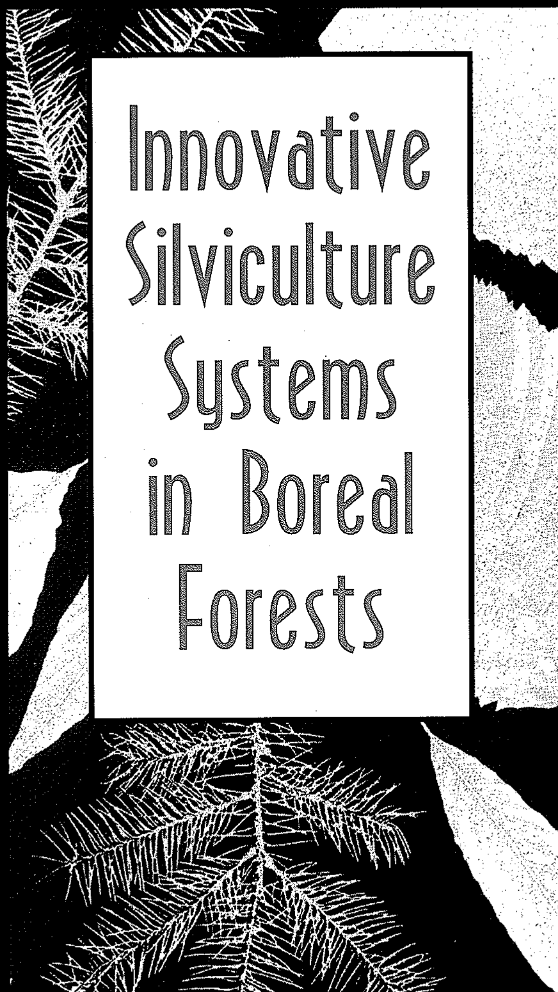
Innovative Silviculture Systems in Boreal Forests



Proceedings:

Innovative Silviculture Systems in Boreal Forests

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edited by Colin R. Bamsey

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Introduction

The long term viability and sustainability of forest management are, in part, influenced by the decisions made when choosing the most appropriate silvicultural system to use in any particular forest. This symposium proceedings presents the findings of current research studies and deals with the application of new or innovative silvicultural systems used in the management of Boreal forests throughout the northern hemisphere. We hope that the information contained here will provide the forest land manager with a fresh outlook, as well as some specific ideas that will help him or her make effective silvicultural choices.

The symposium was particularly effective at generating frank discussion on the current trends, the causes of change, and what new methods are showing promise. Topics covered in the presentations include biodiversity, harvesting and silviculture technology, wildlife interactions, decision support systems, ecology of species and overviews of current trends in Canada, the United States, Europe and Asia.

All papers presented here received peer review by two or three other authors familiar with the subject area. For the most part, peer review comments and changes were incorporated by the editor and accepted by the author, therefore some differences may be noted from the papers presented at the symposium. Some of the papers included were written by scientists whose first language is other than English. The editor has worked with these authors to standardize the terminology for North America, however, there may still be a few areas for which the meaning has been lost. The reader is asked to contact authors directly to discuss specific points that are not clear.

This proceedings book will be a useful reference for all who attended the symposium, and will be of interest to any individual concerned with forest management and forest-related activities in northern forests.

— Colin R. Bamsey

The views, conclusions and recommendations in the proceedings are those of the authors.

Acknowlegments

The symposium papers presented here resulted from hard work and dedication of the authors. We are grateful to them not simply for their own paper, but also for their review of other papers. Dr. Stan Navratil and his assistants provided initial coordination of the peer review and production contract for the proceedings. Colin Bamsey, editor, was assisted by Chris Hammond-Thrasher and Steve Fahnestalk.

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Silvicultural Systems in the Nordic Countries

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Finland, Norway and Sweden are characterized by small privately owned forest holdings, averaging only 60 hectares. The forests were over-exploited during the decades around the turn of the last century. Poor regeneration brought the prevalent partial cutting systems into discredit.

After the Second World War, the call for more efficiency and the development of new technology simplified forest operations. Clearcutting dominated, particularly on the larger estates. The regeneration of spruce, Picea abies, *was often established by planting; while pine,* Pinus sylvestris, *was regenerated by natural seeding with seed trees.*

The forest acts in the three countries in this period were focused on wood production. Today, revised forestry acts and regulations emphasize multiple use forestry and biodiversity. A larger variety of silvicultural systems, from clearcutting to selection cutting, will probably be practical in the future. Among forest owners and professionals on all levels there exists an increasing interest in ecologically-based silvicultural systems. Several research projects are now focused on multiple use forestry, biodiversity and silvicultural adaptation within sustainable utilization of the renewable resources.

Boreal forests dominate in Finland, Norway and Sweden. A narrow zone along the southern coast of Finland and Norway belongs to the boreonemoral region. In south Sweden a larger part of the country has boreonemoral or nemoral vegetation types. Denmark belongs exclusively to the nemoral region. Iceland is not relevant in this connection.

Statistical Information

Land Use

The area of forest, agricultural land, mountains and lakes etc. within the Nordic countries are presented in Table 1. The figures are calculated from The Finnish Forest Research Institute (1993), Norwegian Institute of Land Inventory (1993), and Skogsstyrelsen (1994 a).

The two important conifers are spruce, *Picea abies*, and pine, *Pinus sylvestris*. Birch species, *Betula pendula* and *B. pubescens* dominate among the deciduous trees.

Topography

Finland has a relatively flat or undulating topography with 2/3 of the land area below 200 m a.s.l. Except for the southeastern part, Norway has a much rougher surface with narrow valleys, steep mountain sides, and half of the total land area above the tree line. Sweden's topography is between that of Finland and Norway.

The timberline in the central south of Norway is at about 900 m a.s.l., and at sea level in the far north. The latitude of the three Nordic countries ranges from 55.5°(Sweden) to 71°(Norway).

Ownership, Property Relations

To understand forest conditions and forest management in the Nordic countries, some knowledge of land ownership is necessary. The figures in Table 2 are calculated from Strand (1962), The Finnish Forest Research Institute (1993) and Skogsstyrelsen (1994 a).

The statistics on sizes of forest area of the different owner categories are not complete, but the figures below give some information of average property size in hectares for the three countries:

Finland private	Norway total	Sweden total
25	50	90

Table 1. Groups of land use; area in 1,000 km² and percent.

	Finland area	Finland %	Norway area	Norway %	Sweden area	Sweden %
Productive forest area	201	59	65	20	232	48
Unproductive forest area	61	18	55*	17	57	12
Agricultural area	31	9	9	3	31	6
Mountains, lakes, etc.	44	13	191	60	167	34
Total	337	100	320	100	487	100

*Ministry of Agriculture, unpublished.

Table 2. Land ownership in percent of productive forests.

	Finland	Norway	Sweden
State	24	8	18
Companies	9	8	24
Municipalities	4	9	8
Private	63	75	50
Total	100	100	100

Table 3. Size of forest holdings in Norway and Sweden.

Size groups (ha)	Summarized percents	
	Norway	Sweden
< 50	25	14
0 – 200	50	36
0 – 400	60	44
0 – 5,000	85	
Total	100	100

The size of forest holdings is calculated from Strand (1962) and Skogsstyrelsen (1994 a) (see Table 3).

The northern part of Sweden is dominated by large forest holdings, mostly owned by companies and the state. Otherwise the Nordic countries are characterized by small holdings owned by private persons, often in connection with small farms. Thus, for the most part, the silviculture practiced in the Nordic countries is small-scale compared to other parts of the boreal zone.

Historic View

Ever since the Nordic countries were first settled, some type of multiple-use forestry management has been in use. Trees provided the material for building, for fire-wood, etc., and the forest itself furnished man with wildlife, berries, and later, land for livestock grazing and slash and burn agriculture. The importance of these factors has varied throughout the centuries depending on technological and economical conditions. Mining, tar-boiling, production of charcoal and trading with trees, either as roundwood or as sawed material, had, in many places, a tremendous impact on the forests. There was often overexploitation without thought of regeneration. In many places the result was a forest with sparse tree cover that regenerated poorly (Braathe 1980).

Around the turn of the century, the governments of Nordic countries made attempts to halt this devastation. However, the dominant cutting system continued to be, for many years, cutting of the larger trees or some other kind of selective cutting. Later on, forest regulations reduced the extent of these highly detrimental cutting systems which removed only the best trees.

The devastated forests had to be improved. The important question 60 – 70 years ago was *how?* Some professionals suggested that the sparse coniferous forests, particularly spruce, should be regenerated in a closed system utilizing, for example, shelterwood systems, group systems or selection systems. Others felt that clearcutting was the best way, since the raw humus which dominated the forest floor over large areas needed higher temperatures to decompose and enable regeneration (Braathe 1980). Yield studies had shown high production in stand-managed forests; i.e., clearcutting followed by establishment of even-aged stands (Eide and Langsæter 1941).

Generally, we can conclude that from about 1940 most of the larger holdings started to practice clearcutting of spruce forests followed by planting. In Sweden, this method was also tried in pine forests. Otherwise, the seed tree system and natural regeneration was used for pine. Among the owners with smaller forest holdings, the typical farm forests, the conservatism was stronger, and the influence by the professionals weaker. However, the governments encouraged and provided economic support for planting.

The rapid development of wood processing industries in the beginning of this century created a market for small tree dimensions. Thus, low-thinning became a normal stand treatment, particularly on the larger forest holdings.

Forestry and the forest industry have for centuries been of great value in the Nordic countries. Increasing costs of manual labour, calling for more efficiency and rapid technological development changed the logging operations and further favoured clearcutting. Thus, many factors supported the movement from individual tree treatment towards clearcutting followed by planting. This has been very successful. The forests in the Nordic countries contain nearly 50% more wood today than the degraded forests 70 years ago (Kuusela 1990, Norwegian Institute of Land Inventory 1993). The total increment today is about 190 million m^3 per year. About 2/3 of this volume is cut annually.

Among most foresters, professionals and others, most emphasis was put on production of commercial timber, particularly spruce and pine. The broad-leaved trees which invaded the areas after clearcutting were often removed. With reference to high wood production and profitability we have some examples from the 1950s to the 1980s that the size of a clearcutting area could exceed several hundred hectares. This of course could only take place in special large forest holdings, usually in remote areas owned by the state or companies.

No scientific studies proved that such sizes of clearcuts were favourable, but some reports were misunderstood. Generalization and simplification were at their highest level in those years. Generally speaking, the trend in silvicultural systems in this period followed the trend in the rest of the society; i.e. rationalization and functionalism.

Forest Legislation

The Forestry Acts in the three Nordic countries have been revised several times during this century. In the period between the two World Wars, in Norway the emphasis was on forest protection, while forest production became the dominant element in the rebuilding period in the first two decades after 1945.

The improved economic and material well-being of the population led to more leisure time. Better transportation, both collective and private, increased the physical possibilities for getting out into the forest and into nature in general. Lack of communications between the majority of the population and the primary industries, political trends with less confidence in the idols of pure technology and short-term economic profit, and an increasing understanding of the long-term ecological relationships, all contributed toward forcing the authorities and politicians to revise the Forestry Act.

The purpose of the Forestry Act in Norway from 1965 (Lov om skogbruk og skogvern 1993) with amendment in 1976 is stated as:

> *The purpose of this Act is to promote forest production, afforestation and forest protection. The aim shall be by means of rational tending to achieve satisfactory results for those engaged in forestry and ensure an efficient and regular supply of raw materials for industry. Emphasis shall also be given to the importance of forests as a source of recreation for the public, a major element of the natural scene, a living environment for plants and animals, and as hunting and fishing areas.*

The Forestry Act in Norway has always given the private forest owners freedom under responsibility. They have the right to choose silvicultural systems according to their situation. In Sweden, however, the forest regulations up to 1993 described methods the forest owners had to practice. The goal was to achieve a high volume production in even-aged stands.

The new Forestry Act in Sweden from 1993 (Skogsstyrelsen 1994 b) creates a completely new attitude, with two equal objectives.

> *Environmental Objectives*
>
> *The natural production potential of the forest soil shall be preserved. Biological diversity and genetic variation shall be secured. The forest should be managed in such a way that the flora and fauna which naturally belong to the forest are able to survive under natural conditions and in vigorous populations. Threatened species and habitats shall be protected. The cultural activities in the forest and their aesthetic and social values shall be preserved for the future* (Author's translation).

> *Wood Production Objective*
>
> *The forest and forest land shall be exploited effectively and carefully to give a sustainable high yield. Forestry management shall aim at a production according to variation in environmental conditions* (Author's translation).

In 1993, Finland adopted a New Forestry Environmental Program, which focuses on biodiversity-oriented silviculture and is similar to legislation in Sweden and Norway.

Present Trends in Silvicultural Practice

All types of forestry personnel are today encouraged to take courses to learn multiple-use forestry. This concerns the worker with the chainsaw, the person on the harvester, the forest ranger, the district forest officer, the forest farmer, etc. Several textbooks and booklets have been produced for this purpose (Skogsstyrelsen 1992, Finnish Forest and Park Service 1994, and others).

In the last 10 – 15 years forest research institutions have been more concerned about silvicultural alternatives than previously (Institutionen för skogsskötsel 1992). Both research and experience have indicated that there are both biological and economical reasons for considering other silvicultural systems besides clearcutting. In some places stands still have relatively low density and uneven structure both in height and diameter (Nilsen and Haveraaen 1982). Cutting the most mature trees; i.e., high thinning, and allowing the more vigorous to grow for some additional decades is an alternative to clearcutting (Lundqvist 1989, Andreassen 1994). If recruitment of the younger trees is satisfactory, such high thinnings can follow each other continuously (Nilsen 1988). Where clumps of trees are of even structure, and the trees are old and mature, small gaps or clearcuts up to a few tenths of a hectare can be applied. Research has been initiated to study supplementary planting and natural regeneration in such gaps. The above mentioned cutting system is referred to as the mountain forest selection system and deserves consideration where the forest structure is variable, where the site productivity is too low for investment in complete artificial regeneration, and on localities where regular clearcuts are prohibited. New harvesting technology seems to favour this method in a way which would not have been possible some years ago (Dale, Kjøstelsen and Aamodt 1993).

Although most of the classic silvicultural systems for spruce are now with us again, some are still on a very small scale, such as the shelterwood system, the group system, the edge coupe and the systems related to the selection system.

Most of these cutting systems require a high stability of stands, which today is not satisfactorily fulfilled in spruce forests. Many old stands are unthinned and dense with small tree crowns indicating weak root systems (Nielsen 1990). In addition, spruce on fine textured soils or soils with high water tables develops shallow root systems and is thus exposed to windfall after most cuttings. Early and regular thinnings, and selections of suitable sites, are prerequisites for successful results, particularly with the use of the shelterwood system. Regular stripcutting has also been practiced on a small scale, but is no longer in use, mostly for aesthetic reasons.

On fertile soils, clearcutting leads to development of aggressive ground vegetation making natural regeneration of spruce very risky. Even under shelterwood conditions the weeds are troublesome (Larsson, Kielland-Lund and Søgnen 1994). Planting of spruce is therefore the common regeneration method. The costs of planting with the necessary vegetation management are rising. There is now a trend both ecologically and economically to accept a mixture of spruce and broad-leaved trees on the better sites, and pure stands of broad-leaved trees, which often regenerate well naturally.

Clearcutting for spruce followed by planting, and the seed tree method for natural regeneration of pine are still the dominant systems, and probably will be in the years to come. However, when more serious consideration is given to the ecological variation in our forests, the multiple use aspects, the demand from the public and the buyers of forest products for more emphasis on biodiversity, the extent and sizes of the clearcuts will be reduced and different tending and cutting systems will be practiced.

Since the official forest policy today (Norges offentlige utredninger 1989, Skogsstyrelsen 1994 b, Finnish Forest and Park Service 1994) strongly emphasize the factors mentioned above, changes will come and are already occurring. However, 500,000 km^2 of productive forest area owned by 800,000 decision-makers prevents rapid changes, and many do not need to change their cutting systems drastically. It is generally on the larger forest estates where changes must come and are already in progress.

Mistakes have been made in the past and will be made in the future. Some of the mistakes are visible for the public for many decades, others may only be discovered by specialists. The goal of the forest politics today is to maintain and develop biodiversity and sustainable productivity within the frame of sound resource management.

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Silviculture Systems in Canada's Boreal Forest

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The historical development of silviculture in the boreal forest is reviewed and examples of silvicultural innovation are listed for Canada and Sweden. Changing paradigms, the conditions for innovation, the clearcutting issue, and economics are considered as factors influencing boreal silviculture practice. Great advances have been made in sorting out boreal forest variation in site classification systems which provide one essential framework for innovation.

It is concluded that silviculture manuals and practice codes are not appropriate, but rather silviculture prescriptions prepared by qualified professional foresters are needed. Such prescriptions should design and plan stand development to meet objectives based on analysis and diagnosis at the stand and forest levels. Rapid staff turnover, lack of long term experimental trials on forests and poor feedback on success and failures are current problems.

Five options are presented to address the problem of stand response prediction in slow growing stands: substitution of space for time in retrospective studies; use of computer predictions; keeping foresters in one forest for 20 to 40 years; establishment of long-term experimental forests; and requiring foresters to commit to continuing education.

Introduction

Canada's boreal forest extends across the northern part of the country from Newfoundland to British Columbia. It covers approximately 200 million ha and constitutes about 18 percent of the world's boreal forest. Globally, the boreal forest also occurs in Scandinavia, Siberia, and Alaska, with the majority (74 percent) occurring in Scandinavia.

Historical silviculture practices have not realized the increased fibre production potential in the boreal forest. Innovative silviculture has the potential to substantially increase production in the boreal forest.

The boreal forest is here defined as the forest occurring in the northern latitudes and consisting mainly of spruce, aspen, balsam fir, poplar, and Jack pine stands. For the purposes of this paper the Sub-boreal Spruce, Boreal Black and White Spruce and Engelmann Spruce-Subalpine Fir zones of British Columbia are included in the boreal forest since their ecology and silviculture are similar.

The purposes of this paper are to review the development of silviculture in the Canadian boreal forests, outline the factors that influence silviculture, and present options for innovative silviculture which take into account the slow dynamics of these forests.

Historical Overview

The history of harvesting the vast natural forests in Canada's boreal forest extends over 100 years, starting in the east and moving west. Probably the oldest documented and photographed harvesting took place in the gold-mining town of Barkerville in central British Columbia in the Engelmann Spruce- Subalpine Fir biogeoclimatic zone. A whole valley was clearcut in the early 1860s to rebuild the town which burned. Today the second growth naturally-regenerated forest is still not operable after 135 years, but the spaced naturally-regenerated trees in the graveyard, growing out of and around the tended graves, have been operable for some decades. This is probably Canada's oldest clearcutting example of the beneficial effects of stand tending in boreal forests (Vankka 1982).

A clear pattern is apparent in the historical development of harvesting methods in the boreal forest. Initially, with reliance on river drives, winter sleigh use and horse skidding, the objective was to remove sawlog material by high-grading. There were often variable amounts of advance growth, since most boreal conifer stands were old and often undergoing break-up. These early cuts were often a crude, one-step shelterwood removal. In older black spruce and balsam fir types, there was usually enough advance growth to ensure adequate stand basal area and subsequent good second-growth stands. Where the original stand was red spruce/balsam fir in Quebec and the Canadian maritime provinces, the result was loss of old-growth red spruce and stand conversion to balsam fir, thus making the forest more susceptible to spruce budworm. Most of the red spruce was gone by the 1920s and with it the red spruce sawmill industry. When the massive budworm epidemics came in the 1940s and 1950s and again in the 1970s and 1980s in the forty-year-old plus pure balsam fir stands, harvesting was driven by salvage and large clearcuts were required. Vast aerial spraying programs over 35 years helped keep the old stands alive with little growth until they could be clearcut.

Where spraying was not done, very large clearcuts were required to salvage stands in the 3- to 4-year window after the death of the stands and before the trees were lost to decay. The clearcuts in the Cape Breton Highlands of Nova Scotia in the 1970s and 1980s are a classic example. Similarly, the 48,000 ha Bowron clearcut of the 1970s near Prince George, British Columbia resulted from salvage after spruce beetle attack.

The sheer massive scale of budworm epidemics, with vast moth flights dropping on forests resulting in 100% mortality, meant high risk of loss of forests resulting in the need to remove older age classes quickly — a massive, discouraging situation for any partial cutting system in balsam fir forests. In spite of the reality of this risk of loss, various attempts at true selection have been made in eastern spruce-fir forests, particularly in woodlot situations, but budworm protection is needed.

Red spruce is more budworm resistant than balsam fir and can accumulate on the landscape over several budworm epidemics. This is the reason the red spruce old growth was there. Selection systems, or even shelterwood, which favours this species, hold the promise of budworm resistance for the stands.

The other treatment option in budworm prone stands was to plant black spruce which flushes late and thus misses much budworm instar feeding. In the last 40 years, the Irving Organization in New Brunswick clearcut large areas and crushed the slash with LeTourneau tree crushers. Black spruce was planted and repeatedly herbicided, creating the largest and most successful spruce plantations in Canada. The early plantations are now being thinned commercially.

Most woodlots and even large private ownerships in Eastern Canada, in the absence of any regulation even today, have been repeatedly high-graded. The stands regenerate, but accumulate low value and low quality species and stems. The short-term thinking of small owners, the tax system, and lack of regulation all conspire to make any discussion of applying innovative silviculture systems on small ownerships very academic. High-grading is also the most common practice on private lands in Alberta and British Columbia. Unfortunately, recent opposition to clearcutting has favoured partial cuts which are often, in reality, old fashioned high-grading with "ecological approval."

The high-grading of white pine which had accumulated over centuries in the eastern Canadian boreal forest led to very poor pine regeneration in mixed stands and the collapse of the pine sawmill industry. Today it is very difficult to regenerate white pine on till soils because of competing vegetation. Attempts at using shelterwood systems have had limited success, and radical herbicide treatments may be required (Corbett 1994, Brown 1994).

In pure mature black spruce types the early emphasis was on advance growth protection in hand felling and horse skidding during winter logging on snow. When the pulp industry switched from sawlog to shortwood systems in the 1920s, older stands regenerated reasonably well. In the late 1940s and again in the 1950s, major surveys of regeneration showed that a large portion was from advance growth (Candy 1951, Hosie 1953).

In the 1960s, the invention of the rubber-tired skidder, a massive conversion to truck hauling, use of tree length operations, and a shift to operating in snow-free seasons resulted in a change in the regeneration picture in the eastern pulpwood economy. Advance growth was destroyed and site deterioration due to machinery activity escalated. Much concern was expressed and studies started (Frisque, Weetman and Clemmer 1978). In addition, as always, with no markets for aspen, balsam poplar or poplar, these hardwood species were left on cutovers. For spruce/mixedwood sites the result was Canada's biggest silviculture problem in the boreal forest: the large-scale conversion to relatively pure poplar stands. All the large scale attempts to reverse the conversion by planting spruce and using the herbicide Round-up (much-hailed for its efficiency against poplar) have not been successful. Now with markets developing for poplar, the many cutovers classified as not sufficiently restocked (NSR) for conifers can be reclassified as sufficiently restocked (SR) for poplars and grown in inventory on poplar yield curves. Re-examination of older cut blocks from the shortwood pulpwood logging of the 1930s to 1950s, judged against current concerns for species and structural biodiversity, suggests that conifer yield sacrifices may be offset by some desirable ecological attributes.

A study of the history of spruce planting in boreal mixedwood is not encouraging. One committee and two recent symposia have assessed the problem (Weingartner and Basham 1979, Samoil 1988, Shortreid 1991). The recent excellent review of poplar by Peterson and Peterson (1992) clearly outlines the problems and options.

After concern developed over rubber-tired skidders by the 1980s, harvesting systems switched yet again to year-round full-time logging with feller-bunchers and forwarders, and tree length trucking became standard practice. More stands were cut which were younger and often lacked advance growth. There was more rutting and site damage and concerns were expressed over nutrient export in full-tree logging. This, in time, led to more studies and again re-focused attention on the need to protect advance growth. Both Ontario and Quebec now have some strict regulations about how these machines are used. The nutrient export problem may be resolved by the current trend toward harvesters which debranch at the stump. Single-grip harvesters, which have changed commercial thinning in Scandinavia, are today creating new economic opportunities for commercial thinning and also for other types of partial cut systems, e.g., two-stage shelterwood removal in streamside reserves.

In Jack pine stands across Canada, early winter logging did not create adequate seedbeds. This was resolved in the 1960s by the development of chains, anchors and, eventually, import of Scandinavian scarification equipment, usually trenchers, which adequately exposed the requisite mineral soil.

Effective mechanical seedbed creation on Jack pine and black spruce cutovers led to some large-scale aerial seeding in both eastern and western Canada where large quantities of relatively cheap tree seed were available. Helicopter and snowmobile application technology, and the application of seed on snow, is now well developed (Hagner 1990). British Columbia has never used any of these direct seeding techniques.

Objectives of Silviculture

The primary objectives of silviculture in the boreal forest up to the 1980s were:

1. Effective and low cost mechanical removal of the relatively low value mature and over mature conifers; and
2. Achievement of government-set regeneration standards for conifers as quickly and cheaply as possible.

Often under "oldest first" harvesting rules, boreal silviculturists have been faced with the classic problem of geriatric silviculture: What can be done with high risk old natural forests near the end of their life cycle, and with little money available?

By the late 1980s, new concerns and paradigms about boreal silviculture practice were emerging (Table 1). The objectives of silviculture were expanded to recognize concerns for sustainability, adaptive ecosystem management, biodiversity conservation, mounting opposition to clearcutting, the wish for more natural regeneration, less use of herbicides, and the need for ecolabelling and certification. Achievement of these changing objectives was further complicated by the continued evolution of

Table 1. The Development of Canadian Crown Land Silviculture

Date	Problem Silviculture	Policy	Application Strategic	Tactical	Research
1910-1930	Inventory of forest cover type	Seedling and planting trials	"Get the wood out"	Forest inventory	Silviculture as logging
1931-1970	Unknown silvics of species	Unassisted natural regeneration	Replace old growth by vigorous young stands	Regeneration surveys	- stand development - plantation trials
1950-1970	Inadequate regeneration following unregulated logging	Assisted natural regeneration	Cut modification	Scarification, large scale planting	Silviculture as regeneration: - stocking standards - ecology based regeneration prescriptions
1971-1978	"NSR" plus accumulating "backlog"	Expanded government planting	Site and stand specific prescriptions	Quality planting, site classification	Silviculture as - cutover response - forest tree improvement - site/species matching
1978-1988	Unknown falldown and ACE benefits and risks	All site "basic silvi." by industry plus optional tending	Designing crop planning	Biological and economic efficiency of regeneration and tending	Silviculture as biological basis for sustained yield: - managed yield curves - efficiency of technique - risk assessment
1988-present	Reduce clear-cutting; biodiversity and old growth conservation	Basic silviculture based on natural precedents, limited intensive silviculture	Cut modification and adaptive ecosystem management to achieve desired stand and landscape goals	Use natural regeneration and innovative silviculture systems	Silviculture as a substitute for natural disturbance: - stand structure biodiversity - silviculture systems trials - retrospective studies - geriatric silviculture

harvesting technology. Harvest schedules, block sizes, and patterns in time and space all underwent reappraisal. For some people the way to meet these objectives is seen in more partial cutting. For some it is seen as more true selection management. This has caused more studies, and in particular, retrospective studies of the long-term effects of the high-grading during the last 50 years (Weetman et al. 1990).

Meeting the changing objectives of the last decade has proven to be a challenge for silviculturists. It is extremely difficult to write a prescription which meets all of the objectives.

Prescriptions Used in Boreal Forests

In contrast to more southerly forests, the boreal forest is usually even-aged, nearly all originating from massive fires or insect attacks. The successional patterns after these disturbances are quite well understood. In addition, the provincial site classification frameworks allow information on silvicultural successes and failures to be portable across the landscape. The biological realities of old, even-aged boreal forests originating from massive disturbances often indicate that a form of clearcutting is the only feasible option. While clearcutting meets some of the objectives, it falls short of meeting others.

In British Columbia, where sawlog values have been, and are, higher than elsewhere, there was a very large (125,000 acre) attempt at so-called "selection" in the Sub-Boreal Spruce Zone in old interior spruce forests near Prince George in the 1960s (Glew 1963). The mills only took sawlogs and the resulting partial cuts to supply these mills were not true selection cuts. There is a successful example of true individual selection in the nearby Aleza Lake Experiment Forest (Coates and Jull 1993, De-long and Jull 1991).

When Pre-Harvest Silviculture Prescriptions (PHSPs) have been prepared by students in the Silviculture Institute of B.C. field modules in the Sub-Boreal Spruce Zone near Prince George, some imaginative and innovative silviculture prescriptions have emerged. These have been based on:

a) Careful diagnosis of the stand and site conditions.
b) Realistic evaluation of the stand values and harvesting costs, product values and multiple use objectives; and
c) Examination of local history and evidence of failures and successes.

Figure 1 shows further detail about factors to be considered in a silviculture prescription.

It was found that shelterwood cuts, even some true selection cuts, and certainly various modifications of both, are all feasible. Historically there has been little attempt to evaluate the silviculture prescription options. Usually clearcut/site preparation/plant or "leave for naturals" have tended to be the standard operating procedures. In British Columbia, with mandatory pre-harvest silvicultural prescriptions (PHSPs) signed by registered professional foresters (RPFs), there is a requirement under a new forest practice code to assess carefully the options to conventional clearcutting. Since PHSPs are open to public comment before implementation, there is even more incentive to write prescriptions which attempt to achieve a variety of silviculture objectives.

In Canadian forests, dominated by provincial ownership, political correctness in PHSP preparation can lead to inappropriate treatments receiving consideration. The current fashion in ecology and silviculture is to mimic natural processes, assuming that silviculture actions which closely parallel historic boreal forest fires, windthrow and insect attack have an inherent "goodness" or "naturalness" about them. Leaving snags, large organic debris and residual trees is the current trend. Partial cuts are back in favour, leading to partial cuts which appear to resemble closely "high grading," but have strong public and political support. This trend has led to retrospective studies of old high-graded stands from the horse logging era to try to understand the implications for future stand development and to attempt to calibrate the stand simulation computer models for partial cuts.

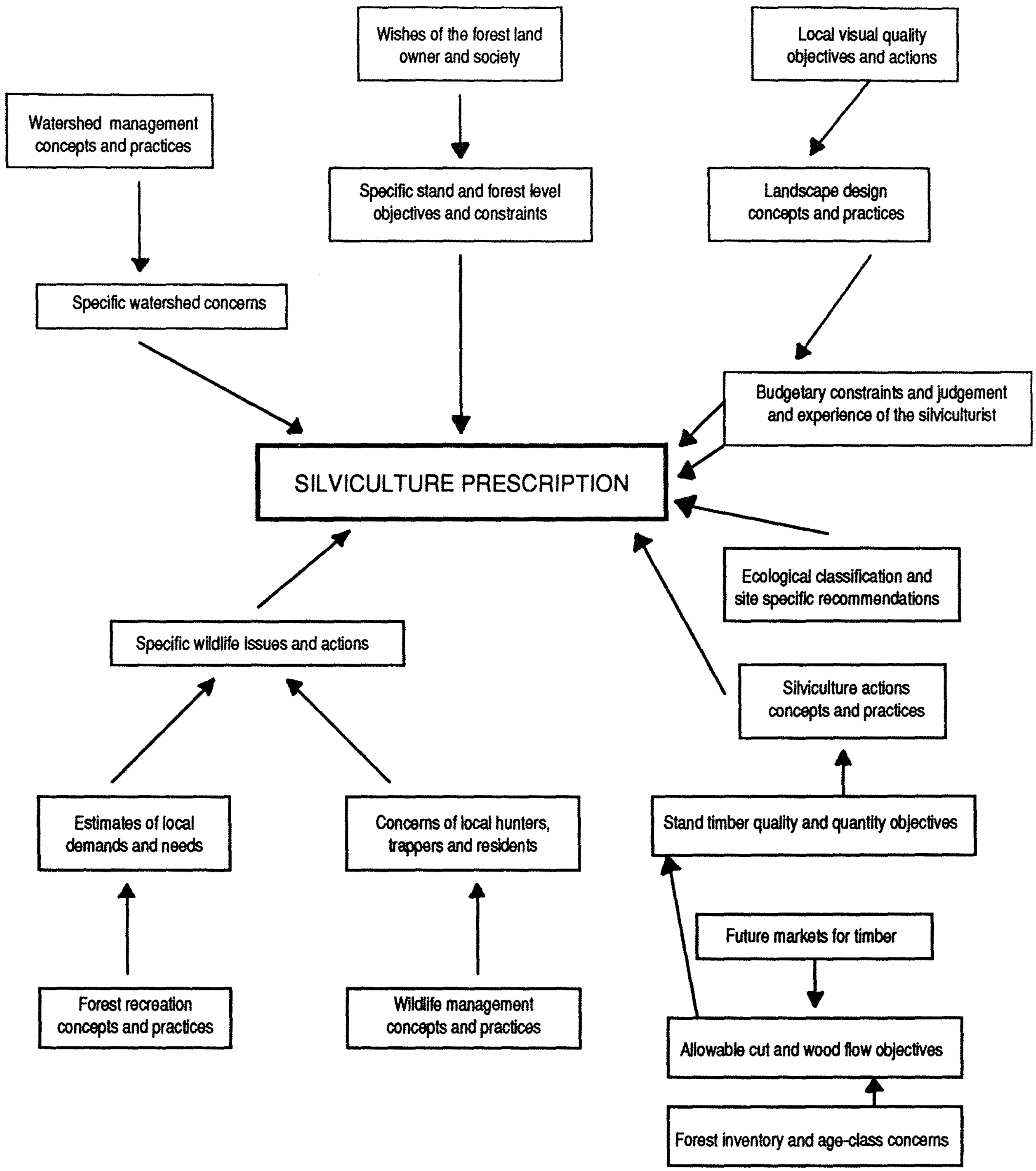
Conditions for Innovation

If innovation in boreal silviculture is to occur, then the following two important conditions must be met.

a) Prescriptions must be based on a process of diagnosis, not just pro-forma attempts. Professional field evaluations should be prepared by foresters who have passed advanced silviculture education modules, such as that offered by the Silvicultural Institute of B.C. There is an essential and large knowledge base that is needed to conduct these diagnoses and is best available through advanced education.
b) The silviculture prescription writer needs a professional background. Full design responsibility, authority and accountability should be accepted when prescriptions are signed. This accountability is best achieved at the professional, not technical, level. The Association of B.C. Professional Foresters has shown how good guidelines on the ethics of PHSP writing can be developed in workshop settings using hypothetical scenarios (Association of B.C. Professional Foresters 1993).

Over 20 years ago, Smith (1972) emphasized that there are many ways to practice silviculture. The problem of lack of innovation lies not in a lack of practices but in using standardized "manual" type thinking and in not having professional foresters prepare silviculture prescriptions. Recent moves in British Columbia to enforce the standardized approach through the Forest Practices Code or to allow technicians to write prescriptions both ignore the design requirement of silviculture treatments which require site specific appraisal by qualified professional foresters. The U.S. Forest Service long ago recognized the need for certification of silviculturist to provide for personnel

Figure 1. The interaction of areas associated with the silviculture prescription



to be both innovative and professional. The experience and popularity of advanced forestry education modules in British Columbia, Ontario and Alberta are an expression of the willingness of foresters to meet the challenges in silviculture today. Collectively, these new challenges are sometimes called "new perspective" forestry. The perspectives, even the paradigms, are certainly new, but the biological issues and challenges are not. They go back to the roots of silviculture practice in Europe (Weetman 1994).

The simulation of boreal stand development by computer has become valuable in forecasting stand dynamics. Because stand rotations are long, often greater than 100 year, and cutover dynamics are slow, computer simulation can be a substitute, of a sort, for decades of field experience and feedback. These simulations can be particularly valuable when interpreted by professional foresters. These substitutions are badly needed since the turnover of silviculturist and technicians in the field is far too fast. Assessment of innovative silviculture trials take a long time — often 20 to 50 years. Commitment, continuity of effort and feedback have been usually absent. Again and again, experimental forests and trials have been neglected.

Networks of experimental forests and standardized trials are invaluable, but inter-provincial cooperation in forestry is rare. The U.S. Forest Service has 84 long-term experimental forests and ranges (Buchanan 1993). I cannot think of any in Canada that have had real continuity of experimental effort in innovative silviculture. In my view, this is a very poor record for a forested nation. Notwithstanding this dearth of long-term experimental data, innovation is still possible in writing silvicultural prescriptions if simulations are considered.

Innovative prescriptions should take into account the history of treatments in Canada's boreal forest. Experience in these forests has shown them to be reasonably resilient, even following very clumsy attempts to harvest them. Almost all areas harvested in the last 100 years have regenerated naturally, except for large areas of heath conversion in Newfoundland. Traditionally the boreal forests have been, and to some extent still are, high graded, and they have been "commercially" clearcut. Despite these abuses, in time the forests do recover.

The implications of innovative silviculture for growth and yield require assessment. When second-growth Site Indexes are accurately assessed and stand yield simulators or Scandinavian yield curves are applied to free-growing, well stocked stands, it is apparent that density control, prompt restocking and mortality recovery will together greatly increase present net merchantable yield forecasts for historical natural stands. These well-known treatment results, which can be seen in Scandinavian boreal forests, are not appreciated or applied in Canada for economic and institutional reasons. Biologically, these improved results are well understood and documented. Hagner (1995) has outlined how innovative silvicultural practices, with due respect for nature conservation and biodiversity, can be applied in Swedish boreal forests.

There are no theoretical reasons that elementary basic silviculture cannot be modified with innovative silviculture prescriptions, appropriately linked to some firm stand and forest level planning objectives to achieve both high timber yields and other multiple resource values across the landscape. The problems lie in our institutions, our lack of planning, and in our inability to implement practices.

Evolution of Silviculture

Of interest is the development of Crown (public) land silviculture (Table 1), and a review of examples of boreal silviculture initiatives (Table 2). In the 1950s the forest industry was keen to achieve successful natural regeneration without major additional logging costs. The assumption behind much of the silviculture research at the time was that since the boreal forests have been historically self-regenerating, it followed that it should not be too difficult to modify harvest practices with no major increase in logging cost to achieve natural regeneration. Experimental forests and trials were set up. One project, RC-17, was a large study at Heron Bay, Ontario to solve the boreal mixedwood regeneration problem by teams of scientists working in a reductionist way to analyze all the major variables (Hughes 1967). This expensive project demonstrated the futility of this approach and led to an appreciation of the value of documenting natural regeneration occurrence with a framework of site classification. Hundreds of empirical trials, without a framework for portability of results and assessment of limiting factors, are of little value. Today we have the boreal species ordinated within edatopic grids, site classification manuals and limited successional information. This common framework of reference, which sorts out boreal forest variation, is vital to implementing silvicultural innovation (Sims, Kershaw and Wickware 1990, Elliot, Morris and Kantor 1993). The current status of Canadian forest site classification is outlined in the Forestry Chronicle Vol. 68, No. 1.

It became apparent that forest harvesting did not create the same regeneration opportunities as did windthrow, wildfire and budworm attack. Successional patterns on cutovers can be different. Documentation of successional patterns in the boreal forest then started to develop, as for example Damman's (1964) work in Newfoundland. Today we still lack the required successional data, especially in western Canada.

It also became apparent in the 1960s that some boreal types needed seedbed preparation for natural seeding. While some could be planted without site preparation, others required site preparation and planting to achieve the tightened new government regeneration standards. Regeneration failures became a national scandal, highlighted at a national regeneration conference in Quebec (Canadian Forestry Association 1977). Federal funds became available to tackle the NSR backlog.

It is interesting that after a 15-year period in which boreal silviculture had been dominated by the challenge of successful regeneration using plantations, in the 1990s

Table 2. Examples of boreal silviculture initiatives and studies

Year	Location	Species	Objectives	Comment	References
1920s	Prince George Aleza Lake	Interior spruce old growth	Selection, ship and block cuts	Successful single tree selection, 40-year record	Coates and Jull 1993
1960s	Prince George	Interior spruce old growth	Large application of ship and "selection" cutting	Quickly abandoned, poor regeneration	Glew 1963; Farnden 1991
1980	Fairbanks, Alaska	White spruce, floodplain, old growth	Clearcutting and silviculture cuts	Both feasible with planting	Youngblood 1990
1900s	Sweden	Scots pine, Norway spruce	Assessment of direct seeding based on 100 years of experience	Recommended for Scots pine on poorer sites	Hagner 1990
1989	Sweden	Scots pine, Norway spruce	Analyze and present natural regeneration research needs in the future	Nineteen conclusions made on research needs	Jeansson et al. 1989
1970s and 1980s	Ontario	Black spruce	Assessment of attempts of strip, patch, block and seed tree cuts	Many black spruce regeneration problems cannot be solved by planting	Jeglum 1989
1920s to 1950s	Quebec	Black spruce	Assessment and analysis of the role of advanced growth in early harvests	Advance growth responds well to release and will produce good stands	Doucet 1990
1950s to 1980	Saskatchewan	Jack pine, Black spruce	Use of prescribed fire to obtain natural regeneration	Use of fire is feasible, but has problems	Chrosciewicz 1980, 1989
1980s	Eastern Canada	White pine, Red pine	Use of prescribed fire for regeneration on rich sites	Appears feasible. Implementation is needed	McRae et al. 1994
1990s	Eastern Canada	Boreal	Review of fire/insect relations	Use of fire proposed to reduce vulnerability to insects	Dupuis 1994
1950s	Heron Bay, Ontario	Spruce/aspen mixed wood old growth	RC-17, Strip and block cuts with seeding and planting by multi-disciplinary team	High-profile science study to solve spruce regeneration problems. Abandoned due to uncontrolled variables.	Hughes 1967
1973 to 1990s	Nipigon Ontario	Black spruce, mature	Strip cutting of black spruce on shallow sites	Strip cutting is feasible	Forestry Chron. 1988. 63: 435-456; 64: 52-75
1940s to 1980	Green River, Edmundston, NB	Balsam fir	Relationship between cutting methods and budworm susceptibility	No partial cutting method influenced the severity of infestation	Baskerville, Hughes, and Louks 1960
1910 to 1970	Fraser Experimental Forest, CO	Engelmann spruce, Subalpine fir	Fifty year assessment. Effects of clearcuts and selection cutting on growth, regeneration and hydrology	Produced excellent guidelines for ESSF management. A model to study for any proposed experimental forest	Troendle, et al. 1987
1993	Kamloops, BC	Engelmann spruce, Subalpine fir	Effects of opening size with and without site on planting	Currently being established	Stathers and Vyse 1993
1993	Prince George, BC	Interior spruce	Single-tree selection trial to 3 residual basal areas	Recently established	DeLong and Jull 1991
1990	Hazelton, BC	Interior spruce	Assess opportunities for alternative silviculture systems	A key provided to analyse opportunities	Weetman et al. 1970

we have returned to a paradigm based on "naturalness" and biodiversity. Once again natural regeneration is in fashion as are trials of silviculture systems to achieve more natural regeneration.

Economics and the Clearcutting Issue

There is a fundamental problem of lack of revenue allocated to finance boreal silviculture. The economic imperatives of the 1950s led to the extensive use of clearcutting as a harvesting practice. The realities of the 1950s, however, are also those of the 1990s when it comes to money for silviculture. Boreal pulpwood forests are still sold for relatively low stumpage prices and there is a chronic shortage of money. Ontario foresters were told by their Minister in 1994 to use more natural regeneration and seeding — exactly what was said in the 1950s.

When Site Index (SI_{50}) values are in the 10 m to 20 m range, and even when some timber goes to sawmills for which the stumpage prices are higher, the net revenues from boreal forests are still low on Crown lands. There is little money for intensive boreal silviculture. However, density control by pre-commercial thinning (PCT) is required in certain situations as part of the obligatory "basic" silviculture for licensees. The objective is to avoid excessive stand densities and accelerate stand operability to overcome forest age class imbalances.

In attempts to mollify European customers who have been told to avoid clearcut timber products, both Sweden and some Canadian provinces are producing press releases that imply "clearcutting" has been abandoned or greatly modified in boreal forests. This new drive for change is causing those interested in forest management to re-examine silviculture systems definitions and meanings, and also to re-examine landscape level design in harvest schedules. The veracity and ethics of some of the press releases are questionable.

Table 3. Problems with Silviculture in Boreal Forests

- Large areas in one age class due to fires and insect attack which are at risk and need to be removed quickly.
- Low stumpage values and long truck hauls — leading to need for large scale mechanized harvesting.
- Old stands, often near break-up with low live crown ratio and high windthrow risk.
- Lack of any historical stand tending leading to high stand densities, small mean diameters and 20-30% mortality loss due to competition and few or no opportunities for commercial thinning.
- Lack of previous road access or only winter access on frozen soil.
- High degree of rot and breakage, especially in true firs.
- Natural precedent is large scale disturbance.
- Limited or patchy advance growth, sometimes of wrong species in poor form at risk of loss or damage due to mechanized harvesting.
- Rapid turnover of silviculture staff.

Table 4. Boreal Forest Characteristics

- Major disturbance driven and very slow in dynamics
- Landscape level diversity — not at stand level
- Monocultures of pine, spruce and fir, simple in structure
- Climate controlled, not latitudinal
- High variation in ecology
- Temperature control through soil processes
- Old forests break up, become diseased; climax, old forests are really not self-sustaining or very healthy
- Healthy ecosystems are usually heavily disturbed, simple in structure and often monocultures
- More southern ecological paradigms for silviculture based on gap dynamics, complex structure, etc., are not relevant for most boreal forests
- Natural precedent, based on major fire and insect disturbances need to be examined closely in each site type as a basis for silviculture practice; clearcutting does not emulate the seed supply and seedbed characteristics and habitat characteristics of fires and insect attack
- Even-aged management is appropriate in most locations using clearcut systems.

While Swedes have flexibility in harvesting silviculturally-tended stands, Canadians have somewhat less flexibility in harvesting old untended boreal stands with competition-induced mortality, and insect and disease attack putting the Canadian stands at risk. The 1994 clearcutting hearings in Ottawa did manage to convince a group of Canadian parliamentarians that clearcutting is an acceptable reality (Nault 1994). They said "clearcutting is entirely appropriate from an ecological perspective for most forest types in Canada." They could have added "and the boreal forest in particular." Innovative silviculture systems for the boreal forest have been, and are today, severely constrained by biological realities of what to do with old black spruce, jack and lodgepole pine, aspen, balsam fir, poplar and black, white and interior spruce stands. In most cases the economically realistic options involve innovation about the size, distribution and timing of clearcuts, which are linked to age class structure and risk of loss of sustained yield. Innovation in silviculture cannot, and should not, just be thought of at the stand level. It must be an integral part of forest level planning. Biodiversity, continuity and fragmentation also should not be considered at just the stand level but also at the forest level where they can have powerful economic effects. Green-up and adjacency constraints alone can greatly reduce allowable cuts with attendant economic disbenefits.

Factors which Influence Boreal Silviculture

Two of the most important factors which influence boreal silviculture are slow stand dynamics and the history of catastrophic disturbance. Each of these factors is discussed in greater detail.

Slow Dynamics

The rate of biological change is slow, thus feedback on success or failure of stand treatments is also slow. In some cases where it takes 20 to 40 years to achieve crown closure, this period is longer than the working life of most foresters. The management problems and characteristics of boreal forests and their silviculture are outlined in Tables 3 and 4.

In order to predict stand response and development in these slow systems, a forester has the following options.

Option 1

Substitute space for time. Stands at differing stages of development across the landscape are examined in chronosequence retrospective studies. In order for information to be valid assurance is needed on two points: a) the equivalence of site conditions in the chronosequence (thus a workable site classification is needed to make stand development information portable across the landscape), and b) equivalence of disturbance history in the chronosequence examined. It is more difficult to provide assurance on the second point because changing harvesting and utilization practices and intensities and seasons of fire and insect attack all make equivalence of disturbance history hard to find in chronosequences. The long time frames usually result in climate and animal damage changes which also change stand dynamics. For much of the boreal forest in Alaska and Canada the long-term successional dynamics have not been well documented. This is partially due to lack of money, the vast areas of forests needing study, and the recent human development of much of the forest.

Option 2

Use stand level computer models. Stand development changes can be simulated in a computer and the stand "grown" through 100 to 150 year time frames. This option is a great improvement over use of traditional empirical or normal yield tables because the stand level computer models can answer important "what if" questions on the effects of changing stand density and site index. The computer models handle competition induced mortality very well, but not other mortality or damage. Also, the models do not handle mixed species stands, and some are poorly calibrated against real data. The outcomes predicted by the models thus tend to be optimistic and foresters tend to discount the predicted yield by "operating adjustment factors."

Computer simulation models allow foresters and biologists to understand how stand changes develop and how these changes relate to soil fertility and stand development concepts. The concepts become real and relevant. In addition the relationships between stocking standards, crown closure, wildlife browse habitat, competition-induced mortality, effects of thinning, diameter and crown development, windthrow hazard and final crop merchantable yield and total yield all become more visual, predictable and understandable.

The recent use of computer models has led to a great improvement in understanding the potentialities for silviculture in the boreal forests. Potential yields are higher and time frames much shorter in tended stands. While this may be patently obvious if Swedish and Finnish boreal stands with equivalent site indices are examined, there has been a reluctance to accept the reality of this potential in Canada. This reluctance is due, in part, to the absence of examples on the ground with documented development.

The growth and yield potential of the boreal forest in North America has been grossly underestimated because: a) growth and yield sampling is based on naturally developed stands with no human intervention, b) the tradition is of only presenting net merchantable yields with no recovery of competition induced mortality, c) site index has been inaccurately determined, and d) historical loss of trees due to wind, ice, snow, insects and disease in untended stands is high.

When simulated stands are grown and put into landscape or forest level models, a much clearer picture develops of long-term change in boreal forest landscapes. The picture is real in the sense that GIS-based forest level models can visually show how the whole forest changes in age class structure through long time frames as a consequence of human intervention by scheduling harvesting and silviculture actions at various locations, in various amounts and at various times.

The combination of stand and forest level modelling of boreal forests is leading to logical planning of silviculture actions across a forest to meet specified land use objectives. The tradeoffs between objectives for boreal forest use become clearer when the development scenarios are run.

The understanding afforded by computer modelling of the boreal forest opportunities and potentialities as a consequence of human intervention in fire protection, harvesting and silviculture has led to tighter government silviculture regulation on Crown lands. For example, the mandatory requirement for pre-commercial thinning in some forest types to accelerate stand operability is designed to overcome age class gap problems in wood supply.

Option 3

Encourage foresters to stay in one forest for 20 to 40 years. Besides looking at stand development chronosequences or using stand and forest level simulations to forecast and understand forest development over long periods, there is the traditional option of encouraging foresters to stay in one forest for 20- to 40-year periods. Every day a forester spends in a forest, the more that person learns about that forest. This accumulation of local knowledge was the traditional basis for developing silviculture systems in Europe when forests had to be reconstructed in devastated landscapes over 100-year periods (Weetman 1995). Chronosequence studies were not possible due to the absence of undisturbed forests, and there were no computer simulations. Many foresters would argue that successful implementation of long-term silviculture and other management actions requires people with good local knowledge and understanding. There is a good argument for community forests, or forests run by resident aboriginal people as a way to provide for continuity of local expertise and employment. Unfortunately, large provincial government or corporate forest administration usually results in rapid staff turnover, particularly in remote boreal forest locations.

Under the circumstances of rapid staff turnover, young foresters need to a) learn quickly to use chronosequence observation and stand simulation for their forests, b) appreciate fully and apply the regional site classification, c) have the temperament and tolerance to take advantage effectively of long-term local residents, workers and technicians who have a good intuitive knowledge of forest development based on experience, and d) have the opportunity to travel to visit long-term studies and trials done in forests of similar ecology.

Faced with rapid turnover and uncertainty or lack of understanding of boreal forest development, there is currently an almost universal tendency to substitute central administrative silviculture regulation to ensure a minimum standard of performance. A biologically blind adoption of silviculture performance regulations, even if linked to a site classification system, has led to bizarre silviculture actions usually not linked or designed to meet any stand or forest level objective. Attempts to decrease the waste in budgets and talent are often dealt with administratively by silviculture audits to determine if performance standards are met. This form of boreal administrative forestry leads to poor morale, costly mistakes and harvesting and silviculture actions insensitive to peoples' wishes. In theory, Pre-Harvest Silviculture Prescriptions can go a long way to overcoming the problem of administrative forestry by placing reliance on professional foresters to diagnose stand conditions and prescribe the appropriate treatment, particularly if people and technicians with good local knowledge are involved in the PHSP process. However, the professional forester still assumes the burden of legal and professional responsibility for the PHSP once it is signed and sealed.

Option 4

Establish experimental forests. The logical and desirable way to predict stand response to treatment in boreal forests is to establish experimental forests in which various treatments are assessed over 25- to 50-year time frames for all resource values. Unfortunately, in spite of various attempts to do so, in the whole of the North American boreal forest there is not a single experimental forest which has had very long term monitoring of various treatments. There have been many short-term trials, and several forest science studies of ecosystem structure and function. It appears to be administratively very difficult to provide long-term commitment to experimental forests. Currently the public desire for "naturalness" in silviculture, plus public opposition to clearcutting, has resulted in new attempts to test and monitor variations in silviculture treatments. Information from long-term experimental forests in the United States has been valuable for Canadian boreal forest understanding.

Option 5

Foresters must commit to continuing education. The final option available for a forester to predict stand and forest development and relate this knowledge to complex demands for forest resource management is for the forester to make a commitment to continuing education. There has been a successful development of, and strong demand for, modules of professional forester education presented in the Silviculture Institute of BC, the Ontario Advanced Forestry Program and the Alberta Advanced Forestry Program. Also, the continuing education courses and networks and updates in professional journals all have been well received. However, mandatory professional forester continuing education has yet to be formally established in British Columbia, Alberta, Ontario, Quebec, or New Brunswick.

History of Catastrophic Disturbance in Boreal Forests

It is obvious that boreal forests are dominated by major fire outbreaks or insect outbreaks which result in very extensive areas of even-aged stands and very high risk of loss as stands age. With quite successful fire protection efforts for 40 to 50 years, fuel accumulates in the stands and aging stands accumulate in the landscape unless harvested. The struggle to protect old stands until age classes can be balanced across the landscape by scheduled harvests occurs over many decades. In many places boreal forest harvesting is driven by salvage cuts and is crisis-driven because the boreal forest is not a man-controlled, but a natural disturbance-controlled, landscape. Marginally economic stands, high road access costs, rapid salvage, low mean diameters and short windows for recovery of dead timber all tend to result in little money left from stumpage to pay for silviculture.

Conclusion

Under the Canadian system of licensing, private companies have cutting rights and management obligations over most of the operable boreal forest. These licensees have little incentive to invest in the boreal forest on public lands. The forest administrative system tends to favour low cost, fast regeneration of cutovers to meet minimum stocking standards. The benefits of boreal silviculture actions in terms of growth and yield may be, and often are, lost in the crudeness and error of the wood supply forecasts whose primary drivers are unbalanced age class structures and high risk of loss. Foresters, therefore, have difficulty justifying increased expenditures in boreal forest silviculture.

The relationships between the licensing system, the administrative system, growth and yield, wood supply forecasts, and risk of loss for any particular forest need to be clearly understood by a forester interested in boreal silviculture. This understanding comes from actively working with forest level models so the sensitivity of the whole forest to protection, risk of loss, age class structure, harvesting and silviculture becomes clear. As forest auditors demand value for money in silviculture, the boreal silviculturist must be able to defend his program to forest level planners. This defence is a relatively new requirement for foresters, but one which is now recognized judging by the popularity of forest level advanced education modules.

Currently there is a struggle between biologists / ecologists and foresters. The former grasp the landscape dynamics in the boreal forests, have faith in "natural processes" as being appropriate and want more control over the forests. The foresters with traditional administrative control must rationalize harvesting and silviculture on a vast landscape in terms both the public and the biologists / ecologists can understand.

It is the understanding of boreal forests by all groups, however, that is leading to a greater appreciation of them. The challenge for foresters is to use the new tools available to meet the challenges and questions posed by the public, politicians and other disciplines in the management of the boreal forest.

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Silvicultural Systems in Boreal Forests in East Asia

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Boreal forests or northern forests cover a vast area in East Asia, and play an important role in timber production and environmental protection. In this paper, silvicultural systems used in this region are reviewed. These silvicultural systems cover clearcutting system, shelterwood system, planting conifers while preserving deciduous, dynamic thinning for larch plantations, and ecological forestry engineering.

Introduction

A silvicultural system may be defined as the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of distinctive form (Matthews, 1989). A silvicultural system consists of (l) regeneration method; (2) the form of crop produced; and (3) the orderly arrangement of the crops over the whole forest, with special harvesting of produce.

There is a long history for the study of silvicultural systems in China and the world. Although various classifications of silvicultural systems have been proposed, I prefer the systems pointed out by Matthews (1989) for its easy use in practice.

Silvicultural systems in use or under experimental development in the region can be grouped into three categories: high forest systems, coppice systems and agro-forestry systems, which is also described as ecological forestry systems. The high forest systems can be classified as clearcutting systems including, the uniform system, group system, irregular shelterwood system, strip system, and wedge system, and selection systems consisting of two-storied high forest, high forest with reserves. Coppice systems include the coppice selection system, coppice system, coppice with standards system. Agro-forestry systems mainly embodies silvo-agricultural system, silvo-medicinal plant system, silvo-pastoral system, silvo-agro-pastoral system, and windbreak system. In this paper, typical silvicultural systems used in boreal forests in east Asia, especially those in northeast China, are reviewed.

Forest Background for Silviculture in Boreal Forests in East Asia

The Mixed Broad-leaved/Korean Pine Forest Region

This forest region embodies the Xiaoxingan Mountains, The Zhangguongcai Hills, the Wanda Mountains, and the Changbai Mountains. The region is near the sea with high humidity. The average temperature in January is -14°C to -28°C. The period with lesser than or equal to 0°C of maxi-

Table 1. Typical forest types in temperate mixed forest of broad-leaved / Korean pine forest

Formation Classes	Formation
Evergreen coniferous dwarfs	*Pinus pumila* forests
Evergreen coniferous forests	*Picea koraiensis* forest *Abies nephrolepis* forest *Picea koraiensis* / *A. nephrolepis* forest *Pinus densiflora* forest *Pinus sylvestris* var. *mongolica* forest
Larch forests	*Larix gmelini* forest *Larix olgensis* forest
Mixed forests of broad-leaved / Korean pine forest	*Pinus koraiensis* / *Abies holophylla* *Carpinus cordata* forest *Pinus koraiensis* / *Betula costata* forest *Pinus koraiensis* / *Picea koraiensis* / *Abies nephrolepis* forest
Deciduous broad-leaved forest	*Betula ermanii* forest *Quercus mongolica* forest (secondary) *Betula dahurica* forest (secondary) *Betula platyphylla* forest (secondary) *Populus davidiana* forest (secondary) *Fraxinus mandshurica* / *Juglans mandshurica* forest (secondary) *B.platyphylla* / *P.davidiana* / *Tilia amurense* forest (secondary) *Ulmus propinqua* / *Fraxinus mandshurica* forest *Alnus hirsuta* forest *Chosenia macrolepis* forest

mum temperature is about 2.5 to 5 months. The average temperature in July-August is 20° to 24°C. The frost-free period is 120 to 150 days. The annual precipitation is 750 mm in the south, the Changbai Mountains, and 550 in the north, the Xiaoxingan Mountains, respectively. The typical soil type under the forest is dark brown forest soil. Dominant forest is mixed broad-leaved / Korean pine (*Pinus koraiensis*) forest. Typical forest types and main tree species in this region enumerated in Table 1.

The Cold Temperate Coniferous Forest Region

This forest region is located in high latitude area with a cold and dry winter of 7 to 8 months. The growing period is only 100 – 120 days. Annual average temperature is lowered than 0°C. The mean temperature and absolutely minimum temperature in January is -28°C and -40°C, respectively. Annual precipitation is about 300 – 500 mm. The typical soil types are gray forest soil in the west, dark brown forest soil in the east, and bog soil in the valleys. Dominant forest types consist of larch (*Larix gmelinii*), Mongolian Scots pine (*Pinus sylvestris var. mongolica*), and spruce (*Abies jezoensis var. ajanensis, Abies koraiensis*) (Table 2).

Table 2. Typical forest types in cold temperate coniferous forest region

Formation classes	Formations
Larch forest	*Larix gmelini* forest
Evergreen coniferous forest	*Pinus sylvestris* var. *mongolica* *Picea koraiensis* forest *Pinus pumila* forest
Deciduous broad-leafed forest	*Betula platyphylla* forest (secondary) *Quercus mongolica* forest (secondary or primary) *Betula dahurica* forest (secondary or primary) *Populus davidiana* forest (secondary) *Chosenia macrolepis* forest *Populus koreana* forest

Forests On Sand Dunes in the West Region

There is a sand dune belt with a length of 800 km and a width of 160 km from Hailar on the south aspect of the Daxingan Mountains to Zhanggutai in the west of Liaoning Province. Following natural forest types can be recognized in this wide area: (1) Mongolian Scots pine (*Pinus sylvestris var. mongolica*) forests in the desert in Honghuarji Region, Inner Mongolia Autonomous Region; (2) Larch (*Larix gmelini*) forest on rocks in Ajinshan; (3) Korean spruce (*Picea koraiensis*) forests in Baiyinaobao; (4) Huabei larch (*Larix principis-rupprechtii*) forest on sand dunes in Wengniute County, Inner Mongolia Autonomous Region.

The Silvicultural Systems Used in Boreal Forests in East Asia

Clearcutting Systems

The clearcutting systems are conducted in either a whole compartment or a part of compartment. Those done in whole compartments are the uniform system, group system, and irregular shelterwood system. Those done in a portion of a compartment are the strip system and wedge system. The definitions of those systems can be referenced in Matthews (1989). Clearcutting systems were frequently used from the 1950s to 1980 and now are being used in some places with limited coupe size in boreal forests in east Asia.

The size and form of coupes varied greatly depending on local topography. Climatic factors and soil characteristics of clearcuts in the mixed broad-leaved / Korean pine forests changed greatly compared to those in the virgin forests (Table 3). Thus, the artificial forest regeneration on clearcuts is greatly different from natural regeneration under the canopy of old trees.

Li Jingwen (1988) studied the regeneration characteristics of clearcuts of the mixed broad-leaved / Korean pine forests and concluded that young Korean pine plantations grow slowly and have difficulty approaching crown closure. Disease and pests occur frequently in the plantation, which causes stem forking and other stem abnormalities. Experimental results show that an effective method of encouraging Korean pine regeneration is to create openings above seedlings while providing side shelter using shrubs and deciduous trees. The direct irradiance from above has a significant positive effect on the growth of DBH, height, and volume. The shelter-shading from side is significant in preventing disease and pest damage (Zhan Hongzhen et al., 1986).

Larch forests and Mongolian Scots pine forests are the dominant forest vegetation in the cold temperate area in the Daxingan Mountains in northeast China. Clearcutting systems are the main silvicultural practice in the area. The size of coupes varies from 5 ha to 10-20 ha. The artificial regeneration with larch seedlings is often used in the area, but natural regeneration or natural regeneration combined with artificial regeneration are recommended (Chen Boxian et al., 1988) when the width of coupes is less than 200 m.

Forests are greatly affected by fire in the Daxingan Mountains. About 1.14 million ha of forested land and woodland were burned (of which, 870,000 ha of forest was damaged) by the May 7, 1987 fire, one of the greatest forest fire in the world (Chen Boxian et al., 1987). Among forest trees damaged by the fire, larch constitutes 77.9% and Mongolian Scots pine 4.6%. Forest regeneration strategies and measures for the burned area are as follows: (1) natural regeneration aided with artificial regeneration is utilized on lightly burned (30% dead trees) or moderately burned (31% – 70% dead trees) areas; (2) For heavily burned areas (70% – less than 100% dead trees) or extremely heavily

Table 3. Changes of climatic and soil factors after clearcutting of the mixed forest of broad-leaved / Korean pine forest

	Within forest	The centre of clears (100 m in width)	The centre of clears (300 m in width)
Tmax (C)	26.6	27.1	29.5
Tmin (C)	17.7	17.9	16.4
Tdif (C)	8.9	9.2	13.1
RHmin (%)	68	53	43
PR (%)	70.9	52.2	-
WV (g / cm-3)	0.81	1.24	-
AW (%)	73.1	67.5	-

Tmax, Tmin, Tdif, and RHmin are maximum temperature, minimum temperature, temperature difference, and minimum relative humidity, respectively, monitored at the height of 1.5 m above the ground. PR, WV, and AW are porosity, weight per volume and absolute water content of soil, respectively, determined at the depth of 10 cm.

burned areas (100% dead trees), natural regeneration is utilized in regions with better economic situations, and artificial regeneration in economically harsh regions; (3) living trees are not allowed to be cut absolutely; (4) artificial regeneration embodies direct seeding, seedling planting, and seed spreading by airplane.

Shelterwood System use in Mixed Broad-leaved/ Korean Pine Forests

Shelterwood systems are used in those high forest systems in which the seedlings and saplings of Korean pine, a shade-demanding species in the young stage, are established under the overhead or side shelter of old Korean pine stems or deciduous trees. The purpose of this type of system to facilitate natural regeneration.

Shelterwood systems have been in use since the 1980s. Presently, four types of shelterwood systems are in use in this region, the uniform system, the group system, the irregular system, and the strip system.

Planting Conifers With Preserving Deciduous Trees

Mixed broad-leaved / Korean pine forests, zonal climax forests, have been destroyed since 1903. A vast area of secondary forests has been developed in the east part of Northeast China (Chen Dake, 1982). Thus, the recovery of Korean pine forest plays an important role from the viewpoint of timber production and environmental conservation. In the last 30 years, a type of silvicultural system "planting conifers with preserving deciduous trees" has been developed to aid forest recovery in the area (Zhou Xiaofeng, 1982). The technique combines artificial regeneration of Korean pine with natural regeneration of deciduous trees.

Korean pine enjoys moderate shade while in early growth stages. We will seldom find seedlings and saplings under old-growth of Korean pine forests. Young trees of Korean pine are common in natural and man-made gaps in the virgin forests. Thus, the mixed broad-leaved / Korean pine forest maintains its stability and structure by providing gap regeneration, as the basic silvicultural system needed to produce multiple-storied high forest for Korean pine.

Dynamic Thinning System of Larch Plantations

Larch (Larix gmelinii, and Larix olgensis) plantations developed quickly in the northeast forestry region in east Asia, bringing much attention to larch plantation management issues. Ding et al. (1986, 1987) worked out a silvicultural system for the management of larch plantations called the dynamic thinning system.

The development of larch plantations is divided into four stages, the surviving stage, initialled stage, tree differential stage, and forest stable stage. This division suggests that the density of larch decreases greatly from the early stage to the equilibrium phase of the forest. Trees are classified into five classes in each seven-tree group called a "mini-population." Class A refers to the tree with the largest height and DBH; class B is similar to class A with the lower part of the crown suppressed; class C refers to those trees which are semi-suppressed; class D refers to those trees which are completely suppressed; and class E refers to trees that are dead or nearly dead.

Class A trees are preserved for later harvesting as large-size timber; class B trees are thinned; class C trees are released; and class D and E trees are removed. The experimental results show that the best thinning intensity is 30% (Ding et al. 1887).

Ecological Forestry Engineering in the Boreal Forests of East Asia

Ecological engineering is a type of technological system for matter production based on species coexistence and recycling of matter in ecosystems in combination with optimum design, which is used in system analysis, for multiple uses of matters. The purposes of ecological forestry engineering are promoting the optimal nutrient cycling in the ecosystem, increasing the productivity of lands, preventing the environment from pollution, and developing ecological and economic benefits simultaneously.

Agro-forestry system

The agro-forestry system is a traditional practice in east Asia. Agro-forestry systems such as silvo-agricultural systems, silvo-medicine plant systems, and alley cropping systems were in use in China one thousand years ago (Chen Dake, 1993). However, scientific studies of agro-forestry systems have a history of about ten years. At present, the agro-forestry systems used in boreal forests in east Asia are the silvo-ginseng systems, silvo-fishery system, silvo-pastoral system, and silvo-agricultural system.

Chinese ginseng (*Panax ginseng*) is a valuable medicinal plant in east Asia. However, the quality of ginseng cultivated in different sites varies. Generally, the quality of ginseng cultivated under / in forests is better than that on bare beds. Silvo-ginseng systems consist of two varieties, planting ginseng alternatively with deciduous trees and planting ginseng under forests (Chen Dake et al. 1990). This type of agro-forestry system is widely used in forested regions in the east part of northeast China, in the mixed broad-leaved / Korean pine forest area.

The silvo-fishery system develops fisheries in lower swamp areas in forested regions, while trees are harvested on mountains. This system is frequently used in the east part of northeast China. In some places, fish pools, paddy fields and forests develop together constituting a silvo-fishery-agricultural system. In the western desert forest area, and some places in the east, especially the "I Three-River Plain" area, animal husbandry develops together with forestry.

Windbreak Systems in the "Three North" of China

The "Three-North" is situated in northern part of China (73°26' – 127°50'E, 33°30' – 50°12') with a length of 4,480 km east to west and a width of 560 – 1,460 km south to north. It covers 551 counties of 13 provinces or autonomous regions (Zhang Peicang et al., 1993). The total area of land is 4.069 million square kilometres which is 42.4% of territory land in China.

The Three-North is a harsh area with strong wind, low precipitation, a large area of sand dunes, deserts, desertification earth, and gobi. There is also a vast area of loess with serious soil and water erosion.

The windbreaks in the Three-North are being established in three stages: 1978-1985, 1986-1995, and 1996 and afterwards. Presently, the second stage is nearing completion. From 1978 to 2050, 35.083 million ha of plantations will be established. Among the plantations, shelterbelts cover 24.986 million ha (71.2%), of which shelterbelts in cropland consist of 2.186 million ha (8.4%), forests for soil and water conservation 8.779 million ha (35.1%), forests for wind prevention and desert stabilization 9.559 million ha (38.3%), forests for conserving water sources 2.098 million ha (8.4%), forests for conserving pasture land 1.597 million ha (6.4%), forests for conserving river banks 415,000 ha (1.7%), forests for conserving roads 243,000 ha (1.0%), and other types of shelterbelts 108,000 ha (0.4%) ; forests for timber production cover 5.351 million ha (15.3%); economic forests cover 2.184 million ha (6.2%); fuel forests cover 2.388 million ha (6.8%); and forests for special uses cover 174,000 ha (0.5%).

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Trends and Use of Silvicultural Systems in the Boreal Forests of Russia

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Russia's forest area is 1.2 billion ha. Almost all Russian forests are Boreal forests. The main characteristics of its forests are its low average volume of timber per hectare and a predominance of conifers. Clearcutting followed by natural regeneration is the dominant silvicultural system used. Current trends are toward more site-specific approaches to cutting and regenerating, employing methods that recognize forest peculiarities and environmental conditions. There is a conviction to reduce the amount of clearcutting and increase the amount of artificial reforestation, and better understand the significance of stand tending without the use of arboricides for this purpose. The most significant feature of Russia's forestry today is the sharply decreasing level of timber harvesting.

As in other countries, the cutting and reforestation methods used in Russia are developing under the influence of objective factors and changes taking place in public opinion regarding the significance of forests on the Earth. At the same time, silvicultural systems are influenced by three main characteristics of Russian forests:

1. the vast territory covered with forests;
2. the huge diversity of natural and economic conditions;
3. the fact that for at least 80 years there were no privately-owned forests, and government institutions continue to manage all Russian forests.

According to the official data (1), the total Russian forest stock area is 1,183 million ha. 94% of the former USSR's forest area falls inside Russia's borders. The forest area itself is 884 million ha, including a forest covered area of 771 million ha. More than one half of the unforested area is occupied by swamps and waters. Total timber growing stock is 81.6 billion m^3, of which 78% is coniferous. The area of the country covered by forest is 45.2%. Most of the forest stock area (1,014 million ha) is under the Russian Federal Forest Service jurisdiction (2).

The population of Russia today is 148.4 million people (3). This means that there is about 5.2 ha of forest covered area and about 550 m^3 of timber stock per capita. These average figures are far from reality because of the uneven distribution of the population and the forests across the territory of the state. More realistically, one needs to consider that in the Asian part of Russia about 78% of the forest area is found, but only 25% its population.

Almost all Russia's forests are boreal forests. They are

Table 1. Boreal Forests of the European Plains of Russia

	Units	Forest-tundra	Coniferous forest (taiga)			Mixed forest
			North	Middle	South	
Share of the forest area	%	10	26	32	14	18
Growing stock of mature stands*	m^3/ha	56	99	136	234	220
Average relative density of mature stands*	quota	0.44	0.57	0.63	0.69	0.72
Bonitet*	class	V. 8	V. 4	IV. 7	II. 9	I. 8
Main tree species	-	spruce pine birch	spruce pine birch	spruce pine birch	pine spruce birch aspen	pine spruce birch oak aspen

* Average data from different sources

situated in three main zones:

1. forest-tundra;
2. conifer forests (taiga) and
3. mixed forests.

The conifer forests zone — the largest by area — is subdivided into three large subzones: northern, middle and southern taiga.

Zones and subzone boundaries do not coincide in the interpretation of different researchers. Nevertheless, zonal differences between forests are the reality (Table 1). In addition, it should be mentioned that approximately one third of Russia's forests are mountainous, and almost all of them are on the east side of the country in regions with extremely severe climatic conditions.

Low growing season temperature is the principle factor defining the character of Russian forests, resulting in low density and low productivity throughout most of the country. The average volume of wood in forests through all the Russia is about 106 m^3 per ha. Not all our forests are suitable for regular commercial timber production. Officially in Russia, the category of "commercial forest" and their criteria have not been determined yet.

In comparison, under Canada's climate and forest stock conditions (which are similar to Russia's), the commercial forests have an average volume of wood of 210 m^3/ha (4). The commercial area is 119 million ha or 28.6% of all Canada's forest land. We could reasonably assume that in Russia the share of such forests is roughly the same as in Canada.

All the Earth's forests are important as a part of the planet's ecosystem. But specific forest plots and forest stands may have an unequal environmental creation value.

In Russia the necessity of protective forests determination was strictly defined by the law adopted in 1888 (5). At that time it was prohibited to carry out any works (including cuttings) in protective forests if they would disorder the stands. A similar decision was adopted in 1943 and duplicated in 1993 (6). According to it, all of Russia's forest stock is divided into three groups of forests according to their state significance:

1. The first group of forests (17.6% of all Russia's forest stock) includes water conservation and protective forests as well as sanitary and special ones (national parks, reserves, etc.).
2. The second group of forests (5.8%) has to fulfil two functions: environmental creation and raw materials production.
3. The third group of forests (76.6%) is mainly managed for timber production.

It is the Federal Government's prerogative to pass a resolution about which groups any forest area is to belong to. Taking into account the environmental significance of the third group of forests, we believe they should be transferred into the second group forests so as to make the rules of their exploitation more strict (7). But this point of view is not generally accepted. At present, all official documents on forest management in Russia are first made up in terms of forest subdivision into three groups, and only then are rules differentiated according to forest stock conditions and the stand's features.

All types of forest cuttings in Russia are grouped into two categories: intermediate cuttings (thinning, sanitation and other stand tending cuttings) and main harvest cutting. The volumes of merchantable wood obtained as a result of intermediate cuttings and main cuttings correlate to each other approximately as l:9 (2). In some categories of the first group of forests, main harvest cuttings are prohibited entirely.

Over the years, Russian forests have been harvested under three main systems: clearcut, successive and selective.

In our distant past selective cutting was the most widespread system used in taiga forests. Trees usually were cut in winter. The intensity of cutting was low and horse skidding was used. It allowed stands to be kept in a good condition. Later, with the appearance in forests of powerful caterpillar tractors, the intensity of cutting increased and the sanitary state of stands after selective and successive cutting became unsatisfactory.

With clearcutting, the situation is not much better. Heavy machines spoil upper layers of soils, increase soil density, and damage and destroy many or all the young trees. On areas with wet and damp soils, clearcutting initiates the process which can cause their swamping. This makes the reforestation time longer, lowers the productivity of stands and in some cases leads to the transformation of forest areas into swamps.

In the near past in taiga there were several hundred thousand hectares of wet forest lands drained annually. In 1993, only 27 thousand hectares were drained (2). This represents not so much a trend in our silviculture, but is more the result of an insufficient forest management expenditure.

Compared to selective and successive cutting, clearcutting is easier and cheaper to carry out. That is the main reason that, at present, selective and successive cutting systems are not widely used in Russia. Even in forests of the first group, they comprise only about 10% of the timber harvested (8). Russia's foresters are of the widespread opinion that for many conditions partial cuttings will effectively increase the total harvest and that they more closely mimic natural disturbances.

Fundamental data about the silvicultural system based on selective cuttings and about advantages of this system in spruce stands was obtained in St. Petersburg Forestry Research Institute by Prof. Stolyarov D.P. (9).

The increasing favour of partial cutting is one of the most significant trends in modern Russia's silviculture. This trend may become realizable owing to the appearance of modern forest techniques (harvesters and forwarders).

The allowable annual cut in Russia's forests is about

Table 2. Permitted technological parameters for clearcutting in the plains forests of the European part of Russia (12)

NN	Normalized	Unit	Coniferous forest (taiga)			Mixed forest
			North	middle	South	
1	Largest permissible cut area					
	a) in coniferous stands (pine, spruce, larch, fir)	ha	10* 15 50	10 20 50	10 20 50	10 20 50
	b) in small-leafed stands (birch, aspen)	ha	15 20 50	15 25 50	15 25 50	15 25 50
2	Maximum cut area width					
	a) in coniferous stands	m	100 150 500	100 200 500	100 200 500	100 200 500
	b) in small-leafed stands	m	150 200 500	150 250 500	150 250 500	150 250 500
3	Minimum period of adjacency of cutting areas (calculated on the following forest regeneration)					
	a) in coniferous stands with pine and larch predominance	year	8 8 8	5 5 5	5 5 5	5 5 5
	b) in coniferous stands with spruce and fir predominance	year	8 8 8	4 4 4	4 4 4	4 4 4
	c) in small-leafed stands	year	5 5 5	2 2 2	2 2 2	2 2 2

* upper figures — in the forests of I group
middle figures — in the forests of II group
lower figures — in the forests of III group

529 million m^3. During the last decade the amount of timber harvested has changed sharply: in 1987, 389 million m^3 (10) and in 1993, 174 million m^3 (2). The general crisis we are in has demolished the balance between branches of industry, resulting in extreme price growth in energy and transport. In one of the largest districts of Siberia-Krasnoyarsk region, transport tariffs increased 5000 times, but prices for forest products only increased 1000 times (11). Now it has become unprofitable to take timber from remote areas. That is why in the Asian part of the country the allowable annual cut was only 22% utilized in 1993 (11). There is no doubt that such a great decrease of harvesting (especially in distant districts) will influence the size and distribution of forest management expenditures.

Methods and technologies of cutting are regulated by official regional rules. In particular, the rules define the maximum size, the maximum width of the cut area and the minimum period of adjacency of cutting areas. As an example, the named parameters are shown in Table 2. It is quite obvious that these parameters need to be differentiated more deeply.

In Russia, the problem of reforestation of clearcut areas and areas with stands destroyed by fires is of great importance. Nowadays, according to the official data, there are about 100 million ha of forest lands in the country which are not covered with forests. In reality this figure is less because it unfoundedly includes about 55 million ha of sparse stands ("open forests") with density less than 0.3.

For the most part, clearcut and burnt forest areas are restored in by natural regeneration. In 1993, for the whole country, the area reforested naturally outnumbered the artificial reforestation by 3.4:1 (2). The proportion of natural regeneration is larger in the north and east. To promote natural regeneration, foresters broadly practice such actions as leaving seed trees and retention of undergrowth and undersized trees.

On poor sandy and sandy-clay soils of the taiga zone, natural regeneration usually takes place without tree species conversion. The situation is different in coniferous forests on the fertile loamy soils of south taiga. Here coniferous stands have, as a rule, more of a birch and aspen component. After clearcutting their suckers grow considerably faster than small coniferous plants, so the reforestation of these areas often reverts to aspen and birch. The main result is a reduced area of the most productive coniferous stands and changes to the environmental conditions there (13).

The future of "second" deciduous forests depends on their initial characteristics and carrying out tending cuttings (thinnings). The main purpose of these thinnings is to release conifers (if there are some) from under the aspen and birch canopy.

Russia's foresters consider tending cuttings to be among the most important actions in forestry. In 1993, thinnings were carried out on an area of 834 thousand hectares (2).

The mechanical removal of unwanted trees and bushes is an expensive and labour-consuming procedure. That is why 30 years ago we began to use salts and ethers of 2,4-D as selective arboricide for treatment of young aspen, birch and alder stands with a sufficient component of spruce or pine trees (14).

In the period 1976-1979, these substances were used on an area of 200-300 thousand hectares per year. Most of the work was carried out by airplanes and helicopters. In some cases results obtained were rather good, but in the period to follow these works were stopped for two main reasons: public protests and imperfection of substances and techniques used .

At present all 2,4-D substance uses are prohibited in our country. In their stead, came more perfect ones (i.e. glyphosate, Velpar) and safer methods for their use. But the work mentioned above has not been restored, so it is possible to add one more trend in our forestry–that is the negative attitude to arboricides use.

We assume the situation may be changed if foresters and villagers get more impartial information about ecological and practical aspects of this young forest tending method. To obtain such information our Institute will to continue the investigations in young stands of different ages and compositions that were treated with arboricides about 20-30 years ago.

As has been mentioned above, in Russia much attention is paid to the forest regenerating problems. In 1993, forest seeding and planting was carried out on an area of 392 thousand hectares (2). Ten years ago this area was twice as large. The correlation between area seeded vs planted is now about 1:5.6 (15). In the past seeding was used more widely. The growing emphasis on planting is a stable trend in our forestry.

The main tree species propagated in Russia are coniferous, mostly spruce (*Picea excelsa)* and pine (*Pinus sylvestris)*. As a rule tree plantations are created pure in composition taking into account the fact that a desirable admixture of deciduous trees and bushes will invade naturally.

In many cases planting is preceded by site and soil preparation. Methods and techniques used are dependant on soil conditions. On damp and wet soils seedlings are planted into micro elevations. To prepare them, special forest plows are used. The initial density of tree plantations ranged from 2-4 thousand seedlings per ha, depending on conditions.

In our near and distant past in Russia, there were outstanding examples of hand-planted forests created (15). Nevertheless, many of our foresters consider planting to be a method of reforestation to be used solely in areas where it is impossible to regenerate forests naturally. From this point of view, if hand-planted forests appear to be no worse than a natural one, it is considered to be a success.

Scientists of our Institute have another point of view on the tree plantation significance and their role in mankind future (7). On the basis of 25 years' investigations we have come to the conclusion that in south taiga areas with rather fertile soils, in spruce and pine plantations, given certain regimes of site and soil preparation and stands tending, it is possible to obtain from one ha at the age of 50 years, about 300 m^3 of balances or at the age of 65- 350 m^3 of saw logs (16).

The results further indicate that:

1. In these tree plantations it is possible, in a shorter time, to get more timber than in natural forests.
2. If the tree plantation is situated not far from a large forest industry centre, the intensive production of timber there may be profitable (17,18).
3. The creation of such tree plantations concentrated on limited areas will make it possible to enlarge the area of non-commercial forests, to reserve them as objects of environmental and recreation significance.

We suppose the trend toward the creation of highly productive tree plantations with shortened cutting ages has the importance not only for areas with a warm or hot, humid climate, but also for the south taiga and mixed forest zones.

The idea is being realized now by some forest farms in the districts of St. Petersburg, Pskov, Vologda, Kostroma, Karelia and Nizniy Novgorod. Simultaneously the investigations in this field are to be continued and we shall be glad to coordinate them with researchers of other countries.

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Growth and Yield in Even-Aged and Uneven-Aged Silvicultural Systems in the Conifer-Dominated Forests of Europe*

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Uneven-aged silvicultural systems have a long tradition in some regions of central Europe, but their occurence is rather limited. Debates about sites, stand composition and management are given. Based on long term experiments, tree growth rate, volume production in diameter classes and financial results are compared for different situations. The conversion of even-aged stands to uneven-aged stands is outlined with some conclusions about management practices.

Introduction

Even-aged silviculture systems were developed in central Europe and have been in use since the beginning of the 1800s. The main reason behind the development of these systems was the widespread lack of timber and fuelwood caused by the overuse of forest resources, due in part to irregular selection cuttings and also to the destruction of natural regeneration from cattle grazing and litter raking. The forest legislation established in all German countries between 1820 and 1850 prohibited selection systems and uneven-aged forestry. Private and commune forest landowners and many foresters, especially in the middle Black Forest, put up strong resistance against this prohibition. There was a long-established and prosperous tradition of irregular forestry.

In central Europe, uneven-aged silviculture systems with irregular forests occur mostly in mountainous areas, from about 400 to 2200 m in elevation. Mixed stands of indigenous silver fir (*Abies alba* Mill.), beech (*Fagus sylvatica* L.) and varying proportions of introduced Norway spruce (*Picea abies* Karst.) prevail at elevations of 400 – 1200 / 1400 m. Pure stands of Norway spruce dominate at higher altitudes in the boreal and (sub-)alpine zones where they are naturally occurring.

Irregularity of forest stands has developed from two silvicultural systems which are termed as "irregular shelterwood" and "selection system."

The selection system is used in parts of Switzerland, southeastern France, both southwestern Austria and Germany, especially in the Black Forest. Their total area is approximately 126,000 ha (Schütz 1994). This corresponds to less than 5% of the total forest area. About another 5 – 10% may be managed using irregular shelterwood systems. In practice, during the period of regeneration, there are many overlapping similarities between the two silvicultural methods.

The appeal of the very old "irregular forests idea" lies in the obvious economic, ecological and amenity benefits. Two of the most important advantages of these systems are that they can produce a higher percentage of big timber, and that the tree species used, the ecology and the "look" of these forests is close to "natural" woodlands. These characteristics have made irregular systems an attractive ideal which some private and most public forest owners now strive for. The original purpose of such very artificial irregular systems, the very special site conditions and stand structures for which they were intended are obviously forgotten.

The following text describes the background and the practice of irregularity and the corresponding silvicultural systems. Some aspects of growth and yield are outlined and, finally, an evaluation of the systems with some conclusions is made.

The Background of Irregularity

Irregular systems are based on the very special shade tolerant characteristics of the silver fir and beech used, as well as on the above mentioned historical reasons and economic considerations.

Irregular forests are owned largely by farmers and rural communes. In the past, irregular harvesting was favoured because of the varying timber needs of these owners. Historically, in the Black Forest the production of larger sized logs (18 m in length and 46 cm diameter on top) was for piles in the Netherlands and ship building. Diameter limits in harvesting were also a contributing factor to the development of irregularity. Today, the most convincing argument for these systems is the cost / price relationship of harvesting large-sized timber. In addition, the tree species used in irregular systems are components of the natural regional woodland. Natural regeneration is used. The shade tolerant characteristics of fir and beech allow them to remain overtopped in the understorey in semi-shade for decades without losing their ability to react positively on release. The irregular overstorey favours natural differentiation of stands and helps to avoid the costly harvesting of small-sized trees. Compared to even-aged stands, there is also a higher stability against windthrow.

* Translation: Philippa Rodrigues, Edmonton, Canada

Silvicultural Systems

In practice, selection and irregular shelterwood systems have overlapping qualities:

In the **selection system**, fir together with spruce, and not more than 10% beech make up a mosaic of trees in different stages of development, ordered next to one another, or over one another, mostly as individuals, and rarely in groups. Young, middle-aged and large old trees are able to make optimal use of the available light and growing space. These forests look "natural" due to the higher diversity in tree sizes as compared to other forests. However, the specialized structure of these forests makes it almost impossible to mistake them for natural origin stands.

The **irregular shelterwood** system generally employs 4 to 10 or even more successive fellings over a 30-60 year or more regeneration period. Young crops are produced with some uneven-aged qualities. For decades these stands may look similar to selection forests, but as they grow to full stand closure, the stand takes on more even-aged characteristics until the regeneration period is started again at the age of 80 to 90 years. Rotation periods of 120 to 150 years are common in such conditions. These systems fully utilize the growth capacity of individual trees.

Selection systems are based specifically on the removal of mature trees and thinning of the immature trees. In the ideal situation, harvesting is a matter of achieving and maintaining the *plenter*-equilibrium. This equilibrium is the stem distribution at which the ingrowth into any single diameter class during a given time period is exactly equal to losses through harvesting or mortality due to harvesting damage or other reasons.

Examples of different diameter distributions in selection forests are given in Figure 1.

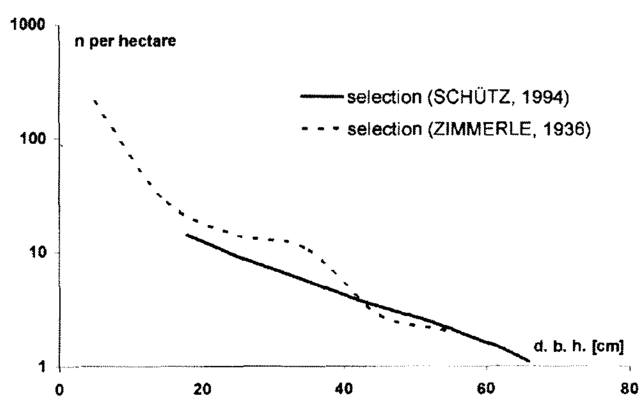

Figure 1. Diameter distributions in selection forests (Schütz 1994, Zimmerle 1936, experimental stand Plw 1612 in Baden-Württemberg)

These diameter distributions are an approach to an ideal. They are not constants and can vary depending on stand treatment. Even-aged forests have higher stem numbers and basal areas in the same diameter class. DUC (1991) investigated how many young trees are required for a sustained selection forest stand.

The specialized structure of irregular stands can only be maintained through regular and diligent entrances into the stands, preferably at intervals of 5-10 years. This ideal equilibrium can be lost in a matter of a few years if the standing volumes exceed the optimum, or if the conditions needed for adequate regeneration are not met. Finally, this equilibrium can also be lost if the medium-sized trees in the stand are destabilized and begin to die off or if they are destroyed by snowbreak. High ungulate game populations today cause very serious problems for the natural regeneration of fir and beech in many areas.

Optimal standing volumes of the fir-spruce (beech) plenter-forests are considered to lie some where between 350 to 450 cu m/ha (Mitscherlich 1952, Schütz 1992). The most important factors for establishing the optimum standing volumes are site quality and the production goals. On better sites, and if the aim is to produce very large diameters, the optimal volumes lie at the higher end of this range. For (sub-)alpine irregular spruce stands Schütz (1994) proposes 220 – 300, i. M. 250 cu m/ha.

Growth and Yield

Discussions concerning the advantages and disadvantages of even-aged versus irregular silver fir-Norway spruce – beech forests go back to the beginning of the 1800s. This gave rise to many studies concerning the growth (Schuberg 1886, Hufnagl 1892, Flury 1927, Hausrath 1938, Zimmerle 1936, 1941, Badoux 1949, Mitscherlich 1952, Assmann 1961, Schütz 1975, 1985), ecophysiology (Kern 1966) and economics of irregular stands (Siegmund 1973, Schütz 1989, Schutz 1993). However, a direct comparison over an entire rotation between clearcutting, selection and irregular shelterwood systems remains, as of yet, missing. The first reason for this being that the characteristics of the tree species involved do not allow mixed stands to be established successfully by plantation or by regular shelterwood regeneration. The second reason is the lack of clear quantitative procedures for experimental treatments in natural regeneration. The third reason is the absence of large areas with comparable sites and stands. Finally, the long experimental period of up to 150 years required to do such a study has also been very prohibitive. The difficulty of using age as a measure of comparison in uneven-aged forests in combination with the questions of stem taper and wood quality are additional, practically insurmountable, problems in undertaking such studies.

Despite the above mentioned restrictions, many relevant results can still be presented:

1. Long-term natural regeneration in wedge or irregular shelterwood systems: a case history

During the 1920s, a number of disputes arose about the most suitable procedures for achieving natural regeneration of stands. Eberhard's approach was especially innovative. In 1927 the Württemberg Forest Research Institute (Zimmerle) started a long term experiment in the forest district of Langenbrand, in a mixed stand of silver fir and pine (Norway spruce, beech). The aim of the experiment

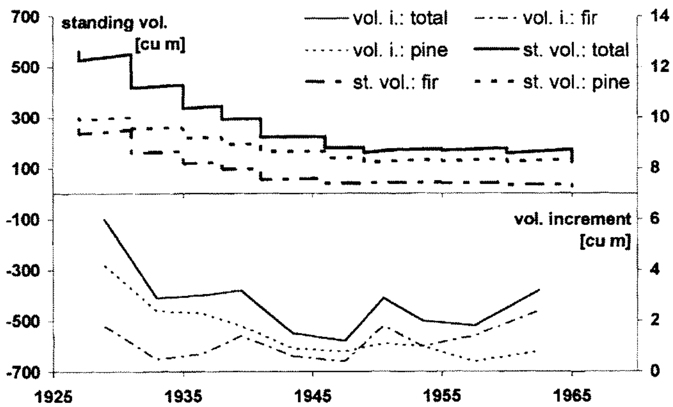

Figure 2. Standing volumes and periodic volume increments in a mixed stand of silver fir and pine from 1928-1965

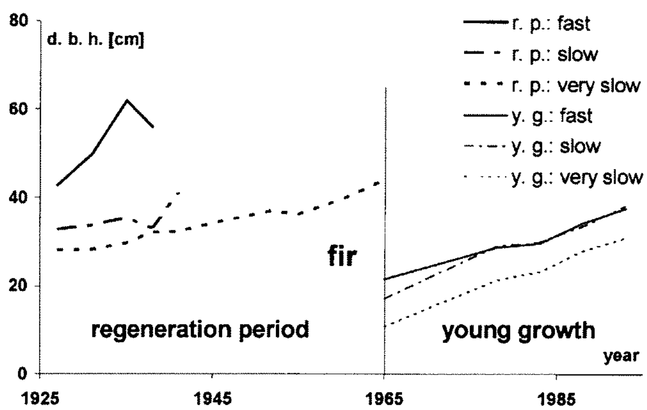

Figure 3. The development of the silver fir mean stand diameters in both the old and the young growth

was to examine the effects of different regeneration procedures. The silvicultural procedure used at the beginning of the experiment was a wedge system, which was later combined with an irregular shelterwood system, or wedge cutting systems (Eberhard 1922). The resulting value relationships when comparing "fast" (5-10 years) to "very, very slow" harvesting and regenerating (nearly 60 years) were 1 to 2 (Kenk 1988a)!

Figure 2. shows the development of standing volumes and increments in the old growth, due to the fellings in the period from 1928 to 1965.

The development of the most important growth component – DBH (cm) is outlined in Figure 3.

The most important point for the successful natural regeneration of these mixed stands was the presence of shade tolerant tree species. It was the precondition for stand stability and value production. Problems for the future species mixture arose from the more light demanding Scots pine. Scots pine disappears with longer regeneration periods or needs to be established using special techniques. The presence of shade-tolerant fir leads to a considerable shortening of the "diameter production period" of 20 – 40 years.

A key problem in both irregular shelterwood and selection silviculture systems is the growth responses of the different crown classes. Positive responses depend strongly on the height / diameter ratio as shown in Figure 4 for some of our experiments.

2. *Selection systems*

Shade tolerant tree species take the most advantage of irregularity. This is shown in Figure 5 using the example of overshadowed silver firs (Mitscherlich 1952).

Fir can survive for decades in the understorey, and does not seem to be markedly influenced after release.

Norway spruce is affected by long periods of suppression in that total height growth is diminished (Weise 1994).

Tree size diversity and the varying growth and competition conditions in irregular stands lead to wider variation in tree ring growth as compared to even-aged stands.

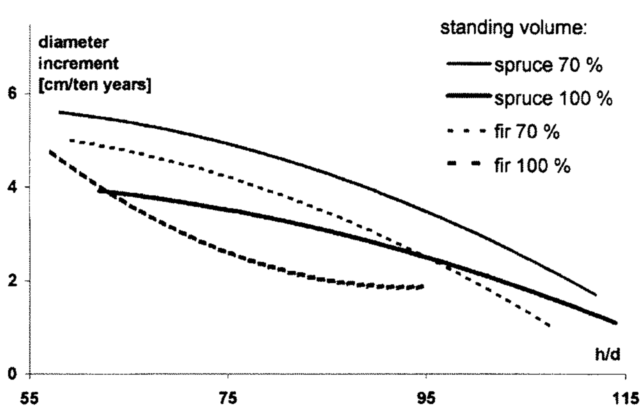

Figure 4. Radial diameter growth as a function of height-diameter ratio in closed and open stands of silver fir and Norway spruce

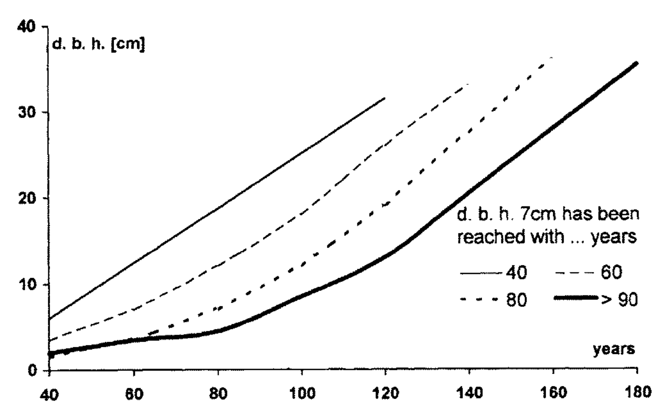

Figure 5. Diameter growth of dominant silver fir after four different durations of suppression (Mitscherlich 1952)

The individual diameter increments depend on site conditions, tree diameter, competition and especially on crown length as shown in Figure 6. The reductions between 1970 and 1980 were caused by very dry and warm summers.

Height growth and height curves in selection forests have been investigated by Zimmerle (1941), Prodan (1944), Leibundgut (1945), Badoux (1949), Mitscherlich (1952), Schütz (1985, 1992). To summarize, total heights in selection forests are lower, probably due to the free-standing dominant trees, and to the lack of competition and intensive impacts of winds (Mitscherlich 1961). Height curves in plenter forests (uneven-aged) are rather constant. Deviations can be observed if the stand structure is moving away from plenter equilibrium to a structure similar to those found in age-class forests.

Higher volumes in the diameter classes lead to an upwards shift in the height growth curve, and lower volumes to a downward shift. Because of this, one may conclude that there is a permanent oscillation between curves.

One open question is the possible effect of changing site conditions. Improvements in site conditions have been widely documented in even-aged Norway spruce forests. These are due to nitrogen input, increases in atmospheric CO_2, higher mean annual temperatures and probably also due to improvement in silviculture practices (Kenk and Fischer 1988, Kenk 1992). There are probably parallel effects occurring in selection forests.

3. *Height-Diameter (H/D) ratios and stem form*

H/D ratios and stem forms are of major importance in irregular stands. They have been investigated by Burger (1941), Leibundgut (1945), Zimmerle (1950), Mitscherlich (1961). Compared to even-aged stands the H/D ratios are lower, but without remarkable differences between silver fir and Norway spruce, examples of which are shown in Figure 7.

The H/D relationships reflect the various growth conditions and give information about the risk of wind and snow break, and taper. In selection forests, trees with small diameters have a more favourable taper compared to those grown in even-aged stands. Silver fir with a DBH over 60 cm and Norway spruce over 30 cm have different tapers (Mitscherlich 1961). This is due to the production of reaction wood in the lower parts of the stems probably caused by constant stress due to wind or storms.

4. *Volume increments*

Basic to the evaluation of both irregular shelterwood and selection systems are volume growth and periodic increments. Most results indicate that the performance of plenter- and even-aged forests is rather similar. The findings of Gerhardt (1934), Mitscherlich (1952), Schütz (1989) and Zimmerle (1936, 1941) show that even-aged stands usually have higher increments, and in only one case was it found to be lower. Assmann (1961) reported better performances of even-aged stands. The long term results of one of our sample plots is shown in Figure 8.

The long-term periodic volume increments are between

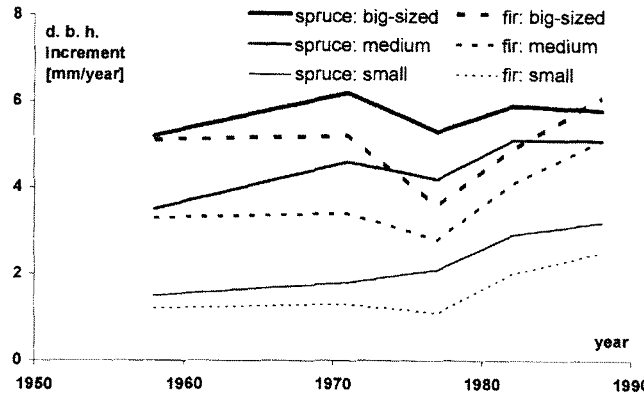

Figure 6. Crown length and diameter growth of fir and spruce 1950-1990 (SPIECKER 1991)

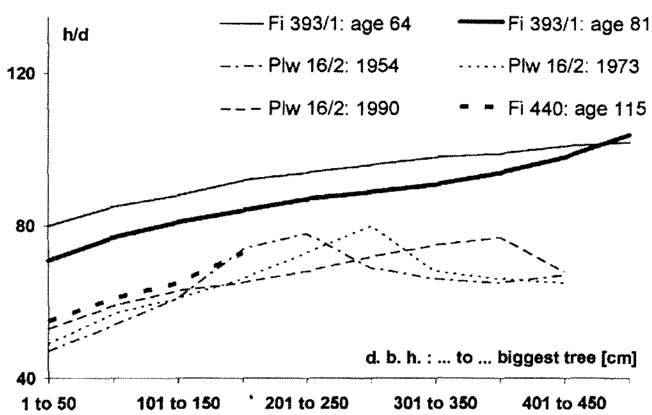

Figure 7. H/D ratios in selection and in even-aged stands by diameter class of the largest tree.

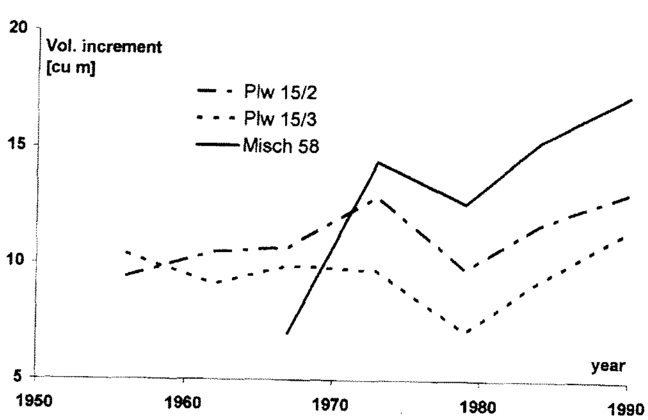

Figure 8. Volume increment in the selection experiment Plw 15/2 and in the even-aged control Misch 58

9 and 11 m^3 per ha per year. Actually we have measured 11-13 m^3/ha/yr.

Volume increment is surprisingly only slightly dependent on standing volumes (Mitscherlich 1961). In years where there was a lack of precipitation during the growing season, volume increments were higher in plots with lower standing volumes (Spiecker 1986). A considerable difference is apparent when a comparison of volume increments in the diameter classes of selection and age-class forests is made.

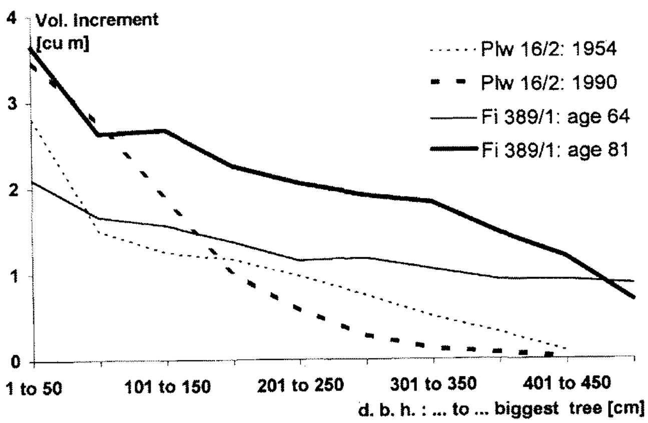

Figure 9. Periodic volume increment by DBH class in the selection experiment 16/2 and in the even-aged Norway spruce experiment-Fi 389

The lower diameter classes contribute proportionally less to the standing volumes and increment growth. The biggest increase in increment per m^2 of canopy and surface area, or per m^3 of crown volume occurs in those trees that are growing from the middle into the upper canopy levels. These trees are free standing but have not as yet developed too broad a crown (Mitscherlich 1961).

Assortment Production, Labour Intensity and Economic Return

The reduction of unprofitable sizes is a key point in improving financial results in central European forestry. It is undisputed that plenter-forests produce higher percentages of large diameter trees in comparison to traditionally treated even-aged forests. There is also a lower labour intensity compared to age-class forests (Siegmund 1973, Schulz 1993 and others).

Figure 10 shows the 1989 state forest assortment distribution compared with the selection forest and two widely-spaced even-aged spruce stands.

Other concepts in treating age-class forests, namely wide spacing and/or early and intensive stand tending, can reduce the proportion of unmerchantable small timber produced. These concepts make it possible to postpone the first entrance into the stand until the trees have reached DBHs of 27-30 cm. This can make age-class forests equal, and in my opinion, superior to plenter-forests. Variation in rotation periods and stand treatment allows greater

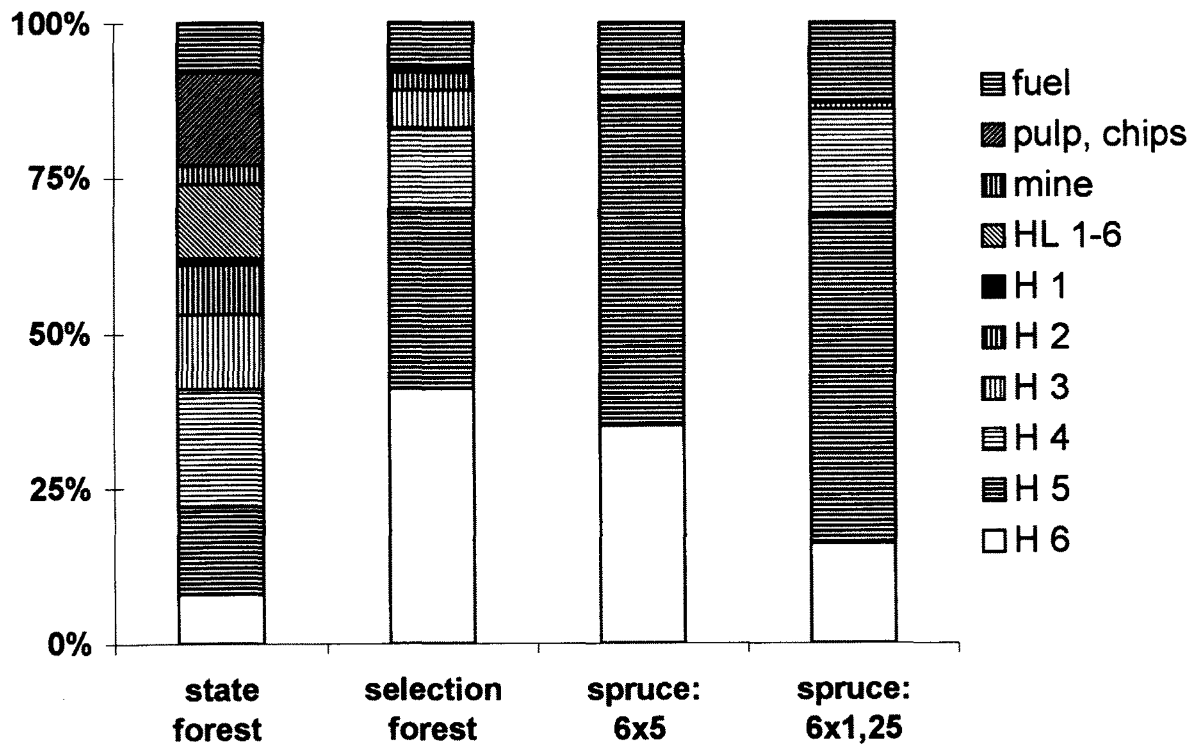

Figure 10. Assortment structure resulting from different stand treatments

spatial opportunities for individual trees.

A new comparison between different plenter-forests in the northern Black Forest and comparable age-class forests (Schulz 1993) determined that there was a 20% net return increase per m^3 because of the larger average diameters and lower harvesting costs (Fig. 11).

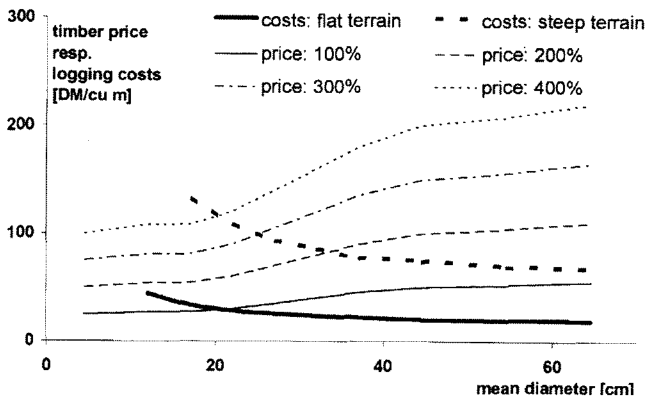

Figure 11. Norway spruce/silver fir — Timber prices and harvesting costs (DM/m^3) for stands of different diameter

The key explanation for such results is our very differing prices for large-sized trees compared to North America. A long term comparison of the labour intensity demonstrates that plenter-forests require 1/5 less hours per hectare (Stibig 1987). This means about 2 to 3 less hours. The reasons for this are the more advantageous assortment distributions and the low costs associated with stand establishment, tending and forest diseases. Road building and maintenance costs are somewhat higher because of the urgent necessity of a denser and continuously operating road network.

In Switzerland, Schütz (1985) calculated the financial result of two plenter-forests at 119% and 124% of the corresponding age-class forest.

In a very detailed comparison of the returns from different silvicultural systems such as, clearcutting, irregular shelterwood, femel, and plenter systems, Siegmund (1973) found the following net value production relationships:

Clear-cutting	Irregular Shelter-wood	Femel	Plenter
100	102	132	145

Successful plenter-forest management does not solely depend on site condition and the absolute necessity of the existence of fir. Equally important, are the existence of a dense road network to help minimize harvesting and skidding damage to small and medium-sized trees. Low game populations also allow the natural regeneration of fir without expensive game protection measures. In addition to this, it is important to establish sufficiently specialized and quality management plans.

Summary

1. In general, selection forests possess exceptional economic, ecological, and aesthetic qualities. In practice, however, plenter-forests are possible only on mountainous sites within the natural range of silver fir and spruce.

2. Maintaining plenter-structures and the natural regeneration of mixed stands depends largely on good accessibility, careful harvesting, low game populations and a competent working force.

3. The growth and yield situations of different silviculture systems are well enough understood to make successful management possible.

4. The economic results of plenter-forests and age-class forests managed according to modern establishment and tending methods, would favour age-class forests — especially if used in conjunction with natural regeneration.

5. Worthy of further investigation is the question of wood quality. Until now comparative studies between age-class forests and plenter-forests have not been attempted. In plenter-forests, sawlog quality might conceivably be poorer because of the larger production of reaction wood, ring shake, clearly greater abnormal taper of the (usually) larger assortments. In addition, fir wood is less appreciated than spruce in central Europe because of its colour and the existence of black knots. On the other hand, fir is less susceptible to fungus and also has greater stability.

6. The conversion of existing fir-spruce-beech age-class forests into plenter-forests is presently being attempted on a large scale. The strategies for this are well known. However, one must anticipate the destabilization of the overstocked old wood, upon removal of the largest stems, the depletion of standing volumes, and the subsequent increase in the roughness of the canopy surface.

7. It is cause for concern that in regions in which plenter-forests might be possible, only 8% in the Black Forest, 20% in Neuchatel, and 32% in the Emmental are thus treated (Schütz 1994).

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Ecology and Dynamics of Boreal Understorey Species and Their Role in Partial-Cut Silviculture

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This review focuses on boreal mixedwood understorey shrubs and herbs and how they will interact with changes in overstorey conditions following partial-cutting. Over the course of stand development following disturbance, light levels in the understorey will be reduced as the leaf area increases and with an increase in the spruce composition of stands. Understorey vegetation density and composition are highly dependent upon overstorey density. Forest shrubs and herbs can be placed into three categories: "Understorey avoiders" are adapted to grow only in open conditions in the period after stand disturbance; these species recruit from long distance dispersal of seed or from seed banks and usually have photosynthetic strategies that demand strong light. "Understorey obligates" must live in the shelter of an understorey; they are usually short in stature, adapted to low light environments and have leaf phenology strategies that allow photosynthesis in periods other than summer. "Understorey tolerators" survive in understorey environments but grow best in open conditions; these are usually taller, summer green herbs and shrubs that can grow over a wide range of light conditions.

The impact of understorey vegetation on the success of partial-cut silviculture systems will depend upon three major factors: 1) The canopy density of the overstorey prior to cutting. If the canopy is heavy, the understorey will be sparse or nonexistent. There will be a lag before the understorey re-establishes following partial-cutting. If the canopy is light, the understorey will be well-established and in position to dominate the site. 2) The tolerance of the tree species to be regenerated relative to the tolerance of the main understorey species will be important in determining how much canopy needs to be retained. 3) The response of the understorey species to disturbance will be important. Frequently, mechanical site preparation is needed to prepare seed beds and planting spots. The time free of vegetation will be critical to the establishment of the target tree species.

Introduction

In northern forests the largest diversity of vascular plant flora is in the understorey species. These species are important in wildlife habitat, nutrient cycling (Tappeiner and John 1973) and ecosystem production. In general there are few studies that examine the effects of forest management on the understorey flora (however, see references below). Recently, there has been increasing pressure to manage forests so that natural ecosystem processes and biodiversity are sustained (Lieffers and Beck 1994). We must develop management systems that are more in tune with natural ecosystem processes. Partial-cut silviculture is one of the treatments that will likely play a larger role in boreal forest management systems of the future. As there have been difficulties in regeneration of late successional conifers using clearcut systems (Eis 1981, Lieffers et al. 1993), partial-cut systems should be explored.

The main objective of partial-cut silvicultural systems is to establish the next cohort of trees in the understorey of the previous generation of trees. This understorey, however, is shared by a diverse assemblage of shrubs and herbs which lives under the canopy of taller trees. Some of these understorey species are the competitors in regeneration of trees immediately after clearcutting (Haeussler et al. 1990). One of the reasons for partial-cut silvicultural systems is to suppress problem vegetation by the use of partial shade to limit the availability of light and other resources during the establishment of the next generation of trees (Holbo et al. 1985; Walstad et al. 1987; McDonald and Fiddler 1993). At this time, however, there has been limited understanding of how most understorey species will interact with partial-cut systems.

Objectives of this paper are to review the information on the ecology of forest shrubs and herbs and to assess how they will react in partial cut silviculture systems. Wherever possible this paper will use examples from the boreal mixedwood forest. These forests of *Populus tremuloides* (aspen) and *Picea glauca* (white spruce) (Rowe 1972) are widespread in the boreal forests of Canada, important economically and have some of the most serious problems with competition during regeneration.

Changes in Understorey Environment Over Time

Because of their short stature, understorey vegetation are greatly affected by the changes in biomass and crown density of taller overstorey trees. This section examines changes in understorey conditions over stand development.

Stand Initiation

Following fire or clearcutting, most of the tall tree vegetation may be removed and nearly full light will strike the ground. In this period, there is also increased soil moisture and nutrient turnover (Borman and Likens 1969). These available resources can result in explosive growth of some species of shrub and herbaceous vegetation, which can severely limit success of plantations (Eis 1981; Lieffers et al. 1993). The period after a major disturbance when even-age stands of trees commonly establish is the stand initiation phase (Oliver and Larson 1990). Following fire, most boreal forest stands regenerate even-aged stands of trees (Dix and Swan 1971). The conditions for establishment and the type and amount of shrub and herb competition, however, are critical for controlling the stand composition in the next decades (McCune and Allen 1985) and the trajectory of succession (Wagner and Zasada 1991). The degree of forest floor disturbance will have an impact on the type of recruiting vegetation. Sprouting vegetation will be encouraged by clearcuts (Brumelis and Carleton 1988) and shallow-burning fires (Ahlgren 1960; Dyrness and Norum 1983; Johnson and Woodard 1985). These species might be killed by hot fires.

The stand initiation phase is marked by establishment of trees, a gradual redevelopment of a tree canopy layer and loss of light to the understorey. The development of a heavy, relatively even-aged tree canopy stops further recruitment and marks the end of this phase. Stand initiation may last only a few years if the trees are fast growing or establishing from clonal reproduction such as aspen suckers (Peterson and Peterson 1992). Development of a heavy shrub / herb layer such as thick beds of *Calamagrostis canadensis* (bluejoint) (Lieffers et al. 1993) will retard tree initiation (Rowe 1955; Eis 1981); in some circumstances it is possible to have a stable grass community that resists establishment of trees (McMurtrie and Wolf 1983). The tree initiation phase is also delayed when trees have slow juvenile growth rates such as with establishing conifers (Waring and Schlesinger 1985). In aspen stands, overstorey transmission of light will drop to about 20% (Lieffers and Stadt 1994) with the development of maximum leaf area and maximum crown length, at about 15 to 20 years (Peterson and Peterson 1992). (Fig. 1).

Mid-Succession

Once the establishing trees reach canopy closure and full leaf area is achieved there is little light transmitted to understorey layers. This phase of low transmitted light associated with a dense canopy of even-aged trees has been termed the stem exclusion phase of stand development (Oliver and Larson 1990). This stage probably results in the lowest level of resources to the understorey. The overstorey canopy density changes with the species composition; in general, in eastern hardwoods, the more shade-tolerant tree species have longer and denser crowns and therefore they transmit less light than intolerant species (Canham et al. 1994). In boreal mixedwoods, aspen transmits much more light than white spruce of similar basal area (Lieffers and Stadt 1994; Constabel and Lieffers unpub.). In general there is a tradeoff between light interception by the tree and the understorey layers; sites with heavy overstorey have a weak understorey and vice versa (Cannell and Grace 1993). Light transmission will be affected by the vigour of the overstorey trees; sites dominated by aspen may show a gradual increase in light transmission from 30 to 120 years (Lieffers and Stadt 1994). Aspen-dominated stands transmit sufficient light to the understorey to allow establishment of advance growth of white spruce (Brace and Bella 1989). The understorey white spruce may be as old as the aspen (Dix and Swan 1971) or may gradually recruit into the stand (Lieffers and Navratil unpub.) If the aspen are gradually replaced by the white spruce, the light levels are reduced (Lieffers and Stadt 1994) (Fig. 1).

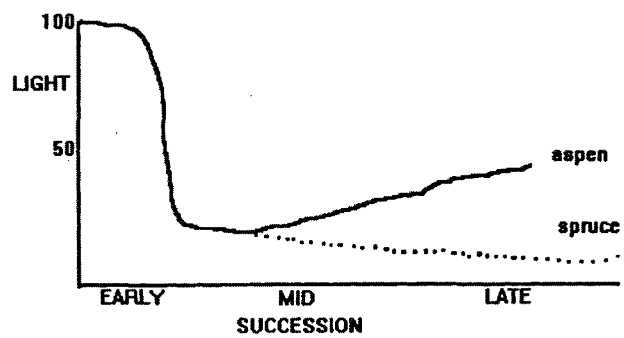

Figure 1. Change in overstorey light transmission in boreal forest mixedwoods with change in stand composition and development. Data from Lieffers and Stadt (1994) and Peterson and Peterson (1992).

In boreal mixedwood stands, the true stem exclusion phase may not occur until white spruce dominate the overstorey. At this stage, light transmission drops to less than 10% of incoming light (Lieffers and Stadt 1994), the substrate becomes dominated by mosses (Rowe 1956; Bonan and Korzuhin 1989) which keep the soil cooler by their insulating effect, and there are also associated reductions in nutrient availability (Kuuluvainen et al. 1993). Part of the reason for the switch from vascular plants to feather mosses relates to the change in litter types; coniferous litter does not bury developing moss layers (Busby et al. 1978), but other soil and light resources are also involved (Kuuluvainen et al. 1993). Small holes in the canopy between leaves and branches result in short periods of high light intensity. These sunflecks can provide a significant part of the daily photosynthesis of some species (Pearcy 1988). While light plays a dominant role in controlling understorey composition, water relations and nutrition associated with individual canopy trees also plays a role in the pattern of understorey development (Kuuluvainen and Pukkala 1989; Kuuluvainen et al. 1993). The diversity of vascular plants in the understorey of northern forests is inversely related to the amount of light transmitted to the understorey (Uemura 1994).

Deciduous overstoreys may transmit relatively little light to the understorey in the summer months, but in the leaf-off period in the autumn, winter and spring there is high light transmittance to the understorey (Hutchison and Matt 1977). In conifer-dominated stands, the highest light transmission is in late spring and early summer (Ross et al. 1986; Gholz et al. 1991); in other seasons the lower solar elevation results in more light interception by tree crowns, and little light reaches the understorey (Constabel Unpub.). This low availability of light in other seasons may be another reason for the reduction in species richness in spruce-fir sites (Uemura 1994), compared to hardwood and mixed forests.

Late Succession

In late succession, overstorey trees begin to lose vigour and there are gaps in the canopy created by the death of some of the even-aged overstorey trees (Bormann and Likens 1969). With the increased light transmission and the renewed possibilities for tree recruitment, Oliver and Larson (1990) described this phase as the understorey reinitiation phase. Larger holes in the canopy brought about by the death of an overstorey tree produce large zones and long periods of high light in an understorey. These canopy gaps can result in a significant shift in understorey composition within a very short distance within stands (Lertzman and Krebs 1991). It is noteworthy, however, that at high latitudes, with its low solar elevation, gaps must be large for successful establishment of trees; trees that establish in small light gaps may experience lower light conditions later in development when their tops grow up into shaded elevations (Canham 1988).

Red:Far Red Ratio

Forest canopies absorb or reflect much of the light in the visible spectrum (400-700 nm), while transmitting most of the light in the far-red spectrum (730 nm) (Larcher 1980). The ratio between the red (660 nm) and far red (730 nm) is known to control the phytochrome pigment systems that control seed germination (Haeussler and Tappeiner 1993), and rhizome and tuber formation in understorey plants (Smith 1982). In midsummer the red:far red ratio is slightly lower in white spruce stands than in aspen-dominated stands but the trend was reversed in September (Ross et al. 1986). In coniferous stands the red:far red ratio decreases with increasing canopy density (Messier et al. 1989).

Characteristics of Forest Shrubs and Herbs

Vertical Layers of Understorey Species

Based upon their usual height, understorey species can be categorized into several canopy layers. Tall shrub, low shrub / tall herb, ground layer are common categorizations of understorey plants (Rowe 1956). The degree of development of each of these layers is dependent upon the amount of light transmitted by the higher canopy layers (Cannell and Grace 1993; A. Constabel unpub.). Aspen canopies which transmit large amounts of light have dense, multi-layered understoreys (Rowe 1956). Conversely, dense overstoreys such as spruce stands have a sparse understorey dominated by feather mosses (Rowe 1956; Kuuluvainen et al. 1993). It is noteworthy, however, that in midsummer, light transmitted to ground level is uniformly low (ca. 6% of incoming) over boreal mixedwood compositions ranging from pure young aspen, to mature aspen to mixtures of mature aspen and white spruce (Constabel and Lieffers unpub).

Phenology Strategies

Because of the seasonal variation in light quantity associated with deciduous overstorey trees, there are opportunities for a range of leaf strategies used by understorey plants. Most tall shrubs and herbs are summer green. Evergreen and biennial leaves are more likely to be developed in short understorey species (Uemura 1994). Similarly, non-differentiated or weakly-differentiated overwintering buds with low levels of dormancy (Yoshie and Yoshida 1989) may allow some shorter species with evergreen and biennial leaf strategies to take advantage of light available in seasons other than summer. If the spring and fall periods of high illumination under deciduous canopies are important in the seasonal carbon budget of understorey species, then these species must be able to photosynthesize at low temperature and withstand nighttime frosts. Part of the mechanism for frost tolerance may relate to short structure that will likely ensure that foliage is covered by snow during very cold temperatures (Uemura 1994).

Shade/Understorey Adaptation

There is variation in the ability of forest shrub and herb species to survive under a tree canopy. In general there has been little detailed work describing the shade tolerance of shrubs and herbs; for most species, information is usually qualitative (Haeussler et al. 1990). Rowe (1956) made the observation that in a particular stand, understorey plants' shade tolerance are inversely ranked in relation to height. The light requirements of some individual species have been determined: *Gaultheria shallon* (salal) is considered to be quite shade tolerant, requiring heavy coniferous canopies to eliminate if from a site (Messier et al. 1989; Bunnell 1990; Huffman et al. 1994). Salal survives in both shaded and open sites because of its abilities to produce both sun and shade leaves (Smith 1991). Bluejoint and *Epilobium angustifolium* (fireweed) thrive under aspen stands with greater than 18% transmitted light but are gradually eliminated from boreal mixedwood stands with a large component of white spruce, because of its large, dense crowns (Lieffers and Stadt 1994). With bluejoint , stomatal conductance tracks changes in light intensity (Greenway and Lieffers unpub.); it therefore will not be able to take advantage of sunflecks in otherwise deep shade. This stomatal tracking strategy (Knapp and Smith 1989) is consistent with a species more adapted for water conservation in open meadows than for growth in understorey environments. *Rubus spectabilis* (salmonberry), *Acer circinatum* (vinemaple) and *Acer macrophyllum* (bigleaf maple) can usually survive under a dense coniferous overstorey but will be of low biomass (Tappeiner and Zasada 1993; Tappeiner et al. 1991).

Classes of Shrubs and Herbs

It is noteworthy that forest shrubs and herbs respond differently to changes in overstorey density (Hannerz and Hånell 1993). When an area is clearcut, some species are virtually eliminated, some species present in the understorey respond positively to the cutting and other new species recruit into the area. Shrubs and herbs in forest environments can be categorized into three broad groups:

Understorey Avoiders

These species grow best in the open conditions immediately after disturbance. They may have little adaptation to survive in the shade of forest stands. This group is analogous to the ruderals of Grime's (1979) classification. Species recruit on these sites by long distance spread of seed from off-site sources such as with *Senecio* and *Cirsium arvense* (Hannerz and Hånell 1993). Recruitment may also be from seed banks, e.g., *Geranium bicknellii* (geranium) and *Prunus pensylvanica* (pincherry) (Marks 1974). The seedbank is a main mechanism to maintain their population on the site after canopy closure. Some species such as *Rubus idaeus* (raspberry) (Whitney 1986) and bluejoint (Conn 1990) also have seedbank strategies but have other adaptations to survive until the next early successional period. The long distance dispersal mechanism of fireweed (Solbreck and Andersson 1989) allows this species to act as an understorey avoider in some circumstances. True understorey avoiders are not likely to be serious competitors in silviculture systems where significant shade is retained.

Understorey Obligates

Understoreys are cooler, have high relative humidity, low evaporative demand and have lower light conditions (Oke 1987). There are some species which are adapted to these conditions and are unable to survive in open conditions. Frequently these species are short in stature and have developed leaf phenology and photosynthetic adaptations to understorey conditions. They frequently lack the protective pigments that allow them to survive in full light conditions (Powles 1984). Examples might be *Aralia nudicalis* (sarsaparilla), *Mitella nuda* (bishop's cap), *Trientalis borealis* (star flower), *Linnaea borealis* (twinflower). Feather mosses such as *Hylocomium splendens* also fit in this category (Busby et al. 1978). Understorey obligates are not likely to be problem competitors in clearcuts but some may be competitive to establishing spruce seedlings in understoreys (Rowe 1955).

Understorey Tolerators

Some species grow best in the open conditions of early succession but are able to persist in the understorey of many stands. This group is usually from the shrub and tall herb category and are spring and summer green species. Examples from the boreal forest are bluejoint (Lieffers et al. 1993), raspberry, *Alnus crispa* (green alder) and *Corylus cornuta* (beaked hazel) (Brumelis and Carleton 1988). Bluejoint can persist at low biomass and size in the understorey until light transmission is reduced to <20%. At this point it begins to die out and is nearly eliminated at 10% of incoming light (Lieffers and Stadt 1994). All of the above species will be eliminated, however, in very dense canopy conditions (Rowe 1956). These species are usually in excellent position for a rapid expansion following overstorey harvest in both clearcut and partial-cut silvicultural systems. Indeed, shelterwood cuts may have more diversity of shrubs and herbs than either mature stands or clearcuts (Hannerz and Hånell 1993)

Established individuals of species of the shade tolerator group are more likely to dominate the site than species which must spread into the area from seed (Tappeiner and Zasada 1993). One could argue that the time after the disturbance is the "moment in the sun" that some species populations have waited for, sometimes for a century or more. For these species to survive the transition from understorey conditions to full light following clearcutting or disturbance they must have highly adaptable photosynthetic pigments and leaf strategies (Powles 1984).

Reproduction of Understorey Species.

Most of the plants that survive in the understorey of mature forest stands rely mostly on clonal growth for maintenance of the population once the stand is in the stem exclusion phase. Understorey salal or salmonberry produce extensive and persistent clonal systems (Tappeiner et al. 1991; Tappeiner and Zasada 1993) and spread horizontally into more favourable growing sites. In understorey sites, with salmonberry (Tappeiner et al. 1991), salal (Huffman et al. 1994) and beaked hazel (Tappeiner 1971; Kurmis and Sucoff 1989) there is a development of an uneven aged structure of stems in individual clones with a constant stream of annual death and replacement of stems. In extremely low light environments, root systems of understorey plants are small in relation to their leaf area compared to open-grown plants; this was noted for bluejoint (Powelson and Lieffers 1992) and salal (Messier et al. 1989). In these conditions, the plant appears to be using all of its energy for persistence on the site it occupies and little for clonal reproduction.

Seed reproduction of some understorey species will occur at moderate light levels; for salal it is at 33% crown closure (Messier et al. 1989; Bunnell 1990), for bluejoint flowering starts at 18% light transmission (Lieffers and Stadt 1994). For most boreal forest species, it is not clear how much seedling establishment is possible in understorey environments, but beaked hazel does commonly establish from seed in the understorey of developing stands (Tappeiner 1971, 1979). There is no evidence that bluejoint or fireweed seedlings will establish in undisturbed understoreys of mixedwood forests. For salal, salmonberry, vine maple and big leaf maple there is more successful germination and establishment in thinned stands than in either clearcuts or unthinned stands

(Tappeiner and Zasada 1993).

Response to Disturbance

The ability of a plant to survive disturbance or aggressively recruit into a site following disturbance plays a major role in how it can be manipulated by silvicultural treatments (Wagner and Zasada 1991). In terms of rootstock / rhizome survival following disturbances such as fire or mechanical damage, the depth of organs in the soil, the thickness of protective tissues and the ability of the below-ground organs to survive dissection into small pieces, will play a critical role. Bluejoint rhizomes will be killed by a hot fire (Ahlgren 1960; Dyrness and Norum 1983). Burning may also damage beaked hazel (Tappeiner 1971, 1979) but Johnson and Woodard (1985) reported only minor damage related to burning. In terms of physical damage to the rhizomes, bluejoint will resprout if segments are at least two nodes in length (Powelson and Lieffers 1991). In terms of other silvicultural treatments to control understorey vegetation, aboveground clipping bluejoint had little impact on the regrowth of bluejoint (Hog and Lieffers 1991) and in other situations, chemical herbicides (Tappeiner 1979) or mechanical site preparation (Örlander et al. 1990) might all be useful.

Use of Canopy Shade as a Biocontrol Strategy

A main objective of silviculture is to direct the trajectory of succession (Wagner and Zasada 1991). Partial-cut silvicultural systems can avoid the earliest successional periods by regenerating the late successional species under the canopy of the previous stand. In devising silvicultural systems there are three important factors that will influence the impact of understorey vegetation on the establishment of trees. The first is the density of the canopy prior to the regeneration phase. If the canopy is uniform and dense there may be little understorey below it. Sparse overstorey canopies will support vigorous and thick layers of shrubs and herbs. The second factor is the shade tolerance of the tree species to be regenerated compared to the understorey species. The third is the response of understorey species to disturbance. The following are different combinations of the three:

1) If the stand is dominated by a dense overstorey of conifers, the understorey will usually be dominated by feather mosses (Rowe 1956; Kuuluvainen et al. 1993). If the desired tree species is shade-tolerant relative to the understorey species then the canopy should be opened sufficiently to allow enough ground-level light for development of the target species but not enough light to promote the dominance of shrubs and herbs. Site preparation will likely be needed to provide a consolidated seedbed. Since the understorey must recruit mostly from seed sources but establishment is slow (Tappeiner and Zasada 1993), there will likely be few problems with competing vegetation.
2) If the overstorey is dense but the target tree species is only moderately tolerant, then more of the overstorey must be removed. Here the understorey tolerators will eventually invade the area. To be successful, the tree species must establish before development of a thick shrub / herb layer. Depending upon the methods of spread; i.e., clonal spread from established plants or germination from the seed bank or spread in from adjacent areas, the period of low competition from the understorey may be variable. Again mechanical site preparation may need to prepare seed beds for trees. Because of the increased availability of resources, however, there may be more rapid expansion of some shrub / herb layers.
3) If the overstorey is sparse prior to the regeneration period, the shrub / herb layer is usually well established. Most mature aspen-dominated stands are in this category (Lieffers and Stadt 1994). Here it is unlikely that any overstorey trees should be removed if a relatively shade tolerant tree is to be regenerated. Understorey mechanical or chemical treatments must be applied to reduce the shrubs and herbs. The removal of the clonal organs provides a period relatively free of competition when the trees can establish. The period of time free of vegetation may be highly variable depending upon the treatment and the overstorey canopy. Heavy blading using a crawler tractor removed roots and rhizomes of understorey plants in a mixedwood shelterwood, and the area remained relatively free of vegetation for five years (Lees 1970).
4) Starting with a sparse overstorey there will be a well-established understorey. If the tree to be regenerated is shade-intolerant, the canopy will need to be opened more to allow recruitment. Site preparation will likely be needed to prepare a seedbed and to remove the clonal organs of the understorey species. Because of the increased resource here, however, there may be rapid regrowth such as with the disc plowing in a heavy shelterwood seeding cut in a Scots pine stand (Kuuluvainen and Pukkala 1989).

Conclusions

Overstorey trees control the amount of light and other resources available to the shorter understorey vegetation during the course of stand development. The growth, reproduction and survival of the understorey vegetation is dependent upon the density and composition of the overstorey trees; a diverse and large understorey layer may thrive under sparse overstoreys compared to a sparse understorey dominated by feather mosses under a dense coniferous overstorey. In turn, however, the understorey plays an important role in ecosystem processes and will have a major impact upon the establishment of forest trees. Regarding the role of understorey plants in partial-cut silviculture systems there are some serious gaps in our knowledge: the shade tolerance and photosynthetic strategies of most species; the ability of species to withstand large changes in light intensity; the nutrient and water use strategies of understorey species and how these species are affected by overstorey species; the seedbank, seed dispersal and clonal reproduction strategies of most species; the response to disturbance and the time needed to recolonize and re-establish full leaf area after disturbance; and the role of understorey species in site nutrient cycling and other ecosystem processes.

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Natural Regeneration of White Spruce — Information Needs and Experience from the Alaskan Boreal Forest

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Alaska's northern forests are the northwestern-most extension of the boreal forest in North America. On productive forest sites, where harvesting and forest management activities are presently concentrated, white spruce is currently the most valuable species. Various combinations of clearcutting, site preparation, planting or natural regeneration make up the regeneration systems used presently. An examination of the reproductive processes of white spruce, and other research conducted over the past 30 years shows that a wider range of options is available for regenerating white spruce than those currently used. These include use of shelterwoods and small clearcuts to create a variety of different forest conditions more favourable to natural regeneration.

Introduction

The Alaskan northern forest is characterized by a relatively small number of tree species growing in a mosaic pattern of pure and mixed stands. Their distribution is determined by site conditions, disturbance history, interaction with other biotic factors, and the autecological characteristics of the tree species. Although simple in composition, these forests often have a complex pattern at the landscape level of resolution.

Maintenance of forest values for the good of local residents as well as society in general requires that forests be treated in a way that maintains their diversity at various spatial and temporal scales of resolution. There are many factors that must be considered in maintaining these values (Rowe 1992, Kaufman et al. 1994). Important among these is the reproductive potential of trees, forests and landscapes following natural or human disturbances. Forests will be regenerated to meet specific objectives or we can accept the results from natural recovery processes.

All northern plant species exhibit some level of resilience in terms of sexual and vegetative reproduction following disturbance. They do, however, vary significantly in their reproductive potential (Burns and Honkala 1992, Zasada et al. 1992, Lieffers 1995). Of the northern trees, white spruce has the lowest potential for rapid regeneration and site occupancy following disturbance for some of the following reasons: vegetative reproduction is rare; no perennial soil seed pool or elevated seed pool in the form of serotinous cones; seed crops tend to be sporadic; and juvenile growth is slow relative to that of associated species (Nienstaedt and Zasada 1992, Zasada et al. 1992, Coates et al. 1994). Although white spruce can regenerate quickly following disturbance, the process of recolonization often occurs over a period of several decades (Youngblood 1992).

Planting following clearcutting and site preparation has evolved to be the most common method of regenerating white spruce throughout the boreal forest. Although there are examples of success with these methods, there are many cases where these methods resulted in poor stocking or plantation failure (Samoil 1988, Shortreid 1991). Because of the problems and expense of these methods, there has been renewed interest in using other regeneration systems on some sites. These regeneration systems would incorporate partial overstorey removal (for example shelterwoods), natural regeneration, planting, seeding, site preparation, protection of advanced regeneration, and weeding in various combinations depending on management goals for a given site (Zasada 1991, Navratil et al. 1994). Although even-aged management is generally the objective of white spruce management, it is possible to maintain stands with several age classes for varying lengths of time. This renewed interest in alternative regeneration systems builds on work from the 1950s and '60s (Lees 1964, Jarvis et al. 1966) which was suspended when the decision was made to follow the relatively intensive silvicultural model mentioned above. Natural regeneration (i.e., regeneration systems relying on natural seedfall) will only be a viable part of these regeneration systems if land managers can predict the probability of success for a given set of site and stand conditions.

In the late 1960s, we were searching for methods to naturally regenerate white spruce in interior Alaska. An analysis of the problem was completed (Zasada 1972) and studies initiated to test some possible methods. The purpose of this paper is to summarize research conducted on upland and floodplain sites over a period of 35 to 40 years. The main objectives of this work were to understand forest dynamics, the place of white spruce in succession, and the natural regeneration process in white spruce. Much of the basic ecological work on plant and soil dynamics in natural forests was conducted by Keith Van Cleve, Les Viereck, Ted Dyrness, Joan Foote, John Yarie, Terry Chapin and their colleagues and graduate students at the University of Alaska-Fairbanks (Can. J. For. Res. 1983, 1993, Van Cleve et al. 1986).

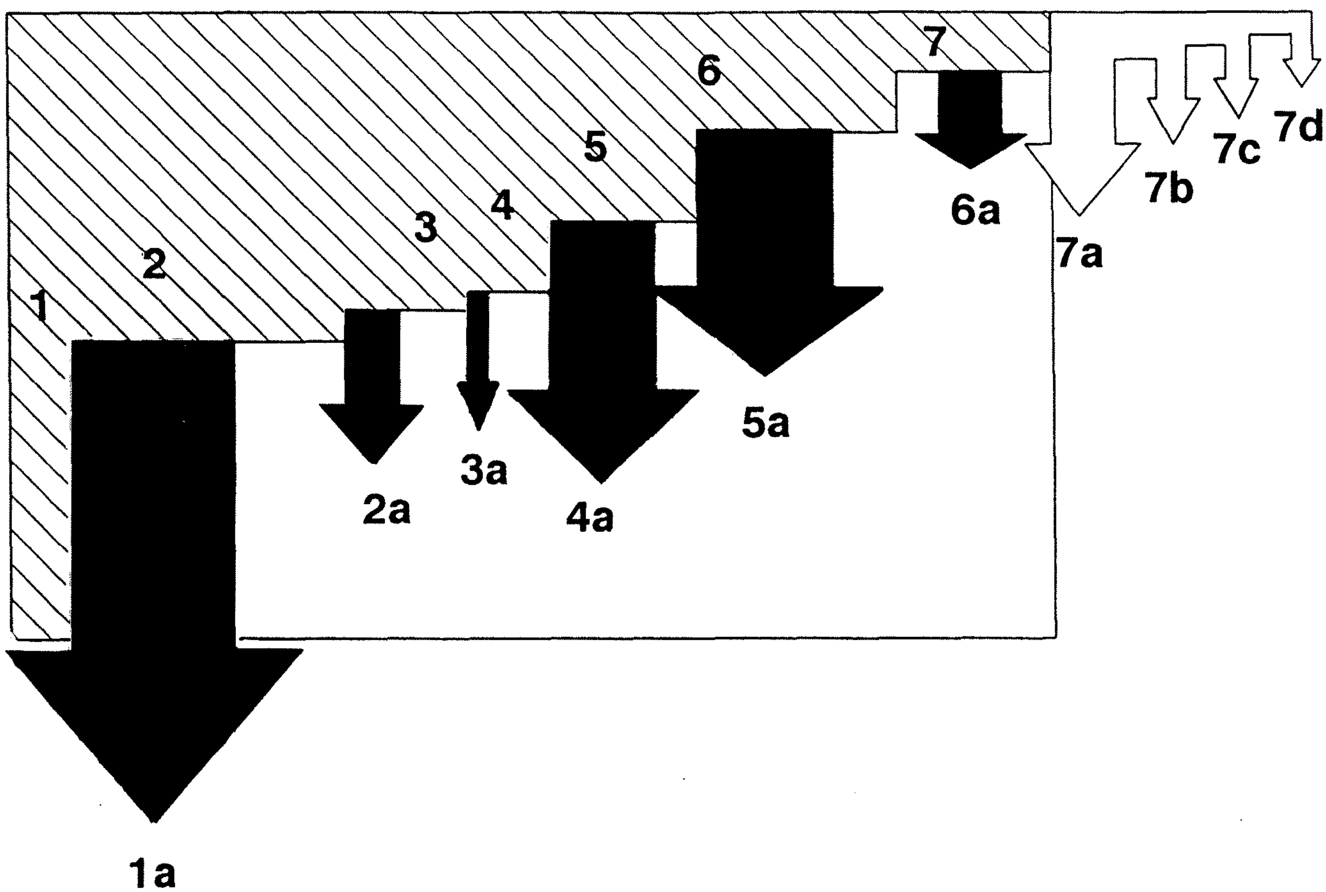
The Reproductive Process in Alaskan White Spruce

As with any species, the reproductive process in white spruce is complex. Natural regeneration from seed consists of a number of components (see conceptual models by Harper 1977, Grubb 1977, Zasada et al. 1992, Maxwell et al. 1993). Each component is affected by different environmental factors or responds differently to the same factors. All parts of the process must operate at some level for one bud cohort to produce cones, seeds and for these seeds to establish seedlings. Fig. 1 goes through a simple example illustrating some aspects of the seed production and dispersal components of the process. Seed production and dispersal are emphasized because less is known about this aspect of white spruce regeneration. Partly because of a lack of knowledge and partly because managers do not have the ability to control some parts of the seed production and dispersal process, it is more difficult to manage seed production and dispersal in natural stands than it is to manage the seedbed and seedling environment to make the most efficient use of the seed that is available. If land managers could better predict seed availability, both production and dispersal components, I believe that they would be more confident about using natural regeneration as part of a regeneration system for white spruce The reader is referred to Zasada et al. (1992), Nienstaedt and Zasada (1992), and Coates et al. (1994) for more detailed information on the post seed dispersal components of white spruce natural regeneration. The following briefly explains behind Fig. 1.

Bud differentiation

From the sites; i.e., apical meristems, available to produce buds, a given percentage become reproductive buds. Factors such as weather, physiological status of the tree, cone production of the previous year and tree age

Figure 1. Conceptual representation of the fate of ovules/seeds in buds/cones during a seed production year in Alaska white spruce



The factors reducing the potential for ovule/seed production will vary from year to year. The relative magnitude of the "importance" (width of arrow) of each factor is a "best estimate" average value based on personal observations and information from the literature. See text for description of each factor. The numbers indicate the following: 1—population of potential ovules that could result from sites available for development of reproductive buds; 1a—reduction in potential ovule population as buds do not develop at each potential site; 2—potential ovule population on reproductive buds in early winter; 2a—over winter loss of potential ovules in dead or destroyed buds; 3—potential ovules in buds at end of winter; 3a—ovule loss resulting from frost; 4—post-flowering ovule population; 4a—ovule/seed reduction from poor pollination; 5—post-pollination ovule/seed population; 5a—prematuration losses; 6—population of mature seeds; 6a—post-maturation seed reduction; 7—pre dispersal seed population; 7a-d—dispersal of seed population in September (7a), October (7b), November-December (7c), and January-May (7d).

determine the percentage of buds that become reproductive. The number of reproductive buds on a tree or in a stand can be estimated by examining buds in late fall or winter. The number of buds establishes the maximum level of seed production for the following year and this phase of the cycle is obviously extremely important (Owens and Molder 1977, 1979, Eis and Inkster 1972, Nienstaedt and Zasada 1992, Coates et al. 1994). There is little information available for predicting when large numbers of buds will differentiate into reproductive structures. One observation which many have made in a qualitative way is that hot, dry weather conditions—years when many hectares are burned by fires—in one summer are followed by large cone and seed crops the next year.

Over winter bud survival

Buds can be eliminated from the reproductive bud population indiscriminately by wind and snow breakage (Van Cleve and Zasada 1970, Sampson and Wurtz 1994) or discriminately by squirrels or birds that feed on reproductive buds during the winter. There is little known about the magnitude of reproductive bud loss during the winter. It is generally assumed that this type of loss occurs at a relatively small level each year with huge losses at irregular intervals, in years with heavy snow breakage for example (Van Cleve and Zasada 1970, Sampson and Wurtz 1994).

Flowering

Flower buds flush prior to foliar buds in the spring and are particularly susceptible to frost. A heat sum of about 125 to 140 degree days (calculated using a 5°C threshold temperature) is required for white spruce flowering in interior Alaska (unpublished data). Frost can significantly reduce the number of ovules through mortality of entire flowers or in some cases only ovules in part of a cone are affected by frost (Zasada 1971). During a 15-year period of observations of cone production, only one frost event occurred that affected cone development on lower elevation floodplain and upland sites in interior Alaska. Thus on the more productive sites, frost appears to be of relatively minor importance in limiting seed production.

Pollination/fertilization

This determines the potential number of seeds per cone. Poor pollination reduces the number of seeds that individual cones produce but not the number of cones. Fertilization occurs approximately 3-4 weeks after flowering. This period is also the time of most rapid cone growth (Zasada et al. 1978). Lack of adequate pollination reduces seed production potential to some degree in every seed crop.

Prematuration cone/seed loss

These losses occur as seeds and cones develop. They can result from physical or biological causes. Damage from wind and rain storms reduce cone populations. Biological factors such as insects and diseases reduce seed populations to a greater or lesser degree every year. The amount of damage caused by insects was reported to be inversely related to the size of the seed crop (Werner 1964). Insects are a major factor determining the availability of viable seeds.

Seed maturation

Seeds require about 650 to 700 degree days (after pollination) to attain anatomical maturity (embryo occupies 75 percent or more of the embryo cavity). This normally occurs by late July or early August on low elevation sites, but may be delayed for from several weeks to a month or more at higher elevation sites. Even at lower elevation sites, seeds may not be biochemically mature until just before dispersal begins (Zasada et al. 1978, Zasada 1988, Edwards 1977, Winston and Haddon 1981). Seed maturation occurs mostly after cones have attained their maximum physical dimensions. The maturation of conifer seeds in high latitude forests has received detailed study in Scandinavia and this work provides important insights for high latitude forests in North America (see review by Zasada et al. 1992).

Postmaturation losses

This is separated from prematuration losses because it is a well defined event that occurs at the end of the summer or in the fall and winter when cones are fully grown and seeds are in the final stages of maturation or fully mature. The best known example is the harvest of large quantities of cones by squirrels. Cones are harvested whenever they are available and the quantity of cones harvested depends on the size of the cone crop and squirrel population. The largest impact is usually in poor to moderate cone years following years with very good cone to excellent crops. Squirrel populations build up to large levels during good years and carry over to poor years when there is not enough food to sustain the squirrel population. Birds (for example, crossbills) also consume seeds while they are still on the tree, reducing the seed population available for dispersal.

Seed dispersal

Seed dispersal varies in time and space. Most spruce seed is dispersed from September through December and dispersal is related to weather conditions (temperature and rainfall) that affect cone moisture content. Hot dry weather accelerates cone opening and release of seeds. Damage to cones by insect and diseases can affect the timing of seed dispersal by delaying the release of seeds. Seed dispersal distance in clearcuts has been described a number of times for white spruce and other similar spruces (Coates et al. 1994, Youngblood and Max 1992). All studies show the classic pattern of a rapid decline in seed density away from the uncut seed source with the amount of seed at a given distance dependent on wind and air turbulence at the time of dispersal. What is lost in standard "seed trap" studies of seed dispersal is that each seed experiences a different flight path depending on the height from which it is dispersed, air turbulence, and wind speed. Thus, the potential for travel varies greatly for each seed on a tree. The other thing that these studies miss is that some seeds rise immediately following release from the cone due to air turbulence and attain heights greater than their point of release giving them the potential, at least, for much longer range dispersal than would be predicted by knowing the height of the cone in which the seed develops (Zasada and Lovig 1983). Secondary movement of seeds from the primary point of landing occurs in a number of ways and serves both to move seeds to other microsites as well as to significantly increase the distance of dispersal. Movement over snow has been of interest in northern forests because of the potential to move seeds significant distances into harvested areas. The importance of over-snow dispersal depends on the timing of dispersal, and wind and snow conditions. In two Alaska studies, 80 to 90 percent of filled seeds were dispersed before mid-October and before significant snowfall had occurred; thus these seeds were covered by the ensuing snowfall (Zasada and Viereck 1970, Zasada 1985). Based on these observations, a relatively small percentage of the total seed crop (although in excellent seed years this could be a large number of seeds) would be available for late winter release from the cones and secondary distribution by wind over a snow surface.

Periodicity of seed crops

The interaction of all of the above factors results in the annual variation observed in the production and dispersal of seed crops. For lower elevation, productive forests in Alaska there is a record of seed production (determined by counting seeds collected in seed traps and cone production observations) in white spruce forests for about 35 years (Zasada and Viereck 1970, Zasada 1980, Zasada et al. 1992, Youngblood and Max 1992, also unpublished data). This record reveals that there were two truly exceptional seed crops in 1957 and 1989 (approximately 3000 to 4000 seeds/m2 as measured by seed traps placed in fully stocked, mature stands) during this period, 1957 and 1989 (both preceded by some of the warmest, driest weather on record in the year before seed production). These two crops really set the standard against which to compare other seed crops in this area and probably come close to indicating the maximum seed production for these stands and site conditions. These records also indicate that the occurrence of 3-5 seed crops per decade in the 200 to 1700 seeds/m^2 range are not uncommon. Crops of this magnitude on these sites would result in good seedling reproduction if good seedbed conditions were available.

Predicting seed crops

There are no models available that would provide an estimate of seed availability in white spruce forests. It is possible, however, to track the seed crop potential beginning one year before seed dispersal. For example one could begin by estimating the number of reproductive buds in fall or winter and follow this up with periodic observations of the number of developing buds, flowers, or cones at appropriate times the following year.

Forest Succession

Generalized successional patterns for upland and floodplain sites for the eastern interior Alaska forest zone (Zasada and Packee 1994) on upland sites (soils of loess parent material) and floodplain sites (soils of fluvial origin) have been described and provide insight relative to what may occur following harvesting (see for example Van Cleve and Viereck 1981, Viereck 1989, Van Cleve et al. 1986, Can. J. For. Res. 1983,1993). Some lessons that we can learn from these patterns are briefly described below.

Upland Forests

The major factor causing landscape level disturbance on uplands is fire. Forest managers have often equated the effects of clearcutting to conditions following natural fire. This is an over-generalization. Although individual fires cover large areas, the conditions within a burned area are rarely as open and exposed as those created by clearcutting as practiced during the past several decades. All of the dead and down material created by the fire provides an infinite number of microsite conditions for germination and establishment. Microenvironmental conditions vary greatly. They can be more like those in a shelterwood than those in a clearcut. The one fact that holds for all fires is that white spruce regeneration will always grow in association with a variety of broad-leaved trees and shrubs, and herbaceous species. With few exceptions, white spruce grows in mixed species plant communities for at least 50 to 100 years. White spruce regeneration can occur immediately after fire if seed is available (Zasada 1985), but spruce may not begin to invade until 20 or more years following fire (Youngblood 1992).

Floodplain Forests

Succession on floodplain sites is different than on upland sites. White spruce always regenerates under the cover of broad-leaved vegetation in stands that develop during primary succession on floodplains. Regeneration events are often related to flooding events that deposit a new silt layer creating a variety of microsites for germination and early seedling growth. Seedlings grow up through an overstorey of alder, willow, balsam poplar or a combination of these species. The white spruce stands that result from this primary succession are generally even-aged. As succession proceeds, the primary spruce stands deteriorate, and white spruce can regenerate in gaps forming multiple-aged stands. Eventually, however, black spruce invades the site and replaces white spruce. On these sites, white spruce regenerates under substantially different soil and site conditions than those found in the earlier stages of primary succession. Productivity on these sites deteriorates as a result of organic matter accretion, decreasing soil temperature, and permafrost development making them less suitable for white spruce.

Natural Regeneration Following Harvesting

Upland Forests

Basic ecological studies and general historical observations firmly establishes that trees readily regenerate following fire and human disturbance on upland sites. Furthermore, these observations indicate that broad-leaved species dominate for varying lengths of time depending on disturbance history, spruce seed availability, and site conditions. Experience suggests there is no single way to assure that spruce natural regeneration will occur immediately following disturbance. Increasing the probability for successful spruce regeneration requires close attention to seed availability and timing seedbed preparation as closely as possible to seed availability. There are three well-documented instances of good natural regeneration on these sites (Zasada and Grigal 1978, Zasada et al. 1978, Wurtz and Zasada 1986, and Packee 1992). Fox et al. (1984) document poor regeneration on sites harvested operationally in the 1960s and '70s. The following briefly summarizes the most detailed of these studies (for more detailed information see Zasada and Grigal 1978, Wurtz and Zasada 1986, Youngblood 1990a, 1990b, Zasada and Wurtz in preparation).

This study, begun in 1972, compared the regeneration of white spruce and associated plant species in shelterwoods (100 uniformly spaced trees/ha with basal area of 9.2 m^2/ha) and small clearcuts (1 ha) on scalped and untreated seedbeds. Regeneration of spruce was exceptional and after 13 years, stocking (based on 1.0 m^2 plots) was 100 percent on scalped seedbeds and 50 to 60 percent on untreated seedbeds (the only disturbance of the surface organic layers resulted from harvesting activities). Seedling density on scalped surfaces was about 35/m^2 in clearcuts and shelterwoods and 3/m^2 on untreated seedbeds. This excellent regeneration followed a very good seed crop (seed rain averaged 350 to 400 filled seeds/m^2 in clearcuts and shelterwoods). Average seedling height after 13 years was 60 to 80 cm with dominant seedlings more than 1.4 m tall; seedlings in the clearcuts were taller than those in shelterwoods. Seedlings on untreated surfaces tended to be taller than those on scalped surfaces.

A concern with use of shelterwoods in white spruce regeneration is windthrow and tree death from exposure and insect attack. Mortality will always occur to some degree when mature stands are opened as in application of the shelterwood method. An important consideration is how to minimize mortality. In this study, dominant and codominant trees were chosen for retention. Using this criteria for tree retention, 20 percent of the shelterwood died or was wind thrown over the 13-year period. The residual shelterwood trees that survived showed a significant increase in growth even though they were about 180-years-old. In this instance, the shelterwood performed very well.

Although this study demonstrated that under the right conditions white spruce could be regenerated naturally, the study was limited to one site and one point in time. The most unexpected results and those which need to be examined with further research and operational trials were the following: 1.) The high frequency of seedlings on untreated seedbeds was much greater than suggested by the literature on white spruce. This result suggested that spruce regeneration can occur on a variety of microsites and not only exposed mineral soil. We were unable to explain this result but it can probably be attributed to the large seed crop, relatively wet conditions during germination and initial year of seedling development and a generally favourable microclimate in the small clearcuts and shelterwoods. 2.) Broad-leaved trees and shrub seedlings were abundant on scalped surfaces as was spruce. However, on untreated surfaces, they were uncommon. This suggests it might be possible to favour spruce by using a type of site preparation that does not completely expose mineral soil. 3.) Five years after site preparation a seed crop of essentially the same size as the one which produced the dense regeneration occurred. Virtually no seedlings were produced by this crop, suggesting that seedbed conditions had degenerated greatly and that only under particularly ideal conditions or following an exceptional seed crop could new seedlings become established on seedbeds of this age. This also suggests that organic seedbeds are receptive only on wet years.

Floodplain Forests

Interior Alaska floodplain forests provide interesting contrasts to the uplands in terms of regeneration systems for white spruce and other species. Instability of the sites and periodic deposition of silt as a result of fluvial processes; and changes in site productivity as soil temperature declines and permafrost develops, as well as other processes make these sites relatively more dynamic than the uplands. Forest management planning in this environment must consider whether a site will be there in the decades ahead before deciding to regenerate harvested areas. An alternative to regenerating harvested areas that will probably destroyed by erosion would be to assure regeneration on earlier successional stands; for example, during the balsam poplar stage of succession.

Regeneration research was mostly concentrated in one large study on Willow Island begun in 1982 (see the following for details of the early results from this research (Juday and Zasada 1984, Zasada and Norum 1986, Putman and Zasada 1986, Zasada et al. 1987, Wurtz 1988, Dyrness et al. 1988, Youngblood and Zasada 1991)). Yarie (1993) has also reported on effects of clearcutting on ecological processes and regeneration on a floodplain site. Although the Willow Island project included two levels of shelterwood density (50 and 120 trees/ha) and clearcuts (2-5 ha in area), planting and spot seeding were used to regenerate spruce and no detailed observations of natural regeneration are available. The studies of spot seeding do provide some insight into the natural regeneration process. Thirty to 60 percent of the unprotected spots on blade and patch scarified microsites had seedlings surviving after 5 years while 40 to 70 percent of spots protected with plastic funnels supported seedlings. Five to 10 percent of the unprotected spots on untreated seedbeds supported seedlings while 10 to 30 percent of protected spots had seedlings. The wetter colder site types tended to have a lower percentage of spots with seedlings. The height of seedlings on the seed spots was 20 to 30 percent of that of planted seedlings on similar microsites. Seedlings in clearcuts tended to be taller than those in shelterwoods but these differences were not consistent; seedlings in shelters on untreated surfaces were about the same size as those on treated surfaces but unprotected seedlings were much smaller than their counterparts on treated surfaces.

Summary

Natural regeneration alone or in combination with artificial regeneration provides a viable option for white spruce in interior Alaska. However, to be successful, careful silvicultural planning must occur to assure that an adequate seed source is available and that site conditions are managed to make efficient use of the seed. An adequate seed supply can be assured by using small clearcuts or trees scattered in groups or randomly on the site to be regenerated. Successful natural regeneration has been demonstrated on research plots but must now be tested on a operational scale. Some important information needs are a better understanding of seedbed requirements under partial conifer and hardwood overstoreys, the rate at which seedbeds deteriorate in relation to efficiency of germination and seedling establishment, and a better idea of how to predict seed crops and seed availability under different stand and site conditions. Development of systems to artificially regenerate white spruce have evolved over a period of several decades and understanding natural regeneration will also be an evolutionary process.

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Silvicultural Systems for Black Spruce Ecosystems

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The silvical characteristics of black spruce (Picea mariana) *and the wide range of sites that it occupies make a number of silvicultural systems possible. Clearcutting with artificial reproduction, group seed trees, strip clearcutting, preservation of advance growth, shelterwood and single-tree selection are all feasible or potentially feasible. Prospects for future innovation include density management, the shelterwood system, mixed-species silviculture, development of harvesting technology, increased operator training, and combined silvicultural systems.*

Introduction

Black spruce *(Picea mariana)* is the most abundant tree species of the North American boreal forest. It occurs across the entire continent, in all of the Canadian provinces and territories, as well as in Alaska, the Lake States and the northeastern States. Unlike many members of *Picea* genus, black spruce is not very demanding in its site requirements. It grows on a wide range of soil types, including wet, nutrient-poor peatlands, shallow soils over bedrock, fertile uplands and dry, coarse-textured soils.

Black spruce has become significant in the economy of the boreal forest region as forest industries have arisen to take advantage of this plentiful resource. Black spruce is used extensively by the pulp and paper industry, and is also used to make lumber.

The ecological and economic importance of black spruce make its silviculture a vital part of boreal forestry. Clearcutting with planting has been the predominant silvicultural system for black spruce, but funding limitations preclude the planting of all harvested black spruce stands in most jurisdictions. These limitations, along with a growing realization that alternatives to this system are often cost-effective and more compatible with an array of forest values, have prompted increased interest in innovative silvicultural systems for black spruce.

The purpose of this paper is to review silvicultural systems that are currently in use for black spruce and to identify potential innovations.

Silvical Characteristics

Black spruce seed supply is abundant and dependable, with good cone crops occurring every 4 years on average. The cones are semi-serotinous, and the seeds are released gradually over a period of years. Even if no cones develop in a particular year, seedfall from previous years' cones is substantial. Average annual seedfall is in the order of 500,000 viable seeds ha^{-1} (Haavisto 1975).

Most black spruce seed lands within several tree heights of the point of release. Effective seeding distance is 50 to 80 m (Payandeh and Haavisto 1982). For seed-dependent regeneration methods, this distance puts an upper limit on the spacing of seed trees and the width of clearcuts.

In addition to a prolific output of seed, black spruce also exhibits effective vegetative reproduction. In many situations, moss grows over the persistent lower branches of black spruce, and a new root system develops from the branch. These "layerings" eventually become independent trees, and in certain forest types, a well-stocked understorey of advance growth develops. Black spruce advance growth is most abundant in wet, nutrient-poor peatlands, particularly in open stands (Groot 1984). Stocking decreases rapidly as fertility improves and as stand density increases.

Black spruce is classified as tolerant, and it is able to grow under moderate shade, though growth may be very slow (Groot 1984). Like most tolerant species, it is able to respond to increased light even after long periods of suppression (Doucet and Boily 1986, Johnstone 1978).

Most black spruce stands originate after fire and are even-aged, but on peatlands, stands often escape fire and develop an uneven age and diameter structure (Groot and Horton 1994). Such stands appear to be stable and self-perpetuating in the absence of disturbance, a relative rarity in the North American boreal forest.

Black spruce seeds can tolerate cycles of wetting and drying (Thomas and Wein 1985), but once the radicle emerges, drying is lethal. Root growth is slow at first, and on coarse-textured soils the rate of drying in the upper soil layer often exceeds the rate of early root growth. Establishment is poor in such situations. Shade may be of benefit by reducing the rate of soil drying.

Black spruce seedlings grow very slowly at first, typically attaining average heights of only 12 cm to 15 cm after 5 years (Fleming and Mossa 1994, Groot and Adams 1994). Growth subsequently increases and seedlings are usually 1 m tall by age 10 to 12. Slow early growth places black spruce at a competitive disadvantage on fertile sites, where other vegetation develops much more rapidly. As a result, black spruce-dominated stands are common on infertile sites, but become infrequent on richer sites.

Black spruce trees are highly prone to windthrow. The species commonly grows on sites where the rooting depth is restricted by shallow soil over bedrock, high water tables or impenetrable clays. Additionally, the species appears to have an inherently shallow rooting pattern. Susceptibility to windthrow increases rapidly with height and with decreasing stand density. As a result, stands tend to break up once a dominant height of 20 to 21 m is attained

(Smith et al. 1987, Robichaud and Methven 1993). Silvicultural systems that incorporate partial cutting or the use of seed trees must take into account the risk of windthrow.

Black spruce is a small tree; individuals with diameters greater than 30 cm are rare, and stand mean diameters are frequently much lower. Size is important silviculturally because it has a strong influence on harvesting methods. Harvesting costs increase rapidly with decreasing diameter, so black spruce harvesting operations are usually costly.

High costs are often exacerbated by low volumes. For example, in northeastern Ontario, extensive areas of overmature, low volume black spruce stands result in license-wide average merchantable volumes of only 60 to 70 m^3 ha^{-1}.

Small size limits the product options for black spruce. It is valuable for pulp and paper and small dimension lumber, but there is little opportunity to produce higher value products such as larger dimension lumber, veneer or poles.

The combination of high harvesting costs and limited product options have created strong pressure for efficient harvesting equipment and techniques. Consequences for silviculture have often been ignored in the drive for harvesting efficiency, and there is strong resistance to changes in operations that threaten to increase harvesting costs. This is a reality that black spruce silviculturists must face.

Harvesting systems in the boreal forest now typically comprise large feller-bunchers and grapple skidders (Gingras and Ryans 1992). The small size of black spruce creates the opportunity to use more compact and manoeuvrable harvesting equipment. Such equipment would be better-suited to silvicultural systems that require partial cutting.

Silvicultural Systems

The silvical characteristics of black spruce make a number of silvicultural systems possible. Some silvicultural systems are highly specific to particular stand and site conditions, so for a given stand, options may be rather limited. Efforts at developing silvicultural systems for black spruce have concentrated on the establishment of regeneration, so descriptions of silvicultural systems centre on reproduction methods.

Clearcutting with artificial regeneration

Mechanization of forest harvesting in the boreal forest started in the 1950s and resulted in larger clearcuts, fewer residual seed trees and greater destruction of advance growth. The inevitable reduction in natural regeneration of spruce and pine eventually prompted large expansions in artificial regeneration programs. Silvicultural effort in black spruce continues to be concentrated on artificial regeneration, particularly planting.

In Ontario, clearcutting with planting is the most widely used silvicultural system for black spruce, and black spruce accounts for about half of the trees planted in the province. Planting is attractive because it simple for the forest manager to administer. It requires the least knowledge of site and stand conditions, and can be adapted to a range of harvesting practices. It is possible to plant large, contiguous areas of cutover forest.

Black spruce is a good plantation species. It is amenable to nursery and greenhouse culture, has few insect and disease problems, does not suffer seriously from "planting check," and can be established on a wide range of sites.

Planting is the best choice for productive sites where timber production is the primary objective. Older black spruce plantations on good sites show that high yields can be obtained. For example, in a black spruce initial spacing trial in Thunder Bay, Ontario the gross total volume of the 1.8 m spacing at 37 years of age was 282 m^3 ha^{-1} (McClain et al. 1994). This is a higher volume than yield tables indicate for natural stands of any boreal species at this age (Plonski 1974). In fact, yield table volumes for Jack pine never reach this value.

Dense (4500 stem ha^{-1}) black spruce plantations near Nipigon Ontario attained volumes of 191 m^3 ha^{-1} at age 22, translating to a mean annual increment of 8.7 m^3 ha^{-1} yr^{-1} (Gordon and Simpson 1991).

Planting has drawbacks, however. It is the most costly silvicultural system, with initial costs typically greater than \$1000 ha^{-1}. Planting has its share of critics, mainly because of its association with clearcutting, but also because its connotation of timber farming and monocultures. These criticisms, along with high cost, are motivating the development of innovative and alternative silvicultural systems.

Direct seeding black spruce following clearcutting is carried out on a limited basis. Encouraged by the success of direct seeding with Jack pine, foresters have attempted to emulate post-fire regeneration of black spruce using broadcast seeding from aircraft. Imitating the natural seeding process following wildfires has proven difficult, however. After fire, the large quantity of seed stored in black spruce crowns showers down on the soil surface, standing dead trees provide shade that ameliorates the harsh near-surface environment, and the burned surface provides a mosaic of microsites for germination and establishment. It is not feasible to carry out broadcast seeding at rates approaching natural postfire rates, and the clearcut environment can hinder establishment of black spruce seedlings. Despite these difficulties, the appeal of treating large areas quickly and cheaply has continued to motivate research on direct seeding.

On upland sites, direct seeding black spruce is most likely to be successful on very fresh to moist moisture regimes, and then only when sufficient, well-distributed receptive seedbed has been created. Layers of soil close to the organic-mineral interface provide the best seedbed on uplands (Fleming and Mossa 1994).

Moisture is plentiful on peatland sites, but seedbed type is still important. Feathermoss seedbeds dry out even in swamps, and poorly decomposed *Sphagnum* is optimum for establishment (Groot and Adams 1994).

Prescriptions for black spruce broadcast seeding rates and amounts of receptive seedbed are being developed for both uplands and peatlands (Fleming and Mossa 1994, Groot 1988, Groot and Adams 1994). Operationally, a seeding rate of 100,000 ha^{-1} is often used.

Spot seeding of black spruce, using various seed shelter designs, has been used increasingly in the past decade. Spot seeding uses seeds more efficiently than broadcast seeding and shelters improve establishment on upland sites (Adams 1994).

Seed-tree method

Because of windthrow, it is generally not possible to use the single seed-tree method with black spruce (Robinson 1970). Chrosciewicz (1976, 1990), however, provides an example of excellent regeneration obtained with residual unmerchantable trees in conjunction with post-harvest burning.

Seed tree groups about 10 m to 15 m in diameter and spaced approximately 90 m apart have been used in the hope of reducing windthrow losses (Jeglum and Kennington 1993). There is little documentation on the effectiveness of this method.

Strip clearcutting

Another seed-based natural regeneration method is strip clearcutting. Large numbers of seed are deposited near the stand edge, and with careful arrangement of strips, windthrow losses can be reduced (Fleming and Crossfield 1983).

Typical strip widths are 40 m to 60 m, although narrower strips are recommended on sensitive shallow soil sites, and wider strips are possible on peatlands. On uplands, site preparation is required. About 15% to 20% cover of receptive seedbed is recommended, although less seedbed may be necessary in narrower strips. In alternate stripcutting, a waiting period of 3 to 5 years is suggested before harvesting the leave strips (Jeglum and Kennington 1993).

Despite its potential and low cost, strip clearcutting remains a minor silvicultural system in black spruce. Drawbacks include the requirement for more administration and harvest planning, extra road costs, increased risk of windthrow and the eventual problem of regenerating the leave strips.

Strip cutting is usually implemented in linear configurations, but configurations taking into account varying topography and stand conditions might be more appropriate. Such configurations have been termed terrain-adapted stripcuts (Jeglum and Kennington 1993).

Preservation of advance growth

Black spruce stands often contain abundant advance growth, particularly on nutrient-poor peatlands, but also on a variety of other sites where the stand is open. Preservation of black spruce advance growth has become an important silvicultural system in central Canada (Archibald and Arnup 1993). This method has been termed "one-cut shelterwood cutting" by Smith (1986), who carefully distinguishes it from clearcutting in order to focus attention on the source of regeneration. Preservation of advance growth is also commonly referred to as careful logging. This can create terminological confusion, because the term careful logging is also applied to operations that do not necessarily have advance growth preservation as an objective.

The principles for careful logging to preserve advance growth are to restrict equipment to repeatedly used trails and to space trails as widely as possible. Harvesting in winter is preferable on sensitive sites (Groot 1987). At present, the best harvesting equipment for advance growth preservation is the single-grip harvester with a matching forwarder (Gingras 1991).

Because of the slow growth of advance growth in the understorey and the frequently poor condition of advance growth following harvesting, many foresters believed that advance growth stems would not develop satisfactorily. Recent research has established that advance growth does respond with increased growth following harvest and develops into desirable stems (Doucet and Boily 1986). Second-growth black spruce stands which developed following harvesting in the first half of the century provide further evidence of the suitability of advance growth. These stands are predominantly of advance growth origin, and volume growth compares well with natural stands (Horton and Groot 1987, Paquin and Doucet 1992).

Selection

Maturing second-growth black spruce stands on peatlands are typically uneven-aged and uneven-sized (Groot and Horton 1994), suggesting that uneven-aged management or selection silviculture is biologically possible. Harvesting equipment has evolved to the point where the selection system may be technically feasible as well. Cut-to-length harvesting equipment is sufficiently small and manoeuvrable to partially harvest such stands.

A trial of the selection system was initiated in the Lake Abitibi Model Forest (near Iroquois Falls, Ontario) in early 1994. Three levels of harvesting intensity were carried out in 63-year-old second-growth peatland black spruce stands, with planned removals of 35%, 50% and 100% of the basal area. The harvests were implemented using diameter limits of 18 cm, 15 cm and 10 cm dbh. Although diameter limit control is a rudimentary means of implementing the selection system, it was effective in this case, and a reverse-J-shaped diameter distribution was maintained after the two lighter harvest intensities.

Depending on the level of removal, a cutting cycle of 20 to 30 years should be possible on these sites. Advantages of the selection system for peatland black spruce include the retention of forest cover, reduced water table rise following harvest, lower losses to mortality, a greater proportion of sawlogs in the harvest and possibly, greater volume productivity.

Disadvantages include greater harvesting costs, the requirement for specialized harvesting equipment and methods, and damage to residual trees.

The selection system for black spruce is applicable mainly to overmature natural stands and second-growth stands on nutrient-poor peatlands. It is not applicable to even-aged stands, which is the most common age structure for black spruce. The system would likely be difficult to apply on more fertile sites, because of the tendency for balsam fir to dominate.

Prospects for Future Innovation

What are the prospects for innovations in black spruce silviculture in future? It seems likely that more innovation will be required. At present the management objective for black spruce ecosystems is usually rather modest: simply to re-establish black spruce following harvesting. Demands on the forest are continually increasing, and to satisfy these demands, forest owners will set more specific and exacting objectives. Meeting these objectives will require additional skill, experience and ingenuity of silviculturists.

Density management

The area of black spruce plantations is steadily increasing, and as goals for plantation growth and yield become better defined, it is likely that closer attention will be paid to density management.

For example, combining high stand volume growth rates with a reasonably rapid development of individual tree size is a silvicultural challenge in black spruce. Careful control of initial spacing and subsequent management of density are likely required. Stand density management diagrams have recently been developed for black spruce (Newton and Weetman 1993, 1994), which will help to design density management regimes to achieve management objectives.

Shelterwood

The shelterwood system is generally not applicable to natural black spruce stands, because the risk of windthrow after the regeneration cutting is high in both overmature and in dense, mature stands. Also, access is usually lacking to make intermediate cuts.

The shelterwood system may be possible in black spruce plantations, however, particularly if it were integrated into a density management regime. Windthrow risks are lower in early and mid-rotation black spruce plantations, because tree heights and densities are less than in mature, natural stands.

Gradual opening of plantations may allow the establishment of seedlings in the understorey, minimize windthrow risks and inhibit the development of competing vegetation.

Mixed stands

Black spruce often grows in mixture with other species, and silvicultural systems involving mixed stands are likely feasible. Species such as Jack pine, tamarack and trembling aspen have more rapid height growth rates than black spruce, leading to two-storied stands. This could lead to a system involving intermediate and final harvests. For example, Jack pine and black spruce can be established together by seeding or planting. An initial harvest of a portion of the Jack pine for pulpwood would be possible after about 40 years, releasing the black spruce understorey and favouring Jack pine crop trees. A final harvest of black spruce pulpwood and Jack pine sawlogs could take place in another 40 years. Similar regimes may be possible for tamarack and aspen with black spruce.

Black spruce also grows in mixture with balsam fir and white spruce, which have similar growth rates. In spruce-fir mixtures, the challenge is to prevent fir from dominating the stand.

Development of Harvesting Technology

Silvicultural systems for black spruce that use natural regeneration or that involve more than one stand entry require the forester to have control of the harvest configuration and intensity. Advances in harvesting technology will increase the range of conditions where such control is economically and technically feasible. Development of equipment will play a large part in this, but so will training of operators.

Combined Silvicultural Systems

Finally, combined silvicultural systems may be used. Examples include terrain-adapted strip cuts; and careful logging combined with planting or seeding in trails, where preservation of advance growth is being used.

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Forestry's Green Revolution in Sweden — AssiDomän's[1] Utilization of Site-Adapted Forestry with Functional Conservation Aspects

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A "green revolution" has quietly taken place within Swedish forestry. Large-scale forestry operations, featuring clearcuts and standardized regeneration methods are being replaced by site-adapted operations. An ecological, holistic approach is gradually permeating day-to-day forestry work with the realization that respect for nature is just as important as timber production. At AssiDomän we give equal weight to environmental and production goals. The management goals of AssiDomän are: 1) to achieve a high and sustainable economic yield, 2) to sustain the production capacity of timberlands and 3) to preserve the biological diversity of the forest. These goals can be integrated. One prerequisite is that operations within each individual area are adapted to the particular natural and productive conditions of that area and its environmental values.

Since 1990, we have conducted a broad training program for our forest workers within the "green" sector. Today the regeneration planning is carried out by the machine operators of the logging crews. This allows for concordance between planning and realization.

The results are followed up and presented in an ecological balance-sheet which is based on an inventory of about 200 randomly-selected final fellings each year. In 1994, AssiDomän presented its first-ever ecological balance-sheet for the day-to-day forestry operations. Within a few years the balance-sheet will also reflect our ecological performance at the landscape level.

At AssiDomän all central and overlapping questions of silviculture and nature conservation are brought before the "green group" at AssiDomän Skog & Trä (Forest and Timber). The "green group" consists of a chief silviculturist, a production ecologist (the author), a conservation ecologist, and a fishery-and-water conservation specialist.

The "Green Network" and the Machine-Teams

Today the main function of the "green group" is to aid our eight forest districts in their planning of silvicultural and environmental conservation measures. Together with the chief silviculturists at the forest districts, we form a "green network" within our business area. The support of the day-to-day forestry operations is as essential as the support of their planning for more long-term production and conservation work. This paper mostly describes the day-to-day forestry operations of AssiDomän.

During the last four years, the "green network" has worked very hard on furthering the education of our 60 forest rangers, but above all, we have concentrated on the solid education of our roughly 250 machine-teams — half of which are involved in final felling and the other half in thinning. Approximately one third are logging contractors who have also been trained by the "green group."

The characteristic feature of AssiDomän is that the machine-teams are gradually taking over the regeneration planning within the felling and thinning areas. This allows for concordance between planning and realization. The success of these efforts have been confirmed in our ecological balance-sheet (see below). It should also be mentioned that the forest workers in Sweden normally are born in the countryside and are persons with strong interests in nature. As a rule, their parents have worked in the forestry industry.

Six Important Reminders

It is very important for the "green" group to introduce clear rules and instructions in order to guarantee that the planners in the machine-teams, when choosing measures and methods, pay proper attention to the natural production conditions and how these vary within the forest land. The working-routines must in the same way guarantee that we, in our day-to-day forestry, pay attention to the needs of nature conservation and other types of environmental factors such as, waterways, landscape, architecture, etc.

At the centre of our routines is what we call "The Forester's Six Important Reminders." These remind us that before making any kind of operation we must always make clear:

1. The need for conservation and environmental protection (flora, fauna, water, soil, landscape, etc.)
2. Climate of the growth site — natural production fac-

[1] The company AssiDomän is not quite one year old. It was formed by a merger between the original state owned forest, Domänverket, including their sawmills, and two forest industries, Assi and Ncb, which specialized in manufacturing sacks, craft paper and liquid packaging board. The result of this formation has become a new strong forest product company, newly introduced on the stock market. AssiDomän is now the largest forest owner in Sweden, with 3.2 million hectares of productive forest land (14% in Sweden); i.e., one of the world's largest private forest owners. "The old Domänverket" was the first forest enterprise in Sweden which employed an ecologist. Six years ago the author, who derives from the Department of Forest Soils at the Swedish University of Agricultural Sciences, was the guinea-pig. Since then, ecologists have been employed in other Swedish forest companies.

tors
3. Soil properties — natural production factors
4. Vegetation and animals on the growth site
   - competition (positive and negative)
   - risk for damage to crops
5. Distinct environmental requirements of various species
6. Effects of previous silvicultural measures including site history

After having analyzed a silvicultural unit according to the main points in this checklist, we combine the six important reminders by thinking in terms of ecosystems; i.e., with regard to the natural conditions. This leads to suggestions of measures and methods for achieving high production results and high conservation results. The means are site-adapted forestry and functional conservation, respectively. Our ambition is to give equal weight to environmental and production goals. It should be observed that in many situations site-adapted forestry in daily operations also results in good conservation results and vice versa.

Regeneration Planning

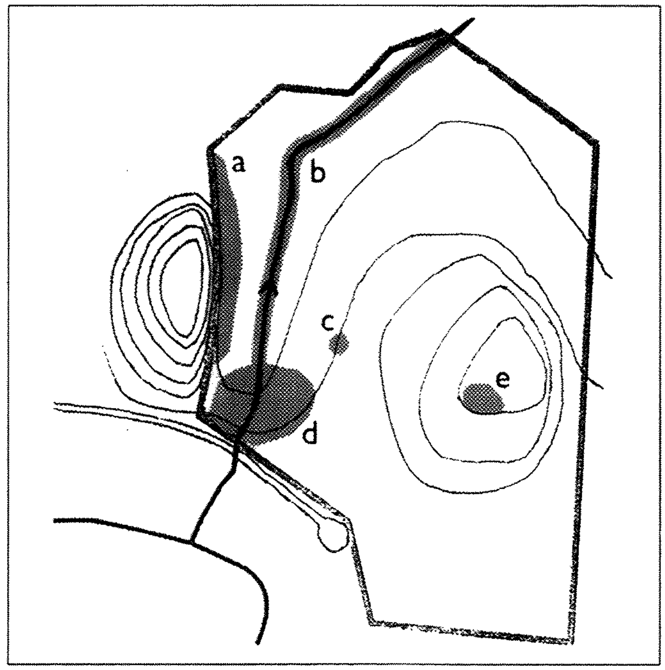
The goal of site-adapted forestry is to make the most of the natural yield capacity of each individual growth site. A further goal is to do this at a reasonable cost and with a simultaneous consideration of sensitive biotopes and other objects with special environmental values. All these conditions require detailed map and field investigations.

The machine-teams have been given the following routine for regeneration planning:

1. Check boundaries of final-felling areas. Delimit sensitive biotopes (Fig. 1).
2. Map the sites (soil material type, soil moisture class and vegetation type are significant site properties)
3. Describe each site and give its area (Fig. 2a)
4. Rank plausible methods
5. Decide how production and conservation goals can be met at the lowest cost (Fig. 2b)
6. Sketch a presentation of regeneration and conservation measures (working descriptions)

Today no final-felling may be done without previous planning according to this routine. It must be conducted during snow-free periods, 1-3 years before harvesting, and we have the rule that each ranger district shall have a rolling bank of planned final-felling areas which includes at least two years cutting. To date, only some of our ranger districts have this rolling bank, due to disruptive reorganizations and reduced staff. In this situation, further education and competence improvement is absolutely necessary if we are to achieve our goals.

Site-adapted forestry with functional conservation is a form of management which employs modern techniques in an effective and biologically appropriate manner. Knowledge of ecology is used to achieve good production and high quality results, as well as to support a long-term, multi-species, living timberland. Large-scale forestry operations typical



Scale 1:20,000 a = cliffside d = old windthrow gap
b = creek area e = rocky outcropping
c = spring

Figure 1. Example of delimited and mapped sensitive biotopes with shelter zones

(a) AssiDomän Skog & Trä

NORTH SWEDEN

REGENERATION PLANNING

Unit: Crown forest Selsta
Forest: 42 Compt.: 106 Date: 940502 Surveyor: J·E Lundmark
Site index: Norw. sp. H100-27 Area: 12 hectares Lat. 60.0 N M.a.s.l. 150 m
T-sum 1350 day-degrees Humidity 0-50 mm

SITE DESCRIPTION

PROPERTIES	Site 1	Site 2	Site 3	Site 4
1 Reforestration area, hectares	3.0	3.6	3.2	1.2
2 Wind exp (influence)	Insignif	Insignif.	Med. Hi	Very Hi
3 Frost risk	Very Hi	Hi	Insignif	Insignif
4 Slope direction (<5%)	—	—	Varying	Varying
5 Soil material type	Peat land	Min. soil	Min. soil	Min. soil
6 Soil moist. class	Moist	Moist	Mesic	Dry
7 Surf waterflow	None	Long periods	Short periods	None
8 Ditches	Yes	No	No	No
9 Soil mateial	Peat	Sediment	Moraine	Moraine
10 Texture/Humif. degree	Med. Humif.	Clay	Fine sand	Sand
11 Soil depth	Thick	Thick	Thick	Fairly shallow
12 Humus layer	>1m	10-20cm	6-10 cm	0-3cm
13 Ground veg. type	Low Herb (Sel. here)	Low Herb	Bilb.	Lich. rich
14 Site index H 100	Sp 26	Sp 29	Sp 27	Pi 20
15 Conif. sedl. (occur)	Abundant	Med.	Few	Med
16 Bearing cap., rock., slope	311	421	233	132
17 Biotic factors	Desid.	Desid.+Grass	Grass	–
18 Degenerated soil	—	—	—	–

(b)

SUGGESTED MEASURES	Site 1	Site 2	Site 3	Site 4
21 Soil cond./air poll., etc	—	—	pH?	pH?
22 Tree species	Spr+Bir+Pi	Spr+Bir	Spr (+Pi)	Pi
23 Regen. method	Shelter w. syst.	Plant	Plant	Nat. reg.
24 Harvest method	Shelter	Shelter	"Clear cut"	Seedtrees
25 Site clearing	No	No	Yes	No
26 Site prep.	—	Mound	Mound	Patch
27 Controlled burning	—	—	—	—
28 Drainage	Ditch clearing	—	—	—
29 Seedling type	—	Bare root (large)	Container	—
30 Plant protection	—	—	—	—

Final felling only on frozen ground

Figure 2. (a) Fundamental site properties are described and classified in this filed-form; (b) The site classification in the field-form is used to suggest appropriate measures for each site

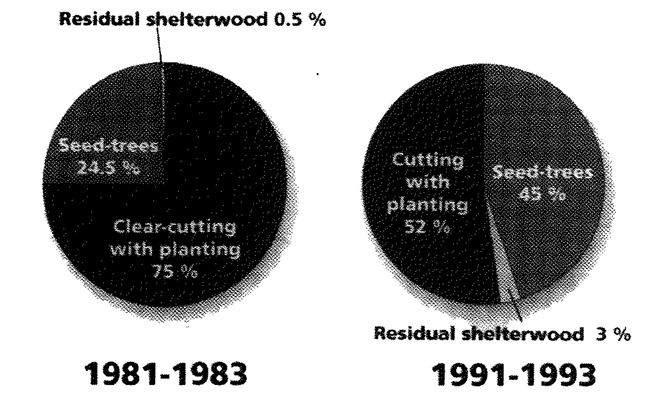


Figure 3a. As a result of site-adapted forestry, the implementation of natural regeneration has increased compared to the earlier large-scale forestry period

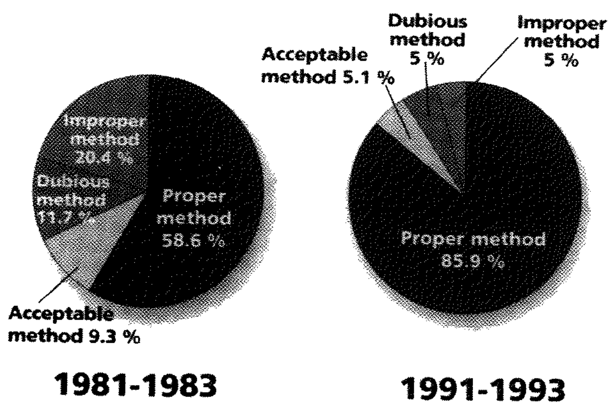


Figure 3b. Harvesting-choice of method. Surveyors' judgement is based on the natural production conditions of each site

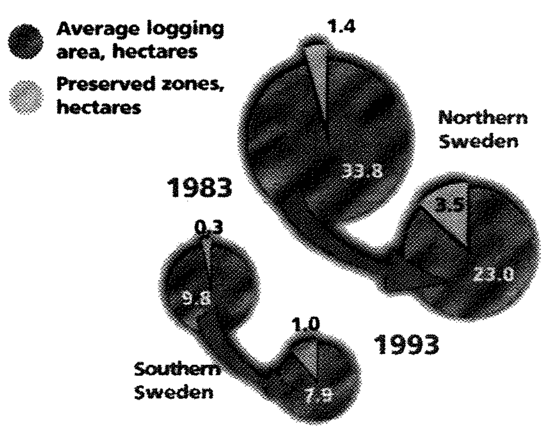


Figure 4a. Logging area and preserved zones in northern and southern Sweden, respectively. Comparison between logging-sites 1981-1983 and 1991-1993

of the 1960s and '70s, with radical and uniformly managed cutting areas, have gone to the grave. These very rapid and far-reaching changes we call the "Forestry's Green Revolution" in Sweden.

Ecological Landscape Planning

In addition to the conservation in day-to-day forestry we have just started an ecological landscape planning process which aims at maintaining or recreating a pattern of sensitive habitats and distribution paths for plants and animals over large areas. This is an important stage in our "green forestry revolution," which will hopefully contribute to healthy forest ecosystems in a significant way.

Ecological Balance-Sheet

In 1994 AssiDomän presented its first-ever ecological balance-sheet. Together with the traditional economic balance-sheet and the rather new personnel-social balance-sheet we have a relatively complete picture of our company's activities and an instrument for measuring the achievement of our goals. To date, the ecological balance-sheet is only a "green" result follow-up of regeneration and conservation measures upon final felling. In the future it will involve thinning, the vitality of the forests, nature conservation on a landscape level, etc.

This first balance-sheet was based on an inventory of 222 randomly-selected final-felling areas, harvested during 1991-93 throughout Sweden. The selected and investigated areas represent about 12% of the total harvested area during the 3-year period.

Five specially-trained surveyors have studied each final felling area and assigned points for 60 main factors or main operations, and a further 360 sub-categories for each area. For comparison, a corresponding grading of some 90 final-felling areas from 1981-83 was also conducted. The purpose of this balance-sheet is to show:

- How we respond to site conditions in our regeneration planning; i.e., if we are applying the correct regeneration measures (planting, seed-tree canopy, etc.), as called for by local site conditions.
- How the extension courses of recent years have succeeded.
- How we respect the need for nature and water conservancy in our everyday forestry practices (respect for rare biotopes, protected zones, forest groups, etc.) and how much timber volume (conifers and hardwoods) should be allowed to remain.
- The extent to which we reach our production and environmental goals of high and sustainable economic returns, in addition to a healthy ecosystem over the long term, and maintaining biodiversity.

Three different sections have been closely observed and graded: site-adapted forestry, nature conservation and water conservation. The grades are set according to a 5-point scale with 5 as the highest. In order to "pass," a grade of at least 3.0 is required.

Figure 3 a shows the choice of harvesting method in percent of the total harvested area. Seed-trees are much more common in the final-fellings during 1991-93 than during 1981-83. Can this change be correct if we consider the site properties and the observance of site-adapted rules? Yes, we now have detailed information about the climate and soil properties of the sites in question which confirm this. Consequently, if we compare the grades, the result is much better in 1991-93 than in 1981-83. Figure 3b shows that proper harvesting methods, grades of 4 or 5 points (the best and second-best), have been obtained on nearly 86% of the harvested area — compared to only 58.6% in 1981-83. Acceptable methods earn 3 points, but some site factors indicate that a better choice had been possible in order to capitalize on the natural production capacity of the site and/or its ability to produce a high-quality yield.

Then we have the grades which indicate an unacceptable choice of measures and methods according to the site properties. We still have 10% to improve (Figure 3b).

The size of the average cut is now smaller than it was ten years ago, while the areas preserved in their natural state have significantly increased in size (Figure 4a). Of course, the amount of residual wood left on the average logging site has also increased.

In northern Sweden, the preserved zones represent 13.2 percent of the productive area — in southern Sweden 11.1 percent compared to 4-5 percent in the beginning of 1980s (Figure 4b). The reduction of volume due to preserved zones comes to 6.5 percent. We calculate that our total investment in preserved biological diversity will be about 8-9 percent of our net yield.

Figure 5 gives an example of nature conservation, which shows that we generally manage to avoid damaging easily identifiable sensitive biotopes; e.g., ravines and cliff sides. However, the percentage of harvesting-related damages in areas more difficult to identify as sensitive, such as waterlogged areas or the areas near springs is unacceptably high. The results point out the need to distinguish and carefully mark out these biotopes prior to felling operations.

How can we benefit by this balance-sheet?

- Foundation for continued education.
- Gives us clues. Are we on the right track? Where do we need to make adjustments?
- In working toward certification, the balance-sheet serves a good guideline.

We have presented grade-point averages to each of our eight districts. In Figure 6 we have the results for the total AssiDomän 1981-83 and 1991-93, respectively. As earlier mentioned, to "pass" you need 3 points. As expected, the results of either site-adapted forestry, nature conservation or water conservation are not so very good for 1981-83. They're much better within the final-felling areas from 1991-93. The trend from 1991 to 1993 is encouraging but we still have a lot to do within the green sector of AssiDomän. That is to say, our "green revolution" is not yet over.

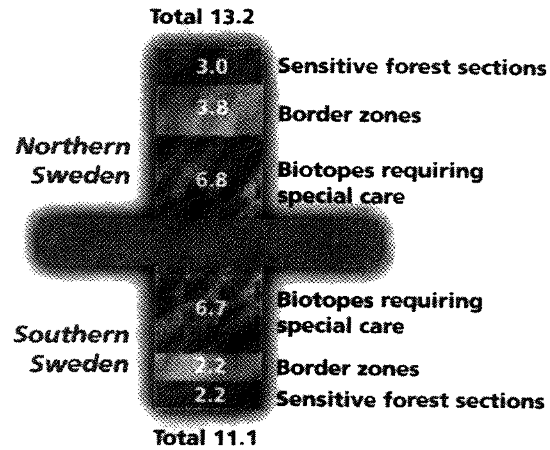


Figure 4b. Preserved zones in percent of productive area for logging-sites 1991-1993

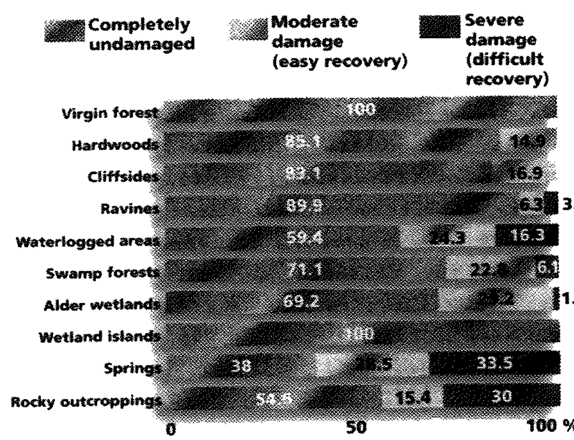


Figure 5. Damage to sensitive biotopes resulting from improper logging, percent of biotope area

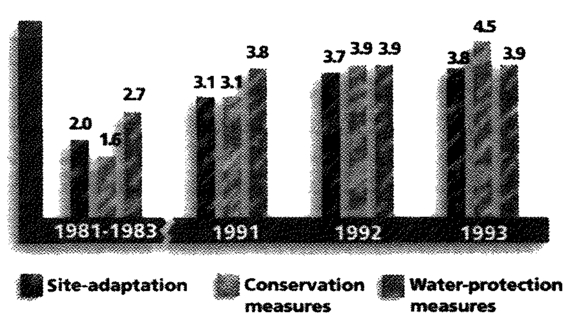


Figure 6. Grade-point averages for logging-sites 1981-1983 and 1991, 1992 and 1993

Harvesting Practices for Alternative Silvicultural Systems in the Canadian Boreal Forest

E.A. (Tony) Sauder

Forest Engineering Research Institute of Canada (Western Division)

Across the Canadian boreal forest region, timber is now harvested in ways that were not considered feasible 10 years ago. There has been a change in harvesting systems, harvesting equipment, and the products produced in woodland operations. In addition, different silvicultural systems are used to reduce regeneration costs, recover fibre from area withdrawals for wildlife and wilderness, and to protect or enhance non-timber resources. Achieving the objectives set-out in silvicultural prescriptions may require that harvesting practices used for conventional clearcut harvesting be changed. This paper identifies the new challenges harvesting must address and how they can be overcome through: improving the planning process, selecting the appropriate equipment, hiring good crew, training workers, developing special operating techniques, and modifying forest practices regulations. In addition, forest managers should recognize that harvesting costs will increase as a result of the new harvesting practices.

Introduction

This paper summarizes the changes in forest harvesting practices that are occurring in Canada's boreal forest and the new challenges forest managers have in designing harvesting strategies to meet the demands of the public and the fibre industry. In addition, the paper outlines the main issues that must be addressed if harvesting is to achieve the desired silvicultural objectives.

Timber is now harvested in the Canadian boreal forest region using systems and equipment that were not considered feasible 10 years ago. There has been a transition from cut and skid operations using manual falling, cable skidders and manual processing, to mechanical harvesting equipment using feller-bunchers, grapple skidders and mechanical processors. There are also Scandinavian style harvesters and forwarders working alongside, and in some regions replacing, the conventional mechanical systems.

The products leaving the cutblocks for the mills are also changing. In eastern Canada there is a shift from shortwood pulp bolts hauled to central woodrooms in pulp mills, to pulp chips derived from in-woods and satellite chipping operations. In western Canada, long-logs to mills are still the dominant product but cut-to-length systems in the woods are producing sawlogs to mill specifications, and in-woods chip production is increasing.

The processes by which forest crops are tended, harvested and replaced are changing across the Canadian boreal forest. Ten years ago, most cutting was undertaken on large clearcuts that relied both on artificial and natural regeneration methods. Today, although clearcutting still dominates, other alternative systems are used which harvest only some of the timber on a block and natural regeneration is more prevalent.

The Canadian forest industry is looking at alternative silvicultural systems to clearcutting for three main reasons. First, the industry is interested in more efficient methods for regenerating the forest crop to reduce the reliance on capital intensive, artificial regeneration and tending methods. Second, the industry is searching for new sources of wood fibre to replace reductions in cuts resulting from area withdrawals for wildlife and wilderness preservation. Finally, the public has convinced the forest industry to try timber cutting methods other than clearcutting.

The variety of harvesting equipment that is now available and the variety of products that mills are accepting provide the boundaries within which the forest industry can select new harvesting designs into their operations. However, many foresters, harvesting supervisors and operators have little experience with silvicultural systems other than clearcutting. As a result, there are a number of challenges that harvesting must address. Some of these challenges include:

- keeping the costs of using the new systems competitive;
- offsetting higher harvesting costs with reduced stand regeneration costs;
- modifying current equipment and work practices for partial cut applications;
- getting the work force to commit to new harvesting practices;
- providing a safe environment for forest workers;
- revising current regulations that may not be appropriate for non-clearcut harvesting; and
- achieving the silvicultural prescription's objectives, especially with respect to stem spacing, opening sizes, site disturbance and quality of residual stems.

These harvesting challenges can be addressed through: planning, equipment selection, the work force, worker training, special operating techniques, and forest practices regulations. However, forest managers should recognize that harvesting costs will increase as a result of the new harvesting practices.

Planning

Planning is the phase where all components of the silvicultural system, from pre-harvest to stand regeneration, must be integrated. Developing operational harvest plans that incorporate alternative silvicultural practices requires knowledge of the silvicultural objectives to be achieved, the timber and site characteristics, and the harvest system that is to be utilized.

The pre-harvest silviculture prescription is the key in developing management strategies to regenerate cutblocks and to protect or enhance non-timber values. This prescription needs to have clear objectives that can be used to carry-out and monitor harvesting results. Once the silviculture prescription has been prepared, harvest methods should be reviewed to ensure they are appropriate to attaining the objectives.

Both silviculture and harvesting foresters should review the silviculture and harvesting prescriptions to ensure they are realistic and achievable. They should "paper plan" skid trail locations and spacing, and make assumptions on trail widths. Both parties should visit similar sites to see if the "paper plan" proposals are feasible. If not, the plans need to be revised, or the harvest methods or the silviculture objectives modified.

Block layouts and harvest prescriptions should recognize that in the boreal forest the majority of harvesting will be undertaken during night shift operations or when visibility is poor. With much of the boreal forest only accessible when the ground is frozen during late fall and winter, it is important that equipment be able to operate 24 hours a day to minimize hourly equipment ownership costs. Harvest methods that leave timber in staggered, random patterns may make it difficult for feller-buncher operators to locate trails and place bunches, or for skidder operators to find deck areas during night operations. However, harvest layouts that organize felling and skidding phases to simple geometric layouts can make it easier for operators to orient themselves during the dark and when it is snowing.

The planner should be on site during harvesting. This will ensure the plan will have the desired results, and if any modifications to the plan are needed, they can be made quickly. While on site, the planner should clearly explain to the harvesting crew the reasons the harvest method is changing, the desired results, and the responsibilities of each crew member in attaining the desired objectives. The planner needs to work with the crew to help them modify their work patterns. Decision-making criteria need to be provided to the operators so they know where trails are to be located or what trees are to be cut. A good test to determine whether the instructions are clear is to observe the amount of nonproductive machine movement and the frequency of rest breaks when the operators are working alone. Operators who find the decision criteria difficult to understand, or cannot achieve the desired results will spend more time making nonproductive machine movement and take more frequent rest breaks compared to operators that understand the decision criteria and can achieve the desired results.

Equipment Selection

The type of equipment used to harvest timber is determined by what is available locally. As a result, planners will incorporate into their harvesting plans the equipment that is more suited to achieving desired log specifications of the local mill rather than to meet the silvicultural objectives. Harvest plans and / or silvicultural prescriptions may have to be modified if the equipment cannot achieve the desired silvicultural and harvesting objectives. When considering the equipment that will be used to harvest a cutblock it is important to recognize the equipment's impact on the site and its operating characteristics.

Cut and skid operations are perceived to have the lowest site impacts when compared to mechanized systems largely because of their ability to work around obstacles. Depending on mill requirements, the cut and skid system can deliver full-length stems or log-length logs to roadside decks. However, cut and skid operations are generally low producers, and have the inherent safety problems associated with hand falling of trees.

There are a number of advantages to utilizing the currently available mechanized equipment that brings full-length stems to roadside decks. First, all crew members sit in enclosed cabs and are protected from limbs falling from trees. Second, the equipment is readily available: this means there are good operators and maintenance people available to ensure that it is productive. In addition, hourly equipment costs should also be competitive because the equipment can be used on conventional operations when special harvesting practices are not required. Third, mechanized equipment can handle the wide range of timber sizes and ground conditions in the boreal forest. Fourth, the quality of log merchandising can be easily and quickly checked because all processing is done at roadside decks. Finally, feller-bunchers can cut and transfer a stem to a specific place for bunching. This ability to control the stem is important when trying to minimize damage to residual stems from the falling phase. In addition, feller-bunchers can work efficiently in stands with dense undergrowth and can grasp stems that have dense branches on their lower stems.

However, roadside harvesting also produces well-defined trails primarily as a result of the wide equipment and the stems dragging behind the skidders. The heavy equipment and loads combined with frequent passes cause soil compaction on the skid trails during summer harvesting. In addition, the dragging stems can damage trailside residuals if the crowns are wider than the trail, or when pulled around curves.

Cut-to length (Scandinavian) equipment was designed to operate in stands that have had some or all of the nonmerchantable stems removed during previous spacing or thinning activities and as a result are relatively free of undergrowth. The equipment is usually limited to handling stems that are under 45 cm diameter. Cut-to-length systems have a relatively low site impact primarily because the system produces short logs that are carried on forwarders rather than dragged to the log deck by skidders. Also, forwarding equipment can travel over a bed of limbs and tops generated by the in-woods processing phase which distributes their weight over more of the soil surface. However, if the ground is too wet and soft, repeated forwarder passes can still cause rutting. In addition, deep accumulations of limbs and tops may interfere with regeneration. Harvesters have long boom reaches that can reach further than feller-bunchers; however, the head and boom assemblies are not designed to hold and carry a severed stem vertically for processing in open areas. Rather, the stem falls into the stand and is pulled toward the harvester during processing. This can damage both the tops and lower stems of residual trees. Also, because of their light, chainsaw type heads, the felling phase can be hampered by small stems and undergrowth that prevent the head from reaching the merchantable stem that is to be cut.

When determining the results that can be achieved using different equipment, planners need to consider the operating area the equipment requires, both with and without a stem or load. The feller-bunchers tailswing and how close the felling head can be crowded into the feller-buncher will determine the minimum trail width a machine can cut. Skidder width, the width of bunches, and the length of logs dragging behind will also help determine the width of skid trails. While it is usually desirable to minimize trail width, consideration should be given to widening the trail if post-harvest skid trail rehabilitation or site preparation equipment requires a wider track. Deck areas for stroke-type delimbers require sufficient room behind and around the delimber to allow the stem to swing free of obstructions. Finally, all machines require cabs that provide good visibility to the front, sides and rear, while feller-bunchers also require good visibility upward to the stand canopy.

Work Force

The key to having the harvesting operation achieve the objectives desired, provided the objectives are realistic and the equipment can accomplish the work required, is the people who have to do the work. From FERIC's experience, most operators want to do a good job and are receptive to changing their practices. Operators and contractors that are not interested in changing their work patterns should not be involved with alternative harvesting operations. Most operators, once they understand what is to be achieved and why, have been more than eager to demonstrate their skills and develop new techniques. However, while peer pressure may overcome some individual operator's reluctance to change their operating practices, if the prime contractor and the company supervisor(s) do not take ownership in the work required it is unlikely the crew will.

The on-site supervisor serves an important role in transferring the harvest objectives identified in the harvest plan into reality. Besides instructing operators in developing new operating techniques, this supervisor should help minimize any harvest cost increases by scheduling equipment to maximize its productivity and coordinating repair and maintenance breaks.

Worker Training

If alternative harvesting practices are to achieve their objectives, all people involved in the harvesting operation should be provided with the basic information they require to make the appropriate decisions. The training of operators and on-site supervisors will provide a firm foundation for them to build on to achieve silvicultural objectives. Training should include instruction in soil science, ecology, silvics, block layout, and wildlife habitat requirements, in addition to operating ground rules and harvesting costs. This will provide them with the knowledge and confidence to change their operating practices when conditions are encountered that are not identified on the plan, and to make the best selection for either cutting or leaving a stem. In addition, equipment operators (especially those involved in activities following falling and skidding) will recognize the costs invested in the residual stand.

If harvesting crews are not trained, licensees will be required to intensify layout to define the areas where felling is to occur, locate skid trails and decks, mark stems that are to be left or cut, and supervise the operation. While this may achieve the desired results, the costs of pre-harvest layout and supervision will increase. Moreover, additional damage to the site or to residual stems may occur if operators are not aware of the impacts their work may have on the silvicultural objectives.

Operating Procedures

Conventional clearcut harvesting is relatively simple: all trees on a cutblock are felled and bunched so the bunches are aligned to the skidding direction, and a skidder drags the bunches to the closest log deck. Feller-buncher operators concentrate on the width of the felled swath, the number of trees in a bunch, and the alignment of the bunch. Providing a perimeter boundary is felled during daylight hours, there is little chance for felling to go beyond the block during night-shift operations. Productivity of equipment is maximized because each unit can work independently of the other, and there are few obstacles that interfere with production.

Harvesting cutblocks where only a portion of the stems are to be removed is very different. First, trails must be located to provide access for the felling and skidding/forwarding equipment. These trails must be carefully located to ensure the trees remaining meet the desired quality criteria and stocking density. Second, equipment must work around and not damage the remaining standing trees. This means that operators need to manoeuvre felling equipment so the felling heads do not inadvertently cut or damage trees that are to be left. Third, felling equipment operators need to think more about their operating cycle, especially when the trees to be cut (or left) are not marked. When deciding whether a stem should be cut, they must learn to look at the full tree, including the crown, and then review the cutting-decision criteria provided in the harvest plan. Fourth, skidder/forwarder operators need to ensure residuals are not damaged when turning or loading. Fifth, cutblock boundaries may be more difficult to identify at night because residuals left on the cutblock will blend into the surrounding standing timber. Sixth, landing and deck areas will probably become more restricted in size and located in specific locations that minimize the area that has to be cleared of trees.

The development of special operating practices can overcome some of the problems related to the different operating environment associated with alternative harvesting practices. The following suggestions are some of the ways crews have successfully achieved the harvest objectives in trials FERIC has been involved with:

- Schedule felling so that day shift fells the perimeter of blocks and night shift fells the interior.
- Raise the stump height to avoid cutting adjacent residuals, or to avoid the head's weight severing supporting roots of adjacent stems.
- Not fully rotating the upper cab of feller-bunchers when working on narrow trails.
- Leave rub posts alongside trails to confine bunches between standing stems or to reduce damage to trailside residuals at corners.
- Repile log decks after delimbing and processing with a hydraulic log loader to allow more wood to be stored prior to hauling.
- Manually cut off the tops of deciduous stems at the deck prior to mechanical delimbing to avoid large piles of tops accumulating in-front of the delimber.
- Fell and skid stems in two passes to minimize skid trail width: first fell and skid the trails, then fell and skid the trees between trails.
- Leave marginally merchantable or merchantable stems standing or lying on the ground if their recovery would mean damaging residual stems.

Forest Practices Regulations

The forest regulations that control harvesting activity in the Canadian boreal forest have been developed for clearcutting practices and need to be reviewed and modified if alternative silvicultural prescription objectives are to be achieved. Some of these changes are related to the following issues:

- slash-free zones around block perimeters that reduce the risk of fire-fuel ladders between cutblocks and standing timber.
- regeneration stocking standards that do not recognize different stocking densities for different age-classes of regeneration.
- utilization standards that penalize operators for leaving merchantable timber lying on the ground or standing regardless of the impact their removal may have on residual stems.
- site disturbance guidelines that do not recognize the benefits of concentrating disturbance to specific trails rather than randomly across a cutblock.

Harvesting Costs

Harvesting costs associated with alternative silvicultural systems will probably increase mainly because mechanized clearcutting harvesting operations are very efficient. Alternative silvicultural systems will require more cutblocks to be developed to meet the volumes generated by clearcutting because block sizes are smaller and the recovery per unit area harvested will be reduced. This means that more road will have to be constructed and maintained, roads may have to be constructed to higher standards because they will be in use for longer periods of time, and the interest costs associated with the investment in roads will all increase. Costs will also increase because alternative harvesting operations will require more intensive planning, more detailed block layouts and harvest maps and more on-site supervision compared to conventional clearcutting operations.

Equipment productivity will probably decrease when harvesting equipment has to avoid damaging stems. Felling cycle times will probably increase because operators have to manoeuvre their machine and the felling head around trees that are to be left standing, and more time will be spent travelling to new work locations. Skidding or forwarding cycle times may increase because operators will have to manoeuvre their machines around the residual stems, and skidding distances may take more indirect routes to log decks. However, skidding or forwarding productivity decreases may be minimal because designated skid trials could minimize the distance to the log deck. In addition, the trails can become fast travel routes because they have few obstacles for the equipment to bounce over. Skidder or forwarder production can also be maximized by positioning the bunches so they are easily picked-up, are of maximum grapple size, or if smaller than maximum, be located so that several bunches can be accumulated in one cycle.

There is also the potential that changes to harvesting may reduce delivered wood costs. For example, on long distance log hauls, it may be more efficient to haul short-logs than long logs, because short-log truck and trailer combinations can maximize payload.

Incentives

Incentives for undertaking alternative harvesting operations should be considered to offset increased harvesting costs, or changes in fibre allocation that may result from changes in stocking when silvicultural objectives are achieved.

Achieving harvesting objectives on an operational basis requires that the parties undertaking the work be reimbursed for any additional costs associated with harvesting. Contractors need to be fully compensated for the additional work required to accomplish the objectives and the additional stresses their equipment may have to endure. Increased harvesting costs that result from company operations need to be acknowledged so that comparisons and performance of company staff are not based solely on cost. Operators also need to be compensated for the high degree of skill that may be required to achieve the harvesting objectives, especially if they are paid on a piece-work basis.

The challenge to managers will be to determine how to reimburse the increased harvesting costs. Silviculture funds could be used to offset costs related to attaining regeneration objectives and increasing the value and volume of fibre. When harvesting operations are recovering portions of a stand that were previously not recovered, higher harvesting costs may be offset by increasing the value of the fibre recovered or converting the roundwood to higher-valued products (such as wood chips).

Regulatory agencies also need to recognize that shifting away from clearcutting operations will require changes to regulations and management philosophies that will provide incentives to the licensees. For example, if immature spruce growing in mixedwood stands is to be protected and left standing after harvesting on an operational scale, deciduous licensees must not loose landbase or future fibre supplies if cutblocks are converted to conifer blocks.

Conclusions

The forest industry in the Canadian boreal forest is using alternative silvicultural systems to clearcutting to ensure there are future timber crops, to protect non-timber resources, and to replace fibre losses from traditional sources. The challenge forest managers have is to change harvesting methods so that timber harvesting meets the needs of the silvicultural systems, forest managers and the public. These changes can occur through:

- planning — setting clear objectives, selecting appropriate silvicultural systems and modifying the harvest prescriptions when necessary.
- adapting the harvesting equipment to the needs of the silvicultural system and the silvicultural system to the equipment.
- working closely with the harvesting crew.
- offsetting some/all of any increased harvesting costs by cost reductions associated with other phases (such as transporting fibre to the mill, regeneration and stand tending), or by increasing the value of the fibre harvested.
- providing incentives to operators, contractors, harvest managers and licensees to offset increased costs.
- developing and conducting training programs for operators and supervisors so they have the knowledge to achieve the desired results.

The successful integration of harvesting and alternative silvicultural systems will allow the Canadian boreal forest to continue supplying both timber and non-timber resources, in cost efficient ways.

Profitable Forestry Methods — Maintaining Biodiversity as an Integral Part of Swedish Forestry

D. Westerberg

Forestry in Sweden today is in the process of developing forestry methods on commercial sites so that conservation becomes an integral part of profitable forestry. Examples of such silvicultural methods are clearcutting, leaving seed trees of pine, shelterwoods and nurse trees over spruce regeneration. Techniques, methods and machines used in different stages of stand development are discussed. The costs, risks and benefits of the different methods are also discussed. To meet the objectives of pursuing a more efficient, sustainable and ecologically-sound forestry, improved planning and monitoring will be needed. Examples include a broader use of GPS and GIS. There is also development towards more environmentally-sound technology in Swedish forestry machines.

Background

Harvesting in Swedish forests has been going on for a long time. In the 18th century there was a lack of wood in the southern parts of Sweden. The 19th century became a period of great exploitation in the northern parts, with almost all the old and large trees being cut down during this period. Today there are only few bits of remaining old growth. Most of the land has been cut over several times with different intensity. In the 1960s there was a solid belief in large scale production and technical development grew rapidly. Both of these factors affected the shape and nature of the clearcuts that were done. It was not until the 1980s that discussions started about the need for site specific planning. In the last decade nature care and biology has grown more and more important and the silvicultural methods have started to diversify.

Why are Swedish forestry methods changing?

Several corresponding factors have contributed to changing nature of Swedish forestry practises.

1. The customers of the forest industry, environmental organisations and the public are demanding environmentally sound industrial processes and products and are also demanding that forest management does not endanger biodiversity. Today's customer is a critical viewer, and in many cases, both aware and knowledgable on environmental issues.
2. In 1903 the first forest resource law in the world was passed by the government of Sweden and the need for regeneration after logging was put into legislation. Several reviews have occurred since then, but in 1994 the national forest policy, for the first time, put equal importance on environmental goals and society's demand for high and sustainable timber production.
3. Technical development has made it possible to adjust the form and size of clearcuts to meet environmental and regeneration demands with acceptable profit.
4. In the early 1990s a recession hit the Swedish forest industry, technical development and staff rationalization could not, within short notice, be driven much further so there was a need to cut all kinds of costs. Eyes were put on the high regeneration costs due to high ambitions and an intense effort laid on scarifying, planting, and cleaning. One way to cut regeneration costs was to adopt a more site-specific forestry and to increase the use of natural regeneration.
5. The conventional way of regeneration had failed on many sites, especially on sites with frequent frosts, high ground water levels and extensive competing vegetation. New silvicultural methods made regeneration easier and more cost-effective.
6. New silvicultural methods are thought to increase yield from the stand. For example, selective cutting can allow leave trees established in dense stands or under shelterwoods, to grow into larger and higher quality timber.

How to meet conservational demands and pursue profitability?

Sweden today has converted all its natural forests into managed forests. From here we can identify two different methods which need to be combined to meet the conservational demands. The first is setting aside land from forest management and the second is to adjust forest management practises to meet conservational demands.

To maintain biodiversity a certain amount of land will likely have to be set aside. This is being done today but the amount and the variety of land preserved needs to be increased. Forest land in the southern parts of Sweden and forest land representing the most commonly managed site types are especially in need of increase.

Setting aside land is not enough though, it needs to be complemented with adjusted management practises on all forested lands, to meet environmental demands. This is being done today in roughly two major ways:

1. By modifying conventional silvicultural methods.
2. By applying new or special silvicultural methods.

For both these ways, the key to meeting the conservational demands is the site-specific regeneration planning that is done before logging (Lundmark 1986, 1988). This site-specific regeneration planning is also an important step towards integration of harvest, regeneration and conservational activities.

1. Modified conventional silvicultural methods

Modified conventional silvicultural methods are applied on forest land subjected to frequent disturbance from fires (i.e., once or twice per century). This includes a variety of land types ranging from dry sparse sites to mesic and shrub sites, which cover approximately 60-70% of the forest land in Sweden. The belief today is that forest management can be done on this land, without endangering biodiversity, if the conventional silvicultural methods are modified and current logging techniques are applied accordingly.

The dominant conventional silvicultural methods used are clearcutting followed by scarification and planting or regeneration under seed trees of pine. A double-grip harvester is the most commonly used machine in final felling operations but single-grip harvesters, designed for final felling operations, are becoming more frequently used, especially in the northern parts of Sweden.

An average clearcut stand in Sweden, according to the 1994 Official Statistics of Sweden, generates about 200 m^3/ha of solid wood and cost about $2,500 US per hectare to log, including: forwarding; transportation of machines; wages; taxes; etc. Scarification is totally mechanized and is done on clearcut areas and under seed trees of pine. Planting is usually done by hand at a cost of around $160 US per hectare, including plants, wages, planning, taxes, etc. Mechanized planting is under development and is currently done on 1-2% of the total area planted each year, at approximately the same cost as manual planting (Thorsén 1994).

The most commonly used methods in stand treatment are cleaning and thinning. Most of the cleaning is motor-manual at a cost of around $270 US per hectare (Official Statistics of Sweden 1994). Mechanized cleaning is done on 3-5% of the area cleaned annually at approximately the same cost (Andersson 1993). The single-grip harvester is virtually the only machine used in thinning operations. An average thinning volume is around 50 m^3/ha of solid wood and is done to a cost of approximately $1 100 US per hectare (Official Statistics of Sweden 1994).

The adjustment to meet environmental demands consists mainly of the following:

- Clearcuts are smaller and more trees and bushes are left on the cutover areas.
- Protective zones of forest are left around lakes, rivers and ravines.
- The intent during logging is to leave some old trees, all dead trees and many hardwoods (e.g., birch, aspen).
- Before logging, the important and rare habitats are identified, delineated and set aside from logging.
- Burning cutover areas is occasionally done to mimic natural disturbance from fire.
- In stand treatment operations, such as cleaning and thinning, more hardwoods are left, especially birch which was earlier cleaned away.

2. New silvicultural methods

New silvicultural methods need to be developed or used on forest land that is seldom or never disturbed by forest fires. These areas of mainly spruce cover approximately 10-20% of the forest land in Sweden and are typically moist sites, with humid conditions and a rich flora and fauna. Besides high biological values, they often have a high ground water level, abundant vegetation and problems with frost (which often results in failure of regeneration under clearcutting and planting). Pursuing forestry on this land requires extra careful management. One suitable silvicultural method to start putting into use on this kind of land is regeneration under shelterwood (other methods, e.g., nurse trees of birch, are also used on this kind of land).

A shelterwood is, per definition (Hagner 1962), an older stand which utilizes the land's production capacity and generates new trees, while suppressing unwanted vegetation and moderating the peeks and changes in temperature. A shelterwood stand usually contains between 150 and 400 mature stems per hectare while a stand of seed trees usually has less than 150 mature stems per hectare. There is also a difference in function–a stand of seed trees has seed production as its main task, not protection of established regeneration as in shelterwood.

Regeneration of Norway spruce under shelterwood — a silvicultural model

Regeneration under shelterwood is in fact an old method that has been modified and put into use again. Even though the method has not been properly evaluated, it is today used at a fairly large scale — regionally up to 10-15% but nationally perhaps not more than 2-4% of the annually regenerated area.

We have formed a four-step model based on our studies, field trials and literature (Hannerz & Gemmel 1994, Westerberg & Hannerz 1994, Scherman 1991). All steps do not have to be done depending on purpose of the shelterwood and the local site conditions.

Step 1. Preparatory thinning

Should be done if the stand is too dense for a shelterwood cut. A preparatory thinning could decrease the risk of windthrow, reduce physiological stress on leave stems, and provide an early indication of stand and site capability for natural regeneration.

Step 2. Shelterwood cut

The main parts of the stand are felled in a shelterwood cut, leaving between 200 and 400 trees per hectare. Most commonly Norway spruce are left as shelterwood trees, but there is a belief that wind resistance, drainage capacity and value yield can be increased by leaving more birch and Scots pine in the shelterwood. The shelterwood trees are preferably chosen among the dominant or predominant trees that have developed wind stability, are healthy, have a well developed root system and will respond favourably growth-wise to thinning.

Step 3. Shelterwood thinning

A shelterwood thinning should be done if there is a need to increase the number of established seedlings or if it is necessary for the regeneration to develop satisfactorily.

Step 4. Final felling

The timing of the final felling is determined on the basis of regeneration height, growth rate and risk factors like frost, water and competing vegetation.

Because seedling protection, e.g., from frost, is the most important function of the shelterwood on many sites, both natural regeneration and planting are acceptable regeneration alternatives in this model. A shelterwood consisting of 115-250 trees per hectare can maintain a night temperature that is 2-5 degrees C higher (at a height of 25 cm) than that experienced in a clearcut area (Lundmark 1988).

Logging technique

In our studies we have found that single-grip harvester productivity was only marginally effected when converting from clearcutting to shelterwood cutting, while double-grip harvester productivity was reduced by 25-30% (Westerberg, The Forestry Research Institute of Sweden, unpublished). This was mainly explained by the fact that the double-grip harvester, while working among surrounding trees, had difficulty felling, handling and bringing in trees to the processing unit at the back of the machine. As well, the operator lost the ability to fell and bring in new trees while processing the former felled tree. The single-grip harvester with its processing unit at the end of the boom was more flexible and suited to work among surrounding trees. This was also was confirmed by the fact that it caused less damage to surrounding trees than the double-grip harvester.

In the final felling both single- and double-grip harvesters can be used. The choice of machine should be governed by the average stem volume in the shelterwood. If the trees are large, the double-grip harvester will get a higher productivity but the net cost per m^3 of processed wood will often be the same for the two machine types because the machine cost per hour is higher for the double-grip harvester. A rule of thumb used for planning is that the single-grip harvester will have an advantage in shelterwood stands with an average stem volume smaller than 0.5 m^3 and the double-grip harvester will have an advantage if the average stem volume is larger than 0.8 m^3.

Risks — windthrow

The risk of windthrow varies throughout Sweden. There is a higher frequency of hard winds, i.e., a higher risk for windthrow, in the southwest parts of Sweden and in west slopes in general (Persson 1975, Hagner 1962). The total yield using a particular silvicultural system is, to a large extent, dependent on the number of windthrown trees and the ability to salvage them.

A heavy shelterwood cut in a dense stand will leave trees with an increased risk of windthrow (Persson 1975). There is also a risk, after a heavy thinning, that spruce trees will weaken and die from physiological stress, or be exposed to insect attacks that will result in volume increment loss and less yield overall. The risk of windthrow can be decreased by good planning such as leaving shelter belts, avoiding clearcuts in surrounding stands, leaving only trees with well developed crowns, and by draining wet sites.

Risks — damage during the final felling of a shelterwood

Two kinds of damage often occur during the final felling: mechanical damage to seedlings caused by the logging operation and physiological damage caused by the removal of sheltering tree crowns.

The amount of mechanical damage is more dependant on the standing volume and the number of felled trees per hectare than of the use of a single- versus a double-grip harvester. In our studies of final felling in shelterwoods, between 30 and 50 percent of seedlings larger than 10 cm got either covered with slash or mortally damaged in stands with around 200 stems per hectare and an average stem volume of 0.8 m^3 (Sikstöm and Westerberg, The Forestry Research Institute of Sweden, unpublished).

After the sheltering stems are removed, access to light, windspeed and variation in temperature will be increased and humidity will be decreased in the regeneration stand. Physiological damage from drought, light and frost will occur. The mortality in the first summer is often as high as 50% for seedlings smaller than 10 cm (Skoklefald 1967). However, if the plants have reached an average height of 25-30 cm the mortality is much lower (Skoklefald 1967). Generally the final felling of the stand should be left until the regeneration has reached an average height of at least 1 meter unless frost, snow, or water conditions indicate otherwise. Both physiological and mechanical damage, as well as the area coverage of slash and timber suggest that the final felling should be done in more than one pass if the shelterwood contains more than 250-300 stems per hectare.

Economy when regenerating spruce under shelterwood

Study results show that on forest land with difficult frosts, high ground water level and rich vegetation, it is possible to lower regeneration costs by up to $1,300 US per hectare (net present value) by using a shelterwood system as compared to clearcut harvesting with mounding, ditching and planting (Westerberg and Sikström, The Forestry Research Institute of Sweden, unpublished) (Scherman 1991). The comparison includes the assumption that natural regeneration establishes under the shelterwood within a reasonable time.

Regeneration under shelterwood will, however, increase logging costs. A shelterwood cut and a final felling of the shelterwood will increase the logging costs by approximately $650 US per hectare (net present value) compared to a clearcut alternative, if the shelterwood final felling is within 10-20 years. The cost estimate includes the assumption that 30% of the shelterwood trees will be windthrown five years after the shelterwood cut. If the whole shelterwood stand blows down following three high wind events at two, four and five years after the shelterwood cut, salvaging the stems would increase the logging costs by an additional $260 US per hectare (net present value).

The value yield from 200 Norway spruce trees on a fairly good quality site can be $390 US per hectare (net present value) higher than if the stand were clearcut. This cost estimate includes that 30% of the shelterwood trees will be windthrown and salvaged at 50% reduced value. Hence, the net income could be $1,000 US per hectare (net present value) higher than if the stand were clearcut. However, if all shelterwood trees were rendered worthless by wind damage or insect attacks, the income would be about $3,900 US per hectare (net present value) lower than if the stand had been clearcut.

Biodiversity

Shelterwood harvests should not be automatically considered to preserve biodiversity because practical experiences are limited. Literature indicates that some sites and species are more suited to the shelterwood regeneration than others. The most suitable sites probably host the species adapted to long continuity of forest communities. These are often sites on moist land with a humid climate and shadowy conditions. On these sites a shelterwood probably causes less change in site conditions than clearcutting and therefore ought to be preferred from a conservational point of view. Studies on sites like these (Hannerz and Hånell 1993) also confirm that the flora changes less under a shelterwood than on a clearcut area. Biodiversity could probably be increased through a shelterwood harvesting by creating small habitats that are lacking in Swedish forests. This is accomplished by practices like leaving more broad-leaved trees in the shelterwood, leaving old trees into the next rotation and by leaving a certain amount of windthrown trees lying on the ground.

Summary — Consequences of applying new and adjusted silvicultural methods

To sum up, the Swedish forest industry uses two different ways to meet environmental demands on managed forest land. First by adjusting conventional silvicultural methods and techniques and second by applying new or special silvicultural methods (e.g., shelterwoods). The key to implementing either method is site-specific regeneration planning done before logging (Lundmark 1986, 1988).

Much remains to be done in the implementation of the new harvesting methods and in evaluating their economic value and value for biodiversity. From what we now can see, changing silvicultural systems will lead to:

- Lower silvicultural costs
- Higher logging costs
- Better overall profitability because the lower silvicultural costs will more than offset the higher logging costs
- Increased potential for producing high quality timber
- Increased demand for resources and accuracy in planning and monitoring, including a wider use and development of forestry applications of GIS and GPS
- A need for better qualified personnel to ensure that the right methods are used according to the individual site conditions
- Accepting an increased risk from windthrow and insect damage.

So far these two ways have proved to be more profitable than the earlier conventional large scale forestry. This indicates that the change has come to stay.

By first setting aside areas and sensitive habitats, and then implementing these two changes to silviculture, we will certainly help to maintain biodiversity in Sweden.

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A Portfolio Approach to Landscape Management: An Economically, Ecologically, and Socially Sustainable Approach to Forestry[1]

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Introduction

As more of the world becomes developed, exploitation of previously inaccessible forests is becoming less the source for forest commodities. Managed forests are producing more of the world's forest commodities, and advances in silviculture are becoming more important. The question of "What will be the future of silviculture?" becomes equivalent to: "Where and how will we manage forests in the future?" As shall be discussed, places where forest commodities are provided will also be the primary place where non-commodity values are provided.

Silviculture may not necessarily be done by all countries or regions in the future, even if they have the forest resources. Regions or countries may choose not to manage their forests, and society will centre around other sources for products—although not necessarily to society's advantage.

In the long run, some countries will probably manage their forests and others will not. Those non-managing regions will probably import forest products, with some countries and regions becoming dominant in the forest management industry. Once this dominance occurs and the forest management industry matures, these countries and regions are likely to remain dominant providers of commodity and non-commodity forest values for a long time. Other areas may become periodic providers of timber as forests grow back after harvest, but may not become sustainable centres of forest management. For example, southern New England has provided timber three times as a result of periodic harvesting—once in the 18th century when the forest was cleared by European-American colonists, once in the late 19th and early 20th century when white pines were harvested after they regrew on abandoned old fields; and now in the late 20th century when oaks and other hardwoods are harvested from stands which regrew after the white pines were harvested (Harvard Forest 1941, Oliver and Larson 1990).

Why will some areas be intensively managed and other areas not? The answer to this question can help public officials develop policies to influence the region's either becoming or not becoming an area of intensive forest management. The answer can also help timber companies invest in favourable countries and regions.

This paper will first examine what gives certain countries and regions competitive advantages in certain industries. Then, it will discuss approaches to forestry which will allow forest management to become or remain active in a region. Finally, it will discuss ways to make one approach the landscape management approach—more profitable.

The emphasis in this paper is NOT on the forest products industry; rather it will treat forest management as an industry—with the production of raw commodities such as logs and non-commodities such as biodiversity as the products.

Factors which Give Competitive Advantages to Regions

Porter (1990) has proposed determinants which give a country a competitive advantage in an industry. Examining these determinants may help explain where and how forest management will be undertaken in the future. When considering forest resource management, some of these determinants seem to apply to regions as well as countries; however, other determinants apply to whole countries where national policies are involved. It may be appropriate even to separate public and private management agencies in places such as the United States where management occurs on both public and private forest lands.

The determinants described by Porter (1990) for industries in general are: factor conditions; demand conditions; related and supporting industries; and firm strategy, structure, and rivalry. Porter also listed chance and government influence as important, but less critical influences.

- **Factor conditions** are the factors of production, including skilled labour, transportation/communication infrastructure, capital, and natural resources for raw materials.
- **Demand conditions** are the nature of demands for the products within the country (or region) of consideration.
- **Related and supporting industries** include supplier industries and others which provide the machinery and other materials for the industry's operation.
- **Firm strategy, structure, and rivalry** include conditions in the country or region which influence how companies are created, organized, and managed as well as the

[1]abstract not available

nature of within-country (or region) rivalry.

- **Chance** plays a role through such events as new inventions; discontinuities or other disruptions caused by wars or politics; and unexpectedly rapid shifts in financial markets, supplies, or demands.
- **Government** may play a much stronger role in forest management than the peripheral position described by Porter (1990). Manipulating forests—a very visible natural resource—has been a public issue for many decades in much of the world. How a country incorporates the public concern into government regulations may be a dominant determinant in management in some places.

No one factor is so overwhelmingly important that it alone determines if management will be strong. For example, the "factor determinants" of suitable natural forests or suitable climates for rapid tree growth seem critical; however, even now areas without these factors are emerging as global leaders in forest management. New Zealand and Chile are world leaders in forest management based primarily on exotic plantations; and Sweden, Finland, and Canada are world leaders even though their adverse climates make tree growth very slow. On the other hand, some tropical countries or parts of the inland western United States have plentiful natural forests and sufficient growth rates but are not centres of forest management. Places like boreal Canada seem to be concentrations of forest management practices, even though there is not an abundance of labour or a well-developed group of supporting industries nearby.

A combination of determinants is probably critical for forest management to be a centre, and strength in one determinant can probably compensate for a weakness of another. To assess the likelihood of a country or region becoming a centre of forest management, a matrix of the above determinants could be developed. Values for such a matrix would be largely influenced by the perspective of the agency developing the values. Development of this matrix is beyond the scope of this paper.

A forest management agency has control over some determinants. Sometimes it has control over where to locate. It generally has control over its organizational strategy and structure. This paper looks primarily at the determinant of management organization and structure: how a management agency can be organized to be most effective at forest management.

Management Organization Strategy and Structure

Management can be organized different ways to fit different cultures and conditions; however, forest management can be classified into three approaches (Oliver 1994a,c): "commodity-based" management and two interpretations of ecosystem management — "preservation" management and "landscape" management.

"Commodity-based" management

Management of the forest for specific commodity outputs, especially certain timber products, has been common in many regions of the world. The forest was maintained in a condition to maximize the economic efficiency of producing these few products.

"Preservation" ecosystem management

This approach is based on the outdated "steady state" ecological theory. Until recently, forest communities were thought to exist naturally in a benign "steady state," sometimes associated with "climax," "ancient," or "old growth" forests (Stevens 1990, Oliver 1992a,b). Disturbances were considered external to the system, usually artificial, and generally harmful. The steady-state forest was assumed to be most conducive to stability and diversity. Recent variations of this theory acknowledge that natural disturbances occur, but believe "Nature" will create forests so different from human manipulations that human intervention other than to preserve forests will be irrevocably harmful to the "natural system."

"Preservation" management assumes "old growth" is an ecosystem and promotes large "reserve" areas to be set aside where human activity is minimized and "natural" processes allow forests to grow to and maintain an "old growth" condition. By some interpretations, some thinning activities and/or protection of forests from natural disturbances is also promoted to increase the amount of "old growth" (Hunter 1990, Everett et al. 1994, FEMAT 1993, Franklin 1993).

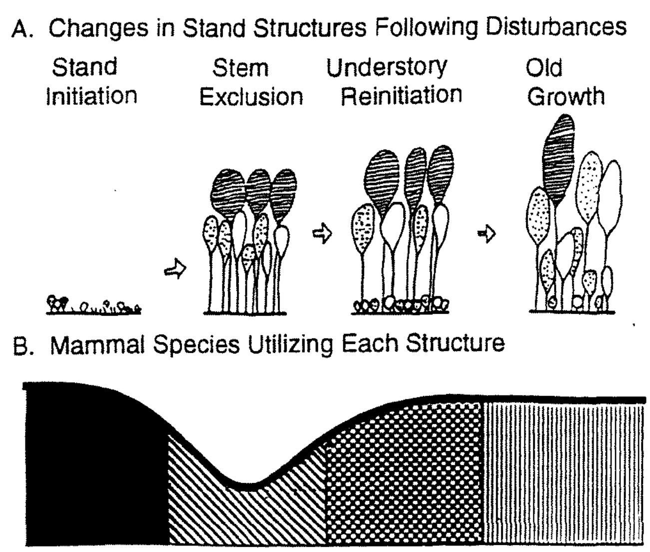

Figure 1. A. According to the most accepted ecological understanding, forest structures change through growth and natural and human disturbances, as shown here simplistically (after Oliver 1981). B. Different plant and animal species utilize each structure as habitat; therefore, all structures are necessary to maintain biodiversity (after Franklin et al. 1986).

"Landscape" ecosystem management

The alternative approach to ecosystem management has been used by various groups (e.g., Johnson and Agee 1987, Salwasser et al. 1992, Everett et al. 1993). It considers managing ecosystems in ways compatible with both ecological processes and human needs and follows the "constant change" theory of ecology. Within the last few decades, this "constant change" theory has gained greater scientific acceptance than the "steady state" theory. It is now accepted that many large and small disturbances periodically occur to forests and there is no stable, "natural" condition (Raup 1964, Botkin and Sobel 1975, White 1979, Brubaker 1987, Botkin 1990, Oliver and Larson 1990, Sprugel 1991). Forests regrow through a succession of structures (Figure 1). Each structure is suitable for some plant and animal species and not for others.

Many forest areas have continuously cycled through large disturbances and regrowth. As the structure changes through growth or disturbances, plant and animal populations change through migration, growth, dormancy, and death. Where large areas of low human population existed, all plant and animal species were maintained as periodic, random disturbances kept at least some area of each structure across a very large area (Oliver et al. 1995).

In the landscape approach to ecosystem management, silvicultural operations are used to coordinate changing forest stand structures to maintain all habitats and reduce risks of uncontrollable natural disturbances (Boyce 1985, Oliver 1992a,b, Boyce and McNab 1994). This coordination is done through a variety of field silvicultural operations such as thinning, uneven-age management, even-age management, controlled fires, active creation of snags, and intentional replanting of open areas (Oliver 1994b, Oliver et al. 1994). Maintaining forests within this variation will involve removing timber and other products and creating employment and other values as byproducts of these efforts.

Management Approaches and Values Provided

The desirability of each approach needs to be viewed in terms of values provided. Much of the world is demanding a variety of values from the forests. These values can be roughly described as global environmental protection, public cost minimization, employment enhancement, and local biodiversity promotion. These values and the impacts of alternative management approaches are described by Oliver (1994a,c).

Landscape ecosystem management provides more values than either commodity-based management or preservation management. All values are negatively affected if preservation management is done, since such forests will undergo large fluctuations of habitats and not produce other values useful to humans—so other areas will have to be managed more intensively to provide human needs. Commodity-based management generally provides an intermediate amount of all values compared to the two ecosystem management approaches. Landscape management may be a lower cost than even commodity-based management if the total value of reduced employment are also considered (Oliver and Lippke 1994).

Where Each Management Approach Will Occur

Each management approach will probably occur under certain socioeconomic conditions:

Preservation Approach

Preservation management can occur either where there is an active decision to set aside reserves, or where there is enough long term uncertainty over the future of forests that agencies consider it too risky to invest in management.

The preservation approach had been used in the United States, Canadian, and New Zealand Park Services—and was usually based on the outmoded concept that these areas could be maintained in a "steady state." Recently, this approach has been expanded by Executive Order in the United States to about 8 million more acres of National Forest in western Oregon, Washington, and northern California (FEMAT 1993).

Management in some regions is "de facto" by the preservation approach where uncertainty over intensive management discourages more active management. In southern New England, landowner perception that forested land could soon be converted residential property has discouraged active forest management investments—even though there is little likelihood that most land would actually be converted (Smith 1969). The polarization of public attitudes between the preservation and commodity approaches is creating a regulatory uncertainty which is discouraging forestry investment on non-federal lands in Washington state (Lippke 1992).

Ironically, the preservation approach may lead to extreme fluctuations of habitat and, sometimes, timber flows. The fluctuations occur in legislatively preserved areas as large natural disturbances kill trees on hundreds of thousands of acres (e.g., Yellowstone fires of 1988). On "de facto" preserved areas, the fluctuations occur after the forest regrows and a temporary forest harvesting industry moves to the region to extract the naturally valuable timber.

Commodity-based Management

Historically, the commodity-based approach has been used in most places and has succeeded in providing a narrow range of timber products at inexpensive prices. This approach has been criticized both directly and indirectly for not providing other public values—such as local biodiversity and high employment. These public values are not incorporated into traditional economic systems, and it is difficult to determine how a management agency can justify providing these societal values without receiving monetary benefit (Lippke 1992).

This management approach will probably be used where there is little public concern about biodiversity or local employment. Such management has been common in areas of low population; in areas where the public has a more manipulative attitude toward the land; in areas where public concern is not organized; and in areas where management of exotic species on previously non-forested land does not appear to impact native biodiversity.

With the increased communication and concomitant increased awareness of "environmental" issues, a rise of non-rural populations, and less concern about local "wood shortages," regions which once tolerated the "commodity-based" management approach are becoming less tolerant of it. In the long term, management in some of these areas may change to a landscape approach. In other places, there may be a polarization between preservation and commodity-based management which will lead to investment uncertainty, and possibly "de facto" "preservation."

Landscape Management

Landscape management provides both commodity and non-commodity values (Oliver 1992a,b); however, such commodity values as biodiversity and employment are provided at a cost to the management agency (Lippke 1992). Landscape management will probably be most effective where it can provide enough economic return for the management agency to continue this management. Where this return is not provided and the agency becomes bankrupt, a "de facto" preservation approach probably results.

Detailed organizational structures and strategies of landscape management would still need to be adjusted to local conditions, social norms, and other region-specific conditions. For a landscape management approach to be successful there needs to be an appropriate technical system, an implementation infrastructure, and a means of maintaining a viable economic return to the landowner.

An Appropriate Technical System for Landscape Management

A technical system capable of maintaining all of the stand structures across the landscape is essential for effective landscape management. Computers, G.I.S., growth models, and visualization systems are allowing such systems to be developed (Boyce 1985, Boyce and McNab 1994, Sessions and Sessions 1992, McCarter et al. 1994). The challenge will be for different land management agencies to incorporate these technical systems into their management organizations.

Implementation Infrastructure

Landscape management will be most effective where there is an infrastructure of professionally trained managers, technically skilled woods workers, suitable machines and servicing facilities, and markets for the variety of products provided by the landscape approach (Oliver et al. 1994).

Maintaining Return to Landowner

The challenge for regions and management agencies is to make landscape management economically feasible. Historically, such commodity values as timber have paid the costs of forest management. Such non-commodity values as the global environment, biodiversity, and employment were either not considered, taken for granted, or assumed to be a public obligation of management. It is uncertain that forest management can subsidize these public values when the wood products have to compete with steel, aluminum, brick, concrete, and other highly polluting products.

Three ways to make ecosystem management economically feasible are for the public to reimburse the forest management agency for the public values provided, for both the price and demand for timber to increase relative to competing products (e.g., steel, aluminum, concrete, brick, and plastic), and for the agency's management system to be so efficient that it can provide these public values and still remain profitable.

Reimbursing landowners for providing public values

Incentives to allow the management agency to provide the public values through landscape management could be in the forms of tax reductions, trust fund allocations, or reduction of competitive advantages of competing industries—such as a carbon tax which reduces the competitiveness of more polluting products. These incentives have been described in detail elsewhere (Lippke 1992, Lippke and Oliver 1993a,b).

Increasing the price and demand for wood

Both the price and demand for timber can increase if wood products can be differentiated from competitive substitutes. Recognition of the ecological and social advantages of using wood can increase both the price and demand through building code acceptances and preferences for wood and through "green certification" which shows the environmental advantages of wood from appropriately managed forests (e.g., Cabarle 1994).

Organizing forest management for efficient provision of commodity and non-commodity values

A forest management organization which is economically efficient for production of timber and other commodities and is compatible with other public values can be made profitable enough to allow the organization to provide more of these public values and still remain solvent. A "portfolio" management approach may help provide this economic efficiency and compatibility with public values (Oliver 1992a).

The remainder of this paper will describe the "portfolio" management approach.

Organizing a Forest as a "Portfolio"

Forests have historically been managed as a "warehouse," in which many stands are grown to similar species and spacings and harvested at a similar ages —

presumably producing similar products in a continuously recycling pattern (Roth 1925). Maximum human benefit from the forest has often been associated with maximum volume of timber produced on a sustained basis; consequently, this approach was considered most efficient—especially when considering the limited inventory, mapping, and growth projection tools of the past (i.e., there were no computers).

Maximizing timber volume often maximizes neither timber value, profits, or revenue nor total forest value (Curtis 1994, Oliver 1994c). In many places, more timber value and profits can be derived in an equal time by managing for high-quality logs rather than for maximum timber volume. In some places, increased forest value can be gained by reducing timber production but increasing wildlife habitat—and hunting leases.

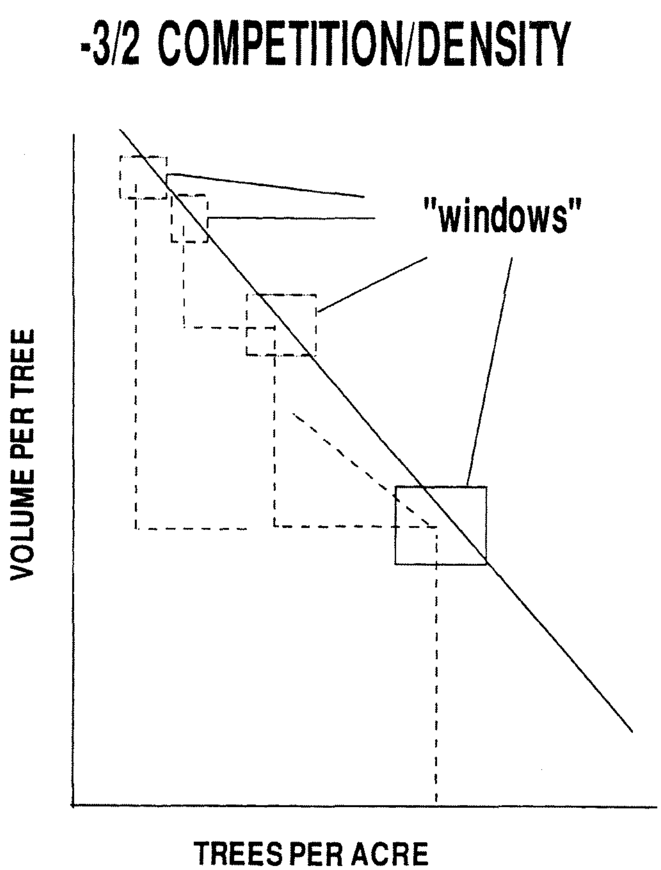

Figure 2. There are critical times in a stand's growth during which a silvicultural operation can most effectively cause a stand to develop a certain structure or species composition and produce certain timber products. These times are referred to as "decision windows" and can be predicted for each stand using modern management techniques. These windows can last from about 3 to 10 years, depending on such factors as site. A density-management diagram can be used to predict some of these "decision windows."

As an alternative, a "portfolio" approach may allow management agencies to internalize many of the benefits of "landscape management" (Oliver 1992a). It is now recognized that each stand has multiple options for management, and each stand has different values at different times. The forest can be managed so that different stands have different species compositions and / or different spacings, among other treatments. The forest can be managed using a "portfolio" approach, with each stand treated as an asset with specific structures and products maturing at different times in different stands, rather than all stands being treated as if they would yield the same structure and product (Boyce 1985, Boyce and McNab 1994). There is presently enough understanding of forest dynamics, enough technology, and enough depth of various markets to allow this approach to be instituted in many places. The remainder of this paper will describe the "portfolio" management approach in detail.

The Stand Dynamics Basis for Portfolio Management

Foresters now understand that certain critical times occur during each stand's development during which it is possible to manipulate a stand so it will readily develop to distinctly different structures (Figure 2; Oliver et al. 1986, Oliver and Larson 1990). These times are referred to as "decision times" or "decision windows" and are specific to each stand. During these "windows," a stand can be influenced to grow to one or another structure, species mixture, or quality of tree stem by selected silvicultural operations. The same silvicultural operation will be much less effective if done before or after this critical time ("decision window").

Many decision windows occur during a stand's development. For example, a "decision window" occurs during the "brushy stage" (Gingrich 1971, Oliver and Larson 1990) of mixed species stands at the beginning of the "stem exclusion stage." During this "window," a stand can be weeded of undesired species and so influenced to develop to any of several species. No weeding will usually allow one species to dominate—while the others are suppressed or killed. Another "window" occurs as stands reach a critical density ("zone of imminent competition-mortality"; Drew and Flewelling 1979). If the stands are not thinned during this window, they will grow tall and thin—sometimes creating valuable "pole" timber but often creating insect susceptibility and mortality, and sometimes becoming unstable to winds (Oliver and Larson 1990). If thinned during this window, they will grow larger in diameter and resistant to perturbations—and so create valuable, high-quality logs. If thinned before the "window," stand volume and value is lost; if thinned afterward, the remaining stand is highly susceptible to blowdown. Similar "windows" can be identified for pruning and for maintaining uneven-aged stands (Oliver and Larson 1990).

The types and timing of various "windows" vary with site, species composition, and stand structure. For example, when 740 Douglas-fir trees / hectare (300 trees / acre) are planted in western Washington on a productive area (site 140 (ft.[43 meters] @ 50 years; King 1966), a decision window for thinning is reached at age 25 years; on a less productive site (Site 100 ft.[33 m]), the window is reached at age 40 (calculated from Drew and Flewelling 1979). A particular treatment alters the time of the next "window" by changing the stand's structure. For example, if the Douglas-fir stand on the productive site is thinned to 420 trees per hectare (170 trees/acre) during the window at age 25, the next window is at age 32. If it is thinned to 200 trees per hectare (80 trees/acre), instead, the next window is at age 42. If it is harvested at age 25 and replanted to 740 trees/hectare (300 trees/acre), the next thinning/harvesting decision window is 25 years later, although there would be intervening "decision times" to decide of what species and spacing to regenerate, if weed control is to be done, and if pruning is to be done.

Silvicultural knowledge and various forest management tools allow foresters to predict these various management "windows" many decades before they occur. Field verification and monitoring is necessary to confirm or modify these long-term prediction of "windows." The "windows" usually persist for about three to ten years, depending on soil productivity and other factors. Timing of silvicultural operations can be done most effectively by identifying these windows and timing the various silvicultural operations to coincide with them.

Inefficiencies in the Historical, Warehouse Approach

Times of forest harvesting have frequently been determined by a stand's location, age, or the needs to produce timber flow, with little regard to "decision windows." Forest inventory and projection systems were often so rudimentary that it was impossible to predict "windows," even if the windows could be identified. Consequently, forest management was not very efficient because some stands were harvested while still growing extremely rapidly (before a window was reached), and others were harvested after many trees had died from suppression (after a window was passed).

Tree species and sizes harvested from natural stands by this "warehouse" approach were variable. Different timber products are most efficiently made from different species, sizes, and qualities of logs. Demands (and prices paid) for these different products are cyclical, but often not synchronous (Figure 3). Consequently, when the variable logs were produced by the "warehouse" management approach, many of them were converted to products which did not efficiently use their size and species—and maximum economic return was not obtained from each stand (Figure 4A).

As management became more intensive, the natural forest was often replaced by stands of uniform species and spacings (e.g., Figure 4B). Where thinnings were done, they often occurred at times which approximated windows, but were done to uniform spacings and so produced a forest with stands of similar structures and wood products at

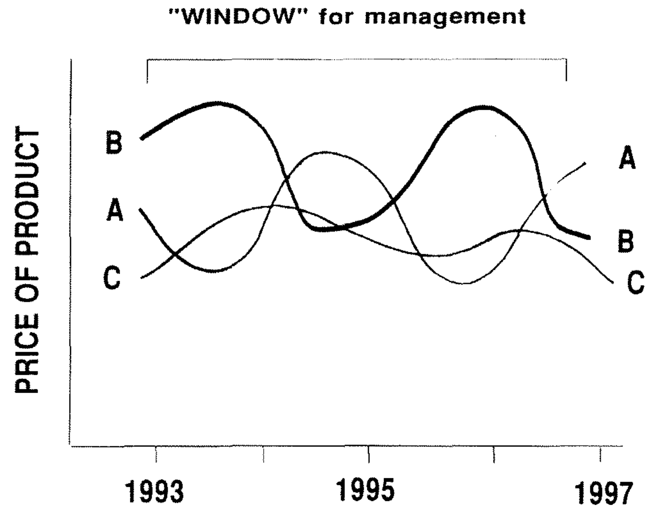

Figure 3. Within the time span of a "decision window," the demand and value of commodities fluctuate (e.g., A, C, & C), but often not synchronously. Portfolio management would allow each stand available for manipulation (within a "decision window") to be harvested when the timber products it could produce were at a high point in their cycle.

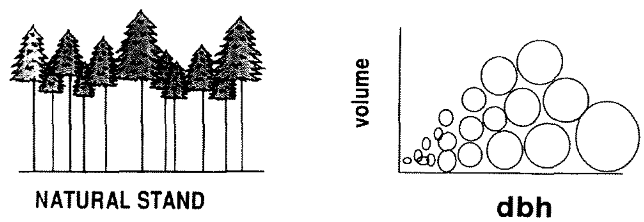

Figure 4A. Natural stands contained an unpredictable, wide variety of tree sizes; therefore, harvesting these stands produced a wide variety of logs—only some of which could be efficiently utilized to make products in demand.

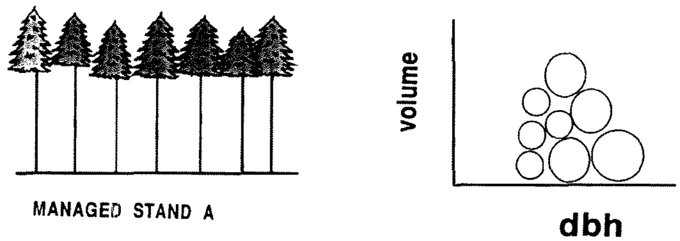

Figure 4B. The "warehouse" approach to management produced uniform tree sizes, which could efficiently suit certain products; however, the value of these stands was low if the products were in low demand (a down-side of the cycle of Figure 3) and only a limited number of habitats were maintained.

times of harvest. Investment decisions were made by compounding of all investment costs from time of site preparation to harvest age to determine the optimum planting spacing, species, and rotation age—even though this required the inaccurate estimating of log values for many decades into the future (Davis 1966).

Managing and harvesting uniform species and tree sizes at a uniform age in a cyclical market meant that logs harvested from stands during a market "slump" were undervalued—and maximum economic return was again not obtained. For example, when the value of conifer timber reached a cyclical low during part of the early 1980s in western Washington, harvesting these conifer stands was not profitable. Many landowners were able to maintain a positive cash flow by harvesting red alder stands—and were very glad they had not converted all stands to a uniform species, stand structure, and tree size.

The simplification of forest stands meant that usually only one or a few species were grown—and all stands were treated similarly. Consequently, the managed forest consisted of only a few species and structures. For example, intensive, even-aged management has been practiced in the Pacific Northwestern United States for the past few decades. The emphasis on conifers, the close spacing, and the lack of thinning led to many stands in the "stand initiation" and "stem exclusion" structures, but few in the older structures (Figure 5, Oliver 1992b). The lack of stands in the older structures led to concerns about extinction of species needing older structures—and a lack of diversity in managed stands.

Management by the Portfolio Approach

Modern understanding of forest stand dynamics and modern technical systems (described above) now allow managers to project and monitor the development of each stand in a large ownership—as well as keep track of the flow of all values across a landscape. In geographic locations where specific information on forests is limited, the present understanding of stand dynamics, the uniformities of ecological processes, and the use of adaptive management enables managers to project stand development quite readily (Oliver 1992c).

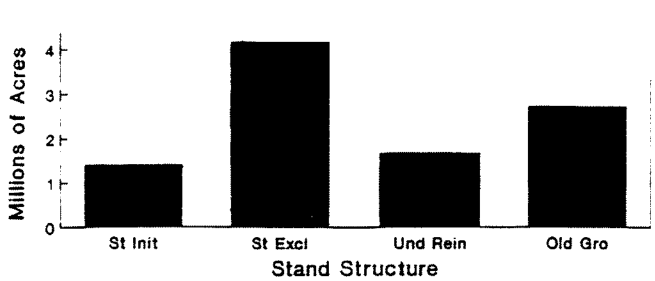

Figure 5. Estimated distribution of acres by structural stages (of Figure 1) in western Washington (from Oliver 1992b). Many stands in western Washington are in the "stem exclusion" stage because of uniform stand treatments following harvesting and replanting.

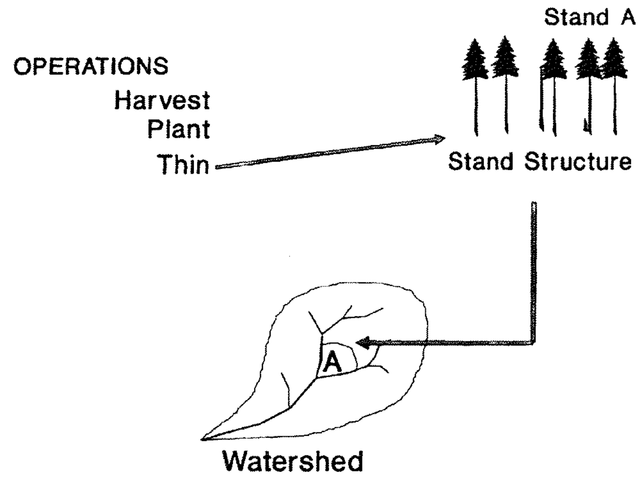

Figure 6. Using a sophisticated information system, treatments to each stand across a landscape (e.g., a watershed) can be coordinated to maintain a variety of stand structures (Figure 1) and commodity products to be managed as a portfolio (after Oliver et al. 1992).

Because each stand can be projected individually, it is not necessary for all stands to be grown to uniform species, spacings, and rotation lengths. Different stands can be managed in different ways—with different species and spacings and by either even-aged or uneven-aged methods (Figure 6). Growth of each stand can be projected based on the species, spacing, and other factors peculiar to that stand; and the "decision windows" for each stand can be projected.

During each management planning period (for example, a 5-year period), all stands which will reach a "window" can be identified. A decision can be made to harvest, thin, weed, prune, or do nothing for each stand during this planning period—depending on the needs for cash flow, investment, stand structure, habitat, and other values. For the targeted thinning and harvesting operations on each stand, markets can be tracked within the window and operations done during desirable parts of the market cycles (Figure 3).

Such a system can allow a diversity of stand structures and species, since these can produce a variety of log sizes and species for which markets can be tracked and maintained. It is not necessary, however, that the stand structures and species mixtures be simple, since the tracking and operational system can monitor quite complex structures (McCarter et al. 1994)—and such structures may be more economically feasible to manage (Oliver 1978).

Unlike the "warehouse" management approach in which the forest structures and species compositions are simplified to fit a simple information and inventory system, the efficiency of managing the forest by a "portfolio" approach is gained by a complex information system allowing managers to take economic advantage of managing complex forests for varied products. The efficiency of "portfolio" management is that the decision of how to manage each stand during its "window" will be made similar to an investor balancing assets in a portfolio—deciding what to do with each asset as it matures during a "window." As a result, the decision of how to treat each stand may be different: some may be thinned, others may be clearcut harvested, and others selectively harvested, and still others left alone. Each operation done within each stand will still be simple; and the log species and size sorting process will be even simpler since each stand will produce more uniform products.

Business Considerations of the Portfolio

Managers of forest agencies are concerned with profitability (return on investment), cash flow, maintaining an infrastructure, and maintaining public values such as biodiversity, among other things. They have to make decisions about long term investments in forest practices even though markets, cash flow needs, infrastructures, and scientific understanding of biodiversity and other public values is constantly changing.

Portfolio management increases the profitability of forest management by enabling specific types of timber to be scheduled for harvest during market peaks (Figure 3). This profitability increases the efficiency of wood use since logs are processed for their highest use, rather than being used for less than optimal products because they have already been harvested.

The "warehouse" approach tended to address concern for the long term investment by planning on short rotations and investing minimal money in silvicultural operations.

Alternatively, the "portfolio" approach addresses concern for the long term investment by considering the time between "decision windows" to be the planning horizon for a stand. At each "decision window," the economic, cash flow, biodiversity, and other considerations will be a comparison of the alternative treatments of the stand—such as harvesting the stand, thinning it, or doing nothing until the next decision window.

At any time, managers using the "portfolio" approach can respond to changed demands for cash flow, since the decision of thinning or harvesting the stand is made at when the stand reaches a window.

Portfolio management allows managers to be more responsive to anticipated shortages and excesses in future supplies and the potential flooding of markets. For example, the age distribution of stands in western Washington in 1989 is shown in Figure 7. Stands younger than about 20 years old (in 1989) are primarily from plantations, and there will be a large volume of plantation-grown wood to be harvested between about 2010 (when the stands are 40 years old) and 2030. If the "warehouse" approach is followed and the stands are all grown at the same spacing and harvested at the same rotation age, the market will be flooded with very many, uniform log sizes—and the price of these logs will probably drop. It may be more appropriate to prune some stands and diversify the thinning treatments to others, as well as harvest the stands at different ages during different windows. In this way, a variety of types of logs will be produced over a longer period—and the risk of having to sell the logs to a single market during a single time will be reduced. At the same time, the manager can grow a small portion of the stands for targeting specialty products—such as very high-quality, wide-dimension lumber from quite old trees. This timber can command a very high price; however, the market is not large and the long rotation does not provide the cash flow some managers need.

By managing stands with a variety of structures and maintaining an accurate inventory and projection of these structures, land managers can also target, control, and market non-timber products and values from the land. Such products include berries, mushrooms, floral boughs, hunting rights, diversity of habitats, and scenic beauty (Oliver 1992a).

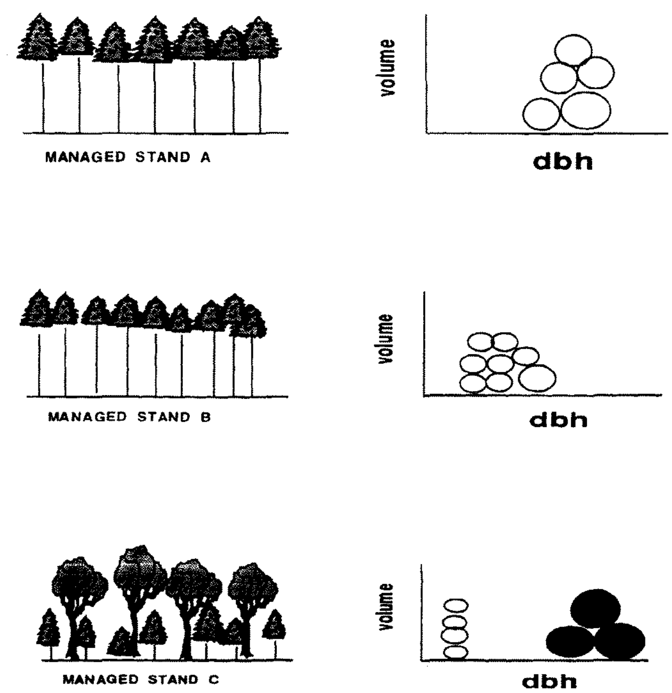

Figure 7. "Portfolio" management can produce the wide variety of stands with simple and complex structures but with predictable product mixes and "decision windows" for thinning, harvest, or other manipulations. Each type of stand can be thinned or harvested within the window at a time when product cycle is high (Figure 3). The variety of stands would better maintain a diversity of habitats (and so biodiversity) across the landscape.

Public Considerations of Portfolio Management

The portfolio approach will ensure a greater variety of public values from the forest (Oliver 1992a). Since a greater diversity of stand structures and species is provided, greater biodiversity will be provided. The increased thinning activity to develop a variety of log products will also produce both employment and higher wood quality (Oliver 1992b, Lippke and Oliver 1993a). The employment would be in the thinning operations, in processing of the thinned material, and in processing the higher quality wood in secondary manufacture.

By both producing higher quality wood and targeting each type of wood more to a specific demand, portfolio management will allow more uniform, high quality wood products to be manufactured more inexpensively. These products will contribute to the global environment as they become economically competitive substitutes for more polluting steel, aluminum, brick, concrete, and plastic (Koch 1992, Kershaw et al. 1993).

The portfolio approach will allow land managers to adjust their management plans rapidly as endangered species and similar environmental concerns change. The management plan can be rapidly changed and incentives can be rapidly instituted and responded to simply by altering decisions made during the windows.

Instituting a Portfolio Management System

Despite its advantages, "portfolio management" will probably not be effective if it is imposed upon an existing forest management agency as a "sweeping" reorganization. Management organizations are a dynamic combination of personalities and formal and informal lines of communication. "Sweeping" reorganization may change the formal organization network, but can not create a synchronous informal network. Consequently, such sweeping attempts to reorganize have generally met with limited success.

"Portfolio" management can probably be readily implemented in newly created management organizations with no history of other management.

"Portfolio" management will probably be successfully implemented in existing organizations through a gradual, evolutionary process. Many field foresters recognize the variation in stand structures and the different opportunities to manipulate them. In some organizations, diversification of timber products is already being done as some managers are planting a variety of species, pruning some stands, thinning to different spacings, and managing to different harvest ages. To the extent field foresters and others recognize the advantages of portfolio management, changing to this system can be done rapidly and easily. In some cases, an explicit acknowledgment of this approach will then allow local foresters to develop an appropriate infrastructure to implement it.

A decentralized management approach will be necessary for implementing the "portfolio" approach, since local foresters will be most capable of identifying subtleties in stand structures which make various windows and options appropriate (Oliver et al. 1994). These foresters should have available technical tools (described above) to allow them to make the portfolio decisions appropriately. Higher, centralized management levels can use their economies of scale to develop and service the management system, to provide information on markets and stand dynamics, and to coordinate among local managers to improve the efficiency of the decisions. The local managers will then have the needed tools and local knowledge to allow them to make appropriate decisions on each stand to meet coordinated needs.

With a portfolio management approach, a more developed infrastructure will increase the ability to manage the forest for a diversity of commodity and non-commodity values. More markets for a variety of timber products will allow a greater variety of stand structures and products to be grown—and so will increase the profit and stability of management. A diverse secondary manufacturing infrastructure will also provide a greater diversity of markets. A skilled labour force to do the variety of management tasks will increase the ways management can be done. A road or other transportation system which will allow management access to stands relatively readily will allow a

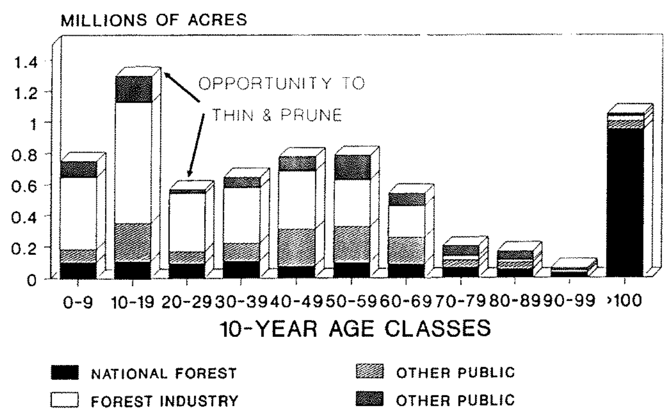

Figure 8. Age distribution of stands in western Washington in 1989 (MacClean et al. 1991a,b,c). There are many stands between 10 and 30 years old. If all the young stands are managed to similar spacings and with similar other treatments, they will all be ready for harvest at a similar time—and there will be an abundance of timber of a narrow range of dimensions and a resulting reduction in timber prices and profitability. There will also continue to be relatively little of the later stand development stages of Figure 1. Alternatively, managing the stands by a "portfolio" approach will provide a variety of stand structures to provide a variety of habitats and a variety of types of timber which can be harvested at different times to fit different market niches during peak demands (after Oliver 1992b).

greater diversity of structures and species to be maintained. This intensive management will not only prove to be economically preferable and readily capable of providing biodiversity and other environmental values, but will also provide stability for the forest management agency since many people will be interested in the strong infrastructure and ecological values provided. This large public support will help insulate the management against regulatory confiscation caused by public dissatisfaction.

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A Pan-European System for Measuring Biodiversity, Succession and Structure of Undisturbed Forests and for Improving Biodiversity-Oriented Silviculture

Jari Parviainen, Andreas Schuck and Winfried Bücking

Protected forest areas of forest reserves are the main remaining samples of undisturbed forests in Europe and are therefore the basic experimental forests for research on natural processes. At this moment in most European countries national networks of strict forest reserves for long-term research exist, but the degree of detail and character of the information supplied differ greatly. Supported by the newly established European Forest Institute, the establishment of a network of strict forest reserves representing all various European forest types has been launched. Biodiversity indicators from undisturbed forests will help to set up guidelines for practical forest management and to integrate characteristics into forest inventories.

There have been two basic approaches for studying natural forest stands; studies dealing with entire ecosystems and studies using traditional stand measurement approaches. An ecosystem oriented approach in managed as well as in undisturbed forests is very common in studies concerning nutrient cycles, dynamics, and structure of forest stands. In Europe there is a very long tradition in the research of natural forests using transect methods. Presently, only a few studies have dealt with the combination of stand parameters and other characteristics of ecosystems using practical, large scale sampling plot methodology.

1. Introduction

Biodiversity and sustainability have become major topics in conservation biology, in forest management, and at an administrative and political level. Many examples support this fact including, Earth Summit in Rio de Janeiro (1992), the Ministerial Conference on Protection of Forests in Europe (Strasbourg 1990, Helsinki 1993) and the follow-up meetings of the Helsinki Conference in Brussels (1994) and Geneva (1994). "Biodiversity," finding its historical origin in ecology, evolutionary biology and genetics, has received high attention in scientific literature since the beginning of the 1980s (Wilson 1988, Dudley 1992, Kouki 1994). The number of publications having biodiversity or biological diversity in their title increased very rapidly during the past 10 years. Many of these studies deal with operational methods which seek to maintain or maximize biodiversity.

In order that silviculture might be practiced on a sufficiently high level of diversity throughout the forest ecosystems, we must learn about the development processes in undisturbed forests. The clarification of these processes require specific research on structure, succession, biodiversity, and long term monitoring of natural forest ecosystems. Protected forest areas or forest reserves are the main remaining samples of undisturbed forests in Europe, and are therefore the basic experimental forests for research on biodiversity.

Due to modern silvicultural practices many important natural forest development features in temperate and boreal forests have disappeared or have become a rare sight, for example:

- Burned areas with large amounts of dead wood
- Dying trees, snags and down logs
- Deciduous components in forests
- Natural development processes: the natural dynamics and development of forests in spatial and temporal respects without human intervention.
- Size: fragmentation of existing natural and semi-natural forests in total.

Trees and stand structures are in close interaction with all other parts of the forest ecosystem (e.g., soil, flora and fauna). Therefore studies on stand structure and dynamic development processes on a stand level play a key role in the description of biodiversity indicators in different forest vegetation types. Parameters of structure, giving valuable information on dynamics and development processes, are easy to measure. A large number of permanent sampling plots have already existed for a long time in many European countries, providing useful data.

The main aim of a feasibility study implemented by the European Forest Institute, Joensuu, Finland (EFI) 1993-1994 was to give background information on the proposed project entitled "Instruments for depicting forest biodiversity using a network of permanent sample plots in undisturbed forests in order to improve silvicultural practices in Europe." This paper is a summary of the original report written by Schuck, Parviainen and Bücking (1994), with some new remarks concerning the boreal forest zone.

2. Present state of research on natural forests in Europe

2.1. *Definitions and features of natural forests for research*

A large number of expressions exist to describe management regimes, protected forest areas, and forest ecosystems. Definitions and the use of these expressions vary in different European countries. Depending on the settlement structures, forest utilization, and industrial development in Europe, forest management has played a different role from one region to another. Manifold classifications have originated related to aims, management regimes, and forest communities. As a consequence it seems reasonable to subdivide the terms as follows:

Origin of forest	**History, management and status of protection**
1) Virgin forest	1) Undisturbed, unmanaged forest
2) Old growth forest	2) Nature conservation area
3) Natural forest	3) Strict nature reserve, strict forest reserve
4) Semi-natural forest	4) Natural reserve
5) Secondary forest	5) Nature park
	6) Wilderness area
	7) Protection forest
	8) Gene reserve forest
	9) Production forest
	10) Artificial and plantation forest

Only a small percentage of forests in Europe are legally protected (Broekmeyer and Vos 1994). These can either be strict forest reserves with a non-intervention status and closed to the public, or other categories allowing limited or specific use, for example, recreation, hunting or controlled management measures. The amount of protected areas is less than 5% in all European countries, and under 1% in most European countries. The highest percentages can be found in countries with a large coverage of woodlands (Finland, Sweden, former Yugoslavia, Russia, Ukraine).

For understandable reasons most natural forest reserves are located in remote areas and on extreme sites (e.g., mountains, peatlands, riparian zones). Accessibility is often very difficult and forest management too expensive. Regions which are intensively managed are usually located on high quality sites. Forest reserves are rarely found in these areas. It would be important for research to close this gap and establish protected areas on all representative and productive sites, to have undisturbed stands in close proximity to managed stands, or as a network, directly in managed forests (Schütz and Matter 1992, Projektgruppe 1993). The first steps towards this goal are being taken in several European countries. Mature and overmature / decaying stands are the most likely to be protected. This protection is legitimate as old forests have become a rare sight throughout Europe.

A very important task is to extend the forest reserve research to the Carelian and Siberian area of Russia, where very large undisturbed and virgin forests of the boreal forest zone still exist. These forests can serve as a fundamental background for forestry management in Northern and Central Europe, where hardly any forests without human influence can be found.

As traditional research has shown, the climax forest is only one of several phases of virgin forest dynamics. The dominance of certain development stages is dependent on the vegetation zone (boreal or temperate zone). Therefore, it is essential for future actions to protect other successional stages, as they will broaden the knowledge on biodiversity, dynamics, and stand structure.

Some forest reserves could be selected in areas which have been destroyed by wildfires (Parviainen 1994a and 1994b) or severely damaged by storms, for example, "Storm forest reserves in Germany" (Bücking 1993). These reserves would give valuable information on natural succession processes in different climatic zones. Also young stands should be selected. Niemelä et al. (1988), Puntila et al. (1991) have shown that species richness of insect fauna is significantly higher in young stands than in old growth forests due to a higher variation in field layer vegetation. The same pattern is most probably true for herbivorous fauna as well.

2.2. Successional phases of natural forests

To understand the function and processes of natural forests, it is important to distinguish the different succession phases. The separation of virgin forest stands into different stages has found its application mostly in Europe. Different phases (initial / optimum / decay) occur adjacent to one another in a temporal and spatial point of view. Remmert (1992) states that it is appropriate to describe a virgin forest as a cycle rather than in a linear form. This leads to the understanding that the climax stage of a natural forest ecosystem is not constant but a mosaic of different phases consisting of different plant communities, different species of flora and fauna, as well as changing soil development processes. As a consequence, old virgin forests can be regarded as a mosaic of desynchronized phases of a cycle. Two development cycles can be distinguished in the most common natural forest stands of Europe as illustrated in Fig. 1 and 2.

The small cycle shows the regeneration in the climax forest. In a slowly decaying stand, shade tolerant tree species regenerate underneath a spatially opened canopy and dominate throughout the entire cycle of development. This process is the most common in Central European virgin

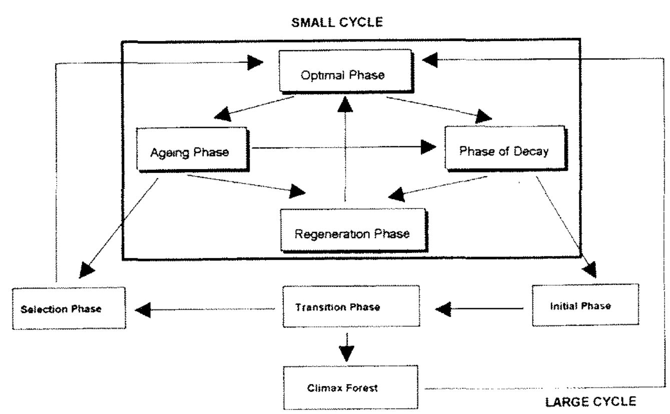

Figure 1. Development stages in virgin forests of Central and Southeast Europe *(In:* Schmidt-Vogt, 1991).

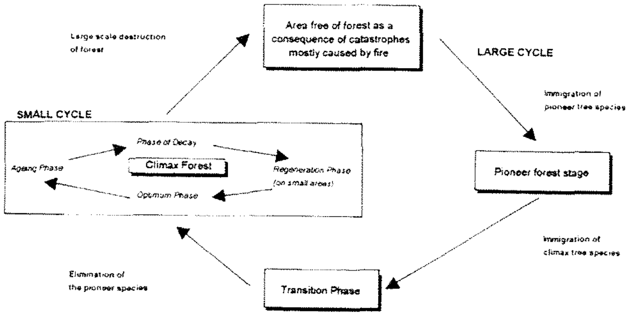

Figure 2. The dynamic development of boreal conifer forests (*In:* Schmidt-Vogt, 1991)

forests, as large scale catastrophes (fire, storm, calamities) only play a minor role in these forest communities.

The large cycle is differentiated and stands totally decay or are destroyed by natural catastrophes. In the initial phase pioneer species form the forest and are overgrown by shade tolerant tree species (transition phase). The development leads to the optimum phase either as a climax forest or under special conditions to an uneven aged selection stand (Schmidt-Vogt 1991).

In the boreal coniferous zone, however, the large cycle predominates. From time to time, the development of natural forest is halted by disturbances and catastrophes. The reason for the natural destruction of forests used to be fire, but insect pests, gales and snow have also had their role. Time series constructed by means of dendrochronological studies have revealed that forest fires have swept through forests on dry mineral soils as frequently as every 70 years. On moist mineral soil sites this has happened at an average interval of 120 years. Where forests have not been hit by fire, forest development has taken the course of the small successional cycle with individual trees dying (Tolonen 1978).

The most interesting stage for all research is the optimum stage, which refers to the period from the time of culmination of height growth until the growth of the basal area reaches its culmination. This stage gives the best opportunity to transfer findings on stand structure and dynamics from virgin forests to managed mature stands because they have many similarities.

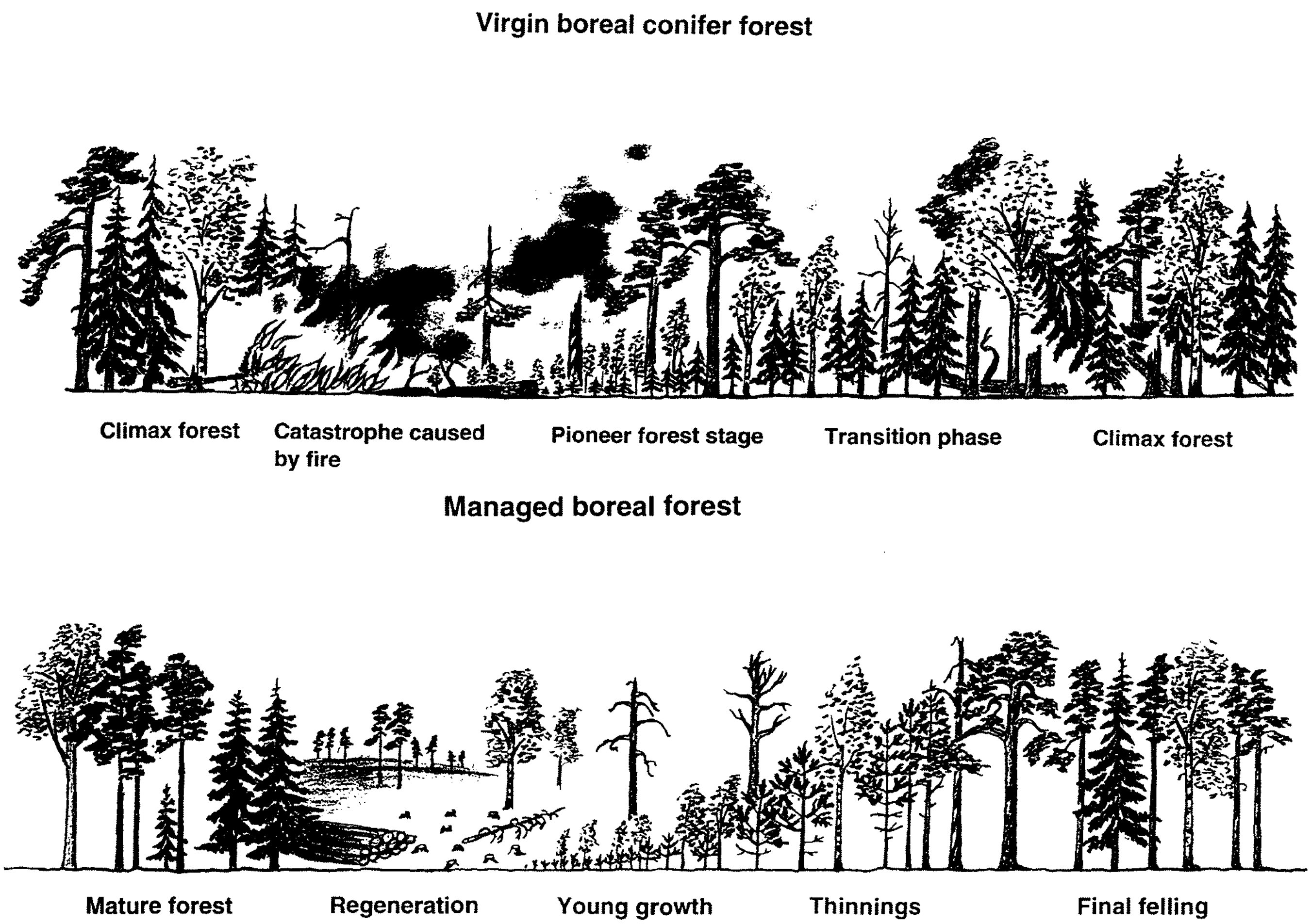

Figure 3. The forests in the coniferous zone may be referred to as catastrophe forests whose natural development is occasionally interrupted by fires, insect pest epidemics or gale. This development is being mimicked in the treatment of commercial forests.

2.3. *Activities in forest research*

Activities in virgin forest research can be divided into two different approaches: the traditional research emphasizing the silvicultural aspects of forest development and the ecosystem approach. The first studies and research questions in virgin forests in Europe concentrated on the description of their structure. In all early studies the main objectives in virgin and formerly managed forests were to intensify the knowledge concerning the original structures of natural forests (Korpel 1978, 1989, Schmidt-Vogt 1991, Leibundgut 1959,1982, Zukrigl 1991). In addition, the natural forest areas should function as a refuge for endangered species of the forest community, which could not otherwise survive in managed forests (Hesmer 1934).

One of the earliest publications dealing with natural forest research was a description of the virgin forest of "Schattawa" in Bohemia (Engler 1904) and a report on the establishment of a forest reserve in the Spessart, Germany, consisting of natural stands of oak forest (Dengler 1908). Research in undisturbed forests in Finland and in the Nordic countries started in the early 1900s. Ilvessalo (1920, 1937) and Cajander (1926) did pioneer research mostly in the field of structure, growth and yield in natural forest stands. A further approach was to set up control plots in managed forest types and to compare them with results gathered in undisturbed areas.

The common technique of forest profile drawings is used to determine a large number of different parameters especially concerning stand structure, dynamics of regeneration, and development stages. Profiles are drawn separately for each stage of development as well as across different phases to get an exact description of natural forests (Leibudgut 1982). In the field, transects of various sizes are used to collect the relevant data. The construction of crown projection maps also is an important tool for analyzing forest stands.

Profile drawings and crown projection maps give basic information on stand structure, tree species, the exact location of each individual tree, tree development, tree height, diameter at breast height, damage, vitality, the position and form of the crown, crown cover, and the amount/type of dead wood (snags and lying dead wood). Hardly any studies exist that join stand structure results and findings on flora and fauna (biodiversity aspects). Transect techniques, however, offer a very good basis to combine research (e.g., insect and fungi) with specific stand parameters on the same area.

Subjects and parameters of traditional forest research in forest reserves are:

1) Description of forest communities and site ecology
   - Forest profile drawings (Transect method)
   - Crown projection maps

2) History of the forest
   - Pollen analysing
   - Anthropogenic influences

3) Stand structure
   - Number of trees in different diameter classes
   - Tree species composition
   - Layering
   - Basal area and yield of individual trees
   - Structure and yield of entire forest land
   - Tree form
   - Mortality

4) Dynamics of regeneration
   - Condition of regeneration
   - Potential of regeneration of forest communities
   - Important factors of regeneration
   - Influence of game browsing
   - Regeneration on decaying wood

5) Dynamics in the development of different forest communities

The traditional research approach has often been criticized because of the difficulties in distinguishing different stages in the field (Albrecht 1990). Virgin forests and semi-natural woodlands often appear as mosaics, showing striking uneven-aged structures and making a classification difficult and subjective. They do not fit into a specific scheme, and therefore development stages should be regarded as a helpful tool of description. On the other hand, the methods using forest profile drawings, crown projection maps, and the charting of dead wood have lead to a large amount of data, which are of high value for describing and depicting biodiversity indicators in forest ecosystems.

Further important characteristics of traditional research methods are the requirements of being non-destructive, practicable, and not too complicated. Examinations are reduced to observation and non-damaging measurement procedures. Conflicts often arise with other fields of science, for example, ecosystem oriented research, which uses experiments for testing.

Research in forest reserves is essentially long-term (Peterken 1993, Projektgruppe 1993). The oldest permanent observation plots had already been established over 100 years ago. Long-term studies, however, require special methodology. The documentation of the exact location of individual trees as well as the description of forest development on a long time scale is only possible using reproducible parameters. In comparison to other fields of research, it requires a large amount of enthusiasm and persistence (Peterken 1993).

A deficit of traditional research in natural forest ecosystems is that biodiversity played only a minor role in studies as biodiversity was not as important an issue 10 years ago.

Morosow was the first to deal with questions on the dynamics and development of forests, especially in the boreal zone, as early as 1914 (Ellenberg 1973). He is regarded as the founder of forest ecosystem research in Europe. In the recent past an ecosystem oriented approach in forest research has found a great deal of attention. With the growing pressure on forest ecosystems caused by human intervention and environmental pollution, programs such as International Biological Program (IBP), Eurosilva, European Network of Permanent Plots for Monitoring of Forest Ecosystems, and the International Cooperative Program on the Assessment and Monitoring of Air Pollution Effects on Forests (IMP) have been initiated by UN-ECE 1989. Many permanent monitoring plots have also been established in forest reserves and national parks.

The main purposes and aims of ecosystem research are (Ellenberg et al. 1986):

1) The analysis of structures: inventory of life forms on a verbal basis: taxonomy inventory
2) Classification and typology: using ecological differences and similarities (e.g., in-site type or vegetation type)
3) Analysis of function and capacity: mostly energy, water, and nutrient cycles
4) Studies on temporal and spatial dynamics: history of development, history of use, succession processes
5) Modelling: verbal, optical, or mathematical modelling
6) Analysis of anthropogenic influences on ecosystems and possible consequences: utilization, dangers, and protection: "Applied ecosystem research"

A multifunctional information system on forest development for management purposes called SILVI-STAR was developed in The Netherlands. It is used for quantitative and qualitative studies on patterns and processes in forest ecosystems under semi-natural conditions (Koop 1985). The main emphasis of SILVI-STAR is the study of forest vegetation structure and species composition on different scales in time and space using stand parameters. The monitoring system especially lacks the integration of faunistic components (e.g., insects, birds and herbivores), fungi and their influences or contributions to a natural forest ecosystem.

Often the results from these studies are difficult to apply to practical silviculture. The methodology in these research branches, however, is very advanced and of great importance for depicting stand biodiversity. Therefore, it will be essential to integrate and combine findings of various research disciplines such as botany, zoology, genetics, soil science, and other more ecosystem-oriented fields with traditional research findings.

As a résumé, studies on depicting biodiversity indicators using stand structure and successional development in undisturbed and semi-natural forests and woodlands in Europe will require both results from traditional research and other research disciplines. It has been emphasized that successional development of natural forests vary in the boreal and temperate vegetation zone. It will result in manifold number of biodiversity indicators having different weighting in the various European vegetation zones.

3. Applications from natural forest research to silvicultural practices

Examples from boreal forest zone

In the pursuit of ecological sustainability, silviculture is expected to follow methods that mimic natural events. In the case of Finland, for example, the way in which silvicultural measures are applied is steered by historical developments (slash-and-burn cultivation, diameter-based selection felling) and, from the viewpoint of natural forests, by forest fires and other natural catastrophes.

Stand structures of production forests should manifest specific features of natural forests, these being related to biodiversity, for example, quantity of standing or fallen dead trees, presence of broad-leaved species and charred wood. Although natural forests are usually the rarest of ecosystems and the richest in biodiversity and specialization, it is too much to expect that forestry could be able to reconstruct equivalent ecosystems in commercially managed forests. The only means to preserve the flora and fauna typical of natural forests is by establishing a sufficiently dense and representative network of conservation areas.

From an ecological point of view, the dynamic development of boreal coniferous forests includes a treeless stage and a catastrophe. This being the case, regeneration felling, for instance, should be assessed in the light of ecological factors different to those applied in Central Europe. A catastrophe prevents the process of invasion by spruce, promotes nutrients bound in the humus back into the cycle, and allows forest regeneration to take place. There are also many reasons creating small openings in the forest cover according to local ecological conditions.

Extensive clear felling operations are a thing of the past in the Nordic countries. New small-scale regeneration methods have been introduced in their place. In order that the management of production forests might more closely resemble the development in natural forests, regeneration sites should be kept small (in Finland, on average, 1-2 hectares on private forest land) and felling areas should be restricted to follow the variation in topography and soil conditions (see Fig. 3). Natural regeneration always has priority. Regeneration sites should show both fallen and dying standing trees left in place. Ecological corridors to facilitate enhanced wildlife movement should be created in the middle and along the edges of the felling sites in accordance with topographic and stand features. In places where the humus layer has to be broken up to encourage restocking, prescribed burning or light scarification are recommended.

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Silviculture Systems to Maintain Caribou Habitat in Managed British Columbia Forests

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The clearcutting silviculture system that is typically used in the ranges of the two ecotypes of caribou (Rangifer tarandus caribou) *in British Columbia is not compatible with maintaining their habitat. Stand-level habitat management objectives for caribou vary from one biogeoclimatic zone to another because of differences in the forest resources used by caribou. Single-tree and group selection systems are currently being tested, along with new approaches to clearcutting, as possible ways of integrating management for caribou habitat and timber. The various trials include assessments of the responses of lichens to treatments, the responses of shrubs to treatments, the success of regeneration, use of the sites by caribou, and impacts on elements of biodiversity.*

Caribou (*Rangifer tarandus caribou*) in British Columbia are considered at risk by the provincial wildlife agency. One reason for the concern is the growing impact of forestry activities on caribou ranges, especially on winter habitat. In the last few years a small group of researchers in British Columbia have been developing and testing silviculture systems that have the goal of maintaining caribou habitat (Stevenson et al. 1994). This paper reports on the direction and progress of those efforts.

Within B.C. there are two ecotypes of caribou. Mountain caribou occupy the mountainous south-eastern and east-central part of the province while northern caribou have a wider range, predominantly in the north (Figure 1). The caribou inhabit several different biogeoclimatic zones[1]. Research is underway in three of those zones to develop silviculture systems that are compatible with maintaining caribou habitat. Development of appropriate silviculture systems depends on an understanding of how caribou use forests in each of the three zones.

Mountain caribou characteristically use two forested zones, as well as alpine tundra. In early winter caribou make their greatest use of the Interior Cedar Hemlock (ICH) zone, which is located on lower slopes and valley bottoms. The lower snowpack combined with the snow interception provided by the forest make low shrubs available for food. Caribou are also effective at locating windthrown trees covered with arboreal lichens that provide another important source of food.

Later in winter, when the high elevation snowpack has settled, most mountain caribou use the Engelmann Spruce

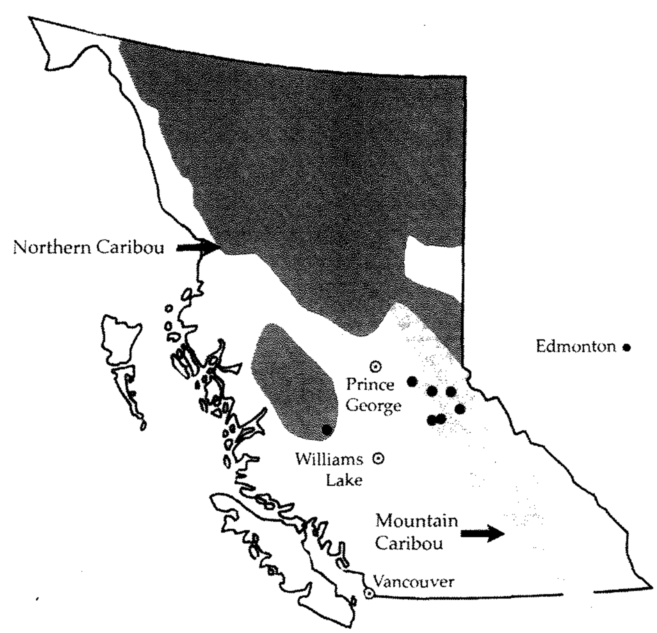

Figure 1. The distribution of caribou in British Columbia, Canada showing the locations of silviculture systems trials

[1] Biogeoclimatic zones are differentiated by distinct patterns of vegetation and soil. B. C. has been divided into 14 climatically distinct areas usually named after the dominant climax tree species (Meidinger and Pojar 1991).

– Subalpine Fir (ESSF) zone, which is located between the ICH zone and alpine tundra. The snowpack, which is often 3 metres or more deep, covers the shrubs, but because of their low foot loading caribou gain access to arboreal lichens on the lower branches of trees. Arboreal lichens are almost the sole forage item for mountain caribou during late winter.

The Montane Spruce (MS) zone is the winter habitat for many northern caribou located on high elevation plateaus where lodgepole pine (*Pinus contorta*) is the predominant tree species. Because this area lies in the precipitation shadow of the coast mountains, winter snowpacks are usually less than 0.5 metres. Caribou dig through the snow (crater) to obtain terrestrial lichens, which are the largest component of their winter diet. Arboreal lichens are the second most abundant dietary item (Cichowski 1989).

Effects of the Clearcutting Silviculture System

Clearcutting is the silviculture system that is normally used in all three zones. Removing all the trees eliminates almost all the winter food for mountain caribou and a significant amount of the winter food for northern caribou. Unlike most other kinds of forage for ungulates, arboreal lichens do not increase after logging. Typically, they do not become abundant enough to be a significant forage source for caribou until the stand is 100-150 years old. Stands in the ICH and ESSF zones that are managed according to the clearcutting silviculture system will be ready to be harvested again before they become suitable as winter range for caribou. Large clearcuts exacerbate the problem, because the rate of lichen colonization decreases with increasing distance from a mature forest edge (Figure 2). After multiple passes into a drainage the landscape could be nearly devoid of stands that support abundant arboreal lichens. While it is likely that caribou are limited by their requirement for space to avoid predators before reaching food limits, that space must be in a suitable condition to produce food.

Northern caribou wintering in the MS zone are affected by reductions of terrestrial lichens, as well as arboreal lichens. Clearcutting in summer disrupts the sensitive terrestrial lichen community, especially if drag scarification is used for site preparation. Even conventional winter logging can reduce terrestrial lichen abundance by over 50%.[2] The long-term responses of terrestrial lichens to logging disturbance are difficult to predict. Most studies have described succession after fire, which may be different from post-logging succession.

Silviculture Systems for Caribou

To be compatible with caribou, silviculture systems must be designed to meet specific habitat objectives. Some habitat objectives apply in all zones. For example, silviculture systems should result in stands that are windfirm and that maintain continuous future habitat. Because caribou tend to avoid places where they cannot see well and move about easily, visual and physical obstructions should be minimized. Other habitat objectives differ from one biogeoclimatic zone to another, according to the way caribou use forests in that zone. These differences necessitate tailoring silviculture systems to meet specific objectives. Table 1 summarizes the caribou habitat objectives for the three biogeoclimatic zones, and gives examples of silviculture system trials in each.

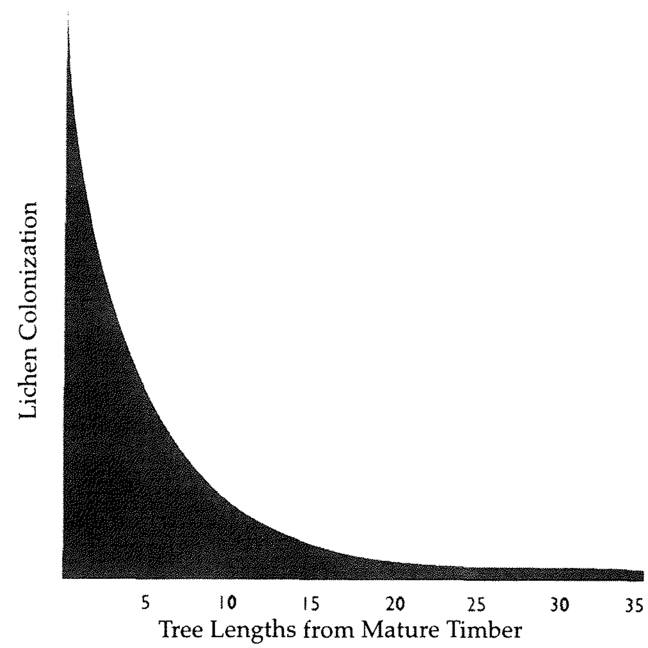

Figure 2. Generalized pattern of arboreal lichen colonization on young twigs in second growth and distance from mature timber (from Stevenson 1988)

The Interior Cedar – Hemlock Zone

In the ICH zone it is more important to provide arboreal lichens as litterfall than on the lower branches of trees, which are largely out of reach for caribou. Maintaining the snow interception capability of the canopy is moderately important. It is most important, however, to maintain the low evergreen shrubs favoured as winter forage by caribou, such as false box (*Paxistima myrsinites*), bunchberry (*Cornus canadensis*), and five-leafed bramble (*Rubus pedatus*), while discouraging invasion of tall shrubs favoured by moose and deer, such as willows (*Salix* spp.) and red-osier dogwood (*Cornus stolonifera*).

Group selection is currently being tested as a system that may be compatible with caribou habitat in the ICH zone. At the Fleet Creek study area, 20% of the block has been harvested in 40 x 60 m (0.24 ha) openings. In some of the openings, a group of 2-4 large lichen-bearing reserve trees was left to provide lichen propagules, structural diversity, and wildlife habitat. Future entries in which 20% of the volume is removed are planned at intervals of 50 years. With this scenario, at any one time the 40% of the

[2] H. Armleder, unpubl. data

Table 1. Examples of silviculture systems trials for caribou habitat retention in three biogeoclimatic zones in British Columbia, Canada

Biogeoclimatic Zone	Zone-specific habitat objectives and their importance[1]	Study area and time of harvest	Silviculture system and prescription
Interior Cedar - Hemlock	• lichen litterfall (H) • avoid enhancing moose forage (H) • snow interception (M) • lichen on low branches (L)	• Fleet Creek • Robson Valley Forest District • winter 1993-94	Group Selection with Reserves • 0.24 ha openings • group of 2-4 large lichen-bearing reserve trees in some openings • 20% volume removal
Engelmann Spruce – Subalpine spruce	• lichen on low branches (H) • lichen litterfall (M) • snow interception (L/M) • avoid enhancing moose forage (L/M)	• Pinkerton Mountain • Prince George Forest District • fall 1994 • Grain Creek • Horsefly Forest District • winter 1992-93	Single-Tree Selection • Q = 1.3 • 32% volume removal • hand-felled Group Selection • 0.03, 0.13, 1.0 ha openings • 30% volume removal • feller buncher • safe snags retained
Montane Spruce	• terrestrial lichen (H) • lichen on low branches (H) • lichen litterfall (M) • snow interception (L) • avoid enhancing moose forage (L)	• Satah Mountain • Chilcotin Forest District • winter 1994-95	Clearcutting with Reserves • reserves of 10-15 trees to 1 ha • 70% volume removal • winter harvesting Group Selection • openings <0.2 ha • 30% removal • winter harvesting

[1]H = high; M = medium; L = low

block that is ≥150 years old is expected to provide adequate lichen litterfall, while the 60% that is ≥100 years old is expected to provide adequate snow interception.

Harvesting was done on about 1 m of snow to minimize soil disturbance. In some openings, about 20% of the area was lightly screefed with a motorized, manually operated scarifier; other openings have been left untreated. The objective of the post-harvest treatments is to identify a treatment combination that results in satisfactory regeneration of crop trees, while minimizing the shift from low shrubs to tall shrubs.

Single-tree selection was rejected as an option at the Fleet Creek site because of the extensive internal decay and defect in the stand. The potential residual trees are of poor quality, and single-tree selection could be hazardous to workers in a stand with many large, potentially dangerous trees. Single-tree selection may be an option on other sites in the ICH where stand structure and quality are suitable.

The Engelmann Spruce – Subalpine Fir Zone

The key management objective in the ESSF zone is to maintain enough lichens in the lower canopy so that caribou will continue to use the stand as winter range. Although caribou also use litterfall lichens and lichens on windthrown trees in the ESSF zone, these can be provided by management that maintains lichens on low branches. Snow interception and shrub management are concerns only on sites in the lower elevations of the ESSF zone and on the ESSF/ICH ecotone.

In some ESSF stands, as much as one-third of the arboreal lichen available to caribou occurs on dead trees (Stevenson et al. 1994. Ordinarily, all snags within and adjacent to active logging areas are felled because of concerns about worker safety. However, the worker safety organization in British Columbia will consider granting permission to selectively retain snags in completely mechanized harvesting operations in which no worker is outside the protection of machinery. As well as maintaining arboreal lichens, snag retention benefits other species that depend on dead trees.

Both single-tree selection and group selection are being tested in caribou ranges in the ESSF zone. At the Pinkerton Mountain study area, data on the distribution of timber volume and arboreal lichens by diameter class were used to develop a single-tree selection prescription that would meet habitat objectives. As only 13% of the arboreal lichen at Pinkerton occurred on dead trees, no special measures were taken to retain snags. A portion of the block was harvested with a feller-buncher, and the remainder was hand-felled. Preliminary comparisons of the two methods indicate that hand-falling was more successful at keeping volume removal at the target level of 32% (excluding roads and landings), and at minimizing damage to the residual stand.

Based on our experience at Pinkerton and at other single-tree selection sites, we recommend that hand-falling rather than feller-buncher harvesting be used for single-tree selection in caribou habitat. A maximum volume removal of 30% (including roads and landings) per entry is recommended to maintain sufficient lichen and to reduce the risk of blowdown. Volume removal and the cutting cycle should be planned to produce a multi-aged stand with many trees older than 150 years, and some older than 200 (Figure 3).

Feller-buncher harvesting can be used successfully in group selection, allowing the opportunity to retain safe snags around the perimeter of openings. Group selection has been used at several sites in the ESSF zone, including Grain Creek (Table 1). Feller-bunchers were used to harvest circular openings that ranged in size from 0.03 to 1.0 ha. Volume removal was limited to 30%.

A group selection silviculture system with 30% volume removal and cutting cycles of 75 years should ensure that a significant component of older trees, rich in arboreal lichens, is always present (Figure 3). Because of the small size of the openings, all the second-growth trees will be near enough to mature trees to become colonized with lichen fragments.

The Montane Spruce Zone

Habitat objectives for caribou in the MS zone are quite different from those in the ICH or ESSF zones. Maintaining terrestrial lichens and arboreal lichens are both important management objectives, but they are not usually of equal importance in any given stand. Because of the low snowpack, snow interception is not an important habitat objective. Shrub management is relatively unimportant in the MS zone, because shrubs are a very small component of the diet (Cichowski 1989), and the potential for a major increase in moose browse is low. Another consideration that affects the selection of silviculture systems is the shade intolerant nature of the principal tree species, lodgepole pine.

The relative importance of terrestrial and arboreal lichens on a given site affects the choice of silviculture system and the development of the prescription. Where management for terrestrial lichens is primary, clearcutting with reserves (variable retention system) of about 30%-50% of the stand volume is planned. Careful winter logging on a settled snowpack using low ground impact machinery is expected to protect the terrestrial lichen community. The reserves are intended to provide a source of arboreal lichen fragments near the second growth, and to minimize impact on both arboreal and terrestrial lichen communities from changes in microclimate.

Group selection will also be tested in the MS zone in stands where arboreal lichens are more important. Opening sizes of 0.2 ha or less are proposed to allow lodgepole pine regeneration but to maintain some of the microclimatic characteristics of the uncut forest.

Monitoring

Research on silviculture systems trials in caribou habitat is ongoing, and the projects are at various stages of completion. To be successful, silviculture systems must be operationally and economically feasible, as well as ecologically viable. Most of the trials include silviculture and ecology components, such as assessing natural regeneration, vegetative competition, and the effectiveness of site preparation and planting. The responses of lichens to the treatments are included in all the projects. Because the prescriptions designed to maintain habitat for caribou affect all species, some projects include assessments of biodiversity, such as small mammals, birds, and various habitat elements (e.g., coarse woody debris, snags).

One of the most problematic assessments is the degree to which caribou actually use the managed stands. Although caribou have been observed after harvesting in most study areas, it is has not been possible to obtain enough quantitative data on caribou use to compare the partial cuts to the uncut forest. Such assessments may not be feasible until more of the landscape is covered by the silviculture systems in question.

Relationships with Landscape Level Planning

The studies we report have focused on stand level approaches to integrating caribou habitat objectives with forestry activities. The success of these approaches in meeting caribou habitat objectives will be uncertain for some time. While we expect these stand level approaches will

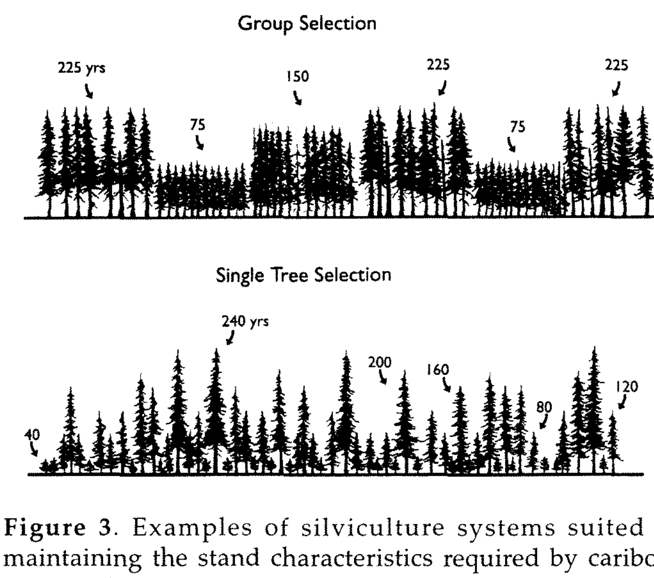

Figure 3. Examples of silviculture systems suited to maintaining the stand characteristics required by caribou: group selection (above) and single-tree selection (below). These examples assume long cutting cycles and low-volume removal at each entry.

contribute to resolving conflicts over management of caribou habitat, they must not be simply expanded to planning at the landscape or regional levels without consideration of other issues. For example, forestry activity is associated with increased road access, which can result in increased snowmobile activity and harassment on winter ranges, increased legal and illegal hunting, and even increased predation where wolves use packed trails to travel through soft snow into caribou ranges. Forestry activity also tends to improve habitat for other ungulates, such as moose and deer. If that occurs, wolf populations may also increase. Such changes are likely to alter predator-prey relationships to the detriment of caribou (Seip 1992).

These concerns can best be addressed for both mountain and northern caribou by zoning at the landscape level. Some core ranges should be protected from forestry activities, road development, and other human-caused disturbances. If necessary, the core ranges may serve as refugia for caribou. In other areas, forestry activities should be restricted to those that are expected to be compatible with caribou; this is the zone in which the silviculture systems reported here would be employed. In less important habitat areas, normal integrated resource management would apply. Such an approach would retain management options by leaving core areas undeveloped, and would improve understanding of the response of caribou to habitat changes at the landscape level.

Conclusion

Applying silviculture systems appropriately has become more challenging in recent years as managers are expected to meet more diverse resource demands on the same land base. Development and testing of innovative silviculture systems should be driven by clearly elucidated objectives. The options that are feasible on any given site depend not only on the management objectives but on site-specific attributes, such as the structure and present condition of the stand. Managers must be aware that habitat objectives for a single species may differ from one biogeoclimatic zone to another because of differences in the way the species uses the forest. Stand-level solutions must be applied within the context of landscape-level and regional management plans.

Acknowledgements

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Ecological Consequences of Intensive Forest Exploitation in Northern Russia

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Natural ecosystems and environmental conditions have changed substantially under the influence of intensive forest cutting. Floristic composition and the structure of forest stands have changed. Reduction of merchantable forests and inadequate reforestation have led to a negative balance of organic carbon. Softwood cutovers have become a source of carbonic acid. Heavy logging equipment has been detrimental to forest soil and vegetation. Long-term forest exploitation on vast taiga areas has changed the animal world, resulting in fewer of the most valuable species living in it. Ecological preservation of taiga forests and improvement of the environment is a necessity for the forests of northern Russia.

Introduction

Forests and forest production are of great importance for the economy of the Russian north. The forest industry has a long history here, and currently accounts for about 50% of the region's economic gross product. It maintains a lead position in production of lumber and pulp, boxboard and paper. The forest is not only a source of wood and wood working products, but is also of great ecological importance.

Forests of the Russian north are the main source of enrichment of the air basin by oxygen and the absorber of carbonic acid. The result of the reduction of total forest area and amount of mature forest has been a change of floristic composition and age distribution of the stands. Intensive industrial forest cutting leads to breaking of the region's natural ecosystem. It took many centuries for the taiga ecosystem with its components to be formed. Forest biogeocinoses are the main components of the taiga ecosystem. The forest biogeocinoses are constantly changing and developing. The main forces of their development are the contradictory interactions between live organisms and their inanimate medium. Being natural objects, forest biogeocinoses are mutually connected with elements of biosphere. They strongly influence environmental and ecosystem components.

Forest Ecosystem Changes

The natural ecosystems of the Russian north are broken down by the increase in the level of economic activity. There is an inherent contradiction between "natural" ecosystems and man's involvement both intellectually and through his economic activities. Forest ecosystems cannot bear great anthropological loads; in fact, they barely defend the man's habitual intrusion in the Russian north. For example, about 23% of the Arkhangelsk region's forest resources have been cut, 54% of the forests are very exhausted and on only 22% is the concentration level of merchantable forests near a natural level. The Arkhangelsk region contains 1.2 million cubic metres of exploitable wood stands (Gusev 1993).

The long-term economic activity of people on the vast territory did not greatly change the continental forested land percentage, which was equal to 73.6% in January, 1993. It should be noted that this favourable forest land percentage condition should not calm managers and ecologists. The changes in forest conditions, species and age composition that intensify transformation of ecological factors of biogeocenoses existence. Fast-growing species as birch (*Betula spp*) and aspen (*Populus spp*) occupy the best forest lands where pine (*Pinus spp*), spruce (*Picea spp*) and larch (*Larix spp*) previously grew. Extremely uneven distribution of merchantable forests in some regions of the northern Russia, their considerable depletion, small quantity of ingrowth and shortage of middle-aged stands create a disturbing situation. Young growth occupy 20% of the forest areas, middle-aged growth 14%, ingrowth stands 4%, merchantable and overmature 62%.

Approximately 80% of cutting areas are successfully reforested by natural means, but with a high percentage reverting to hardwood. About 57% of cutting areas are reforested predominantly to birch and aspen, with 30% reforested to softwood and 13% which are not reforested. Artificial reforestation is not widely used.

Affects on the Soil

Heavy logging equipment takes its toll the soil and vegetation, especially on podzol, bog-podzol, and argil sand soils. The forest mat can be broken and its density increased up to 4 times. Soil compaction on the logway increases bulk density 2.4-2.6 times at a 10 cm depth and 1.8-2.4 times at a 20 cm depth.

Wheel machines of the "Sophit" and "Skidder" type are considered more respectable. They preserve ground vegetation on a considerable part of cutover areas. These machines don't strip forest litter and they only pack soil 2.5 times. The soil on swath logways is packed less. It is impossible to completely eliminate the negative consequences of modern logging equipment on the soil and vegetation. It is possible, however, to modernize the logging equipment and create new modifications with less pressure on the soil, to work out new technological schemes of logging for taiga conditions. Logging equipment needs to preserve up to 75% softwood undergrowth, up to 80% of cutover area forest litter and stay within an acceptable soil packing limit at the 15 cm depth.

The North region continues to experience the most impact ecologically. It was the first to experience heavy harvesting levels because of its high quality timber, and now because it is a highly productive forest with favourable physiological processes and hydrological regime. On account of this, the proportion of low productivity, swampy forest is increasing, causing a rise in land with poor assimilative and natural resilience. The forest has special ecological attributes for protecting and improving the environment, but its possibilities are limited. Special emphasis should be given to intensifying the ecological importance the forest.

Atmospheric Concerns

The region's deforestation leads to increasing carbonic acid in the atmosphere and creates a special anxiety surrounding the problem of global climate warming, the cause of which is connected with "greenhouse" effect, caused by increasing amounts of carbonic acid in the atmosphere. Cutting of merchantable forests has changed the balance of natural functions of forest biogeocenoses (carbonic acid absorption and oxygen exudation). For example, in the Arkhangelsk region carbon excudation in the atmosphere is 1.8 million tons more than its absorption. The tendency of negative balance of organic carbon is especially high in the districts which have exhausted merchantable forest resources (occupying 77% of the forest area). These districts which cut merchantable coniferous forests have become a source of carbonic acid and create a crisis ecological condition in the atmosphere.

A change of solar energy consumption takes place when forests become cutover areas. In coniferous forest about 70% of solar energy is used for biological processes. Most of the heat energy in cutover areas is spent for physical processes that take place in the atmosphere and soil, and these contribute to climate change. In summer, 1 ha of mature forest absorbs 220-280 kg of carbonic acid and exudes 180-220 kg of oxygen.

Animal Habitat Changes

The long period of industrial exploitation over large forest areas has led to changes in the animal world. Forest cutting creates favourable conditions for one animal species and poorer conditions for others by changing dwelling conditions, alarming and so on.

Numerous researchers show that the most productive forests, from a wildlife standpoint, are coniferous and leaf-bearing ones comprised of a mixture of mature stands and new cutting areas. The taiga forest cuttings promote increasing the number of elk (*Alces alces*), hare (*Lepus timiaus*), ermine (*Mustela erminea*), weasel (*Mustela nivalis*), fox (*Vulpes vulpes*), heathcock (*Lururus tetrix*), willow ptarmigan (*Lagepus lagopus*). But the cutting of mature forests decreases the number of the most valuable species of animals forming the base of the northern Russia economic trade business. The number of squirrel (*Sciurus vulgaris*) decreases by 1.8 times, marten (*Martes martes*) by 2.2, hazel-grouse (*Tetrastes bonsia*) by 2.1 and wood-grouse (*Tetrao-urogalus*) by 2 times.

Forest harvesting, especially in taiga forests, is not simply a profitable branch of the economy. The effects it has on the inter-related components of the ecosystem are very complicated. Only a comprehensive analysis can help to preserve ecological importance of the taiga forests and their biological variety, and even improve an environment that is a vital necessity of northern Russia.

Undergrowth as a Regeneration Potential in Finnish Forests

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Finland lies exactly within the boundaries of the boreal coniferous zone and therefore well represents the boreal forest. The Finnish forests have been inventoried eight times since 1921. The third inventory (1951-53) was the last one to be completed before most stands had undergrowth cleared by low thinning. Thus the stand structure resembled that of naturally developed forests. Each sample plot represented a uniform stand; i.e., it was located entirely within one stand. From each plot the stand structure was determined based on the range and form of DBH frequency distribution. Storeyed stands (an empty intermediate diameter class within the range of 6-18 cm) amounted to 11% of stands. Most of the stands, 65%, were regularly all-sized (size-frequency distribution resembling a reverse J). In all stands, the trees under 10 cm in DBH, the lower storey, was considered to be undergrowth. The great majority of the undergrowth was thus outside the storeyed stands. In total, fully-spaced undergrowth with at least 1 000 stems/ha of small-sized (2-10 cm) trees included 41% of the sample plots. Undergrowth, of course, includes also trees under 2 cm in DBH; these were estimated to be 500 stems/ha. Their amount was also remarkably high at that time. Understorey has been undervalued but forms a rich and diverse regeneration potential.

Introduction

Finland is located within the boreal coniferous zone. The southern borders coincide while the northern border of the zone traverses Finnish Lapland. Consequently, the forests of Finland serve as a demonstrative example of the boreal coniferous forest.

Norway spruce (*Picea abies* (L.) Karsten), Scots pine (*Pinus sylvestris* L.), downy birch (*Betula pubescens* Ehrh.) and silver birch (*B. pendula* Roth.) are the main tree species in Finland. Next in frequency are gray alder (*Alnus incana* (L.) Moench) and aspen (*Populus tremula* L.). All these species are native to Finland and form undergrowth. Spruce, as a climax species, forms vigorous undergrowth on sites of medium and high fertility, be they peatland or mineral soil. Pine is typically a species of poorer sites. Birch undergrowth occurs mainly on spruce sites and prefers sparse overstorey (Laiho 1992).

Finland's forests have been inventoried eight times since 1921. Data on undergrowth were also collected. The emphasis has been on the visual appraisal of undergrowth capable of further development. Useful undergrowth was defined as follows: sufficient density, commercially valuable tree species, specific development class of the dominant storey, and two-storeyed stand structure (Ilvessalo 1929, 1951, Kuusela and Salminen 1969, Laiho 1992, Salminen 1993). Consequently, the proportion of officially reported undergrowth was low (2-3% of the area of forest land) in all the inventories conducted (Ilvessalo 1942, 1956, Kuusela and Salminen 1983, Salminen 1993).

Undergrowth has not been utilized actively, and has generally been deemed of low value because of high risk of being damaged when the overstorey is removed. Indeed in the 1960s, even natural regeneration was made questionable. Mechanized site preparation, highly-efficient production of planting stock in greenhouses, and an abundant supply of labour made it possible to expand artificial forest regeneration. At the same time, tree breeders promised productivity gains of some tens of percent.

However, breeding gain has so far remained modest. Pine plantations demonstrate poor quality; i.e., the trees are heavy-limbed, butt sweep is typical, and annual rings are wide. Given that labour costs have risen, stumpage prices have gone down, and plantations have been "invaded" by wildlings, the emphasis is moving back to natural regeneration. Now, even small clumps of natural seedlings are accepted as young growing stock despite their lack of homogeneity.

The changed situation is directing more interest towards the undergrowth. Research has demonstrated a high value of the undergrowth as the starting point for the new tree crop (Seppälä and Keltikangas 1978, Isomäki 1979). Consequently, more detailed knowledge of the extent of naturally occurring undergrowth is needed.

The present study is based on the third (1951-1953) national forest inventory (NFI). This inventory was extensive and, because it was the last inventory completed before wide scale low thinning and undergrowth clearing, it is representative of naturally occurring forests. Another positive feature of this inventory was the use of fixed-area sample plots as opposed to relascope based plots of subsequent inventories (Kuusela and Salminen 1969). Fixed-area plots enable the plot-specific assessment employed in this study (Laiho et al. 1994a).

Material and methods

In the 3rd NFI, sample plots were located at one kilometre intervals along the survey line (Ilvessalo 1951). Each sample plot represented a uniform stand; i.e., it was located entirely within one stand. Thus, the structure on any plot could not be a mixture of different stands. Both mineral soil sites and peatland sites were each divided into a series of seven fertility classes according to fertility and drainage. This study was restricted to advanced stands (including young and advanced thinning stands, mature stands and stands whose development class had not been determined) with a growing stock of at least 40 m^3/ha. This volume limitation reduced the number of sample plots by 23% in South Finland, and by 48% in North Finland. The final material included 8,698 sample plots.

Trees greater than 10 cm were assessed in circular plots of 0.1 ha. Smaller trees were tallied within a concentric circle 0.01 ha in area. The smallest trees tallied were 2 cm in DBH. The tallying had been done by tree species but without classifying trees into storeys. For the purposes of this study DBH-classes, originally 2 cm wide, were combined into nine 4-cm classes (2-6, ... > 34 cm). The stem distribution thus formed was used in the determination of individual stand structure for each sample plot.

Stand structure was determined in the same way as in previous studies (Lähde et al. 1991, 1992, Laiho et al. 1994b). It was based on the range and shape of the diameter distribution, as obtained from the inventory plots, with emphasis on small trees. The following is a detailed description of the classification.

- Even-sized stands: Trees present in less than four consecutive diameter classes (even-sized in strict sense), or stem tally resembling normal distribution (even-sized in broad sense). Due to the small number of strictly even-sized stands, they were combined with broadly even-sized stands (Gibbs 1978). Thus the term even-sized refers here mainly to all-sized stands (trees present over a range of at least four diameter classes).
- Storeyed stands: At least one empty intermediate diameter class within the range of 6-18 cm.
- Regularly all-sized stands: Size-frequency distribution resembling a reversed J; trees present at least in the four smallest diameter classes, with the mode in the first or second class.
- Other all-sized stands

Stands with a separate understorey form only part of the undergrowth. It also includes stands where the storeys almost or slightly overlap. These sample plots have a twin-peaked diameter distribution. In this material the understorey peak had to be situated in either of the two smallest DBH-classes. Often it was formed by another tree species than the dominant storey. These twin-peaked sample plots were classified into the broadly even-sized or regularly all-sized stands.

Regularly all-sized stands in their typical form have no distinguishable storeys. The practice is to use height, for instance, as a classification criterion. The lower storey (corresponding to the understorey), is then delimited either in relation to top height (less than 50%; Assmann 1970) or in absolute measure (less than 10 m; Kern 1966). In this study, DBH was used instead of height. Trees with DBH less than 10 cm were included into the lower storey. Because this study does not show a great proportion of undergrowth (trees less than 2 cm in DBH and new growth (seedlings and seedling material)) a density of 1,000 stems/ha (2-10 cm) was considered as a fully-spaced undergrowth.

Results

Storeyed stands amounted to 11% of the sample plots (Fig. 1). Small trees (DBH 2-6 cm; the smallest measured) amounted to half (469 stems/ha) of the number of stems per hectare. The treeless intermediate class usually was the second (6-10 cm). On 13% of the sample plots the understorey reached 1,000 stems/ha.

Regularly all-sized stands amounted to 65% of the plots. These stands were characterized by a high stem tally (2,079 stems/ha); this was more than twice that of storeyed stands. Small-sized trees of the lower storey (2-10 cm) numbered 1,544 stems/ha. This was 12 times larger than storeyed stands. 61% of the sample plots in regularly all-sized stands had at least 1,000 stems/ha of small-sized undergrowth.

Stand density (stems/ha) and stand volume were smaller and the proportion of pine greater in North Finland as compared to South Finland. No differences were, however, observed in the occurrence of undergrowth. Forest stands on peatland were characterized by a higher stem tally and smaller stand volume compared to forests on mineral soils. Regularly all-sized stands were more common in peatland stands (89% of peatland plots compared to 75% on mineral soil plots), whereas storeyed stands were less common, respectively.

Sample plots carrying both conifers (pine and spruce) and broadleaves represented two-thirds of the study material. The stem tally of pine was the smallest. The amount of small pine trees was low but its proportion increased with increasing diameter. Spruce was the most numerous species with broadleaves, amounting to one third. The proportion of small-sized broadleaves was clearly higher than that of small-sized conifers. Of the average stem tally of 1,657 stems/ha, 45% was accounted for by the smallest diameter class and 23% by the 6-10 cm class.

Discussion

According to the results of the third NFI conducted in 1951-1953, useful pine understorey was officially recorded at 1.1% and spruce understorey at 1.7% (Ilvessalo 1956). At that time, understorey consisting of broadleaves were deemed useless. The determination of the useful understorey had been assessed visually per compartment. In our re-examination of these data, the proportion of sample plots with a separate understorey (storeyed stands) amounted to 11%. If the original criteria of the visual appraisal were applied to these sample plots, the said proportion would have also been reduced to less than 1%. In reality, however, most of the undergrowth was located outside storeyed stands. Regularly all-sized stands represented 65% of the plots. All these stands had undergrowth in the lower storey. When the understorey included in even-sized stands is added to this, the proportion of stands containing undergrowth rises to about 80%. 41% of plots

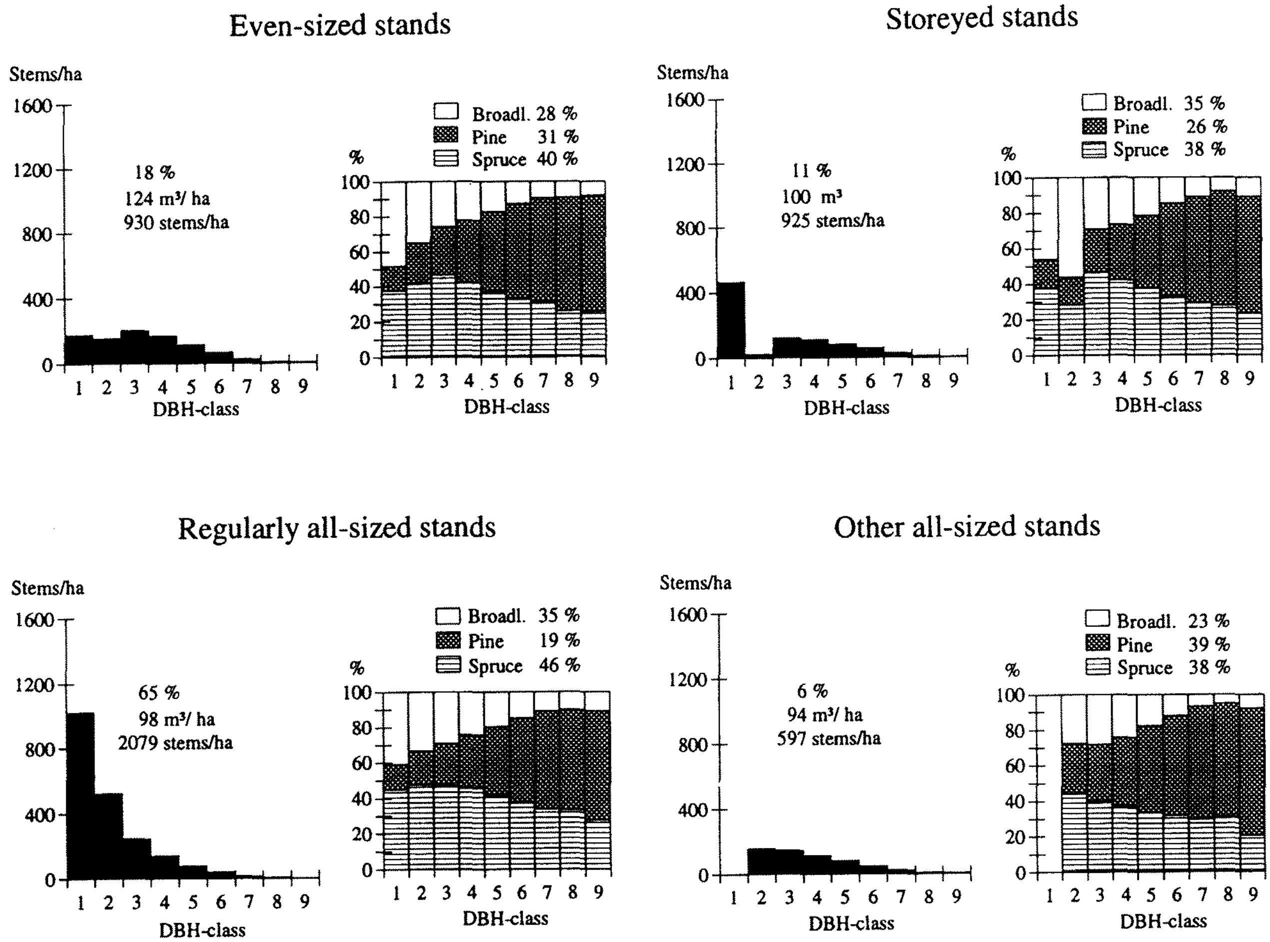

Figure 1. Occurrence (%) of stand structures with their average volume, stand density and stem distribution by tree species in 1951-53. Total number of sample plots 8 698. DBH-classes: 1 = 2-6, ... 9 > 34 cm.

had fully-spaced undergrowth with at least 1,000 stems/ ha of small-sized trees. Therefore, the proportion of 2-3%, as officially indicated in the inventory results, has clearly been an underestimate.

The abundance of undergrowth in Finnish forests is supported by a study concerning so called "natural normal forests" (Ilvessalo 1920). Although its purpose was to deal with pure even-aged stands, 39% of the sample plots had to be accepted with distinct undergrowth. Undergrowth has also caused confusion in the development of the age class distribution of the Finnish forests. When the first NFI was conducted in 1921-1924, 10-year-old forest amounted to 4.8% of the forest area, but, 40 years later, 50-year-old forest covered 19% (Kuusela 1972). This increase in the area has its explanation in undergrowth and improper classification of the stands. A high proportion of this age class had been hiding as undergrowth and had been liberated in felling operations during the intervening years, usually at the age of 20-40 years. For such a great increase in acreage, the coverage of undergrowth must have been considerable.

It has proven difficult to assess the utility of stunted undergrowth to recover. The development of undergrowth under a dense canopy is slow; a tree 50 years old may not necessarily have reached breast height (Pöntynen 1929, Sirén 1951). Even the weakest undergrowth, however, is capable of recovering if liberated properly. Usually recuperation takes a few years (Cajander 1934). Serious growth stagnation, advanced age, and large size do, however, hinder recuperation (Vaartaja 1951). Once recuperated, formerly stunted undergrowth will grow at the same rate as free-grown seedling stands of equivalent size (Näslund 1944, Sarvas 1951, Hatcher 1967, Vuokila 1970, Indermühle 1978, Nilsen and Haveraaen 1983, Klensmeden 1984).

In older stands, most of the small-sized trees belong to the undergrowth. In these stands of the early 1950s, this undergrowth averaged over 1,000 stems/ha. Of course, undergrowth also includes trees with DBH less than 2 cm and seedlings that have not yet reached breast height. Unfortunately, the trees with DBH 0-2 cm had been determined only as crown coverage in the third NFI. However, they can be assumed to have been at least equal to the smallest size class of the fourth NFI ten years later (i.e., about 500 stems/ha; Ilvessalo 1962). Again, however, new growth was not counted. New growth varies from stand to stand, but on average is great (Sarvas 1944, Räsänen et al. 1985, Hagner 1992, Lähde 1992a, b). Thus the regeneration potential of naturally developed forests is very high.

The value of this potential is further increased because even sparse undergrowth does not mean significant losses in yield (Gustavsen 1992). In addition, silver birch and even downy birch are now acceptable tree species. The full utilization of the undergrowth in partial-cut silvicultural systems will likely minimize the need for artificial regeneration, shorten the rotation, enhance yield and increase the internal biodiversity of stands.

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Scarification, Fertilization and Herbicide Treatment Effects on Seedling Growth and Quality, and Soil Fertility

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*The influences of soil surface modification (blade scarification and plastic mulching), fertilization and herbicide application on planted Jack pine (*Pinus banksiana *Lamb.) and black spruce (*Picea mariana *(Mill.) B.S.P.) trees were examined after seven years on one site within the Boreal forest region of Canada. Seedling survival, growth and quality; and foliar, forest floor and mineral soil nutrient status were assessed. Seedling survival doubled with scarification, but declined generally from 84 to 75% (mean for both species) during the last five years.*

Combined silvicultural treatments increased productivity as much as 20 times for Jack pine and 120 times for black spruce; however, negative impacts on seedling quality were noted, especially by herbicide application, and scarification reduced the carbon and nutrient reserves in the forest floor. Foliar nutrient concentrations were little affected by the applied treatments. Soil temperatures increased in response to scarification during the frost-free growing period, but no seasonal differences in soil moisture were noted. Innovative future management approaches in such stands should include the use of softer approaches to vegetation management that reduce plant competition levels without significantly lowering forest floor carbon and nutrient reserves or reducing tree quality.

Introduction

In 1987, a study was set up on three forest clearcut areas distributed within Canada's major climatic zones to provide quantification of soil changes and tree response to factorial combinations of scarification, fertilization and herbicide use (Brand and Janas 1988). Growth analysis techniques were applied to evaluate early tree response (Brand 1991) and some of the early impacts on soil fertility were studied by Munson et al. (1993). Significant treatment effects were noted on the growth of white pine (*Pinus strobus* L.) and white spruce (*Picea glauca* (Moench) Voss) and on soil nutrient reserves seven years after outplanting at the site located within the Great Lakes-St. Lawrence forest region (Burgess et al. 1995). This paper describes results collected seven years after outplanting Jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* (Mill.) B.S.P.) trees at a second site within the Boreal forest region. The objectives of this work were to evaluate (1) survival, growth, and quality of outplanted Jack pine and black spruce trees, (2) foliar nutrient concentrations, (3) forest floor and mineral soil organic carbon and nutrient contents, (4) changes in environmental parameters including light, soil moisture and soil temperature, and (5) to integrate results to help explain observed differences in tree growth response to scarification, fertilization and herbicide treatments.

Materials and Methods

Site and treatment description

The study site is near Foleyet, Ontario (lat 48°22', long 82°27') at an elevation of 300 m and was described previously (Brand 1991). The silvicultural treatments applied to the site included three soil surface modification treatments: control (T0), blade scarification in which the entire duff layer was removed (T1), and blade scarification with plastic mulch placed around the seedlings (T2); two fertilization treatments: control (F0) and fertilization with Osmocote® a 17:6:10 N:P:K plus micronutrients at an annually increasing rate from 30 to 200 g per tree (F1); and two brush control treatments: control (BC0) and annual applications of Vision TM (n-phosophonomethyl) as required to remove competing species (BC1).

Experimental design and Statistical Analyses

Treatments were set up in a split plot design with one replicate of each treatment in each of four blocks. Soil surface modification treatments were applied at the main plot level and a factorial combination of fertilization and brush control treatments was applied at the subplot level giving a total of 48 experimental plots. Half of each plot was planted with 100 Jack pine seedlings while the other half was planted with 100 black spruce seedlings at a 2m by 2m spacing. All outplanted seedlings were 1-yr-old overwintered nursery stock produced in paperpot containers. Statistical analyses were completed using SuperAnova Version 1.11 (Abacus Concepts Inc., Berkeley, CA). The assumption of homogeneity of variance was tested in each analysis and data were transformed where required. Data collected for Jack pine and black spruce were analyzed independently.

Tree survival, growth, and quality

Tree survival was assessed by surveying all trees within study plots. An arcsine transformation was applied to the survival data before statistical analysis. Height and diameter measurements were collected for nine living trees per plot selected at random and used to calculate stem volume (1/3 basal area x height). In three of the four field replicates, quality of the nine trees used for height and diameter measurement was assessed using a predesigned survey (Table 1). Treatment influences on tree quality were assessed statistically using the percentage of excellent or good trees.

Little difference was noted between tree growth on scarified and scarified plus mulch treatments. Tree growth data pertaining to plots which received the mulch treatment will not be presented. Foliar and soil sample collections and analyses were not completed on plots receiving the scarified plus mulch treatment.

Foliar sampling and analyses

One year-old foliage was collected from six of the Jack pine and all nine of the sample black spruce trees used to assess height and diameter in each treatment plot. Samples of south facing branches containing the appropriate age needles were clipped from the upper third of the crown and chilled in coolers. A constant number of needles (10 for Jack pine and 20 for black spruce) were removed from the clipped branches, dried at 60°C to constant mass, weighed and ground. Needle dry mass was calculated and total N, P, K, Mg, and Ca contents of the ground samples were determined according to Burgess et al. (1995).

Forest Floor and Soil sampling and analyses

Composite samples of forest floor and mineral soil were collected from each plot. A five cm diameter core of the

Table 1. Influence of factorial combinations of scarification (T), fertilization (F), and brush control (BC) with herbicide on quality of black spruce and Jack pine trees seven years after outplanting (n = 27, except for the first two treatments listed below when for both species, n = 7 to 21 because of poor tree survival).

		Quality Assessment (% of trees sampled)			
Species	Treatment	Poor	Fair	Good	Excellent
Black spruce	T0F0BC0	77	19	4	0
	T0F0BC1	41	26	26	7
	T0F1BC0	53	10	37	0
	T0F1BC1	48	22	19	11
	T1F0BC0	7	19	44	30
	T1F0BC1	15	33	26	26
	T1F1BC0	4	33	22	41
	T1F1BC1	41	26	22	11
Jack Pine	T0F0BC0	29	33	37	0
	T0F0BC1	74	26	0	0
	T0F1BC0	83	17	0	0
	T0F1BC1	78	18	4	0
	T1F0BC0	30	18	37	15
	T1F0BC1	37	41	22	0
	T1F1BC0	26	30	37	7
	T1F1BC1	82	7	11	0

Excellent: stem with only slight bends or curves; branching characteristics consisting of fine branches with a large distance between whorls; current growth and health is vigorous; high sawlog and pulp potential.

Good: stem with only slight to moderate bends or curves and no significant forks; branching characteristics consisting of fine to moderate branches with medium distance between whorls; current growth and health is productive; medium sawlog potential and/or high pulp potential.

Fair: stem quality with moderate bends or curves; basal forks usually caused from planting; branching characteristics are consisting of moderate to large branches with a medium to short distance between whorls; current growth and health is showing signs of diminishing vigour and productivity; pulp potential only

Poor: stem quality with moderate to severe bends or curves, multiple competing stems and/or leaders; branching characteristics consisting of large to grossly misshapen branches with short distance between whorls; current growth and health is such that development into a natural tree form is uncertain; doubtful commercial potential either as pulpwood or sawlogs entire forest floor was collected from 6 to 18 positions within each plot. Forest floor thickness was recorded at each sampling location. The number of sampling positions varied in order to obtain enough sample to complete the desired chemical analyses. For mineral soil samples, all forest floor material was removed and a 4.76 cm diameter core was collected from the 0-20 cm layer at three locations within a plot. Composite forest floor and mineral soil samples were mixed and air dried. Air-dry sample masses were recorded and corrected for gravimetric moisture content, and then used with depth measurements to calculate bulk density values. The dried samples were ground to 2.0 mm. Soil pH, total carbon and nitrogen and available P and K contents were determined as described by Burgess et al. (1995). All carbon and nutrient values were converted into kg ha^{-1} using the calculated bulk density values.

Treatment effects on the carbon and nutrient contents of the 0-20 cm mineral soil layer were either not significant statistically or minor in comparison to those observed for the forest floor. Therefore, only forest floor results are presented.

Environmental monitoring

Soil temperature and water potential, photosynthetically active radiation, wind speed, and precipitation were monitored and recorded throughout the growing season with a Campbell Scientific CR21X datalogger (Campbell Scientific, Logan, UT). Temperature probes were placed 2 and 10 cm below the mineral soil surface in two replicates of each treatment combination. Soil temperatures reported are the average of the two depths. Soil moisture blocks (Delmhurst Instrument Co., Model 223) were inserted 10 cm below the mineral soil surface in two replicates of each treatment combination. A quantum sensor (Li-Cor LI190SB, Li-Cor, Lincoln, NE) was positioned in an opening away from any influence of vegetation and five other sensors were distributed randomly in plots without brush control (positioned above ground at seedling height) to estimate the level of light interception by competing vegetation.

Competing Vegetation

Competing vegetation was surveyed in the control (T0F0BC0) and scarified, unfertilized, and herbicide treated (T1F0BC1) plots of each block. Average height was measured and percent cover estimated for each species of competing vegetation.

Results

Black Spruce

Survival, Growth, and Quality

Scarification and brush control treatment effects interacted (p=.0001) to alter black spruce survival (Fig. 1a). Survival varied from 7.7% in the plots receiving no scarification or brush control to 91.6% where scarification and brush control were applied. Survival had declined in these plots from 26.0% in plots receiving no scarification and brush control treatments and from 96.8% in treated plots where both scarification and brush control were applied, since 1988.

The interactions of scarification and brush control (p=.0001) and brush control and fertilization (p=.0274) affected height growth, but only brush control (p=.0001) and scarification (p=.0009) affected mean stem basal area. Mean height ranged from 0.53 m in control plots to 1.88 m in plots that were fertilized, scarified and treated for brush control. Brush control and scarification increased stem basal area from 4.2 cm^2 to 18.5 cm^2 and from 8.6 cm^2 and 13.5 cm^2, respectively. Stem volume (Fig. 1c) was increased by brush control (p=.0001) and scarification (p=.0007). Stem volume of black spruce that received the combined silvicultural treatments was about 120 times higher than controls. Stem volume on plots with brush control was about four and one-half times higher (272.8 versus 1246.1 cm^3) than plots that did not receive brush control while on scarified plots it was about 1.8 times higher (502 versus 909.4 cm^3) than on unscarified plots.

Scarification and brush control (p=.0048) and scarification and fertilization (p=.0613) interacted to affect tree quality. On unscarified plots the percentage of excellent or good trees was increased from 20% to 31% by brush control; but brush control reduced this percentage from 68% to 42% on scarified plots. Fertilization increased the percentage of good and excellent trees on unscarified plots (from 18.5 to 32.4%) but decreased this percentage on scarified plots (from 63.0 to 48.1%). Poor quality trees suffered from greater weevil damage and stem forking, more frequent and severe stem curving, and retarded volume growth.

Needle Mass and Foliar Nutrient Content

Needle mass (Table 2) was affected by a scarification brush control interaction (p=.0037). Brush control resulted in higher needle masses in both unscarified and scarified plots, 0.512 g and 0.509 g, respectively. In the absence of brush control, needle mass was lower in unscarified than scarified plots, 0.306 g and 0.423 g, respectively. Fertilization did not significantly affect foliar nutrient concentrations (Table 2). Foliar N content was higher where herbicide was used to control brush, 11.8 versus 14.1 mg g^{-1} (p=.0175). No significant treatment effects were noted on foliar P content. Brush control decreased foliar K content in the unscarified plots but increased it in the scarified plots (p=.0188).

Forest Floor

Total forest floor C and N contents (Table 3) were affected only by scarification (p=.0005 and .0027, respectively). The unscarified plots had total C and N contents of 40.2 and 1.96 Mg ha^{-1} while those measured for the scarified plots were 16.9 and 0.72 Mg m^{-3}, respectively. An interaction between scarification and fertilization treatment effects was observed for available P content (p=.0022).

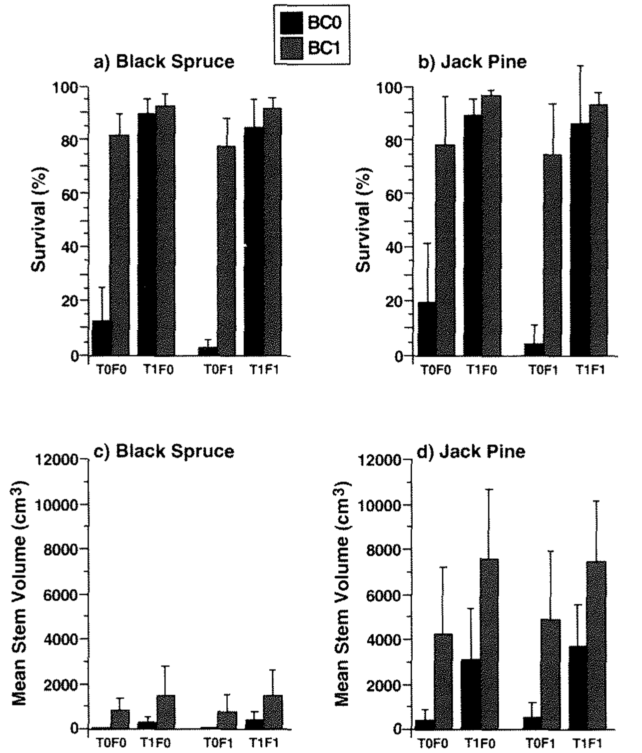

Figure 1. Percent survival and mean stem volume for black spruce (Figs. 1a and 1c) and Jack pine (Figs. 1b and 1d) seven years after outplanting (T = scarified, F = fertilized, BC = brush control; 0 = control, 1 = treated).

Available P contents of 19.5 and 30.6 kg ha^{-1} were obtained for the unfertilized and fertilized plots in the unscarified treatment, respectively, while values of 12.5 and 96.1 kg ha^{-1} were obtained for those in the scarified treatment (Table 3). The content of available K was not influenced by the applied treatments.

Jack Pine

Survival, Growth and Quality

Jack pine survival was improved significantly as scarification and brush control interacted (p=.0001), from only 12.2% in control plots to 95.8% in plots that were scarified and brush controlled (Fig. 1b). Tree survival declined more in control plots (from 26.8% to 12.2%) from 1988 to 1993 than in scarified and brush controlled plots (from 99.0% to 95.8% survival).

Tree height was influenced by scarification (p=.0001) and brush control (p=.0002) and was greatest (3.66 m) on plots that were most intensively treated as compared with 1.51 m on control plots. Scarification (p=.0001) and brush control (p=.0001) improved basal area with tree basal area ranging from 5.8 cm^2 in control plots to 67.8 cm^2 in plots that received all site preparation treatments. Scarification (p=.0001) and brush control (p=.0001) improved stem volume (Fig.1d), but fertilization had no significant effect (p=.5308). Mean stem volume of Jack pine that received the combined silvicultural treatments (Fig. 1d) was about 20 times higher than controls. Mean tree volume on plots with brush control was two and one-half times higher than plots that did not receive brush control while mean tree volume on scarified plots was about two and one-third times that on unscarified plots.

Jack pine tree quality was affected adversely by both brush control (p=.0063) and fertilization (p=.0869), but scarification (p=.0086) improved tree quality (Table 1). Excellent or good quality trees were rare on plots that received brush control with only 9.3% of the trees sampled entering into these categories, compared with 36.4% of trees from plots without brush control. Scarification increased the proportion of excellent or good trees from 11.1% to 32.4%. Fertilization decreased the percentage of excellent or good trees from 27.8% to 16.1%. Poor quality trees suffered from greater weevil damage and stem forking, heavier branching and more frequent and severe stem curving.

Needle Mass and Foliar Nutrient Content

Significant scarification by fertilization (p=.0302) and scarification by brush control (p=.0032) interactions were found for first year needle mass (Table 2). Fertilizer addition resulted in a lower needle mass in unscarified plots but a greater needle mass in scarified plots. Larger needle masses were measured in the brush control plots of both unscarified and scarified plots, but the increase was much larger for the unscarified plots. No significant treatment effects were noted for foliar N and K contents and values ranged from 13.1-15.3 mg N g^{-1} and 4.4-5.0 mg K g^{-1}. Foliar P content was affected (Table 2) by an interaction between scarification and brush control (p=.0165). In unscarified plots, lower foliar P contents were obtained by controlling brush, 1.31 versus 1.44 mg P g^{-1}; however, the opposite was observed in the scarified plots, 1.36 versus 1.31 mg P g^{-1}.

Forest Floor

Total forest floor C and N (Table 3) contents were only influenced by scarification (p=.0015 and .0029, respectively). Unscarified plots contained 1.75 Mg N ha^{-1} and 36.3 Mg C ha^{-1} while scarified plots contained 0.60 Mg N ha^{-1} and 15.1 Mg C ha^{-1}. A significant interaction between scarification, fertilization and brush control treatments on plant available P and K was noted (p=.0117 and .0257, respectively). In the unscarified plots, fertilizer application only increased plant available P when applied in combination with herbicide. Fertilization increased plant available P in the scarified plots, but to a larger extent in the absence of brush control. Plant available K was always higher in plots which did not receive brush control, and was higher where no scarification occurred. The influence of fertilization on plant available K content was small compared to the effects of scarification and brush control (Table 3).

Environmental conditions and competing vegetation

Soil temperatures varied among treatment plots (Fig. 2a). During the frost-free period, soil temperature was

Table 2: Influence of factorial combinations of scarification (T), fertilization (F), and brush control (BC) with herbicide on needle mass and foliar N, P and K concentrations for Jack pine and black spruce seven years after outplanting. Standard deviations in parentheses.

Species	Treatment	Needle Mass (g)	Foliar Nutrient Concentration ($mg\ g^{-1}$)		
			N	P	K
Black spruce	T0F0BC0	0.27 (0.14)	13.6 (0.7)	1.68 (0.02)	7.38 (0.01)
	T0F0BC1	0.53 (0.21)	13.4 (1.2)	1.32 (0.12)	5.34 (0.54)
	T0F1BC0	0.34 (0.14)	12.5 (0.3)	1.40 (1.58)	8.20 (3.25)
	T0F1BC1	0.50 (0.21)	15.7 (1.0)	1.53 (0.10)	5.43 (0.78)
	T1F0BC0	0.40 (0.16)	11.6 (1.9)	1.20 (0.20)	5.60 (1.24)
	T1F0BC1	0.45 (0.17)	13.0 (0.5)	1.28 (0.11)	6.23 (0.75)
	T1F1BC0	0.44 (0.21)	10.7 (3.8)	1.32 (0.18)	5.74 (0.28)
	T1F1BC1	0.57 (0.20)	14.4 (1.6)	1.40 (0.16)	5.88 (0.57)
Jack pine	T0F0BC0	1.12 (0.13)	14.6 (0.6)	1.36 (0.06)	4.43 (0.57)
	T0F0BC1	1.44 (0.50)	14.7 (0.7)	1.28 (0.12)	4.88 (0.45)
	T0F1BC0	0.71 (0.48)	13.1 (6.5)	1.52 (0.22)	5.00 (0.08)
	T0F1BC1	1.31 (0.33)	14.3 (2.3)	1.33 (0.14)	4.64 (0.57)
	T1F0BC0	1.22 (0.58)	15.0 (1.2)	1.32 (0.06)	4.57 (0.47)
	T1F0BC1	1.08 (0.50)	14.8 (1.0)	1.36 (0.11)	4.64 (0.54)
	T1F1BC0	1.20 (0.62)	15.3 (0.3)	1.30 (0.08)	4.75 (0.60)
	T1F1BC1	1.46 (0.45)	14.7 (0.7)	1.36 (.06)	4.70 (0.46)

Table 3: Influence of factorial combinations of scarification (T), fertilization (F), and brush control (BC) on the amount of carbon, nitrogen, and plant available P and K in the forest floor. Standard deviations in parentheses.

Species	Treatment	Total Carbon ($Mg\ ha^{-1}$)	Total Nitrogen ($Mg\ ha^{-1}$)	Available Phosphorus ($kg\ ha^{-1}$)	Available Potassium ($kg\ ha^{-1}$)
Black spruce	T0F0BC0	39.1 (9.7)	1.94 (0.50)	17.7 (2.5)	119 (30)
	T0F0BC1	37.8 (9.8)	1.86 (0.48)	21.2 (6.3)	108 (31)
	T0F1BC0	33.2 (9.9)	1.47 (0.58)	12.6 (3.1)	90 (14)
	T0F1BC1	50.8 (11.8)	2.55 (0.80)	48.7 (20.9)	130 (56)
	T1F0BC0	12.9 (5.3)	0.56 (0.26)	13.4 (4.4)	163 (78)
	T1F0BC1	23.9 (17.9)	0.75 (0.65)	11.7 (8.1)	113 (63)
	T1F1BC0	15.3 (7.8)	0.73 (0.43)	121.6 (73.8)	310 (176)
	T1F1BC1	15.5 (7.8)	0.74 (0.25)	70.6 (66.1)	188 (172)
Jack pine	T0F0BC0	30.5 (9.1)	1.58 (0.40)	16.8 (6.0)	132 (39)
	T0F0BC1	39.6 (7.9)	1.68 (0.54)	14.9 (11.8)	66 (23)
	T0F1BC0	38.5 (9.1)	1.76 (0.42)	13.2 (3.6)	107 (22)
	T0F1BC1	36.6 (7.5)	1.98 (0.38)	26.4 (11.9)	98 (25)
	T1F0BC0	14.1 (8.2)	0.46 (0.33)	6.4 (2.7)	72 (32)
	T1F0BC1	17.0 (19.4)	0.74 (1.21)	8.0 (9.4)	38 (42)
	T1F1BC0	10.8 (3.4	0.50 (0.14)	32.1 (17.0)	120 (30)
	T1F1BC1	18.4 (10.2)	0.72 (0.62)	13.8 (2.5)	60 (6)

lowest in the unscarified and no brush control plots and highest in the brush control only plots. For the scarified plots, brush control did not alter soil temperature and temperature values were intermediate between no brush control and brush controlled plots. Soil water potential varied between -0.03 and -0.07 Mpa throughout the growing season and no particular treatment affected water potential values consistently (Fig. 2b). Where brush control was not applied, light intensity (Fig. 2c) was reduced to as low as 30% of that experienced by trees growing in the open brush controlled plots.

Pin cherry (*Prunus pensylvanica*) was a major plant competitor on both scarified and unscarified sites, but its distribution was reduced from 49.5% to 13.5% by scarification. A total of 40 plant species were found in scarified plots and 43 species were found in unscarified plots. Height growth after seven years was greater on unscarified plots for the major competing species found on both scarified and unscarified plots.

Discussion

A greater understanding of forest ecosystem processes is needed to evaluate adequately and improve silvicultural practices. Plantation development from planting to canopy closure is characterized by high vulnerability to competition and great opportunity for maximizing production through innovative silviculture (Nambiar 1990). In this study, scarification and brush control improved black spruce and Jack pine survival and growth. However, these gains were achieved at high costs with scarification resulting in a two-fold reduction in soil carbon and significant losses in nutrient capital. Yield declines from such site preparation treatments were reported earlier (Binkley 1986), but their severity in terms of soil carbon or nutrient losses, or soil compaction are not often reported. The link between soil productivity and losses in soil organic matter is known generally, but is not understood in detail, especially in the long term (Powers et al. 1990).

Controlling brush by repeated annual herbicide applications as was done experimentally in this study is too costly operationally, but it was successful in lowering plant competition and improving tree growth. These results suggest that light was the major factor limiting growth of both Jack pine and black spruce, although less plant competition would also improve water and nutrient availability. Under improved environmental conditions, trees in plots with brush control were able to take greater advantage of the short growing season.

Differences in foliage nutrient concentrations were small among treatments, indicating that none of the treatments in this study improved tree nutritional status greatly above control levels. The large differences in tree and needle size demonstrate though that significant differences in nutrient uptake occurred. Fertilization did not improve tree growth significantly, but resulted in a positive growth response, especially for black spruce, when combined with the other treatments. Fertilization did improve the nutrient capital of the soil in some cases and this may be

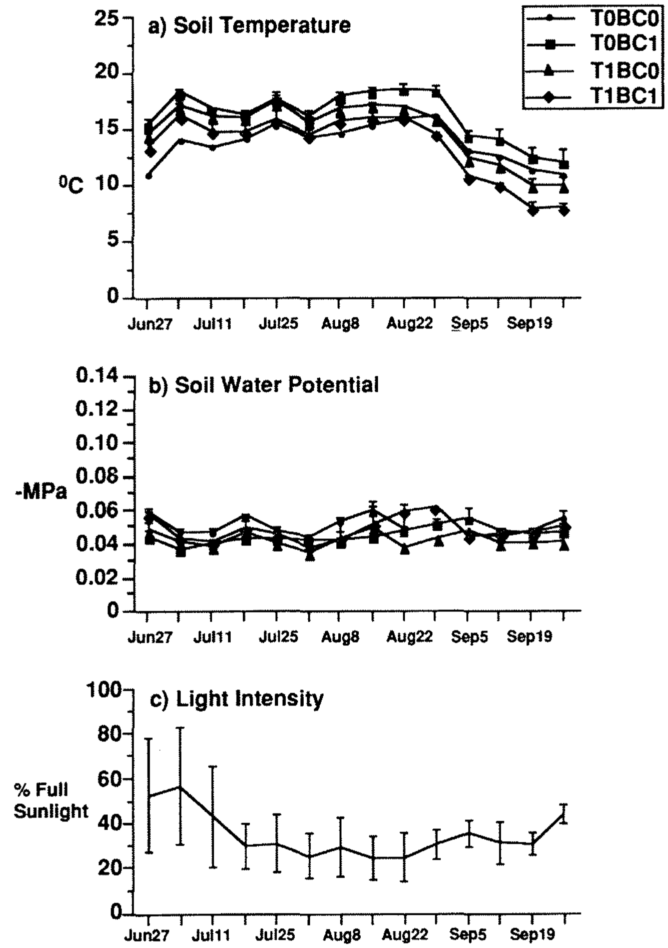

Figure 2. Soil temperatures (Fig. 2a), soil water potential (Fig. 2b) and light intensities(Fig. 2c) during year seven after establishment in unscarified (T0), scarified (T1), no brush control (BC0) and brush control (BC1) plots.

reflected in improved growth in future years. It is not clear why the fertilizer response in areas receiving brush control was not more positive, as most studies have found an increase in conifer growth after fertilization (Neilsen et al. 1992, Elliott and White 1993). Broadcasting of slow release fertilizers as was done in this study is probably not an effective method of applying fertilizers. Foliar N concentrations for both species have declined significantly during the last five years when compared with data reported earlier and greater differences in soil temperatures and soil water potentials between treatments were also noted previously (Brand 1991).

Jack pine is still outgrowing black spruce, but the fastest growing trees of both species were often of inferior quality. Seedlings in brush controlled plots suffered from greater weevil damage and stem forking, heavier branching, more frequent and severe stem curving and retarded growth. Some of these problems may be solved through genetic selection as long as early growth is not reduced significantly (Morris et al. 1991), but the use of innovative silvicultural techniques to control plant competition at acceptable levels appears more promising, at least in the foreseeable future. There is a need to advance forest vegetation management on many fronts (Wagner 1993). Based on the tree quality survey in this study, a plant competition level that reduces productivity only slightly, but encourages good stem form and branching is one such need and should be a goal of forest vegetation management where improvements in stem quality for sawlog production is a concern.

In conclusion, a combination of silvicultural treatments is needed to maximize early growth of planted conifers. Since light, nutrients, water and soil temperature are affected and may be limiting growth, they must all be considered in designing optimum management regimes. Further, increasing early growth by eliminating plant competitors can have negative effects on tree quality. Some forest management techniques such as blade scarification can result in significant losses of soil organic carbon and nutrient capital and may cause losses in future forest productivity. Brush control was the most effective single treatment for maximizing growth in this study, but a softer approach; e.g., alternatives to herbicides or lower herbicide application rates or fewer application times may reduce the negative effects on tree quality.

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Patch Retention Harvesting as a Technique for Maintaining Stand Level Biodiversity in Forests of North Central British Columbia

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The primacy of timber as the principal objective of forest management is giving way to the broader objectives of maintaining biodiversity, maintaining long-term site productivity, and sustainable use of renewable resources. We present a flexible approach for retaining structural attributes within harvested units that contributes to maintaining biodiversity at the stand level. Retaining approximately 10% of a harvested unit in patches of mature and immature trees provides habitat not found in conventional clearcuts. In the Sub-Boreal forests of north central British Columbia, patch retention mimics (to a certain extent) the effects of wildfire, the dominant agent of natural disturbance. Guidelines are presented for the successful application of patch retention. Patch retention is one of many approaches required to maintain biodiversity in managed forests.

Introduction

The concern for biodiversity and the maintenance of ecological systems are central themes in forestry today. The notion that the primary objective of forest management is to convert old-growth into regulated forests with balanced age classes up to, but not beyond, an economic rotation age is the subject of considerable debate. Modern forestry practices must balance timber production with the need to maintain forest biodiversity and the health of forest ecosystems. Biodiversity encompasses all levels of biological organization from genetic through population, species, community and ecosystem, and includes functional diversity (the myriad processes by which organisms interact with each other and the physical environment). The reasons for maintaining biodiversity are many (Pojar 1990, Bunnell 1991, Burton et al. 1992). They range from the ethical argument for the intrinsic value of all forms of life, to the very practical reasons of providing resources for people, and maintaining ecosystem productivity, function and resilience.

Scale is an important consideration in biodiversity management. Some organisms may spend their entire life on a single tree, while at the other extreme, some range over hundreds of square kilometres or even between continents. For practical purposes, most foresters and field ecologists consider biodiversity management at two scales: the forest stand level and the broader landscape level. The landscape level considers the broad distribution of forest stands through space and time, while the stand level deals with the structure and composition of those stands.

Forest management, especially the conventional three- or four-pass clearcutting silvicultural system, can lead to simplification of forest ecosystems at several scales. These include genetic, structural (the stand, small spatial scale), landscape (large spatial scale), and temporal (successional) (Franklin et al. 1989, Hunter 1990, Hansen et al. 1991). At the stand level, simplification can reduce tree species diversity, the abundance and distribution of large live trees, snags, wildlife trees, and coarse woody debris (downed logs), horizontal and vertical stand structure and the composition of shrub and herb communities (Steventon 1994). These structural features are important habitat for a wide variety of forest wildlife and other organisms, which in turn play many roles in forest ecosystems. Stand level management for biodiversity seeks to maintain these important structural attributes in the managed forest.

Our understanding of forest ecosystems has increased greatly in recent years, yet our knowledge of the interactions among organisms and the inanimate environment is still poor. We should not, however, wait until all the detailed answers are in to begin applying new management approaches. An adaptive management strategy should be encouraged, where we intelligently apply new ideas in

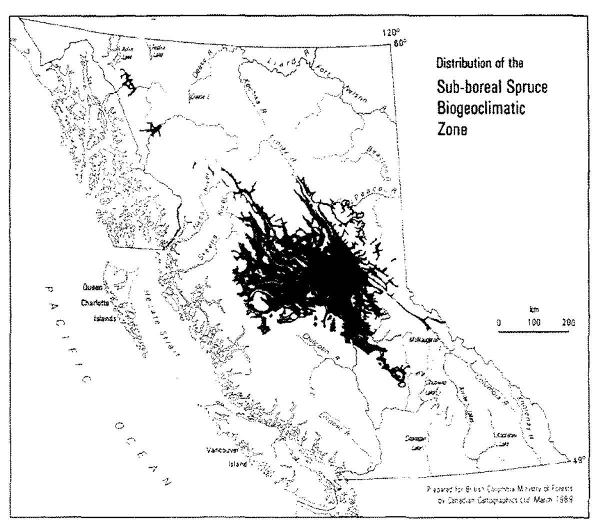

Figure 1. Distribution of the Sub-Boreal Spruce biogeoclimatic zone in British Columbia.

operational management while monitoring and learning from results as we go.

Our purpose here is to describe a stand level biodiversity management approach developed to maintain structural diversity in managed stands. It is only one of many possible approaches for conserving biodiversity at the stand level. We believe it is a very practical approach that can easily be applied over a wide range of ecological conditions. Conserving biodiversity at the stand level is one component of a broad landscape-based management strategy.

Patch Retention

The use of patch retention harvesting, as a stand level habitat/biodiversity management strategy, is now operational within the Sub-Boreal Spruce (SBS) zone of British Columbia (Fig. 1). In the Prince Rupert Forest Region, approximately 130 patch retention units have been harvested. Patch retention, as applied to date, involves retaining approximately 10% of the area of a harvested unit in discrete patches of mature and/or immature trees. Clearcut silviculture with prompt reforestation is practiced on the remaining 90% of the harvested unit (Fig. 2). Although application has been mostly in the SBS zone, patch retention has potential for use in any forest type where retention of structural attributes is desirable. Patch retention is not a silvicultural system (see Mathews 1989 for a description of the traditional systems), but rather a modification of even-aged silviculture to maintain structural diversity within second-growth stands. Figure 3 illustrates schematically how patch retention compares with traditional silvicultural systems and "new forestry" (Franklin 1989) as a means of retaining old-growth structural attributes.

Why Patch Retention?

In the SBS zone, wildfire has been the dominant natural disturbance agent (on a 70- to 200-year return interval; Parminter 1983), resulting in a forest landscape of predominantly even-aged stands of variable size and successional stage. Burns vary in size from less than a hectare to many thousands of hectares and can be either catastrophic high-intensity fires or much lower-intensity fires that leave individual trees or, more commonly, patches of trees relatively undamaged. Surviving patches of trees are often associated with riparian areas, gullies, or north-facing slopes, or are simply areas that the fire skipped. A reasonable assumption is that the plants, animals, and microorganisms of the SBS zone are adapted to the prevailing natural disturbance pattern. Conventional clearcut harvesting

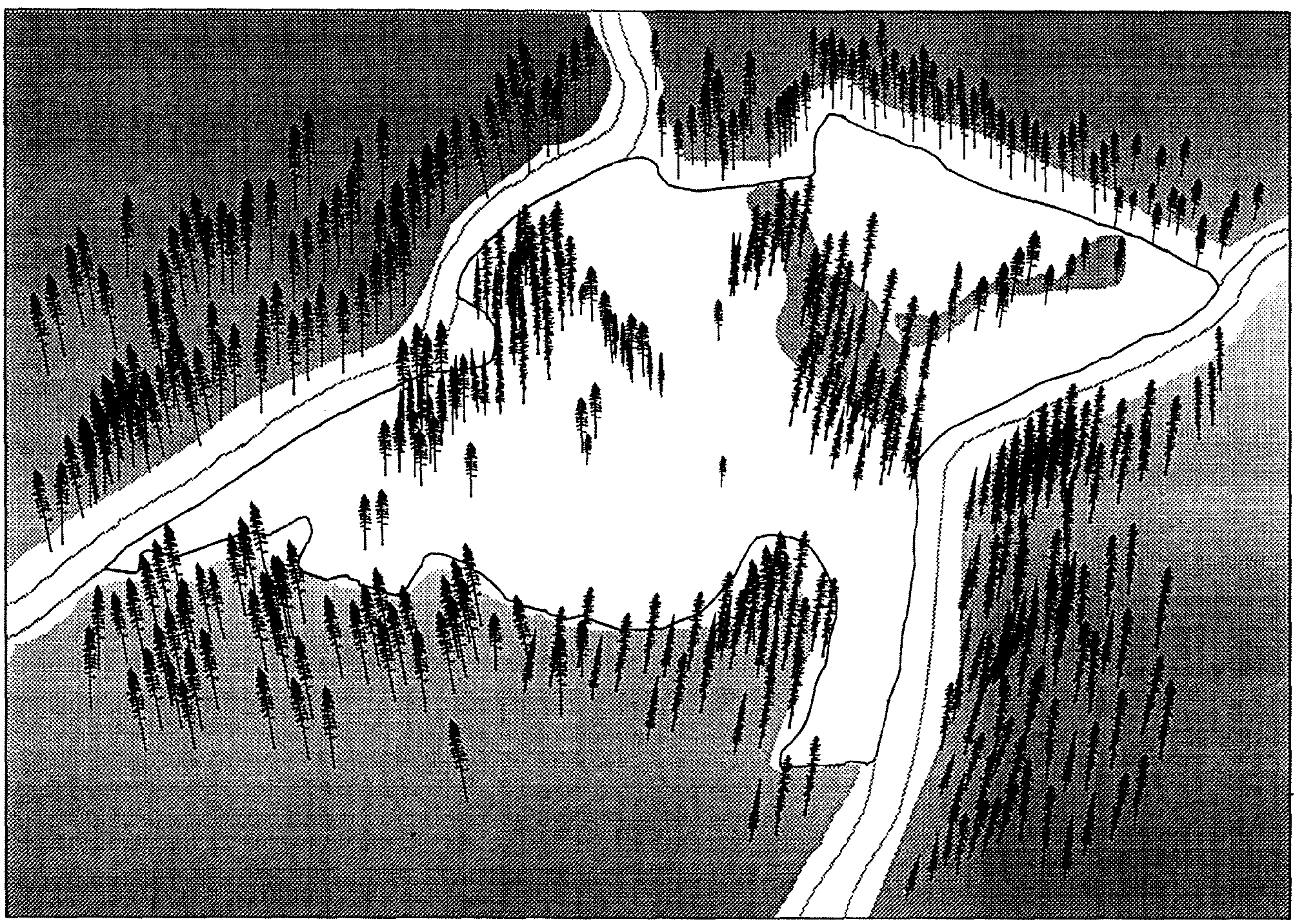

Figure 2. A schematic representation of a patch retention unit

on a 75- to 110-year rotation, to a certain extent, mimics the fire disturbance regime, but unless specifically planned for, snags, large/old trees and coarse woody debris will be much reduced. Patch retention is a method for retaining these structural features in second-growth forests, while minimizing safety concerns and operational complexity.

Patches of standing timber retained in a harvested unit provide immediate post-harvest habitat for many plants, wildlife, insects, and micro-organisms. For example, a patch retention unit near Smithers, B.C. was found to support a much higher diversity of birds immediately post-logging than adjacent clearcuts[1]. Retention of specific structural features such as snags of a suitable size and form for cavity nesting birds immediately provides habitat that is not found in a conventional clearcut. Snag recruitment will occur continuously as trees within the patches age and die. This ongoing supply of snags is also not provided for within a conventional managed forest. Small patches of mature timber retained in harvested units will probably be unsuitable habitat for organisms that require extensive areas of mature closed forest, however, for many plants, small vertebrates, insects and microorganisms, the patches may adequately maintain local populations that would not necessarily be found in the clearcut areas.

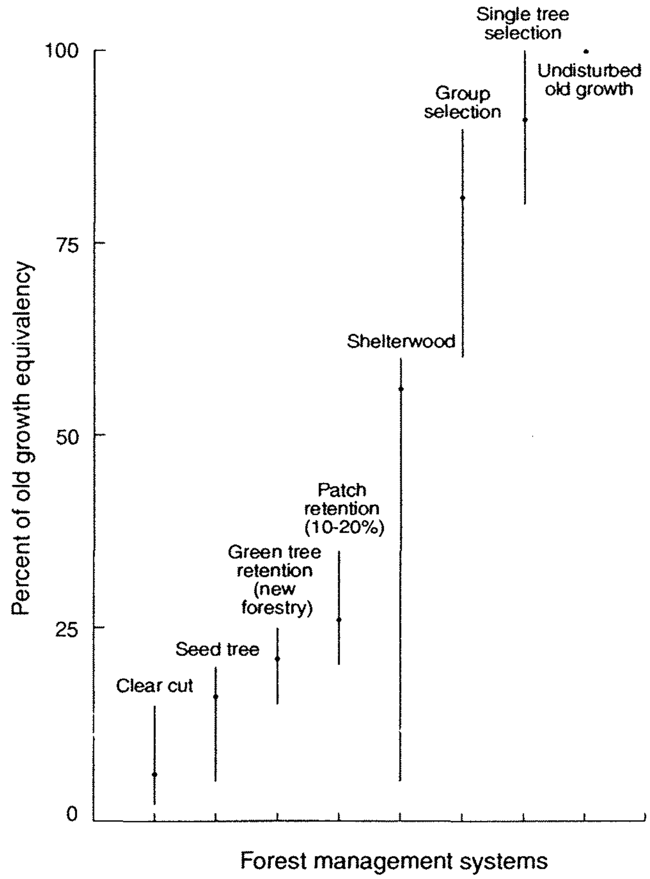

Figure 3. The percentage of old-growth equivalency of traditional silvicultural systems, green tree retention (new forestry), and patch retention. Equivalency in stand level forest structure refers to the species, age, size, and number of tree species present, number and type of snags, and quality of woody debris.

Guidelines for Patch Retention

While we can provide some general guidance in the application of this technique, the best results require site-specific professional judgment rather than rigid rules of application.

Biodiversity, and Wildlife Tree Considerations

Patch retention should be considered whenever the benefits of greater structural diversity are desired in the stand. Since the potential benefits of patch retention for wildlife habitat and biodiversity are considerable, we suggest foresters make use of any opportunity to apply some form of retention. Some stands, however, are more amenable to patch retention than others and, from a wildlife habitat perspective, the urgency to retain structure varies among landscapes (see Landscape Considerations to follow).

Generally, 5-20% by area is the range of retention to be considered. This is similar to what is found as survivor patches in wildfires, and should meet stand level wildlife tree and biodiversity objectives (Steventon 1994). Any patch size is acceptable, but most will be between 0.1 and 2.0 ha. Both the amount and pattern of retention appropriate in the harvest unit will vary with the type of forest and surrounding landscape. For example, in a large uniform area of lodgepole pine (*Pinus contorta*), a few large patches may be appropriate. On a more diverse unit, smaller more frequent patches may better fit the terrain and diversity of forest types.

Any patch composition, even an individual tree, has some habitat value. To maximize structural diversity, however, patches with a variety of tree species, sizes and decay condition are generally favoured over patches of uniform tree species, size and condition. Emphasis should be given to rare features such as wetland edges, patches of less common tree species (including deciduous), or existing or future large snags. Riparian ecosystems, the area immediately adjacent to a waterbody where the vegetation is influenced by the water, are probably the most important special habitat on the landscape. As the interface between terrestrial and aquatic ecosystems, riparian areas contain a high diversity of plants and animals, including some that are not found in other ecosystems (Hunter 1990). Riparian areas within stands are usually good choices for retention.

Silvicultural/Operational Considerations

The presence of unharvested patches within harvest units generally should not impede operations within the

[1]MacKenzie, K. 1993. Short term impacts of patch retention timber harvesting on breeding birds assemblages. Unpubl. Rep., B.C. Min. For., Res. Sec., Smithers, BC.

unit, except possibly broadcast burning or aerial herbicide application. Indeed, this is one of the benefits of patch retention over individual stem retention. With larger harvest units there will be more flexibility in patch size and location and better opportunities to utilize terrain features.

By concentrating patches around wet areas, gullies, deciduous or other difficult to harvest or regenerate locations, the loss of merchantable timber is minimized and logging or silvicultural costs are potentially reduced. Patches with advance regeneration or trees suitable for release can provide structural diversity while also providing immediate silvicultural and future growth and yield benefits.

We believe that in most cases it is not necessary to make design and layout of patch retention units a complicated procedure. Initial assessment can be made from air-photos and during a site reconnaissance. Successful examples of patch retention have been accomplished when, after being advised of the purpose and principles to follow, logging personnel were able to adjust the treatment as they proceeded. As foresters and logging personnel gain experience and feedback on their efforts, cost effectiveness will follow.

Pest and disease implications should be considered when planning patch retention. For example, stands, or portions of stands, heavily infected with mistletoe are poor candidates. Fewer, large patches with selective removal of tall infected trees within patches would reduce the risk of mistletoe spreading into the new stand.

One of the most frequently voiced concerns over patch retention is the potential for windthrow. Patches should be selected and designed to minimize the risk of windthrow (Stathers et al. 1994), but some loss can be expected to occur. This is acceptable, even desirable, for future recruitment of downed logs. In cases of extreme windthrow (especially of interior spruce (*Picea glauca* x *engelmannii*) where spruce bark beetle hazard is of concern) salvage may be considered.

Large patches provide greater opportunities for maintaining existing snags within the patch without compromising safety during harvesting operations or later during silvicultural activities adjacent to the patch. As an alternative to large patches, no-work zones can be established around patches or individual dead trees assessed as a safety risk.

If patches are to provide habitat and stand structure in the second growth forest, they have to remain for at least the length of the rotation, or until replacement patches develop suitable characteristics. Some stem removal within patches is acceptable provided close to typical levels of dead and declining trees remain, along with enough green stems for future recruitment of snags. If the patches are heavily harvested, then a greater area of retention should be considered to compensate. For example, if a patch is set aside to help meet wildlife tree needs, but is thinned to half of typical densities, then twice the area would be needed to provide equivalent habitat value.

Landscape Level Considerations

The need for patch retention should be considered in terms of the overall landscape. As discussed above, some portions of the landscape are more suited for applying retention then others. The same considerations for selecting patches within a stand (Table 1) apply to assessing stands within a landscape. It is also important to ensure a good representation of sites, tree species and sizes across the landscape.

Patch retention should be considered as part of a comprehensive biodiversity management strategy that includes reserves outside of harvest units, patches and individual stems left within harvest units, or a combination of approaches. There is less urgency for retention within the harvest units themselves if very little of a landscape is to be developed, harvesting is only beginning, or there is a greater use of reserves (ecosystem networks, riparian buffers).

One approach to assessing the priority for patch retention is to divide the landscape into cells (such as the UTM grid of 100 ha). The amount of retention in each cell is based on the percentage of the overall landscape to eventually be harvested, and the proportion of the harvesting completed at any given time (Table 2). The result is a greater emphasis on retention in landscapes that are, or will be, more intensively managed. Retention is not necessarily applied in each harvest unit, but rather is applied to each landscape cell. Retention can be planned within harvest

Table 1. Some Criteria For Selecting Patches and Stands

Biodiversity / Wildlife Considerations	Silvicultural / Operational Considerations
- adjacent to wetlands and riparian areas	- advanced regeneration or trees suitable for release and further growth
- rock outcrops / bluffs	- suitable seed-trees for natural regeneration
- diverse tree species and canopy layers	- gullies or other difficult terrain
- less common tree species	- deciduous and / or brush patches
- large snags, or potential snags	- windfirmness
- evidence of present wildlife use (e.g., nests, feeding activity)	- visual screening
	- low disease / pest spread potential
- diverse, well-developed shrub / herb layers	- broadcast burning not prescribed
- unusual or rare plant communities	

Table 2: Patch Retention Objective For Each Landscape Cell

Minimum area (%) in retention for the cells in which development is occurring at any given time. Note that if cells are re-entered at a later date, a new objective applies. Can be calculated from formula: % Retention in cell = (% of the landscape available for harvest + % of the available area harvested to-date) / 10. The numbers given here are preliminary recommendations to illustrate the concept (concept developed by H. Armleder, W. Klenner, D. Seip, D. Steventon).

	% Landscape Available for Harvest									
% Harvested	100	90	80	70	60	50	40	30	20	10
10	11	**10**	09	08	07	06	**05**	04	03	02
20	12	11	**10**	09	08	07	06	**05**	04	03
30	13	12	11	**10**	09	08	07	06	**05**	04
40	14	13	12	11	**10**	09	08	07	06	**05**
50	**15**	14	13	12	11	**10**	09	08	07	06
60	16	**15**	14	13	12	11	**10**	09	08	07
70	17	16	**15**	14	13	12	11	**10**	09	08
80	18	17	16	**15**	14	13	12	11	**10**	09
90	19	18	17	16	**15**	14	13	12	11	**10**
100	**20**	19	18	17	16	**15**	14	13	12	11

Example: 60% of the landscape is available for harvest. When only 10% of the *available* area has been harvested, the minimum retention objective in a cell is 7%; when 90% harvested the retention objective is 15%.

units or outside harvest units, so long as the objective is met in the cell.

This approach is intended to provide operational flexibility in designing harvesting operations, while ensuring structural retention across the landscape. A 100 hectare cell size is suggested as reasonable for allowing dispersal of smaller organisms into the second growth stand and for ensuring sufficient numbers and dispersion of wildlife nesting opportunities while still providing operational flexibility. This approach will work best when applied in a plan that specifies where harvest and retention will occur during each development pass.

These guidelines are probably not as specific as many would prefer, but represent our current level of understanding. Successful application will depend on professional judgment and application of the principles in a site- and landscape-specific context. We expect, through a process of learning from experience, that more specific guidelines will evolve.

Acknowledgements

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