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Developing Forest Management Strategies Based on Fire Regimes in Northwestern Quebec, Canada

Development of a forest management strategy based on natural disturbance for the western Québec and eastern Ontario black spruce ecosystem.

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With the collaboration of

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EXECUTIVE SUMMARY

Introduction

Forest ecosystem management that is based on the understanding of natural disturbance regimes has recently been suggested as a means to maintain biological diversity and productivity in forest systems. Figure 3 illustrates such a management strategy as proposed for black spruce (*Picea mariana* (Mill.) B.S.P.) dominated forests. The forest dynamics model illustrated in the figure suggests that the current diversity of forest types presently found in the landscape reflects the natural disturbance regime present across it. The model also proposes that the use of a variety of silvicultural treatments will enable the maintenance of the diversity of forest types. The present paper aims at illustrating how we have developed and initiated the implementation of a forest ecosystem management strategy based on this model in Northwestern Quebec

Methods

The development of the strategy is based on data obtained from 3 different research themes. Each theme focuses on a different aspect of the model and encompasses several research projects carried out in the Matagami ecoregion.

- Documenting and characterizing the historical natural disturbance regime, notably fire frequency, size and severity.
- Documenting and characterizing natural forest dynamics and the response of organisms to the change in forest composition and structure.
- Documenting the effects of different silvicultural treatments on various stand components and biological diversity.

The knowledge acquired in these first three research themes serves as a basis to the implementation of the strategy in a pilot territory covering more than 4500 km^2. This implementation is performed through a fourth research theme.

- Establishing management objectives for the pilot management unit, assessing the impacts of different management strategies, and developing tools that will facilitate the implementation of the strategy at the different levels of forest management planning.

Results and Discussion

A fire history reconstruction has shown that fire frequency within the study area has varied over the last 300 years resulting in an elongation of the fire return interval: 80 years before 1850, 150 years between 1850 and 1920, and 325 years since 1920. Furthermore, the analysis of the last 60 years of fire records from the Quebec Ministry of Natural Resources has indicated that fires ranging in size from 950 to 20000 ha could be considered characteristic for the black spruce zone of Western Quebec. It is important to note that although they account for less than 10% of occurring fire events, fires of 1000 ha or more generate close to 90% of the burned areas. Finally, the examination of 16 fire severity maps shows that although the proportion of unburned forest (preserved islands) was relatively constant (5%), the proportion of partially burned forest varied from 30 to 50%, while 45 to 65% of the forest was severely burned. The results of these three studies demonstrate that fire frequency, size, and severity are all characterized by a certain range in variability.

This disturbance regime has generated the forest mosaic presently observed over the landscape. For example, 57% of the study area is composed of forests that have burned more than 100 years ago while 20% of it is composed of forests that are older than 200 years. This suggests that under a natural disturbance regime, a significant proportion of the stands in the region have been exempted from fire for long time periods and that there exists a natural forest dynamics that describes the changes that occur within a forest stand over time. The results of several studies conducted in the study area show that the intervals between successive fires on a particular site have a strong influence on forest structure and, to a lesser extent, tree composition. For example in stands older than 100 years, canopy density and height tends to decrease with increasing time since the last fire. Furthermore, the analyses show that the forest dynamics is influenced by the surficial deposit. It was also observed that the presence and abundance of species (birds, insects, vascular and non-vascular plants) gradually change along the time since fire sequence, with very few species restricted to a particular stand age.

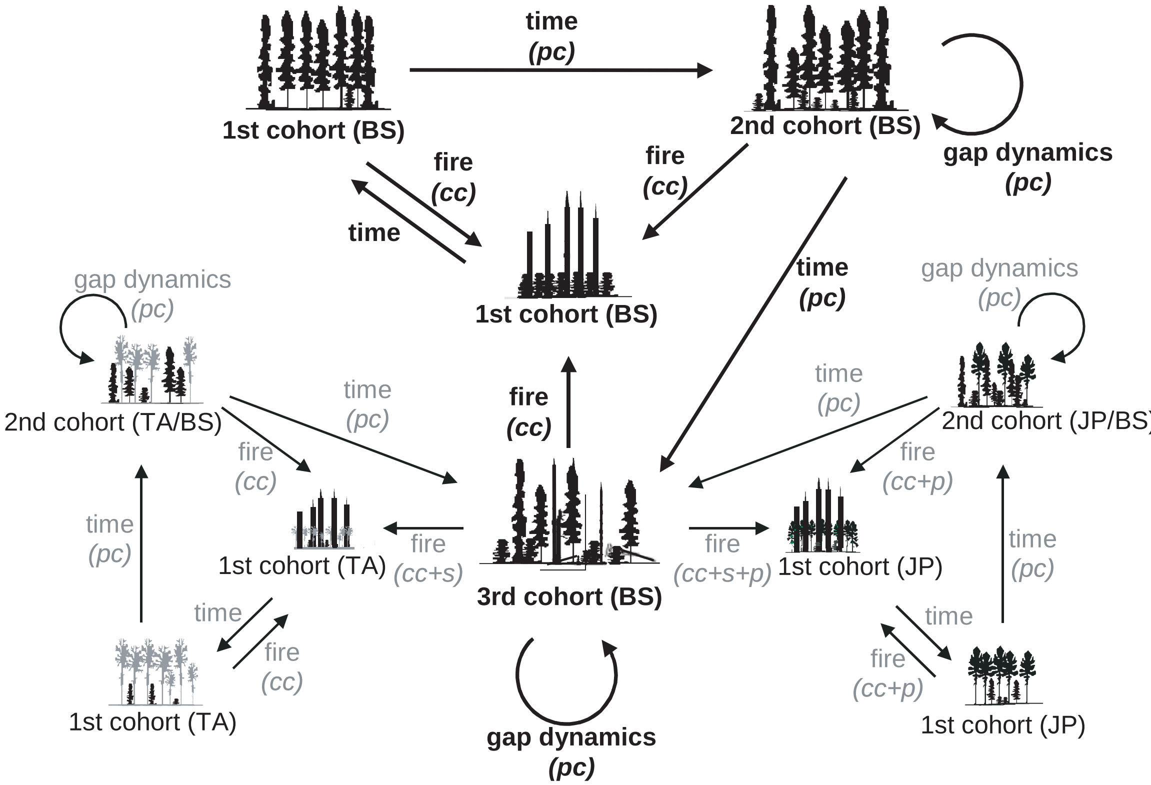

Figure 3. Conceptual model of natural forest dynamics proposed for the Matagami ecoregion and the corresponding management strategy. BS = black spruce (*Picea mariana* [Mill.] B.S.P.), JP = jack pine (*Pinus banksiana* Lamb.), TA = trembling aspen (*Populus tremuloides* Michx.), **cc =** clearcutting, **pc =** partial cutting, site preparation (s), plantation (p).

The baseline data on the response of organisms to the natural dynamics of the forest mosaic was a prerequisite condition for the assessment of the key differences that possibly exist in biodiversity patterns between managed forests and naturally disturbed forests. Several studies aiming at evaluating the effects of different silvicultural treatments on forest stand components and biological diversity are presently being conducted in the study area. Preliminary results suggest that partial cutting will maintain or produce forest stand structures characteristic of older forests.

The results obtained from the three first research themes are currently being used to develop tools and guidelines that will facilitate the implementation of the proposed strategy. This requires the integration of a number of elements related to natural disturbance regime and natural forest dynamics at the different levels of forest management planning. For example, the development of a 25-yr strategic plan requires the establishment of management objectives at a landscape level. We propose that a management strategy based on the use of a variety of silvicultural systems (even-aged and uneven-aged silviculture) will maintain the observed natural diversity resulting from the fire regime variability in terms of size, severity and intervals. Preliminary results indicate that the implementation of such a strategy would not significantly affect timber supply while favouring the maintenance of a variety of stand types.

The implementation of the strategy in a 5-yr tactical plan requires the development of tools for evaluating the potential for the different silvicultural systems in different management subunits. It also requires the development of guidelines for the spatial and temporal distribution of these different silvicultural systems. So far, our analyses indicate that the implementation of the strategy at this level of forest management planning is mainly limited by the nature of the information available in forest resource inventories. Finally at the 1-yr operational planning level, field guides are being developed as tools for silvicultural diagnostic, prescription, and evaluation in the context of mixed silvicultural systems.

The implementation of the proposed strategy is a good example of adaptive management. The continual arrival of new results from the first three themes of research facilitates and improves the development of the tools and guidelines stemming from the fourth research theme. In this regard, the monitoring of the managed forests is an integral part of the strategy and it can easily be incorporated in the different research themes.

INTRODUCTION

In the boreal forest, fire is the main natural disturbance that initiates succession and creates a mosaic of forest stands of different ages and compositions, in conjunction with the physical configuration of landscapes (Johnson 1992; Gauthier et al. 1996). Until recently, it was generally assumed that the North American boreal forest was characterized by short fire cycles (fire cycle: the time needed to burn a total area equivalent to the size of study area), resulting in forest mosaics composed of even-aged stands (Heinselman 1981; Johnson 1992). This generalization has often been used to justify forest management based on clearcutting and short rotations (the age at which the forest is harvested). On the other hand, long fire intervals that allow for changes in canopy dominance and the development of uneven-aged forests have also been reported, particularly in the eastern boreal forests of North America (Cogbill 1985; Foster 1985; Frelich and Reich 1995; Bergeron 2000; De Grandpré et al. 2000; Gauthier et al. 2000; Lesieur et al. 2002; Lefort et al. 2003). Bergeron et al. (2001) have shown that in four regions of eastern Ontario and western Quebec, more than 50% of the area is occupied by stands that burned more than 100 yr ago. Therefore, using a short industrial forest rotation can lead to a dramatic decrease in stand diversity (composition and structure) at the landscape level (Gauthier et al. 1996), with potentially significant consequences for biological diversity (Hunter 1999).

Forest ecosystem management based on an understanding of natural disturbance regimes has been suggested as a means of maintaining biological diversity and productivity in forest ecosystems (Attiwill 1994; Bergeron and Harvey 1997; Angelstam 1998; Bergeron et al. 1999b, 2002). Management strategies aimed at maintaining stand and landscape compositions and structures similar to those that characterize natural ecosystems should favor the maintenance of biological diversity and essential ecological functions (Franklin 1993; Gauthier et al. 1996; Hunter 1999; MacNally et al. 2002). Hence, forest characteristics such as the age-class distribution, the stand composition and structure, and the spatial arrangement of stands in natural landscapes should be key indicators for the implementation of sustainable forest management. This knowledge must also include forest succession, a key process that structures ecological diversity and determines the availability of timber, habitat for wildlife, and other resources.

Recently, Bergeron et al. (1999b) proposed an approach in which diverse treatments can be applied in order to maintain the forest's structural and compositional diversity without lengthening the timber rotation. The main objective of this chapter is to show how knowledge of natural forest dynamics can be simplified and transposed into a management strategy. We will illustrate the development and initial implementation of this strategy using a pilot study in the black spruce (*Picea mariana* [Mill.] B.S.P.)—feathermoss (*Pleurozium schreberi* (Brid.) Mitt.) ecoregion of northwestern Quebec.

FRAMEWORK AND APPROACH

The development of the management strategy was based on four different research themes. The first theme documented the characteristics of the region's fire regime, particularly the variability in fire frequency, size, and severity. The variability imposed by permanent site features that influence the thermal, hydric, and nutritional regimes, combined with the disturbance regime, is responsible for the variety of forest habitats in a region and thus determines the "coarse filter" on which to base the maintenance of biodiversity (Attiwill 1994; Bergeron et al. 2002). The second theme documented the natural forest dynamics that occur on the region's main surficial deposits. To assess whether key differences in patterns of biodiversity exist between managed and naturally disturbed forests, and how critical these differences are to the maintenance of biodiversity, we required baseline data on the responses of organisms to the natural dynamics of forest mosaics. In consequence, the third theme had the objective of defining these responses with respect to various components of forest stands, including structural elements (e.g., forest composition and structure, coarse woody debris, etc). These first three research themes allowed us to define a number of objectives (e.g., landscape, stand ecological type, and stand level) that could serve as targets at different phases of management planning. The fourth theme examined the integration of these objectives within management planning.

STUDY AREA

The data used in the development of the management strategy were collected in a subsection of the Matagami (6a) ecoregion (Saucier et al. 1998; Figure 1). This ecoregion is part of the black spruce -feathermoss bioclimatic domain, a subregion of Quebec's boreal forest (Saucier et al. 1998). The area belongs to the Northern Clay Belt forest region (Rowe 1972), which is characterized by forest stands generally dominated by black spruce and jack pine (*Pinus banksiana* Lamb.). There are also mixed stands of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* [Moench] Voss), and balsam fir (*Abies balsamea* [L.] Mill.) on coarser tills and alluvial deposits along rivers and lakes.

The regional climate is continental, with a mean annual temperature ranging between –2.5 and 0°C; the January and July temperatures average -17.5 and 17.5 °C, respectively. Annual precipitation averages about 1000 mm. The ecoregion lies within the James Bay watershed, and plains form the dominant landscape, with occasional hills; the average altitude is 284 m above sea level. The area's surficial deposits are predominantly clays and silts associated with the glacial Lake Ojibway. Subsequent readvance of a glacial lobe created a clay-textured Cochrane till in the northwestern part of the region.

The management strategy described in this chapter is currently being implemented in part of the Lac Grasset (119) regional landscape unit at the western end of the Matagami ecoregion. The Lac Grasset landscape is characterized by relatively flat topography (an average slope of 1%) and predominantly hydric and subhydric soil moisture regimes (Robitaille and Saucier 1998). As a result, more than 60% of its soils are classified as organic (an organic horizon deeper than 40 cm), with the better-drained sites associated with the Harricana moraine that crosses the unit from south to north and with scattered buttes. The management area covers about 4750 km^2 (from 49°37'30'' to 50°22'30'' N and 78°30'00'' to 79°30'00'' W) and includes part of a Forest Management Unit licensed by Tembec Industries Inc. and Norbord Industries Inc.'s Nexfor division .

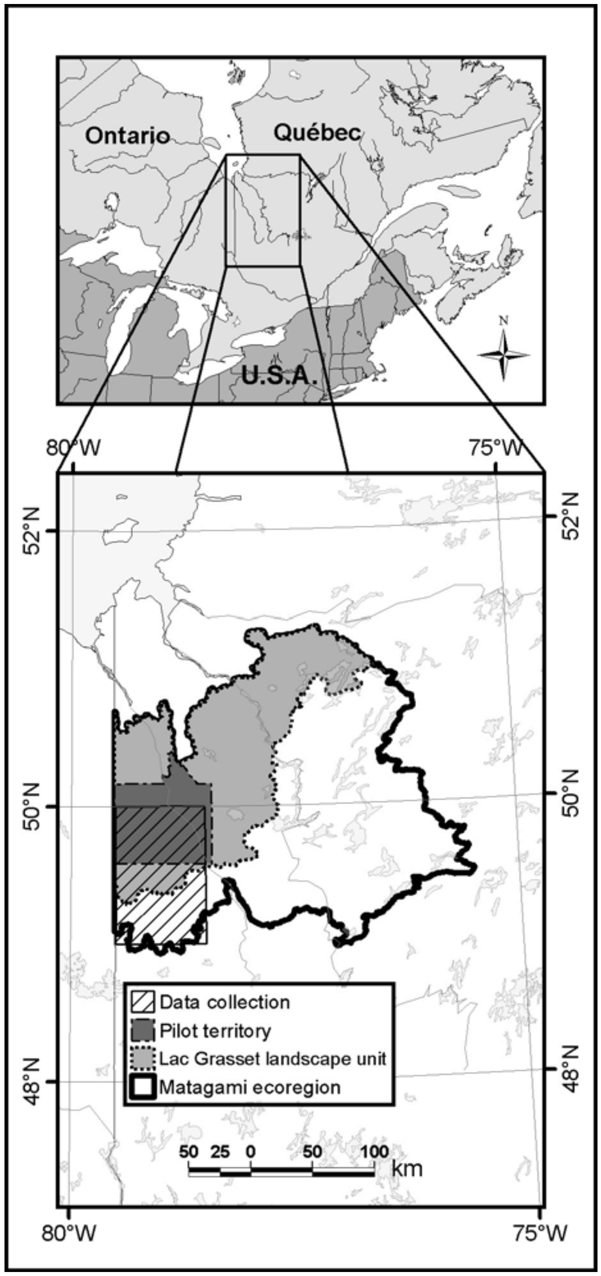

Figure 1. Locations of the areas used for data collection and for the pilot management study.

According to the forest inventory conducted by Quebec’s Ministère des Ressources Naturelles, only about 50% of the area is covered by commercial forest, and large areas are covered by bogs. This commercial forest is primarily black spruce stands (87%), with occasional jack pine (8%) and trembling aspen (5%) stands on the better-drained sites. Three major fires have occurred in the last 40 yr (1962, 1976, and 1997) and harvesting operations have taken place since 1984. The regenerating forests represent about 30% of the land area occupied by the commercial forest, and about half of the regenerating forest originates from harvesting activities. Although industrial forestry only began around 20 yr ago in this region, the territory has been partially accessible for about 30 yr due to the construction of primary roads to two mines in the area. However, many parts of the territory are only accessible in winter because the extensive bogs and major rivers can only be crossed when they are frozen. Fire suppression was minimal before 1970, as the territory was mostly inaccessible and the usage of “water bombers” only started at that time. Moreover, the area was only included within the province’s zone of intensive fire protection once harvesting activities began.

KNOWLEDGE OF NATURAL DYNAMICS

Variability in Natural Disturbance

Data on the region’s fire history and forest dynamics were mostly gathered in the southwestern subsection of the Matagami ecoregion (from 49º00 to 50º00’N and 78º30’ to 79º30’W (Figure 1). Using archival data, air photos and ground-truthing techniques, the fire history for the last 300 yr has been reconstructed; see Bergeron et al. (2001) and Gauthier et al. (2002) for a complete methodology. This reconstruction showed that large areas are still covered by stands that have not burned for a considerable period of time; 57% of the data collection area is composed of forest that burned more than 100 yr ago, and 20% is older than 200 yr (Figure 2). This suggests that under a natural fire regime, a significant proportion of the stands were undisturbed by fire for long periods.

However, fire cycles have changed within the last 300 yr (Bergeron et al. 2001). From the short cycle of around 100 yr before 1850, fire cycles increased to 130 yr by around 1920, and have increased since then to an estimated 400 yr (Table 1). As this change started before human settlement, it appears to be related to climate change, which became less conducive to large fires after the end of the Little Ice Age (Bergeron et al. 2001; Lefort et al. 2003). The more recent increase in fire cycle (from 1920) may have also resulted from human activities such as road construction and fire suppression.

As Table 1 shows, the mean stand age also increased from 1850 to the present, but more slowly than the increase in fire cycle. The age structure of the forests has a certain inertia with respect to changes in the fire cycle. Moreover, the mean stand age integrates the changes in the fire cycle over the past 300 yr. For these reasons, we suggest that the average stand age in the study area (expressed in terms of time since the last fire) can be used as a baseline for planning harvesting activities in order to estimate the desired proportion of each age class to be maintained by means of different silvicultural treatments. This is discussed in more details later in this chapter, and in terms of the cohort model of Bergeron et al. (1999b, 2002). For the study area, the mean age was estimated at 151 yr.

Table 1. Fire cycle, 95% confidence interval of fire cycle, and mean stand age estimated in the southwestern section of the Matagami ecoregion
(See Figure 1 for the location of this region)

	Fire cycle (yr)		
	Before 1850	Before 1920	Today
Cycle	103 (80-131)	133 (106-167)	398 (302-524)
Mean age	87 (66-114)	102 (85-123)	183 (154-218)

We used the data from the same area to study the fire-size distribution (Figure 2b). Whereas the majority of fires were smaller than 1000 ha, these fires were only responsible for a small fraction of the total area burned (Bergeron et al. 2002). Consequently, large fires (those larger than 1000 ha) were responsible for most of the area burned, and therefore created much of the age structure and configuration of the landscape in terms of stand composition (Johnson et al. 1998). Bergeron et al. (2002) suggested that the characteristic size of these fires varied from 950 to 20 000 ha, and that regeneration areas should therefore fall within this range of sizes.

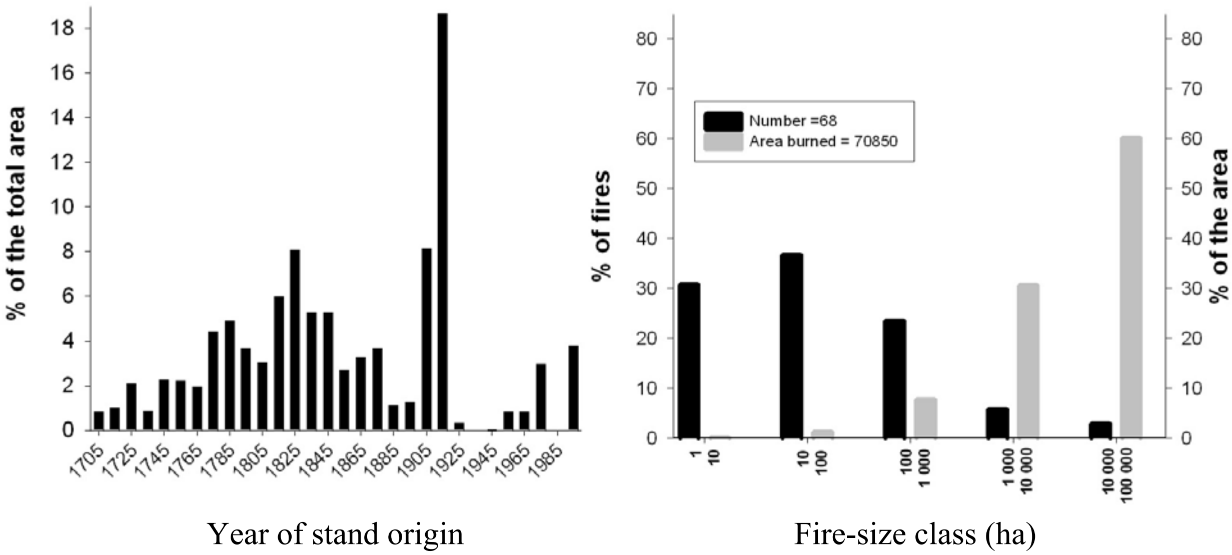

Figure 2. The post-fire origin of stands in the study area (% of total area; left panel) and fire-size distribution (1945-1998; right panel) in the southwestern section of the Matagami ecoregion.

It must be recognized that severity varies within any single fire, especially if the fire covers very large areas and burns for longer than a day; as a result, the fire will leave patches of living trees behind (Van Wagner 1983; Turner and Romme 1994; Kafka et al. 2001; Bergeron et al. 2002; Ryan 2002). Although the areas that totally escape burning (preserved islands) appear to be relatively constant from year to year, at around 5% of the total area (Eberhart and Woodard 1987; Bergeron et al. 2002), the zones of low fire severity depend greatly on seasonal weather. In fact, “low-severity zones”, which include areas that totally escaped the fire and those that only sustained intermittent crown fires, may occupy up to 50% of a burned area, depending on the type of forest, especially when the prevailing weather conditions are relatively mild (Bergeron et al. 2002). The presence of these lightly burned zones suggests that the pattern of mortality generated by fire is very distinct from that which results from conventional forest harvesting. Trees that survive a fire not only appear to play a determining role in regenerating burns (Greene and Johnson 2000), but also represent refuge (shelter) habitats for wildlife in the regenerating forest and increase the spatial heterogeneity of the forest mosaic that results from the fire.

Forest Dynamics

Many studies on vegetation dynamics have been conducted in the Matagami ecoregion (Bergeron et al. 1999b; Gauthier et al. 2000; Harper et al. 2002, in press). Although the data on the vegetation were obtained from chronosequence studies, the congruence between these results and the results from permanent sample plots (Lesieur et al. 2002) in another region of western Quebec's boreal forest supported our interpretation of successional trends. The results of these studies are summarized in the next section and in Table 2. After a fire, stands are recolonized mainly by three species, black spruce, trembling aspen and jack pine, and these species show some preference for specific types of surficial geology. For instance, jack pine and trembling aspen are more common on rock, sand, or clay till sites than on organic sites, whereas black spruce is present on all sites.

Table 2. Mean importance values [a] and standard error *(italics)* for 8 tree species for the main surficial geology types[b]

			Mean importance value							
	Time since fire (yr)	**No. of stands**	**Black spruce**	**Jack pine**	**White birch**	**Balsam fir**	**White spruce**	**Trembling aspen**	**Balsam poplar**	**Larch**
Surficial geology										
Rock	50	5	29.7	46.8	9.2	2.8	0.4	9.0	0.0	2.2
			18.9	*29.1*	*13.6*	*6.2*	*0.9*	*20.1*	*0.0*	*5.0*
	150	2	64.0	34.2	1.8	0.0	0.0	0.0	0.0	0.0
			0.3	*2.8*	*2.5*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Clay till	50	12	23.9	52.3	6.3	6.3	2.2	9.1	0.0	0.0
			25.1	*35.0*	*13.6*	*13.8*	*6.5*	*24.3*	*0.0*	*0.0*
	150	4	41.2	18.1	7.1	1.4	0.0	22.5	7.9	1.8
			36.6	*36.2*	*8.2*	*2.9*	*0.0*	*29.8*	*15.7*	*3.7*
	250	1	1.8	95.3	0.0	0.0	0.0	2.9	0.0	0.0
			--	--	--	--	--	--	--	--
Sand	50	9	26.0	58.7	9.3	0.9	1.5	3.6	0.0	0.0
			20.6	*23.8*	*17.8*	*1.6*	*3.1*	*8.0*	*0.0*	*0.0*
	150	3	45.5	20.8	6.0	22.8	0.0	5.0	0.0	0.0
			27.5	*19.5*	*10.3*	*39.5*	*0.0*	*8.6*	*0.0*	*0.0*
Organic	50	35	61.8	22.8	1.7	4.3	3.4	4.2	0.0	1.8
			31.6	*27.4*	*7.2*	*11.7*	*12.6*	*11.5*	*0.0*	*6.3*
	150	20	85.7	5.4	0.9	6.6	1.0	0.0	0.0	0.5
			24.8	*18.0*	*2.8*	*12.8*	*4.4*	*0.0*	*0.0*	*1.4*
	250	17	92.4	0.0	0.8	6.1	0.0	0.0	0.0	0.6
			17.3	*0.0*	*3.4*	*14.1*	*0.0*	*0.0*	*0.0*	*1.9*

[a] (relative frequency + relative basal area) /2

[b] Larch = *Larix laricina* (Du Roi) K. Koch.

Within the first 100 yr, on organic sites, the majority of stands on organic soils are dominated by black spruce (Table 2; Gauthier et al. 2000; Harper et al. 2002), though some stands are dominated by jack pine or trembling aspen. As the time since the last fire increases, the presence of both pioneer species tends to decrease considerably while the importance of black spruce increases. In black spruce stands, the vertical structure becomes irregular over time; for example, stand height and density both tend to decrease with increasing time since the last fire even while the abundance of canopy gaps is increasing (Harper et al. 2002). On the other site types, canopy dominance changes from deciduous stands or stands dominated by jack pine to stands dominated by black spruce when the interval between fires is long enough. For instance, on rocky and sandy site types, jack pine tends to dominate young stands, but black spruce becomes dominant in stands older than 100 yr. Moreover, if the time between fires is sufficiently long, the pioneer species may disappear from the stand. Because the fire cycle in this region typically exceeds 100 yr, change in both species composition and stand structure represents a significant component of vegetation dynamic in the area (Carleton and Maycock 1978;, Gauthier et al. 2000; Harper et al. in press).

Harper et al. (in press) also conducted a stand-level study of structural changes along a chronosequence, and found that the stand-level structural characteristics of old-growth forests differed among site types. On organic sites, the abundance of snags and logs was highest in the oldest stages, as would be expected for old-growth forests (Kneeshaw and Burton 1998), whereas snags and logs were least abundant in the oldest stages of clay and sand site types; the peak value for these two structural attributes was observed at around 150 to 200 yr. As stands converge towards pure black spruce, both the canopy cover and the canopy height tend to decrease (Harper et al. 2002). The old-growth phase is also characterized by an increasing thickness of organic matter and increased richness and cover of *Sphagnum* spp. compared with younger sites (Boudreault et al. 2002; Harper et al. in press).

Responses of Organisms to Natural Dynamics

The non-vascular and vascular understory species composition as well as that of epiphytic lichens have been studied along a stand chronosequence defined in the forest dynamics section of this chapter (Boudreault et al. 2002; Harper et al., in press). For these three groups, the composition of the species assemblages changed along the chronosequence, mainly in response to changes in the degree of canopy closure, time since the last fire, or depth of organic matter. The non-vascular terricolous assemblages responded mainly to changes in the stand composition, time since the last fire, and depth of organic matter. The floor of the mature forest, with its high basal area of trees and relatively low depth of organic matter, was characterized by a carpet of mosses typical of closed boreal forests, such as *Pleurozium schreberi* (Brid.) Mitt., *Ptilium crista-castrensis* (Hedw.) De Not., *Polytrichum commune* Hedw. and *Dicranum polysetum* Sw. (Boudreault et al. 2002; Harper et al. 2002). Such a species composition persists through the early stages of old-growth development (>100 yr). When tree basal area begins to decline, at about 150 yr after a fire, the species richness and percent cover of *Sphagnum* spp. increased together with the increasing thickness of the organic matter horizons.

Differences in the species composition of understory vascular plants were also strongly related to the basal area of live trees and the time since the last fire (Harper et al., in press). In young and mature forests, which are closed-canopy stands, there was greater cover and richness of herbs and low shrubs, as well as greater fern richness, than in older forests. With the increasing dominance of black spruce, and as tree basal area decreases in the absence of fire, the understory became dominated by ericaceous species. Finally, epiphytic communities mainly responded to variations in the stand composition, time since the last fire, and tree age. The total number of species of epiphytic lichen was greater in forests in the early stages of old-growth development and where trembling aspen or jack pine were still present in the canopy (Boudreault et al. 2000, 2002). The abundance of epiphytic lichens was closely and positively related to mean tree age.

Drapeau et al. (in press) have studied bird communities in the same area along a 300-yr chronosequence. They showed that bird communities are also responding to changes in the degree of canopy closure: more species associated with closed-canopy forests were observed in forests that are in the early stages of old-growth development (100 to 120 yr), whereas in the oldest forests (>200 yr), bird assemblages were dominated by species associated with or tolerant of more open canopy conditions. Moreover, primary and secondary cavity nesters associated with standing dead wood (such as woodpeckers, nuthatches, and creepers) were also more abundant in landscapes that had not burned for 100 to 120 yr than in our oldest forests (>200 yr). This result is not surprising given the low densities of snags observed in the oldest forests of our study area (Drapeau et al. 2001; Harper et al. in press). Old-growth forests in their early stages retain a closed canopy with large trees while snags start to accumulate. This combination of canopy closure with attributes that generate structural heterogeneity (snags and downed woody debris) meets the habitat requirements of many forest-dwelling birds. Such conditions are lost as the forest becomes older than 200 yr. Bird communities in old-growth forests thus change considerably as the forest ages (from 100 to 200 yr) and the composition of these species assemblages closely reflects the changes that take place in the structure of the vegetation.

Finally, forest fires in this region extend over very large areas and produce large areas covered by stands with a similar age and structure. Such a coarse-grained landscape mosaic also affects the distribution patterns of organisms. Several studies have shown that mobile organisms such as birds are affected by the nature of the landscape that surrounds their habitats in the boreal forest (Edenius and Elmberg 1996; Schiemegelow et al. 1997; Drapeau et al. 2000). In the black spruce ecoregion, the spatial adjacency of similar structural conditions over large areas (10 to 100 km^2) was an important factor affecting the composition of bird communities (Drapeau et al. in press).

Overall, our studies show that regardless of the taxonomic group selected, many species reach their peak of abundance in the early stages of old-growth development (between 100 and 200 yr after a stand-replacing fire), when highly diversified structural conditions occur. This phase corresponds to the start of decadence in the post-fire cohort, which begins to die and be replaced in the canopy by trees recruited from the understory (see the next section for details). These conditions do not persist in forests older than 200 yr, so species associated with more open habitats occupy these forests. For this reason, the portions of the chronosequence that cover old-growth development prior to 200 yr after a fire are key habitats from the perspective of biodiversity for the black spruce forest ecosystem. Because these forests cover more than 20% of the land base in the study region, they may have a strategic importance in the population dynamics of many forest-dwelling species by being source habitats.

A Conceptual Model of Natural Disturbance and Forest Dynamics

As suggested by Gauthier et al. (1996) and discussed by Bergeron et al. (1999b, 2002), maintaining the region's observed biological diversity requires the development of management strategies that will maintain a forest mosaic similar to that observed under natural conditions. To accomplish this goal, the proportions of the area occupied by different stand types (based on composition and structure) must be kept similar to those observed under the forest's natural dynamics, the spatial patterns of harvesting must resemble natural spatial patterns, and a variety of disturbance severities must be maintained within harvesting areas. The information presented in the previous section can serve as a basis for designing such a strategy.

As a first step, we have illustrated a simplified version of forest succession in the pilot study area (Figure 3). Three main pathways have been defined, depending on the relative importance of the main species that form the post-fire cohort: jack pine, trembling aspen, and black spruce (the most common species in our study area). The post-fire cohort forms the 1st cohort, and if a fire occurs while the stand is within that stage, cyclical succession would occur, as is observed in many boreal regions (Johnson 1992). Given that the fire cycle is relatively long in the study region, the interval between fires at many sites is longer than the normal longevity of individual trees in the post-fire cohort, and these sites succeed to the old-growth forest stage (Kneeshaw and Gauthier, in press). With a long fire interval, the species composition (or stand structure) changes from a forest regenerated by a shade-intolerant post-fire cohort (trembling aspen or jack pine) to stands recolonized by black spruce. These changes reflect the replacement of individuals that became established immediately after a stand-replacing fire and that initially formed the stand's canopy (the 1st cohort) by individuals that previously occupied the understory (the 2nd cohort). Moreover, in the continuing absence of fire, gap dynamics perpetuates the replacement of individuals from these first two cohorts by individuals from later cohorts (collectively called the 3rd cohort because the individual cohorts gradually become harder to distinguish). It is important to realize that the rate of these transitions may vary among site types and types of transition. For instance, Bergeron (2000) and Cumming et al. (2000) have shown that trembling aspen is capable of recolonizing gaps and maintaining itself in stands for more than 200 yr.

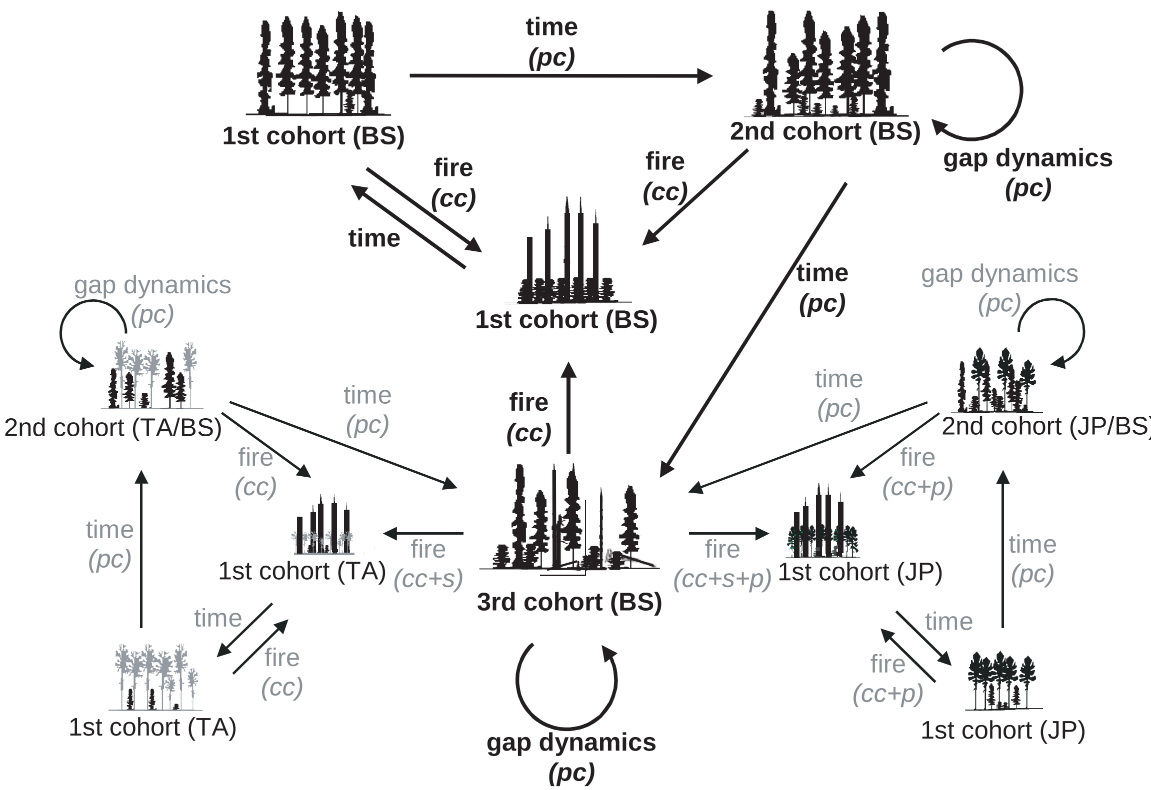

Figure 3. Conceptual model of natural forest dynamics proposed for the Matagami ecoregion and the corresponding management strategy. BS = black spruce (*Picea mariana* [Mill.] B.S.P.), JP = jack pine (*Pinus banksiana* Lamb.), TA = trembling aspen (*Populus tremuloides* Michx.), **cc** = clearcutting, **pc** = partial cutting, site preparation (s), plantation (p).

These three developmental stages (cohorts) cover a gradient in the time since the last fire (*temporal* cohorts) that is also associated with gradients in a stand's horizontal, vertical, and compositional structure. Thus, the three stages can also be described using different stand structural attributes (*structural* cohorts). More specifically, forest stands associated with the 1st cohort are usually closed-canopied and have a relatively simple vertical structure that lacks distinct canopy layers. When shade-intolerant species are present (which depends on the composition of the initial regeneration), these trees are found in the dominant canopy layer of stands in the 1^{st} cohort. In stands of the 2^{nd} cohort, the canopy is often semi-open and usually has several distinct canopy layers. These stands are composed of both shade-intolerant and shade-tolerant tree species when the stand's composition is mixed. Finally, stands in the 3^{rd} cohort are primarily composed of shade-tolerant species, have an open canopy, and possess a continuous vertical structure (i.e., numerous indistinct canopy layers in which trees follow an inverse-J diameter distribution).

Our results have also shown that the species assemblages of forest flora and fauna respond to changes in stand structure, mostly in terms of changes in the abundance of individual species, with few species restricted to a particular stand age stage. Consequently, we have chosen to use structural cohorts in our operational model to simplify the implementation of the management strategy that more closely resembles the effects of natural disturbance because a stand's structural attributes are easier to measure in the field than stand age; in addition, species respond more to the changes in structure than to changes in stand age *per se*, and silvicultural treatments directly modify stand structure. For these reasons, we have simplified the patterns of natural disturbance and forest dynamics in the Matagami ecoregion using the cohorts illustrated in Figure 3. In this model, the 1^{st} cohort has been divided into two distinct developmental stages (regenerating and mature) with significant differences in stand structure. Figure 3 also uses different successional series to illustrate the differences in composition observed among site types, for instance. All three successional series converge towards the primarily shade-tolerant 3^{rd} cohort of black spruce, but this convergence may take different lengths of time depending on the successional series or site type. In all, our conceptual model of forest dynamics includes 10 main stand types.

This conceptual management model assumes that we can manage for the 10 main stand types by means of several types of silvicultural intervention (Figure 3). The proposed mixed (even-aged and uneven-aged) management strategy uses clearcutting to initiate stand regeneration and uses partial harvesting techniques (partial cutting or selective cutting) to maintain or establish the structural and compositional characteristics of later successional stages (Bergeron et al. 1999b). Thus, it aims at preserving the integrity of the forest ecosystem through the maintenance of its different ecological elements and processes.

IMPLEMENTATION OF A FOREST MANAGEMENT MODEL BASED ON NATURAL DISTURBANCE

Landscape-level Objectives

Implementation of the model based on natural disturbance that we developed for the Matagami ecoregion is currently being tested in a pilot study area in the Lac Grasset regional landscape unit (Figure 1). In this area, the forest management strategy presented in Figure 3 has been integrated within different levels of forest management planning (Tittler et al. 2001) in order to assess the feasibility and possible repercussions of implementing the management model. At the strategic level, regional objectives for cohorts in the study area were established as follows: 62% of the area would be covered by stands in the 1st cohort, 21% by stands in the 2nd cohort, and 17% by stands in the 3rd cohort. As suggested by Bergeron et al. (1999b), these proportions were established using the predicted negative-exponential curve for age distribution (Van Wagner 1978), with an average stand age of 151 yr (determined for the pilot study area using the fire history map described previously) and with transition ages of 150 and 275 yr between the 1st and 2nd cohorts and the 2nd and 3rd cohorts, respectively. The proportions of the total area in each cohort represent overall objectives for the three successional series. Note also that specific objectives for each forest composition can be derived using the same procedure.

To compare the ability of different management strategies to achieve the regional cohort objectives, a timber-supply analysis was carried out using three different management strategies (Nguyen 2000). At the start of the analysis, the three cohorts occupied 58, 28, and 14% of the total area (1st, 2nd, and 3rd cohorts, respectively). The first strategy is an even-aged management system based on clearcutting with the protection of regeneration and soils (equivalent of

Quebec's CPRS: *coupe avec protection des sols et de la régénération*). The two others are mixed management systems based on clearcutting and partial cuts with a 14-cm diameter limit (equivalent of Quebec's CPPTM: *coupe avec protection de petites tiges marchandes*, CPPTM14) or with a 16-cm diameter limit (CPPTM16). The timber-supply analyses indicated that at the end of the 150-yr simulation period, the mixed management systems came closer than the even-aged management system to meeting the cohort objectives (Table 3). The analyses also suggested that a mixed management system would not significantly affect annual allowable cuts, which remained at the same level for all scenarios (Table 3). Note, however, that in the mixed management strategies only 15 to 20% of the managed forests were considered suitable to partial harvesting.

Table 3. Annual allowable cut (AAC), and proportions of treatments and area (%) of the land base in the pilot study occupied by the three cohorts at the end of the simulation horizon (year 150) for the different management strategies. The timber-supply analysis used the SYLVA II model (Ministère des Ressources Naturelles du Québec 1997)

	Management scenario[a]		
	CPRS	CPPTM14	CPPTM16
AAC (m^3/ha)	130 000	132 000	132 000
% of area			
clearcut	100	76	74
partial cut	0	24	26
% of commercial area suitable for partial treatment	0	21	17
1st cohort	75	69	65
2nd cohort	19	22	26
3rd cohort	6	9	9

[a] CPRS = clearcutting with the protection of regeneration and soils; CPPTM = harvesting with the protection of small merchantable stems (14 and 16cm dbh diameter limits, respectively).

Spatial Patterns of Harvesting

The region's fire regime, which is dominated by large fires, is responsible for the large areas covered by stands with similar ages and structures. Old-growth forests are therefore extensive and represent unique and a significant structural features of the landscape. This contrasts with the patterns in western Canada, where old forests are mostly remnant patches that have not burned in recent fires (Johnson et al. 1998). At the tactical planning level, we devised a strategy for determining the spatial and temporal distribution of harvesting activities inspired by those natural patterns. The strategy is built upon two main elements: management *zones* that represent the individual management units to be managed over time and management *complexes* that determine the spatial distribution of harvesting activities within a management zone. Management zones represent the individual disturbances that have historically shaped the forest landscape, whereas management complexes correspond to the patterns of disturbance severity historically observed within the area affected by each disturbance.

Figure 4 illustrates a portion of the initial strategy proposed for the area of the pilot study based on a preliminary analysis of the potential agglomeration of harvesting activities (management complexes) in different management zones. It proposes three types of management zones: even-aged management based primarily on clearcutting, uneven-aged management based primarily on partial cutting, and "light" management based on limited harvesting in areas dominated by non-productive forests. These zones range from 5000 to 40 000 ha in size.

Table 4 describes the management complexes for three of these zones and Figure 4 illustrates the spatial distribution of the harvesting systems, which is quite distinct for the three zones. Each zone will be managed over a period of 5 to 10 yr. Following the strategy illustrated in Figure 4, 63% of the pilot area consists of even-aged management zones over the course of a rotation, versus 9% of the area in uneven-aged management and 28% in light management zones. Compared with the regional cohort objectives, this strategy yields a deficit in the 2nd cohort and a surplus in the 3rd cohort. This discrepancy reflects the difficulty of properly identifying stands eligible to partial harvesting exclusively from current forest inventory maps (Nguyen 2001, 2002). Tactical planning of a mixed management strategy will benefit from the ongoing development of complementary analytical tools.

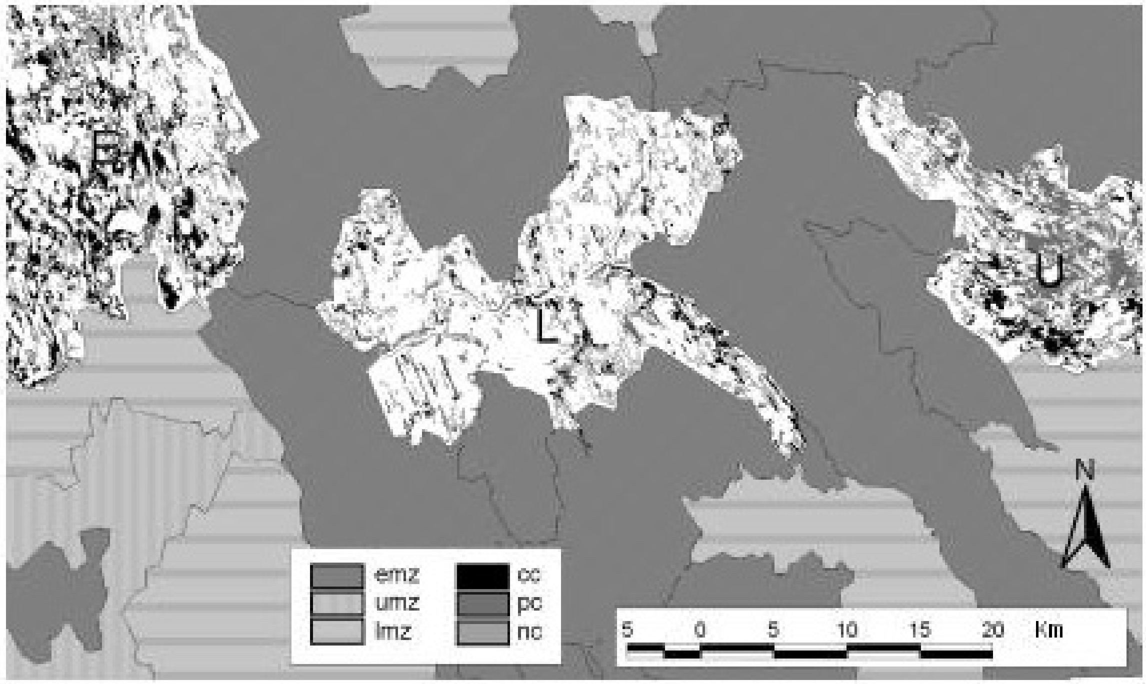

Figure 4. Initial proposed strategy for the agglomeration of harvesting activities (management complexes) in three management zones. Types of management zones: emz =even-aged management zone, umz = uneven-aged management zone, lmz = light management zone. Harvesting blocks within a given management zone: cc = clearcut harvesting, pc = partial-cut harvesting, nc = no harvesting -unexploitable. One zone in each category has been selected to show the array of treatments possible. These units would be affected entirely by treatments within 5 to 10 yr. Note, however, that because the white areas are those that are non-commercial forest areas, they would remain intact .

Table 4. Proportions of the area in each management zone occupied by the different types of harvesting blocks.

Three of the management zones illustrated in Figure 4 are examined in more detail.

	Proportion (%) of area in management zone		
	Even-aged management	Uneven-aged management	Light management
Type of harvesting			
Clearcut (cc)	50.7	16.5	27.9
Partial cut (pc)	20.5	56.3	22.0
No harvesting (nc)	28.8	27.2	50.1

Field Silvicultural Guide

The final planning level at which the mixed management strategy must be integrated is the operational level. This requires the development of field recognition guides for the 10 main stand types represented in the conceptual model in Figure 3. It also entails the development of silvicultural guides that will be used by forest managers to establish the appropriate silvicultural prescription for a given stand. Finally, it requires the definition of criteria that can be used to evaluate the success of the different silvicultural interventions.

Monitoring

The forest management model in Figure 3 assumes that partial harvesting will maintain or establish forests that possess the ecological elements associated with older forests. To begin validating this assumption, several partial-cutting trials have been performed or are currently underway in the Matagami ecoregion. The dendrological, floristic, and faunal data collected prior to and following these interventions will serve to document and test the assumptions. Although the overall study is not yet completed preliminary results from an analysis of the dendrological data collected in the Maskuchi partial-cutting trials (Morasse 2000) suggest that partial harvesting (in this case, a 17-cm diameter-limit cut) can successfully maintain the irregular (uneven-aged) stand structure associated with the 2nd and 3rd cohorts. Similar results have been reported by MacDonell and Groot (1996) in diameter-limit cuts performed in black spruce stands of the nearby Ontario Claybelt. Monitoring the responses of organisms in these trials and comparing their distributions to those in natural stands in the 2nd and 3rd cohorts is required for us to assess the effectiveness of such a forest management strategy for maintaining biodiversity.

CONCLUSIONS AND FUTURE IMPROVEMENTS

The implementation begun 3 yr ago is already providing promising results in terms of forest sustainability. For instance, preliminary simulations of AAC suggested that the strategy can be implemented with very little effect on timber supply while helping to maintain the forest's structural and compositional diversity. Moreover, preliminary results are also beginning to show that treatments can be developed to maintain the structural characteristics of mature, overmature, and old-growth stands, at least in the short term. It appears that the present scientific knowledge of the natural ecosystem's dynamics on which we based the development of the management strategy was sufficient to initiate the implementation of such a strategy. Moreover, the ongoing input provided by new results from the first three research themes facilitates and improves the development of tools and guidelines that stem from the fourth research theme. In this sense, the monitoring of managed forests forms an integral part of the strategy and can easily be incorporated in the different research themes.

On an operational level, there is still a need to continue developing silvicultural treatments and planning tools. In fact, considerable work will have to be devoted to the development of practices that have ecological effects that resemble those of fires. The work done on ecosite classification by the classification group of Quebec's Ministère des Ressources Naturelles will help to refine the silvicultural prescriptions, as has been done for the boreal mixedwood forest (Bergeron et al. 1999a;, Harvey et al. 2002). Moreover, information on stand structure, which is difficult to derive from current forest resource inventory data, will become easier to derive using tools that are currently in development (Boucher et al. in press). We do not yet have wood-supply models that can simulate partial or selective cutting. However, our management knowledge and tools are rapidly improving.

It is at the social and institutional levels that successful implementation of the strategy remains uncertain. The use of management strategies based on natural disturbance and of mixed management (even-aged and uneven-aged) systems in the boreal forest is not yet fully acknowledged in Quebec's forestry policies and regulations. The social acceptability of these strategies and systems (at the aboriginal, local community, regional, and provincial levels) also remains to be assessed. Increased public participation in the strategic planning process and an adaptive management approach would facilitate the implementation of the proposed strategy in the province's forest management units.

However, there is an urgent need to develop and implement strategies for the conservation of biodiversity. Current forestry practices, which target mostly mature and overmature forest, will considerably modify the proportions of these types of forests in the land base, particularly in eastern Canada, where they represent large, continuous areas. This will in turn affect the biodiversity of these forest regions. We trust that in many regions of Canada, disturbance-based strategies will offer a coarse-filter solution that could mitigate these predicted changes in biodiversity and that can be developed and implemented quickly. It is urgent to do so even though our knowledge is incomplete and imperfect because it will be easier to implement strategies such as the one we have proposed while we still have virgin forest than it will be to restore vanished ecosystems, as is presently the case in Europe (Kuuluvainen et al. 2002).

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