

I am extremely grateful to Drs. J.B. Scarratt and A. Groot for gratiously providing information on their research projects, and to Drs. Scarratt, Groot and D.H. Weingartner for their kind and helpful review comments and suggestions. The author takes full responsibility for any errors of interpretation, omissions, or lack of proper emphasis or credit in this extremely broad and important topic.

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Supplementary planting of conifers and birch in open spruce regeneration

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Braathe, P. 1996. Supplementary planting of conifers and birch in open spruce regeneration. Norwegian Journal of Agricultural Sciences. Supplement No. 24 1-6. ISSN 0802-1600

The reduced yield of timber volume within a rotation period as a result of open and irregularly spaced regeneration is well documented. Investigations in 1949-52 with spruce demonstrated reduction in yield of 25 % in low density regeneration with a zero-square percentage of 60. We have conducted three separate investigations using supplementary planting as a method to avoid or reduce volume loss.Using spruce as a supplementary tree is most successful in open regenerations where height is not greater than 4-6 dm. Pine may be successfully used in regenerations with height up to 8 dm. The height of the seedlings used for supplementary planting is of significant importance. Taller seedlings can better compete.Siberian larch had a satisfactory survival on only one plot, where it showed a very rapid height growth. The remaining plots had a high rate of dying, most likely the result of unsuitable provenance. We need additional data before we can recommend larch as a supplementing species.Silver birch has a very rapid growth and reached more than 12 m height in 15 years on a high site class. Plots with supplemented silver birch are few, but our data indicate that it is the most promising species for supplementing open spruce regeneration.

Key words: Birch, conifers, supplementary planting.

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As early as 1949 The Norwegian Forest Research Institute began investigations concerning the natural regeneration of Norway spruce *(Picea abies* (L.) Karst.) which is irregularly distributed and of varying density. A report on this work was published in 1953, based on 19 plots in middle aged forest which were measured and analysed backwards to the seedling stage (Braathe 1953). For control and verification of the results from 1953, a long range series of permanent plots was established to examine open regeneration in young and middle aged forest. The series consisted of 12 plots laid out in 1954-59.

Further, the question of what to do with open and irregularly spaced regeneration to improve the yield and quality was important. In the years 1960-63 36 plots were supplemented with seedlings of spruce, Scots pine *(Pinus sylvestris* (L.)), larch *(Larix sibirica* Ledeb.*)*. The development and results from these plots up to the last remeasurement in 1985-88 were published by Braathe (1992).

A fourth series was started in 1975 to study the improvement of open regeneration by leaving natural broadleaves, mostly birch *(Betula pen-dula* Roth. and *B. pubescens* Ehrh.*)* as fill in trees. In addition silver birch was supplemented in seven areas where natural birch was absent (Braathe 1988).

In all of these series, consisting of 207 separate plots, the single tree location and measurements are adopted. By measuring the coordinates of all the trees on the plots, it is possible to follow the development and the situation at different stages, as well as to calculate competition between the trees. In studies and experiments containing several categories of trees such as natural, planted and supplemented, as well as two or more different species, the knowledge of the single tree positions is a necessity (Braathe 1992).

Another important feature throughout the series is the zero-square percentage (ZSP) as a practical and scientific measure for the density of regeneration. This measure, 2 x 2 m squares without plants in percent of all squares, has been used since 1950. It is especially suitable in natural regeneration, but can be used for plantings as well. It focuses on the empty areas in which there is no or reduced yield throughout the rotation period. A similar density measure, the stocked quadrat which is a milliacre = 4 m^2 with living plants, was used in USA and Canada (Kerr 1953 and Hosie 1953).

The first plots were compared with the yield table (Eide and Langsæter 1941) for corresponding site and age, and the total yield of the plots at 55 per cent of the rotation age was expressed as a percentage of the table values. The equation curve between the ZSP and yield in Figure 1 has $R^2 = 0.9612$. More interesting is the yield for the full rotation period, which is estimated to fall within the shaded area.

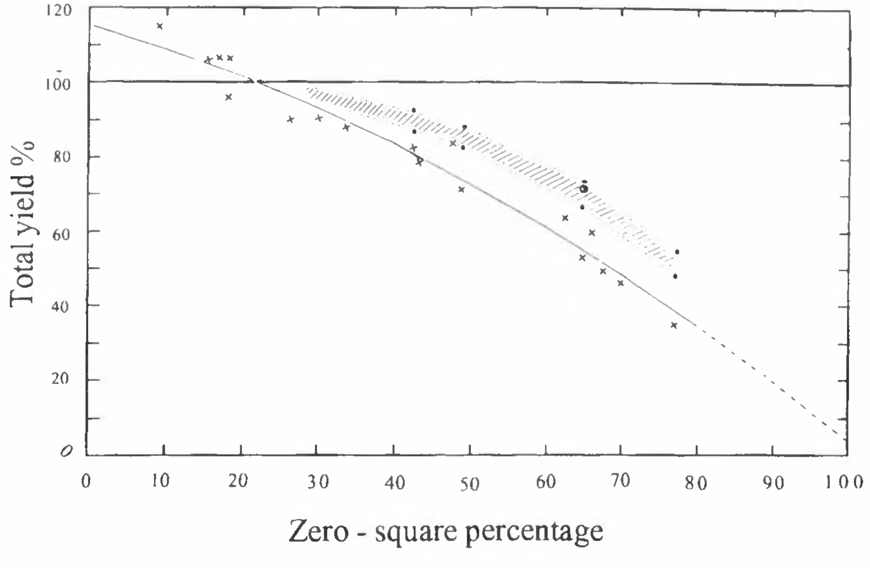

Fig. 1. Total yield of volume at different densities (ZSP) of spruce regeneration. Solid curve: yield at 55 percent of rotation age. Shaded area: estimated yield for the whole rotation period.

At ZSP of 20 normal yield may be expected. By increasing zero-square percentage, the yield decreases. At ZSP of 60 the yield will be about 75 per cent of normal.

Results and discussion

Supplementation with spruce and pine

The loss in open regeneration at high ZSP is considerable, and efforts to reduce the loss are worthwhile. In the supplementing experiments, the seedlings were planted in the open spots with spacing 1.5 m x 1.5 m, but not closer than 0.5 m to living branches of other trees.

The results of supplementation for spruce are measured by the number of trees per daa (0.1 ha) reaching 6 m or more in height within the 25 year period of experiment (NH60). The independent variables are the following and are chosen on a strictly logical basis:

1. The zero-square percentage (ZSP, range 20.2-63.9). This is the most im portant measure for the proportion of unoccupied space in the regeneration to be supplemented.

2. The height of regeneration (HRE, average height of tallest tree within each square; range 5.2-17.7 dm). This is a direct measure of the stage of development and level of competition on supplemented seedlings.

3. The average height of supplemented seedlings (HOSu, range 1.1-2.3 dm) measured in the field immediately after planting.

4. Number of years between supplementation and measurement (YEARS, range 20-28).

5. Site class (H_{40}, range 15.3-22.1), which is an expression of the productivity.

Using the data derived from the 14 plots with spruce supplementation in the equation

$$NH60 = - 304.69 + 9.057 \cdot ZSP/(HRE + 0.5) + 27.764 \cdot HOSu + 5.523\ i\ YEARS + 5.367 \cdot H_{40}$$

the squared multiple correlation coefficient $R^2 = 0.9425$.

The values derived for supplemented spruce seedlings 1.7 dm tall are shown as a diagram in Fig. 2 for site class $H_{40} = 17$ after 25 years.

The data indicate that the two dominating factors for a successful supple-mentation are the zero-square percentage (ZSP) and the height of regeneration (HRE).Therefore, open regenerations with low height characteristics, are good objects for supplementation. For spruce the average height of regeneration should be in the range of 4-6 dm to assure good results.

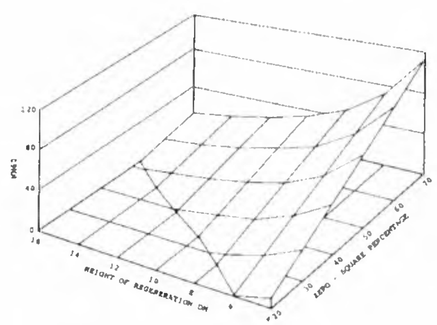

Fig. 2. Diagram showing the number of supplemented spruce trees per daa (0.1 ha). with height greater than 60 dm (NH60) after 25 years. $H_{40} = 17$. HOSu = 1.7 dm.

The height of supplemented seedlings (HOSu) had a significant effect. Taller seedlings can better compete in the regeneration.

Young Scots pine trees grow taller at a more rapid rate than Norway spruce. NH80 was the most suitable measure of the supplementation results because a greater number of pines have exceeded the lower height classes, and reached 80 dm or more.

After several years of the experiment, moose grazing disturbed five of the eleven plots and these were excluded from our calculations.

The following values were measurements from the remaining 6 plots:

$$NH80 = -64.20 + 5.551 \cdot ZSP/(HRE + 0) + 3.058 \cdot H_{40}$$

$$R^2 = 0.9166$$

The equation for pine supplementation is shown as a diagram in Fig. 3 for site class H_{40} = 17, after 24 years. The equations may be tabulated for various combinations of the variables. Due to the rapid height growth of pine, supplementing may be successful in regenerations, were height is as great as 8 dm.

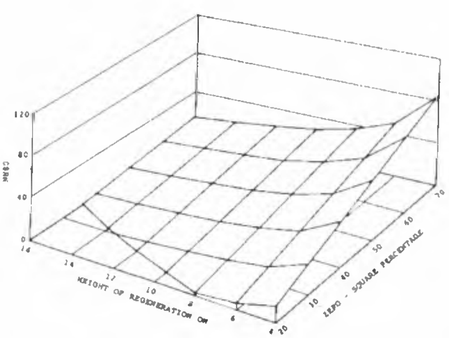

Fig. 3. Diagram showing the number of supplemented pine trees per daa (0.1 ha) with height greater than 80 dm (NH80) after 24 years. H_{40} = 17. (HOSu = 1.0 dm).

Supplementing with larch

Siberian larch was added to the experiment due to its rapid growth. Growth is especially rapid during the first juvenile years, but also later the larch trees have a high increment, exceeding that of pine. Therefore, the larch should compete favourably with the spruce, even when added to a spruce regeneration which has already attained some height. Generally, however, the larch failed as a supplementing tree in this experiment, most likely due to unsuitable provenance. The seedlings surviving the first years gradually were damaged, and the death rate was very high. Many seedlings had dry tops and most of them died gradually. Fraying by roe dear and moose grazing were common on most of the plots.

Those trees which escaped all of these early damages showed good height growth and competed well with the natural spruce trees. However, over time the number of these was gradually reduced. Many of them were bent down by snow.

Eighteen years after supplementing, only one experimental plot remained. This plot was thinned and the development up to 23 years is shown in Fig. 4. The best larch trees had reached more than 12 m in height, and confirm the suitability of supplementing, if a provenance with higher survival could be found.

Supplementation with birch

Seven areas of open spruce regeneration were supplemented with silver birch in 1975-76. Most of these areas had by nature a large number of birch mixed in. Six of the plots had a high density of spruce with zero-square percentages ranging from 1 to 26. Only one of the areas,

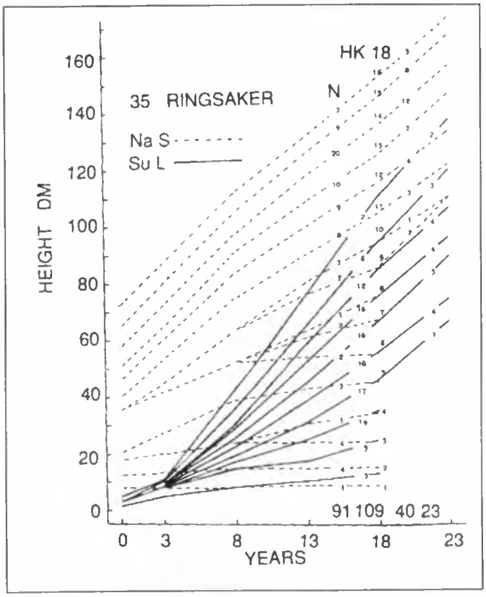

Fig.4. Height class diagram for Siberian larch as a supplementary species. ZSP = 76.8. HRE = 50.1 dm. H_{40} = 18.6. HOSu = 2.3 dm.

Notodden, had a ZSP of 56 on the supplemented plot, where 72 birch seedlings per daa (0.1 ha) were planted. ZSP for the Notodden plot was reduced to 31.

The Notodden area belongs to a series with different mixtures of conifers and broadleaves than in the other supple-mental series; therefore exact comparison with the referred series of supplementing conifers is not possible.

The height class diagram in Fig. 5 shows very good growth for silver birch. Silver birch compared well with the rapidly growing spruce and attained more than 12 m in the 15 years following supplementation. The average height of the supplemented birch seedlings (HOSu) was 6.6 dm. Interestingly, a spruce tree with a height of 17 dm at the time of supplementation had reached a height of more than 12 m.

The results of the birch supplemented plot indicate that silver birch is the most promising species for supplementation in open spruce regeneration. The site class on this particular plot is very high (H_{40} = 23.5), and it remains to be seen whether the relation between spruce and birch is the same in lower yield classes. Despite such uncertainties, silver birch may be considered a very good species for supplementing. Growth potential for silver birch exceeds that for larch, and there are fewer provenance problems with this species.

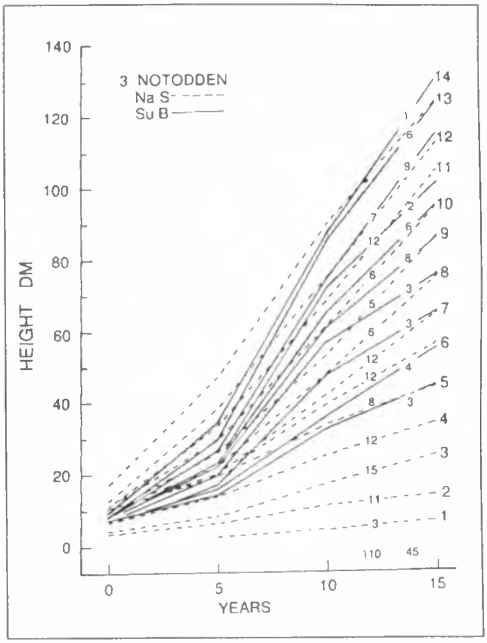

Fig. 5. Height class diagram for silver birch as a supplementary species. ZSP = 56.0. HRE: spruce 9.7 dm and natural birch 20.8 dm. H_{40} = 23.5. HOSu = 6.6 dm.

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Yield and quality of planted silver birch (*Betula pendula*) in Finland - Preliminary review

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Niemistö, P 1996. Yield and quality of planted silver birch (*Betula pendula*) in Finland - Preliminary review. Norwegian Journal of Agricultural Sciences. Supplement No. 24:55-64. ISSN 0802-1600.

The yield of commercial and non commercial wood and the technical quality of stems were studied on 74 silver birch plantations at the age of 30 years and in four spacing experiments at the age of 20 years. On abandoned agricultural land the total and the commercial yield of silver birch were higher than on forest land at the same dominant height. The initial spacing of 1600 trees/ha is recommended except on the most fertile agricultural land, where the density should be higher but not above 2500 trees/ha. The external quality of planted silver birch stems was slightly better than that of natural birch, but the internal quality was not very high because of discolorations.

Key words: *Betula pendula*, branchiness, decay, defect, discoloration, growth and yield, spacing, stem quality.

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Planted silver birch stands cover more than 100 000 ha in Finland. The majority of birch plantations have been established on abandoned agricultural land in the southern and central parts of the country. Birch planting was started on a wider scale in the late 1960's with annual rates of 5000-8000 ha in the years 1971-1976. After that, the annual planted area decreased for ten years because of damage caused by unfavourable sites or animals such as vole, moose or hare. In the mid 1980's the area of afforested agricultural land increased again and at the same time the planting of silver birch rapidly increased to 15 000 ha/yr and 3000 ha/yr for pubescent birch on abandoned agricultural peatland.

In Finland the spacing applied in birch plantations is 1600 seedlings/ha. Only fertile mineral soils are recommended for silver birch. There are few studies on the forestation, spacing and early growth of silver birch in Finland (Raulo & Koski 1977, Raulo 1978 and 1981, Niemistö 1995a,b). Growth and yield tables for silver birch plantations in southern Finland were published by Oikarinen in 1983. The study material was at that time, unfortunately, very limited.

During the last few years several studies dealing with birch plantations have been started in Finland because of the increasing demand and price for pulpwood and the lack of high quality veneer logs. Presently there is also more research material from mature birch stands in Finland. Some preliminary results from the project «Yield and quality of planted silver birch» are presented in this paper. The total yield of silver birch plantations on former agricultural land and on forest land are compared. The exterior and interior quality of planted silver birch at the age of 30 years are studied. The influence of spacing on stem quality and on the yield of commercial and non-commercial wood are quoted from recent studies by the author (Niemistö 1995a,b).

Material and methods

A. The material for the project «Yield and quality of planted silver birch»:

The establishment of the first large-scale silver birch plantations in Finland was organised by Dr. For. Jyrki Raulo in 1964. The initial number of plantations was 160 using 390 000 seedlings. These were planted in private forests of southern Finland. The condition of the sapling stands was investigated in 1978 (Raulo 1979). At the age of 14 years, 21 % of the plantations were excellent, 28 % good, 25% satisfactory and 26% poor. The main reasons for damage were vole and moose and too wet or poor soils.

In the summer of 1993 at the age of 30 years, 74 stands were measured. This material is the first representative sample of the oldest birch plantations in Finland for which the stand history is well known. One randomly placed circular plot (300 m^2) was measured and 5 randomly placed sample trees (1 from the lowermost third part, 2 from the medium part and 2 from the topmost part of the diameter distribution) were felled in each stand for stem analysis. Breast height diameter (or diameter of a stump) and tree height were measured and external quality of stem was recorded for each tree. Annual radial growth to the nearest 0.01 mm and internal quality were analyzed for discs cut at absolute heights of 1.3 and 6.0 metres, at the base of living crown and at relative heights of 2.5, 10, 30, 50 and 70 percent of the total height. The volumes for standing and removed trees were calculated by KPL-program (Heinonen 1994).

B. Spacing experiments:

Four spacing experiments were measured 10, 15 and 20 years after planting (39 exp. plots).

The experiments were established by Prof. Yrjö Vuokila in the 1970's with spacings of 400, 800, 1100, 1600, 2500 and 5000 trees/ha. This material has been presented earlier by Niemistö (1995 b).

Results

Total yield of silver birch plant-ations on agricultural land and on forest land

The average planting density in 1964 was 2400 birch/ha (standard dev.=550) and before the first thinning the average stem number was 1300 trees/ha (standard dev.=400). The first thinning had not yet taken place in 16 % of the birch stands at the age of 30 years.

The total production of stem wood in planted silver birch stands at the age of 30 years was equal to that of Oikarinen's model on forest land (Tab. 1), although the stem number before the first thinning was assumed higher in the model (2000-2300 trees/ha). At the site index of H_{50}=24 (=mean height of the 100 largest diameter trees per ha at a total age of 50 years, according to Oikarinen 1983) the total yield was lower than what the model indicates. On former agricultural land the stem number was as low as on forest land, but the total yield was 10-40 m^3/ha higher than the model indicates. On average, the

Table 1. The total yield of stem wood in silver birch plantations at the age of 30 years compared to the averages in yield tables of Oikarinen (1983)

Site index, H_{50}	Former agricultural land	Forest land	Growth and yield tables of Oikarinen
		m^3/ha	
24		124	157
26	201	192	196
28	270	233	229
30	312	294	284

total yield was 30 m^3/ha higher on former agricultural land than on forest land (Fig. 1). The difference was statistically significant in spite of wide variation between the stands at equal dominant heights.

Influence of spacing on the yield of commercial and non-commercial wood in birch stands

In the spacing experiments, the production of commercial wood (top diameter over bark > 7 cm) up to the age of 20 years was highest at the initial density of 2500 birch/ha or more (Niemistö 1995 b, Fig. 2). At the density of 2500/ha the yield

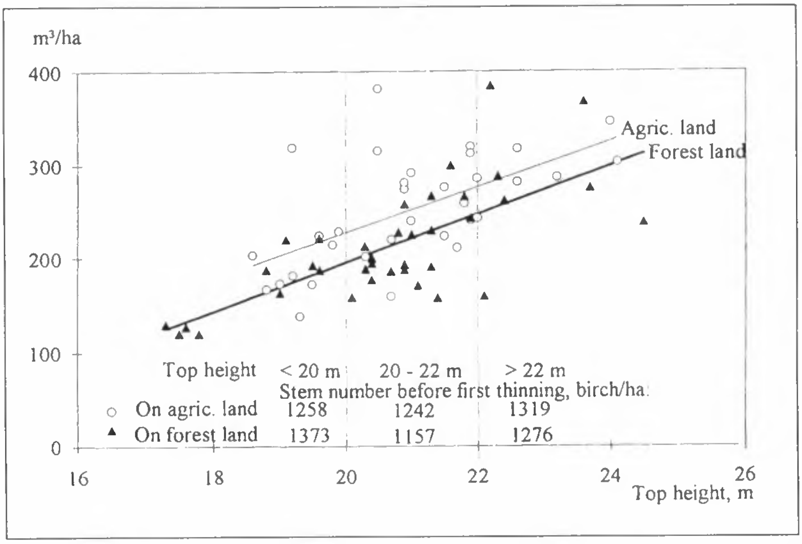

Fig. 1. Total yield of planted silver birch on former agricultural land and on forest land as a function of dominant height at the age of 30 years.

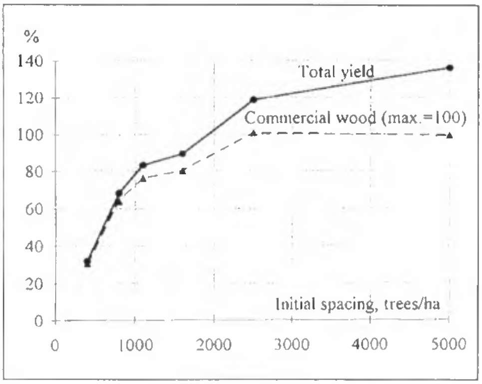

Fig. 2. The influence of initial spacing on the total yield and the commercial wood production (top diameter > 7 cm) in planted silver birch stands at the age of 20 years.

of non-commercial small-diameter wood was about 15 % of the total yield. At the initial density of 5000 birch/ha the total yield was higher, but the amount of small-diameter wood was also higher, 27% of the total yield. The yield of pulpwood increased by 20 m^3/ha with the initial spacing of 2500 stems/ha or more, instead of 1600 stems/ha. The maximum survival in the silver birch stands was 4000 planted trees/ha at the time of the first thinning (dominant height 13-14 m). At a dominant height of 17.5 m, the corresponding figure was 3000 trees/ha.

The annual volume increment at the age class of 11-20 years increased from 7 to 11 m^3/ha/year, when the initial spacing increased from 800 to 2500 trees/ha. Greater stand density of 5000 trees/ha did not increase volume growth. The spacing experiments included different planting designs: equal densities/ha with square planting or row-to-row distances of 3.5 and 5 m. Volume growth was not reduced until the row-to-row distance exceeded the plant-to-plant distance in rows by 3 times or more.

Only in extreme cases did stand density influence height increment of birch. In the least dense (400 trees/ha) experimental plots the dominant height increment was reduced by more than 15% at the age of 10-20 years. With the initial spacing of 5000 trees/ha the over-density began to slow down height and volume increment in the birch stands at the dominant height of 15 m. The spacings of 800-2500 birch/ha did not show differences in top height increment. Competition between trees reduced diameter growth of the 100 largest-diameter trees/ha by one third when the density increased from 1100 to 2500 trees/ha. Spacings below 1100 trees/ha no longer resulted in increased diameter growth of the dominant trees.

In the 30-year-old silver birch stands the production of non-commercial stem-wood was about 10 m^3/ha, when stand density before the first thinning was 2000 trees/ha, 30 m^3/ha at a density of 3000/ha, and 50 m^3/ha in 20-year-old stands at a density of 4000/ha (Fig. 3). Most of this wood was removed in first thinnings. On former agricultural land the amount of non-commercial wood was a little less than on forest land. In natural thickets of pubescent birch (5000-10000 trees/ha) on fertile peatland the amount of small-diameter wood has been 50-60 m^3/ha (Niemistö 1991).

Influence of spacing on the stem quality of planted silver birch

The correlation between stem diameter and branchiness was strong. The diameter of the thickest branch along the length of the butt log averaged 23 mm in the densest stands; the corresponding value in stands at 400 trees/ha was 31 mm (Niemistö 1995 a). However, the diameter of the thickest branch in stems of the same size was not increased by wider spacing. The thickest branch is usually the last one shed. It is also the one that is used

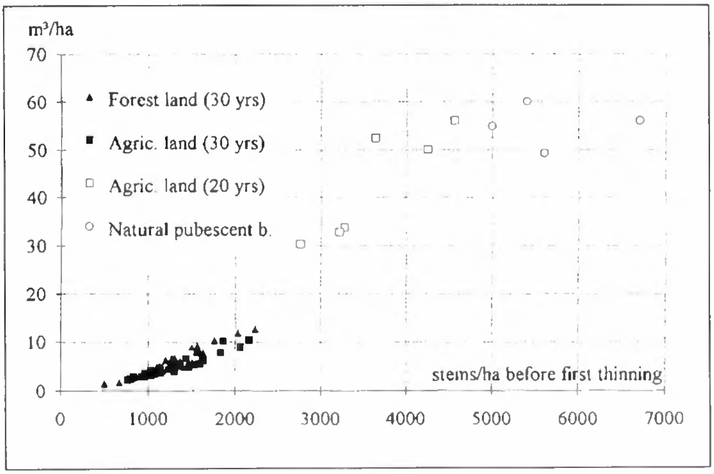

Fig. 3. Production of non-commercial wood (diameter < 7 cm) in planted silver birch stands at the age of 30 (or 20) years as a function of stand density before first thinning (+ natural thickets of pubescent birch on peatland by Niemistö 1991).

for grading logs.

Stem taper was measured as the difference between stem diameters at the heights of 1.3 and 6.0 m. While stem taper was linearly dependent on tree diameter, it was also clearly influenced by stand density. Taper in trees of the same size increased by approx. 10 mm when planting density was decreased from 5000 to 800 trees/ha.

The vigour of birch is reduced if the proportion of live crown falls to less than half of the stem height (Niemistö 1991). With the lowermost live branch as the basis, 55 % may be considered as the limit below which the crown proportion should not be reduced prior to first thinning. This means that the first thinning in a stand with 5000 trees/ha should have been carried out no later than at a dominant height of 12 m (Fig. 4) without pulpwood being yet available. Pre-commercial thinning means in this case extra costs. In stands established at 2500 trees/ha, green crowns maintained adequate vitality up to the dominant height of 14 m, at which point intensive first thinning becomes economically feasible. Thinning has to be precisely timed before the tree crowns contract too much. At a density of 1600 trees/ha, the corresponding dominant height limit was 17 m with 3-4 years available for carrying out a profitable first thinning.

Exterior defects on the stems of planted silver birch at the age of 30 years

All ocularly observable defects that will decrease the value of stems as plywood were recorded and classified according to Table 2. All trees in the 74 sample plots were investigated, but the results were calculated only for the 600 stems/ha of greatest diameter, because this is the maximum number of plywood stems (dbh > 20 cm) produced during the whole rotation period. The number of crooked stems was higher (60%) on abandoned agricultural land than on forest land (44%) (Tab. 2). Also defects on stem surfaces were more common on agricultural land.

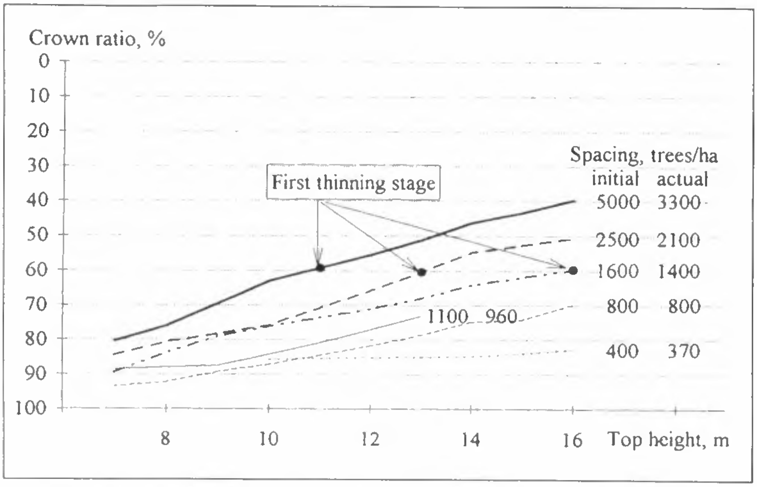

Fig. 4. The development of mean crown ratio of silver birch in the spacing experiments.

Table 2. The percentage of 600 greatest-diameter stems/ha containing exterior defects in planted silver birch at the age of 30 years

Defects	Agric. land	Forest land	Total %	Natural silver birch (Heiskanen 1957, OMT)
Vertical branches	9.4	10.7	10.1	11
Forked stems	2.5	1.8	2.1	27
Sweep stems (one-side)	4.6	4.0	4.3	
Butt crooks	16.2	12.2	14.0	
Upper crooks	11.2	7.6	9.2	
Twisted stems	27.5	20.7	23.8	
Total of crooked stems	59.5	44.4	51.3	54
Surface defects	14.1	8.81	1.2	12
Stems free from defects	27	40	34	

On forest land 40% of the 600 stems of greatest diameter were free from external defects; on former agricultural land this figure was 27 %. The number of vertical branches in this material corresponded to that in natural silver birch stands (Heiskanen 1957). On former agricultural land the number of crooked stems was also equal to that in natural stands.The percentages of forked stems and surface defects were lower in planted birch stands.

Discoloration of wood in stems of silver birch at the age of 30 years
A total of 2676 discs from 366 sample trees were analyzed. The proportion of sample trees with rot or discoloration on the outer surface of the stem was 5.4 % on former agricultural land and 10.4 % on forest land. The difference was not statistically significant. Scars on the surface of the stem were mainly caused by a crack in the stem or a logging injury.

The reason for discoloration between bark and pith of the stem was in most cases a knot scar. The frequency of discolorations of this kind was highest in the butt log (52 % of discs on agricultural land and 43 % on forest land) and lowest in the top section of a stem (Tab. 3). In this respect the quality of silver birch stems was better on forest land than on agricultural land.

The maximum radius of the discoloured area in the pith was on average 31 mm on former agricultural land and 21 mm on forest land. This was the only statistically significant difference between discolorations in the pith of birch stems on forest or on agricultural land (Tab. 4). These figures did not include the cases in which a knot scar and a discoloration in the pith had merged. In most cases the maximum radius of the discoloured area

Table 3. The frequency of sample discs including discoloration between bark and pith of the stem in planted silver birch stands at the age of 30 years

Situation of discs	Number of discs	Discoloured	Percent
In the butt log (<4.5 m):			
On agricultural land	521	271	52
On forest land	597	256	43
In the second log (4.5-8.5 m)			
On agricultural land	331	131	40
On forest land	398	150	38
In the top section (>8.5 m):			
On agricultural land	401	128	32
On forest land	428	105	25

Table 4. The percentage of trees including discoloration in the pith classified by the maximum radius and the longitudinal extension of the discoloration

Maximum radius	No discolor.	<20 mm	21-40 mm	41-60 mm	>60 mm
On agricultural land	6	42	24	14	14
On forest land	9	57	20	10	4
Longitudinal extension	No discolor.	<2 m	2-4 m	4-6 m	>6 m
On agricultural land	6	26	24	24	20
On forest land	9	31	24	24	12

was encountered in the disc from breast height, not at the lower heights. The vertical extent was on average 4.1 m on agricultural land and 3.5 m on forest land, but this difference was not statistically significant.

Correlations between the extent of discoloration and some stand parameters like the geographical location or the site index were studied, but no influence was observed. The preliminary results in younger silver birch stands indicate that discoloration is nearly as common but much more narrow in planted silver birch stands at the age of 20 years than in older ones.

Microbes were isolated from the discoloured pith in 84% of the birches investigated. The most common microbial community consisted of *Phialemonium*-type fungi and bacteria belonging to the *Enterobacter* group (Hallaksela 1995). The fungi were generally more common in discoloured areas, but bacteria were also found in sound samples. Rotten wood and decay fungi were present in only 3% of sample trees.

Discussion

The results obtained indicate that the best planting density for silver birch is 1600 trees/ha as long as initial damage remains low. With this spacing there will be 3-4 years for a profitable first thinning at the dominant height of 14-16 m. On abandoned agricultural land and other exceptionally fertile sites, higher initial spacing with earlier first thinning is advisable to reduce the branching. Natural broadleaved trees, removed when stand height is below 10 m, are also suitable for this purpose. There is minor advantage in exceeding the initial density of 2500 trees/ha. These instructions lead to branch death along the length of the butt log by the time of the first thinning to a density of 700-800 birch/ha.

According to the preliminary figures for total yield in planted silver birch stands at the age of 30 years, it will be necessary to formulate new growth models, expecially for abandoned agri-cultural land. The total yield of stem wood was 230 m^3/ha on average (nearly 400 m^3/ha maximum) at 30 years. Together with younger and also some older birch plantations, the material from 30-year-old birch stands presented in this study will be used as the basis for new growth models at stand and tree levels.

External defects investigated from the same material indicated equal or slightly better stem quality in silver birch plantations compared to natural stands in the 1950's (Heiskanen 1957). The number of forked stems and surface defects was lower in planted stands. The main reason for this is assumed to be more intensive silviculture with selective thinnings and cessation of cattle pasturing in forests.

However, the internal quality of planted birches was not very high. Discoloration in the pith of the stem and knot scars were very common. More profound analyses will be necessary to estimate the yield and quality of veneer or saw timber in the future.

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Grey alder in forestry: a review

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Rytter, L 1996. Grey alder in forestry: a review. Norwegian Journal of Agricultural Sciences. Supplement no. 24: 65-84. ISSN 1806-1600.

During recent decades increasing interest has been shown in the pioneer deciduous tree species *Alnus incana* (L.) Moench. despite its limited contribution to total tree volume in its native countries. This can mainly be assigned to the high production potential, soil improving effects, and good adaptation to prevailing growth conditions of the species. In this review, current knowledge of grey alder regarding biology and silvicultural aspects (e.g. production levels, establishment and regeneration, nitrogen fixation, soil demands, tolerances, wood properties) is compiled and discussed. From presented data three main future applications of the species were distinguished: 1) pure stands for fuel, pulp and/or timber, 2) nurse or shield trees for protection against browsing and frost damage, and 3) soil improver in mixed or alternating stands, and on land areas that have been abandoned due to contamination.

Key words: abiotic tolerance, *Alnus incana*, biotic resistance, CAI, MAI, N_2 fixation, silviculture, sprouting, stand establishment, wood properties

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Grey alder (*Alnus incana* (L.) Moench.) is a pioneer tree species that efficiently colonizes new bare land areas. Mature trees may reach about 25 m in height and seed production starts at 6-15 years of age (Tallantire 1974). However, its duration as a dominant tree on new sites is relatively restricted (~50 years). Grey and black alder together only constitute 1.2% of the total tree volume in Sweden, or 8.0% of the hardwoods (Eriksson 1991). In Norway grey alder constitutes 6.3% of the hardwood species (Johnsrud 1978). After World War 2 the land areas occupied by grey alder have increased in Poland (Krzysik & Nadowski 1975) and eastern Germany (Schrötter 1983), where former pastures have been invaded by self-seeding thickets, but the total areas are still restricted. In Lithuania (Gostzýnska-Jakuszewska & Lekavicius 1994) and Estonia (Tullus et al. 1995), grey alder thickets constitute about 5% of the total forested area. Despite the limited contribution to the standing tree biomass in forests of the native countries and the low-valued wood (e.g. Hakkila 1971), the species has attracted growing interest during the last 20-30 years. It has been included in the Swedish Energy Forestry Programme since the late 1970s. Within the frame of IEA, studies of alders, including grey alder, were performed in the late 1980s (Hall & Burgess 1990). The objectives of those studies were to make an international evaluation of *Alnus* species and provenances, to increase the availability of selected seed sources, and to improve the exchange of information on alders. In Austria, grey alder is included in the Energy Forestry programme performed in Styria (Unteregger 1985). The interest in grey alder may be attributed mainly to a high production potential, an improving effect on soil fertility caused by the ability to fix atmospheric nitrogen in symbiosis with the actinomycete *Frankia*, and good adaptation to growth conditions in temperate and boreal regions. The main objective of this paper is to review biological and silvicultural aspects of grey alder important for forestry, including short rotation plantations. Another purpose is to identify knowledge gaps where more information about the species is needed.

Taxonomy and distribution

The genus *Alnus* belongs to the family *Betulaceae*, subfamily *Betulinae*, and is thus related to the genus *Betula*. The alders are mainly distributed in the northern hemisphere. Some botanists consider the Eurasian grey alder (subsp. *incana*) as one of four subspecies included in the species *A. incana*. The others are: subsp. *hirsuta* in central and east Asia, subsp. *tenuifolia* in western North America, and subsp. *rugosa* in eastern North America (Hulthén & Fries 1986). This review will only deal with subsp. *incana*. Grey alder (*A. incana* subsp. *incana*) is a European - West Siberian boreal-montane species. In Fennoscandia it can be found over nearly the whole of Norway and Finland, and in Sweden it is only absent in the very southern part and along the coasts up to 61°N latitude (Fig. 1). Grey alder is

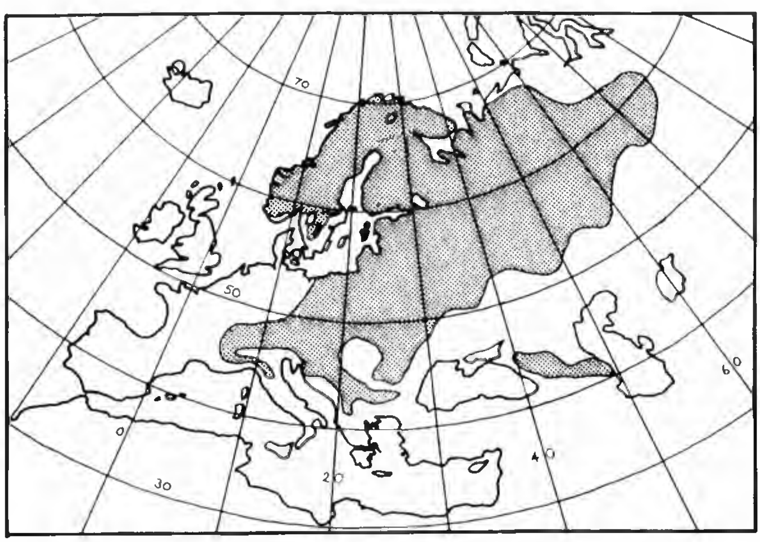

*Figure 1. The natural distribution of grey alder (*Alnus incana *subsp.*incana*). Redrawn from Hulthèn & Fries (1986)*

naturally present in east-central Europe and in European mountain regions and extends eastwards to the taiga in Siberia. It has also been reported from the Caucasus. However, a strict determination of the distribution is difficult because the species has often been cultivated and from such places it has continued in the wild. The eradication by foresters and farmers in lowlands (cf. Gostzýnska-Jakuszewska & Lekavicius 1994) acts in the opposite direction. Grey alder was established in Finland, Sweden and Norway around 6000 B.C. (Tallantire 1974).

Establishment and growth performance

Initial establishment

Grey alder is a pronounced pioneer tree which, in addition to planting, can be established from seeds, root suckers and stump sprouts. The light seeds are easily spread in water, but can also be dispersed up to 30 m by the wind (Johansson 1991). They have a good capability to grow on bare soils, and thereby are promoted by, for example deglaciation, forest fires, and avalanches. The germ plants are small without any significant nutrient reserves and thus are hampered by thick humus layers and competition from other plants.

Production levels

Perhaps the most important characteristic of trees lacking extraordinary wood properties (see below) is their growth potential. In the genus *Alnus* we can find one of the most fast-growing species of the temperate region, namely *A. rubra* Bong., with a mean annual increment (MAI) of woody biomass of 6-8 Mg DM ha^{-1} yr^{-1} in natural stands (Zavitkovski & Stevens 1972). Although grey alder has not generally reached such high production levels, it still has shown good growth performance. In comparison with black alder (*A. glutinosa* (L.) Gaertn.), whose distribution area to some extent overlaps that of grey alder, grey alder is often considered as more fast-growing in the juvenile phase but with a shorter life-span. However, there are only few well-documented comparisons on this subject (Ljunger 1972).

In the literature, there is a large variation in reported values of grey alder growth (Table 1). The highest values come from dense plantations with MAI levels of 6-8 Mg DM ha^{-1} yr^{-1} (Saarsalmi et al. 1985, Granhall & Verwijst 1994). The highest annual production rate of above-ground woody biomass of grey alder ever recorded, as far as the author is aware, is 17.3 Mg ha^{-1} yr^{-1} (48 m^3) in irrigated and fertilized (including N) plantations at Ultuna, Uppsala in Sweden (Granhall & Verwijst 1994). Remarkably good growth was reported by Rytter et al. (1989) and Rytter (1995) for plantations on a sphagnum peat bog with initially a very low site index and severe climate, with frequent frosts in early summer. The peak in current annual increment (CAI) was over 10 Mg DM ha^{-1} yr^{-1} with only small benefits from irrigation and N supply. However, the site was thoroughly prepared by liming with dolomite and later all essential elements were added to all stands except N, which was only supplied to some stands and thus a treatment variable. The study of Utkin et al. (1987) of 19 grey alder stands in the Yaroslavl region in Russia, shows highly varying growth figures with MAI from 1.6 to 7.1, and CAI at given stand age from 2.8 to 11.9 Mg DM ha^{-1} yr^{-1}. Low production records were reported for natural stands in Finland (Saarsalmi & Mälkönen 1989, Saarsalmi et al. 1991). The figures given in Table 1 indicate that, generalized, grey

Table 1. Reported above-ground woody biomass production of *Alnus incana* stands given in chronological order. Mean annual increment (MAI) of obtainable biomass for the given age and, when possible, highest measured current annual increment (CAI) during the period are given. Values in $m^3\ ha^{-1}$ are transformed into $Mg\ ha^{-1}$ using the basic density 360 kg DM m^{-3}, i.e. 1 Mg = 2.78 m^3 (cf. Nagoda 1968, Hakkila 1971, Björklund & Ferm 1982). n.r. = not reported.

Reference	Stand Age (yrs)	Stems (no ha^{-1})	MAI (Mg DM $ha^{-1}\ yr^{-1}$)	Max CAI (Mg DM $ha^{-1}\ yr^{-1}$)	Remarks
Ozols & Hibners 1927[1]	15	6500	4.1	n.r.	from yield table at max MAI
Raukas 1930[2]	15	11700	3.7	n.r.	from yield table at max MAI
Miettinen 1932	35	3610	2.8	3.1	9 stands, *Oxalis-Majanthemum*-type, at max MAI
	35	4180	2.3	2.5	31 stands, *Oxalis-Myrtillus*-type, at max MAI
Lysberg 1956[1]	40	2050	3.3	n.r.	unthinned stand
Børset & Langhammer 1966	30	2550	4.4[3]	5.7	site class 1, 26 natural stands, at max MAI
	35	2400	3.3[3]	4.5	site class 2, 21 natural stands, at max MAI
Björklund & Ferm 1982	8	39300	4.7	n.r.	thicket
Unteregger 1985	17	n.r.	5.0	n.r.	plantation
	3	n.r.	3.7, 4.4	n.r	plantations: unfertilized, fertilized
Saarsalmi et al. 1985	5	40000[4]	5.8-6.1	n.r.	plantations, 4 nutritional treatments
Utkin et al. 1987	3-50	n.r.	1.6-7.1	11.9	19 different stands
Rytter et al. 1989	7	40000[4]	3.9, 4.3	10.9	peatland plantations, 2 treatments
Saarsalmi & Mälkönen 1989	35	6072	0.8	n.r.	natural stand
	35	11666	1.9	n.r.	natural stand
Saarsalmi et al. 1991	25	2807	2.2	n.r.	natural stand
	8	c. 40000	1.8-3.9	n.r.	coppice stands, 4 treatments
Saarsalmi et al. 1992	9	10000[4]	1.8-2.5	n.r.	plantations, 3 nutritional treatments
Johansson 1992a	27	3000	4.0	n.r.	stand originating from seed
	25	13133	5.8	n.r.	root sprouts
	35	10958	5.0	n.r.	root sprouts
Elowson & Rytter 1993	5	20000[4]	2.0	6.0	plantation on sand
Hendrickson et al. 1993	5	20000[4]	3.7	n.r.	plantation
Granhall & Verwijst 1994	7	20400[4]	8.2	16.5, 17.3	plantation, 2 N treatments
Rytter 1995	13	6400	4.7[5]	8.2	thinned plantation on peatland
	13	22500	4.4	10.9	unthinned plantation on peatland

[1] quoted from Børset & Langhammer 1966
[2] quoted from Miettinen 1932
[3] based on total yield produced
[4] initial stem number
[5] thinned biomass included

alder stands can be expected to produce 4-5 Mg DM ha^{-1} yr^{-1} (11-14 m^3) as a mean over the rotation time, and that productivity can be strongly improved by management measures.

More expanded biomass studies of grey alder stands, resulting in yield tables, were done 30 or more years ago (Ozols & Hibners 1927, Raukas 1930, Miettinen 1932, Børset & Langhammer 1966). Given that the maximum value of MAI indicates an appropriate rotation time of a stand, the yield tables of Ozols & Hibners (1927) and Raukas (1930) point to an optimum rotation time of about 15 years, whereas those of Miettinen (1932) and Børset & Langhammer (1966) suggest a longer period of 30 to 35 years. The MAI-increase in the two latter yield tables was, however, small during the last 10-15 years before the actual maximum. In the study of Rytter (1995) in plantations on peatland, MAI had seemingly culminated at the end of the study, i.e. at a stand age of 13 years. From the experiences in the literature it may be concluded that in order to maximize yield, dense plantations with a rotation period of 10-20 years can be recommended.

Regeneration

Grey alder is known to regenerate by root sprouting. Schrötter (1983) reported that root sucker production generally starts at a stand age of 25-30 years. In other experiments (Rytter unpublished), it was seen that harvest of very young stands resulted in a regeneration of only stump sprouts, but already before 10 years of age root suckers began to appear in areas that had been cut. After harvest, grey alder readily sprouts. In a study of Paukkonen & Kauppi (1992), sprouts were formed on stools within three weeks of coppicing performed in May. However, the time of harvest is most certainly of great importance for regeneration. No data on this exist for grey alder but can be found for other fast-growing hardwoods. In a review on coppicing, Sennerby-Forsse et al. (1992) concluded that for many hardwood species resprouting is negatively affected by harvest in an actively growing stage, i.e. the vegetation period. Johansson (1992b) found the lowest survival of stumps from 10-50-year-old *Betula pubescens* after felling in late spring/early summer. Therefore, harvesting should be done during the dormant period of the trees.

From studies of Rytter & Sennerby-Forsse, cited in Rytter (1994), a productivity of about 1 Mg ha^{-1} of woody dry matter was recorded in the first year after winter harvest of 10 and 35 year old grey alder stands. In the second year, the productivity increased to 5-6 Mg ha^{-1}. These figures are not as high as has been recorded after harvest in willow stands (Christersson 1986, Rytter & Ericsson 1993, Willebrand et al. 1993), where a total of 20 Mg ha^{-1} can be reached two years after harvest, but the grey alder stands had never received irrigation or fertilization. Ferm (1990) noted that sprout-originated birch stands seemed to proceed through the fast-growing juvenile stage more quickly than seed-originated ones. This interesting finding, which affects the rotation periods after the first harvest, has to be verified for grey alder.

In the study of Rytter & Sennerby-Forsse mentioned above, the dominating number and biomass of shoots resprouting after harvest came from root suckers. Because of this, the new generation presumably becomes uniform with small effects from preceding self-thinning. Root sprouting also gives rise to straight tree-formed individuals, thereby favouring form and wood quality.

Nitrogen fixation

On most forest sites, nitrogen fertilization improves forest productivity because the natural inputs from fixation and other sources are seldom sufficient for optimal tree growth (Dawson 1983). During recent decades the cost of nitrogen fertilizers has increased and this has led to suggestions that N_2-fixing woody species could be used in commercial forestry instead of nitrogen fertilizers (Gordon & Dawson 1979). In this context grey alder is both a N_2-fixing species and a useful tree. Alders fix nitrogen in root nodules in symbiosis with the actinomycete *Frankia*. Presumably all *Alnus* species form root nodules (Bond 1976). The reported annual fixation of nitrogen in alder stands ranges from a few kg up to 300 kg ha^{-1} yr^{-1} (Binkley 1981).

Table 2 shows estimations of annual nitrogen fixation rates in grey alder stands. In stands where the canopy probably was closed, i.e. stand age 7 years, an annual rate of 50-100 kg N ha^{-1} can be expected. The highest values come from irrigated and fertilized stands with high productivity (Rytter et al. 1991). The productivities in the stands of Stassen & Behrisch (1925), Ovington (1956), and Johnsrud (1978) are not known but are, because of low management intensity, presumably lower than that of Rytter et al. (1991). The lower fixation figures of newly established stands (Table 2) are most probably an effect of the crop not fully occupying the sites at the time of measurements. Huss-Danell et al. (1992) commented on the 22 kg N fixed ha^{-1} yr^{-1} in their stand with the spacing 1 m 1.3 m. If the ARA (acetylene reduction assay) values were valid also for denser stands, a spacing of 0.5m 0.5m would have corresponded to 113 kg N ha^{-1} yr^{-1}, which is about the same rate as found in the closed stands of Rytter et al. (1991). There is clearly a positive relation between photosynthesis, with the amount of carbohydrates produced, and the rate of fixed N_2 (cf. Bormann & Gordon 1984, Vikman et al. 1990), emphasizing the utmost importance of growth conditions and leaf area index for rate and quantity of fixation. Under most circumstances, the amount of fixed N_2 is of an order that gives a significant addition to the nitrogen supply of the ecosystem. As far as can be seen from Table 2, grey alder seems to be self-supporting with nitrogen and only marginally better growth per-formances have been reported where nitrogen has been added as fertilizer in the field (Rytter et al. 1989, Granhall & Verwijst 1994).

High nitrogen concentrations in the soil may have harmful effects on the *Frankia* symbiosis, but low concentrations of inorganic nitrogen have stimulated nodulation and nodule activity of alders (e.g. Stewart & Bond 1961, Zavitkovski & Newton 1968). Ingestad (1980) showed under controlled *in vitro* conditions that N_2 fixation in nodulated grey alder seedlings increased in absolute terms up to high nitrogen addition rates. This stresses the importance of the supply regime, where small repeated doses adjusted to the actual uptake capacity of plants can stimulate activity of the N_2-fixing enzyme nitrogenase. The findings of Ingestad can be applied to field conditions where, as long as ammonium and nitrate concentrations in the soil are kept low, even if the flux is high, a high nitrogenase activity can be maintained. If the inorganic nitrogen concentration in the soil increases, nitrogenase activity decreases. This behaviour was seen in the study of Rytter et al. (1991). As mentioned above, the productivity in grey alder stands can be somewhat improved by supply of nitrogen fertilizer but it is doubtful if this can be economically justified.

Table 2. Reported annual rates of N_2 fixation in grey alder stands. Methods: ARA = acetylene reduction assay; BC = balance calculation as the difference between output and input of nitrogen; CP = compared plots with and without grey alder

Reference	**Rate of N_2 fixation** (kg N ha^{-1} yr^{-1})	**Stand age**	**Method of measurement** (yrs)
Stassen & Behrisch 1925	c. 50	30	CP
Ovington 1956	c. 50	21	CP
Johnsrud 1978	43	30	ARA
Rytter et al. 1991	85-115	7	ARA
Huss-Danell et al. 1992	22	2	ARA
Ericsson & Rytter 1996	1[1]	2	BC
	32[2]	2	BC

[1] supply of N fertilizer amounting to 51 kg N ha^{-1} the 2nd year
[2] no supply of N fertilizer

What happens on a site when the soil becomes nitrogen saturated? Will the N_2 fixation of alder continue and thereby become a threat to the environment? This question has not yet been reliably answered, but in accordance with the discussion in the previous paragraph, nitrogenase activity will presumably decrease when nitrogen concentration in the soil increases. This means that the system would be self-regulating with respect to nitrogen support and would not be an environmental danger.

Demands and tolerances

Grey alders prefer moist and nutrient-rich sites with access to lime but can also be found on poorer and drier sites (Schrötter 1983, Mann 1987, Frivold 1994). Grey alder can grow at a lower mean temperature during the growing season and has lower hydrological demands than black alder (Tallantire 1974), but is less tolerant to stagnated water with limited oxygen availability (Noack 1983, Mann 1987). Somewhat surprisingly therefore, Hall and Burgess (1990) found low drought tolerance of tested grey alder provenances in an IEA study in Canada. Alders are generally considered as trees with high water demands but Braun (1974) showed that black alder had a higher water use efficiency than *Salix alba*. Within the Department of Short Rotation Forestry at the Swedish University of Agricultural Sciences, Uppsala, Sweden, studies are being made of the water use efficiencies of grey alder and basket willow (*S. viminalis*) in situations of optimum, as well as limited, water and nutrient availability (Rytter et al. 1996).

In the study of Ericsson & Lindsjö (1981), a high tolerance to different pH situations in the growth substrate was reported for grey alder and silver birch (*B. pendula*). The tested pH span was 3.8 to 6.7 and within this range no differences in shoot development could be detected for either species. In the same study, *S. viminalis* and *Populus trichocarpa* were included and showed high sensitivities to low pH, but they also showed growth reductions at the highest pH value. Nevertheless, Mann (1987) reported that grey alder is more sensitive to low pH than black alder. It should also be kept in mind that although plant growth may be unaffected by low pH, nodulation and nodule function in alders seem more sensitive to acid conditions (Griffiths & McCormick 1984).

Because grey alder can be found up to latitude 70 °N it may be considered as well adapted to climatic conditions in the boreal and temperate regions. Christersson & von Fircks (1984) showed that grey alder and birch were more tolerant to below-zero temperatures in the growing stage than tested species and clones of *Salix*, an important fact to know when selecting suitable tree species for sites with frost nights during the growing period.

Grey alder is capable of growing on heavily polluted areas, for example mine spoils, but opinions about the degree of its tolerance diverge. Hawrys (1987) tested 30 tree species in 10 years on areas polluted with SO_2, Zn, Pb and Cd compounds in Poland, and grey alder was found among the most suitable species for reforestation of heavily polluted sites. Grimstad (1985) in Norway, on the other hand, regarded grey alder an intermediate tree species in resistance to damage caused by soil pollution, and Braun et al. (1978) reported grey alder to be sensitive to salt (NaCl) contamination of the soil. Freer-Smith (1984) found grey alder to be the most susceptible to SO_2 of six deciduous species tested. It is obvious that grey alder can be used on polluted areas but also that the kind of pollution in question will affect the suitability of the species.

Hubbes (1983) reported that no severe infestation of insect or fungi had been observed in grey alder stands. Since then, stem canker caused by *Cytospora* sp. has been seen on alder in Oregon (Filip 1991), and *Valsa oxystoma* has caused tree death among black alders in Europe (Mann 1987). There is, consequently, a risk of future fungi attacks in grey alder stands.

Successful establishment of forest stands includes avoidance of browsing in game-dense areas. It is common knowledge that grey alder generally has a low preference for browsing (e.g. Sennerby-Forsse 1982, Schrötter 1983). Hjältén & Palo (1992) investigated woody browse during winter by two vole species and hare on four hardwood species. The overall consumption in two patch types was lowest in grey alder. They suggested that digestibility and the concentration of plant secondary metabolites determine vole and hare browsing during winter, whereas nitrogen concentration in plant tissues is of minor importance. Danell et al. (1991) studied foraging decisions by moose during winter conditions in stands of pine and aspen, pine and grey alder, and pure pine. As predicted, grey alder showed the lowest preference to moose. Wentz (1982) reported that the only tree species that survived browsing on two hill-slopes with dense games populations in Bavaria, Germany, was grey alder. One way to succeed with establishment of more long-lived broad-leaved deciduous tree species on the sites was to plant them close to, and preferably physically attached to, grey alders. It may thus be concluded that dense populations of browsing animals should not obstruct the use of grey alder in forestry, but instead increase its usefulness.

Wood properties

Because grey alder wood is easy to work and form, the traditional use has been for household utensils, clogs, shoe heels, and bobbins among other small items. It has also been used as raw material for charcoal production (Matthews 1987), and for production of generator gas, used as fuel for vehicles, during World War 2 (Frivold 1994). Børset & Langhammer (1966) noticed a change from tradition applications in that grey alder wood had started to be used in the chemical industry and in board production. The suitability for board production has later been stressed also by Hakkila (1971), Krzysik & Nadowski (1975), and Schrötter (1983).

The alder wood is dark and red in contrast to the white wood of, for example, birches and poplars, and this means that alder wood is less attractive for use in high-quality pulp. The problem of non-polluting bleaching methods has not yet been solved. However, the fibres of alder are short, and this is a necessary characteristic for improving printing properties of paper (Berggren et al. 1994). The timber is not naturally durable when used in exposed positions but is permeable to preservatives and takes stain well (Matthews 1987). Possibilities to use grey alder wood in the manufacture of furniture has been investigated (Klugis 1978).

Grey alder wood is light compared with most other tree species (Table 3). In the three studies of Nagoda (1968), Hakkila (1971), and Björklund & Ferm (1982), the basic density of stems was found to be in the range 360-365 kg DM m^{-3}. Björklund & Ferm also included branches in their examination.

Nurmi (1993) studied the heating values of small-sized trees, including grey alder, in order to establish practical information for fuelwood users (Table 3). The differences between species were small at the whole-tree level, with only 5% difference between highest and lowest effective heating values. The differences were concluded to be so insignificant that they should not affect the price-setting of fuel-wood. Instead, the moisture content and the quantity of fuelwood per unit of land area were considered much more important factors than the species. The findings of Nurmi are in contrast to statements that grey alder has a low heating value (e.g. Mann 1987), at least when calculated per unit of weight. From the review by Keeney et al. (1990), slightly higher heating values than those of Nurmi were generally found for fast-growing poplars and willows. However, values diverged between cited studies suggesting that comparisons between different studies may be difficult to make.

Grey alder wood is not regarded as

Table 3. Effective heating values of oven dry stems and basic density of stems from Finnish investigations. Heating values are quoted from Nurmi (1993) and basic density from Hakkila (1971).

Species	**Effective heating value of whole stem** (MJ kg^{-1})	**Basic density of stem** (kg DM m^{-3})
Alnus incana	19.000	361
A. glutinosa	19.305	-
Betula pubescens	19.187	482
B. pendula	19.151	497
Populus tremula	18.652	-
Pinus sylvestris	19.333	409
Picea abies	19.022	387

being of high quality, but in Norway Nagoda (1968) found it a valuable raw material in the forest industry and he also noticed that there was increased interest in the properties of grey alder wood. According to Hakkila (1971), the main use of grey alder wood should be found in the pulp, paper and board industries because of its poor stem form and small diameter, but other views will be discussed below. It can, of course, also be successfully used as fuel wood.

Silviculture and fields of application

When the objective is to produce timber of high quality, thinning is a tool to transfer the future growth of a stand to fewer selected trees and thereby increase size and quality of them. It is therefore difficult to judge the log quality of grey alder because few thinning trials have been conducted. Economic calculations of grey alder forestry by Opdahl & Veidahl (1993) showed that one or two thinnings and a rotation time of 40 years was most profitable, and unthinned stands were not recommended. It has also been shown by Brantseg (cited in Børset & Langhammer 1966) and Rytter (1995) that the amount of woody biomass obtained and usable may be larger in thinned than in unthinned stands, although the total woody production is higher in the latter. The time of thinning is important and when delayed the remaining trees do not respond (Matthews 1987, Rytter 1995). In the study of Rytter (1995) on peatland in central Sweden, the trees remaining after the second thinning did in fact decrease their diameter growth in the year after thinning compared with the previous year, and this is generally seldom the case. The initial spacing is, of course, important when discussing thinnings. In short rotation forestry research, dense plantings are favoured (Table 1) because the main objective is to produce a maximum amount of biomass of fuel and pulp wood in the shortest possible time. Matthews (1987) reported that in other cases 1600 to 2500 plants per ha are common. My own experience is that grey alder has a strong form, i.e. it develops into a tall tree with a small stem diameter, and therefore can withstand relatively dense spacings before self-thinning occurs. However, the effects of late thinnings mentioned above must be stressed. As can be seen, knowledge of the silvicultural aspects on grey alder is insufficient. This is clearly an area where more research work is needed, both for natural stands and plantations.

In general, much of the nitrogen taken up by trees and transported to leaves is retranslocated back to branches, stem and root tissues before leaf abscission. More than 50% of the foliage-N content can be saved by hardwoods in this way (van der Driessche 1984). In N_2-fixing species, the need for retranslocation of nitrogen at the end of the season is small and most of the foliage-N remains in the leaves at the time of litterfall. This has been verified for black alder (Dawson & Funk 1981) and grey alder (Rytter 1990). As a consequence, alder leaf litter is rich in nitrogen and easily decomposable (Danière et al. 1986, Slapokas & Granhall 1991). In closed fast-growing grey alder stands about 100 kg N ha^{-1} yr^{-1} may reach the ground with leaf litter (Rytter et al. 1989).

The use of grey alder in forestry has brought about changes to the original soil properties. In a study by Kulig et al. (1974) soil changes were followed during 20-25 years after introduction of grey alder on former agricultural sites. Porosity and organic matter increased in the soil while soil bulk density and pH decreased.

Increased soil acidity has also been reported on red alder sites (e.g. Franklin et al. 1968, Bormann & DeBell 1981). A probable explanation is decreased anion uptake (low NO_3^-) compared with base cation uptake of N_2-fixing plants (Ingestad 1980). On the other hand, Schalin (1966) showed the basic properties of grey alder leaf litter. The use of grey alder litter in a pine stand resulted in a pH increase of 0.4-0.8 units after three growing seasons.

The increase of nitrogen availability caused by N_2 fixation in alders has been used to improve growth of other tree species. The most common way of taking advantage of the improved nitrogen situation is mixed plantations of alder and other tree species. This has been reported successful for a number of species where growth has been increased (e.g. Schalin 1966, Burgess & Hendrickson 1988, Melzer 1990). Interplanting is, however, a difficult task because it means that the species involved must have about the same growth rate and growth rhythm to avoid outcompeting each other, unless the alder is used together with a shade-tolerant species like spruce. Accordingly, problems with competition between species have been reported from mixed plantings (e.g. Burgess & Hendrickson 1988, Moffat et al. 1989, Saarsalmi et al. 1992). From the Nitrogen fixation section, we can see that the advantage of the alder as N_2-fixing species is almost only of significance when alders are among the dominating trees in a stand. Alders that are shaded and suffer from carbon limitation will most probably deliver small contributions to the nitrogen gain. Another possible solution to this problem may, therefore, be to alternate rotations of alder and a non-fixing species, and thereby make use of the nitrogen fixation.

Nitrogen gain is not the only reason for mixed plantings with alder. In Germany grey alder has been used together with more valuable broadleaved trees to improve their form and quality (Schrötter 1983, Mann 1987). Alders are also used as shelter trees to provide frost protection for various other more sensitive species (Mann 1987, Matthews 1987). Ljunger (1959) reported that black alder and grey alder had shown antagonistic effects against root rot fungi and therefore had been used to decontaminate infected areas. This statement, however, needs to be verified.

Because of good rooting capacity and ability to tolerate problematic soil conditions (see above), grey alder has been used for reclamation of contaminated land areas. Tarrant & Trappe (1971) gave examples of where alders had been used to improve soil conditions. From their survey, it was seen that grey alder has been used mainly in Europe to prevent erosion and mass soil movement, and reforestation of mining spoils, exhausted farmland and sites with iron pan and high water table. More recently, grey alder was recommended for reforestation of areas polluted by heavy metals from the industry (Hawrys 1987). In this context, it would be interesting for grey alder to be tested in afforestation of abandoned refuse dumps.

Conclusions and future prospects

From the discussion above, three main applications of grey alder in future silviculture can be distinguished: 1) pure stands for fuel, pulp, and/or timber production; 2) nurse or shield trees for protection against browsing and frost damage; 3) soil improver in mixed or alternating stands, and on land areas that have been abandoned due to contamination.

In addition to a high growth potential, grey alder has a high budding capacity, ability to produce suckers, and ability to withstand repeated coppicing. This suggests that grey alder is an interesting alternative in coppice forestry for biomass production. The low preference for browsing is a valuable attribute in game-dense areas. The wood is at the moment not highly regarded and therefore the most realistic use, besides as fuel, should be in pulp and paper industries when the problem of non-polluting bleaching methods has been solved, and in board industries, although other possibilities like raw material for furniture should not be overlooked.

Because of high frost tolerance and low browsing preference, grey alder has been tried as nurse and shield trees for other tree species regarded as being more valuable. These applications of mixed stands are probably more successful than interplanting where the goal is to improve soil fertility and thereby transfer nitrogen from the alder to neighbouring trees of other species with a resulting increase in productivity. Highly productive mixed plantations assume nearly equal productivity and growth pattern of the species involved. Otherwise, one of the species will rapidly be overtopped. Mixed plantings with alder and a secondary species, e.g. spruce, and alternate rotations of alder and another species may be solutions to this problem.Moderate demands on soil acidity and ability to grow on poor and derelict land means that grey alder is a promising possibility for reclamation of areas polluted by, for example, industry, mining spoils and refuse dumps.

One important factor to be considered, but which has not been mentioned before, is the future potential in breeding work. So far very little ennobled material has been used in research work. Matthews (1987) regarded alders as promising subjects for breeding because they flower at an early age with high seed production, and can also be vegetatively propagated by cuttings, tissue and cell culture. Ljunger (1972) and Mejnartowicz (1982) have shown higher growth rate of hybrids between grey and black alder than in the pure species, and Hendrickson et al. (1993) reported that clones of grey and black alder exceeded seedlings in growth. It may, therefore, be concluded that there is a large potential for genetic improvements which, in turn, may increase the field of applications for grey alder. It is obvious that grey alder has a broad field of applications and that more research work is needed for evalu-ation of the biological and economic potential of the species. Thinning opera-tions, mixed/alternate plantations, and breeding are examples of important topics that need further studies.

Acknowledgements

This review work was supported by the National Board for Industrial and Technical Development in Sweden and the Swedish University of Agricultural Sciences. I wish to thank Lars Christersson, Per-Magnus Ekö, Lisa Sennerby-Forsse, and Martin Werner for valuable comments on the manuscript.

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Are climatic temperature changes a threat to broadleaves?

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Dietrichson, J.1996. Are climatic temperature changes a threat to broadleaves? Norwegian Journal of Agricultural Sciences. Supplement No.24:7-16. ISSN 0802-1600

Climate change, as it has been predicted within a time frame of 40-50 years, is analysed. In the north summer and autumn temperatures are often growth limiting for trees. However, provenance studies in conifers have shown positive effects upon growth for sources moved from a cooler to a warmer summer climate. Therefore, increased summer temperatures of a few degrees, and in the absence of severe droughts, might be expected to act positively upon the growth of broadleaves also.The effect of climatic change is more complex in areas where northern boreal trees, due to the change, might come into a transition zone towards a nemoral warmer winter climate. Thaw and freezing conditions in the winter can make the trees susceptible to freeze damage. Genetically controlled winter chilling requirement, threshold temperatures and the heat demand in order to start the growth processes after the winter season, are all important factors. Damage will depend upon loss of frost resistance too early in the late winter or spring season, and temperatures falling below the tolerance limit. During budburst,broadleaves and Norway spruce, used here as a model tree, seldom tolerate temperatures less than -5°C to 7°C. After thaw conditions in late winter, the tolerance level is lower. Experimental injury has been induced by freezing from -13°C and less. There is little doubt that climate change will be a threat to provenances or ecotypes of broadleaves not adapted to fluctuating winter temperatures. Much information regarding genecology has been gained as the result of provenance studies in the conifers. Such studies are also needed for broadleaves.

Key words: broadleaves, climate change , frost damage , forest decline ,genecology

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Climate change is considered to be a threat to forests. The reason is that trees are long lived and that the changes might occur faster than trees can adapt.

The changes in north-western Europe over 40-50 years might be the following (NILU, 1990):

1. Temperature, +2° and + 4° C warmer in summer and winter, respectively
2. Higher humidity - higher frequencies of floods and droughts
3. Increased wind speed
4. Increased CO_2 in the air

Under northern conditions the increase in temperature might be considered the most important.

To evaluate how trees might respond to a temperature change, their genecology must be known. It is necessary to determine whether the annual growth cycle will be synchronised with the new climate.

The annual cycle is defined as all of

the developmental and physiological stages, such as budburst, shoot elongation, growth cessation, frost hardening and dehardening, that northern trees undergo within a year. In tree breeding these have been important research topics for many years. Unsuccessful transplantations of seeds or plants, transferred from their native climatic habitat, were related to the fact that the trees maintained an annual growth rhythm out of phase with the new climate (Dietrichson 1964a). The lack of success with seed transfers can be attributed to several factors. The first is that the physiology of the trees does not always fit into the new climate and they are damaged by physiogenic responses such as frosts or droughts, and the second is that this lack of fitness leaves the trees more susceptible to pathogens and insects (Day 1931, Dietrichson 1968). There is a great deal of interaction between genetics and environment, and a model of some of these relationships is shown in Figure 1.

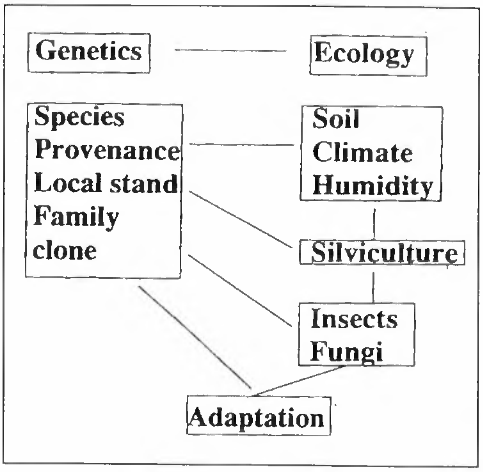

Figure 1. A model for the possible types of interactions between genetics and environment leading to stress or decline in forest trees.

Summer climate

The northernmost and highest altitudinal distribution limits of different tree species have often been determined by the summer climate. If the heat sum and the length of the growing season fall below a certain limit, some species will not be able to survive or reproduce. The under-lying theory is that energy is needed for growth, reproduction and the build up of sufficient frost resistance in the following autumn (Dahl 1990). Furthermore, this energy is released by respiration of the photosynthetic products. Studies have shown that growth in Norway spruce is highly correlated with respiration rate (Dahl and Mork 1959). As an example, respiration curves of wych elm (*Ulmus glabra* Huds.) and Norway spruce (*Picea abies* (L.) Karst.), as a function of temperature, are different (Skre 1979). Below 10 °C wych elm has a higher respiration rate than Norway spruce; how-ever, above 10°C the opposite is true. Thus, wych elm should, for active summer growth, have an advantage in a cool coastal long growing season, and Norway spruce in a shorter and warmer growing season. Norway spruce as a species, requires less total heat for summer growth.

Silviculturists, on the basis of the most northern or altitudinal limits have listed the minimum requirement of the tetraterms for the air temperature from June to September for a number of species (see Table 1). It should be noted that the seven most summer cool tolerant species are among the species which also grow in or near the alpine or Arctic timberline in the Euro-Asiatic continent. Forestry trials have also shown ecotypic variation within species in summer heat demand for growth (Dietrichson 1964a, 1964b). In areas where summer heat is a limiting factor for growth, a climate change will

Table 1. The minimum tetraterm from June to September for some important broadleaves in northern Europe compared to Norway spruce and Scots pine temperatures from Helland (1912), except for silver birch revised later.

Beech (*Fagus silvatica L.*)	13.4 ° C
Summer oak (*Quercus robur* L.)	12.6
Hazel (*Corylus avellana* L.)	12.5
Small leaved lime (*Tilia cordata* Mill.)	12.5
Norway maple (*Acer platanoides* L.)	12.5
Black alder (*Alnus glutinosa* L. Gaertn.)	12.4
Ash (*Fraxinus excelsior* L. Esche.)	12.4
Wych elm (*Ulmus glabra* Huds.)	11.2
Silver birch (*Betula pendula* Roth.)	10.1
Rowan (*Sorbus aucuparia* L.)	7.,7
Grey alder (*Alnus incana* (L.) Moench)	7.7
Goat willow (*Salix caprea* L.)	7.6
Aspen (*Populus tremula* L.)	7.6
Downy birch (*Betula pubescens* Ehrh)	7.5
Norway spruce (*Picea abies* (L.) Karst.)	8.4
Scots pine (*Pinus sylvestris* L.)	8.4

likely be more positive than negative. Recently, studies which reanalysed the growth performance of different provenances from several old Finnish provenance trials with Norway spruce and Scots pine were completed. There was an increase in wood production when trees, originating in the northernmost sampling areas, were transferred southward to an improved temperature climate with an annual mean effective temperature sum close to that which is expected in northern areas as a result of the projected climate change (Beuker 1994).

The long term result of improved summer climate will be a northern and altitudinal expansion of many of the broadleaves. This is in agreement with the historical evidence from 2500- 6000 years ago when the climate in north-western Europe was nearly as warm as the projected climate change.

Autumn climate

Shorter days in the early autumn halt shoot elongation in most species. A hardening process begins in the autumn, which is completed in the winter rest. Trees in deep winter dormancy will normally be very frost resistant. The most practical knowledge about the hardening process has come from provenance trials. Due to photoperiodism, sources moved northwards normally cease shoot elongation later in the early autumn than the more northerly ones. If the weather becomes cool after the end of the shoot-growth, the hardening processes that end in deep dormancy may be affected differently. Under cool autumn conditions, warm-tolerant provenances (ecotypes) are not able to complete their growth processes properly. This often leads to frost damage in the autumn or the following winter. If the damage occurs when the trees are in active growth, the injury manifests itself by damage to the xylem through cavitation of the vessels and tracheids in the sapwood. In conifers frost damage to the cambium results in the formation of frost rings. Under northern Arctic conditions, or near the alpine timberline, the frost ring formation in Norway spruce is also extremely high during the growing season (Dietrichson 1964 a).

In the case of a climate change it is expected that summer and autumn temperatures will increase, as well as the length of the growing season above temperatures of 5° C or 6° C. This will result in an improvement of the over-wintering capability, except in cases where severe droughts during summer delay the hardening process. In late winter 1977, and after a very dry summer in 1976, many Norway spruce trees of European continental origin planted in south-east Norway were damaged by late winter frosts, while the Norwegian controls were nearly unaffected. The summer drought of 1976 followed by an unusually cool October was considered to be the primary reason for the damage occurring the following winter. The cold hardiness level of the more southerly spruces was insufficient when compared to the native controls (see Dietrichson & Skrøppa 1977, Horntvedt and Venn 1980, Skrøppa and Dietrichson 1986).

Winter climate

Northern trees require a winter rest, and there is a chilling requirement to be fulfilled before efficient response to warm winter or spring weather can occur. Rest break is defined as the time in the winter when the chilling is almost complete, and the trees can respond efficiently to heat first by dehardening, and finally, by budburst in spring. Chilling has been investigated in several studies. It is clear that chilling is a gradual process, and that the most efficient chilling temperature is not known for the different species. Furthermore, it is rather difficult to determine the rest break accurately. In some studies the chillingtemperatures have been determined to be greater than the threshold temperature, above which growth processes are initiated in trees. If "such chilling" lasts for a sufficiently long time, it can lead to budburst (Murray et al. 1989, Skuterud & Dietrichson 1994). In the literature there is much confusion regarding the chilling demand and the heat demand to reach budburst.

Auclair et al. (1992a) evaluated several forest dieback episodes in the US and Canada in this century. It is evident from those studies that meteorological events such as rapid and longlasting thaws, often in February and March, are related to several of the diebacks in many of the broadleaves. According to these authors, such thaws led to sap ascent, rehydration, and partial dehardening of tissues, which, when followed by freezing events in early and mid-March, have damaged tissues such as the cambial and conductive systems. On the basis of an extensive review of American and Canadian literature, Braathe (1957, 1995) has reached the conclusion that warm late winter and spring weather followed by spring frosts in May must have caused the birch dieback in yellow birch (*Betula alleghaniensis* Brit.) and paper birch (*Betula papyrifera* Marsh.) affecting 490 000 km^2 in the eastern US and Canada and in the early 1950s. Braathe has ex-perimentally induced injury at -5° C and colder in mid May, and has demonstrated damage to yellow birch. He hypothesised that the same kind of injury also might reduce the root systems and render the trees susceptible to injury (Figure 1).

Norway spruce is a continental species widely planted outside its native range westward in Europe, and in warmer winter environments. Occasionally, after very warm winters, Norway spruce is subject to mortality (Murray 1957, Schoenfeld 1973, Ravensbeck 1991). Auclair (1992b) made an evaluation of the climate at Lahr, Germany, and reached the conclusion that droughts in the summer of 1976, as well as thaw-freeze events in the preceding winter 1975-76, were of sufficient severity to cause sapwood cavitation injury in oak trees. In southern Sweden most likely the same type of oak decline was observed in the years from 1987 until 1990 (Barklund 1991). Auclair (1992b) also hypothesised that severe thawfreeze events, followed by droughts, were the likely cause for the decline in Norway spruce as well as other conifers in central Europe.

Dietrichson (1993) reported Norwegian experiments with detached shoots of Norway spruce from 50 different full sibling progeny within and between different provenances, after three years with good summer and autumn conditions. The shoots were sampled from January to March and kept in growth chambers at different temperature regimes before freeze testing. The thaw conditions in the growth chambers at 9°C and 12°C dehardened the shoots and made them susceptible to freeze damage at -13°C to -16°C. in March. As the freezing temperatures were lowered, the damage increased. A similar effect occurred with increasing the period of thaw conditions. The genetic variation in freeze damage susceptibility was high, and was strongly and positively correlated with the se-quence of the budburst of the ortets in the field trials the following spring. White-Russian Norway spruce trees, known for late budburst in the spring (Langlet 1960, Krutzsch 1975), were the most resistant to thaw/freeze conditions in the winter. Early budbursting Scandinavian families were the most susceptible. According to these studies, winter climate and its effect upon subsequent dehardening and bud-burst seems very important. This is also evident from phenological studies of broadleaves. A little- known study should be mentioned. During nearly 200 years of an observation series, from 1751 to 1947 in Great Britain, the budburst of ash and summer oak varied as much as 63 and 54 days, respectively (Williams 1953). Several researchers, working with different species, have studied both the genetic and environmental components of budburst phenology (Nienstaedt and King 1969, Campbell and Sugano 1975, Campbell 1978, Cannell and Smith 1983, Cannell 1984, Murray et al. 1989, Heide 1993). Differences in budburst between years within the same species must be explained as an effect of the winter and spring climate.

As a result of climate change, the frequency of thaw/freeze conditions in the winter might increase. After a sufficient chilling period, towards spring, trees of northern species respond to increased warmth by budburst according to the formula :

$$\text{Heat sum} = \Sigma\,(T - b)$$

T = The daily mean temperature *
b = The threshold temperature of the plant material

In the formula b is the threshold tempera-

**Meteorological stations measure air temperature. Due to radiation the temperature in plant tissues can, during sunshine, be much higher than the air temperature.*

ture, defined as the lower limit for the temperature at which growth or other life processes take place in a tree (Arnold 1959). If the trees are kept experimentally in different temperature climates, and one assumes that, within certain limits, they respond linearly to temperature by budburst, the threshold for a group of trees can be calculated by solving the equation as follows:

$$n_1 (T_1 - b) = n_2 (T_2 - b)$$

In this formula n_1 is the number of days one fraction of the material is kept at temperature T_1, and n_2 is the number of days the other fraction of the same material is kept at temperature T_2.

Forest trees have different threshold values in their response to temperature, as is evident from the trials and experiments of Sarvas (1972), Worrall (1983, 1993), Skuterud and Dietrichson (1994), Skulason (1994). Aspen in southern Finland has a threshold value of -1° C, silver birch from southern Norway and southern Finland -2°- 0°C. Conifers such as sub-alpine larch (*Larix lyallii* Parl.), amabilis fir (*Abies amabilis* Forbes), subalpine fir (*Abies lasiocarpa* Nutt.) and Norway spruce have thresholds from 1.5° to 5.7°C. The thresholds also seem to be dependent on the provenance. Evidently, high altitude alpine provenances have lower thresholds than the lowland southern ones. The consequence of lower thresholds is that the number of days to reach a certain heat sum will be reduced (Figure 2). Since response to temperature is not necessarily linear and, in addition, the total heat sum requirement for a certain growth stage will also vary, differences in threshold values cannot alone explain why trees react to winter and spring temperatures as they do. Obviously much more knowledge about the effect of heat on different tree species during the annual cycle is needed.

Conclusions

Based on old provenance trials with Norway spruce and Scots pine in Finland, where heat often is at a minimum, increased summer temperatures increase wood production for trees moved southwards. Though old provenance trials have not been performed with several of the broadleaves, the same results would be expected. In addition, warmer autumns will increase the length of the growing season and give the trees a possible enhanced dormancy and a higher winter frost resistance. The most serious threat might come in the transition between the hemiboreal and nemoral vegetation zone and southwards. In cases where the winter weather becomes very warm after chilling, the cool-demanding trees will respond by faster dehardening than the warm-demanding ones, and become more easily subject to late winter and early spring frost damage. In decidous trees damage to the cambium is a serious problem which can lead to sudden death of branches or whole trees. In many cases it must then be considered to be a parallel to the high frequencies of damage observed on Norway spruce in Denmark in years when the winter climate has fluctuated between cold and rather warm periods. More studies of genecology to identify warm- and cool-demanding broadleaved trees are obviously needed.

Acknowledgement

I thank Dr. Bill Mason, Forestry Commission, Northern Research Station, Roslin, Midlothian, Scotland and Dr. Geor-

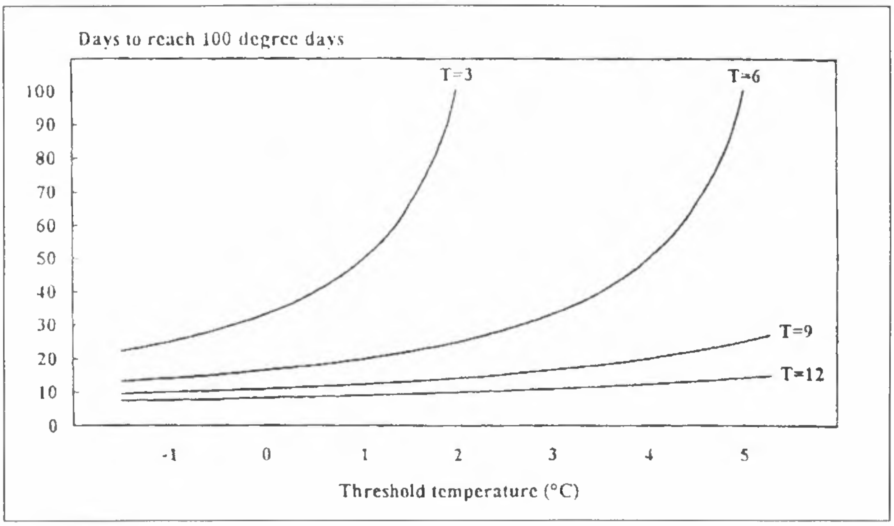

Figure 2. The number of days required by different growth temperatures (T) to reach 100 degree days by different thresholds from - 1 to +5°C. Calculations made on the basis of the formula in the text.

gia Hammond, Ås, Norway, for the corrections of the English manuscript.

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