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INTRODUCTION

In the last four decades there has been a dramatic evolution in forest management. When forests were considered inexhaustible, there was little concern for sustained management beyond the legislation of diameter limit cutting. The best trees of the most commercially valuable species were cut as needed, and the forest was left to care for itself. As demand for wood products increased and even-age single species management systems were increasingly adopted, much more use was made of clearcutting. Stands were either left to regenerate naturally with variable success, or remedial measures were employed (most often planting). When it became mandatory to ensure regeneration of all logged stands, planting programs were simply escalated. Simple stand structures were favoured, and this meant managing for pure, even-aged stands. Sites that were classified as mixedwoods were typically managed as either pure coniferous or pure deciduous stands, depending on the pre-harvest proportion of the species. After logging they were frequently classed as monocultural stands and managed accordingly.

With the recent development of the concept of ecosystem management (Rowe 1992) there is an increasing interest in using, on a large proportion of the forest landbase, management systems that more closely mimic natural stand dynamics, and this interest can be driven by financial rather than environmentalist concerns. Ecosystem management often means maintaining mixtures of species that naturally occur together. Maintaining mixedwood boreal stands as an integral part of the forested landscape is being recognised as a priority across the boreal forest. One such mixture, typical of mesic stands in the southern boreal forest, is that of white spruce (*Picea glauca* (Moench) Voss)), balsam fir (*Abies balsamea*) and trembling aspen (*Populus tremuloides* Michx.). The three species have ranges extending meridionally from the interior of British Columbia (or western Alberta for fir) to the Maritime provinces (Nienstadt and Zasada 1990; Perala 1990), and they are often found growing together in various proportions, from pure stands of one species all the way to pure stands of the other. In the west, white spruce and aspen are the main constituents of mixedwood stands (Lieffers et al. 1996a). In the east, balsam fir is more prevalent than white spruce and typically white spruce is only a very minor component (Kneeshaw and Bergeron 1998); nonetheless there is keen interest in increasing the presence of white spruce. Although black spruce may not be much rarer than white spruce in upland eastern stands promoting black spruce stocking is not part of the silvicultural goals entertained here.

Our objective is to see how currently available knowledge can be used to develop management prescriptions aimed at obtaining full conifer stocking, perpetuating mixed stands, or pushing them silviculturally toward a larger coniferous component. Historically, mixedwood stands do not maintain a composition that is static. Rather composition often shifts from hardwood dominance to conifer dominance at the stand scale although at the landscape level relative proportions may remain more or less constant. Being able to use the resources found within a stand to manipulate regeneration and future composition will be important for foresters working within the boreal mixedwood zone.

Here we will not deal with mixed stands that are primarily coniferous; we will assume the stand in question has a conifer component ranging from 1 to about 50% of the stand. Moreover, we deal here only with the stand establishment phase; subsequent growth will vary with size and light environment (Messier et al, 1999). In practice, many of our prescriptions are based on the establishment and growth of spruce and/or fir in the understory of aspen stands and, since the aspen matures earlier than the conifers, harvesting some or all of the aspen but retaining the advance conifers. In this paper we begin with an examination of a prescription based on understory planting of white spruce. We then turn to prescriptions for white spruce and fir that rely on advance regeneration or understory scarification during a mast year. Our fourth prescription is for the direct seeding of white spruce. We conclude with an evaluation of the reliability of each prescription and then a sketch of the comparative costs of the various prescriptions relative to the more conventional regime of clearcutting followed by planting.

Every prescription discussed here (or variants of them) has been tried, at least on a trial basis, somewhere in Canada. Some have been deemed too unreliable. Our primary objective here is to show how better knowledge of the regeneration ecology of the two conifer species will permit us to quantify where and when a particular prescription will give both high reliability and low comparative cost per hectare. (The reader is forewarned that only present costs are used and that discounting of future operations is not included in the analysis). This paper is, thus, to some extent a review of the relevant scientific literature as well as of ongoing projects and we hope that it will provide the forester with a palette from which variants of the discussed prescriptions can be drawn.

The four alternative prescriptions that we develop (and their possible variants) will serve as alternatives to planting in clearcuts. The first prescription, *understory planting*, is presently undergoing many trials in western Canada. Large stock white spruce is planted under aspen canopies with light transmission rates of about 15-40%. The procedure is based on the ecological knowledge that regenerating spruce, following fire, invariably grows more slowly at first than the asexually recruited aspen. Nonetheless, our prescription has been guided as much or more by concerns of reliablilty and cost than with the ideology of mimicing nature.

The second prescription, *reliance on advance regeneration*, is already common with both black spruce and balsam fir stands in eastern Canada, and is likely to become increasingly common in mixedwood stands (aspen, white spruce, and fir). For this prescription we develop a simple model, based on the protection of small pre-established stems (in Quebec: CPRS (Coupe avec Protection de la Regeneration et des Sols); in Ontario: CLAAG (Careful Logging Around Advance Growth). In some cases, larger stems may be protected leading to uneven age stands (in Quebec: CPPTM (Coupe avec Protection de Petits Tiges Marchand; in Ontario: HARP (Harvesting with Advance Regeneration Protection); and in Alberta, Corridor Cutting with the protection of larger sub-dominant stems during the harvest. Our model incorporates pre-harvest advance regeneration density, expected mortality during the operation, and the relationship between stocking and density, to arrive at the pre-harvest density required to obtain adequate stocking. For this prescription, white spruce and fir are treated as if they have similar intra-harvest and post-harvest mortality.

The third prescription, *reliance on natural regeneration following understory scarification in a mast year*, has never been used operationally anywhere in Canada. Nonetheless, trial operations during mast years (e.g. Stewart et al, in press; Lees, 1963, 1970; DesJardins, 1988) show that this method can be effective, and that seedbeds remain receptive for three to five years with blade, mixed, or rake scarification. The model elaborates the expected relationship between seed production, juvenile survivorship, and scarification intensity. The full stocking version of the prescription would occur in the following sequence: (1) recognition that a mast year is occurring (June); (2) understory scarification prior to seed abscission (July/August); (3) winter or early spring harvest (January to April) after the seed abscission is essentially completed in autumn. As white spruce and fir are typically found together, especially in eastern Canada, with aspen on mesic sites, and given the similarity of their seedbed requirements and masting schedules, we have lumped the two conifer species together for this prescription. It is recognised that spruce will usually dominate in the west and fir in the east.

The fourth prescription, *reliance on direct seeding following scarification*, has been tried many times before with white spruce and that trial record is, on balance, one of poor reliability (Waldron, 1974). We use the same equations as in the preceding two prescriptions to show the relationship between the scarification intensity and the sowing rate required for adequate stocking. The results of our modelling exercise indicate both why white spruce aerial seeding has seldom succeeded (too few seeds; too little scarification), and why the prescription is unlikely to be widely used (the great number of seeds required per ha precludes it from being a common practice: it would simply be too costly to collect sufficient seeds to treat every cut mixedwood area in this manner). An analysis of direct seeding during mechanized scarification operations (i.e. the same machine scarifies and sows) shows this to be a viable method both biologically and in terms of cost, but more trial are required with white spruce to legitimize the approach.

Following the presentation of the four prescriptions, we briefly sketch out the likely present costs of each, and then compare them with a more conventional operation where a large clearcut is followed by planting. Our main conclusion from this costing exercise is that, where stand conditions permit, reliance on advance regeneration in the east and understory planting in the west are invariably the cheapest alternatives. The other prescriptions, under certain conditions, are typically cheaper than conventional clearcut/planting operations, especially where herbicides are prohibited.

We conclude with a decision key that synopsizes the results as it combines the biotic constraints (basal area per ha of the conifer seed sources, aspen canopy light transmission rates, and advance regeneration stems per ha) and cost minima to render the best prescription. Suggestions for possible variations on the proposed prescriptions for moderate stocking (i.e. true mixedwood management) will also be presented in the key.

We make an important caveat here. Although we discuss the possible consequences of competition for our prescriptions at no point do we explicitly account for the enhanced mortality due to the more severe competition problems. We most certainly expect aspen to resprout vigorously in these mixed stands, and, consequently a weeding operation is included in the cost for every prescription (except understory planting) if quick conversion to a conifer dominated stand is the objective. If the interval between recruitment and overstory removal is on the order of two decades or more, understory scarification in a mast year may not require weeding of the aspen. Furthermore, in the west the grass *Calamagrostis* can envelop and kill the typically slow-growing spruce (Lieffers et al, 1993), while in the east shade-tolerant shrubs such as mountain maple (*Acer spicatum*) can quickly overtop both small advance regeneration and post-harvest stems of spruce and fir, and greatly reduce both their growth rates and age-specific survivorship. Although the single weeding operation envisioned here may in most cases permit free-to-grow status for the conifer, in some cases it will not. It should be stressed that where a particular competitor is expected from on-site examination to create a severe, recurrent problem, the choice of prescription should be guided more by consideration of what retards the invasion and/or growth of the competitor than by, as here, the mere satisfaction of the stocking criteria in the first few years after harvest. Certain partial harvesting techniques can limit the spread and growth of *Calamagrostis* and other competitors (Lieffers et al, 1999) and could be considered where these competitors may be a recurrent problem.

We should also point out that there is considerable controversy regarding management goals for mixedwood forests. On public lands, the silvicultural objectives of an organization are frequently focussed on achieving the current regeneration/stocking standards for a particular *stand* that has been cut. Most of the current standards were developed by regulators under the assumptions that a particular stand should be regenerated as a fully stocked, even-aged monoculture despite the fact that where aspen is present, conversion to a conifer monoculture is usually exceedingly expensive. The company that cuts a stand must by law achieve the regeneration performance dictated in the regulations. If a company wishes to cut more forest and maintain its allowable cut, it is critical that it achieves these standards on the areas it has already cut. For many of the mixedwood management scenarios we suggest below (the moderate conifer stocking prescriptions), mixed-species composition, multi-age structures and partial conifer stocking may be viable options, and should be considered so by the regulators. Certainly, they can be regarded as (at least) less costly options in the short term. We think it is important that an organization be granted some flexibility with regard to composition and age structure at the stand scale, with more inflexible standards reserved for the landscape scale. Some of our prescriptions assume therefore that current regeneration/stocking standards will be, in the near future, relaxed to reflect a much wider range of possibilities for forest composition and age structure, and that compositional and growing stock targets will be critically evaluated at the landscape level (Kneeshaw et al. In-press). It will then of course be necessary to develop yield models for the mixed stands envisioned in some of these scenarios (work now being undertaken by the SFMn), but this requirement is no different from any other management system one might entertain.

Prescription 1: Underplanting white spruce

Planting white spruce under *maturing* aspen stands is a viable way of establishing white spruce. It has been tested in Alberta (Lees, 1963; 1970; Stewart et al, 1999), in Northeastern British Columbia (Tanner et al, 1996), and in Ontario (Groot, 1999), and will likely play a significant role in mixedwood silvicultural systems (Lieffers et al, 1996a). White spruce has also been planted under lodgepole pine canopies in north-central British Columbia (D. Coates, personal communication). Understory planting is more advantageous than planting clearcut areas in that it should decrease the incidence of frost damage to seedlings as well as to root rot during subsequent stand development. It may also reduce overwinter injury by maintaining a snow cover. Incident of insect attack such as terminal weevils and spruce budworm are also greatly reduced in mixed species stands compared to spruce monocultures (Taylor et al, 1996; Su and MacLean, 1996; Mann and Lieffers, 1999).

Understory planting should also decrease site preparation and weeding costs. This may be important on sites where overstory removal will lead to the recruitment of a dense layer of *Calamagrostis*, raspberry (*Rubus* species) or mountain maple (Lieffers et al, 1999). It has also been suggested that the nutrient status of white spruce will be greater in underplanted spruce through improved nutrient cycling and possibly through sharing of resources via mycorrhizae (e.g. Simard et al, 1997). A further advantage to this technique is that it provides greater long-term tree retention and will thus have positive impacts on visual quality objectives. Historically mixed stands have been important in the landscape, and understory planting may help to maintain or increase their abundance in the managed landscape.

Required conditions for understory planting to be successful

Acceptable height growth of spruce seedlings (i.e. 10 cm or more: Ruel et al, 1999) can be maintained in maturing aspen stands (Lieffers et al, 1996b) in the west that transmit 15 to 40% of above-canopy light (Lieffers and Stadt, 1994; Constabel and Lieffers, 1996). This corresponds, generally to 40-60 yr old aspen stands with greater than 50% cover or 800 stems/ha (DeLong, 1997; G. Grover, pers. obs.). DeLong (1997) suggests that stands with less than 1200 stems/ha or 35 m^2/ha basal area would provide suitable light levels for adequate spruce height growth. At present, there is insufficient information on light transmission in juvenile aspen stand to assess the possibility for good spruce growth in fully-stocked juvenile stands. Preliminary data, however, from B. Pinno suggest that fully stocked juvenile stands may have more opaque canopies than maturing stands that could slow the height growth of spruce. Also, aspen stands in Quebec appear to have more opaque canopies than those in Alberta (Messier et al, 1998) and the opportunities for underplanting will be reduced in the more humid east.

Results from silvicultural trials suggest that spruce seedlings have higher survival on average to moderately dry sites (mesic to sub-mesic) than on wetter sites because understory competition was less important. Similarly sites with shallow or poorly drained soils may have greater damage to understory spruce due to a higher wind throw hazard to overstory trees (Brace, 1992).

Potential problems associated with understory planting (i.e. when not to apply this technique)

One of the critical issues regarding underplanting is competition from understory and shrub layers (Groot, 1999). Constabel and Lieffers (1996) showed that understory layers in mature aspen stands in the west carried more leaf area than the overstory. This results in very dark conditions near the ground but once a seedling grows in height it gradually reduces some of the leaf area of these shrub/herb layers via competition (Lieffers et al, 1996b). Underplanting into tall and dense understories of green alder, beaked hazelnut, mountain maple or *Calamagrostis* is unlikely to be successful (usually associated with very open overstory conditions, i.e. < 50% overstory cover, as determined from aerial photos (G. Grover, personal observation)). These sites are more likely to need understory site preparation than sites where overstory light transmission is between 20 and 40% transmission (approximately 50-75% overstory cover). In most circumstances understory site preparation to temporarily control the understory is useful (for the spruce) (Lieffers et al, 1999). There are apparently some sites (based upon

Weyerhaeuser Alberta's experience) where spruce were successfully established without site preparation. It is not clear, however, what the impacts of site preparation on the aspen are over a period of 10 years.

Potential problems - Nursery management

An issue related to understory planting that has not been well-studied but could be a considerable problem based upon observations is the survival of nursery borne diseases in the understory. Leader growth of understory plantings of white spruce are frequently attacked by gray mould (V. Lieffers, pers. obs) which presumably was transported to the planted sites from the nursery. Presumably this mould would simply dehydrate in clearcut planting sites but survives and kills the expanding leader of underplanted white spruce. Nurseries will have to take special precautions to ensure that this mould is not present in their seedlings when it is destined for underplanting. Secondly, foresters should probably relax their concerns for producing sturdy stock (low height to root collar diameter) for seedlings to be planted in understories. Growth of seedlings above shading layers of shrubs and herbs may be more important than sturdiness in understory environments.

Potential problems - Browsing control

Browsing damage by wildlife, particularly snowshoe hares (Radvanyi 1987) and grouse (Coates pers. Comm.) is a concern for underplanted spruce. Adding to the issue of herbivory, underplanted seedlings are often more heavily browsed during the first year in the field than than naturals in the stands. Suggestions to reduce this problem include using bareroot stock (which presumably is less palatable than container stock) and seedlings that were not given the last dose of fertilizer before shipping. Also, gearing up planting programs immediately after peaks in hare or grouse populations may allow successful establishment. ALPAC is also identifying sites within the landscape matrix that offer poor habitat conditions for snowshoe hare in which to do underplanting operations. Essentially, this approach is based on the knowledge that snowshoe hare require young dense aspen stands and dense black spruce stands in close proximity for greatest survival and conversely that mature aspen stands in which there is little food or shelter are poor habitats. Planting in the interior of extensive mature aspen stands may therefore greatly decrease browsing pressure.

Potential problems –Access

One of the potential problems with this technique, one that is associated with all silvicultural techniques that require repeat entries onto the site, is that of access. To be successful this technique requires that foresters have access to all stands to be underplanted 20 to 40 yrs before initial harvest. Although this should not be a problem in subsequent rotations when road networks are well established it will be a major stumbling block before access to stands has been created.

Success of underplanted seedlings

Mortality rates of under planted seedlings are generally considered to be on the order of less than a few percent (although it has varied between studies as e.g. < 1%, G. Grover, personal obs.; <4% Tanner et al 1996; up to 70% after twenty years but with poor growing stock DeLong 1998; average 4% Delong et al. In-press). Both frost damage and chlorosis of seeedlings were also five to twenty times lower in seedlings planted in understories vs clearcuts (Tanner et al 1996, DeLong et al, in press).

In studies of naturally regenerated understory white spruce, survival following harvesting of overstory aspen varied from 40-61% with feller-bunchers and grapple skidders to 21-30% using cut-to-length equipment (Navratil et al, 1994). Survival also depended on density, size and quality of white spruce individuals. Following release, spruce height growth responded slowly with little increase in the first five year period but with an average 42% increase after 30 years compared to unreleased trees (Yang, 1989), although another study has shown that significant growth increases were noted 5 years after harvest (DATE). The greatest release occurred in individuals 2 to 6 m in height, and between 14 and 40 years of age (Yang 1989).

Suggested Prescriptions

Large seedling stock should be used (e.g. 410's) in stands past the self-thinning stage (approximately 30-60 years old: Delong, 1997) under at least 50% canopy cover (to reduce understory competition). Seedlings can be planted at 800 to 1400 stems/ha but extraction trails (to harvest the aspen) must be left and seedlings should be at least 1 m from live dominant hardwood stems. Seedlings should be planted as early as possible in the spring (i.e. when moisture is highest and before bud-break and the strong reductions in light levels associated with leafing out). On sites with no understory brush competition site preparation will probably not be necessary (i.e. planting can be done with boot screefing), site preparation will however be required where understory competition is important. The overstory may be harvested as early as 10-15 years after underplanting has occurred if seedlings are planted under mature aspen stands (Brace and Bella, 1988; DeLong, 1997). The overstory aspen stand should not be removed before it is fully merchantable nor before the spruce seedlings are tall enough to withstand post-harvest competition. Spruce seedlings may also be underplanted into young 25-40 year old aspen stands, which may better mimic some of the naturally occurring white spruce understories, with overstory harvest commencing at overstory merchantability and before leader whipping of the understory occurs which could be 20-50 years later.

Johnson (1986) suggests that understory spruce should have a minimum height of 2.5 m before harvest. This is to ensure that the spruce will be large enough to be successful among aspen root suckers and above any *Calamagrostis* competition, and that feller buncher operators will be able to see them. Yang (1989) on the other hand, shows that on some sites white spruce should have a minimum height of 3.4 m in order to not be overtopped by aspen suckers. Spruce seedling height in experimental projects established by the CFS in the west are 1.9-2.4 m twenty years after planting (DeLong, 1997). Since, light levels underaspen are much lower in the east (Messier et al, 1999), we expect growth to be lower and inter-rotation periods longer. Operational field trials with current seedling stock suggest that even greater height growth may be obtained (G. Grover, pers. obs.). After 80-100 years the mixed spruce-aspen stand can be cut (longer rotations may also be desirable) and will grow back as a pure aspen stand that can be underplanted 25-40 or 40-60 years later (Tanner et al, 1996). The absence of significant numbers of white spruce on the site has the potential of reducing losses from root rots (*Inotonos tomentosus*).

Mann and Lieffers (1999) also suggest that partial cutting techniques such as shelterwoods may provide the best compromise between clearcuts and underplanting in terms of light levels and moderated microclimate. Height growth of tolerant species such as spruce and fir plateaus above a threshold light level. Mann and Lieffers (1999) and Groot (1999) both argued that maximum growth of spruce occurred at 70-80% light while others suggest that height growth of white spruce and fir reaches a plateau above about 40% of full light levels (Lieffers and Stadt, 1994; Coates and Burton, 1999; Wright et al, 1998a). Improved climatic conditions (decreased incidence of frost events, warmer minimum temperatures, lower maximum temperatures, higher humidity, etc) reduced planting check and improved seedling survival are also associated with partial cutting techniques.

THREE ALTERNATIVES TO PLANTING

Here we examine three alternatives to the prescriptions based on planting. We begin with an examination of what is known about the regeneration ecology of spruce and fir. Ultimately, the subject matter consists of births and deaths (including death during harvesting operations), and we will attempt to reduce this knowledge to a system of equations that will guide the subsequent prescriptions.

Regeneration Ecology of White Spruce and Fir

A. Seed production.

General summary of the ecology.
Seed production for North American trees (including fir and white spruce) is highly dependent on the basal area of the seed trees (Greene and Johnson, 1994). Secondarily, and for less shade tolerant white spruce only, seed production is dependent on light receipt (D.F. Greene, C. Messier, H. Asselin, and M.J. Fortin, submitted manuscript) while fir appears to be much less affected. That is, subcanopy spruce will produce many fewer seeds than expected from equation (2) below. Thus, in practice, fir basal area per ha calculations can include all fir stems while, in the east at least, spruce basal area per ha estimation should be limited to dominant and co-dominant trees. The situation in the west, where the aspen canopy transmission rates are higher, is not clear but should be investigated.

Temporally, it has long been recognized that these two species, like most North American species, produce crops of widely different size from one year to the next. Greene and Johnson (manuscript in preparation) reviewed about 40 studies of long-term (>10 years) seed production in a number of North American hardwood and conifer species and found that all the distributions were strongly right-skewed (i.e. mean >> median). Generally, the biggest crop in a decade was 5 times the long-term mean while the median crop was about $1/4^{th}$ of the long-term mean. A crop bigger than or equal to the mean (defined here as a mast year) would occur about once every 3.5 years. (The reader is warned there is no implied cycle here. One might obtain two good crops in three years or wait many years for the next mast year. Further, in a decade, the three best years of cone production will account for about 80% of all the cones produced and will recur only about once every three to four years (a very general result but for examples with white spruce and fir, cf. Randall, 1974; Raymond, 1998). In relation to forestry planning, a good crop can be expected at least once during a five year interval about 90% of the time.

For spruce and fir, sexual reproduction is a two-year process with buds differentiating in the first year into sexual (male or female) or asexual (new leaf-bearing shoots). The female buds are concentrated in the upper third of crowns while the male buds are mainly in the middle third of the crowns. Pollination occurs in the late spring of the second year, followed by seed maturation during June to mid-August, and seed abscission in the autumn. The mast year can be evaluated in late June of the second year (the year in which treatments will occur) using binoculars to count the enlarging seed cones. Potentially, a mast crop could be evaluated in the first year (thus providing much more flexibility in planning) through laboratory examination of buds from the upper crowns of spruce trees harvested in nearby cut-blocks, or through flushing of buds on harvested branches after a post-chilling submersion in water.

At present there is no way to predict the mast years many years in advance but it is known that mast years tend to occur in the summer after a late spring (the time of bud differentiation) characterized by warm temperature and low rainfall. Interestingly, these weather stimuli appear to be broadly the same for both fir and white spruce. A number of west coast studies have shown a strong correlation between the masting behavior of these two genera (fir and spruce) (e.g. Franklin, 1968). We can only find two studies that have data for both white spruce and balsam fir simultaneously (Randall, 1974 in Maine, and Raymond, 1998 in Quebec) and the agreement (r^2= 0.92 or 0.95, respectively; $p<0.05$) in the size of the annual crop between the two species is very strong (although we point out that for each study there is only a 6-year record).

Equations used for the prescription models.
The general equation for seed production by North American trees has been written by Greene and Johnson (1994) as:

$$\overline{Q}=3067m_s^{-058}B^{0.92} \qquad (1)$$

where $\overline{Q}$ is the mean annual filled seed production of a single tree with basal area B (in m^2) and seed mass m_s (in grams). Note that this equation was based on seed trap studies and thus pre-abscission losses to seed eaters has already been taken into account. (Note that Greene and Johnson (1994) show some evidence that the pre-abscission loss is about 50%.) Given that m_s=0.0022 (white spruce) and 0.0065 (fir), and that these values vary only marginally (less than 40% across Canada and Alaska), then

$$\overline{Q}=106686B^{0.92} \text{ (white spruce)} \qquad (2)$$
$$\overline{Q}=56915B^{0.92} \text{ (fir)} \qquad (3)$$

Further, we can deal with an area source (collection of seed sources) by replacing $\overline{Q}$ with $\overline{Q}_D$ (mean annual seeds per m^2) and $B^{0.92}$ with B_D (basal area/area (m^2/m^2)):

$$\overline{Q}_D=106686B_D \text{ (white spruce)} \qquad (4)$$
$$\overline{Q}_D=56915B_D \text{ (fir)} \qquad (5)$$

Lessons for prescriptions.

1. In a mixed stand of spruce, fir, and aspen, any treatment that increases the seed production of either fir or spruce, or takes advantage of a mast year for either species, will simultaneously be augmenting the natural recruitment of both species.
2. If foresters are going to use a mast year, they will need great flexibility in planning. While bud differentiation occurs in the preceding year, it requires destructive testing to sample the upper branches where the female buds lie. This could be done in association with harvesting operations, such that white spruce branches from dominant trees are collected from different cut blocks and brought in to a laboratory for evaluation. This is probably the preferred method as it will allow companies greater planning time. Alternatively, by late June of the following year, the pollen cones (middle branches) and female cones (upper branches) are clearly visible with binoculars, and an assessment can be readily made. In this scenario, one pictures the forest company having a few stands of trees (perhaps near company headquarters) that they regularly monitor each June for a cone crop assessment.
3. The flexibility required to take advantage of mast crops is complicated by the fact that one might go up to five years without a good crop (although such a lengthy interval would be quite rare). Generally, one to two good seed crops should be expected within any given five-year planning period. The company could focus on other types of stands within their area during the interim period (e.g. pure aspen; jack pine; black spruce). Nonetheless this underlines the importance of flexibility in the scheduling of the harvest and other treatments.

B. Abscission and dispersal of seeds.

General summary of the ecology.
There is great variation in the timing of seed abscission but certain generalizations can be made. First, about 90% of the crop of either species is dispersed between Sept 15 and Dec 15 (Greene and Johnson, 1997). Second, the great majority of the abscission events take place in a few episodes (each lasting a few hours) where (1) the relative humidity has plummeted (thus flexing open the cone scales in spruce or making brittle the attachment of the scale to the central cone axis in fir) AND (2) the wind speeds are great (supplying the motive force for abscission: branch vibration). As a general rule for the boreal forest, given the prevailing westerly and northwesterly winds, seed deposition from the west and north sides of a clearing will be 2-4 times greater than dispersal from south or east edges (Stewart et al, 1998; Haavisto 1979 for black spruce). Note that this would not necessarily be true for the west coast where low relative humidity air masses will typically be associated with the rarer easterly flow (Harris, 1969), and, consequently, deposition of seeds is about equal for west and east edges (Dobbs, 1976).

As for dispersal, Greene and Johnson (1989) and Greene and Johnson (1996) have determined the equations for dispersal from a point source (single tree) or area source (forest of conspecific trees abutting a large clearing), while Stewart et al (1998) provided the equation for seed dispersal from a patch of source trees through a maturing aspen stand. The main lesson to be gleaned from the validation of these models is that the density of deposited seeds declines quickly with distance from a single tree, forest edge, or patch, and the curve of seed density versus distance begins to flatten strongly at around 150 m. Therefore, large cuts engender a strong dilution in deposited seed density with distance and are unlikely to be fully stocked from seed dispersing from edge trees. As shown by many authors, neither clearcuts (e.g. Timoney and Peterson, 1996, for white spruce) nor burns (e.g. for both fir and spruce: Galipeau et al 1997; MacArthur 1964; Greene and Johnson, submitted ms) are adequately stocked beyond about 25-75 m from even a strong (large basal area per area)) residual source. However, if the management goal is to maintain a low level of conifer stocking in mixedwood stands then long distance dispersal (defined here as >150 m; i.e. the distance at which the dispersal curve begins to flatten strongly) of seeds can, given good seedbeds, provide up to about 100 well-spaced trees/ha in mixedwood stands (Stewart et al, 1998).

Lessons for prescriptions.

1. If we choose to use a mast crop, flexibility in planning is called for. The cutting must take place between Dec 15 and about May 15 (i.e. after the bulk of abscission events but before germination begins). Site preparation for the creation of receptive seedbeds must take place before Sept 15 (onset of abscission). (For example, near Edson, Alberta a shelterwood trial with a good seed crop prior to a February harvest was then scarified in the spring, effectively removing the seeds from the bladed areas, and leading to no recruitment at all: V. Lieffers, unpublished data.).
2. In a 2-pass system, understory spruce that were formerly poor seed producers will begin producing much larger numbers of cones. Raymond (1998) found that white spruce following a shelterwood treatment (25% removed) in a primarily fir forest had about three times more seed production than in nearby control stands during the ensuing six years (although there was no attempt to differentiate the response of the canopy and understory spruce). In the west, Lieffers (unpublished data) found there was about a 4 year lag between the harvest and the first good crop by the formerly understory trees, while Greene and Messier (unpublished data) in Quebec found that understory spruce in a narrow creek-side residual strip responded well to the first regional post-harvest mast year that occurred (three years after the harvest). Given that seed production is a two-year process, the minimum time for response by the understory spruce should be two years. By contrast, fir will be much less affected in the short term, but in the long term enhanced growth will lead to larger size, greater stand level basal area per area, and therefore to larger seed production per area.
3. Dispersal is so constrained that the distance from the seedbed to the edge of a conifer area source should never exceed about 25 m. Thus, cuts of simple geometry (e.g. strip-cuts) should never be wider than about 50 m if full stocking is the management objective. (The exact maximum width depends of course on the source strength (basal area per area).) If less than full stocking is acceptable, then upwind sources could be as much as 150 m away and still provide moderate stocking.

C. Juvenile survivorship.

General summary of the ecology.

The great majority of seeds never become germinants, and the great majority of germinants never become harvestable trees. We can divide the mortality facing deposited seeds into two stages. The first stage is the transition from seed to germinant, and this is where seedbeds and seed predators intervene. The second stage begins to occur in the second or third year for a cohort and is where, under intact canopies only, the mortality is strongly linked to low light availability (Kobe and Coates 1997). While the effect of light was important in the section where we dealt with understory planting it need not be a direct concern here as we consider prescriptions for reliance on advance regeneration or by immediate post-harvest cohorts. However, the slow-growing spruce and fir post-harvest cohorts (and the shorter advance regeneration) can certainly be overtopped by grasses, shrubs, and hardwoods, and thus treatments that retard the spread and growth of competitors are often necessary.

Germination schedules. Neither species has a persistent soil seed bank; germination will occur during the fist growing season after abscission (Johnson, 1975). Almost invariably, the great majority of germination events take place between about June 1 and July 10 in the boreal forest (e.g. Zasada et al, 1978; Charron and Greene, submitted manuscript) and this is true even after an extended spring drought (Calogeripolos, Messier, and Greene, unpublished data).

Seed predation. Pre-abscission losses to seed-eaters are implicit in equation (1). Post-abscission losses occur in the autumn and in the spring (after snowmelt). Greene and Johnson (1998) estimated the mean loss as 57%. However, local, landscape, and temporal variation around this mean is very large, and thus prediction is difficult. Whether local predation rates vary by seedbed type is not known. Whether predation rates are independent of density or relative density (i.e. relative to the other species' seed production) is not known.

Seedbeds. A number of studies (e.g. Wright et al, 1999; Duchesneau and Morin, 1999; Charron and Greene, submitted manuscript; Greene and Johnson, 1998; Simard, 1999; see Coates et al (1994) for an exhaustive review of the earlier literature) have shown that spruce and fir have their best survival on the low porosity seedbeds that, by definition, have the highest moisture retention capacity and hydraulic conductivity. (Actually, this seedbed preference is a general argument for all small-seeded species Greene et al (1999).) The better seedbeds are rotted wood, exposed mineral soil, and humus (i.e. O_h, the humic layer). Moss layers sufficiently thin (<3 cm) that they pose no barrier to contact with the first three substrates, are also good (e.g. Parker et al, 1997). *Sphagnum* mosses provide good seedbeds as they retain moisture better than other moss species (Duchesneau and Morin, 1999; Groot and Adams, 1994). The worst seedbeds (high porosity and, therefore, prone to rapid drying following rain) are leaf litter and deep feather-mosses (i.e. O_f). In addition to rapid drying, falling leaves can also of course "smother" (deny light) to the initially very small fir and spruce germinants. The low porosity seedbeds engender a survivorship about 50 times higher than the poor seedbeds. (Of course, rocks, fresh logs, and puddled ruts have a survivorship of 0 but they typically occupy a small fraction of the ground and can be ignored.)

The better seedbeds are relatively common after a fire (5 to 50% coverage for burned humus and mineral soil: Charron, 1998). But within 3-5 years they are largely replaced by aspen litter or, in the areas were aspen suckering is of low density, by developing *Polytrichum* mats (Arlidge, 1967; Zasada,et al, 1978; Fleming and Mossa, 1995; Parker et al, 1997; Charron and Greene, submitted manuscript). The *Polytrichum* layer, while it is still thin, is as good a seedbed as mineral soil (Charron and Greene, submitted manuscript). At some poorly understood point in stand development (say, 10 years after fire) the *Polytrichum* mats have become too thick for good survival of germinants, or in other places have been replaced by thick feathermoss layers.

Similarly, development of *Calamagrostis* swards results in a thick litter layer that is totally unsuitable for spruce germination or establishment (Hogg and Lieffers, 1991). In contrast, some competitors (e.g. fireweed (*Epilobium angustifolium*)) do not produce a persistent litter and, consequently, good seedbeds will last longer under a cover of such competitors (Hogg and Lieffers, 1991). Until the first of the fallen burnt bole cohorts are sufficiently decomposed to serve as good seedbeds (say, around 1% coverage beginning about 40 years after fire), there should be essentially no useful substrates. Thus, speculatively, we picture the age structure of a 75 year old mixed stand as consisting of a strong post-fire cohort of aspen, spruce, and fir (if the stand is within about 100 m of surviving fir and spruce seed sources) that dominates the canopy and taller part of the subcanopy, a small contribution by spruce and fir in the interval 5-15 years after fire to the subcanopy, and then a gap in the age structure until small numbers of spruce and fir begin to colonize on fallen logs after about 40 years. As rotation age aspen stands have, at best, only 1% low porosity seedbeds (rotted wood in this case: Simard, 1999), then any prescription relying on post-harvest recruits will certainly require scarification.

Equations used for the prescription models.

Greene and Johnson (1998) offer the following equations for $\overline{S}$, the cohort mean juvenile survivorship from abscission to about the third growing season:

$\overline{S}=0.43(1-\exp(-1.83m_s^{0.43})$ (low porosity) (6)

$\overline{S}=0.43(1-\exp(-0.33m_s^{0.77})$ (high porosity) (7)

with the coefficient 0.43 (outside the exponential term) accounting for survival through the granivory period. Given the m_s values (above) of 0.0022 (spruce) and 0.0065 (fir) grams, we have

$\overline{S}=0.081$ (fir; low) (8)

$\overline{S}=0.0029$ (fir; high) (9)

and,

$\overline{S}=0.053$ (spruce; low) (10)

$\overline{S}=0.0013$ (spruce; high) (11)

Note that if we multiply equations (4) and (5) by either equations (8) and (9) or (10) and (11), respectively, we have the product $F_D=Q_D\ \overline{S}$ where F_D is defined as mean annual recruits per m^2:

$F_D=4610B_D$ (fir; low)

$F_D=5654B_D$ (spruce; low)

$F_D=165B_D$ (fir; high)

$F_D=139B_D$ (spruce; high)

And, since the effect of seed mass (m_s) has largely canceled out, we propose to use a single value of F_D for both species:

F_D (low)$=5132B_D$ (12)

F_D (high)$=152B_D$ (13)

The reader is reminded that this argument is for situations where light receipt is not a factor; that is, about the first two years for a cohort in intact forest, and about the first 5 years (there is little mortality after year two) in more open conditions.

Lessons for prescriptions:

1. Seed losses can be reduced if seeds are sown in the spring rather than (as with nature) in the autumn. Spring sowing gives the seed eaters less opportunity to find and consume the seeds.
2. Seedling density across the harvest block will be directly proportional to the intensity of scarification (% of the area scarified) as the non-scarified portion of the block is expected to contribute little to the regeneration density.
3. Scarification need not expose mineral soil; a deep cutting of moss layers or a removal of the fibric (O_f) material (last two autumn cohorts of leaves), or a mixing of the fibric, humic, and mineral layers, is sufficient. A very deep scarification, as with blading, will remove potential asexual competitors, but is prone to puddling problems and may lead to short-term (a decade) fertility constraints on growth of establishing spruce or fir (Stewart et al, in press; Greene and Messier, unpublished data).
4. Mineral soil and exposed humus are virtually non-existent in rotation-age mixed stands. Well-rotted logs are typically only about 5% (or less if the pre-fire stand was young) of the substrate in such mixed stands (the rest consisting of aspen litter and some feathermosses). Scarification is an absolute necessity in any situation where the forester hopes for post-harvest recruitment to meet even moderate stocking goals.
5. In addition to recognizing a spruce/fir mast year in advance, foresters must also keep an eye on paper birch masting. As a small-seeded species, birch will take advantage of the same seedbeds that sponsor the great majority of the spruce and fir germinants (e.g. Zasada et al, 1978). Birch is not as variable in its masting behavior as spruce or fir; the coefficient of variation is only about half that of the conifers. Further, judging from the six-year record of Randall (1974: admittedly too short a record but it is the only study of which we know that simultaneously includes birch, spruce, and fir), it is modestly synchronized with the two conifers (R^2=0.45; not significant with a sample size of 6 years). J.C. Zasada (pers. comm.) has reported a tendency for paper birch to encroach on sites mechanically treated for white spruce regeneration in Alaska. In short, while the developing cohort of female catkins could be evaluated with binoculars by late June (like the conifers), it seems more prudent to state that any treatment relying on post-harvest sexual recruitment of the two conifers is not recommended if paper birch comprises more than about 1 m^2 of basal area per ha, and weeding is not part of the prescription.

D. The relationship between density and stocking.

General summary of the ecology.

Necessarily, the foregoing equations have been phrased as densities (basal area per area; recruits per area) but foresters are also interested in the spatial distribution of the recruits. Stocking will be controlled by the density of recruits (F_D), the size of the survey plot (A in m^2), and the degree of clumping. The clumping, in turn, will be due to a non-random distribution of good seedbeds as well as a non-random distribution of source trees at the scale of say 30 m. As the sources become very patchy (with large distances between patches of source trees), wind directionality can also increase the clumping of the recruits. Further, small advance regeneration will, unlike post-harvest recruits, have an additional source of clumping: variation in the light environment (canopy gaps to closed canopy conditions). In short, we expect short advance regeneration to be even more clumped than post-harvest recruits.

Equations used for the prescription models.

The expectation for stocking success (T, where T is the proportion of survey plots of size A (m^2) with one or more stems) given a purely random arrangement of stems would be a Poisson function of F_D (stems/m^2):

$T=1-\exp(-AF_D)$

But of course the stems will not be randomly arranged, and to account for the clumping we will modify the Poisson as:

$T=1-\exp(-a(AF_D)^b)$

with a and b empirical coefficients dependent on the degree of clumping. Using post-harvest data sets (varying sites) for white spruce and fir from Timoney and Peterson (1996), Pike and Waldron (1966), Jarvis (1966), Fox et al (1984: only the two more recent clearcuts listed in that paper), and Griffin and Carr (1973), we obtain:

$T=1-\exp(-0.52(F_DA)^{0.90})$ (post-harvest) (14)

($N=29$; $r^2=0.93$). By contrast, using the data for advance regeneration of white spruce and fir (both pre- and post-harvest) from Timoney and Peterson (1996), Groot (1995), Roberts and Dong (1993), and Kneeshaw and Messier (unpublished data), we have

$T=1-\exp(-0.44(F_{DAR}A)^{0.69})$ (advance regeneration) (15)

($N=35$; $r^2=0.95$) and F_{DAR} refers to the density of the advance regeneration. As expected, the advanced regeneration stems are considerably more clumped than the post-harvest recruits. For example, with $AF_D=AF_{DAR}=2$ stem/m^2, the expected stocking is 0.62 (62%) for post-harvest recruitment but only 0.51 (51%)

Lessons for prescriptions.

1. Foresters require lower stem densities to meet their stocking standards with post-harvest stems than with small advance regeneration because the post-harvest recruits are not as clumped.
2. Different provincial stocking standards are roughly congruent. For example, Quebec requires 60% stocking with 4 m^2 plots while Alberta requires 80% stocking with 10 m^2 plots, and from equation (14) we see that Quebec requires 4700 post-harvest stems/ha while Alberta requires 3500 stems/ha. We find a similar congruence with equation (15) for advance regeneration.
3. The equations ((14) and (15)) are based on a wide variety of empirical situations and they should hold tolerably well in all except the most extreme circumstances (e.g. all spruce seed sources are in one corner of a clearcut). Indeed, they should apply to sexual stems of *any* species (for example the predictions are quite good for the empirical data of Groot and Adams (1994) and Newton (1998) for black spruce post-harvest or advance regeneration stems).

E. Mortality of advance regeneration following CPRS harvesting.

General summary of the ecology.

Earlier harvesting systems that made no attempt to protect small advance regeneration (strip-cuts; clearcuts; selection cuts; etc) permitted the survival, on average, of only about 20 to 30% of the small stems of fir and white spruce in New Brunswick and Quebec (Frisque et al, 1978; McInnis and Roberts, 1994), and less than 20% (V. Lieffers, personal observation) in Alberta. By contrast with systems such as CPRS, MacDonnell and Groot (1997) reported higher survival rates (as of the end of the first growing season following harvest): 32 to 56% for the most numerous class (<1.5 m tall), and 33-80% for non-merchantable stems taller than 1.5 m.) Techniques in which small merchantable stems (e.g. 10 cm dbh) are protected (e.g. CPPTM (coupes avec protection de petits tiges marchands) in Quebec or Corridor Cutting in Alberta) leads to greater survival of the larger stems. An Ontario study of HARP cuts (A. Groot, unpublished data) one full growing season after harvesting found that survival was related to height and position (on or off the skidpath) in black spruce (Table 1):

Table 1. Survival of non-merchantable stems (as a proportion) after HARP harvesting.

Stem size	skidpath survival	non-skidpath survival
height<50 cm	0.23	0.46
50<height<250 cm	0.36	0.75
>250 cm but diameter<10 cm	0.16	0.80

Note that survival is greatest for largest non-merchantable stems (50 cm in height to 10 cm dbh), and that, not surprisingly, mortality is greater on the skidpath than on the adjacent non-skidpath area. In what follows we will assume that the Ontario data in Table 1 are typical of fir as well as white spruce where the prescription calls for protection of the shorter advance regeneration.

Most of the total mortality of the shorter stems occurs during the harvesting operation and first summer. Subsequently, while some stems continue to die for the next few years due to injuries or scalding, age-specific survival after the first year is much higher than depicted in Table 1. Ruel et al (1995) reported survival of about 75% during the first few years after the harvest for balsam fir and black spruce whereas Groot (unpublished data) placed the survival at about 90%. Let us take the median figure of 82.5% for the subsequent survival.

Equations used for the prescription models.

Let us assume (relying on an unpublished study by Kneeshaw and Messier of the stem sizes of advance regeneration of fir and white spruce in western Quebec) that the very small stems (<50 cm height) in Table 1 constitute 75% of all the advance regeneration stems, the next larger class (50<height<250 cm) comprises 25%, and that taller non-merchantable stems represent only a negligible fraction. Weighting the results in Table 1 by these assumed proportions, and then multiplying by 0.825 to account for subsequent survival, we have:

$$S_k=(0.26)(0.825)=0.21 \quad (16)$$
$$S_n=(0.53)(0.825)=0.44 \quad (17)$$

where S_k is the survival on the skidpath and S_n is the survival on the non-skidpath.

We now must consider the widths of skidpaths and the intervening non-skidpath areas. Skidpaths are typically 3 to 6 m wide (Doucet, personal observation). We will assume a width of 4.5 m. Further, the inter-skidpath strips are typically about 10.5 m. Thus, dividing the cut into the proportions p_k and p_n (proportion of the harvest block comprised of skidpath and non-skidpath, respectively), we have:

$$p_k=0.3 \quad (18)$$
$$p_n=0.7 \quad (19)$$

Lessons for prescriptions.

1. Clearly, given the poorer survival on skidpaths, any technique that minimizes the relative width of skidpaths, increases the distance between the skidpaths, or minimizes the mortality on the non-skidpath areas will improve the probability of adequate stocking (given some pre-harvest advance regeneration density).
2. Any field procedure that minimizes skidpath mortality will lead to a greater increase in stocking than would one that similarly minimized non-skidpath mortality. This is because the majority of the unstocked plots will be found on the skidpaths. But of course, only very small stems can survive on the skidpaths.
3. The prescriptions we will develop below assume that the great majority of the spruce and fir advance regeneration is short (<2.5 m in height). If much of the regeneration is taller than this, then a shelterwood approach is recommended (Navratil et al, 1994).
4. If stocking standards can be relaxed, protection of conifer advance regeneration on the non-skidpath portions will maintain the conifer representation in the subsequent stand and, thus the present conifer yield in the mixedwood landbase.

Prescription 2a (Eastern Canada): advance regeneration with small stems (goal: fully-stocked conifer component).

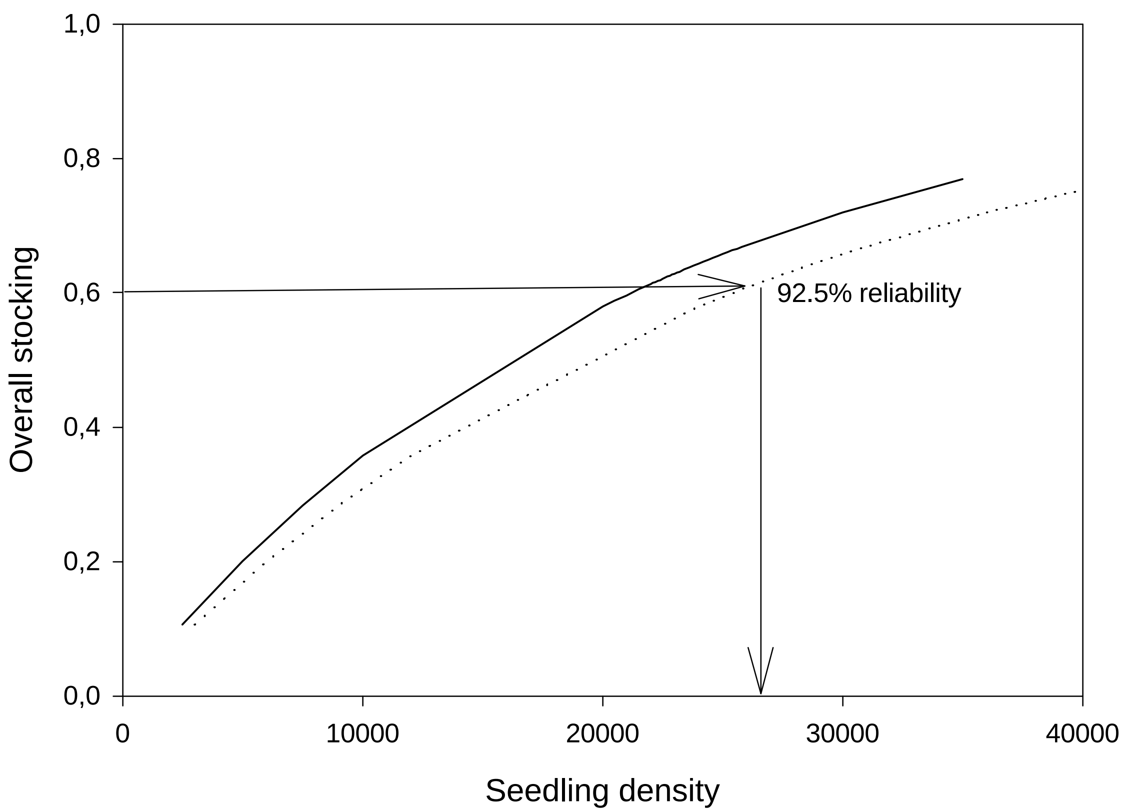
Conditions: let us assume that the survey quadrat area (A) equals 4 m^2 and that the minimum proportion of stocked plots (T) is 0.6. Further, let us assume a CPRS harvesting design (i.e. we are seeking to minimize damage to the small pre-harvest stems) with the 4.5 m wide skid paths occupying 30% of the area (equations (18) and (19)), and that any non-harvested stems of spruce and fir will be too small to produce significant numbers of seeds. We have:

$$T=(p_k(1-\exp(-0.44(AF_{DAR}0.21)^{0.69}))) + (p_n(1-\exp(-0.44(AF_{DAR}0.44)^{0.69}))) \qquad (20)$$

From equation (20) (as represented in Figure 1) we can calculate that the pre-harvest density (F_{DAR}) must be greater than 2.1 (21000 stems/ha). In Alberta (A=10; the minimum T = 0.8), then $F_{DAR}>1.9$ (19000 stems/ha). Note however that either of these required pre-harvest densities would be expected to give the forester adequate post-CPRS stocking only 50% of the time because there is some error in the relationship between stocking and density. In equation (13), the regression of stem density on stocking proportion, the standard error of the estimate of the log-transformed values was 0.33. Using an 85% confidence interval around the required stem density, 92.5% reliablity requires that the densities obtained above must be multiplied by about 1.2 times.

We conclude therefore that the Quebec stocking standard requires $F_{DAR}>2.52$ (25,200 stems/ha) while in Alberta the figure would be $F_{DAR}>2.28$ (22,800 stems/ha), and that the stocking standard would be exceeded 93% of the time. This high reliability however depends on good pre-harvest assessments of pre-harvest density. Using this method, pre-commercial thinning is likely to be required in the future. This result agrees tolerably well with the contention of Zelasny and Hayter (1991) that advance regeneration density prior to harvest should be about 30000 stems/ha for black spruce and fir. (We know of no such recommendation for white spruce.)

Relationship between pre-harvest denisty and post-harvest stocking for $4m^2$ plots



Likewise, for less careful harvesting, where we might assume that the entire cut undergoes the mortality associated with CPRS skidpaths (equation (16)), we would require (A=4) about 41000 stems/ha prior to harvest, and this prescription agrees fairly well with the findings of Frisque et al (1978) in New Brunswick and Quebec.

In most cases, we can expect that a mixedwood forest will result when conifer advance regeneration densities are less than the values proposed above.

Prescription 2b (Western Canada): advance regeneration with large stems (goal: moderate conifer stocking).

Mixedwood stands in the west will almost never support the high advance regeneration densities required in the foregoing prescription. Further, at the time of aspen maturity, white spruce advance regeneration is typically concentrated in stems 5 to 15 m tall. In Alberta, Navratil et al (1994) considered stands with advance growth stem densities of 500-2000/ha (>0.5 m height) as meriting special understory protection strategies. They reported that the stems must be sheltered from strong winds by either cutting in narrow strips (as with Corridor Cutting) or cutting in stages using shelterwood techniques. Because of the expected near-100% mortality of the spruce on and near the skid trails (e.g. Table 1), it is expected that the future stocking on the trails will be composed of suckering aspen.

Prescription 3a (Eastern or Western Canada): post-harvest natural sexual regeneration (goal: full conifer stocking).

Conditions: we assume a winter CPRS (protection of small stems) design if there are enough short conifer stems to justify it. Otherwise, we assume a conventional (winter) clearcut. The schedule calls for (1) determination that a mast year is occurring (preceding year or current year - June); (2) understory scarification (July/August); and a few months later (3) winter or early spring harvesting after the autumnal abscission season (but before germination of the mast cohort begins in early June). For simplicity in the calculations we assume $Q = \overline{Q}$ (the year is treated as a mean year although foresters would usually take advantage of years with greater than average seed crops). We have an understory scarification operation taking place in the last half of the summer; i.e. prior to the onset of the abscission season (September 15) but after determination of the crop size (after around late June). The scarification is done mechanically by rake and is expected to expose around 35% (p_{sc}=0.35) of the area as mineral soil or humus. It is assumed that the passes of the machine are sufficiently close together so that it would be impossible for a 4 m^2 or 10 m^2 survey quadrat to not contain some mineral soil or humus. (In practice of course, some survey plots would not contain any mineral soil or exposed humus because the machine must weave around boles.) It is assumed that the great majority of the recruits will be found on the better seedbeds at such high densities that pre-commercial thinning will be required. We denote the proportion scarified by p_{sc} and the proportion not scarified as $1-p_{sc}$. The expected post-harvest recruitment density is from equation (12) (scarified) and equation (13) (unscarified). In these equations the potential contribution of small advance regeneration stems surviving the scarification and subsequent harvesting operation is ignored although, in some stands, it could potentially constitute an important component of the stocking on non-scarified portions of the harvest block. Thus, we have

$$T=1-\exp(-0.52(AB_D(p_{sc}5132+(1-p_{sc})152))^{0.9}) \qquad (21)$$

Where T, as before, is the stocking proportion. Solving for the required basal area density (B_D) of the conifer component (e.g. all fir and only dominant and sub-dominant spruce), we have B_D>0.00025 (2.5 m^2/ha) with 4 m^2 quadrats, and 0.000185 (1.85 m^2/ha) with 10 m^2 quadrats. In practice, avoidance of boles and other obstacles will mean that somewhat less than 35% of the area will consist of scarified strips. Setting p_{sc} at a lower value (p_{sc}=0.25) leads to a basal area density limit of 3.4 m^2/ha or 2.5 m^2/ha for survey plot sizes of 4 or 10 m^2, respectively, and these are the values we will use from here on.

In a sense this is a seed-tree retention system (e.g. 25 trees/ha each with a 40 cm dbh provides about 3 m^2 of basal area/ha). However, the retention interval is only for the few months of the abscission period in the autumn. The company need not return to the site except for the weeding/thinning operation. As an alternative, a company could use the model outlined here to better plan variable tree retention programs to better ensure good natural recruitment.

The main source of unreliablity with sexual regeneration after harvest (ignoring for the moment competition problems) is masting behavior, but of course this prescription aims to eliminate that source of uncertainty. The second most important cause of unreliability is fluctuations in the populations of seed-eaters and in the weather (especially extended drought). Nonetheless, as shown by Greene and Johnson (1998) in their review of white spruce seeding experiments, 84% (i.e. one standard deviation) of the trials would be included if we adopt a survivorship value about 2.5 times lower than the mean values we used in equations (12) and (13). Now, given that we deliberately set the seed production value as a mean year (equation (1)) and that the mast years in practice will average 2-3 time larger than that expectation, then this is equivalent to having set the survivorship one standard deviation lower than the mean. In short, sufficiently high seedling densities should be obtained in 84% of the attempts. Thus, the reliability of this approach should be quite good. Where the prescription has been for scarification prior to harvest, but after a mast year (e.g. Stewart et al, in press; Lees, 1963, 1970; Desjardins, 1988), this approach has always, to the best of our knowledge, resulted in very high seedling densities on the scarification paths. The main potential problem with the reliability of this approach is not the biology but the geometry: if the distances between the scarified strips become too wide, then too many of the survey quadrats contain little or none of the prepared seedbeds and thus few seedlings.

This prescription may also lead to the presence of slash on the recently prepared seedbeds, if stem only harvesting and debranching on the site is used. Moderate depths of slash will not adversely affect establishment because they retard evaporative water loss from the seedbed on sandy soils and shade the ground on clay soils.

Note that this prescription should not be adopted where paper birch is a large fraction of the surrounding area unless, as envisioned here, a weeding operation is planned for. Birch will take advantage of the same scarified strips as spruce and fir, and it is so well dispersed that, even if it does not have a mast year for another two or three years after the harvest, the scarified seedbeds are sufficiently durable to sponsor a large, rapidly-growing birch cohort.

Prescription 3b (Western or Eastern Canada): post-harvest natural recruitment (goal: moderate conifer stocking).

Condition: we assume a stand in the west or east where the conifer seed sources are dominant and co-dominant (or that the aspen light transmission is sufficiently great that understory spruce produce seeds commensurate with their basal area), and comprise less than the required basal area calculated above (i.e. less than about 3 m^2/ha). For simplicity we assume that small advance regeneration is non-existent. The intention of the operation is not to obtain full conifer stocking but rather to increase the coniferous component at minimal cost. Scarification is the only cost and the stands need not be harvested immediately after the abscission season as in the preceding prescription. As before, it is assumed that scarification takes place during a mast year in the late summer (just before abscission of seeds). From equation (21), with a plot size of 10 m^2, a basal area density of 1 m^2/ha would provide a stocking of 51% while a plot size of 4 m^2 would permit this same source strength to yield 27% stocking.

Note that these predicted stocking levels have to be overestimates because, as conifer seed source basal area density becomes a very small value, the distances between source patches becomes greater, and dispersal constraints appear.

Note that if the harvest is delayed for at least a few years following scarification then a large basal area density of shade intolerant paper birch in the vicinity is unlikely to be successful at establishing a regeneration cohort on the scarified strips under the intact canopy. Delaying harvest could also be applied in the preceding section (Prescription 3a).

A variant on this prescription is that the company performs the understory scarification without regard to current seed production, and delays harvesting for 4 years. The scarified seedbeds should remain receptive for about 4 years, and there would be about a 75% chance that a mast year would occur within that interval. Of course, when the harvest eventually occurs, the scarified paths must be avoided during the skidding.

Prescription 4: aerial seeding following the harvest (goal = full conifer stocking).

Condition: we assume no particular harvest design, the scarification takes place among the stumps after the harvest. As an example, a disk trencher is employed to provide 0.7 m wide furrows separated by 1.3 m intervals, resulting in 35% mineral soil and humus exposure (p_{sc}=0.35). Scarification can be done in the autumn or in the spring. Aerial seeding should be done after snowmelt (and of course after scarification) but before about June 1 (when germination begins). It is assumed that the cleaned seeds have the same germinability as the filled seeds of a mast crop (around 80-95% germinability). We assume seeding would be done with white spruce rather than fir and, therefore, we use the survivorship equations (10) and (11). However, to allow for 85% (one standard deviation below the mean survivorship) reliability, each of the survivorship expectations is multiplied by 0.38; thus, the juvenile survivorship (for at least 84% of the trials) is expected to be 0.02 on the furrows and 0.00049 off of the furrows. (Note: as we let the reliability rise higher, the sowing rates will quickly become astronomically high.) Modifying equation (21) we have:

$$T=1-\exp(-0.52(AQ_D((p_{sc})0.02)+((1-p_{sc})0.00049))^{0.9})) \qquad (22)$$

where Q_D (seeds/m^2) is a sowing rate and T, as before, is the stocking proportion. From equation (22) we obtain a required sowing rate of Q_D=64.27 (642,664 seeds/ha) with a 4 m^2 plot or Q_D=48.1 (480,692 seeds/ha) with a 10 m^2 plot. The required sowing rates are therefore enormous. These rates of scarification and sowing are much higher than foresters have usually tried (more typically, scarification intensity is about 17% (Fleming et al, 1987, for a wide variety of machinery)) and sowing rates (during the last few decades) have been about 50-300 thousand seeds/ha) and it is thus not surprising that, as summarized by Waldron (1973), direct seeding trials with white spruce have tended to be inadequately stocked.

Note that the only competition allowed for is aspen suckering, and this competition would be addressed by a subsequent weeding/thinning operation. However, if *Calamagrostis* is expected to provide strong competition (in the west only), then this prescription should not employed as the grasses will too easily engulf the small natural seedlings, and require repeated weeding episodes.

As a more realistic alternative, the direct sowing rate would be reduced by about two-thirds if a scarifier/seeder machine was used. With a scarifier/seeder, single seeds are dropped behind the disks of the scarifier directly on the furrow instead of being broadcast. Given (as shown below), that much of the cost of an aerial seeding operation is the purchase of seeds, then the cost of seed procurement is reduced by about two-thirds. Further, the scarifier/seeder engenders a more even distribution of seeds along the furrows than broadcast seeding.

Synopsis of Reliability Estimates for the 4 Prescriptions.

According to G. Grover (unpublished data), understory planting has met its management objectives (survivorship greater than 90%, good annual height growth) in more than 95% of the 20 trials during the interval 1994-1998. Most of the trials reported in the literature also suggest that mortality rates will be on the order of 5% or less if good growing stock is used (Tanner et al, 1996; Delong et al, in press). Risk factors associated with frost damage and seedling chlorosis will be less in understory planted spruce. Further, to ensure its reliability, understory planting should be applied where risks to damage from snowshoe hares are minimal. This may mean, in large contiguous aspen stands with little cover protection to hares (conifer cover, dense shrub cover, young dense aspen stands e.g.< 20 yrs that have not undergone natural thinning), by avoiding planting in years where hare population cycles are at there 10-year peak, and by planting stock that did not receive a nutrient boost in the nursery just before outplanting (L. Roy, personal communication)

Reliance on advance regeneration via techniques such as CPRS or HARP has been successful (met the stocking standard a few years after harvest) only about 70% of the time in Ontario and in Québec (A. Groot and D. Cormier, pers.obs.). However, it has been pointed out that companies have not been as careful as they might be in evaluating the suitability of stands prior to harvesting, perhaps because of provincial financial incentives for such operations, and that success rates could easily be higher. We argued above that careful pre-harvest evaluation should lead to a success rate greater than 90%.

Understory scarification during a mast year has been tried so seldom that we cannot seriously evaluate its success rate. We can only point out that very high spruce densities on prepared ground have been the result of every trial of which we know. (We should point out that these trials were with blading whereas we recommend raking to provide a more even coverage of disturbed ground at the spatial scale of a survey quadrat.) Thus, the main impediment to success can only be the interaction of the proportion of the area scarified and the spatial distribution of the prepared portion in relation to the size of survey quadrats. Our estimate above is that the procedure would be, in the absence of dense *Calamagrostis* swards, successful 84% of the time (with the failures attributed to unusually high densities of seed-eaters or herbivores, and to extremely dry growing seasons).

Aerial seeding of white spruce has a very spotty record. However, as we argued above, invariably foresters have used too few seeds and prepared too small a portion of the ground. Further, the technique cannot be reliably applied where dense *Calamagrostis* regrowth can be expected. We estimate that, like the previous prescription (and for the same reasons), success rates could be as high as 84%. Direct seeding behind a combination scarifier/seeder would have these same high success rates, with 1/3 the number of seeds.

Conventional plantations in clearcuts usually have stem survivorship of greater than 90% (R. Doucet, Quebec Ministry of Natural Resources; D. Coates, British Columbia Forest Service), and thus reliably meet the stocking criterion for density. Frequently, however, grass and shrub competition has been so intense that a second weeding operation is required (especially in the west).

COMPARATIVE COSTS

In the preceding sections we have discussed the biotic limitations of various prescriptions. Further, we have found that the various treatments have roughly equivalent reliability when all the necessary requirements are met (e.g. seed year, seedbeds, light, lack of competition). Here we discuss the costs associated with each prescription, including the costs associated with conventional clearcutting/planting. In this section we focus solely on full conifer stocking as an objective. We do not discount costs as a function of time of application nor are the incremental harvesting costs (relative to large clearcuts) taken into account.

Most of the following costs were calculated using Interface, a decision-support software developed by FERIC for the analysis of harvesting and regeneration costs. Costs for understory planting were based on the operational experience of G. Grover and V. Lieffers in Alberta.

A. *Site preparation*.

We will not entertain prescribed burning as part of a prescription. The cost is often more than mechanical site preparation (unless the harvest blocks are very large) and, further, this treatment tends to be avoided because of the risks and because of smoke management problems. It should be pointed out, however, that on certain sites it may be the most appropriate technique when other considerations (e.g. nutrient availability, soil pH, elimination of disease, etc) are included.

Mechanical scarification via disk-trenching of clearcuts that are to be planted or aerial seeded is assumed to be generally about $200/ha to scarify about 35% of the ground.

Mechanical understory scarification with a rake (35% exposure of mineral soil and humus) is expected to cost $400/ha.

It is assumed that understory planting sites have been chosen for minimal grass and shrub competition, and, since the harvest will take place 10-15 years later when the planted stems are well above any potential competitors, there is no need for site preparation.

B. *Planting.*
For conventional planting of white spruce after a clearcut we assume $700/ha (based on 2500 seedlings per ha, regular container stock ($0.10/seedling), and a planting cost of $0.18/seedling).

In Alberta, Grover has used a larger planting stock (410 and 415B: $0.25/seedling) with planting costs of $0.3/seedling. As the future (pre-marked) skid-trails need not be planted, planting density is typically about 1500 seedlings/ha, and therefore a total planting cost of $825/ha is expected.

C. *Aerial seeding*. We place the seed cost at $1.5 per thousand white spruce seeds. Application by plane will be $20/ha.

D. *Reduction of competition and weeding*. We assume that all prescriptions in these mixedwood, aspen-dominated stands (except understory planting or the use of tall dense advance regeneration) will result in dense aspen recruitment that overtops the short conifer regeneration. Thus, in all these other prescriptions, weeding will be required. Further, the prescriptions relying on natural regeneration or aerial seeding will lead to stands that are too dense and will, therefore, require thinning. We assume that mechanical weeding operations are about $1000/ha with some thinning performed simultaneously for the non-plantation prescriptions. Conventional plantations using herbicides for the weeding operation (not permitted on crown land in Quebec after the year 2001) are much cheaper: $200/ha although no thinning will be performed.

Synopsis of Costs:
Total costs for each prescription are presented separately in Table 2 full conifer stocking and moderate conifer stocking only. The reader is reminded that present costs only are used, there has been no discounting of costs for operations that take place at different times, nor is there any estimate of additional harvesting costs per ha for these prescriptions relative to conventional clearcut and planting operations.

Full conifer stocking.
The cheapest prescription is understory planting. But recall that this treatment is limited essentially to the west, and then only to the portion of the mixedwood landbase where aspen light transmission rates are greater than 15% but less than 40%.

The cheapest treatment in the east is reliance on advance regeneration. But this prescription is limited to the mixedwood stands where conifers (mainly fir) have at least 25,000 pre-harvest stems/ha. Conventional plantations with herbicide application are about as cheap as reliance on advance regeneration (Table 2), however, given that some jurisdictions are starting to ban the use of herbicides and that some forest certification programs require a voluntary avoidance of this practice, a comparison with planting followed by mechanical tending is probably more pertinent. For sites with less than 25000 but greater than 10000 advance regeneration stems per ha, infilling of skid trails with white spruce will cost somewhat more than conventional planting with herbicide application.

Understory scarification is cheaper than conventional clearcut/plantations only where herbicides are prohibited.

Without herbicides, aerial seeding in the east is the most expensive technique of all. However, the use of a scarifier/seeder could reduce the cost of seeds by 65%, and thus the total cost of direct seeding would be lowered to $1537/ha (no herbicides) or $1259/ha (herbicides). We omit this technique below because there have been too few trials with white spruce to permit evaluation of its reliability.

Moderate conifer stocking.
Here we assume the goal is to achieve 20-50% conifer stocking on sites where conifers are present as a small proportion of the site, and the company is content to modestly increase the representation across a rotation at minimal cost. Free-to-grow status is not required and thus weeding and thinning operations need not be performed. It is assumed that the slow growing conifers will be in the shade of competitors (primarily aspen).

Reliance on advance regeneration is by far the cheapest option. We require only that there have been, prior to the harvest, about 1000 tall white spruce stems per ha in the west or about 3500 short conifer stems per ha (presumably fir) in the east. Much of the mixedwood landbase in both regions meets this minimum requirement.

Table 2. Comparison of per ha costs. The first half of the table is for full conifer stocking; the last half is for moderate conifer stocking. For aerial seeding leading to full conifer stocking we assume, as in the text, 642,000 seeds/ha in the Quebec and 481,000 seeds in Alberta. Further, it is assumed that the Quebec total seeding operational costs reflects the looming prohibition on herbicides.

	Under. plant	Adv Reg.	Adv Reg. w/ fill	Under. Scarif.	Aerial seeding (no herb.)	Aerial seeding (herb.)	Convent. Planting (no herb.)	Convent. Planting (herb.)
Full stocking								
Site prep	0	0	0	400	200	200	200	200
regen	825	0	394	0	964	741	700	700
Thinning/comp. reduction	0	1000	1000	1000	1000	800	1000	200
Total costs/ha	825	1000	1394	1400	2164	1741	1900	1100
Moderate stocking								
Site prep			0	400	200	200	200	200
regen	415		0	0	393	393	350	350
Thinning/comp. reduction	0		0	0	0	0	0	0
Total costs/ha	415		0	400	593	593	550	550

SYNOPSIS

All the techniques outlined in this paper (including of course conventional plantations) should have good reliability when applied to the appropriate sites under the appropriate conditions. An understanding of the ecology of the species involved can also be used to develop partial cutting systems that will have good reliability in regenerating stands. Many partial cutting techniques will be natural off-shoots of techniques discussed here. Similarly, such techniques may be most appropriate when attempting to imitate natural stand dynamics (e.g. replacement of aspen by conifers in the overstory) as well as ensuring good natural regeneration.

We can synopsize the results diagramatically as below with Alberta and Quebec representing western and eastern Canadian conditions (constraints). The costs/ha are placed in brackets. For Quebec, we have assumed that herbicides are illegal. Further, for Quebec we assume that it is very unlikely one would find a stand with extremely low advance regeneration density and yet enough basal area per ha to permit understory scarification . The recommendations below are derived entirely from consideration of what is biotically possible and what is cheapest. Issues of aesthetics or biodiversity are not addressed but could be a consideration for the adoption of any one system. The inclusion of other issues and their associated constraints may in fact make some of these alternative systems even more attractive. Reduction of cut widths to promote natural regeneration from seeding, the retention of residual patches of seed trees, the maintenance of continual cover from properly applied CPRS, CPPTM or understory planting will all help in maintaining visual objectives. Retention of wood as a biological legacy has been identified as important for biodiversity. Scarification of sites with organic matter build-up will improve long-term soil productivity. As demands for the inclusion of all resources become legislated or required through voluntary certification programs, alternative techniques to regenerating forest lands may provide forest companies with some of the extra tools that will be needed.

ALBERTA

	15<light<40%	understory light>40%
Full conifer stocking with conifer basal area/ha less than 2.5 m^2	understory plant ($825/ha)	conventional ($1100/ha)
Full conifer stocking with basal area/ha greater than 2.5 m^2	understory scarification ($1400/ha) (or $400/ha with delayed aspen harvest)	conventional ($1100/ha)
Moderate conifer stocking	Protection of tall adv. regen. or understory scarification	

QUEBEC (assuming no herbicides)

Adv. Regen >25000/ha	CPRS ($1000/ha)
10,000<Adv. Regen <25,000/ha.	CPRS with fill planting ($1394/ha)
3,000<Adv. Regen <10,000/ha	CPRS with fill planting (<$1900/ha; cost varies with the density of advanced regeneration) or conventional plantation ($1900/ha)
Moderate stocking	Protection of tall adv. regen., or understory scarification (if at least 1 m^2 of basal area)

EAST	
1a. If the objective is full conifer stocking …………	2
1b. If the objective is a mixed stand with an important conifer component..	4
2a. Advance regeneration > 25,000 stems/ha……………….……………..	CPRS (or CPPTM) with weeding of conifers or CPRS alone to get mixedwood stand
2b. Advance regeneration is greater than 10,000 but less than 25,000 stems/ha…………………………………………………………………..	CPRS (or CPPTM) with fill planting or mast yr techniques
2c. Advance regeneration is greater than 10,000 but less than 3,000 stems/ha…………………………………………………………………..	3
3a. If understory light at seedling level is 15-40% …………………………	Understory plant
3b. Understory light <15% or >40%……………………………………...	4
4a. Basal area of conifer seed trees < $3m^2$/ha………………………………	Conventional planting or direct seeding from scarifier
4b. Basal area of conifer seed trees > $3m^2$/ha………………………………	Understory scarification during a mast yr

WEST	
1a. If the objective is full spruce stocking …………	2
1b. If the objective is a mixed stand with an important spruce component..	5
2a. If advance spruce regeneration (>0.5m in ht) > 2000/ha……………….	Corridor cutting with regeneration augmentation (fill plant or seed tree)
2b. If advance spruce regeneration (>0.5m in ht) <2000/ha ………………..	3
3a. Basal area of spruce seed trees > 3 m^2/ha……………………………	Understory scarification during a mast year
3b. Basal area of conifer seed trees < 3 m^2/ha	4
4a Canopy light transmission is between 15-40% (e.g 800-1200 overstory aspen/ha)…………………………………………………………………...	Understory plant
4b Canopy light transmission < 15% ……………………………………...	Partial cut and re-evaluate or conventional
4c Canopy light > 40% …………………………………………………	Eliminate understory competition and underplant or conventional
5a Spruce saplings and pole-sized stems >500/ha…………………….	CPPTM
5b Spruce basal area is low but > 1 m^2/ha…………………………………	Understory scarification during a mast year

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