Alternative Silvicultural Systems for Ontario's Boreal Mixedwoods: A Review of Potential Options

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ABSTRACT

This report summarizes the potential use of alternative silvicultural (harvesting) systems on the productivity of boreal mixedwood forests. It provides detailed reviews of modified clear-cutting systems (including strip cutting, patch cutting, and seed-tree cutting), shelterwood systems, and selection systems (including group selection and individual tree selection), and briefly discusses the environmental considerations that are associated with these systems. The report will serve as a reference for forest managers in Ontario who are contemplating alternatives to traditional clear-cutting in boreal mixedwood forests.

RÉSUMÉ

Les auteurs examinent l'utilisation potentielle de différentes méthodes sylvicoles (de récolte) et les effets de ces méthodes sur la productivité des forêts mixtes boréales. Ils passent en revue, de façon détaillée, les méthodes modifiées de coupe à blanc (notamment la coupe par bandes, la coupe par blocs et la coupe avec réserve de semenciers), les modes de régénération par coupes progressives et les coupes jardinatoires (notamment le jardinage par arbres et le jardinage par bouquets) et ils décrivent brièvement les considérations environnementales rattachées à ces méthodes. Ce rapport se veut un document de référence pour les aménagistes forestiers de l'Ontario qui envisagent de recourir à d'autres méthodes que la coupe à blanc traditionnelle dans les forêts mixtes boréales.

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1.0 INTRODUCTION

The mixedwood forests of Ontario's boreal region comprise some of the most complex ecosystems in the province's north. Attempts to develop appropriate management strategies for these forests are complicated by changing markets and business environments, evolving public attitudes, and expanding knowledge of the effects of various forest management practices on timber and nontimber values. For the most part, experience in managing boreal mixedwood forests has been limited to the clear-cut silvicultural system, or to selective cutting practices that have been labeled "clear-cut" to rationalize their use.[1] These techniques generally do not accommodate all of the complexities of such ecosystems, nor do they allow a broad range of forest management options.

With forest management practices under scrutiny in many parts of North America, the time is ripe to consider the use of alternative harvesting and silvicultural systems in Ontario's boreal mixedwood forests. A number of recent developments point to the need for new approaches, viz:

- The new provincial silviculture directions for Ontario (Ontario Ministry of Natural Resources 1993a) call for reducing reliance on intensive renewal of forests (i.e., planting and tending) and for increasing reliance upon natural regeneration. Planting and tending have been the staple method for regenerating clear-cut mixedwood sites up to the present, as natural regeneration is rarely appropriate for regenerating such sites. Increased reliance on natural regeneration will likely necessitate the use of alternative harvesting systems.

- Demand for the hardwood (mostly aspen, *Populus tremuloides* [Michx.]) component of mixedwood forests shows strong growth that is likely to continue in the future (Beck et al. 1989, Brennan 1991, Ontario Ministry of Natural Resources 1992). Silvicultural systems directed at harvesting and regenerating both coniferous and deciduous trees need to be practised to ensure that the increasingly diverse market for forest products is maintained.

- An increasing body of scientific opinion suggests that alternative harvesting and silvicultural methods need to be practised along with clear-cutting so as to protect ecosystem values such as biodiversity and integrity (Hunter 1990, Booth et al. 1993, Thompson and Welsh 1993).

- Public sentiment against clear-cutting is becoming increasingly strident. Although valid arguments can be made that public opinions are not based on full knowledge of the natural dynamics of Ontario's boreal ecosystems, the need to be responsive to public wishes is an important consideration for those with both provincial and local responsibilities for forest management.

The intent of this report is to provide Ontario forest managers with a summary of past and recent experience in the application of alternative silvicultural systems in boreal mixedwoods, and to provide some insight into how these alternative systems may be applied in Ontario. The report will serve as a reference for forest managers who are contemplating alternatives to traditional clear-cutting in this forest type, and will direct them to literature that further explores the advantages and disadvantages of the various systems and the specifics of their application. A companion electronic bibliographic database, assembled during the course of preparing this report, is available from the Great Lakes Forest Research Centre in Sault Ste. Marie, Ontario (*see* inside back cover for details).

There has been relatively little investigation into the use of alternative silvicultural systems in Ontario's boreal mixedwoods in recent years (MacDonald 1993), although much work was done in the 1950s and 1960s (*see* Section 3.2). Consequently, much of the material used in preparing this report is based on research conducted several decades ago or carried out in other parts of North America with similar mixedwood forests (primarily eastern Canada, the prairie provinces, and the northeastern USA; some work from British Columbia, Alaska, and the Rocky Mountain states is also relevant). Because of similarities in climate, forest composition, and in some cases, management history, experience from areas outside of Ontario can be valuable in helping forest managers identify opportunities for developing alternative management strategies.

1.1 Terminology

Forest management is more rife with terminology than many other resource management disciplines. This terminology has made it difficult for forest managers to

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[1] Note that selective cutting is very different from the selection harvesting system. Selective cutting, or highgrading, is a harvesting practice in which only the best quality trees are harvested. The selection system (Section 5 of this report) consists of frequent and careful felling of trees in all size classes with an objective of leaving the remaining forest with a specific size–class structure.

communicate both with the public and with each other. In this document, some important terms are defined when first used. A recent comprehensive glossary (Forestry Canada 1992) provides the primary basis for these defined terms. A more detailed explanation is provided for terms with a history of misuse or misunderstanding.

1.2 Organization of this Report

This report is divided into eight sections. After an overview of the ecology of boreal mixedwoods in Ontario (Section 2), various silvicultural systems are reviewed in Sections 3 to 6. Silvicultural systems are often grouped into a small number of general categories; this report uses a common general convention by separately discussing the clear-cut system, modified clear-cut systems, the shelterwood system, and the selection system. The clear-cut system is described in Section 3 as a basis for comparison with those systems discussed in Sections 4 to 6. Section 7 outlines some of the environmental considerations relevant to these silvicultural systems, and Section 8 summarizes the information and research needs that are discussed in the previous sections.

At the conclusion of Sections 4 to 6, the advantages and disadvantages of each system are listed. These represent the authors' own interpretations based upon the literature, discussions with colleagues, and reflections upon applications. Cross-references between sections serve to illustrate the diversity of opinion associated with some of the systems.

2.0 THE ECOLOGY OF BOREAL MIXEDWOODS

A thoughtful forest manager's perspective on the ecology of boreal mixedwoods influences their choice of silvicultural systems. In practical terms, this ecological viewpoint must be weighed within the context of factors that conspire to shape management objectives: current economics, available technologies, institutional mandates, and policies. These objectives in turn influence the implementation of silvicultural systems.

All too often, however, preference for a given system is based upon the manager's comfort and experience with one system, based upon that system's predictable performance. As noted earlier, clear-cutting is the system used most often in the boreal forest (Canadian Pulp and Paper Association 1992).

To encourage experimentation with alternative silvicultural systems, this section presents an overview of boreal mixedwood ecology. It is through an understanding of ecology that alternative silvicultural systems can be used with some measure of predictability. When results are

compared to anticipated performance, corrections to practice and new levels of ecosystem comprehension are achieved (Lee 1993).

2.1 Definition of Boreal Mixedwoods

Before the development of Ontario's current inventory system, productive forest land in Ontario was classified into four broad cover types: coniferous, deciduous, mixedwood, and reproducing forest (Dixon 1963 *in* Armson 1988). In this system, if less than 75 percent of the stems in a stand were either coniferous or deciduous, the stand was classified as mixedwood. While useful at the time, this approach is too limited to suit the needs of today's forest managers.

A seemingly obvious way to define a boreal mixedwood forest is according to its tree species composition. Any boreal tree species can occur in mixed associations, although the five species that most often occur in mixtures in Ontario's boreal forest are white spruce (*Picea glauca* [Moench] Voss), black spruce (*P. mariana* [Mill.] B.S.P.), balsam fir (*Abies balsamifera* [L.] Mill.), trembling aspen, and white birch (*Betula papyrifera* [Marsh.]). Boreal mixedwood tree species within a stand quite often form vertically stratified mixtures (Smith 1986). Poplar may often dominate the canopy, while spruce and fir often form the understory.

When planning silvicultural operations, it is as important to understand the nature of the site as it is to know the tree species that are found there (although the two are clearly related). To facilitate this, a definition of mixedwoods based on site has evolved. Boreal mixedwoods are "sites that support, or could support, good growth of the five main component species..." (Weingartner and Basham 1979, McClain 1981).

Boreal mixedwood stands can occur on fertile landforms and soil types with soil Moisture Regimes that range from Fresh to well-drained (Pierpoint 1981, Baldwin et al. 1990, Sims et al. 1990). There can be considerable variation within such a broad site generalization. For this reason, boreal mixedwood sites might best be defined by describing the growing conditions in which they are not found. Excessively moist to wet sites develop black spruce and cedar (*Thuja* spp.) stands, while soil at the drier end of the moisture spectrum develop jack pine (*Pinus banksiana* Lamb.) stands. These extreme moisture conditions may also be associated with poor nutrient availability. The remaining favorable site conditions of intermediate moisture and medium to rich nutrient regimes are capable of growing mixedwoods. The obvious variability within such an all-encompassing boreal mixedwood site type is the essence of both management problems and opportunities.

This site-based definition of mixedwoods is useful because of both its simplicity and breadth. Since it does not narrowly define boreal mixedwoods as stands with specific proportions of species, the definition encompasses areas of forest that could contain the five main tree species mixtures by virtue of either succession or management. The breadth of the definition may be contentious for some, as a significant portion of Ontario's boreal forest falls into sites defined in this manner. Furthermore, at various times these mixedwood sites may be occupied by single-species stands. However, the scope of the definition is consistent not only with the range of management challenges posed by boreal forests with mixtures of tree species, but also with the dynamics of the ecology of mixed-species forests. A more restricted or arbitrary definition would not reduce the management issues related to boreal mixed-species forests.

Tree species other than the five noted above may also be present on mixedwood sites. These secondary species include jack pine, eastern white cedar (*Thuja occidentalis* L.), and eastern larch (tamarack) (*Larix laricina* [du Roi] K. Koch) (McClain 1981). However, the site-based definition assumes that the most productive mixedwood sites are those that tend to be dominated by spruce, fir, and hardwoods if left undisturbed over relatively long periods of time.

Nontree species should also be included in the concept of boreal mixedwoods (MacLean 1960, Armson 1988, Peterson 1988). Shrubs such as beaked hazel (*Corylus cornuta* Marsh.), mountain maple (*Acer spicatum* Lam.), and red osier dogwood (*Cornus stolonifera* Michx.) are often important components in the dynamics of mixedwood sites, as are nonwoody plants such as fireweed (*Epilobium angustifolium* L.), bracken fern (*Pteridium aquilinum* L.), and blue-joint grass (*Calamagrostis canadensis* Michx.). It is important to include these species in the concept of mixedwoods because: 1) on many sites, shrubs and nonwoody species can provide significant competition to trees by impeding both establishment and growth (Rowe 1955, MacLean 1960, Armson 1988, Peterson 1988, Delong 1991), and 2) many of the nontree species that frequently occupy or use mixedwood sites have considerable nontimber value, such as providing habitat or food for wildlife.

The most recent and comprehensive attempt to classify boreal mixedwoods in an ecological context was completed for much of northern Ontario's commercially important forest during the last decade (Jones et al. 1983, Sims et al. 1989, Sims and Uhlig 1992). The Northwestern Ontario Forest Ecosystem Classification (FEC) (Sims et al. 1989) identifies 38 vegetation cover types or classes on the basis of an analysis of more than 2 000 plots where relative abundance of tree, shrub, herb, and moss cover was recorded in mature undisturbed forests. Of the 38 cover types, seven are considered to be conifer dominated boreal mixedwoods and six are hardwood dominated boreal mixedwoods. Ontario's eastern Clay Belt is floristically and topographically less complex than northwestern Ontario, and only 22 vegetation types are identified in that region's FEC. Documentation for both regions' FEC provides detailed descriptions of the common plant and soil/site associations of boreal mixedwood sites (Jones et al. 1983, Sims et al. 1990).

Vegetation and soil types can be aggregated into groups that are expected to respond in similar ways to specific management interventions. Over time, these groups can be tested and refined to improve predictability of a certain type of forest ecosystem's response to various treatments. Racey et al. (1989) describe forest management treatment interpretations for mixedwoods and other forest types.

Despite the potential of the FEC as a planning tool, the provincial standard for planning and reporting forest management activities is the Forest Resource Inventory (FRI), developed in the 1960s (Ontario Ministry of Natural Resources 1993a). This system describes forest cover and can be correlated to FEC types. FRI description of forest cover, limited to the relative abundance of commercial tree species on the basis of basal area estimated from aerial photographs, does not account for other plant species. However, important stand structure attributes that are lacking in the FEC classes are included in the FRI. These include stocking (an indication of canopy closure), age, and estimates of productivity on the basis of height/age relationships. The FRI standard descriptive framework is consistent across the province and is updated on a 20-year cycle.

Both the FRI and FEC provide a good basis for understanding and managing boreal mixedwood ecosystems, although the FRI remains the mapping standard. While the FRI describes even-aged forest structure reasonably well, it has limited utility in uneven-aged forests. This is a significant institutional barrier to managing boreal mixedwoods under alternative silvicultural systems.

2.2 Extent of Boreal Mixedwoods in Ontario

Armson (1988) calculated that there were approximately 7 million ha of mixedwood forest in Ontario, assuming that approximately one-third of each of the poplar, white birch, and spruce FRI working groups represented boreal mixedwoods. This estimate is based on an implicit species mixture definition of mixedwood forests, and while it may be useful to know the amount of land covered by mixtures of tree species, it is not consistent with a site-based definition of mixedwoods. Therefore, this figure is likely

a significant underestimate of the extent of mixedwood sites in the province.

Adapting statistics provided by Dixon (1963) with a site-based definition of boreal mixedwoods, McClain (1981) estimated that approximately 45–50 percent of northern Ontario's productive forest land could be classified as boreal mixedwood forest. This estimate is in close agreement with Brennan (1991), who reported that northern mixedwoods and northern hardwoods comprised 49 percent of Ontario's forest cover. Given that northern Ontario has about 21 million ha of productive forest land (Ontario Ministry of Natural Resources 1993a), one can assume that 10–11 million ha are boreal mixedwood sites.

2.3 The Physical Environment of Boreal Mixedwoods

The ecology of Ontario's boreal mixedwoods can be examined from a variety of spatial, temporal, and functional perspectives. The following overview considers the large scale processes of the physical environment that influence boreal mixedwood vegetation patterns.

2.3.1 Climate

Ecosystem structure and function are strongly dependent upon climate (Aber and Melillo 1991). The cold, dry climate of boreal forests results in low productivity (1–4 m³/ha per yr) and slow decomposition of organic matter on the forest floor. The boundaries of the boreal forest coincide with the positions of seasonal air masses and summer isotherms (Bonan and Shugart 1989). White spruce predominates in those areas of the boreal forest affected by Pacific air masses, whereas black spruce dominates those areas affected by Arctic air masses (Larsen 1980). In addition to patterns of species composition, Ritchie and Hare (1971) revealed striking correlations between net radiation and different boreal forest structures (from open to closed conifer forests).

Hardwoods are more common as one moves from the drier cold north to the more moist south, where productivity can be as high as 6 m³/ha per yr (Plonski 1981). It is in this southern portion of the boreal forest that commercial mixedwood forests abound.

There are significant regional climatic variations within these continent wide associations of vegetation and climate. Central Canada, for example, is vulnerable to Arctic air mass and Gulf Stream air mass temperature extremes because the Rocky Mountains interfere with atmospheric circulation. For this reason, Ontario's climate shows more extremes and on average experiences colder temperatures than other areas of the same latitude around the globe, with the notable exception of central Siberia. The Great Lakes, James Bay, and Lake Nipigon appear to influence the local

climates of Ontario's boreal forest to a significant degree. The broken ground and rapid elevation changes (200–600 meters) around Lake Superior further contribute to the lake effects and influence local climatic variations.

Hills' (1952) pioneering forest ecology work divided Ontario into site regions, which are defined as areas of land within which vegetation response to landform follows a consistent pattern that is driven by climate (Wickware and Rubec 1989). These site regions were defined by gradients of temperature (north–south) and humidity (east–west), and today form the basis for administrative boundaries used by the Ontario Ministry of Natural Resources (OMNR) for planning and operations.

Recent work (Whitewood and MacIver 1991) has shown that climate patterns are remarkably diverse across the range of Ontario's boreal mixedwoods. Although the basic patterns are consistent with Hill's site regions, there is considerable variation in some climatic variables within these regions.

Whitewood and MacIver's (1991) atlas linked 30 years of weather station observations with a Geographic Information System (GIS) model to reveal the following general trends for the range of boreal mixedwoods:

- mean annual temperature ranges from 2°C in the southwestern edge of the range to -2°C in the northeast;

- a similar trend in total growing days above 5°C, with increased rates of change prevalent along the southern edge of the range;

- monthly variations in temperature show a cool trough stretching from James Bay through Lake Nipigon, and sharp lake effects along the east shore of Lake Superior in spring and fall; and

- the probability of damaging frosts and growing season length show the most striking local variation; many cold spots appear, specifically, east of Lac de Mille Lac, north of Lake Nipigon, and in the region of the towns of Kapuskasing and Hornepayne.

Precipitation varies from 550 mm along the western margin of the boreal mixedwood range to 900 mm in the east, with most precipitation falling in the summer. The shallow and coarse soils of northwestern Ontario contribute to significant water deficits in some areas, thereby restricting the development of boreal mixedwoods. The monthly mean precipitation varies considerably from region to region, and does not precisely follow the longitudinal or latitudinal gradients exhibited by temperature.

2.3.2 Landform

Landforms within the range of boreal mixedwoods generally result from the most recent episode of continental

deglaciation, which began about 11,000 years ago. The bedrock geology of the Canadian Shield significantly influences the character of the terrain. In turn, forest tree species composition is strongly influenced by landform type within a climatic region.

Areas with similar terrain, or landforms within a site region, were recognized by Hills (1952) as "site districts". Wickware and Rubec (1989) built upon Hills' work, and a variety of other surveys of surficial geology and soil type, to create a hierarchical ecological land classification scheme for Ontario. According to their system of classification, boreal mixedwoods occur principally within five climatic ecoregions. Twenty-two ecodistricts, characterized by a distinctive pattern of relief geology, geomorphology, vegetation, soils, water, and fauna, are nested within these five ecoregions.

The western edge of the boreal mixedwood range in Ontario is characterized by coarse shallow tills over bedrock, large sand deltas, kames, boulder-rich moraines, and occasional clay deposits. Lacustrine clay deposits become more frequent as one moves from the west toward the east, and often create swampy conditions in the generally flat terrain of northeastern Ontario. The relief is greatest and most broken near the shore of Lake Superior, it becomes less broken as one moves from south to north and from west to east. Broken bedrock controlled relief causes significant local variation in edaphic (i.e., soil/site) conditions over extremely small areas.

2.3.3 Vegetation

Rowe (1972) described eight forest regions in Canada. The largest of these is the boreal forest region which forms a continuous belt from Newfoundland to the Yukon. Forest regions are characterized by vegetation patterns of uniform structure and species composition at a very large scale. The boreal forest in Ontario is further divided into seven sections, which are based upon distinct patterns of tree species associations. The many forest sections, and the large number of ecodistricts that support boreal mixedwoods, attest to their diverse nature across Ontario.

The Northern Coniferous forest section in the far northwest of Ontario consists largely of black spruce forests on thin rock outcrops. Mixedwoods occur on south-facing slopes, lake margins, and in river valleys where more favorable conditions for good tree growth occur. The Lower English River section straddles the Ontario/Manitoba border and supports abundant mixedwood forests on the extensive clay deposits that characterize the section. The Upper English section, dominated by rolling terrain and coarse-textured soils, favors the jack pine and black spruce forests that originate from frequent wildfires. Mixedwoods occur throughout the area in varying

proportions within the matrix of pine/spruce types. The broken and varied topography of the Superior section has extremely variable forest cover, with mixedwoods scattered throughout the area. The small Nipigon forest section supports mostly a black spruce and jack pine forest. Productive mixedwood sites with fine-textured, fairly deep soils occur throughout the large Central Plateau section. These conditions occur on drumlinized till uplands and along river and lake margins. The impressively vast black spruce forests of the Northern Clay section give way to mixedwoods whenever slight changes in elevation or soil parent material improve drainage.

Of what significance are these large scale patterns of climate, landform, and related vegetation to forest managers? First, the large variation in growing conditions across the range of Ontario's boreal mixedwoods requires local testing or calibration of different silvicultural systems. Experience with one system will likely not be directly transferable from one geographic region to another. Second, but perhaps most significant, variations in the physical environment across this mixedwood range is an important evolutionary force shaping adaptive gene complexes. Regional differences in a species' response to silvicultural treatments can be expected, while the transfer of seed from one area to another must be done with caution. Silvicultural systems that encourage natural regeneration reduce the risk of introducing poorly adapted individuals to specific locations (Gill 1983, Riggs 1990, Parker 1992). Finally, an understanding of physical macroenvironmental effects upon vegetation allows one to gain insights into vegetation response to changes in microenvironments resulting from either succession or the application of various silvicultural systems.

Variations in the physical environment at stand-level scales are of greatest interest to foresters because it is at that scale that silvicultural systems are most often prescribed. Patterns of vegetation, including the occurrence of boreal mixedwoods as individual stands, are strongly determined by landform and soil parent material. Hence the authors' use of a site-based definition of boreal mixedwoods in this review.

Baldwin et al. (1990) described how forest managers might anticipate local trends in vegetation and soil site relationships by identifying landforms from geological survey maps, aerial photographs, or field inspection. In this way, operational "rules of thumb" or actual maps showing various forest ecosystem communities, including boreal mixedwoods, could supplement existing forest cover FRI maps. Recent work by Mackey and McKenney (1994) used GIS-based models of climate, site, and vegetation relationships to estimate site potential and examine trade-offs between competing forest uses. These same

models have been combined with other models to forecast effects of global warming (Mackey and Sims 1993).

2.4 The Dynamics of Boreal Mixedwoods

Climatic and edaphic conditions provide only the basic requirements for the development of boreal mixedwood stands. The disturbance history of a site by weather, fire, insects, or human-induced changes has a major impact upon boreal mixedwood stand development. These processes operate over both short- (succession) and very long-term (evolution) horizons, interacting with existing forest and stand structures. An understanding of these dynamics is necessary if forest managers are to make reasonable forecasts about the development of future stand and forest conditions arising from the application of alternative silviculture systems.

2.4.1 Evolutionary Forces

Considerable evidence shows that boreal tree species are highly adapted to climate patterns (Joyce 1987, Parker 1992). Surprisingly, there has been no conclusive evidence of edaphic adaptive variation of trees in Ontario's boreal mixedwood range (Fowler and Mullin 1977). Some foresters suspect that upland ecotypes of black spruce may differ from lowland types in germination and rooting characteristics, although no conclusive studies have yet supported this contention (Bichon 1993). To the south, granite and limestone ecotypes of white spruce have been reported, and upland/lowland cedar types have been described in Wisconsin by Musselman et al. (1975). Perhaps the rapid recolonization of northern Ontario following the retreat of ice 10 000 years ago (Ritchie 1987) has not allowed sufficient time to elapse for the emergence of edaphically adapted races within boreal mixedwood species. If such ecotypes did exist, this would have implications for artificial regeneration and the control of seed movement that go well beyond the current climate-based seed zone guidelines.

In a similar vein, there is no evidence that boreal mixedwood plant and tree species have coevolved. If coevolution were a factor, essential interdependencies would be expected between the various mixtures of trees within a stand (mutualism or symbiosis) that would preclude conversion of mixedwoods to pure species stands.

With the exception of white spruce, most boreal mixedwood species in Ontario are commonly found naturally in pure even-aged stands. It is therefore unlikely that the tree species have co-evolved or exist in a mutualistic state. Reconstructions of forest cover at the peak of the last ice age show that boreal tree species cohabited sites with temperate species and migrated along the retreating ice edges fairly rapidly in response to climatic improvements

for tree establishment and growth (Ritchie 1987). Unlike temperate and tropical forest trees that rely to varying degrees upon animal vectors, all commercially important boreal tree species rely upon wind to transfer pollen and seed, thereby suggesting an absence of coevolution between animals and trees. Ecosystems where coevolution is present, such as tropical rainforests or temperate forests, are more complicated and demand more cautious management than does the boreal forest.

This absence of coevolution suggests that boreal forests are robust ecosystems. For this reason it is doubtful that clear-cutting or alternative silviculture systems can be considered either harmful or helpful from an evolutionary ecological perspective. It would seem prudent, however, that studies continue to search for edaphic patterns of variation and coevolution in boreal mixedwoods.

Prudence also has a place in forest management. Franklin (1992) argues for the retention of some green trees, large woody debris, and other measures during harvest to provide for a biological legacy across the generations of forest cover. These legacies offer protection against irreversible damage in the event that coevolved life systems, which depend upon one another, are discovered in the future. This is the essence of "new forestry". Most alternative silvicultural systems provide for such biological legacies.

Several adaptive traits appear to have evolved in response to processes (e.g., fire) in the boreal forest. Day and Harvey (1981) describe the resilience of reproductive structures (e.g., cone serotiny), and the flammability of some species (e.g., balsam fir and white birch), to encourage fire spread as adaptive strategies to promote regeneration.

The choice of a silvicultural system has important implications for genetic conservation, as it influences different selection pressures and changes tree mating patterns. For example, jack pine cone serotiny characteristics may change within one generation following clear-cutting in place of fire (McDonald 1987). Further selection favoring cones that open without fire could, within one or two generations, make it practical to implement jack pine seed tree systems without underburning (Chrosciewicz 1988). However, this operational advantage may come at the expense of the species fitness to regenerate following wildfire. More genecological studies are required to explore the consequences of alternative silvicultural systems upon the genetics of other tree species in boreal mixedwoods.

2.4.2 Succession

Dynamic processes, like fire, work on time scales that are much shorter than evolutionary time frames, and directly influence forest succession. However, evolutionary forces

operate in concert with succession and are ongoing processes; although evolution works across many generations, succession is part of that process. Silvicultural systems attempt to mimic, to one degree or another, successional processes. Most forest management practices seek to encourage patterns of succession that create "desirable" forests.

Kimmins (1987) defines succession as "changes in the types, numbers, and groupings of organisms occupying an area and concomitant changes in certain features of the physical microenvironment." The various stages of succession with distinct groups of organisms are called seres.

Clements (1949), one of the first to develop the concept of succession, proposed that plant communities can be viewed as an organism with predictable development from an immature to a mature sere. The climax forest is a mature sere, the structure of which is governed largely by climate. Climax forests are stable in that they resist change and are basically self-perpetuating. In this way, boreal mixedwoods dominated by white spruce might be considered climax forest on productive sites, while pure black spruce might be considered climax forest on rock outcrops and swampy areas.

The climax mixedwood forests might arise from earlier seres of, for example, pure poplar following fire. A basic premise is that one sere (pioneer) so modifies the microenvironment that another sere is favored and soon follows. Eventually a climax state is reached. This pattern of succession is also called relay floristics. Presumably, over time, plant communities modify the soil to such an extent that a single climax type eventually dominates the landscape in the absence of disturbance. This is known as a monoclimax state that has been achieved through ecological/successional convergence. The relay floristics model holds that disturbance merely starts a new cycle of succession through various seres until the same climax state is reached.

The key feature of Clementsian succession is its linear progression from one sere to another and the predictability of the final climax forest state on the basis of climate and edaphic features of the physical environment. It also assumes interdependencies between one sere and a preceding sere.

There have been numerous debates and modifications to the Clementsian model (see Kimmins 1987, Robertson 1993). Elliot et al. (1993) have compiled an annotated bibliography and electronic database with 888 records on forest succession. The two most significant and recent developments in the thinking about forest succession relate to theories of gap dynamics and multiple-path models.

Gap dynamics hypothesizes that a climax-like steady state prevails amidst repeated short-term cyclical variations in the composition of small patches of vegetation (Kimmins 1987). Gap dynamics seems to work well in tropical and temperate rainforests where single tree canopies give way to large gaps when the tree dies, thus creating openings suitable for tree regeneration (Shugart 1984). Bonan and Shugart (1989) suggested that the low sun angle in boreal forests makes the idea of single tree gap dynamics untenable for boreal mixedwoods. They inferred that groups of trees must die to produce gaps large enough to stimulate reproduction. But group gaps often do occur through windthrow and outbreaks of the eastern spruce budworm (*Choristoneura fumiferana* [Clem.]). No rigorous work has yet explored the application of gap dynamics models to boreal mixedwoods.

Multiple successional pathway models (Kimmins 1987) have been developed for a few forest types in western North America. System knowledge is gained through the testing of these models. The models are based upon assumptions of cause and effect relationships that are more complex than the Clementsian directional succession models, but are perhaps more realistic. Shugart et al. (1992) and Solomon and Shugart (1993) have provided an account of the state of the art of computer simulated forest succession model development.

How do these ideas relate to silviculture practices in boreal mixedwoods? Most forest managers' preferences for certain silviculture systems or silvicultural practices are based upon their perceptions of natural succession. Those who subscribe to Clements' (1949) idea of climax forests might favor a selection system that maintains the climax forests, or systems such as the shelterwood system to move certain seres more quickly toward their climax state in the name of promoting "healthy forests". Others who perceive that fires occur too frequently for climax forest to exist will manage for a specific sere using clear-cutting systems. Both approaches are based upon "ecological principles".

For example, Quinby (1991) argued in favor of selection systems in the management of eastern white pine (*Pinus strobus* L.) in northern Ontario on the basis of log and residual stand observations that implicated gap dynamics as an explanation of current forest structure. His conclusions were contrary to other models that have assumed that catastrophic fire is necessary to favor white pine regeneration and maintenance. The latter case would suggest that heavier cutting is required to favor white pine in the absence of fire. In fact, the uniform shelterwood system is widely used to regenerate white pine (Chapeski et al. 1989).

As discussed earlier, most commercial boreal mixedwood tree species can be found in pure even-aged stands, usually arising from fire. This implies that relay floristics, integral to Clementsian directional succession models, are not the dominant mechanism. Mixedwood stands usually show a pattern of initial floristics where, although all species are of the same age, they occupy different strata due to their ability to occupy certain niches and their differing growth rates (Day and Harvey 1981).

White spruce's relatively unique occurrence in mixedwoods and its absence in pure stands in Ontario has led some individuals to consider the role of gap dynamics in the perpetuation of this species in boreal mixedwoods. A. Gordon[2] (personal communication) suggests that the eastern spruce budworm is a driver of boreal mixedwood succession. The gap dynamics involve the decay of older poplar and the budworm's preferential feeding on balsam fir relative to the longevity of white spruce. The dead fir logs rot over time, thereby allowing white spruce seed to germinate and grow within the gap among a poplar-dominated canopy. Mineral soil exposed by uprooted windthrown trees also provides an excellent seedbed for all boreal tree species. In Ontario's boreal mixedwoods, openings in the canopy generally result from the loss of large groups of trees, as opposed to individual trees.

Mixedwoods are often thought to be more resistant to insect attack and fire than are pure stands. When stable stands are affected by disturbance, they quickly return to their previous condition. Because of this perceived stability, mixedwoods are considered by some to represent the climax state in many temperate and boreal forests, by definition uneven-aged because they are self-perpetuating. This is the basis for "natural forestry" as practised in Germany, where selection and shelterwood systems are used to perpetuate mixedwoods (Odum 1993, Robertson 1993).

Many foresters in Ontario have observed that pure white spruce plantations are subject to intense eastern spruce budworm attack and frost damage. These problems do not appear to be as prevalent for white spruce in mixedwood stands. However, there is no hard evidence that trees in mixed stands are more resilient to attack during localized outbreaks. It would seem that the concept of stability of mixedwoods may be a fruitful area for study (Section 7.4.5).

Most foresters feel that catastrophic disturbances define the pattern of natural succession in boreal forests. Analytical techniques and the study of charcoal deposits, fire scars, dendrochronology, and palynology have revealed the frequent and widespread nature of catastrophic disturbances from storms, insects, and wildfire (Oliver and Larson 1991).

Fire and insects have the greatest impact on boreal forest structure (Dix and Swan 1971, Cogbill 1985). Fire intervals range from 20 to 135 years in Ontario's boreal forest, with the drier climates having more frequent and hotter fires (Ward and Tithecott 1993). However, no single successional pathway appears to follow fire. Postfire vegetation is a complex function of the preburn stand characteristics, time of burn, severity of burn, and other site-specific features (Payette 1992).

Empirical studies by Carelton and Maycock (1980) found no evidence for directional succession across the range of Ontario's boreal mixedwoods. Only balsam fir forests and lowland spruce forests seem stable and capable of perpetuating themselves in the absence of fire. In balsam fir forests, eastern spruce budworm is often the instrument for forest renewal (Zoladeski and Maycock 1990).

Indeed, it has been suggested that, in the absence of disturbance, a true climax forest on boreal mixedwood sites in Ontario would likely feature the occasional tree (probably white spruce) in the overstory and smaller trees emerging through small gaps in a mountain maple/beaked hazel thicket (Rowe 1961, Day and Harvey 1981). Examples of such stand types occur in northwestern Ontario where fires have not burned upland sites for more than 200 years. Only hazel and mountain maple seeds can germinate and grow on forest floors with accumulated leaf litter; these species can also reproduce vegetatively beneath partially closed canopies (Bell 1991).

Disturbance by industrial harvesting is a relatively recent phenomenon in the boreal mixedwood forest; it began in earnest only about 40 years ago (Armson 1988). The total area harvested remains a distant second to areas disturbed by fire and insects (Runyon 1991). Harvesting, however, has a profound impact upon forest structure. Taken together, fire control and logging may have caused a proliferation in the occurrence of mixedwood types (Hearnden et al. 1992). Much silvicultural effort has gone into attempts to convert mixedwood and hardwood cover types to pure even-aged spruce or pine, supposedly mimicking the effects of an intense fire regime. However, without intensive silvicultural maintenance, many of these sites revert at least temporarily to mixedwood cover types. (Hearnden et al. 1992).

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It would seem that the traditional Clementsian model of succession has serious limitations in boreal mixedwoods. The development and testing of multiple successional pathway and gap dynamic models for boreal mixedwoods appears to be an appropriate research priority.

2.4.3 Stand Dynamics

Succession and stand dynamics are interrelated concepts, with the former being the traditional domain of ecologists and the latter that of foresters. An understanding of stand dynamics complements or drives projections in multiple successional pathway models. For the present purposes, stand dynamics are changes in forest structure over relatively short periods of time and space compared to forest succession. Stand dynamics alter ecosystem structure and function to a lesser degree than does succession.

Stand dynamics may be studied in two ways: from the viewpoint of a single tree in relation to its surroundings (autecology/silvics), and from the viewpoint of a stand as a system (synecology or community ecology). Both viewpoints provide insight into the workings of different silviculture systems.

Silvics

Silvics deals with the underlying principles of the growth and development of individual trees and the forest as biological units (Smith 1986). Bell (1991) has compiled a detailed account of the silvics of boreal species in northwestern Ontario, while Nikolov and Helmisaari (1992) have summarized the silvical characteristics of boreal mixedwood species from around the world. Dix and Swan (1971) found that an understanding of tree and shrub silvics helped to interpret their boreal forest succession observations in Saskatchewan. Silvicultural practice is traditionally governed by the silvics of the species being managed.

Given the lack of evidence for mutualistic coevolved associations, a mechanistic view of individual plants competing for growing space (Oliver and Larson 1991) allows one to intuitively forecast stand development in boreal mixedwoods. It is possible to anticipate the reaction of species to various silvicultural manipulations on the basis of the silvical characteristics of the species and the nature of disturbances caused by silvicultural activities that alter growing space (e.g., Wagner and Zasada 1991).

The silvics of boreal species has led to a preference for specific silvicultural systems on the basis of regeneration reliability. Figure 1 presents a modification of Day's (1993) summary of appropriate silvicultural systems on the basis of a species' silvics and reliability of regeneration.

Aggressive reproductive and juvenile growth strategies are silvical characteristics of boreal hardwoods that allow them to outcompete conifers. For this reason, without intensive regeneration treatments, the harvesting of boreal mixedwoods usually results in mostly pure hardwood, second-growth stands. The establishment of white spruce or upland black spruce trees on harvested mixedwood site types remains the principle challenge to be met with creative application of silvicultural systems. Otherwise, upland conifers will be poorly represented in future forests.

Synecology

Although the evidence for interdependencies is rather weak in boreal mixedwoods, it does not mean that there are no interrelationships. Forest managers are faced with broader considerations than the silvical characteristics of the species they are managing when they must refine their choice of silvicultural system (Matthews 1989). For example, the relationships between forest and wildlife, and forest vegetation and soil fauna, are both critical, yet they are poorly understood. Even the relationship between trees of different species has implications for forest productivity.

A stand dynamics model based on the interaction of the silvical attributes of individual trees does not account for any interrelationships aside from competition from other plants. Although silvics are a reasonable starting point, a synecological viewpoint may be more useful.

When one looks at mixedwoods from a synecological perspective, there may be some advantages to maintaining mixtures even at the expense of compromising the optimum growing conditions of one species to maintain another. This trade-off is central to forest ecosystem management, where the broader ecological considerations discussed thus far become an integral part of the silvicultural planning process.

For example, the calcium content and deep root systems of poplar can improve site quality and the growth response of conifers by ameliorating nutrient and moisture regimes (Matthews 1989). Experimental mixed plantations of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) are significantly more productive than are single species plantations. Soil fauna may be more diverse in the mixed litter, making nutrients more readily available and possibly stimulating the production of fine roots (McKay and Malcolm 1988).

Strong and La Roi (1983) noted that the different rooting habits of mixedwood species allow trees to exploit different niches without competing with one another. Specifically, spruce roots tend to exploit the surface layers of the

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Selection system / Species	Clear-cut	Strip cut	Seed-tree Single tree	Seed-tree Group tree	Two-pass	Shelterwood Uniform, group or irregular	Shelterwood Strip or wedge	Selection Single tree	Selection Group tree
White spruce	■	■	▨	▨	■	▨	■	■	■
Black spruce	■	■		▨	■	▨	■	▨	
Balsam fir	■	■			■	▨	▨	▨	▨
Trembling aspen	■	■			■				
White birch		■				■	■		

Legend

■ Highly appropriate system

▨ Additional possible system

Figure 1. Summary of appropriate silvicultural systems for boreal mixedwood species (adapted from Day 1993).

soil, while pine and poplar roots can deeply penetrate the soil horizon. For these and other reasons, boreal mixedwoods might be able to produce more total biomass compared to pure stands of the same species. However, documented and convincing evidence for these productivity gains is absent for Ontario. Studies of productivity interrelationships among boreal mixedwood species are currently underway (MacDonald 1993).

2.5 Landscape Ecology

Until recently, the processes of climate, evolution, succession, and stand dynamics were thought to adequately explain patterns of forest cover. Forest pattern itself has now been perceived to influence forest ecosystem function. This perspective of pattern influencing process is the foundation of landscape ecology, which emerged as a science in the late 1970s. Ecosystems and their related processes and patterns are scale dependent. At large scales, the shape and spatial arrangement of vegetation types have a significant impact upon the movement of materials and energy within the system being studied (Turner 1989). Foresters who take into account the structure and species composition of neighboring stands when considering the outcome of silvicultural treatments upon

a subject stand, have an intuitive understanding of landscape ecology.

Alternative systems to the conventional clear-cutting of boreal mixedwoods will generate different patterns in the forested landscapes of Ontario. The cumulative effects of alternative silvicultural systems requires a landscape ecology perspective and analysis to balance stand-level perceptions.

2.6   Summary and Conclusion

It appears that boreal mixedwoods are robust ecosystems capable of responding to silvicultural systems in a variety of ways. The FEC and FRI are useful frameworks for describing ecosystem characteristics of boreal mixedwoods. However, the imperfect state of knowledge about these ecosystems and the broad range of stand conditions expressed by boreal mixedwoods requires the application of keen professional judgement to develop successful silvicultural prescriptions.

The idea of a deterministic pattern of succession and stable climax in the absence of fire and insect attack has little merit in Ontario's boreal mixedwood forests. Evidence suggests that these productive sites will tend to develop into poorly stocked beaked hazel parklands if left undisturbed.

The eastern spruce budworm may perpetuate uneven-aged mixedwood forests, particularly in the eastern part of Ontario where higher rainfall limits fire occurrence. Gaps in the canopy created by budworm feeding, combined with windthrow, may allow for regeneration of boreal tree species. Fires may create even-aged mixedwoods, but varying growth rates between species can result in stratified mixtures. Finally, clear-cutting can lead to the development of mixedwoods in the absence of intensive silviculture. It would seem that a variety of silvicultural systems in both even-aged and uneven-aged management settings are possible given the ecology of the important tree species in boreal mixedwoods.

An understanding of ecology at all levels, from individual-tree silvics to a landscape perspective, can help to predict the outcomes of silvicultural systems. When these predictions are compared to observations, new systems knowledge is gained. This is the critical component of adaptive ecosystem management (Lee 1993) and the cultivation of professional judgement.

Given the silvics of the boreal mixedwood species, the establishment of white spruce and upland black spruce on harvested mixedwood site types remains the principle challenge to be met with the creative application of silvicultural systems. Otherwise, these species will be poorly represented in future forests.

Despite the current sense of urgency to manage forests as ecosystems, one cannot select a silvicultural system on the basis of its harmony with nature alone. Practical considerations concerning economics, site productivity, stability, wildlife, and aesthetic values must be taken into account. Some of these considerations are addressed in subsequent sections within the context of each silvicultural system, with a particular emphasis on productivity.

3.0   SILVICULTURAL OVERVIEW

This section provides background information on the range of issues that must be addressed when choosing a silvicultural system. It briefly introduces three alternative silvicultural systems, reviews the historical context for the clear-cut silvicultural system, and discusses some important aspects of artificial and natural regeneration.

3.1   Silvicultural Systems in the Boreal Mixedwoods

Definitions of silviculture abound in the literature (Spurr 1979, Smith 1986, Matthews 1989, Forestry Canada 1992). Silviculture generally refers to the use of specific techniques to control the establishment and growth of forest stands to meet certain objectives. Because silvicultural techniques are often applied in conformity with definitive, methodological, and repetitive patterns, they can be considered as systems. Silvicultural systems are typically named in accordance with the harvesting method used (Forestry Canada 1992). As harvesting methods are usually employed to facilitate a specific manner of regeneration, names that refer to specific silvicultural systems often (but not always) imply an approach to both regeneration and harvesting. For example, in referring to the shelterwood silvicultural system, a forester would understand that not only is the forest to be harvested in a series of successive cuts of a specific type, but that natural regeneration will be fostered.

In subsequent sections of this report, three broad alternative silvicultural systems are discussed: modified clear-cutting, the shelterwood system, and the selection system.

In the modified clear-cutting systems considered in this report, all or most of the merchantable timber is removed from an area in one pass. They differ from traditional clear-cutting primarily in terms of the planned regeneration method and/or the size and shape of the cut. In the seed tree system, all trees are removed from the cutover area except for a small number of selected ones that are left to provide a seed source for natural regeneration. In the strip or block cutting system, the size and shape of cuts are such that trees in adjacent uncut strips or blocks provide the seed source. The two-pass harvesting system might be considered a hybrid between a clear-cut, a selection cut,

and a shelterwood cut. It was devised specifically for the white spruce/aspen mixedwoods of western Canada (Froning 1980), although it has potential for application in Ontario. In the first pass, the overstory of merchantable trees is removed, leaving immature understory trees to provide the basis for the second cut some years later.

In the shelterwood system, two or more cuttings are made at reasonably close intervals to establish regeneration under the protection of the partial forest canopy or "shelterwood". The sheltering layer of trees is removed once the seedlings are established and able to dominate the site (Forestry Canada 1992).

The selection system differs from all others in that felling and regeneration are not confined to specific areas within a stand or forest (Matthews 1989). An uneven-aged or irregular stand structure consisting of three or more distinct age or size classes is maintained through the careful felling of trees in all size classes, either singly or in small groups or strips (Forestry Canada 1992).

For each of these silvicultural systems, a number of variations or subsystems use the same general philosophy and approach to harvesting and regeneration, but vary in the manner of application. Although there is a clear distinction between silvicultural systems when considered at the general level, at a more detailed level the distinctions begin to blur. For example, although the difference between the clear-cut system and the selection system initially seems obvious, the distinction becomes less clear when one considers the difference between the group selection system and the block clear-cut system. The size of the cuts in these subsystems may no longer be sufficient to distinguish them from each other, and often, neither does the intended manner of regeneration.

Not only is there a continuum of sizes within the variations of silvicultural systems, but there is also a continuum of other attributes such as volume of cut, number of entries to harvest the stand, etc. Table 1 illustrates the relationship between these management issues and the range of silvicultural systems.

3.1.1 Clear-cutting in Boreal Mixedwoods

No forestry term has as many definitions, or evokes as much confusion, as "clear-cutting". (Smith [1986] referred to it as a "semantic morass".) Much of the confusion surrounding the term is related to the proportion of trees removed from a site. Although most definitions of clear-cutting refer to the removal of all, or virtually all of the trees on a site (Daniel et al. 1979, Ontario Ministry of Natural Resources 1986, Smith 1986, Forestry Canada 1992), areas traditionally referred to as clear-cut in Ontario often have a considerable proportion of the original stand left standing after the cut. This discrepancy between the semantic and *de facto* definitions of clear-cutting cause significant difficulties in communication among professional foresters.

A distinction between commercial and silvicultural clear-cuts helps distinguish between the two very different approaches. In a commercial clear-cut, all the commercially merchantable timber is removed from a site (Davidson et al. 1988). Consequently, commercial clear-cuts may or may not be cut clear of trees (that is, have all standing timber removed), depending upon the merchantability of the trees on the site. Merchantability considerations are the primary (or only) factors determining the harvesting system.

Smith (1986) suggests that the term "silvicultural clear-cut" be used to refer to areas where there has been a virtually complete removal of vegetation and where all the growing space is available for new plants. This definition implies that both merchantability and renewal are key factors in the use of silvicultural clear-cuts. The silviculturally prudent philosophy of including renewal considerations into clear-cutting is reflected in Forestry Canada's (1992) definition of clear-cutting as "a method of regenerating an even-aged forest stand in which new seedlings become established in fully exposed microenvironments after removal of most or all of the existing trees".

Unfortunately, the lack of differentiation in the use of terms related to clear-cutting is rooted in the history of boreal forestry and mixedwood management in Ontario. This report will distinguish between silvicultural and

Table 1. Management issues and the silvicultural system continuum.

Management issues	Silvicultural system continuum	
	Selection→Shelterwood→Clear-cut	
Scale of management	Tree	Stands
Regeneration effort	Low	High
Tending effort	Low	High
Protection effort	Low	High
Harvest effort	High	Low
Infrastructure effort (roads and planning)	High	Low
Canopy opening	Small	Large
Vertical structure	High	Low
Within-stand diversity	High	Low
Between-stand diversity	Low	High
Tree species types favored	Tolerant	Intolerant
Intervention frequency	High	Low

commercial clear-cuts where appropriate, based on philosophical differences between the two systems.

Most authors who have commented on the history of boreal mixedwood management in Ontario, or provided a dated description of "present" management practices (MacLean 1960, Hughes 1967, Heikurinen 1981, Jovic 1981, Matiece 1981, Wainwright 1981, Armson 1988), reported a harvesting and silvicultural scenario that is best described as commercial clear-cutting followed by planting or natural regeneration. Harvested areas not commercially clear-cut were subjected to "selective" or "partial" cutting, that could often be characterized as highgrading. These practices arose, obviously, from the pursuit of softwood species for both pulp and timber, with only a limited use of hardwood due to the absence of hardwood markets.

Commercial clear-cutting is still the dominant method of harvesting in boreal mixedwoods in Ontario (Scarratt 1992, MacDonald 1993), and is the traditional method used in other North American mixedwood forests (western Canada, Schneider 1988; eastern spruce–fir, Blum et al. 1983; Alaska white–spruce/hardwood mixtures, Zasada and Argyle 1983).

Clear-cutting is used in most applications because it is, in theory, the simplest way of creating an even-aged stand (Smith 1986, Matthews 1989). The regeneration objective of boreal silviculture in Ontario has usually been to create even-aged jack pine, black spruce, or white spruce stands. Although there is not a great record of success in achieving this objective on mixedwood sites in Ontario (particularly for the spruce species) (Brand and Penner 1991), this has been the rationale for the use of the clear-cut silvicultural system on mixedwood sites.

The result of these historical management practices has been evident for some time. MacLean (1960) used analyses done by Candy (1951) and Hosie (1953) to show that balsam fir and aspen become the dominant species after mixedwood sites have been commercially clear-cut. Understory balsam fir is released when spruce are removed from a site, and prolific aspen sucker growth often results from the intrinsic fertility of mixedwood sites and the higher soil temperatures that result from clear-cutting (MacLean 1960, Scarratt 1992). In the Rainy River and Fort Frances areas of northwestern Ontario, where "clear-cutting of marketable material" is the traditional harvesting system for mixedwood sites (Matiece 1981), the conifer content has virtually disappeared from mixedwood stands. These sites now support almost 100 percent poplar, with small amounts of balsam fir (Matiece 1981). Similar practices elsewhere in north central Ontario have also resulted in increased poplar and balsam fir contents at

the expense of the spruce component on mixedwood sites (Jovic 1981, Yang and Fry 1981).

Although the stocking of these cutover sites may be high (MacLean 1960, Matiece 1981, Jovic 1981, Yang and Fry 1981), their value (in forestry terms) is limited given the present low market demand for these species in Ontario. This situation is forcing forest managers to confront two related problems: how can the conversion of productive forest land to less desirable species be prevented, and how can the utilization of aspen, poplar, and balsam fir be increased?

3.2 History of Alternative Silvicultural Systems Research and Application

Surprisingly, numerous initiatives were undertaken in eastern Canada following World War II to test the applicability of different silvicultural systems in Canadian settings (Robertson 1945; Johnson 1950, 1951; Lafond 1955; Jarvis and Cayford 1961; Croome 1970; Peterson and Peterson 1994). In northern Ontario, a significant cooperative project known as RC-17 was undertaken in the 1950s to study the problem of obtaining coniferous regeneration on mixedwood sites (Hughes 1967). This project examined primarily clear-cutting and mechanical scarification techniques. In 1954, Abitibi Price Inc. established an experimental forest on private lands 100 km west of Thunder Bay, Ontario, to test various silviculture systems (Breckenridge 1955). The objective of most of these efforts was to maintain upland spruce as an important component in harvested forests through the application of classical silvicultural systems.

This postwar period of experimentation with alternative silvicultural systems in the boreal forest was shortlived. By the 1970s, relatively few articles were being published on the use of such systems in the forests of eastern Canada. A number of factors contributed to the abrupt shift to almost total reliance upon clear-cutting, *viz*:

1) Before 1960, mainly horses were used to skid wood in northern Ontario, thereby making the cost differential between various harvesting systems less pronounced than under mechanized harvesting (*see* Belotelkin et al. 1941). The river drives actually created an environment that favored the adoption of the selection system, as larger logs eliminated sinkage loss (Johnson 1951). As forest operations became more mechanized, beginning in 1960, worker safety and machine productivity were greatly enhanced by the clear-cutting method. Since silvicultural concerns had low priority, the clear-cutting system became the system of choice.

2) In Ontario, the responsibility for regeneration initially rested with the licensee. With the Crown Timber Act

of 1966, this responsibility was transferred to the Crown. This separation of responsibility for harvesting from that for regeneration coincided with a major thrust for mechanization in the forests. The result was that harvesting efficiency assumed paramount importance, reflected in the rapid increase in clear-cutting, and relatively little concern for the regeneration impacts. The use of alternative systems (with generally higher harvesting costs and lower regeneration costs) is hindered by a system in which the payment for regeneration activities is not directly linked to harvesting costs. (These circumstances have changed in recent years. Through Forest Management Agreements, and most recently the Crown Forest Sustainability Act, the responsibility for regeneration has returned primarily to the licensee.)

3) Most of the boreal forest had an even-aged structure due to the history of wildfire. This structure is relatively easy to harvest with the clear-cutting system.

4) European-trained foresters settled in the boreal forest following World War II. They brought with them European theories of forest management and attempted to apply these in their new homeland. The forces cited above made the application of classical silvicultural systems difficult at best, and reduced their ability to influence younger foresters to adopt and customize such alternative systems to local conditions. Thus, their influence lasted only a few decades.

3.3   Regeneration

A constant theme in discussions on the difficulties associated with boreal mixedwood management is regeneration, specifically that of conifers (Heikurinen 1981, Jovic 1981, Drew 1988, Navratil et al. 1991, Scarratt 1992, Peterson and Peterson 1994). Artificial regeneration techniques are commonly used in an attempt to establish conifers on clear-cut mixedwood sites in Ontario. In practice, most foresters now realize that even with frequent tending (i.e., herbicide applications), conifer planting on mixedwood sites will result in mixedwood stands. The best that can be hoped for, from a conifer regeneration point of view, is to maintain or supplement the "natural" conifer content in future stands.

While natural regeneration may be attempted for both conifers and hardwoods, in many instances its use to manage for coniferous species (other than fir) has not been much more than site abandonment and wishful thinking. Many of the problems relating to the composition of second-growth forests noted above are likely the result of a natural regeneration strategy.

3.3.1 Artificial Regeneration

Planting

Conifer planting generally has the goal of either conversion to conifer-dominated stands, or maintenance of the conifer component of a mixedwood stand (Jarvis et al. 1966, Hughes 1967, Jovic 1981, Drew 1988, Peterson and Peterson 1992). In Ontario, planting programs are generally based on a conifer pulpwood market, and black spruce is the species most often planted on productive mixedwood sites (Scarratt 1992).

Although there are many examples of successful black spruce plantations on mixedwood sites in Ontario, all were expensive to establish and depended upon the use of herbicides (Scarratt 1992). Jovic (1981) refers to studies carried out by R.S. Hosie and A.S Mitchell justifying the capital investment for planting conifers on mixedwood sites in Ontario. Jarvis et al. (1966) refer to several unpublished studies showing that white spruce plantations in the mixedwood section of Alberta and Saskatchewan have been successful.

There are, however, many other sources that document the relative failure of conifer planting on mixedwood sites. Brand and Penner (1991) refer to the unpublished findings of an OMNR survey in which less than one-half of the black spruce and white spruce plantations in northern Ontario met both stocking and free-to-grow standards. White spruce plantations on mixedwood sites were identified as a particular problem. In a comparison of natural stands and plantations of black spruce and white spruce on mixedwood sites in northern Ontario, Morris et al. (1988) noted that plantations had greater mortality rates and lower relative height growth rates than did natural stands.

Site preparation and vegetation management

Site preparation is believed to be essential for planting conifers on clear-cut mixedwood sites (Hughes 1967, Heikurinen 1981, Leblanc and Sutherland 1987, Armson 1988). The main result of the cooperative project RC-17 was to show the importance of mechanical site preparation for facilitating softwood regeneration on mixedwood sites (Hughes 1967). Mechanical site preparation is used to expose mineral soil to create suitable microsites for seedling establishment, and to eliminate competition. The required severity of mechanical site preparation depends upon how much competition for growing space is anticipated, which, in turn, is largely dependent upon the fertility of the site. Light scarification, such as plowing shallow furrows, may be sufficient if microsite exposure is the only objective, but heavier techniques may be needed if objectives include the destruction of residual balsam fir trees or damage to aspen root systems (Davidson et al. 1988, Morris et al. 1988).

Mechanical scarification alone is rarely sufficient for conifer establishment on mixedwood sites; some form of vegetation management is also necessary (Heikurinen 1981, Scarratt 1992). Many conifer plantings in Ontario mixedwoods require three or more herbicide applications before reaching the free-to-grow stage (Scarratt 1992). There are two obvious concerns regarding this heavy reliance upon mechanical site preparation and herbicide application. First, the costs are very high. In times of declining or uncertain silvicultural funding (Ontario Ministry of Natural Resources 1993b), strategies that require a high level of investment over large areas of land are susceptible to deterioration. Second, the heavy reliance upon herbicides also makes the strategy vulnerable. Given the increasing societal disapproval of the use of chemicals in forest management (Wagner 1992), and the possibility of restrictive legislation in the future (Scarratt 1992), the continuation of such a strategy is uncertain, even if silvicultural funding remains adequate.

The Ontario Ministry of Natural Resources' Vegetation Management Alternatives Program (Wagner 1992) was developed partly in response to concerns about the future availability of herbicide use in the province. Although a variety of innovative experiments and applications of alternative vegetation controls are being examined and tested, no panacea or widely applicable low-cost alternative is apparent.

Prescribed burning, a site preparation alternative that is not widely practiced in boreal mixedwoods, can be an effective way of eliminating slash and exposing mineral soil for planting. It can also be used to control balsam fir (Heikurinen 1981, Jovic 1981), and if the fire reaches a sufficient depth, can kill aspen roots (Davidson et al. 1988). However, just as prescribed burning can make a site hospitable for the establishment of conifers, it can also make it suitable for competitor species. Abundant hardwood regrowth, particularly of aspen, may occur if the fire is not deep; elevated soil temperatures resulting from the clearance of overhead cover will also encourage vigorous aspen growth (Peterson and Peterson 1992). Other difficulties with prescribed burning (i.e., heavy reliance upon weather conditions and uncertain success in removing slash) have also been disincentives for its use on mixedwood sites. Finally, the use of prescribed burns generally does not mitigate the need for vegetation control following planting.

Although not specific to boreal mixedwoods, the recent Ontario Provincial Silviculture Strategy (Ontario Ministry of Natural Resources 1993b) formulates a situation in which, as a result of fiscal constraint, there is likely to be a greater reliance on low-cost regeneration methods, and less reliance upon planting. Although this is contrary to the views of those who advocate a paradigm shift away from extensive regeneration and toward intensive regeneration of mixedwoods (Drew 1988), it is consistent with the view that advocates acceptance of hardwoods on mixedwood sites and the role that they play in mixedwood ecosystems (Peterson and Peterson 1992). Furthermore, without significant expenditures on vegetation management, a mixedwood stand seems to be the almost inevitable result of planting on typical mixedwood sites. Consequently, a prudent management strategy may be to acknowledge that this is a likely result and to implement practices that will maintain both the softwood and hardwood components, rather than the more expensive and rarely successful strategy of conversion to softwoods.

Direct seeding

Direct seeding has been used sparingly in Ontario mixedwoods, and then only to foster the regeneration of conifers. It is generally considered to be very unreliable for spruce regeneration (Sutton 1969, Jovic 1981, Arnup et al. 1988). Smithers (1965) reviewed the results of 34 trials of direct seeding white spruce in eastern Canada and found that only one-quarter had been moderately successful. Sutton (1969) suggested that drought and frost heaving are the most common cause of seedling mortality, even on well prepared sites where competition is not a factor in seedling establishment.

Haig (1959) documented an instance in which white spruce seeding, undertaken in western Manitoba, resulted in very dense stocking (from 8 395 to 12 345 stems per ha of 6-m trees). The sites were very intensively prepared (disked six times) prior to seeding. Jarvis et al. (1966) cited a number of studies that showed that seeding can be successful if site preparation and seedling protection is provided.

> More recent studies have been undertaken to study germination and seedling survival on various seedbeds....Results from these studies indicate that mesic sandy loam and clay loam sites in the Mixedwood Forest Section can be regenerated to white spruce by artificial seeding (Phelps 1948, Rowe 1953, Waldron 1966). Prerequisites for successful establishment are that mineral soil seedbeds must be prepared, potentially competitive cover must be eliminated prior to seeding, and young seedlings must be protected from browsing and competition by reinvading vegetation.

Very little reference was found to direct seeding on mixedwood sites in Ontario. Jovic (1981) noted that "most of the seeding techniques were tried in the mixedwood stands at one time or another and usually failed because of the severe competition." There are no records from

Ontario's mixedwoods of seeding in conjunction with site preparation as intensive as that discussed by Haig (1959) and Jarvis et al. (1966) in western mixedwoods. It would seem reasonable to suppose that efforts as intensive as those reported could also be successful in Ontario. However, given the expense of such intensive treatments; the liabilities of direct seeding in general (and of spruce on mixedwood sites in particular), such as unreliable germination and survival; and the erratic patterns of stand density (Johnson et al. 1971, Jovic 1981, Arnup et al. 1988, Navratil et al. 1991) the consensus as indicated by present practice seems to be that regeneration efforts are better spent on planting.

3.3.2 Natural Regeneration

The spruces, natural seeding, and windthrow

As described earlier (Section 3.1.1), the Ontario history of black spruce and white spruce regeneration on untreated sites following traditional commercial clear-cutting practices is one of equivocal success at best. Sutton (1969) stated that natural regeneration of white spruce in mature mixedwood forests has generally been more successful in eastern Canada than in Ontario, probably due to slight differences in temperature and moisture regimes that favor spruce reproduction and cause differences in forest composition (i.e., greater spruce–fir mixtures and less spruce–hardwood mixtures).

For the spruces, natural regeneration following harvest depends on seed from residual standing trees or from seed banks, or upon advance growth (seedlings or layers). Natural regeneration is a vital component of all the alternative silvicultural systems discussed in this report. For example, in the seed tree and two-pass systems, standing trees are left in the harvested area; in the strip, or block cut system, cuts are designed so that trees adjacent to the harvested area will provide seed. A significant limitation of these systems, particularly the seed tree system, is the susceptibility of spruce species to windthrow because of their shallow rooting systems (Westveld 1953, Frank and Bjorkbom 1973, Blum et al. 1983, Arnup et al. 1988). As a general rule, Oliver and Larson (1991) suggested that trees greater in height than 100 times their diameter are particularly vulnerable to windthrow. Field observations suggest that mature black spruce are nearly always above this ratio.

Although concerns related to windfirmness do not negate the potential utility of these silvicultural systems, they may pose some significant constraints on their manner of implementation and will require that forest managers modify the systems for their particular circumstances. As will be noted later, systems that use seed tree groups rather than individual trees, and orienting strip cuts with prevailing winds in mind may help to avoid some of these problems.

Natural regeneration is economically attractive because of its lower cost vis-a-vis planting. By allowing trees to naturally develop their root systems, natural regeneration also contributes to forests that are well adapted to their environment (Section 2.4.1). There is always root deformation with planting (Smith 1986), although this does not necessarily cause problems with tree survival and growth. Finally, the residual trees constitute a biological legacy that not only provides seed for natural regeneration, but also ensures mycorrhizal transfer and contributes to other important interactions between plants and their environments (Franklin 1992).

Aspen

While it seems that natural regeneration of spruce on mixedwood sites is problematic, natural regeneration of hardwoods, particularly aspen, following clear-cutting is not. The possession of both sexual (seedling) and vegetative (sucker) methods of reproduction gives aspen an advantage over the boreal mixedwood conifers (Peterson and Peterson 1992). Vegetative reproduction has received the most attention in the literature because aspen vigorously reproduces from suckers following silvicultural clear-cutting (Perala and Russel 1983, Davidson et al. 1988, Navratil et al. 1990, Peterson and Peterson 1992). The mechanisms governing vegetative aspen reproduction are well documented (Navratil and Chapman 1991, Perala 1991, Peterson and Peterson 1992). In general terms, sucker regeneration is controlled by apical dominance, soil temperature and moisture, light intensity, soil density, and mechanical root disturbance. The first two of these factors are generally considered to be the most important (Peterson and Peterson 1992).

Given the importance of increased soil temperature for vegetative reproduction, silvicultural clear-cutting is the best way to stimulate aspen regrowth in mixedwood stands. Harvesting during the dormant season usually results in maximum aspen suckering during the next growing season, although if the stand is healthy and well stocked, harvesting at any time will be followed by sucker regeneration (Peterson and Peterson 1992). The importance of soil temperature in stimulating vegetative reproduction can be used by forest managers to either encourage or limit such growth. If aspen reproduction is not desired, then harvesting practices should leave residual shading from either shrubs or trees so as to minimize the soil temperature increase and thereby limit suckering.

Clonal silviculture for aspen may not be a panacea for aspen reproduction (Peterson 1988). Trees generated from seeds usually live longer than those of sucker origin and

produce higher quality wood. There is, however, very little silvicultural literature on the production of aspen from seed. This may reflect the relative ease of fostering vegetative reproduction, and the relative difficulty of fostering seedling establishment.

Because aspen seeds lack endosperm (and therefore any ability to sustain themselves), they must come into immediate contact with moist soil and nutrients after being released from the parent tree (Doucet 1989). Apparently even a few hours of drought can cause seedlings to wilt (Peterson and Peterson 1992). Mineral soil seedbeds are the best substrate for seedling establishment, but they must be continually moist during the short period of seed viability and throughtout early root growth (Peterson and Peterson 1992).

Reproduction by seed may be more important in the northern parts of aspen's range because the relatively cold soil conditions are not favorable for suckering (Doucet 1989). Peterson and Peterson (1992) cite this speculation with respect to aspen in Alaska, although given the northwest–southeast pattern of temperature isobars in northern North America, it may also be relevant for boreal mixedwood sites in Ontario, particularly those that occur in the cold areas of the province described earlier (Section 2.3.1).

4.0 MODIFIED CLEAR-CUT SYSTEMS

4.1 Seed-tree System

4.1.1 Definition and History

In the seed-tree system, the stand is cut clear except for a few trees that are left standing either singly or in groups to provide seed to restock the cleared area (Smith 1986, Forestry Canada 1992). Because some trees are left standing within the cutover area, several authors (e.g., Smith 1986, Matthews 1989) consider the seed-tree system to be a variant of the shelterwood system. However, in Ontario, the system is used as and referred to as a variant of clear-cutting (Arnup et al. 1988, Anderson et al. 1990).

It is likely, however, that the seed-tree system evolved from the shelterwood system (Matthews 1989). Whereas trees are left for both shelter and seed in the shelterwood system, the unharvested trees in the seed-tree system are left only as a seed source. As the shelterwood system was applied to intolerant species, the virtue of leaving few enough trees so that shading was not a problem, and a sufficient number of trees to supply an adequate seed source, became apparent.

There is relatively little documentation on the use of the seed-tree system in boreal mixedwoods. The system is prescribed for black spruce stands on shallow mineral soils or, more commonly, on organic soils (Arnup et al. 1988). However, these are not typical mixedwood sites. Jovic (1981) reported that "the white spruce seed-tree method was used quite successfully in a few areas of our District" (north central Ontario), but provided no details on either use or regeneration performance. R. Sims[3] (personal communication) suggests that the method is "not uncommon" in some Ontario districts with boreal mixedwoods. Little mention is made of the seed-tree system in recent publications on mixedwood forestry in western Canada (Samoil 1988, Shortreid 1991). The most comprehensive documentation on the application of the seed-tree system to boreal mixedwoods is that of Lyon and Robinson (1977), who describe its applicability for white spruce.

4.1.2 Basis for Application

The seed-tree method is typically used as an alternative to artificial regeneration. The costs of regeneration are less than planting, although site preparation must often be used to ensure a receptive seedbed (Lyon and Robinson 1977, Smith 1986, Arnup et al. 1988). In northern Ontario, one use of the system may be for small or inaccessible areas where other regeneration methods are impractical. However, if accessibility is a concern for implementing artificial regeneration, it will also likely be an issue for site preparation. Smith (1986) suggests that the attractiveness, in terms of economical regeneration, of the seed-tree system is tempered by the need for site preparation, and that unwillingness to invest in site preparation costs has led to poor implementation of the system by many North American foresters. As few sincere attempts have been made with the seed-tree system, the results have generally been poor (ibid).

Matthews (1989) noted that: "The success of the seed-tree method depends on:

1) careful choice of seed bearers for phenotypic quality of stem and branching habit, absence of serious damage by disease, evidence of ability to produce seed, and windfirmness;

2) high production per tree of viable seed;

3) adequate dispersal of seed onto well-prepared seedbeds; and

4) good survival of seedlings during the critical early stages of growth."

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Major factors influencing the success of the seed-tree method are the periodicity and predictability of seed years.

From the above, it is apparent that the seed-tree method is not applicable to all boreal mixedwood species. Clearly, spruce and pine are the most logical candidates since they reproduce by seed and are desired crop trees. In areas where few trees are left standing, aspen would likely reproduce vigorously by suckering, so the seed-tree method is probably unnecessary where this species is a major stand component. Similarly, the system is unnecessary for fostering balsam fir reproduction (should it be desired), as it reproduces quite well naturally. Although birch reproduction is generally not fostered in boreal mixedwoods, there may be in greater demand for this species in the future. According to Perala and Alm (1990) seed-tree cutting can be used to regenerate white birch in circumstances where the birch trees in uncut stands are too far away to supply seed to adjacent cutover areas.

4.1.3 Operational Considerations

Windfirmness

The lack of windfirmness in exposed situations is the most significant liability for applying this system to the spruces. Robinson (1970) reported that 95 percent of all black spruce seed trees were blown down within 2 years of logging at a study site in western Newfoundland, and that 80 percent of seed trees were blown down within 6 years at a study site in central Newfoundland. Alexander (1986) stated that the seed-tree method is not suitable for regenerating spruce–fir stands in the central and southern Rocky Mountains because of susceptibility to windfall. Lees (1964) reported no significant problems with blowdown in experimental applications of white spruce seed-tree logging (and other systems) in central Alberta. However, the treatment plots were less than 1 acre in size (0.405 ha), so wind velocity and tree susceptibility to blowdown would likely not have been much greater than in an unharvested forest. In reviews of silviculture for spruce–fir forests of eastern North America, Westveld (1953), Frank and Bjorkbom (1973), and Blum et al. (1983) all recommend not using the scattered seed tree system because of the susceptibility of spruce trees to windthrow. However, Lyon and Robinson (1977) suggest that windfirmness need not be an overriding concern in applying the system for white spruce, provided that the right (i.e., dominant and therefore windfirm) individuals are selected for retention. Site selection is also an important criterion in the application of this system; exposed locations should obviously be avoided.

Given concerns about their windfirmness, is there any way that the system can be used with spruces in Ontario?

For black spruce, the system may be practical if seed trees are left in groups, rather than singly. Arnup et al. (1988) suggest that groups of black spruce seed trees may be left on shallow mineral soils or on organic soils. Being somewhat more stable, this approach would seem viable, but perhaps not as mandatory, for white spruce also (in instances where they occur in groups). Leaving groups of trees has other advantages: operationally, it is easier to leave groups of trees rather than individual trees, and a smaller proportion of trees are likely to be damaged (and therefore prone to windthrow) if groups rather than single trees are retained.

Square or round groups of trees may strike the best balance between exposure to wind as a liability (windthrow) and a benefit (for scattering of seed). This is contrary to the advice of Jeglum and Kennington (1993), who recommend leaving linear seed tree groups to reseed black spruce sites following strip cutting operations. Implicit in their recommendation is the recognition that the seed trees will blow down, and no return harvest will be attempted. Should a forester desire to forestall blowdown, or return to harvest the seed trees, this approach may not be desirable.

Factors determining the timing of the cut and the number of seed trees

A key consideration in applying the seed-tree system is the timing of the cut relative to seed crop production. It is important to take into account the autecological characteristics of the specie, summarized for the spruces (and other species) by Sims et al. (1990) and Bell (1991). Black spruce produce heavy seedcrops about once every 4 years, and most years produce a moderate number of seeds. Seed crop periodicity is more variable in white spruce, which produce heavy seed crops every 2 to 12 years, with inconsistent seed production in intervening years. The periodicity of good white spruce seed crops varies from one part of Ontario to another. Seeds of both species are generally dispersed a relatively short distance (about 40 to 100 m), although some may travel considerably farther. Seed longevity is generally greater for black spruce (about 4 years), than for white spruce (usually only 1 or 2 years).

Because of infrequent good seed years, the timing of harvest is particularly important for white spruce (more so when windfirmness is a concern). Lyon and Robinson (1977) recommend monitoring the development of white spruce buds to predict the size of seed crops. Although their recommendation was made in the context of planning site preparation activities, the same rationale is appropriate for harvesting. Where possible, cuts should be timed to coincide with seed crop production. Waldron (1959) reported on the regeneration results of several cutting methods, including the seed-tree system for white spruce, attempted in the mixedwood forest of Saskatchewan

35 years earlier. In four different implementations of the system, in which the number of trees left and the treatment of hardwoods varied, he found no significant difference in the resulting stocking of spruce. This result was attributed largely to the fact that 1924 (the year of the cut) was a very heavy seed year for white spruce. Although this experiment provides little direction on the number of spruce seed trees to leave in attempts at implementing the system, it does emphasize the point that seed-crop periodicity is a significant consideration. If windfirmness is a concern, the system is best implemented during good seed years.

Clearly, the unpredictability of seed years is a significant operational constraint upon the application of any type of natural regeneration system in the spruces, particularly the seed-tree system. This is especially true of white spruce and has major operational implications for the scheduling of other silvicultural activities associated with the regeneration cycle.

This, of course, poses a very practical problem; it is difficult to plan to take advantage of good seed years given the present harvest and silviculture planning practices in Ontario. To do so effectively will require a great deal of flexibility and foresight (both in planning and funding) if the seed tree system is to be used as a serious alternative to traditional clear-cutting.

The factors that should be used to determine how many trees, or groups of trees, to leave are similar to those used in determining when to cut: the frequency of good seed years; the number of seeds per tree; the seed dispersal distance; the survival time of seed trees in terms of windthrow and other losses; the seeds/seedling ratio; and the desired density of the reproduced stand (Daniel et al. 1979). There has been relatively little practical experience with the seed-tree system in Ontario's boreal mixedwoods. Using seed dispersal data, Lyon and Robinson (1977) calculated that approximately 2.5 white spruce trees/ha were theoretically adequate to provide sufficient seed. However, they recommend leaving 5–12 trees/ha to allow for uncertainty in the local seed production capacity of white spruce, differences in year-to-year seed production among individual trees, and survival of the seed trees. For black spruce, Virgo (1981), *cited in* Arnup et al. (1988), recommends leaving groups of trees 20 m^2 in size spaced at 90- to 150-m intervals between the centers of each group.

Site preparation and competition

Given the general recognition that site preparation is either a prerequisite, or at least a significant aid, in natural and assisted natural regeneration for the spruces, it is not surprising that the length of time the seedbed is receptive is an important consideration in determining how to use the system. Most mixedwood sites are fertile and rich in nature, so the duration of seedbed receptivity is short, even if mechanical and/or chemical site preparation are used. Because the receptivity of prepared sites declines dramatically 2 or 3 years after site preparation, Lyon and Robinson (1977) recommend that seedbed preparation should be undertaken during the summer of the seed year. The best situation would be no delay between harvesting and site preparation, with both occurring during heavy seed years. If successful regeneration is to be achieved, there should be minimal opportunity for vegetation competition to develop.

The environment created by spruce seed tree cutting on mixedwood sites is favorable for aspen regeneration due to high light intensity and soil temperature, and release from apical dominance. If significant aspen regeneration is not an acceptable result, the cost of competition, either in terms of vegetation management or reduced softwood yield/increased rotation times, may offset any economic savings associated with the seed-tree system.

Some of the most instructive experiments on competition and site preparation in seed-tree harvests in mixedwood forests were conducted in the prairie provinces in the 1960s. Lees (1964) reported on a comparison of eight harvesting treatments in an experiment in the mixedwood forest of central Alberta. The eight treatments included several selection and shelterwood variations, clear-cutting, and seed tree felling. The preharvest composition of the stand was approximately 2/3 white spruce, and 1/3 hardwood by volume. Two spruce seed trees per hectare and all aspen were left standing. Ten years after harvest, white spruce stocking compared favorably to clear-cutting and moderately well to the shelterwood and selection systems. (A system comparable to a two-stage shelterwood produced the most favorable results for white spruce stocking.) Although the white spruce seed trees produced sufficient seed to stock the surrounding areas, Lees reported considerable difficulty with spruce regeneration survival on seed-tree and clear-cut areas due to competition from grasses, and from aspen and balsam poplar suckers. Competition from aspen and other vegetation was considerably less severe in partially cut areas.

In a similar study in the same area, Lees (1963) investigated the effect of scarification in fostering spruce natural reproduction in mixedwood stands subjected to a number of partial cutting treatments. In the treatment that most resembled seed-tree cutting, about one-quarter of the white spruce volume was left standing and all aspen trees were left unharvested. In all treatments, scarification greatly facilitated natural reproduction. In unscarified stands, there was virtually no stocking of seedlings 4–7 years after harvest. White spruce regeneration on the heaviest cut (similar to a seed-tree cut) was comparable or

slightly better than that of lighter treatments, leading to the conclusion that the creation of a receptive seed bed was important for regeneration success. Competition from hardwoods does not appear to have been a significant concern in this study.

Other considerations

There are a number of other positive aspects of the seed-tree system, compared to traditional clear-cutting practices and/or other alternative systems:

- The seed tree system provides for a more uniform distribution of seed. Spacing the seed trees appropriately throughout the cut enhances the distribution of seed and seedlings.

- Access to harvestable trees is less restricted than in some other systems. Although access is not as unrestricted as in the traditional clear-cut system, fewer impediments to individual trees occur in the seed-tree system than in shelterwood and selection systems.

- Aesthetically, the seed tree system is marginally better than is traditional clear-cutting.

Economically, the seed-tree system has both assets and liabilities. As noted earlier, Smith (1986) suggested that economic concerns are often of primary importance when deciding whether or not to implement this system. The harvesting costs for the system are low compared with alternative harvesting systems, as few extraordinary procedures are needed (i.e., to avoid damage to residual trees or to protect an understory crop). Some economic loss may be incurred (relative to clear-cutting) if return cuts are not part of the prescription and the seed trees are not harvested. On the other hand, return cuts to harvest the few remaining seed trees are probably not economically justifiable in most circumstances. Furthermore, harvesting the seed trees may result in significant damage to regenerating trees. For this reason, Lyon and Robinson (1977) recommend not returning to harvest white spruce seed trees.

Advantages and disadvantages

The advantages of using seed tree systems include:

- Planting costs are avoided.

- Conventional logging, aerial tending, and site preparation techniques are relatively unrestricted.

- The loss of seed trees is planned for, as they are not expected to provide revenue in some future harvest.

- Exposure to sunlight favors rapid growth, especially of intolerant species.

- Biological legacies are provided for (Sections 2.4.1, 3.3.2).

- Site-adapted seed is assured (Sections 2.4.1, 3.3.2).

- Seedlings from seed have well developed root systems. Hardwoods originating from seed are thought to live longer than hardwoods from root suckers (Section 3.3.2).

- Perches and nesting sites are provided for birds (Section 7.4.4).

- Aesthetics are improved over clear-cutting.

The disadvantages of using seed tree systems include:

- Costs associated with selecting and leaving seed trees.

- Trees are susceptible to windthrow.

- Uncertain seed crop size from year to year.

- Uncertainty over the ability of seedlings to emerge free of competition. There may be a greater requirement for vegetation management to release conifers than if the area was planted.

- Control of regenerating species composition and tree density may be difficult; supplementary planting may be required if natural ingrowth fails to produce a desired stand density or, if the density is too great, this may slow the development of individual trees to commercial maturity.

- A possibility that white spruce seed trees might attract budworm (Section 7.4.5).

4.2 Strip Clear-cutting

4.2.1 Definition and History

Strip clear-cutting entails removing a crop of trees in strips in one or more operations (Forestry Canada 1992). The most common implementation of strip cutting is a two-cut system in which alternate strips are cut, and intervening strips are left uncut. In progressive strip clear-cutting, more than two cuts are used in a progression across a designated area, and a leave period between each cut is provided in which natural regeneration can take place (Jeglum and Kennington 1993). The name of the system implies that cuts proceed in strips that are longer than they are wide. Although this is correct, the same regeneration premise is true for block cutting. Since the only difference between the two systems is the implied shape of the cut, both are treated together here.

Strip cutting requires natural or assisted natural regeneration. The premise behind the system is that by leaving a seed source close to a cutover area, a natural supply of seed will facilitate reforestation, and the uncut strips will provide the cut area with some protection from harsh environmental conditions following harvesting. When regeneration in the cut strips has been established, the leave strips are in turn harvested.

Matthews (1989) traced the history of strip harvesting systems in Europe over the last 150 years. A strip variation of the shelterwood system evolved in which harvesting took place in a series of successive strips at right angles to, and advancing against, the prevailing wind direction.

Jeglum and Kennington (1993) have recently produced an excellent strip clear-cutting guide for the practising forester. Although this publication is primarily intended to provide a guide for implementation in black spruce forests, much of the information contained in it is applicable to other forest types.

Strip cutting has a long history in Ontario, where it has been used primarily in black spruce forests. However, some attempts have been made to examine its utility in other boreal forest types (Hughes 1967). The system was originally used shortly after the turn of the century. Horses and handfelling were used to harvest parallel strips of spruce forest about 20 meters wide (Jeglum and Kennington 1993). The leave strips were harvested after the cut strips had regenerated naturally. As mechanization facilitated large clear-cut areas through the 1950s and 1960s, natural regeneration suffered and artificial regeneration could not keep pace with harvesting operations. This lead to a renewed interest in strip cutting. Since the 1970s, strip cutting has been implemented mostly in black spruce forests, but has been the subject of considerable experimentation in Ontario (Fraser et al. 1976, Robinson 1987, Jeglum and Kennington 1993, and many others). Elsewhere, the system has been applied to the hardwood forests of the northeastern United States. (Metzger 1980, Tubbs et al. 1983, Hornbeck and Leak 1992) and is recommended for birch-dominated forests both there and elsewhere (Safford and Jacobs 1983, Perala and Alm 1990).

4.2.2 Basis for Application

Strip cutting has been recommended for sites with one or more of the following characteristics:

- low productivity;
- difficult to access;
- located on rough terrain;
- suitable forests occur as small pockets in an area dominated by other forest types;
- environmentally sensitive; and
- no significant advanced regeneration is present (Westveld 1953, Robinson 1987, Jeglum 1987, Arnup et al. 1988, Jeglum and Kennington 1993).

For sites that are a considerable distance from the mill or base of operations, contain islands of suitable forests, or are located on rough terrain, the logistic difficulties and

expense of conducting site preparation and planting activities may be uneconomical (Jeglum 1987, Jeglum and Kennington 1993). If these sites support species with wind-dispersed seeds for which regeneration is desired, strip cutting may be an alternative option.

Westveld (1953) recommends using strip cutting rather than clear-cutting for eastern spruce–fir forests in areas where advanced regeneration is insufficient to provide for the next crop. The logic of this recommendation is apparent, although the basis upon which it rests is less applicable today than it was 40 years ago. Advanced regeneration may survive clear-cutting harvest operations in significant enough quantities to provide a new forest (Archibald and Arnup 1993), but the effort and practices required to accomplish this are not routinely applied in today's clear-cutting practices.

Strip cutting has been recommended to reduce the susceptibility of spruce–fir forests to eastern spruce budworm (Lancaster 1984, Blum 1985). By splitting the forest into a variety of age classes, the suitability of the forest to widespread budworm infestation declines.

White birch is well suited to regeneration using strip cutting because it is shade intolerant and regenerates well from seed; the usual range of seed dispersal being within 100 m (Sims et al. 1990). Safford and Jacobs (1983) and Perala and Alm (1990) recommend clear-cutting in blocks, strips, or patches to foster white birch regeneration.

Arnup et al. (1988) do not consider strip cutting to be suitable for white spruce mixedwoods, because their fertile nature leaves them susceptible to competition. This concern is related to the difficulties associated with tending. Aerial tending options are limited due to the interspersion of cut and uncut areas. This fits with the earlier recommendation that the system is best suited to sites with lower productivity. However, this should not be taken to imply that the system is inappropriate for all mixedwood sites. Jeglum and Kennington (1993) noted that strip cutting has good potential for white spruce–black spruce–trembling aspen mixtures, and white spruce–tamarack mixtures. The presence of black spruce and tamarack on these sites indicates that they would be less productive than rich mixedwood sites, and therefore less prone to competition problems.

Strip cutting may be considered in instances where concerns about environmental impacts are important. Environmental issues that may favour strip cutting over clear-cutting include:

- areas in which runoff or erosion are concerns, as the interspersed nature of a strip cut forest minimizes these effects;

- areas in which wildlife management is intended to foster species that favor edge habitats; and

- locations in which aesthetic concerns need to be accomodated, as strip cuts can be less visible than large clear-cuts. (Strips can be further camouflaged in sensitive areas by orienting them at an angle to the primary line of view. The viewer is then faced with an apparently solid wall of forest, except when looking directly down a strip.)

4.2.3 Operational Considerations

Strip width

The size or width of the cut is the central variable that can be manipulated when using strip and block cutting. The width of the cut is a critical factor, as it influences reproduction (seed dispersal and seedling protection), as well as the economics and logistics of harvesting operations.

From trials of different strip widths southeast of Lake Nipigon, Jeglum (1987) found that 80-m-wide strips gave adequate black spruce stocking, although seedling numbers were slightly lower in the strip centers. He suggests an optimum strip width of 60 m (the trials did not include 60-m strip widths). Auld (1975) found that 50-m widths resulted in better seed coverage and afforded better protection than did 80- or 100-m widths for black spruce regeneration near Thunder Bay. Kolabinski (1991) recommends a strip width of 40–60 m for regenerating black spruce in Manitoba. These estimates, taken together, suggest that widths of about 40–60 m are best for black spruce, and are consistent with recorded effective seed dispersal distances (Bell 1991). Hughes (1967) reported that spruce regeneration (species not specified, but probably white spruce) on mixedwood sites was "acceptable" in strips 6 chains (approx. 120 m) wide, although regeneration was not examined at narrower widths.

In addition to seed dispersal, Jeglum and Kennington (1993) suggest that strip width should take into account site conditions and the amount of site protection needed or desired to be provided by the uncut strips. For dry sites on shallow soils, narrower widths (10–30m) are recommended for black spruce; for moist mineral soils and wet organic soils, widths should be from 70–100m.

Jarvis et al. (1966) found that seed was well dispersed 1 and 2 years after cutting across the entire width of 2-chain (40-m) strip cuts in pure white spruce stands in central Saskatchewan. In one of the few documented applications from white spruce mixedwoods, Johnson and Gorman (1977) found that stocking of white spruce regeneration in north central Alberta was not appreciably different 80 m from a stand edge than it was much closer to the edge. In this study, however, a considerable number of non-

merchantable, seed-producing trees were left in the cutover areas. This may have complicated the findings. Given that the maximum distance for the spread of significant quantities of white spruce seed is about 46–62 m (Bell 1991), strip-width guidelines similar to those for black spruce may be appropriate.

For eastern spruce–fir forests, Westveld (1953) recommends that strip widths not exceed 150 ft (46 m). While Johnson (1960) suggests that widths not exceed one and one-half times the height of trees in the uncut stands, Blum et al. (1983) recommend using strips only half as wide as the height of border trees in the same forest type. Since these publications refer to the regeneration of spruce–fir forests, rather than the individual species, the authors have assumed that the suggested guidelines for strip width are based as much on regenerating balsam fir as white spruce, and are therefore less applicable to Ontario's boreal mixedwoods, where spruce regeneration is a priority.

For birch, strip widths of 50 m and 100 m are common (Marquis et al. 1969). In Alaska, Zasada and Gregory (1972) found that birch seed production was inadequate to regenerate 30-m-wide strips for 3 out of 4 years. Perala and Alm (1990) note that cool moist climates and good seed crops might allow consistently good regeneration of 50-m-wide cuts, but that small crops and dry climates may dictate cuts half as wide.

Orientation

Orientation of the cut is an important consideration. Logically, the long axis of the strip cut should be at right angles to the prevailing wind direction to facilitate seed dispersal. This also enhances stand stability by minimizing blowdown (Alexander 1986, Smith 1986). Matthews (1989) and Alexander (1986) recommend that for progressive fellings strips should be oriented with the long axis of the cuts proceeding into the prevailing wind direction in successive cuts.

Jeglum and Kennington (1993) suggest that in Ontario, strip orientation for black spruce regeneration may be more important for protecting the germinant than for seed dispersal. The leave strips provide protection from the drying effects of the sun and wind and tend to preserve moisture longer in the surface horizons, thereby creating conditions that facilitate germination and establishment (Matthews 1989, Jeglum and Kennington 1993). Jeglum and Kennington (1993) recommend that strips be oriented in an east–west manner to provide shading and protection from the sun during the warmest and driest time of day, from noon to mid-afternoon.

Jarvis et al. (1966) found that white spruce stocking in Saskatchewan was usually more successful on the southern half of strips than on the north half, presumably

because the shade cast over the south half of the strips created a better environment for regeneration. The implication of this consideration for strip width is also apparent.

Marquis (1965) reported that both east–west and north–south strips provided good germination of yellow birch (*Betula alleghaniensis* Britton) and white birch seedlings, providing that the strips were narrow.

In Ontario, where prevailing winds are from the west, seed dispersal concerns suggest that strips be oriented in a north–south manner. However, where seedling survival and soil desiccation concerns are paramount, east–west orientation may be more appropriate. This implies that foresters should let biological considerations and local climate determine the orientation of the cut.

Site preparation

Site preparation is an important operational consideration for strip cutting applications. As with the seed-tree system, site preparation should be conducted as soon as possible after harvest to provide a receptive seedbed, and to capitalize immediately on seed production in case windthrow occurs around the margins of the remaining stand (Jeglum 1987, Kolabinski 1991). This is particularly relevant when dealing with black spruce.

On strip-cut, white spruce mixedwood sites in Alberta, 50 percent scarification resulted in from two to ten times more white spruce seedlings over a range of distances from a cut edge 5–10 years after cutting than did 0–10 percent scarification (Johnson and Gorman 1977). Areas farthest from the cut edge had the greatest relative difference in stocking. Jarvis et al. (1966) reported on two similar experiments, one in pure white spruce stands in central Saskatchewan, the other in white spruce–trembling aspen stands in western Manitoba and southern Saskatchewan. In both cases, scarified strips yielded greater seedling stocking than did unscarified strips. Since scarification is often necessary to facilitate white spruce germination and survival regardless of the harvesting system, it seems a reasonable assumption that scarification to enhance white spruce reproduction is necessary on strip cuts.

For birch, scarification is generally necessary to ensure regeneration using strip cuts (Perala and Alm 1990, Hornbeck and Leak 1992).

Strip cuts and small block cuts may impose constraints on the use of conventional silvicultural tools. The threat of the adjacent uncut forest catching fire restricts the use of prescribed burning. Aerial tending may also be impractical because of the interspersion of cut and uncut areas. Therefore, on mixedwood sites, even relatively poor ones, heavy site preparation may be necessary to control vegetation competition (*see* Section 3.3.1). This may be particularly relevant for strip cuts because, as noted earlier, aerial tending is often impractical due to the interspersion of cut and uncut areas.

Leave period

The uncut strips can be harvested once regeneration has been established in the cutover strips. Jeglum (1987) found that 2 years was insufficient for adequate black spruce stocking to become established near Nipigon, and recommends that at least 3 years be provided. Jeglum and Kennington (1993) suggest a minimum of 3 to 5 years for black spruce. On upland sites, which are more likely to have mixedwood forests, these authors suggest 5 to 7 years. This recommendation is based on the length of time the seedbeds are likely to remain receptive, and is longer than that advocated by other authors (Lyon and Robinson 1977). This may reflect the view that strip cutting is more appropriate for poorer sites, even within the range of mixedwood areas.

If seedbed receptivity declines before sufficient regeneration is established, additional scarification may be necessary. This will mean that the leave time must be increased. This highlights the fact that the leave period is dependent upon the specific conditions of the site and should not be considered absolute for any strip or block cut operation (Jeglum 1987). The strong link between site preparation, seedling establishment, and the leave period is obvious.

Perala and Alm (1990) suggest that 1 to 2 years should be sufficient to provide birch regeneration.

Regeneration of the final cut

Given that the rationale for strip and block cut systems is that uncut stands will provide seed to cutover areas, the question of how the last strip will be regenerated after harvest is a significant issue. In alternate strip cutting, the proportion of forest to be regenerated after the final cut can be up to one-half. Unfortunately, relative to efforts devoted to regenerating first-cut strips, this problem has received little attention. Options include: not harvesting the leave strips; seeding-in from first-cut strips; leaving cone-bearing slash on-site during harvesting; leaving seed tree groups; direct seeding or planting; and careful logging around advance growth.

Seeding from first-cut strips would require that the leave period be long enough for the regenerated trees to produce seed. This would take between 30 and 60 years for white spruce, between 25 and 40 years for black spruce, and at least 15 years for birch (Sims et al. 1990, Bell 1991). For spruce, the obvious problem is that trees in uncut strips may be too old for commercially viable harvesting after 25 to 60 years. Also, mortality and blowdown may have claimed a significant proportion of the remaining stand.

If leave strips are not harvested, the cost of lost timber should be considered in calculating regeneration costs (Jeglum and Kennington 1993). A decision not to harvest the leave strips should be made before the first cut, so that the leave strips can be as narrow (i.e., contain as little timber) as possible.

Natural regeneration of the last-cut strips can be fostered by using a logging system such as tree-length or cut-to-length that leaves cone-bearing slash in place. One should anticipate that regeneration on these strips will be less successful than on the first-cut strips. Seed trees can be left from the last-cut strips to provide seed. Jeglum and Kennington (1993) recommend leaving linear black spruce seed tree groups. As discussed in Section 4.1.3, square or round cuts may have advantages in some circumstances.

Direct seeding or planting can be used to regenerate uncut strips. However, if the initial decision to use strip cutting was based on economic issues, these issues are likely to remain important at the time of the last cut and may preclude these more expensive regeneration options.

Where present in sufficient quantitites, careful logging around advance growth is a possible alternative for regenerating final cuts on black spruce sites (Jeglum and Kennington 1993). There is considerable documentation on the effects of mechanized harvesting on spruce regeneration (Weetman et al. 1973, Gingras et al. 1991). Archibald and Arnup (1993) presented statistics on stocking levels 5 years after careful logging to protect advance growth on black spruce and mixedwood sites in northeastern Ontario. On mixedwood sites, stocking ranged from 50 percent to approximately 70 percent; on black spruce sites it was somewhat higher.

Other considerations

The economics of strip cutting have been relatively well studied (Ketcheson 1977, 1979; Ketcheson and Smyth 1978; Johnson and Smyth 1988). These studies generally compared the costs of strip cutting to those of clear-cutting with different regeneration alternatives. Among the significant points to emerge in these analyses were:

- Road construction and maintenance costs are the most significant additional costs of strip cutting. Main access roads must be constructed sooner, maintenance is required for longer periods of time, and reconstruction of tertiary roads is usually necessary.

- Additional planning, layout, and supervision costs are required for strip cutting.

- Equipment overhead, and the moving and servicing of equipment add marginal costs to strip cutting. So also do costs associated with roadside delimbing (delimbers must make two passes of the same area when alternate strip cutting is used).

- Operational restrictions, such as constraints on felling direction and skidding trails, add some costs; however, these are less significant on wide or long strips than they are on narrow or shorter strips.

- Blowdown losses in strips may add to costs by reducing timber yield.

- Costs rise as leave time increases, mainly because of the extra costs associated with road construction and maintenance.

The extra costs of strip cutting can be more than offset by the savings associated with renewal operations. The relative savings depend largely on the method of renewing the last-cut strip, and on the clear-cutting renewal method that is the basis for comparison. Johnson and Smyth (1988) compared the costs of a number of strip cutting and clear-cutting renewal scenarios and concluded that in general terms strip cutting results in (i) lower net costs compared with clear-cutting followed by planting, and (ii) higher net costs compared with clear-cutting followed by aerial seeding.

These economic studies were based on comparisons of strip cutting with clear-cutting in black spruce forests. While many of the findings may apply to other forest types, foresters need to use caution in applying them to mixedwoods forests. Some factors, such as the possibly greater need for vegetation control, need to be taken into account when considering the economics of strip cutting in mixedwoods.

Advantages and disadvantages

The advantages of strip cutting include:

- Planting costs are avoided and the method may be well suited to sites with poor access, difficult planting conditions, or where windthrow may be a risk factor.

- Conventional logging, aerial tending, and site preparation techniques can be practiced, although there may be restrictions on the use of prescribed fire.

- Harvesting residual strips will not cause damage to seedlings on regenerated strips.

- Exposure to sunlight in portions of the strip favors rapid growth, especially of intolerant species. Shade from the strip edge may favor the establishment and growth of spruce and balsam fir. This is particularly true for narrow east–west strips. Strip orientation must strike a balance between the need for seed dispersal by prevailing winds and the need to create suitable microenvironments for seedling growth.

- Cone/seed crop periodicity is somewhat less of a concern than is the case with seed tree or shelterwood systems because of the many tree donors in the residual strip.
- Site-adapted seed is assured (Sections 2.4.1, 3.3.2).
- Seedlings originating from seed have well developed root systems. Hardwoods originating from seed are thought to live longer than hardwoods arising from root suckers (Section 3.3.2).
- Aesthetic improvement over clear-cutting.
- New vegetation growth following harvest may create habitats that are beneficial to moose and other wildlife species that inhabit forest edges (Section 7.4).
- Operational experience with black spruce strip cutting could be helpful in implementing this system in boreal mixedwoods.

The disadvantages of strip cutting systems include:

- Costs are associated with additional road layout and maintenance.
- Harvesting and mechanical site preparation costs will be greater than with clear-cutting and seed-tree systems.
- Wood volume loss to windthrow can be significant depending upon site conditions.
- Uncertainty over the ability of seedlings to achieve free-to-grow status. There may be a requirement to use more intensive vegetation management to release conifers than if the area were planted.
- Composition of regenerating species and tree density may be difficult to control. Supplemental planting may be required if natural ingrowth fails to produce the desired stand density or, if density is too great, it may reduce individual tree growth.
- Harvesting and regeneration of the final residual strip may require conventional clear-cut treatments.
- Residual strips might attract budworm (Section 7.4.5).

4.3   Two-pass Harvesting

4.3.1   Definition and History

The two-pass harvesting system, as described here, was developed largely for implementation in the mixedwoods of Alberta and Saskatchewan (Brace and Bella 1988, Brace Forest Services 1992, Sauder 1992). As noted earlier (Section 3.1), it is a hybrid between a clear-cut, a selection cut, and a shelterwood cut although arguments could be made for considering it a variant of systems other than a clear-cut. It is included here because, as with other clear-cut variants, all or most of the merchantable timber in a stand is removed in one cut.

The mixedwoods of the prairie provinces tend to be less complex than those of Ontario. The typical application of the two-pass harvesting system is in a forest with a mature hardwood overstory and an immature softwood, primarily white spruce, understory. Balsam fir is much less common in the prairie provinces and aggressive shrub species are also less prevalent. Although these factors do not necessarily negate implementation of the system in Ontario's mixedwoods, they should be taken into account.

The premise for the system is that by using careful harvesting techniques, commercially viable crops of both hardwoods and softwoods can be harvested from the same stand. Mature hardwood is removed in such a way as to minimize damage to immature softwoods and advance regeneration. The remaining softwoods will provide the second harvest some years later when they have reached harvestable size (Brace and Bella 1988, Brace Forest Services 1992, Sauder 1992).

Harvesting operations that concentrate on removing only a portion of mixedwood stands have been used extensively in the past, and continue to be used in some areas (e.g., selective high-grading and commercial clear-cutting) . These practices, although similar in the respect that not all standing timber is removed in a single operation, should not be confused with two-pass harvesting. Selective high-grading and commercial clear-cutting are done neither with the intent of returning to the site at a later time to harvest other species, nor with the intent of minimizing damage to advance regeneration during the initial harvesting operations.

Although the idea of two-pass harvesting in boreal mixedwoods is not new (Lees 1963), only in recent years has it begun to receive serious attention in Canada. The widespread use of clear-cut oriented mechanized harvesting machinery in boreal mixedwoods raised the incidental destruction of advanced regeneration and nonharvest trees to much higher levels than had previously existed. Fellerbunchers and skidders were designed to minimize handling times and maximize harvested volumes; protecting advance growth was not typically a concern in their design or operation. Conventional logging in mixedwood stands typically resulted in the destruction of most of the softwood understory.

The increased demand for and value of aspen and balsam poplar (Beck et al. 1989, Brennan 1991, Ontario Ministry of Natural Resources 1992) is leading to efforts to maximize utilization of the hardwoods in mixedwood stands. However, this is tempered by the economic logic of doing so at the expense of the softwoods present. The two-pass system provides a way of addressing this issue in some mixedwood stands.

Protection of advance regeneration became a concern not long after the use of heavy harvesting machinery became common (Roe et al. 1970). It was felt that protecting white spruce advance regeneration while harvesting crop trees would supplement efforts directed at artificial regeneration, which historically had not been overly successful. Archibald and Arnup (1993) have described current approaches to careful harvesting so as to protect black spruce advanced growth in pure stands. This is slightly different from the focus of two-pass harvesting (which is centered around creating harvest opportunities for different species of trees at staggered intervals), but the relationship between the two ideas is obvious. Similarly, strategies for releasing spruce trees from aspen competition on mixedwood sites have been the subject of considerable consternation and research (Cayford 1957, Lees 1966, Steneker 1974, Yang 1989).

Two-pass harvesting is the logical result of certain local circumstances, *viz*: the increased demand for aspen and poplar, the historical lack of success in reestablishing white spruce by planting, the growth benefits achieved by releasing spruce advance growth from aspen competition, and, ultimately, the desire to minimize waste and maximize the potential fibre harvest from mixedwood sites.

4.3.2 Basis for Application

Because specific silvicultural techniques define the two-pass silvicultural system more distinctly than other systems, this section will include more extensive discussions of technique.

The two-pass harvesting system as employed in western Canada is intended for application in mixedwoods with a white spruce understory and an aspen and poplar overstory. As noted earlier, Ontario's mixedwood forests often have a significant balsam fir component. Could such a system work in this mixedwood forest type? When the hardwood overstory of a forest is removed, the white spruce and fir present in the understory will respond with increased growth rates. The fir growth rate will likely be at least as great as that of spruce, and might be greater. At the time of the next harvest, therefore, the forest would consist of a spruce–fir overstory. In a more extreme situation where the fir growth rate exceeded that of the spruce, fir would be the principal species available for the second harvest. Spruce, perhaps, could be taken in a third pass. In either of these scenarios, fir would be an important component of the second harvest, or at least a significant factor to be dealt with after the first harvest.

This suggests that in the multispecies stands common in Ontario, forest managers would need to assess their objectives with respect to balsam fir before applying the system. If fir were to become a commercially sought-after species,

the approach could be a very useful one. If fir is significantly less common than spruce, the approach would be viable even when fir is not a commercially valuable species. However, if the demand for fir remains low, and the species is present in significant amounts in the understory, the approach becomes less valuable in the absence of some strategy to control fir growth following the first (hardwood) harvest.

Although multispecies stands are common in Ontario, many do not have a continuous softwood understory and aspen overstory. Nevertheless, the principles of the two-pass system (careful removal of the overstory to facilitate a sooner-than-normal return for the next harvest) are still relevant for such stands. Furthermore, should other alternative systems, such as shelterwood harvesting (Section 5), be successful in promoting white spruce regeneration under aspen overstories, then the two-pass system could provide a viable subsequent management approach.

One obvious impetus for considering the utility of two-pass harvesting is that the greater total harvest and reduced crop rotation times provide significant economic rewards. Maintaining a flow of both hardwoods and softwoods from the same land base also has the potential to add stability to the forest industry.

Another significant argument for the application of a two-pass system is its compatibility with integrated resource management objectives. After the first harvest, the remaining forest has much more vegetation structure than it would following clear-cutting. This provides more wildlife habitat, better aesthetics, and more recreational utility.

Recent trials of two-pass harvesting have been documented by Brace Forest Services (1992) and Sauder (1992). From 1988 to 1990, various techniques were tested at three study areas in central Alberta to examine the level of understory protection that could be provided during the first-harvest phase of a two-pass system. The techniques included preharvest planning, designated skid trails, rub stumps beside skid trails, topping and delimbing stems prior to skidding, and the use of on-site supervision. The study also compared the effectiveness of conventional feller-bunchers and grapple skidders with that of Scandinavian single- and double-grip harvesters (cut-to-length [CTL] systems) and wheeled forwarders.

The results indicate that it is possible to protect a high proportion of understory trees from damage. When conventional harvesting practices and equipment are used, the understory vegetation is generally completely destroyed. Across all study locations, it was found that the proportion of understory stems injured and destroyed decreased from 82–91 percent with conventional equipment and practices

to 35–47 percent when highly protective measures were applied. The supposedly less intrusive Scandinavian equipment did not improve the level of understory protection (Sauder 1992). The CTL systems injured significantly more understory (51–52 percent), but destroyed slightly fewer understory stems (17–18 percent) compared to conventional equipment (which injured 14–30 percent and destroyed 13–25 percent when comparable levels of protection were attempted).

Understory stems were damaged by the Scandinavian equipment primarily because it was not used to perform directional felling. Felled stems pulled toward the carrier during the cut-to-length process also damaged understory trees.

Jewiss (1992) described many benefits of using CTL harvesters similar to those used in the studies described by Sauder (1992). These included advance growth protection, reduced site disturbance, increased ability to harvest from reserves, and the ability to leave biomass (and seed source) at the stump. Although there is some discrepancy between Jewiss' (1992) implication that CTL systems are better suited for advanced growth protection and the findings of Sauder (1992), it seems clear that, while there are many benefits of CTL systems, their use is not absolutely necessary to carry out effective two-pass harvesting.

Sauder's (1992) results are similar to those of Froning (1980), who was among the first to examine the effects of careful harvesting practices on understory spruce in mixedwoods. Working in central Saskatchewan, he found that 56 percent of white spruce were damaged in a 60-ha study area where logging was conducted without special practices. In nearby trial areas where understory protection was integrated into the harvesting and skidding operations, only 12 percent damage and 7 percent destruction of white spruce occurred. Practices used to afford protection included conducting surveys prior to logging, laying out skid trails so as to avoid spruce concentrations, bunching logs in the direction of felling, leaving guard trees and high stumps to prevent skidding damage, and providing on-site supervision during logging.

4.3.3 Operational Considerations

Windthrow

As with virtually all alternative harvesting systems, windthrow is a potential concern in two-pass harvesting. Removal of hardwoods from a mixedwood stand may leave the remaining spruce trees more exposed, and therefore more susceptible to windthrow (Froning 1980, Brace Forest Services 1992). Using preliminary data from the same study sites as Sauder (1992), Brace Forest Services (1992) found that blowdown affected 5 percent of the residual white spruce, and that it increased with height, reaching 24 percent in the 14- to 15-m class.

One would anticipate that the risk of windthrow for the remaining understory trees is partly dependent upon the initial relative stocking of species within the stand. Softwoods in a stand with a greater initial hardwood stocking would likely be more susceptible to windthrow after the hardwood was harvested. Froning (1980) suggests that leaving some hardwood trees on the logged area would provide a certain amount of protection for such spruce trees and therefore reduce wind damage. Obviously the trade-off between unharvested hardwood trees and softwood trees saved from blowdown would need to be considered.

Regeneration following the first cut

After the mature hardwoods are removed from a mixedwood stand, two outcomes are likely: softwoods respond by increasing their growth rate, and hardwood regeneration occurs. In a two-pass harvesting situation, the aspen growth response would likely not be as vigorous as it would be after a conventional clear-cut. Reduced light intensity (compared to a clear-cut) and lower soil temperatures would occur because of the shading provided by the remaining softwood trees. Shading would also result from the slash left on site, especially if a CTL system was used. Baker (1925) *reported in* (Navratil et al. 1991), found that a residual canopy allowing 50 percent sunlight reduced suckering density by an order of magnitude from 98 000 to 7 400 stems/ha. Perala (1977) reported that as little as 1–1.5 m^2/ha of basal area of residuals may slow sucker growth by 40 percent.

If some residual hardwoods are left to protect softwoods from windthrow, the maintenance of apical dominance in these trees would also reduce suckering. Further, the reduced site disturbance resulting from attempts to preserve young spruce trees would stimulate aspen suckering less than the site disturbance normally associated with clear-cutting.

If the softwood stocking provided by unharvested trees is not at desired levels after the first cut, conditions should be reasonably well-suited for their natural or artificial establishment. Supplementary planting could be an option for increasing the softwood stocking of harvested stands. While silvicultural practices such as intensive site preparation would not be appropriate, competition between hardwoods and young softwoods might be less severe because of less favorable growing conditions for the hardwoods.

Timing of the cuts

Most of the attention in discussions of the two-pass system has focused on the preservation of advance regeneration during the first cut. Assuming that this is successful, forest managers must determine when to return for the second harvest. This decision will be based on stand volume, and on planning and operational concerns such as the relative availability of wood in the area, the age distribution across the entire forest, etc. However, for simplicity's sake, these concerns can be implicitly addressed by discussing the relative ages of the hardwood and softwood components of the forest.

In Ontario's boreal forest, the rotation age of aspen is about 30–40 years less than that of spruce. Ideally, therefore, the first harvest should take place about 40 years before most of the spruce in the stand reaches maturity. Jewiss (1992) anticipated this when he suggested that the second cut take place when hardwoods reached 40 years of age. The timing of the second cut, therefore, is determined by desired rotation for the softwood component in the stand. Although the hardwoods might not be at a prime harvest age, a reasonable return should be achieved.

In stands with an abundance of balsam fir in the understory, and assuming that fir is to be managed as a commercially valuable species, the second harvest might need to occur earlier so as to allow for the shorter biological rotation of fir compared to spruce. (If fir continues to have low commercial value, such stands may not be appropriate for management under a two-pass system.)

As many mixedwood forests in Ontario do not have a distinct two-storied structure, circumstances may be such that the relative ages of hardwood and softwood components do not lend themselves to a "correct", or obvious, harvesting strategy (Beck et al. 1989). Nonetheless, it may be best to attempt to schedule the final harvest so that a clear-cut occurs. In doing so, the postcut silvicultural options are maximized, thereby avoiding having to deal with the a situation in which only the softwoods are removed from a stand. Assuming that a new mixedwood forest will be fostered on the site, the stage is well set for repeating the two-pass operation (i.e., hardwoods will establish fastest and again be ready for harvest before the softwoods).

Other considerations

For understory trees, skidding is one of the most destructive stages in the harvesting operation (Johnson et al. 1971, Froning 1980, Sauder 1992). Nondragging extraction (e.g., forwarders for cut-to-length logs) can avoid some of the damage caused by skidding. In addition, a number of techniques are available that can reduce the impacts of a two-pass harvesting operation. These include:

- skidding many loads along routes already traveled;

- removing the tops of trees prior to skidding;

- bunching felled trees in the direction of skidding; and

- leaving rub-posts or standing trees to deflect skidded material around curves or turning points (Froning 1980, Brace Forest Services 1992, Sauder 1992, Peterson and Peterson 1992).

Sauder (1992) found that on-site supervision is very important in ensuring the successful application of understory protection measures. Although this is undoubtedly true, it may pose a significant impediment to routine use of the system if on-site supervision were constantly necessary. As with any new practice, however, close supervision is necessary during initial implementation or until operators become familiar with procedures and goals.

The economics of two-pass harvesting are relatively complex. Costs are somewhat higher during the first harvest operation, but are likely to be offset by long-term savings associated with increased yields per unit area. Sauder (1992) calculated costs associated with each stage of operations in both control (i.e., normal operations) and first pass harvest blocks for different levels of understory protection. Costs for an intermediate level of protection ranged from approximately 94–118 percent of that for no protection, while those for a high level of protection were increased by 124–169 percent. The additional costs were associated with:

- extra time required to organize equipment prior to harvesting;

- greater need for supervision during harvest operations;

- extra effort required to manually delimb and, in some circumstances, to top stems prior to skidding;

- increased time for felling and bunching as a result of traveling time to new areas and harvest blocks; and

- increased skidding distance to pick up and back loads to roadside (it was found that this cost could be reduced by using designated skid trails).

In discussing the benefits of a Scandinavian CTL system similar to that used by Brace Forest Services (1992), Jewiss (1992) noted that regeneration costs were considerably lower than with conventional harvesting. This saving obviously applies to two-pass harvesting no matter what machinery is used, but can vary considerably depending on whether the natural reproduction needs to be augmented through artificial means.

Obviously, the extra revenue associated with the greater volumes available for harvest during a second pass is a key economic consideration. In such circumstances, where significant economic rewards are reaped decades after the initial costs are incurred, the real economics are

complicated. Forestry companies cannot be certain that they will still have tenure or harvesting rights to reap the delayed reward. Furthermore, during difficult economic times, it is easy to sacrifice long-term return to short-term considerations.

Advantages and disadvantages of two-pass harvesting

Advantages include the following:

- Making use of advanced growth eliminates the need for planting and site preparation following the first pass.
- Release of advanced growth in the understory can greatly improve gross timber yields compared to clear-cutting.
- Harvesting equipment operators have clear objectives because a particular species and canopy stratum are harvested while the other is protected.
- Techniques to protect advanced growth are fairly well developed in Ontario's spruce forests and central Canada's mixedwoods. New logging technologies (eg., CTL systems) may facilitate application of these techniques in Ontario's boreal mixedwoods.
- Advanced growth is well adapted to the site and will have natural rooting habits (Section 3.3.2).
- Advanced growth provides continuous cover on a site and may be more environmentally acceptable than clear-cutting.
- Provision is made for biological legacies (Section 2.4.1).
- Small mammal habitat and moose browse remain intact (Section 7.4).

Disadvantages include the following:

- Harvest costs for the first cut are higher than for conventional clear-cutting.
- A skilled labor force must be developed to implement the system. Developing this skill will be costly at first, but might lead to greater productivity and savings in the long term.
- The understory in Ontario's boreal mixedwoods is often dominated by balsam fir. Release of this understory may lead to the development of forests with a substantially increased fir component, thereby increasing susceptibility to severe budworm attack and creating a fire hazard over the long run (Section 2.4.2).
- Regeneration following the second cut may involve expensive silviculture inputs.
- Control of regenerating species composition and tree density may be difficult.

5.0 SHELTERWOOD SYSTEM

5.1 Definition and History

In the shelterwood system, the stand is removed in a series of cuts made at reasonably short intervals. A key feature is the establishment of essentially even-aged reproduction under the protection of the partial forest canopy or "shelterwood". (Smith 1986, Forestry Canada 1992). The shelterwood system is especially appropriate when protection is needed for the new regeneration, or where the shelterwood provides the regeneration with an advantage over undesired competing vegetation (Burns 1983).

The shelterwood system was first developed in the early 1800s to regenerate beech (*Fagus* spp.) and oak (*Quercus* spp.) stands in northern Germany (Hannah 1988). Conceptually, it involves three cutting stages (Smith 1986). First, a preparatory cut is made to set the stage for regeneration by improving the vigor of potential seed-bearing trees, and to prepare the forest floor as a seed bed. Next, a seed (or establishment) cut is made, ideally before or during seed dispersal, to open up the stand and to allow for the establishment of regeneration. This cut may also be accompanied by site preparation to create appropriate seedbed conditions (Hannah 1988). Finally, one or more removal cuts are made, the last of which is referred to as the final cut. These cuts remove the remaining overstory, and occur only when the new regeneration is established and dominates the site.

While the shelterwood system may involve three or more stand entries, for economic reasons it generally involves only two in North America. Trees remaining after the initial cut are generally the most vigorous of the desired species, and provide the best trees for a seed source and for additional volume growth before the final cut (Blum et al. 1981, Brace et al. 1990).

There are a number of variations to the spatial and temporal arrangement of cuts in the shelterwood system; these are generally categorized as uniform, strip, group, and irregular (Smith 1986, Matthews 1989):

5.1.1 Uniform Shelterwood

With this system the forest canopy is opened uniformly over the entire stand. From the literature reviewed, it appears that the predominant shelterwood system used in North America is a two-stage uniform one. Here the preparatory and establishment cuts are combined into a single cut, which is subsequently followed by a single removal (or final) cut a few years later.

5.1.2 Strip Shelterwood

Here, the three cutting stages (preparatory, seed, and removal) are moved progressively across the stand in

strips (Smith 1986). Beginning on one side of the stand, a seed cutting is made on the first strip. After a few years, a removal cut is made on this first strip and a seed cut is made on the next, adjacent strip. This process is continued strip by strip across the stand until the entire stand is harvested. The strip shelterwood method requires repeated entries into the stand and careful planning, but can have certain advantages over the uniform shelterwood method (Smith 1986), viz:

- walls of standing trees can be used to provide predictable belts of side shade;

- if progressive strips are cut into and at a right angle to the prevailing winds, the risk of windthrow in residual trees can be reduced; and

- felled timber from each cut can be extracted through the uncut stand rather than through the regenerated strips.

5.1.3 Group Shelterwood

With this system the cuts occur in a pattern of expanding groups or patches (Smith 1986). These are generally arranged to correspond to existing patches of advance regeneration, with all of the groups eventually coalescing to cover the entire stand. The major advantage of the system is that it makes use of patches of advanced growth to start the regeneration process. It is difficult to manage, however, because of the numerous scattered and small centers of regeneration (Matthews 1989).

5.1.4 Irregular Shelterwood

The regeneration period for this system is extended beyond that of a traditional shelterwood, thereby resulting in a new stand that is less even-aged (Smith 1986). This method differs from the other shelterwood variations in that the resulting forest canopy is irregular with respect to its tree heights. An important feature is the continuous improvement of the growing stock through thinning and tending (Matthews 1989). The technique can be applied in a uniform, strip, or group pattern. As different species seldom reach maturity at the same stages of stand development, the irregular shelterwood method provides the flexibility to manage for several species at once, and is often associated with the maintenance of a mixture of species (Smith 1986). Like the group shelterwood method, however, it can be difficult to manage.

The shelterwood system has been used in the United States and Canada since 1900 to regenerate a wide variety of species. In the northeastern United States it has been used for several conifer species, including red spruce (*Picea rubens* Sarg.), white spruce, balsam fir, white pine, jack pine, and red pine (*Pinus resinosa* Ait.). It has also been used for hardwoods, including oak, American beech

(*Fagus grandifolia* Ehrh.), yellow birch, and sugar maple (*Acer saccharum* L.) (Hannah 1988). In Ontario, shelterwood cutting has been used with tolerant hardwoods, particularly sugar maple, white ash (*Fraxinus americana* L.), and red oak (*Quercus rubra* L.) (Anderson et al. 1990).

In Canada, the uniform shelterwood method has been tried in boreal mixedwood forest types. This is generally the simplest form of shelterwood cutting, particularly when it is undertaken with only two cuts (i.e., the two-stage uniform shelterwood). Considerable research was conducted in the 1950s and 1960s on the use of a this system for regenerating white spruce in the mixedwood white spruce–trembling aspen forests of the prairie provinces (Lees 1963, Jarvis et al. 1966, Brace et al. 1990). The two-stage uniform shelterwood method has also been used in the Maritime provinces to harvest and regenerate spruce–fir stands (Baldwin 1977, Hannah 1988).

No published accounts of shelterwood cutting in Ontario's boreal mixedwoods were found. Consequently, the remainder of this section focuses upon experiences with shelterwood systems in other parts of North America, under stand and site conditions similar to those found in Ontario's boreal mixedwoods. Much of this experience indicates that there are no universal rules and prescriptions for applying a shelterwood system: most authors have simply presented their findings, outlined management objectives for the particulr tree species and site conditions, and suggested that only through trial and error can one really determine if and how a shelterwood system should be applied in other situations.

5.2   Basis for Application

The shelterwood system is generally recommended for regenerating relatively shade-tolerant species, particularly when shelter is needed to give the new regeneration an advantage over undesired competing vegetation (Burns 1983, Brace et al. 1990). Because the seed source is retained on the site until the new stand is established, the shelterwood system is also recommended in situations where a seed source must remain for several years in order to ensure adequate natural regeneration (Smith 1986). The shelterwood system can often be used in mixed stands to change the species composition by removing unwanted trees during the seed cut (Burns 1983).

Burns (1983) suggests that the system is unsuitable when there are significant insect or disease problems (e.g., eastern spruce budworm), as these can be passed from the overstory to the new regeneration. It is also not recommended for species and sites that are prone to windthrow, because the residual overstory trees can be subject to damage after the initial seed cut.

The shelterwood system has been recommended for even-aged management of spruce–fir stands in the northeastern United States, where balsam fir will often dominate the conifer regeneration unless special efforts are taken to promote spruce (Hannah 1988). Spruce regeneration can be encouraged by leaving a high proportion of spruce seed trees after the seed cut. The shelterwood system is particularly recommended for spruce–fir stands where the stand is close to maturity and does not have sufficient seedlings in the understory to establish a new stand (Blum et al. 1981), and where soils are deep enough and sites protected enough to prevent windthrow (Burns 1983, Gibbs 1983).

In comparing the relative value of different silvicultural systems for managing white spruce–aspen stands in the mixedwood section of the boreal forest in Alberta, Jarvis et al. (1966) suggested that the "uniform two-stage shelterwood cutting system shows [the] most promise". Youngblood (1991) compared the growth of residual trees in a mature stand of white spruce (with some scattered white birch, balsam poplar, and trembling aspen) in interior Alaska to the growth in a similar uncut stand. He found a 27 percent increase in basal area of the residual trees over the 14 years following the initial cut. This compared with a 16.5 percent increase in the uncut stand. He recommends that for shallow-rooted species vulnerable to wind damage, such as white spruce, thinning a stand prior to the first shelterwood cut can help to develop windfirmness.

The shelterwood system is generally not recommended for regenerating upland black spruce (Jarvis and Cayford 1961, Burns 1983). Since the survival and growth of black spruce seedlings is better in the open than under a canopy, the residual overstory of the shelterwood system generally leads to poorer development of black spruce seedlings (Burns 1983). The difficulties of preparing suitable seed-beds have also been noted (Jarvis and Cayford 1961, Kolabinsky 1991). Older black spruce trees are generally quite susceptible to windthrow, and residual trees left after the shelterwood seed cut are often broken or uprooted by wind. The shelterwood system can be used, however, in small, windfirm stands in which clear-cutting is undesirable for other reasons.

While choice of cutting method (including shelterwood) had little effect upon the success of upland black spruce regeneration in Manitoba's mixedwood section of the boreal forest (Jarvis and Cayford 1961), uniform and group shelterwood systems were successful in regenerating black spruce only on spruce lowland and midslope stands (Losee 1961, 1966) in Abitibi's woodland laboratory (Breckenridge 1955). Many of these shelterwood cuts suffered from blowdown, and little harvesting of the residual overstory has occurred because of a lack of

management continuity and commitment at the site. Most upland sites have since developed balsam fir understories (Prairie 1994)

Traditionally, the shelterwood system has not been recommended or used for regenerating aspen because of its intolerance of shade and physiological requirements for suckering (Ohmann et al. 1978, Burns 1983). Shading by the residual overstory of the shelterwood system reduces the number of stems and is detrimental to sucker growth; as little as 1–1.5 m^2/ha of basal area of residuals may slow sucker growth by 40 percent (Perala 1977). However, this reduced vigor of aspen suckers could be beneficial in promoting the growth of desirable conifer regeneration in a mixedwood stand. If the seed cut leaves a residual overstory with both aspen and conifer trees, aspen suckering may present less competition to the softwood regeneration.

Notwithstanding the above, Ruark (1990) has suggested that the clear-cut management approach traditionally used for regenerating aspen often produces dramatically overstocked stands. This leads to a large proportion of the aboveground biomass production being added to unmerchantable stems, and displaces nutrient capital from potential crop trees. As an alternative for managing aspen stands in the north central United States, he offers an as yet untested approach refered to as "reserve shelterwood". With this system, some aspen trees are left uncut to suppress the initial suckering, thereby directing a higher amount of production onto potential crop trees at an early age.

The shelterwood system is recommended for regenerating white birch in areas where summer precipitation is limiting in either amount or frequency, and where aspen reproduction might dominate large clear-cuts (Burns 1983, Perala 1989). White birch seedlings can prosper in 50 percent sun and can endure as much as 90 percent shade for a few years, although they will not become established under dense forest canopies (Perala and Alm 1989). In Minnesota and Wisconsin, where white birch has difficulty regenerating because of the aggressive root suckering of aspens and frequent summer droughts, the shelterwood system is gaining popularity (Perala and Alm 1989).

According to Hannah (1988), the shelterwood system has not been widely used in many parts of North America primarily for economic reasons, as the harvest costs are generally greater than those for traditional clear-cutting. Hannah (1988) suggests, however, that the cost of shelterwood harvesting is probably not vastly different from that of selection cutting. The major economic considerations associated with shelterwood harvesting include (Day 1970, Smith 1986, Hannah 1988):

- harvesting may be more costly than clear-cutting because of the lower per hectare removals at each cut, and the additional expenses for marking, felling, and extracting the timber;

- as the best trees are generally left as residuals, the quality of harvest from early cuts may be poorer, thus having less value;

- residual trees can have a rapid increase in growth after the initial seed cut, and thus are able to increase in value before being harvested; and

- as all regeneration is natural, there are no costs for planting or seeding.

To conclude, the shelterwood system may be most appropriately used in Ontario's boreal mixedwoods to help regenerate white spruce, and possibly white birch, in areas where balsam fir and aspen would otherwise dominate. Leaving a high proportion of white spruce or white birch in the shelterwood overstory after the seed cut, with a few scattered aspen (to suppress sucker growth), may encourage the regeneration of these species. Mature to overmature stands, with moderate to low stocking and emergent white spruce/black spruce, are likely good candidates for shelterwood treatment because the trees have enough crown and taper to remain windfirm. Fully stocked stands will be spindly and more prone to windthrow unless preparatory cuts are made while the stands are quite young and "short". A major issue in boreal mixedwoods, however, will be how to prevent balsam fir from dominating a site, particularly after the final shelterwood cut opens the canopy.

5.3 Operational Considerations

Factors that must be considered when using the shelterwood system include the following:

- the arrangement of the cuts (i.e., uniform, strip, group, irregular);

- the number of cuts (i.e., entires into the stand);

- the timing of cuts;

- the number and type of trees removed in each cut; and

- site preparation requirements.

5.3.1 Cutting Patterns

The timing of the initial cut should generally occur before a stand has reached maturity, so that the residual trees are able to continue to grow rapidly without danger of windthrow and decay (Blum et al. 1981). The trees removed in the initial cut should be the least desirable trees in the stand, particularly those that are unhealthy or misshapen, or those likely to incur windthrow damage (Day 1970). If the objective is to encourage the regeneration of one or more specific species, such as white spruce or white birch,

then trees of any undesirable species (balsam fir and/or aspen) should also be removed (Smith 1986). The residual trees should be vigorous and able to withstand a more open site, so that they can have a rapid growth response before the final cut (Godman and Tubbs 1973).

The number of trees removed in the initial cut is generally determined by observation and experimentation, and will vary for different species and sites (Smith 1986). The residual canopy should provide a reasonable trade-off between controlling unwanted vegetation and providing enough light for seedling establishment (Godman and Tubbs 1973). A number of measures can be used to guide the removal of trees in the initial cut; however, the best index is considered to be the percent of residual crown cover (Godman and Tubbs 1973, Anderson et al. 1990). Since this is generally difficult to measure, basal area, or sometimes even volume/hectare, is more commonly used (Smith 1986).

The final cut should occur as soon as the seedlings have established deep root systems, are able to withstand exposure to complete sunlight, and dominate the unwanted vegetation (Godman and Tubbs 1977). If there is no delay in the development of the new regeneration, this usually occurs within 3 to 10 years of the initial cut (Smith 1986). The final cut will often cause injury to the new stand, and should occur while the seedlings are still flexible (Smith 1986). Winter logging, where snow covers the new seedlings, can also help to protect the new stand (Godman and Tubbs 1977).

A study of the effect of a two-stage uniform shelterwood system on spruce and balsam fir regeneration was undertaken in northwestern New Brunswick between 1959 and 1974 (Baldwin 1977). The 50-year-old forest had an initial basal area of 17 m^2/ha with a composition of 53 percent spruce (white, red, and black), 30 percent balsam fir, and 17 percent hardwood (primarily aspen and birch). The study compared two forms of shelterwood cutting to a control. The three treatments involved removing 40 percent, 20 percent, and 0 percent (control) of the basal area in spruce and fir (with a diameter at breast height [dbh] of 12 cm or greater) in the initial cut. Ten years later, the remaining softwood overstory was harvested on all treatments (including control). The results showed that:

- Five years after the final cut, the density (stems/ha) of hardwoods in the shelterwood treatments was much lower than in the control; the proportion of hardwood to softwood stems was 51 percent for the control, 44 percent for the 40 percent shelterwood, and 36 percent for the 20 percent shelterwood.

- The shelterwood treatments contained a much higher number of spruce seedlings than did the clear-cutting treatment; stocking and density of spruce 5 years

after the final harvest was highest for the 40 percent shelterwood treatment (2 247 stems/ha) compared to 1 210 stems/ha for the 20 percent shelterwood, and 444 stems/ha for the clear-cut; and

- The final cut in the shelterwood system can be accomplished without significant seedling mortality as soon as the softwood seedlings average 30 cm or more in height.

In Nova Scotia, the Scott Paper Company has used the three-stage shelterwood system in mature red spruce (*Picea rubens* Sarg.)–balsam fir stands. Here 20–30 percent of the volume is removed in the first cut, and up to 60 percent of the volume is removed 4 years later. Two-stage shelterwoods have also been used, about 30 percent of the stand volume being removed in the first cut, with the final cut 5 to 10 years later. The final cut is made when the spruce and fir seedlings are 13–25 cm high, preferably after a good seed year (Hannah 1988).

Several studies were undertaken in the 1960s and 1970s to examine the effects of shelterwood harvesting on white spruce regeneration in the mixedwood section of Alberta's boreal forest. Jarvis et al. (1966) suggest that the initial cut must be made before the stand reaches maturity in order for the stand to show an increase in timber yield at the final harvest. Mature white spruce stands are subject to higher residual mortality after a partial cut due to windthrow, sunscald, and top break. The first cut should be made when the stand is about 70 to 80 years of age, and should leave about 9 to 14 m^2/ha basal area of white spruce. Lees (1963, 1970), in studies of white spruce regeneration in the same area, examined two-stage uniform shelterwood cutting in 110-year-old spruce–aspen stands, leaving varying levels of residual stand densities after the initial cut. The treatments compared included: no logging (144 m^3/ha white spruce), heavy residual (111 m^3/ha white spruce retained), medium residual (100 m^3/ha white spruce retained), and light residual (86 m^3/ha white spruce retained). In all cases, only white spruce was harvested; all the hardwoods were left behind. Spruce regeneration was not significantly affected by residual stand density, while spruce in the residual overstory exhibited good growth rates. Based on these findings, Lees recommended that shelterwood cutting, removing up to 70 percent (by volume) of spruce in the initial cut, could be used for regenerating white spruce in Alberta's boreal mixedwoods.

Burns (1983) suggested that in the spruce–fir forests of the northeastern United States the final cut may have to be delayed 10–15 years to allow the regeneration to develop sufficiently. He recommended removing less than one-third of the basal area prior to the final cut on sites known to have a windthrow problem. Blum (1973), in a study of a spruce–fir forest in Maine, examined the regeneration

and establishment of seedlings following a two-pass uniform shelterwood harvest. Here the initial cut removed 34 percent of the original basal area; the final cut occurred 10 years later. Johnson (1951) suggested that the time between the initial and final cuts in spruce–fir forests should generally be from 10–25 years.

Perala (1989) examined the regeneration of white birch following a shelterwood cutting of a mature aspen and white birch stand (60 years old) in Minnesota. With white birch, the main value of the shelterwood canopy is in providing abundant seed; the residual overstory should be light, thereby conserving soil moisture by shading without hindering seedling development. Perala and Alm (1989) recommend removing 60–80 percent of the crown cover in the initial cut. Perala (1989) further suggests that the residual overstory should be removed after only 2 years so as to minimize deterioration of the residual birch and the development of shade-tolerant species.

Despite the absence of published reports of shelterwood harvesting in Ontario's boreal mixedwoods, research from other parts of North America suggests that the technique might be used successfully to achieve white spruce and white birch regeneration. If the management objective is to promote regeneration of white spruce relative to aspen and balsam fir, then a two-pass uniform shelterwood system might remove 40–70 percent of the basal area in the initial cut. The residual overstory should contain a high proportion of spruce, and the final cut would occur 10–15 years later. To encourage regeneration of white birch, however, the initial cut should be heavier (60–80 percent), thereby allowing more light to reach the birch seedlings; the final cut should occur sooner than for white spruce so as to minimize the development of shade-tolerant species.

5.3.2 Site Preparation and Tending

Existing literature provides little guidance on the specific nature of site preparation that should accompany shelterwood harvesting in boreal mixedwoods, except to say that the requirements vary for different species and sites. Scarification can be used to prepare the seedbed, and some form of vegetation control, such as cutting, burning, or herbicides, can also be used to control undesired competing vegetation (Hannah 1988).

Jarvis et al. (1966) concluded that the use of a shelterwood system for regenerating white spruce in spruce–aspen mixedwood stands is not sufficient in itself to ensure that the spruce will continue to regenerate adequately. Without site preparation, the white spruce is likely to disappear after several successive cuts. Lees (1963, 1970), in similar studies, concluded that only scarified seedbeds with mineral soil exposure would encourage satisfactory white spruce establishment and regeneration. He also found that

spruce regeneration in a two-stage shelterwood cut could be improved significantly using scarification (85 percent stocking compared with 30 percent stocking on unscarified ground, based on 900-milacre plots).

Some form of site preparation to control balsam fir and other vegetation, while at the same time providing a receptive seedbed, appears to be essential to encourage white spruce regeneration under the shelterwood system. Small bulldozers (D-4 size) can be used to effectively prepare the ground beneath white pine shelterwood. Underburning beneath the thick-barked white pine residual overstory also shows promise. The higher density of thin-barked stems in the smaller trees of boreal mixedwood, coupled with shallow rooting, may make these techniques impractical in such areas. Instead, small excavators may work well by reaching into areas of the shelterwood from skid trails to create seedbeds, uproot balsam fir, and perhaps create soil mounds of mineral soil.

Tending in shelterwood systems will necessitate ground application of chemicals, motor-manual cleaning, or aerial application of granular formulations of herbicides (e.g., pronone) to penetrate the overstory. The vast majority of tending under clear-cutting systems uses aerial application of glyphosate 3–5 years after plantation establishment. Both tending schedules and treatment techniques will require significant modification to match shelterwood conditions (although less tending of softwoods may be necessary in shelterwood situations as the residual canopy will inhibit aspen suckering).

For white birch, Perala (1989) suggests that successful regeneration under a shelterwood system requires scarification both to control competing vegetation and to provide a suitable seedbed. According to Perala and Alm (1989), a strip shelterwood, which is disced within 2 years after a good seed crop, may be as good as or better than a uniform shelterwood. The discing incorporates organic matter, controls competing vegetation, and drills the seed to its optimum depth.

Advantages and disadvantages of shelterwood systems

Advantages include the following:

- Planting costs may be eliminated.
- Shading by residual trees may encourage conifers and discourage intolerant hardwoods, thereby reducing dependency upon herbicides.
- Residual trees may gain in size and value before the final harvest.
- Damage during the final harvest of residual trees may "thin" dense pockets of regeneration.

- Seed crop periodicity is somewhat less of a concern compared to seed-tree systems (Section 4.2.3).
- Provision is made for biological legacies (Sections 2.4.1, 3.3.2).
- Site-adapted seed is assured (Sections. 2.4.1, 3.3.2).
- Seedlings from seed have well-developed root systems, and hardwoods from seed are thought to live longer than hardwoods from root suckers (Section 3.3.2).
- Forest cover, and all its amenities, is maintained on a site longer than with clear-cutting (Section 7.4.1).
- The system is more environmentally acceptable than clear-cutting.
- Provision is made for early winter moose habitat.

Disadvantages include the following:

- Harvest and access maintenance costs are increased.
- Specialized harvest equipment and training are required. (However, it is possible that a well-trained work force may become productive and, through pride in their role in forest management, develop safe work environments.)
- Harvest of residual trees may damage established regeneration.
- There is no opportunity for aerial tending.
- Risks of windthrow and residual tree damage are very high if older stands are scheduled for treatment.
- Modification of technique, as well as increased site preparation and tending costs, may be required if balsam fir is not desired in the new forest.
- Control of regenerating species composition and tree density may be difficult.

6.0   SELECTION SYSTEM

6.1   Definition and History

The selection method involves frequent and careful felling of trees in all size classes, either singly or in small groups or strips (Forestry Canada 1992). While the resulting stand structure can be considered a mosaic of small even-aged stands, taken as a whole it is essentially an uneven-aged stand.

Visually, true selection forests take on a "wall of green" effect in summer, making it almost impossible to discern the distinct strata. This results from the recruitment of natural regeneration into a continuous series of size classes. In this way, a single stand provides a continuous and sustainable timber yield, where mortality and harvesting are balanced by new growth and recruitment.

The wall of green effect distinguishes the selection system from other systems, such as two-pass harvesting, which maintain stratified mixtures of tree species. Other systems may also involve individual or group tree selection, but the resulting forest structure is different. Place (1953) noted that the care taken to maintain both horizontal and vertical stand structure sets the selection system apart from selective cutting (i.e., economic selection, diameter limit cutting, partial cutting, high-grading). The selection system also differs from all others in that felling and regeneration are not confined to specific areas within a stand or forest (Matthews 1989).

In the mid-1800s, Swiss foresters began using "more natural methods" than the dominant German even-aged forestry model. By the early 1900s, the basis for the selection system was firmly established. Controlling stand structure through tree selection and marking, based on an understanding of stand growth (de Liocourt 1898 *as cited in* Oliver and Larson 1991, and others), was central to the development of the system.

The selection system has become a fairly common practice in central Ontario's tolerant hardwoods (Anderson et al. 1990), drawing upon more than 40 years of experience with selection harvesting in the forests of the northeastern United States. Although documentation is fragmented, selection systems have been tried in every major North American forest type except for boreal mixedwood and boreal pine forests. In Ontario, this can be explained by the predominantly even-aged forest structure, poor road access prior to the 1980s, and the dominant pulpwood end use. At first glance, there appears to be relatively little basis for applying selection systems to boreal mixedwoods.

6.2 Basis for Application

Selection systems are suitable when forest cover must be maintained over long periods of time for environmental reasons, *viz*:

- to protect water quality by maintaining riparian forest cover;
- to protect scenic values and maintain old-growth stands;
- to protect sensitive forest soils from erosion or loss of nutrients;
- to maintain wildlife corridors; and
- to maintain wind breaks.

Areas currently bypassed to protect riparian zones, aesthetic features, or wildlife values are candidates for use of the selection system in the boreal forest. The relationships between silvicultural systems that prolong or maintain forest cover and environmental quality is examined in greater detail in Section 7. The selection system might also be used in commercial forest areas to:

- create and maintain stand structure and species diversity for economic, forest productivity, wildlife, and genetic conservation reasons;
- slowly shift species composition to favor one species or group over another;
- provide a sustained and continuous flow of timber from relatively small woodlots;
- develop growing stock capital that produces a few large trees of considerable value in every cutting cycle (10–20 years); and
- develop growing stock that is capable of responding quickly to shifting timber markets and makes maximum use of the growth potential of a site.

An intriguing element of the selection system is the large inventory of growing stock that is maintained compared to even-aged management systems. This growing stock inventory might provide for a superior ability to react to shifts in market demand.

Selection methods might also help cope with age/size class distribution problems in Ontario's boreal forest. For example, many forests in northwestern Ontario have large areas of old conifer stands that are steadily declining in volume and commercial value, while there is a shortage of middle-aged types. As production capacity grows to match the accelerated harvest of mature and overmature forests, potential shortfalls can arise when the middle-aged stands grow to be of harvestable size. One current strategy is to accelerate diameter growth by juvenile spacing so that younger stands become commercially mature when the anticipated shortfalls occur. But what if overmature stands were managed under the selection system? As initial harvests focus upon the larger stems prone to decay, openings would be created, thereby allowing smaller stems to grow to harvestable dimensions. Spruce growing in the understory may be released by this type of operation. In this way, the older stands would be made to last longer rather than relying only upon efforts to speed up the development of younger stands.

By implementing the appropriate selection cutting strategy, high value large diameter trees can be produced in the boreal forests of Ontario. Although pulpwood markets currently dominate, valuable white birch and poplar veneers are found in mixedwoods throughout northern Ontario and are commercially exploited. Despite this, there are no current management strategies to grow intolerant hardwood veneer. Selection methods could be employed in strategically located stands to provide long-term supplies of veneer-grade hardwood from boreal mixedwood forests. Silviculture systems other than the selection

system can also produce large-diameter wood, but which system is most cost-effective? Proponents of the selection system argue that the large inventory of growing stock associated with this system provides a more economic supply of large wood than does clear-cutting (Place 1953).

Furthermore, since forests comprised of mixtures of species and tree sizes can best exploit all niches and growing space, selection management leads to greater productivity (*see* Section 2.0). Smith (1986) called this phenomenon "telescoping." For example, Kotschy (1964) reported that changing from clear-cut to selection systems doubled the allowable annual harvest volumes and raised the mean growing stock from 268 to 285 m^3/ha in an Austrian forest of 4 000 ha. Johnson (1951) reported a 30–40 percent increase in periodic diameter increment following selective cutting of spruce–fir forests in eastern Canada. Brown (1948) recommended selective cutting Douglas fir and larch stands in the western United States to capture an additional 50 percent in volume, which normally would be lost to mortality as stands self-thin with age. The 30 years of permanent sample plot data from Boise Cascade Canada's forest in northwestern Ontario show that losses to stand development due to tree mortality from self-thinning are equal to their current allowable cut (J. Kragg[4], personal communication).

However, many of the potential gains in productivity attributed to the selection system could also be achieved through careful harvest scheduling and thinnings under even-aged management based on clear-cutting systems. In Finland, Mikola (1984) found that even-aged management was 50 percent more productive in terms of mean annual increment (MAI) compared to uneven-aged management using the selection system. The results depended on the nature of the selection method used. With large diameter limits, a significant portion of the growing stock was of an age where the MAI had declined. Many trees in a selection system will be growing under the shade of neighboring trees. Shading and other elements of intertree competition may explain why selection forests have poorer MAIs.

Guldin and Baker (1988) examined yields from seven long-term studies of loblolly dominated pine stands and concluded that even-aged plantation management produced more wood than did uneven-aged management. Their empirical analysis is probably the most comprehensive and reliable in North America, and covers 36 years of management. Uneven-aged management produced higher sawlog yields. The authors concluded that maximum fiber production is probably most efficient using even-aged plantation management, but "the market flexibility, low

out-of-pocket capital investment and aesthetic advantages of the [selection] system for the nonindustrial private landowner and for certain forest industries will continue to make such uneven-aged systems a feasible alternative in the repertoire of the silviculturalist."

While the selection system has many advantages, uncertainty over patterns of regeneration, future species, and size composition (stand dynamics) as well as operational and economic uncertainty explain why it is not used in boreal mixedwoods.

6.3 Operational Considerations

6.3.1 Regulating the Cut

The idealized, irregular, uneven-aged stand in a selection forest has an inverse J-shaped curve depicting the frequency of size classes (diameter distributions) defined by the following negative exponential model:

$$Y=ke-aX$$

where Y is the number of stems per hectare, X is the stem diameter at breast height (1.3 m), k is a constant reflecting the stocking of very small seedlings, and a is a constant governing the relative frequencies of successive diameter classes (Matthews 1989). The constant e (e=2.718...) is the base of the "natural exponential function". This relationship is made linear through a logarithmic transformation.

De Liocourt (1898) first described this diameter distribution in a simplified way as follows:

$$q=(N_i-1)/N_i$$

where N_i is the number of stems in diameter class i. The value termed "q" is derived from the ratio of the stem numbers in a small size class to its next largest size class. De Liocourt's "q" is closely related to the slope of a line derived from the first equation, representing the transformed negative exponential function of diameter distribution. This line's intercept is defined by stand basal area or stem number along one axis and maximum diameter along the other axis.

This linear relationship and de Liocourt's "q" have been used as a simple means of describing stand structure objectives that guide tree marking in selection systems (Meyer 1943, 1952, 1961; Leak 1963, 1964, 1965; Moser 1976; Hann and Bare 1979; Smith 1986). These relationships are also used as a means of harvest volume control in whole forests (Smith 1986). Despite the fact that few stands occur in nature that conform to De Liocourt's model, it remains the foundation or normal reference point for selection prescriptions in North America, and is

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[4] Forester, Rainy River Forest Products, Fort Frances, Ontario.

analogous to the normal yield tables used in even-aged management (Plonski 1981).

Individual tree selection is the trademark of the selection system. Tree marking is a skilled craft, blending the art and science of forestry into one activity. The selection system is considered by some to be the highest form of silviculture because of the level of skill required to implement it (Place 1953).

The selection method involves the removal of different species and tree sizes during each cutting cycle. By setting a maximum diameter goal, establishing a cutting cycle (interval between fellings), and determining a minimum basal area or the related q value, a variety of wood production and multiple-use goals can be realized.

6.3.2 Residual Stand Damage and Windthrow

Residual tree damage from felling and skidding is a significant concern when implementing selection systems. Scrapes and broken tops of residual trees following cutting allows entry of infectious agents, which can lead to significant losses to cull in subsequent harvests. Damage to fine roots through skidding and compaction can also be a problem.

Careful planning and operating can help diminish damage to residual trees. For example, rub trees should line skid trails and be removed in the last pass. Winter cutting also reduces residual tree and site damage. The use of specialized equipment, such as cut-to-length systems, further reduces the likelihood of damage (Jewiss 1992).

Experience in eastern hardwoods has shown that as the stand develops an uneven-aged structure, small saplings that never reach harvest size usually bear the brunt of logging damage. As a result, cull becomes less of a problem over time (Lamson et al. 1985). Anderson et al. (1990) provided an excellent summary of studies on residual tree damage from selection fellings in tolerant hardwoods. It is difficult to forecast the level of cull that might be experienced in boreal mixedwoods if these forests were brought under uneven-aged management.

Windthrow of spruce trees is probably less of an issue in the selection system than with other systems because the postharvest and adjoining stands are less open to wind. However this is not to imply that the issue can be ignored altogether when planning or implementing the selection system. To manage against windthrow, spruce-rich boreal mixedwood stands should be marked for cutting beginning at a young age, the removal of tall spruce trees should be favored, and topographic features should be used for wind protection when allocating stands (Weetman and Algar 1976, Alexander 1986).

6.3.3 Regeneration

Despite careful management of tree size distribution and harvesting operations, successional changes in species composition can occur in selection forests unless additional measures are employed to assure regeneration of desirable species. In the temperate selection forests of North America, this lack of care has resulted in the dominance of hard maple (*Acer nigrum* Michx. f., *Acer saccharum*) and the exclusion of valuable oak and yellow birch trees (*Betula lutea*) (Zillgitt and Eyre 1945, Smith 1979).

Selection systems will also shift the composition of species in boreal mixedwoods. McLintock (1948) recommended selection methods to shift balsam fir to black spruce in order to improve a stand's budworm resistance. However, Croome's (1970) work suggests that without measures to eliminate fir regeneration and improve spruce regeneration, the opposite effect occurs.

The selection system could be used to increase or decrease the composition of hardwoods in a mixedwood forest. Cain (1991) found that under both selection and shelterwood systems loblolly pine had superior growth and regeneration when hardwoods were a component of the understory, as hardwoods seemed to reduce vigorous herbaceous competition. Although hardwoods also compete with pine, they respond to vegetation management treatments, such as herbicides and site preparation, more favorably than do herbs and grasses. Cain speculated that hardwoods may have an "antagonistic symbiosis" with pine by controlling herbaceous competition while at the same time competing with pine under certain conditions. Hardwood trees and shrubs in boreal mixedwoods might have the same effect upon spruce and grasses.

Selection cutting in boreal mixedwoods and North American spruce–fir types tends to regenerate tolerant firs and gradually eliminates intolerant hardwoods. Although this would decrease the requirement for herbicides to stimulate the development of spruce, increased fir composition may reduce growing space for spruce and may attract spruce budworm. Lack of midtolerant spruce regeneration has been observed as a problem in selection forests (Croome 1970, Weetman and Algar 1976, Frank and Blum 1978).

In Europe, the inconsistent regeneration of Norway spruce (*Picea abies* [L.] Karsto) under selection led to the widespread adoption of clear-cutting and planting methods (Holmgren 1942, Soderstrom 1971). The common perception is that the selection system is inappropriate for shade-intolerant species (Franklin 1978, Smith 1986, Davidson et al. 1988). Given the lack of convincing and current data for regeneration under selection management in the boreal forest, this perception is influencing present practices.

Although difficult, regenerating midtolerant and intolerant species is not impossible with the selection system. Even the intolerant loblolly pine can be grown with selection methods (Edwards 1987, Guldin and Baker 1988, Cain 1991). Group selection, rather than single tree selection, might be more effective for pine, spruce, and aspen regeneration in boreal mixedwoods (Mayer 1971, Ohmann et al. 1978).

A unique regeneration problem associated with group selection is the creation of frost and snow pockets (Aulitzky 1965). Snow-press problems occur with spruce trees on some grass-covered clear-cut areas in northwestern Ontario and could thus be a problem in group selection forests.

The humid, moderated environment of a selection forest should favor the development of spruce regeneration. Successful spruce and pine regeneration in selection forests depends upon the presence of advanced growth (Mosandl 1984), suitable seed beds (mineral soil), adequate seed sources, and the maintenance of suitable growing space (Jarvis and Cayford 1967). This might be accomplished through short cutting cycles with associated ground disturbance to reduce fir (Day 1945, Ohmann et al. 1978), or site preparation and other silviculture activities, including spruce planting (Mosandl 1984). It would require considerable effort and skill to provide for the appropriate conditions for spruce and pine regeneration under the selection system.

It is unlikely that one can count upon unassisted natural regeneration of black spruce and white spruce arising from selection cutting alone. Site preparation to expose seed beds and to reduce fir or other competing vegetation will be necessary, and planting may also be required. These measures challenge the cost-effectiveness of selection systems in boreal mixedwoods compared to other silvicultural systems.

In the 1960s and 1970s tunneling with small bulldozers beneath selectively logged mixedwoods was followed by planting large white spruce under the residual poplar canopy. This and other underplanting practices in northwestern Ontario often failed unless some form of tending followed the planting. Where the white spruce were able to establish themselves, a thriving mixedwood was maintained.

The use of conventional site preparation and tending treatments is near impossible within the confines of a selection forest. Girdling, injection, spot treatments, hand scalping, and other motor-manual treatment options are the only practical treatments for single tree selection forests. These labor-intensive treatments are quite expensive. Small specialized machines would be required to work economically in group selection settings.

Advantages and disadvantages of the selection system

Advantages include the following:

- Planting costs may be eliminated.
- Shading by residual trees may encourage conifers and discourage intolerant hardwoods, thereby reducing dependency upon herbicides.
- Residual trees will gain in size and value, and large inventories of growing stock will be maintained.
- Damage to residual trees is concentrated upon smaller saplings, which often die from self-thinning, thereby making stem decay less of a problem than with other systems (e.g., shelterwood).
- Provision is made for biological legacies (Sections 2.4.1, 3.3.2).
- Site-adapted regeneration is assured (Sections 2.4.1, 3.3.2).
- Seedlings from seed have well developed root systems and hardwoods from seed are thought to live longer than hardwoods from root suckers (Sect 3.3.2).
- This system is more environmentally acceptable than clear-cutting.
- Forest cover and related site features (soil, water, and habitat quality) are maintained for a long period of time (Section 7).

Disadvantages include the following:

- Harvest and access maintenance costs are significantly increased.
- Specialized harvest equipment and highly skilled operators and/or tree markers are required. (However as with the shelterwood system, it is possible that a well-trained work force may become motivated and productive).
- Significant modification of technique and increased site preparation and tending costs are required to prevent an increase in the balsam fir content of mixedwood forests.
- There is no opportunity for aerial tending.
- If underplanting is required, it will be expensive and may require costly tending.
- Control of regenerating species composition and tree density may be difficult.

7.0 ENVIRONMENTAL CONSIDERATIONS

Timber production is not the only issue to be considered when deciding upon a management strategy for forests and the stands they contain. Nontimber values are becoming an increasingly important concern in forest management, as are demands for integrated resource management and ecosystem-based management approaches (Hunter 1990, Franklin 1992, Thompson and Welsh 1993). Boreal mixedwoods may present good opportunities for attempting new management paradigms because of their broad nontimber values and the range of silvicultural approaches that are possible.

This section briefly discusses some of the environmental considerations that mixedwood managers should take into account when deciding which silvicultural approaches might be implemented.

7.1 Soil Nutrients

During harvesting, nutrients are lost both directly, through the removal of the timber crop, and indirectly through hydrologic losses that occur after harvesting due to erosion, surface runoff, and leaching to groundwater (Mann et al. 1988).

Boreal mixedwood sites generally support relatively low biomass and productivity relative to the nutrient-rich state of their soil reserves. Thus, they can be expected to have relatively short replacement times for the nutrients removed by harvesting (Gordon 1981). Gordon has estimated that it takes about 20 years for nutrient replacement to occur following a single full-tree (i.e., total removal of all aboveground portions of trees) clear-cut harvest of a mature stand in the boreal mixedwood forest (Table 2). Removing the standing crop typically represents a loss of less than one-half of the nutrient reserves and less than one-third of the total nutrient pool (Davidson et al. 1988). Weetman and Webber (1972) concluded that weathering, atmospheric inputs, and vegetation development quickly offset nutrient losses following harvest in boreal forests. However, nutrient drain may occur after several rotations, particularly when full-tree harvesting is combined with short rotations.

Table 2. Estimated number of years required to replace, through input, nutrients lost in a single crop removal in boreal mixedwoods. (*based on* Gordon 1981.)

Mixedwood composition	Years to replace nutrients				
	N	P	K	Ca	Mg
25% softwood 75% hardwood	19	15	17	17	14
50% softwood 50% hardwood	20	16	19	17	14
75% softwood 25% hardwood	21	19	22	18	15

Several studies of nutrient losses have compared the effects of different types of clear-cut harvesting. A study of nutrient losses 8 years after strip clear-cutting in the spruce–fir forests of Maine found no significant differences between clear-cut and uncut areas in the forest floor or mineral soil nutrient levels (Czapowskyj et al. 1977). Experiments in northern hardwood forests at the Hubbard Brook Experimental Forest in New Hampshire have shown nutrient levels returning to preharvest levels after only 10 years (Hornbeck et al. 1987). Comparing the effects of strip and block clear-cutting on nutrient losses, they further found that strip cutting moderated the initial nutrient losses. Freedman et al. (1981), comparing nutrient losses between full-tree and tree-length (stem-only) harvesting in a red spruce–balsam fir forest in Nova Scotia, found that full-tree logging significantly increased nutrient losses. While full-tree logging resulted in 30 percent more biomass being removed from the site, the increase in nutrient losses was much greater: 99 percent, 93 percent, 74 percent, 54 percent, and 81 percent for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), respectively.

The effects of clear-cutting on hydrologic losses of nutrients have also been studied extensively. Mann et al. (1988), in a review of research undertaken in 11 different clear-cut stands (6 hardwood and 5 softwood) across the United States, examined hydrologic losses of N, K, and Ca after clear-cutting. They concluded that, for most forest systems, hydrologic nutrient losses are much less than direct direct nutrient losses through timber removal. Furthermore, hydrologic losses returned to normal within about 3 years. Full-tree harvest had little additional effect on such losses when compared to tree-length harvest.

Shelterwood and selection cutting generally result in less immediate losses of nutrients than does clear-cutting, as less timber is initially removed from the forest. However, over a rotation, the losses would be the same as for clear-cutting, for the total biomass of nutrients removed would be identical (Alexander 1977). The harvest method and the level of tree utilization seem to have more impact upon forest soil fertility than do the silvicultural systems themselves. Harvest method and silvicultural system are interrelated, however. For example, selection systems preclude full-tree logging because of the restricted working space and the desire to avoid damage to residual trees.

7.2 Soil Erosion

Forest soil formation rates, governed by climate and lithology, are estimated to range between 0.6 and 15 mg ha^{-1} yr^{-1} (Miller et al. 1988a). Ontario's boreal mixedwoods would tend to be at the lower end of this range. Miller et al.'s (ibid) stream sediment data from a replicated experiment of alternative silvicultural systems in the pine forests

of the Ouachita Mountains in Arkansas revealed significant differences in estimated soil losses between silvicultural systems. They estimated that soil losses for clear-cutting, selection, and unharvested control would be about 0.05, 0.04, and 0.03 mg ha^{-1} yr^{-1}, respectively, over a 35-year rotation period. As these values are well below estimated soil formation values, forest harvesting of any form will likely not cause serious soil losses.

It could be argued that selection cutting may be the least intrusive means of harvesting forests from a soil conservation perspective. However, selection harvests require high road densities and frequent stand entries. Soil conservation goals might be affected more seriously by these conditions than by any gains made through the retention of forest cover. Frequent stand entries can also adversely affect soils through compaction (Utzig and Walmsley 1988). This is especially important in boreal mixedwoods, which tend to occur on fine-textured soils that can be easily degraded by compaction.

In very steep terrain, however, soil erosion caused by clear-cutting and resulting renewal activities can temporarily increase erosion by as much as ten times that for undisturbed forests (Utzig and Walmsley 1988). Mass wasting or landslide potential is significantly higher in clear-cut areas than in forested areas, quite apart from roads (Smith 1986). The root mat that binds the soil together against sheer forces decomposes before the roots of regenerating trees develop fully in clear-cut areas. In Ontario there are few places prone to mass wasting, although a significant slide involving boreal mixedwood cover types occurred in 1992 on the banks of the Nipigon River in northern Ontario. Although nearby logging was initially implicated, further study concluded that fluctuating river levels from a power dam were the principal factor that led to the slide (R. Booth[5], personal communication). This river contains extremely productive trout (family: Salmonidae) spawning beds which are vulnerable to siltation from mass wasting.

Although few of Ontario's boreal mixedwoods are found on sites that could be characterized as having sensitive soils, many important riparian zones support mixedwoods. Riparian zones filter water entering streams by removing sediment and excess nutrients, provide critical corridors for wildlife movements, reduce shore erosion, moderate water temperatures, and provide critical levels of litter fall to support food chains in headwater streams (Franklin 1992). Ontario's timber management guidelines (Ontario Ministry of Natural Resources 1988a) call for a variety of buffer strips to be maintained around water bodies.

Selection and shelterwood systems, as well as modified clear-cutting systems, might be used to maintain these strips.

7.3 Water Resources

There is a direct relationship between soil erosion and water quality. Stream sedimentation increases with erosion, adversely affecting water quality. Although the effects of harvesting on soil erosion in boreal mixedwoods seem fairly limited, there are effects upon water yield and streamflow.

A significant loss of forest canopy after harvesting can cause a reduction in the interception of precipitation and in evapotranspiration rates, resulting in wetter soils and increased streamflow. Changes in water yield are generally less in upland mixedwood and hardwood forests, because of the lower interception rates and greater water storage capacity (Davidson et al. 1988, Hornbeck and Leak 1992).

Clear-cutting generally leads to an increase in water yield shortly after harvesting, due to the loss of forest canopy. Clear-cutting on steeper hillsides can also expose a site to erosion and subsequent runoff (Matthews 1989). The increase in water yield is generally greatest during the first year after clear-cutting, and diminishes as revegetation appears (Ohmann et al. 1978, Arnup et al. 1988). Hornbeck et al. (1987), studying hardwood forests in the Hubbard Brook Experimental Forest in New Hampshire, found that water yields increased after block clear-cutting, but returned to normal levels within 10 years. Furthermore, they found that strip clear-cutting, when compared to block clear-cutting, moderated the initial increase in water yield.

Alexander (1977) suggests that the size and arrangement of cut blocks is important in determining the effect of harvesting upon water yield. In the Engelmann spruce (*Picea engelmanii* Pang)–subalpine fir (*Albies lasiocarpa* [Hook.] Nutt.) forests of the Rocky Mountains, he found that postharvest peak flows were highest, with 30–40 percent of the drainage harvested in 1.2- to 2.0- ha clear-cuts. Larger clear-cuts reduced the streamflow. This was due to the effect of different sizes of clear-cuts upon wind movement in the stand, and the subsequent accumulation and melting of snow in the openings. The increase in streamflow was found to persist until trees in the openings were tall enough to change the pattern of wind movement, which for his study area was about 30 years.

Harvesting techniques that maintain vegetation on site, such as shelterwood cutting, moderate the increases in water yields normally associated with clear-cutting

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[5] Resident Forester, Domtar Inc., Red Rock, Ontario.

(Arnup et al. 1988). Based upon research in Engelmann spruce–subalpine fir forests, Alexander (1977) found that the increases in water yield for uniform shelterwood cutting were negligible as long as the overstory remained. After the final harvest, water yield was similar to that for patch clear-cutting, and depended upon the size and arrangement of cuts.

In theory, by maintaining a constant forest cover after harvesting (Arnup et al. 1988, Matthews 1989), selection cutting can further reduce the potential for soil erosion and increased water yield that is associated with clear-cutting and shelterwood systems. Based upon research in Engelmann spruce–subalpine fir forests, Alexander (1977) found that group selection cutting increased water yield in a similar manner to patch clear cutting, if the openings were as large as 1 hectare in size. With individual tree selection he found little or no increase in water yield, as evapotranspiration and fall recharge requirements were only slightly less than for uncut stands.

In a replicated experiment to test the effects of no harvest, selection cutting, and clear-cutting with site preparation and planting in the pine forests of the Ouachita Mountains in Arkansas (Miller et al. 1988a, 1988b), 3 years of observations revealed no differences in peak flows or water yields. Sediments were significantly greater in the clear-cut area in the first year following harvest, but the differences were insignificant by the second year. The porous rocks may have dampened some of the responses and differences might be greater in Ontario's shield country, but their findings are in line with work done in the granite-based Appalachian Mountains of the northeastern United States.

To conclude, water quality response to the application of different silvicultural systems is specific to the climate, lithology, topography, and vegetation of each watershed (Miller et al. 1988a). Professional judgement is therefore required to prescribe a specific system to meet water quality objectives. Riparian zones deserve special consideration from a water quality perspective, as water temperature will increase in streams where shoreline trees are harvested and shade is removed. Single tree selection cutting might be used along shorelines of coldwater streams to help protect fish habitat by maintaining streamside shade (Ontario Ministry of Natural Resources 1988a).

7.4 Wildlife

Historically, the effects of forest management on wildlife in Ontario have been addressed primarily in terms of featured species (Wedeles et al. 1991) where, for a given forest site, the emphasis is on the habitat needs of a single species. However, a new focus upon forest sustainability and ecosystem management is emerging that will change this narroaw perspective. The recent report of the Ontario Forest Policy Panel recommends that a key objective of future forest management will be: "To ensure that current natural biological diversity of forests is not significantly changed and where necessary and practical, is restored" (Ontario Forest Policy Panel 1993). Definitions of "wildlife", as put forward by the Ontario Wildlife Working Group (1991) and the Wildlife Ministers' Council of Canada (1990), now explicitly include all wild plants and animals. This new ecosystem approach to forest management is still very young, however, and much of the existing literature describing the effects of forest management on wildlife addresses only the more traditional featured species such as moose (*Aces alces*), deer (family: Cervidae), furbearers, and birds. While the discussion in this review is limited to these species groups, a brief assessment of the effects on habitat diversity is also included.

7.4.1 Habitat Diversity

The habitat diversity of a forest can be measured both horizontally (i.e., the spatial pattern of habitats over an area) and vertically (i.e., the number of vertical strata in the forest) (Crawford and Frank 1987). The diversity of the forest, with respect to a particular species, depends upon the scale at which it is viewed by that species (Hunter 1990). Different animal species have different requirements for habitat diversity; some can live in a variety of habitats, some require a diverse habitat, and some require a uniform habitat. For species with small home ranges, a mature forest with many gaps may represent a spatially diverse habitat. Diversity for species with larger home ranges, however, may be a mosaic of stands of varying ages and species composition (Hunter 1993).

The forest that results from timber harvesting will not be the same as the forest that existed prior to harvest. There will be a change in density and species composition after harvesting. It is generally not possible to accommodate the needs of all wildlife species in an area following a disturbance, due to the different habitat requirements of each species. Wildlife species in the boreal forest are generally adapted to periodic disturbances, such as those created by fire, insect damage, and wind storms, and can for the most part adapt to disturbances created by timber management operations, provided that the pattern of harvesting mimics the natural events as much as possible (Arnup et al. 1988, Thompson and Welsh 1993).

In the years immediately following traditional silvicultural clear-cutting, vertical habitat diversity is almost nonexistent, as the overstory is completely removed. This reduction in vertical diversity is not as great following commercial clear-cutting, however, as some trees are left standing. While it is not uncommon to have greater numbers of animals in the early successional stages following

clear-cutting, the diversity of species is generally less than in stands with greater vertical diversity (Crawford and Frank 1987). Clear-cut logging also can lead to re-duced structural diversity in the second growth, as specific habitat features found in mature forests (e.g., fallen logs, large diameter trees with cavities, and snags) are not found in successional or plantation forests (Thompson and Welsh 1993). The "New Forestry" approach, developed in the Pacific Northwest of the United States (Franklin 1989), advocates leaving large trees, snags, and fallen logs in clear-cuts to provide habitat for cavity nesting birds and other organisms (Boyle 1991, Thompson and Welsh 1993).

The scale and pattern of clear-cuts is important in deter-mining the response of different species to disturbance. Horizontal habitat diversity will vary as a function of the size and arrangement of the cuts. As a general rule, management that creates forest fragments smaller than a species' home range will result in a reduction in abun-dance of that species (Boyle 1991). Several authors now advocate using a range of harvesting patterns, including larger clear-cuts, to create landscape-level diversity (Hunter 1990, Hunter 1993, Thompson and Welsh 1993). They suggest that clear-cuts be used to mimic the landscape patterns of disturbances created by natural processes, such as fire and insects. Such cuts would create habitat for early successional species, and would eventually become large, relatively uniform stands. To promote diversity across the entire spectrum of possible scales, they recommend har-vesting forests at a range of different scales. Patch cuts or small clear-cuts can be used to create a mosaic of stands of different ages and species composition, and thus are appropriate for creating mid-scale diversity (Hunter 1990). Thompson and Welsh (1993) suggest that boreal forest management should include a mix of partial cuts, shelterwood cutting (particularly in mixedwoods), many small clear-cuts, and a few very large clear-cuts.

Shelterwood harvesting generally provides more vertical diversity than does clear-cutting. Part of the canopy is retained until the final cut, and regeneration provides a degree of vertical diversity thereafter (Crawford and Frank 1987). The structural diversity of shelterwood stands also tends to be greater than that in clear-cuts, and trees suitable for cavity-nesting birds and other animals can be left for several years. The horizontal diversity of habitats will be similar to that of clear-cutting, and will depend upon the size and arrangement of cut and uncut areas.

Selection cutting is generally better than either shelterwood or clear-cutting for maintaining horizontal habitat diver-sity on a small scale (Hunter 1990, Hornbeck and Leak 1992). It creates discontinuities in tree size (or group of trees) and thus ensures that there will be trees of many different ages in a stand (Hunter 1990). Both group and

individual tree selection cause fine-scale disturbance, so stand level vertical structure is usually high, edge and fragmentation effects are often low, and stand heterogene-ity is generally high relative to even-aged management (McComb and Hansen 1992).

Single tree selection allows for the greatest vertical diver-sity, as it provides more canopy layers than any other har-vesting system (Crawford and Frank 1987). Group selection lessens the continuity of vertical habitat, but increases the horizontal diversity; there is more understory vegetation, fewer openings, and plant growth is more clumped. An even distribution of low understory vegetation results from individual tree selection, which Crawford and Frank (1987) suggest should generally support low but constant populations of terrestrial wildlife.

7.4.2 Ungulates

The ungulates found within Ontario's boreal mixedwoods include moose, white-tailed deer (*Odocoileus virginianus* Zimmerman), and woodland caribou (*Rangifer tarandus*) (McNicol and Timmermann 1981, Arnup et al. 1988). Optimum moose habitat generally comprises an intersper-sion of food and cover within the home range. Food is generally found in early successional plant communities that develop following disturbance by fire, insect damage, wind storms, or logging; shelter generally consists of semimature or mature conifer stands (Ontario Ministry of Natural Resources 1988b, Timmermann and McNicol 1988). For white-tailed deer, good habitat comprises dense conifer stands (for winter shelter) in close proximity to smaller openings with early successional stages for browse (Arnup et al. 1988, Davidson et al. 1988). Woodland caribou are found primarily in the northern, unlogged boreal forest, although a few scattered local herds survive further south in areas that have been harvested (McNicol and Timmermann 1981). Unlike moose and deer, which thrive in early successional forests, caribou prefer mature and overmature coniferous forest (Darby et al. 1989)

Moose generally benefit from a mosaic of food and cover habitats, such as those that result from some forms of clear-cutting (Timmermann and McNicol 1988, Boyle 1991). The effect of clear-cutting on moose habitat de-pends upon the spatial pattern of the cut blocks, the structure of the vegetation that remains both within and outside of the cut areas, and the type of silvicultural treatment.

The OMNR, in their guidelines for moose habitat manage-ment, recommend that clear-cut blocks be no larger than 80–130 ha (Ontario Ministry of Natural Resources 1988b). Buffer zones between cutovers should be of a similar size, and scattered 3- to 5-ha patches of trees should be left within cutovers. Moose should always have shelter within

400 m, and the shelter should have a significant conifer component. McNicol and Timmermann (1981) suggest that full clear-cutting of mixedwood stands is detrimental to moose. They recommend harvesting only the mature softwood component (i.e., partial cutting or two-pass harvesting), leaving the mature deciduous component and advance coniferous regeneration. Cuts with irregular edges are also preferred for moose, as this increases the amount of available edge habitat (Arnup et al. 1988). Strip cutting can also be used to increase the length of time that browse is available (Hornbeck and Leak 1992).

Different silvicultural treatments have different effects on moose habitat (McNicol and Timmermann 1981). Scarification and artificial regeneration generally shorten the early succession period for cutover areas. As this succession period has historically supported growth in moose populations, the effect of these treatments on moose habitat is generally negative. Because herbicides result in only a temporary setback for most moose browse species, their effect on moose habitat is considered minimal. Prescribed burning is generally good for moose, providing that the residual deciduous component is not destroyed, because the rapid return of nutrients to the soil can lead to an increase in the quantity and quality of browse.

Selection cutting does not disturb the forest canopy enough to create significant successional growth, and thus is not recommended for enhancing moose habitat. Selection cutting will generally produce smaller amounts of browse and fewer plant species than even-aged harvests (Hornbeck and Leak 1992), and the diversity of plant species is limited to shade-tolerant species (Anderson et al. 1990). In large cutover areas, however, selection cutting may be used to harvest within uncut patches that have been left to provide shelter for moose (Ontario Ministry of Natural Resources 1988b).

The habitat requirements for deer differ somewhat from those of moose. Small cutovers (less than 50 ha) interspersed with leave blocks should provide the best areas (Arnup et al. 1988, Anderson et al. 1990). Clear-cutting deer yarding areas, such as wintering areas, should be restricted. Shelterwood cutting, used as an alternative to clear-cutting in deer wintering areas, can provide shelter for the animals between the first and final cuts (Anderson et al. 1990, Crawford and Frank 1987). As with clear-cutting, however, the effect of shelterwood harvesting on wildlife depends upon the pattern of cut and uncut areas, and the structure of the vegetation that remains within and outside of the cut areas. Group selection can also be used to provide good year-round habitat for white-tailed deer, as it creates a mosaic of browse and cover habitats (Crawford and Frank 1987).

Clear-cutting mature conifer is generally detrimental to woodland caribou (Darby et al. 1989), as clear-cuts of all sizes cause a displacement of the animals. Harvesting also increases moose and deer densities, which may in turn increase the number of predatory wolves (Darby et al. 1989). Arnup et al. (1988) recommend that cutting be avoided in the core winter range, near calving sites, and along migration routes.

7.4.3 Furbearers

In general, the habitat requirements of black bear (*Ursus americanus*) are the same as those of deer, provided that den sites such as large trees and snags are protected (Anderson et al. 1990). Lynx (*Felis lynx*) are obligate predators of hare (*Lepus* spp.), and hare habitat choice reflects this; optimum habitat for the latter includes a high density of successional browse shrubs interspersed with mixed or coniferous trees less than 3 meters tall (Thompson 1988). The use of stands by lynx has generally been found to be highest in successional stands 10–30 years after clear-cutting (Thompson 1988). A mosaic of small cut and uncut stands, which maximizes the amount of uncut/successional edge, creates a mix of cover and early successional feeding areas that provides optimal habitat for this species (Arnup et al. 1988, Thompson 1988). The effects of silvicultural treatments, such as scarification and artificial regeneration, on lynx habitat are similar to those described for moose. Highest lynx densities can be expected on naturally regenerating sites in the sapling and young tree stages (Thompson 1988).

Marten (*Martes americana*) appears to be the only boreal furbearer that achieves its highest densities in mature conifer and mixedwood forests, and requires large tracts (250–400 km^2) of continuous old growth (Thompson 1988, Thompson and Welsh 1993). Because of their reliance upon mature and overmature forest, marten densities decline for many years after clear-cutting. In a study in the boreal forest, Thompson (1991) found that densities remained 67–90 percent lower in second-growth stands compared with uncut, overmature mixedwoods for up to 40 years following clear-cutting. He suggests that scarification and artificial regeneration will result in even lower marten densities in the second-growth stands when compared to sites that regenerate naturally, through a reduction in habitat diversity and reduced prey densities. Other studies suggest that marten may make use of mature coniferous islands within cutovers. In a study in Maine, Soutiere (1979, in Thompson 1988) found that marten continue to use large islands of uncut coniferous forest within cutovers. Snyder and Bissonette (1987) found that marten in Newfoundland used only those stands that were 15 ha or larger.

Single tree selection cutting, where much of the horizontal and vertical habitat diversity of a mature forest is preserved, may be the most appropriate harvesting system for supporting marten habitat (Crawford and Frank 1987). Soutiere (1979, *in* Thompson 1988), working in Maine, found marten use of areas logged by diameter-limited selective cutting was no less than for unlogged areas.

7.4.4 Birds

Over 150 species of birds breed in the boreal mixedwood forest. Of these, about 85 species are terrestrial passerines that are totally dependent upon some stage of the forest for their survival (Welsh 1981). Of these species, most (approximately 20–25 species) are wood warblers (family: Parulidae). Other significant groups are thrushes (family: Turdidae), finches and sparrows (family: Fringillidae), flycatchers (family: Tyrannidae), swallows (family: Hirundinidae), vireos (family: Vireonidae), and woodpeckers (family: Picidae).

Inasmuch as mixedwoods provide "habitat" for eastern spruce budworm, their importance as habitat for insectivorous songbirds is heightened. At least 15 species of songbirds, mostly warblers, increase in population when there is a rise in endemic numbers of budworm (Kendeigh 1947, Crawford 1983). Songbirds play a beneficial role by exerting a controlling effect on the budworm when populations are not at epidemic levels (Crawford 1983). Once populations reach epidemic levels, however, bird predation has little effect. Diamond (1993) draws a parallel between severe declines in warbler populations in Saskatchewan and unusual outbreaks of spruce budworm.

As many passerines are dependent upon different successional stages and forest compositions, some species disappear after clear-cutting while others replace them (Boyle 1991). Welsh (1987) found this to be true in boreal mixedwoods but noted that, although there was a change of species after clear-cutting, the overall number of birds and density of bird species remained relatively constant. A few species were found to persist through most forest successional stages, but many were only common at a single stage.

In spruce–fir stands in Maine, Titterington et al. (1979) found that the presence or absence of a softwood overstory was the most important habitat feature in determining whether or not a habitat was suitable for a particular bird species. Timber management practices that result in a range of age classes and stand types will provide habitat for a diversity of bird species (Titterington et al. 1979, Boyle 1991).

Shelterwood harvesting generally creates better habitat for crown-dependent bird species than does clear-cutting, and less habitat for birds that prefer shrubs and saplings (Crawford and Titterington 1979). As shelterwood harvesting retains part of the canopy for a number of years after harvesting, there is greater vertical diversity of habitat prior to the final shelterwood cut than there is with clear-cutting. This can help to maintain a greater diversity of bird species (Crawford and Frank 1987).

Single tree selection, through its positive effect upon vertical diversity, provides suitable habitat for birds preying on insects from leaf surfaces and on or within the bark (Crawford and Frank 1987). As the harvesting interval increases with group selection, birds dependent upon low vegetation generally increase in numbers, while those dependent upon overstory habitat decrease (Crawford and Frank 1987).

7.4.5 Insects and Diseases

The most disruptive insect in the boreal mixedwood forest is the eatern spruce budworm (Howse 1981), and the major disease is root rot (*Armillaria mellea* [Vahl ex Fr.] Kumm.) (Whitney 1981).

The primary hosts of the spruce budworm are balsam fir, white spruce, and to a lesser extent, black spruce. Historically, extensive and prolonged outbreaks have occurred throughout the boreal forest on a recurring 40–70 year cycle, causing sustainable harvests to be reduced by up to 60 percent during an outbreak (MacLean 1990). Budworm-killed balsam fir stands can create explosive fire conditions under certain circumstances. Table 3 lists the

Table 3. Factors that increase the amount of volume loss and tree mortality due to severe spruce budworm outbreaks. (adapted from Witter et al. 1984.)

Factor	Condition leading to severe damage
Species composition	Stands with large balsam fir components have greater potential for mortality than do stands comprised mostly of spruce or hardwoods.
Stand age	Mature fir stands (60 years or older).
Stand density	High basal area of balsam fir and white spruce.
Stand structure	Open stands in which spike tops of host species protrude from the forest canopy.
Stand size	Extensive stands of mature host trees (except black spruce).

principal factors that affect the vulnerability of a stand to spruce budworm outbreaks.

The following steps have been recommended to reduce the risk of budworm damage in mixedwood stands:

- reduce the proportion of balsam fir and white spruce (Baskerville 1975);

- allow balsam fir to grow beneath a hardwood overstory (Kemp and Simmons 1979, Witter et al. 1983);

- avoid even-aged management that might create extensive stands of mature balsam fir (Watt 1992); and

- avoid protection of large areas of mature and over-mature forest, which will lead to more frequent future outbreaks (Blais 1974, Baskerville 1975).

Clear-cutting of mixedwood stands without subsequent site preparation to destroy balsam fir advance growth can lead to second-growth stands with high balsam fir contents, thereby increasing the risk of incurring severe budworm damage at some later date. Watt (1992) suggests that clear-cutting practices that encourage the development of mixedwood stands will help to reduce the future vulnerability of the forest.

Stands with dominant host trees are more vulnerable to spruce budworm outbreaks (Witter et al. 1983). This suggests that mixedwood stands with a significant hardwood component in the overstory are less at risk. Kemp and Simmons (1979) found that budworm larval survival is reduced when balsam fir grows beneath a hardwood overstory. In the U.S. Great Lakes states, clear-cutting and natural regeneration are used to convert spruce–fir stands to aspen stands (Blum and MacLean 1985). The fir understory of these stands is protected from spruce budworm attacks by the aspen overstory, and itself becomes the overstory when the aspen is harvested. However, this management strategy may carry a high budworm risk.

In areas already undergoing a spruce budworm outbreak, clear-cut harvesting is recommended for budworm-ridden stands. Residual overstory host trees should be removed to prevent budworm larvae from dispersing downwards to the new regeneration (Blum and MacLean 1985). Block cutting can be used to isolate susceptible stands, which may help to limit the extent of an outbreak (Baskerville 1975).

Shelterwood harvesting is generally appropriate when no major insect or disease problems exist. If high populations of spruce budworm are present in a stand cut under a shelterwood system, direct suppression of any insects remaining in the overstory may be necessary in order to guard against larvae dispersing downward onto the developing regeneration (Blum and MacLean 1985). A shelterwood system can be used, however, to reduce the vulnerability of a stand to budworm damage. By controlling the species composition in the shelterwood overstory, the amount of regenerating balsam fir can be reduced as long as the desired species are represented in sufficient numbers in the overstory (Blum and MacLean 1985). It should be noted that budworm feeding can significantly reduce spruce and fir seed yields for the duration of a budworm outbreak.

Uneven-aged management of spruce–fir stands can be used to favor spruce and thus help to reduce a stand's vulnerability to budworm attacks. This is accomplished by maintaining a tall tree cover, removing the fir periodically, and providing a good source of spruce seed (Lancaster 1984). Individual tree and group selection can be effective in reducing the vulnerability of stands if they are used to alter the species composition of the stand (i.e., by reducing the proportion of balsam fir). Otherwise, selection cutting in boreal mixedwoods maintains a continuous canopy of mature or nearly mature trees with a significant component of white spruce and balsam fir, both of which are highly vulnerable to spruce budworm attack (Baskerville 1975, Blum et al. 1983, Blum and MacLean 1985).

From an 11-year study in Ontario's boreal forest (Whitney 1989), it has been estimated that the volume of wood lost to root rot amounts to 33 percent, 23 percent, and 16 percent for balsam fir, black spruce, and white spruce, respectively. Significant amounts of root decay (>30 percent of root volume) occur at the age of 60 in balsam fir and at the age of 80 in black spruce and white spruce. To prevent such root rot losses, Whitney (ibid) recommends that balsam fir be harvested before reaching the age of 65, and that upland black spruce be cut before the age of 75. Selection cutting is well suited for preventing root rot losses, as susceptible trees can be removed before damage occurs. However, selection cutting, and to a lesser extent shelterwood cutting, can both lead to an increased incidence of disease if a significant number of residual trees are damaged during harvesting. Appropriate harvesting controls and preventive measures are essential if such damage, and ensuing infections, are to be avoided.

7.5 Aesthetics

Some aspects of clear-cutting are less aesthetically pleasing than others. Slash piles and sharp cut boundaries are most often listed as offensive by viewers (Hunter 1990, Hornbeck and Leak 1992). Shelterwood harvesting is generally found to be more aesthetically pleasing than are most forms of clear-cutting (Matthews 1989). Selection cutting is considered the most pleasing of all, as it creates the most gradual transition from a mature crop to a new crop (Duffield 1970).

Visual Landscape Management Guidelines in British Columbia and the Pacific Northwest of the United States feature certain visual quality objectives (VQOs) for areas scheduled for harvest (K. Fairhurst[6], personal communication). Because so much of the region's mountainous forest land is visible to residents, the blending of forest harvest operations into the landscape is of great strategic importance. A critical element of VQOs is the effective green-up period in which landings and skid trails become indistinct. Selection systems allow harvests to occur in visually sensitive areas with fewer restrictions to operations than do clear-cutting or shelterwood systems in areas where VQO guidelines must be followed.

Visual landscape management issues may seem irrelevant in Ontario's relatively flat landscape. However, lakes and hunting areas, popular as remote tourism destinations, are often accessible only by floatplane. The view of cutovers from an aircraft can undermine tourists' sense that they are in a remote area. Selection cutting could be used to maintain forest cover, hide roads and harvest areas, and thus preserve the sense of remoteness (Ontario Ministry of Natural Resources 1987).

Significant portions of the forested landscape are viewed by people while on one of the many thousands of lakes that characterize northern Ontario. For example, one of the oldest skyline lake reserves in Ontario is along the shores of Lake Temagami. The reserve was established in 1901 to protect the forest and aesthetic values, and is linked to the high property values of cottage lots on the lake's islands. Beautiful large red pine and white pine trees within the reserve contribute to the southern Ontario wildland ethic and imagination. Similar issues regarding the management of old growth have been raised for Ontario's boreal forest. Selection systems might be used to maintain and produce large trees while continuing to supply local mills with necessary fiber (Quinby 1991).

8.0 SUMMARY AND INFORMATION NEEDS

Most harvesting and silvicultural experience in boreal mixedwoods has been with either selective cutting of softwoods or commercial clear-cutting and plantation culture. Due to the combination of a general lack of experience with alternative systems and the diverse nature of boreal mixedwoods, there is little evidence in the literature that indicates the superiority of one silvicultural system over another, either from an economic or an ecological perspective.

This lack of experience with alternative systems and the uncertain result of their use reinforces the use of the clear-cutting systems, and creates a situation in which it is difficult to move beyond the *status quo*. This section attempts to summarize the areas of uncertainty in the application of alternative systems and the perceived problems that have limited their use in boreal mixedwoods.

8.1 Semantics

An undisciplined use of terms throughout the forestry literature is the basis for the semantic morass referred to by Smith (1986). Such use contributes to a sense of confusion regarding the utility of the various systems. Although classical definitions (Smith 1986, Matthews 1989) may be helpful, to be truly useful, published reports on the use of different silvicultural systems need to have a considerable amount of detail on preharvest conditions and the sum of silvicultural activities employed. There are few studies with this level of detail.

Bradshaw (1992) argues that the principle difference between silvicultural systems lies in the proportion of the patch or canopy gap that is influenced by edge effect. He proposes that there is no static edge effect associated with a given silvicultural system; rather, edge effects are dynamic and form a continuum across the range of classic silvicultural systems. Consequently, he considered that there are a range of interventions that are not well represented by the classical definitions of silvicultural systems. While classical definitions provide a useful framework for discussions (as in this report), Bradshaw (1992) reminds us that these definitions are somewhat artificial models that serve to portray how various systems may work, but should not constrain the range of possible interventions that could be considered.

8.2 Lack of Examples in Boreal Mixedwoods

Of the approximately 1 500 publications reviewed in the preparation of this report, there are few thoroughly documented accounts of alternative silvicultural applications that can provide foresters with clear directions on technique and expected outcomes applicable to boreal mixedwoods. Silvicultural systems that are documented and tested using rigorous experimental designs are rare in general and absent within the Ontario boreal mixedwoods range. Therefore, the suitability of one system over another remains largely a matter of intuitive or professional judgement.

However, with greater interest in the proactive management of boreal mixedwoods, recent initiatives by the

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[6] Landscape Officer, B.C. Ministry of Forests, Vancouver, British Columbia.

federal and provincial governments in Ontario are important steps toward improving this situation. First, ecological land classification programs (e.g., Sims et al. 1989) now help to provide a common descriptive framework of preharvest conditions. Second, demonstration forests are being established to feature examples of various silviculture systems in different forest types. (This program will provide an opportunity for resource managers to develop their prescriptive skills based upon actual field observations.) Third, controlled experiments are now being established that seek to evaluate forest and ecosystem responses to different harvesting and silvicultural regimes in boreal mixedwoods. These are all encouraging signs.

8.3 Understanding Boreal Mixedwood Ecology

While it seems possible to manage boreal mixedwood tree species under almost any type of silvicultural system, there is no evident "best system" from an ecological perspective. Given that a best system is inevitably geared to some specific objective, and that objectives often change over time, an understanding of mixedwood ecology may be as useful as an understanding of the detailed workings of a specific application. This inferential framework would rest upon an improved understanding of both the genetic and evolutionary aspects of boreal mixedwoods, and the interplay of silvicultural systems with these genetic and evolutionary forces. These forces include interspecies relationships and biophysical considerations, such as the relationship of mixedwoods to spruce budworm and fire dynamics.

Silvicultural systems will alter gene frequencies over short periods of time, but the extent and consequences of these changes are unknown. Little work has been done to consider the effects of various silviculture treatments on the genetic structure of boreal mixedwoods. These considerations may be important factors in determining the ultimate utility of various silvicultural systems. What levels of inbreeding depression will occur with group selection when small gaps are filled by one or a few parent trees? Does partial cutting favor more shade-tolerant conifer tree species with less fire-resistant qualities that may make future forests less adapted to fire? Will stock from current tree breeding programs be suitable for use in underplanting? Should seed-tree cuts be timed to occur after cone development so as to avoid inbreeding? Is vegetative reproduction of hardwoods less desirable than regeneration from seed? The genetic and physiological implications of alternative silvicultural systems need careful scrutiny.

Because of the competitive environment on mixedwood sites, natural selection of regeneration will likely favor vigorous genotypes. Gill (1983) estimated that genetic gain is higher in naturally regenerated stands compared to bulk seed-source plantations because of these selection pressures. In this sense, plantations developed from improved seed might reverse this situation. Although improved seed is currently available only in limited quantities in Ontario, the implications of its use warrant consideration.

Other genecological studies may help to answer important questions regarding the composition of mixedwood forests. Why are western boreal mixedwoods more fully stocked with white spruce and Ontario's mixedwoods so prone to shrub competition and the ingrowth of balsam fir? Are there important racial differences between the species in these communities?

Simulation models are powerful tools that can assist in understanding the ecology of mixedwoods. The suitability of gap dynamics and multiple succession pathway models should be tested for boreal mixedwoods. The work required to develop and test these models will improve our understanding of mixedwood ecology. This increased understanding may improve the confidence of forest managers when prescribing new systems, as they will have greater knowledge on which to predict performance. Ontario's Growth and Yield Program may provide data and tools to build and test these models over time.

From an evolutionary point of view, evidence that boreal mixedwoods support mutualistic and stable arrangements of trees and plants appears to be rather weak. Research confirming or disproving these observations deserves some attention. Coevolution of spruce budworm and other wildlife with trees and plants within the boreal forest is another matter. An understanding of mixedwood forest ecology must encompass plant and animal interactions. Interdisciplinary research is clearly required.

Alternative silvicultural systems may have the potential to be important landscape management tools. For example, clear-cutting, using a variety of patch sizes and arrangements, can be made to resemble fire disturbance patterns common in northern Ontario. Alternative silvicultural systems could also produce patterns similar to wind- or insect-caused disturbances. Landscape ecology studies in boreal mixedwoods should help to provide insights into the possible consequences of different forest patterns arising from the application of different silvicultural systems.

Some direction is required on how the basic sciences of population ecology and genetics, among others, might be used to strengthen our understanding of boreal mixedwood ecology in ways that will support the use of alternative silvicultural systems. Perhaps a task-focused program

should be established similar to Ontario's Vegetation Management Alternatives Program (Wagner 1992). Such a program would provide the framework for undertaking basic research in a coordinated fashion.

8.4 Basis for Applying Alternative Silvicultural Systems

Unquestionably, alternative silvicultural systems can be used to maintain forest cover longer in specific locations compared to forests that are managed exclusively by clear-cutting. This may encourage certain types of regeneration, stand structure, wildlife habitat, or scenic value. For this reason, their application is logical in reserves along lakes, streams, and wildlife or transportation corridors. In addition, they have the potential to be used where forest management objectives must accommodate nontimber values.

In terms of the total commercial forest land base, the economic advantage of one system over another is open to debate. Intuitively, stands that are already multilayered, uneven-aged, and rich in species diversity might be easier and less expensive to manage in that condition by alternative silvicultural systems. Conversely, even-aged stands are easiest to manage under the clear-cutting system.

This unique interplay between existing stand structure and optimum financial harvest strategies led Haight and Monserud (1990) to propose methods of any-aged management. Their analysis of a western mixed conifer midelevation forest type using the stand simulator "Prognosis", revealed that maximum present value was attained with a management regime best described as a selection system. However, even-aged plantations or shelterwood systems with natural regeneration produced maximum merchantable volumes. The simulation results were dependent upon initial stand structure.

Any-aged management problem solving techniques applied to boreal mixedwoods would provide invaluable insights for choosing among different forest management options. Any-aged management problems cannot be solved without a well tested single tree growth model. It would seem that progress in understanding both the ecology and economics of boreal mixedwood management will be best facilitated by the development of single tree growth models or ecological-process models (Kimmins 1987)

Economic analysis should not be limited to single stands. What are the economic implications of the cumulative effects of stands managed by different silviculture systems at the forest level? For example, lower forest renewal costs associated with shelterwood systems may be offset by higher harvest, marking, and transportation costs. To be truly useful, economic analyses of alternative systems

need to consider much more than just harvest and renewal costs. Economic analyses, such as those of strip cutting carried out by Ketcheson (1977, 1979), are needed for other alternative silvicultural systems.

8.5 Operational Considerations

Almost all practical skills, technologies, and management planning techniques that have been developed for boreal forests are based upon the clear-cutting system in even-aged stands.

Recent advances in the development of small, versatile logging equipment like cut-to-length systems make the application of alternative silvicultural systems operationally feasible (Jewiss 1992). A new generation of site preparation equipment is now required to match the size, agility, and flexibility of this new generation of harvesting equipment. Perhaps small forwarders can be fitted with tools to create mineral soil seed beds or planting sites.

Vegetation management strategies become much more complicated with alternative systems than they are with clear-cutting. Cutting and residual overstory patterns may reduce hardwood tree, shrub, and grass competition, but may not eliminate it. Ubiquitous balsam fir may crowd out preferred spruces if it is not removed by site preparation or tending. Residual trees preclude conventional aerial application of herbicides. Granular herbicides and ground application technology (McGlaughlan 1992) will be required, while motor-manual thinning and cleaning techniques may be necessary on many sites.

The establishment and maintenance of spruces on mixedwoods sites will require many of the above inputs and may also necessitate supplementary planting. These factors combine to challenge the notion that alternative silvicultural systems will, through careful logging alone, develop acceptable patterns of "low-cost" regeneration. Without site preparation and tending, mixedwood forests will become dominated by poplar and fir to the relative exclusion of spruces and birch. If we are prepared to accept the continual decline of upland spruce, short cutting cycles of these fast-growing but short-lived species will become commonplace. However, more frequent harvests may cause operational problems and site damage.

One of the main operational concerns in the application of alternative silvicultural systems is the potential for loss of trees through windthrow and residual tree damage. The literature identifies a number of strategies for avoiding such losses: selection of leave trees, arrangement of cut and leave blocks relative to prevailing winds, and landscape features that offer protection from wind damage.

Another strategy to mitigate windthrow losses and residual tree damage involves harvest scheduling. Preparatory

cuts allow the remaining trees to develop taper, crown, and root characteristics that increase windfirmness. This means that a stand must be accessed while it is quite young, with the result that the trees removed may be small and expensive to harvest. This, together with the extensive permanent road systems needed to support some silvicultural systems, may have important implications for management planning, both at the stand and forest scales. Thus, initial forest structure may have as much to do with the suitability of a particular silvicultural system as does individual stand structure.

Young mixedwood stands are particularly suitable for a form of two-pass harvesting because species mixtures are often stratified. Logging practices to protect small trees in the understory are fairly well developed in Ontario's black spruce forests. It would seem that many of these techniques could be applied to certain mixedwood forests.

But what about the regeneration following this second pass, or following the last strip cut? Reports often describe techniques to regenerate the forest after the first intervention, but fail to discuss long-term regeneration problems caused by later harvests. The only complete analysis of this type (Jeglum and Kennington 1993) is for strip cutting black spruce.

Many institutional problems in forest management planning must be overcome if alternative silvicultural systems are to be practiced widely. How will regeneration surveys be conducted? What will new free-to-grow standards look like? Vertical patterns of stand development will become as significant as horizontal patterns (stocking). The Forest Resources Inventory would require modification. For example, in some forest units in southern Ontario, stands are assigned a U-designation on FRI maps to indicate uneven-aged management. Will such simple modifications be adequate or is a whole new system required?

Regulating the cut also becomes far more complicated with the adoption of alternative silvicultural systems. There are no forest forecast, harvest regulation, or harvest scheduling models available in Ontario that accommodate uneven-aged management systems.

The complexity of operations and planning associated with alternative systems requires training and education at the vocational, technical, and professional levels of management. For these reasons, new agreements are needed among responsible organizations to reinforce the linkages between forest harvest and forest renewal.

ACKNOWLEDGMENTS

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SUPPLEMENTARY REFERENCE DATABASE

Nearly 2 000 references were consulted during the preparation of this report. Of these, 1 362 citations for published books, reports, journal references, etc., have been assembled into a bibliographic database that is available upon request. While the database does not claim to be comprehensive, it contains numerous additional references not included in this report that are relevant to a study of boreal mixedwoods or the application of alternative silvicultural systems in the boreal forest.

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