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A biological and economical analysis of silvicultural alternatives to the conventional clearcut/plantation prescription in Boreal Mixedwood Stands (aspen/white spruce/balsam fir)

by

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ABSTRACT

We evaluate the biological and economical limitations and constraints of four prescriptions that serve as alternatives to conventional clearcutting followed by planting in boreal mixedwood stands. These alternative prescriptions for full or partial conifer stocking are (1) reliance on advance regeneration with or without augmentation by fill-planting; (2) understory scarification during a mast year; (3) direct seeding either aerially or with a scarifier-seeder; and (4) underplanting. Our main conclusions concerning the biological constraints are that (1) advance regeneration, mainly of fir in the east and white spruce in the west, requires >26,000 and > 4,000 trees, respectively to achieve full conifer stocking, but of course much less to achieve moderate stocking; (2) reliance on a mast year requires at least 6 m^2 of conifer basal area/ha, but a good deal less if some advance regeneration is present or only moderate stocking is desired; (3) aerial seeding with 30% scarification requires about a half-million seeds/ha to achieve full conifer stocking, while a scarifier-seeder would require only a third of this application rate; and (4) underplanting is constrained to aspen stands with 25% light receipt at planting height. 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 biological and costing exercise is that, where they can be practiced, reliance on advance regeneration or understory planting are invariably the cheapest alternatives to achieve full or partial conifer stocking. With the exception of full conifer stocking in situations where there is little advance regeneration (and where herbicides are permitted), conventional plantations are never the cheapest approach. In these other situations, fill planting, reliance on a mast year or use of a scarifier-seeder also becomes viable options. We conclude, based on fragmentary data, that there is enough conifer basal area in most of the boreal mixedwood of Canada to allow for the use of either or both reliance on a mast year and reliance on advance regeneration to achieve full or partial conifer stocking. Finally, because of light constraints, understory planting appears to have a much wider applicability in the west than in the east.

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Introduction

In the last four decades there has been a rapid evolution in mixedwood management. Diameter limit cutting, where the most commercially valuable species and individuals were cut as needed, was coupled with a laissez faire attitude that resulted of course in variable stand establishment success. A few decades ago, this approach was replaced by clearcutting and even-age, single species management. Given provincial regeneration standards, planting has been used to ensure stocking of conifers. Much more recently, some flexibility was introduced as mixedwoods could be regenerated as either pure coniferous or pure deciduous stands, depending on the pre-harvest proportion of the species.

With the recent developments in ecosystem management (Rowe 1992), there is an increasing interest in using management systems that more closely mimic natural stand dynamics; this interest can be driven by financial as well as by environmental concerns to maintain the mixed species composition. Further, this recognition has begun to lead to changes in management objectives. For example, a number of provinces have recently produced new provincial regeneration standards that attempt to replicate the proportion of conifer in the stand prior to harvest. That is, we now beginning to see a gradient of stocking criteria that depend on the pre-harvest composition.

The mixedwoods of the boreal forest are found on mesic stands from Alaska to the Maritimes, and are composed of white spruce (*Picea glauca* (Moench) Voss)), balsam fir (*Abies balsamea*), trembling aspen (*Populus tremuloides* Michx.) and other minor species. White spruce and aspen are the main constituents of mixedwood stands in western Canada (Lieffers et al., 1996a). In the east, balsam fir is much more common than white spruce (to some degree this is a result of previous high-grading) (Kneeshaw and Bergeron 1998). For commercial reasons there is interest in increasing the abundance of white spruce in the east via silvicultural manipulations.

The first goal of this paper is to quantify the biotic limitations on white spruce and balsam fir regeneration alternatives for the mixedwood forests of Canada with an emphasis on prescriptions that keep costs low. While these alternative may fulfill other objectives such as maintaining a natural composition and structure, and maintaining biological legacies (i.e. standing live and dead trees), that is considered here to be a serindipitous result. Every prescription discussed here (or variants of them) has been tried, at least on a trial basis, somewhere in Canada.

Our second objective is to show how the cheapest prescription available can depend on the stocking objective. As the full stocking criterion is relaxed, some prescriptions are dramatically favored relative to the conventional clearcut/plantation.

Our final goal is not merely to quantify costs but to deal with a central concern of companies: reliability. For simplicity, we have chosen 84% (one standard deviation beyond the mean) as our standard of reliability. (I.e. the prescription is expected to meet the stocking criteria in 84 of every 100 blocks.) We would have preferred to use estimates of the reliability of the clearcut/plantation option but, surprisingly, we could find no summary evaluation of current success rates.

Aspen regeneration strategies for mixedwood stands are not discussed here, but see (Peterson and Peterson 1992, Lieffers et al. 1996a) for a discussion. Indeed, in this paper aspen is seen merely as a potential competitor.

Alternative prescriptions

Prescription 1: Reliance on advance regeneration.
This has recently become common in parts of eastern Canada (Doucet 1992), and is likely to increase in importance. For this prescription we develop a simple model that 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 balsam fir are treated as if they have similar intra-harvest and post-harvest mortality.

Prescription 2: Fill planting.
This prescription calls for fill planting where advance regeneration is insufficient to meet the stocking standard. The reader is warned that we view fill planting as a gradient that ranges from essentially no intervention (i.e. advance regeneration is nearly enough by itself to meet the standard) to a conventional plantation (there is no advance regeneration at all).

Prescription 3: Regeneration from seed following understory scarification in a mast year.
While this prescription has rarely been employed, trials during mast years (Lees 1963, 1970; DesJardins 1988, Stewart et al., 2000) show that this method is effective. Our model evaluates the relationship between seed production, juvenile survivorship, and scarification intensity.

Prescription 4: Direct seeding following scarification.
This prescription has been tried many times with white spruce (our modeling effort ignores fir) and trial records indicate poor reliability (Waldron, 1974). We model the relationship between the scarification intensity and the sowing rate required for conifer stocking. As a variant on aerial seeding, we examine direct seeding by a scarifier-seeder machine.

Prescription 5: Understory planting prior to logging.
This prescription is currently being tested in western Canada (Stewart et al. 2000; B. Grover pers. comm.). It has the advantage of establishing the conifers well before the often severe competition that can develop after canopy tree removal on mixedwood sites across Canada (Lieffers et al. 1993b, Groot 1999). We ignore fir and limit the prescription to the more valuable white spruce.

Review of biotic constraints and model formulation

Recruitment by seed
The basic equations governing the success rate of recruitment by seed are provided here as a preamble to the prescriptions development. The mean annual number of filled seeds/m^2 (Q_D) produced by a single stand of spruce or fir is directly proportional to its basal area (B_D) expressed in m^2/ m^2, and inversely proportional to mean seed size (m, expressed in grams (Greene and Johnson, 1994)):

$$Q_D = 3067\ m_s^{-0.58} B_D \qquad (1)$$

Seedbeds of well decomposed organics or exposed mineral soil confer elevated juvenile survivorship (see below) for new cohorts for only about 4 years (Coates, et al., 1994) after which the seedbeds rapidly lose their receptivity due to leaf aggradation. Hence, we can multiply equation (1) by 4 times to express the mean expected summed deposition of seeds that arrive on good seedbeds. However, Greene and Johnson (submitted manuscript), using long-term forestry records, have shown that the large variation in seed production of conifer seeds over time (strongly right-skewed temporal variation) can be adequately modeled as a log-normal distribution. Serendipitously, there is an 84% chance that the summed (4 year) seed production will exceed the value in equation (1). Thus, equation (1), the prediction for the mean year, can now be, quite accidentally, construed as the minimum sum we expect over 4 years in 84% of the cases we might examine. (Recall that we will use 84% as our reliability standard.)

We often lump spruce and fir together as a single conifer component in our models. This will have no effect on our expression of the temporal variation in seed production as these two species appear to respond to meteorological cues for masting in an almost identical manner (Raymond, 1998, and Randall, 1974: n=6 years and $r^2>0.92$ ($p<0.05$) for both studies).

We should point out that the measured basal area per area (B_D) applies primarily to dominant and co-dominant spruce and fir. Subcanopy trees produce far fewer seeds per basal area than expected from equation (1); i.e. seed production is dependent on light receipt as well as tree size (Greene et al., submitted)

Juvenile survivorship

The greatest annual mortality experienced by a sexual cohort occurs in the two years from seed abscission to the end of the second summer (cf. the review by Greene et al., 1999). To simplify seedbed effects on juvenile survivorship we divide upland substrates into two groups: optimal (humus and mineral soil) and poor (fibric organic layers of leaves or non-*Sphagnum* mosses) (Greene and Johnson (1998; cf. Wright et al., 1998a; Greene and Johnson, 1998; and Coates et al., 1994). Juvenile survivorship (S) can be expressed as

$$S_o= 0.43\ (1-\exp(-1.83m_s^{0.43})\ \text{(optimal)} \qquad (2a)$$
$$S_p= 0.43\ (1-\exp(-0.33m_s^{0.77})\ \text{(poor)} \qquad (2b)$$

where m, as before, is seed mass (g) and the coefficient 0.43 is the assumed survivorship through the granivory stage (i.e. 57% of the abscised seeds are eaten). For small-seeded species such as white spruce or balsam fir, equation (2) argues that there is about a 30-fold difference in survivorship between optimal and poor seedbeds.

As shown by Greene and Johnson (1998), the expected survivorship in equation (2) for white spruce shows large temporal variation (but this is much less than temporal variation in seed production). A reliability of 84% requires that we reduce the survivorship values in equation (2) by 2.5 times. As there are too few studies on direct seeding of balsam fir to allow characterization of the temporal variation in juvenile survivorship, we will blindly assume that the same reduction (2.5 times) as for white spruce is acceptable. Dividing equation (2) by 2.5, and assuming that seed mass (m in grams) is 0.0022 for white spruce and 0.0065 for fir, then we have (as listed in Table 1) a survivorship of 0.021 on optimal and 0.00052 on poor seedbeds for white spruce, or 0.0324 on optimal and 0.0012 on poor seedbed s for fir.

We assume no interaction between seed production and juvenile survivorship. Density-dependent predation on seeds (prior to or after abscission), germinants, and seedlings is assumed to be a minor contributor to the total variation in recruit density and is simply ignored.

Recruitment density and stocking proportion

By coupling equation (1) and the survivorship values for balsam fir and white spruce on the different seedbeds with a seed dispersal term, one can provide an estimate of the minimal seedling density 84% of the time at any particular distance from an area source. While tested dispersal functions exist for predicting regeneration density (e.g. Stewart et al. 1998; Greene and Johnson 1996), we adopt a simpler approach here. We express stocking proportion as a function of seedling density on a large spatial scale using published forestry records. Thus, we make the assumption that the effects of clumping of conspecific sources, the constraints of dispersal, and any clumping of the optimal seedbeds will be implicit in the empirical relationship, and we can, therefore, bypass explicit consideration of the spatial positions of regeneration survey plots and of individual source trees.

We can develop estimates of stocking for natural and advance regeneration from the literature. The expectation for stocking success (T, where T is the proportion of survey plots of size A (m^2) with one or more conifers) given a purely random arrangement of stems would be a Poisson function of F_D (recruits/m^2):

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

To account for the clumping so typical of smaller stems, we 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 recruitment data sets (varying sites) for fir and (small) white spruce 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:

$$T=1-\exp(-0.52\,(F_DA)^{0.90}) \qquad \text{(post-harvest recruitment)} \tag{3a}$$

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

$$T=1-\exp(-0.44\,(F_{DAR}A)^{0.69}) \qquad \text{(advance regeneration recruitment)} \tag{3b}$$

(N=35; r^2=0.95) and F_{DAR} refers to the density of the advance regeneration.

The advance regeneration stems are more clumped than the post-harvest recruits. For example, with $AF_D=AF_{DAR}=2$ stems/m^2, the expected stocking is 0.62 (62%) for post-harvest recruitment but only 0.51 (51%) for advance regeneration. To achieve 84% reliability, we lower the intercept within the exponential term by one standard error. Thus, from equation (3a) we reduce the intercept from 0.52 to 0.48; likewise, in equation (3b) the value is reduced from 0.44 to 0.37. These reduced values are listed in Table 1 with the other default values.

However, the taller white spruce advance regeneration stems typical of western mixed forests do not appear to be so markedly clumped as in the east. Given that aspen canopies are less opaque in the west than in the east, we believe one-sided competition (Weiner and Thomas, 1986) breaks down the clumped distribution. Thus, we will portray white spruce advance regeneration as randomly distributed, with the intercept and exponent (Table 1) set equal to 1.0 (i.e., a Poisson distribution, as above). We admit however we can find no data sets on the spatial distribution of taller white spruce in the west for a test of this assumption.

Equations (1) through (3) permit us to state the required seed-source basal area (expressed as m^2/m^2) and site preparation intensity that will permit natural regeneration to meet a stocking objective. Nonetheless, remember that some steps in the derivation of these equations have relied on inadequate data sets (e.g. there are relatively few long-term seed production studies for white spruce and balsam fir, and our equation (1) is a general argument based on many North American species); and, in two cases, an unsubstantiated assumption (the temporal variation in age-specific survivorship of fir is similar to spruce; tall advance regeneration of white spruce in the west is randomly distributed).

Mortality of advance regeneration following careful harvesting

Earlier harvesting systems that made no attempt to protect small advance regeneration (strip-cuts; clearcuts; etc) permitted the survival of only 10 to 30% of the small fir and white spruce stems in New Brunswick and Quebec (Frisque et al., 1978; McInnis and Roberts, 1994; Harvey and Bergeron, 1989), and less than 20% (V. Lieffers, personal observation) in Alberta. By contrast, systems designed to protect advance regeneration (e.g., MacDonnell and Groot 1997) report much higher survival rates after logging (32-80%). We use data from Ontario (Table 2) showing differences in mortality based on seedling size that we think are typical of fir as well as white spruce where the prescription calls for protecting advance regeneration.

Most mortality of shorter stems occurs during the harvesting operation and first post-harvest summer. Subsequently, while some stems continue to die for the next few years due to injuries or exposure, age-specific survival after the first year is much higher than depicted in Table 2. Ruel et al., (1995) reported survival of about 75% during the first few years after the harvest for balsam fir and black spruce whereas A. Groot (unpublished data) placed the survival at about 90%. Research by Lieffers et al. (1993a) suggests that white spruce is little affected by changes in exposure (however these authors do not provide mortality estimates. We use the median figure of 82.5% for the subsequent survival, although it may be species-specific or region-specific and clearly requires further study.

For the east, we 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 2 constitute 75% of all the advance regeneration, the next larger class (50<height<250 cm) comprises 25%, and that taller non-merchantable stems represent a negligible fraction. Weighting the results in Table 2 by these assumed proportions, and then multiplying by 0.825 to account for subsequent survival, we have a survivorship of 0.21 (S_k in Table 1) on the skidpath and 0.44 (S_n in Table 1) on the non-skidpath area.

The west is different. Subcanopy white spruce in Alberta's mixed stands are much larger on average than are fir in the east. The smallest height class (<50 cm) had 11% of the stems, the next tallest class (50<height<250 cm) comprised 32% of the stems, while the tallest stems made up 58% (Lieffers, Stadt and Navratil unpub. data). In an early study of some of the first understory protection logging in Alberta it was suggested that about 20% of the spruce was lost in non-skid areas (Navratil et al. 1994). It is now assumed that survival has increased as skills have improved, but without current data we will use the results in Table 2. Thus, as before, weighting the size-related mortalities in Table 2 by the relative frequency of the size classes, we arrive at average figures (Table 1) of 0.19 on the skidpath and 0.62 on the non-skidpath.. Skidpath survival is less in the west than the east because the taller spruce have higher mortality than the shorter fir. By contrast, non-skidpath survival is substantially greater in the west because, again, the average stem is taller.

Mortality of taller stems due to windthrow appears to be, generally, quite small when adequate aspen leave strips are retained in windy areas. G. Grover of Alberta-Pacific reported windthrow losses of only 0.2 to 3.4% over a 4-year period for carefully harvested sites. Such negligible losses can be ignored in the model. We assume the width of a skidpath to be 4.5 m with a 10.5 m inter-skidpath strip. Thus, dividing the cut into the proportions (p) for the skidpath (p_k) and inter-skidpath (p_n), we have p_k=0.3 and p_n=0.7.

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.; we know of no summary data). However, it can be argued that a large proportion of failures result from cursory evaluation of the suitability of stands prior to harvesting and inadequate amounts of advance growth. We assume that reliance on advance regeneration can meet the stocking standard 84% of the time given suitable pre-harvest evaluation.

Issues associated with underplanting

Planting white spruce under maturing aspen stands will likely play a significant role in future mixedwood silvicultural systems (Lieffers et al., 1996a). Understory planting should decrease seedling damage due to frosts, root rot, terminal weevils, and spruce budworm (Taylor et al., 1996; Su et al., 1996; Man and Lieffers, 1999). Further, it can reduce site preparation and weeding costs on sites where overstory removal will lead to recruitment of a dense layer of *Calamagrostis*, raspberry (*Rubus* species) or mountain maple (Lieffers et al., 1999). A final advantage is that it provides greater long-term tree retention and will thus have positive impacts on visual quality objectives, and help maintain mixed stands in the managed landscape.

Shelterwood harvests may provide the best compromise between clearcuts and underplanting closed stands in terms of light levels and moderated microclimate (Man and Lieffers 1999). Groot (1999) 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., 1998b).

Required conditions for understory planting to be successful.

The first criterion for successful understory planting is adequate survival of the planted trees until growing conditions are improved by partial or complete overstory canopy removal (Coates 2000). Spruce should be planted under aspen 10-20 yrs prior to time of harvest of the aspen. We expect unacceptably high rates of mortality of planted understory trees at light levels of less than about 20% full sun based on studies by Kobe and Coates (1997) and Wright et al. (1998b), in northwestern British Columbia for subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) and hybrid spruce (cross of white spruce and Sitka spruce (*P. sitchensis* (Bong.) Carr.). This precludes underplanting extremely dense *juvenile* aspen stands in the west where, light receipt may be as low as 5% (Pinno 2000). Any situation with tall and dense understory shrub and grass layers, particularly green alder, beaked hazelnut, *Acer spicatum* or *Calamagrostis* is also unlikely to deliver enough light at the seedling level ((Messier et al., 1998; Lieffers et al. 1999).

In operational trials, mortality rates of underplanted seedlings with good stock have generally been low: <4% (G. Grover, pers. obs.; Tanner et al., 1996). Both frost damage and chlorosis of seedlings were also five to twenty times lower in seedlings planted in understories vs clearcuts (Tanner et al., 1996, DeLong et al., submitted). Mortality after 20 years with poor stock has been somewhat higher (an average of 4% with one outlier of 70%: DeLong 1997; DeLong et al., submitted).

Growth rates of understory spruces and firs are low in the understory when light levels are less than 30%. Spruce height growth of 10 cm or more per year can be maintained under maturing aspen canopies (Lieffers et al., 1996b; Ruel et al., 2000). This corresponds, generally to 40-80 yr old aspen stands with 51-70% cover or 800 stems/ha (DeLong, 1997; G. Grover, pers. obs.), but of course the main criterion is light availability rather than stand age. 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.

While there is minimal data on effects of extended suppression period (10-40 yrs) on the ability of the understory trees to release Wright et al. (2000), suggest firs and spruce will release after extended periods of suppression; subalpine fir responded quickly to increased light while spruce release was more gradual. These results for spruce are supported by Yang (1989) where following release, spruce height growth responded slowly for the first five years but an average 42% increase over controls was observed after 30 years. The greatest release occurred with trees 2-6 m in height and between 14 and 40 years of age (Yang 1989). Studies of other conifers have shown height growth release occurring 2-4 years after overstory removal (Murphy et al., 1999; McCaughey and Ferguson 1988; Kneeshaw et al. 1998; Kneeshaw et al., submitted).

Understory spruce should have a minimum height of 2.5 m before harvest of the aspen (Johnson 1986) to ensures that the spruce will be large enough to successfully compete with aspen root suckers and/or *Calamagrostis*, and that they will be seen by feller buncher operators. Yang (1989), however, suggests spruce should be 3.4 m in height to avoid overtopping by aspen suckers. Spruce seedling height in experimental projects established by the CFS in the west are 1.9-2.4 m 20 years after planting (DeLong, 1997). Operational trials with current large seedling stock (e.g. 4-15's) suggest that greater height growth may be obtained, one trial showed an average white spruce seedling height of 70cm after 5 growing seasons (G. Grover, pers. obs.). Since light levels under mature aspen are somewhat lower in the east (Messier et al., 1999), we expect growth to be less and rotation periods longer.

Browsing damage by snowshoe hares (Radvanyi, 1987) and grouse (K.D. Coates, pers. obs.) may also be problematic for underplanted spruce. Suggestions to reduce this problem include using bareroot stock (which presumably is less palatable than container stock) and not giving seedlings the last dose of fertilizer before shipping. Also, gearing up planting programs immediately after peaks in hare or grouse populations may allow successful establishment. Alberta-Pacific is also attempting to match underplanting operations with stand and adjacency characteristics that offer poor habitat conditions for snowshoe hares..

Finally, to be financially successful, this technique requires road access to all stands to be underplanted one to two decades before expected harvest of the aspen. This should not be a problem in subsequent rotations when road networks are established.

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 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).

Results and Discussion

Biotic Limitations on the Prescriptions

Prescription 1: reliance on advance regeneration

Conditions: Let us assume a careful 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, and that any non-harvested stems of spruce and fir will be too small to produce significant numbers of seeds. We have, from the modified Poisson equation (3a):

$$T = (p_k(1-\exp(-a_{AR}(AF_{DAR}S_k)^{bAR}))) + (p_n(1-\exp(-a_{AR}(AF_{DAR}S_n)^{bAR}))) \qquad (4)$$

(A summary of symbols and default values is provided in Table 1.) Results are given in Figure 1. From equation (4) we calculate that the pre-harvest density (F_{DAR}) for full stocking (60%) must be greater than 2.6 (26000 stems/ha) with a survey plot size (A) of 4 m^2. This result agrees tolerably well with the rule-of-thumb of Zelasny and Hayter (1991) that advance regeneration prior to harvest should be about 30000 stems/ha for *black* spruce or fir. There are no similar suggestions for white spruce in the east.

Table 1. Default values for various parameters discussed in the modelling section. AR=advance regeneration; PHR=post-harvest regeneration.

	Alberta (white spruce)	Eastern Canada (fir)
Plot size (m^2)	A=10	A=4
Survival on optimal seedbeds	S_o=0.0324	S_o=0.021
Survival on poor seedbeds	S_p=0.0012	S_p=0.00052
Seed size (grams)	m_s=0.0065	m_s=0.0022
AR survival on skidpaths	S_k=0.19	S_k =0.21
AR survival on non-skipaths	S_n=0.62	S_n =0.44
Power-law intercept (AR)	a_{AR}=1.0	a_{AR} =0.37
Power-law exponent (AR)	b_{AR}=1.0	b_{AR} =0.69
Power-law intercept (PHR)	a_{PHR}=0.48	a_{PHR} =0.48
Power-law exponent (PHR)	b_{PHR}=0.90	b_{PHR} =0.90

By contrast, in the west much lower densities are required because of the better survival of stems through the harvesting operation and because of the less clumped spatial distribution of stems. Full stocking (80%) for Alberta (A=10 m^2) requires 4000 stems/ha. 50% stocking can be achieved with 1500 stems/ha, while 30% stocking requires 750 stems/ha. In these latter cases we can expect that a mixedwood forest will develop. Inspection of equation (4) leads to the following operational recommendations. Any technique that minimizes skidpath width or minimizes mortality on the non-skidpath areas will increase the stocking as most of the unstocked plots fall on the skidpaths.

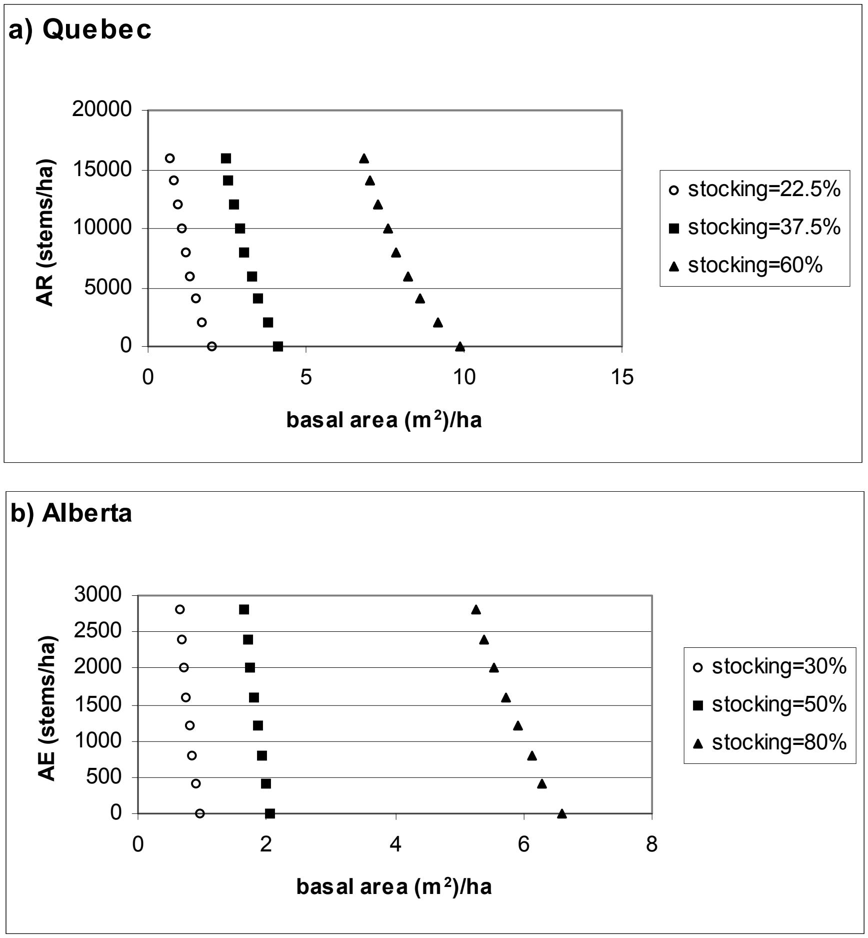


Figure 1. Required advanced regeneration (AR) (stems/ha), based on basal area m^2/ha, for minimal (m) , moderate (n), and full (s) stocking in (a) Quebec and (b) Alberta

For the less careful harvesting prior to the 1990s, where we might assume that the entire cut undergoes the mortality associated with CPRS skidpaths (Table (2)), we require (A=4) about 50000 stems/ha prior to harvest, which agrees with Frisque et al., (1978) from New Brunswick and Quebec.

Table 2. Survival of non-merchantable stems (as a proportion) after CLAAG 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

Prescription 2: reliance on a mast year.

Conditions: we assume a careful cut in an area with an adequate amount of spruce and/or fir seed trees. The schedule calls for (1) determination that a mast year is occurring. This can be done in the preceding year by microscopic examination of buds taken from the tops of trees harvested in nearby stands or in the present year (May or June) by binocular examination of trees. (2) Understory scarification takes place in the period July to mid-September (i.e. before seed abscission begins). Skidpaths are laid out at this time and no scarification takes place on the eventual skidpaths. Scarification covers 35% of the block and thus, given that skidpaths occupy 30% of the block, the scarified portion is 50% of the non-scarified part of the block. (3) The harvest takes place in the winter when the great majority of seeds will already have abscised. It is assumed, reasonably, that no advance regeneration stems survive in the scarified areas.

Clearly, many of the regeneration survey plots will straddle the interface of the skidpath and the non-skidpath areas. To simplify the modeling, let us idealize the block as consisting of three proportions: $p_k = (4.5-\sqrt{A})/15$; $p_n = (10.5-\sqrt{A})/15$; and $p_{nk} = (2\sqrt{A})/15$ where p_k is the proportion of survey plots consisting solely of the skidpath, p_N is the proportion consisting solely of the non-skidpath area (with 50% exposure of the optimal seedbeds); and the remainder p_{kn} is an even mix of skidpath and non-skidpath. At the scale of the block,

$$T = p_k X_1 + p_n X_2 + p_{kn} X_3 \qquad (5)$$

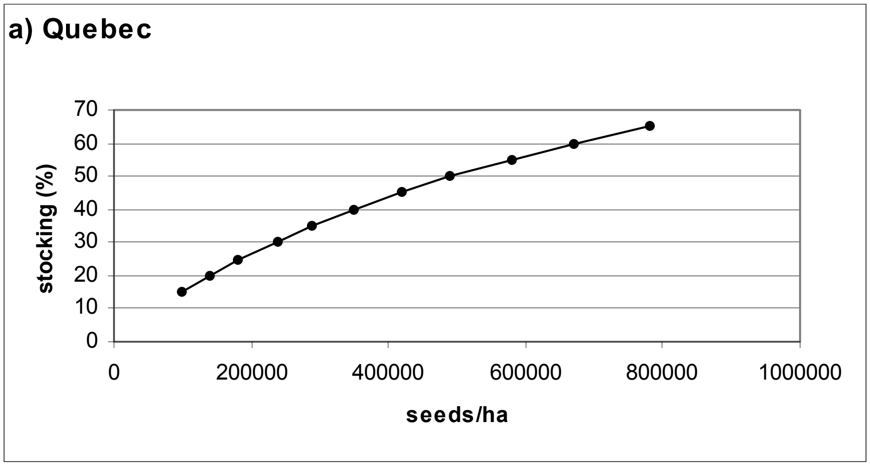
where the X values are modifications of equation (4) for the relationship between plot area (A), stem density (advance regeneration (F_{DAR}) or post-harvest regeneration (F_{DPHR})), and stocking (T). F_{DAR} is multiplied by the assumed survivorship on skidpaths (S_k) and non-skidpaths (S_n) during the harvest operation while F_{DPHR} is the product of the seed supply (in turn, a function of seed mass and basal area/area) and the juvenile survivorship on optimal (S_o) or poor (S_p) seedbeds. (The default values are given in Table 1.)

$$X_1 = 1-\exp(-a_{AR}\,(AF_{DAR}S_k)^{bAR});$$
$$X_2 = 1-\exp(-a_{PHR}(A3067m_s^{-0.58}B_D\ 0.5\ (S_o + S_p))^{bPHR});$$
$$X_3 = 1-\exp(-a_{PHR}\,((A3067m_s^{-0.58}B_D\ 0.25(S_o + S_p)) + (AF_{DAR}0.5S_k))^{bPHR})$$

Note that in X_3 we have, for simplicity, used the post-harvest equation (3a) for the combined advance regeneration and post-harvest seedlings as we assume the latter will comprise the great majority of the stems.

From the equations above it can be argued, uninterestingly, that the stocking proportion will rise with an increase in either F_{DAR} (advance regeneration density in stems per m^2) or B_D

(basal area per area in m^2). Solving iteratively to find the required B_D and F_{DAR} given the survey plot area (A) and the required minimal T for full stocking success (60% with A=4 m^2 and 80% with A=10 m^2), we plot the results in Figure 2. Figure 2 assumes that the species is white spruce in the west and balsam fir in the east.



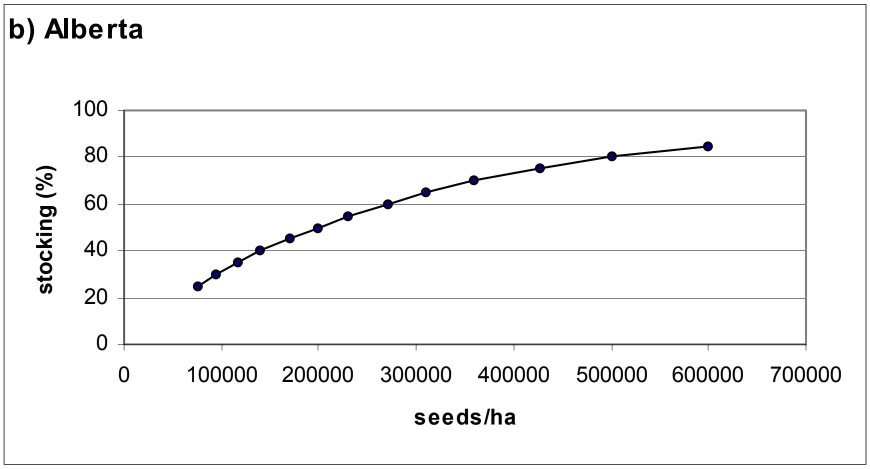


Figure 2. Stocking (%) potential with increasing seed density. Results are based on 35% mineral soil exposure in (a) Quebec and (b) Alberta.

With FDAR=0, the required basal area/ha is, in Alberta, 6.6 m^2/ha for full stocking (80%), 2 m^2/ha for moderate stocking (50%), and 1 m^2/ha for minimal stocking (30%). The corresponding values for fir in Quebec are almost twice as high. This is due to the fact that spruce is expected to have somewhat higher fecundities than fir, and because it is somewhat easier to satisfy a given standard with A=10 m^2 (Alberta) than A=4 m^2 (Quebec). Little advance regeneration survives on skidpaths and all of it is removed on scarification paths. In a sense this prescription is a seed-tree retention system (e.g. 75 trees/ha each with a 40 cm dbh provides about the required basal area/ha for full stocking). However, as the seed is dispersed before the harvest in winter, all of the trees in the cutover can be removed, and thus it is a very brief retention interval. As an alternative, a company could use the model outlined here to plan variable tree-retention programs to promote modest natural recruitment of fir and spruce.

Now, the main source of unreliability 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. Other uncertainties are fluctuations in populations of seed-eaters and weather (especially extended drought). However, our derivation of equation (3) took this variation into account. 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 during a mast year (e.g. Stewart et al., 2000; Lees, 1963, 1970; Desjardins, 1988), this approach has resulted in very high seedling densities on the scarification paths. The main problem with the successful application of this approach is not the biology but the geometry; if the distances between the scarified strips becomes too wide, then many survey quadrats contain unprepared seedbeds and thus have few seedlings.

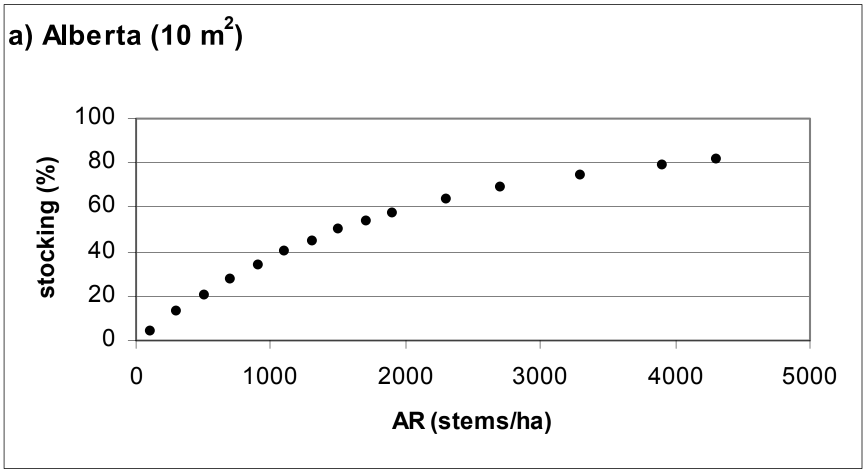
Prescription 3: seeding following the harvest.

Condition: Scarification takes place in the autumn or spring after the harvest. We assume it results in 35% mineral soil and humus exposure ($p_{sc}=0.35$). Seeding should be done after snowmelt but before early June (when germination usually begins). We assume 80-95% germinability for cleaned seed and our example uses white spruce rather than fir. Invoking equation (3a), we have:

$$T=1-\exp(-a_{PHR}\,(AQ_D[(p_{sc}S_o)+((1-p_{sc})S_p)]^{bPHR})) \qquad (6)$$

where Q_D (seeds/m^2) is now construed as an aerial sowing rate and T, as before, is the stocking proportion. Results are presented in Figure 3. From equation (6) we obtain a required sowing rate of 670,000 seeds/ha for full stocking with a 4 m^2 plot (A) or 500,000 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. It is thus not surprising that, as summarized by Waldron (1973), direct seeding trials with white spruce have tended to be disappointing. Indeed, with only 17% of the block being scarified, it would require 1.4 million seeds/ha (A=4) for full stocking. As shown in Figure 3, required sowing rates for reduced stocking standards are smaller but still substantial, e.g. in Alberta with a 10 m^2 survey plot, 30% stocking would require sowing about 100,000 seeds/ha.

Note that we have not considered any role for advance regeneration because we primarily see this prescription used on harvest blocks where there is little conifer advance regeneration.



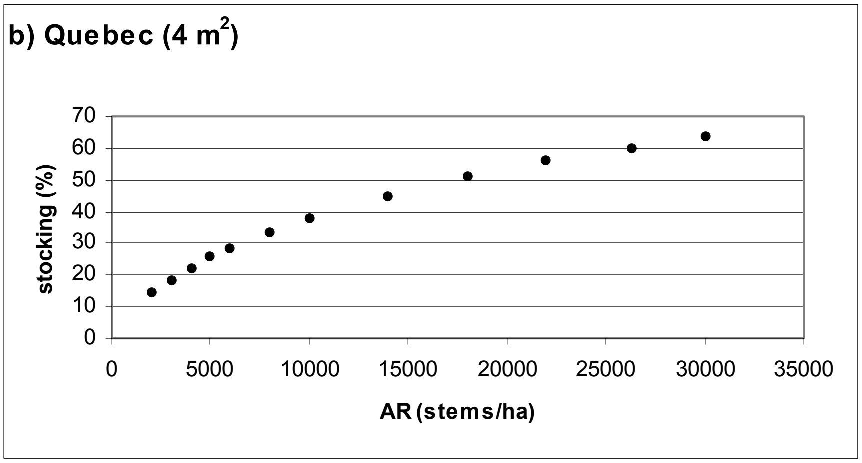


Figure 3. Predicted stocking (%) versus advanced regeneration (AR) (stems/ha), based on reliance on FDAR for (a) Alberta (10m^2)and (b) Quebec (4m^2)

We believe that use of a scarifier-seeding machine is to be preferred to aerial application. Seeds are dropped behind the scarifier directly on the furrow instead of being broadcast. In Quebec, S. Boris and C. Calogeropoulos (unpublished data) attached a scarifier-seeding machine to an all-terrain vehicle and obtained 6% first-year survivorship of sown white spruce on very thick, disked leaf litter (no mineral soil was exposed) under an intact aspen stand. (Note: 6% is slightly above the mean value expected from equation (3a) above.) This direct sowing would reduce seed use and cost by two-thirds as seeds are sown only on optimal seedbeds and these constitute 35% of the block. Further, the scarifier/seeder provides a more even distribution of seeds in the scarified strips than broadcast seeding. This may be a useful alternative to understory scarification in a mast year (Prescription 2) when there is insufficient conifer basal area per ha or where the company wants to free itself of the planning constraint imposed by the unpredictability of mast years.

Finally, we consider direct seeding of any kind to be inappropriate where *Calamagrostis* is expected to engulf the small seedlings, and thus one would require repeated weeding episodes. Our direct seeding prescriptions assume only competition from suckering aspen that can be addressed by a subsequent weeding/thinning operation.

Prescription 4: understory planting.

Condition: An aspen stand should be about 20 years from the planned logging and the manager wishes to increase the conifer component in the next cohort. Light transmission at seedling height should be >25% with no serious pre-harvest competition problems so that the operator is assured of low mortality and acceptable growth rates.

The Available Landbase in Relation to the Biotic Constraints

In what follows we discuss the likelihood that the above silvicultural practices might be applied given the biotic constraints noted above. We limit the evaluation to mesic stands older than 40 years.

Conifer basal area per area.

Conifer basal area per area is usually available from forestry inventories. In eastern Canada much of the landbase will have a coniferous basal area per area greater than our limits 10, 4 or 2 m^2/ha (i.e. corresponding to the requirements for full, moderate, or minimal stocking in the absence of any augmenting advance regeneration), and thus the prescription for reliance on a mast year should have wide applicability. For example, in the Abitibi region of Quebec, 25% of the landbase (mesic, older than 40 years) has conifer basal area/area (mostly fir) exceeding 10 m^2/ha, 51% < 10 m^2/ha, and 25% is pure hardwood forest (unpublished data, Jean Noël, Quebec Ministry of Natural Resources). As the conifers have slow juvenile growth older stands usually have greater conifer basal area.

In the west (to use an example from ALPAC's FMA in Alberta), areas where the white spruce basal area per area exceeds 7 m^2/ha (i.e. the value corresponding to full stocking) comprise about 26% of the total. This is similar to that found in the east at least for the two areas that were compared. In summary, the prescription for reliance on a mast year may vary widely from one forest management unit to another, but only a small proportion of the landbase will not meet the minimum basal area standards necessary to achieve a minimal conifer stocking and a mixed stand condition.

Advance regeneration density.

The proportion of the mixedwood landbase on older mesic sites in the east that barely satisfies the full stocking criterion (>26,000 stems/ha) is more difficult to appraise because advance regeneration density has not been a standard measurement in inventories. However, extrapolating from the data of Arnup (1996) in eastern Ontario, fir (vastly more common than white spruce) advance regeneration will exceed 26,000 stems/ha (the minimum for full stocking) in about 10% of the landbase. Further, Arnup's (1996) data indicate that an additional 40% of the landbase would have $10{,}000 < F_{DAR} < 26{,}000$ stems/ha (the range, recall, for moderate stocking levels). Thus, we estimate that managers can rely on advance regeneration solely for about 70% of the area. This proportion is greater in Quebec (and, one might guess, in New Brunswick) where Doucet (1988) found that over half the forests with even a modest fir component had advance regeneration densities exceeding 20,000 stems/ha, and likewise over half the hardwood-dominated stands had at least 6,000 conifer stems/ha (minimal stocking required at least 4,000 stems/ha).

As for the west, while we have no data sets as useful as that of Arnup (1996) or Doucet (1988), there is little doubt that advance regeneration of white spruce occurs at lower densities (Navratil et al. 1994). Correspondingly, the required densities with these taller, more randomly distributed stems, is a good deal lower (4000, 1500, and 750 stems/ha for full, moderate, or minimal stocking, respectively). Data from four management units in western Alberta suggest, however, that only a small proportion of the hardwood landbase (<2%) would have more than the 1500 stems/ha that we suggest would be necessary for moderate to full stocking. Another 4% would meet the minimum stocking standards. These data suggest that the use of white spruce advance regeneration would only be appropriate on a relatively small proportion of the landscape. Even the density interval 100 to 750 advance regeneration stems/ha would only add another 13% of the hardwood landbase.

In summary, reliance on advance regeneration (especially in combination with fill planting) can be widely practiced in the east (and indeed presently is widely practiced). In the west, full stocking would be an extremely rare prescription, while moderate and especially minimal standards may be met on some small fraction of the landbase.

Light transmission.

The prescription for underplanting calls for light transmission >25% at 1 m height and without dense herbaceous or woody competition below that height. The age for underplanting aspen stands is 40 to 50 years assuming planting is done 20 years prior to the aspen harvest at 60 to 70 years. The reader is warned that the paucity of light measurements in mixedwoods makes our estimates below quite speculative.

We expect light levels to be much lower in aspen stands in the east than in the west because (1) eastern stands are older and have a higher coniferous component; (2) with the exception of fertile sites in British Columbia, canopy aspen are much larger in the more humid east and have more opaque crowns (Messier et al., 1998); and (3) shade tolerant shrubs are a more common understory component. Just below eastern aspen crowns, light levels are between 10 and 20% (Messier et al., 1998; D'Astous, 2000) but competitors such as mountain maple will often leave very little light (much less than 10%) at planting height. Lacking data, we speculate that less than 5% of the immature mixed or monocultural aspen stands in the east will satisfy the light transmission criterion. In the west, however, Lieffers and Grover (personal observation) suggest that half of the maturing aspen stands (> 60 years) and up to 30% of younger (30-40 year old) stands would satisfy the light constraints.

Comparative Costs/ha and Costs/scenario

Here we compare the costs of the conventional clearcutting/planting prescription with the alternative prescriptions. 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.

The following per ha costs were calculated using Interface, a decision-support software developed by FERIC (Forest Engineering Research Institute of Canada) for the analysis of harvesting and regeneration costs. The exception to our reliance on this software is for the costs of understory planting which were based on the operational experience of G. Grover in Alberta. Dollar figures are 1999 Canadian dollars.

Costs/ha.

Mechanical scarification via disk-trenching of clearcuts is assumed to be $200/ha to scarify about 35% of the ground. Mechanical understory scarification with a small bulldozer equipped with a piling-rake (35% exposure of mineral soil and humus) is $400/ha while an excavator would be more expensive.

It is assumed that understory planting sites have been chosen for minimal grass and shrub competition, and, since the harvest will take place 10-20 years later when the planted stems are well above any potential competitors, there is no need for site preparation except boot-screefing.

For conventional planting of 2500 stems per hectare after a clearcut we assume $700/ha (regular container stock [$0.10/seedling], and a planting cost of $0.18/seedling). In Alberta, G. Grover has used a larger planting stock (410 and 415B: $0.25/seedling) with planting costs of $0.3/seedling for underplanting. As the future (pre-marked) skid-trails need not be planted, planting density for underplanting is typically about 1500 seedlings/ha, and therefore a total planting cost of $825/ha is expected. For simplicity, we assume fill planting costs will be similar to conventional plantations.

For direct seeding, we place the seed cost at $0.85 per thousand white spruce seeds. Application by plane will be $20/ha. We assume that a scarifying/seeding machine will scarify one-third of the area and thus use only 33% of the seeds used for aerial seeding.

We assume that for all prescriptions (except understory planting or the use of tall advance regeneration) dense aspen recruitment (augmented by a dense shrub component in the east) will overtop the short conifer regeneration. Thus, weeding will be required for subsequent conifer dominance. Herbicides (prohibited in Quebec after 2001) will cost $200/ha. Mechanical weeding is much more expensive: $600/ha. Precommercial thinning costs $750/ha. However, for the portions of the block relying on non-planting prescriptions, the weeding and thinning treatments can be performed simultaneously at a total cost of $1000/ha.

Costs/scenario.

The costs/ha outlined above are for a fully-stocked stand but they need only be applied to the portion of the harvest block where we must intervene in the cases of moderate or minimal stocking criteria (Table 3). The cost/scenario is defined as the cost/ha for a prescription multiplied by the proportion of the harvest block to which it is applied.

In the preceding analysis of biotic limitation, we have emphasized relying on advance regeneration that survives the careful harvesting. We thus have three fractions in any harvest block: i = no conifer advance regeneration, h = abundant conifer regeneration, and g = some conifer regeneration (of course, g+h+i=1.0). In the fraction, g, some regenerative prescription must be applied (e.g. fill planting, seeding, etc) to increase the block-wide stocking level. This fraction g is given as:

$$g = (T_s - T_o) / T_f \qquad (7)$$

where T_s is the stocking standard (Table 3), T_o is the stocking due to the advance regeneration found elsewhere in the block (*not* in g), and T_f is the full stocking standard (Table 1) and the one we will apply, locally, to this fraction, g. Note that when there is no advance regeneration in the block, then $T_o=0$, and if the block-wide standard is for full stocking ($T_s = T_o$), then, from equation (7), g=1 (i.e. we must treat the entire block). Likewise, if there is abundant advance regeneration essentially everywhere, then T_o satisfies the block-wide standard (i.e., $T_s = T_o$) and we need do nothing (g=0).

Table 3. Conifer stocking criteria for areas using a 10 or 4 m^2 survey plot size. As only Alberta has set out quantitative standards for partial stocking options, the 4 m^2 criterion is based on the new Alberta guidelines for minimal and moderate stocking (i.e. 37.5/60 = 50/80; 30/80=22.5/60).

	Stocking criterion (%) with a 10 m^2 survey plot (Alberta)	Stocking criterion (%) with a 4 m^2 survey plot
Minimal (pre-harvest aspen-dominated mixed stand)	30	22.5
Moderate (pre-harvest conifer-dominated mixed stand)	50	37.5
Full	80	60

The fraction, h, is where advance regeneration is concentrated and here only weeding and thinning are applied. Unfortunately, we know of no data sets that allow us to define this fraction with any rigor at the scale of a harvest block (a few ha to a few hundred ha). Nonetheless, we can make two points: first, the local advance regeneration density within the h fraction is sufficiently large to warrant protection. Second, with equivalent densities, the contribution this advance regeneration makes to the block (T_o) will be proportional to the survey plot size. Let us assume that

$$h = T_o / T_f \qquad (8)$$

or, in effect, that locally (i.e. within h) the advance regeneration is fully stocked (T_f).

Finally, fraction, i, is aspen dominated, and there is no conifer advance regeneration. Except in the case of full stocking, there is no intervention in this portion of the block.

Results of the cost/scenario analysis

We now arrive at the comparison of cost/scenario in a harvest block for each prescription based on the stocking derived from advance regeneration (which may of course be zero). Underplanting will be dealt with separately at the end of this section.

Herbicides permitted.

When the advance regeneration is zero or very low, and full conifer stocking is required, the cheapest prescription is a conventional plantation (Table 4). Thus, the analysis confirms present practice. At lower stocking standards, fill planting becomes the cheapest alternative (merely the convention applied to a fraction of the block).

With a reasonable contribution from advance regeneration (as in Table 4: half the total required stocking), fill planting and use of a scarifier-sowing machine are roughly cost-equivalent prescriptions for moderate or minimal stocking criteria. Aerial seeding and reliance on a mast year are the most expensive alternatives.

Table 4. Cost/scenario for various prescriptions with and without herbicides.

Results are presented for full, moderate and minimal stocking. The block-wide contribution of advance regeneration (T_o) to the total stocking is shown at three levels: T_o=0, T_o=0.5T_s, and T_o=T_s where T_s is the block-wide stocking criterion. F_{DAR} is total reliance on the advance regeneration (T_o=T_s); aerial refers to aerial seeding; SS is use of a scarifer-seeding machine; mast year refers to reliance on a mast year following understory scarification (note that if T_o = 0 then there is no advance regeneration and we assume therefore few or no source trees for this prescription); fill plant refers to the fill planting prescription (note that when T_o = 0, there is no advance regeneration, the entire treated area is planted, and this is equivalent to a conventional plantation).

	With herbicides			Without herbicides		
	To=0	To=Ts/2	To=Ts	To=0	To=Ts/2	To=Ts
Aerial						
full	1595	1273		1790	1395	
moderate	997	795		1119	872	
minimal	598	477		671	524	
SS						
full	1292	1121		1390	1195	
moderate	808	701		869	747	
minimal	485	421		521	449	
F_{DAR}						
full			950			1000
moderate			594			625
minimal			356			375
Fill plant						
full	1100	1025		1500	1250	
moderate	688	641		938	782	
minimal	413	384		563	470	
Mast yr						
full		1350			1400	
moderate		844			875	
minimal		506			525	

In summary, a conventional plantation should only be undertaken if there is essentially no advance regeneration and full stocking is called for. Otherwise, fill planting is cheaper. As the amount of advance regeneration increases, the scarifier-seeder begins to approach fill planting as the method of choice.

Herbicides prohibited.

While no other jurisdiction has followed the lead of Quebec, the banning of herbicides has a tremendous effect on the comparative costs in Table 4. Not surprisingly, all costs rise as the weeding is done by mechanical rather than chemical means, but the effect is especially pernicious for conventional plantations. All options except aerial seeding and reliance on a mast year are now cheaper than conventional clearcut/plantations no matter what the stocking criteria or contribution of advance regeneration density.

The cheapest approach is now the scarifier-seeder. Fill planting is modestly more expensive, and mast year reliance and aerial seeding are the most expensive of the alternatives to conventional plantations.

Underplanting.

With herbicides permitted, underplanting is essentially unaffected by the level of advance regeneration because the two prescriptions have virtually identical total costs/ha. Reliance on advance regeneration for full stocking is $750/scenario (Table 4) while underplanting costs $825/scenario in the absence of any advance regeneration. Thus, relying on advance regeneration for any of the stocking makes little difference in the present cost. There would be, of course, a difference if interest costs, road maintenance or AAC were taken into account. Note that the two prescriptions are fundamentally incomparable as underplanting is limited to stands where light levels are very high. If advance regeneration existed in such stands, they would also be capable of becoming very tall, thus within a few decades obviating the weeding cost we have attached to reliance on advance regeneration.

Conclusion

Our analysis of biotic and cost constraints leads, essentially, to an endorsement of emerging contemporary practices in the boreal forests of Canada, especially those that use protection of advance regeneration to partially or fully stock mixedwood stands after logging. Our results, however, also show why industrial forestry has favoured clearcutting, planting and herbicides. except where advance regeneration densities exceed 4,000 (west) to 26,000 (east) stems/ha. The range in density required is a function of tree species, tree height and the spatial distribution of the advance regeneration (random or clumped). In general, lower densities are adequate in the west for white spruce and higher densities necessary in the east for balsam fir. Without high densities of advance regeneration, or the use of herbicides in conventional clearcuts, direct seeding with a scarifier-seeder augmented with some advance regeneration replaces conventional plantations as the most cost effective alternative. Underplanting approximately 20 years prior to logging appears to have considerable merit, especially in the west, if suitable access is available. This prescription is, after all, simply the artificial establishment of an advance regeneration component into mixedwood stands. We have demonstrated why aerial seeding of white spruce on boreal mixedwood sites has been so unsuccessful. The unreliability is due to too little seed and too little scarification. Increasing the reliability of aerial seeding is costly because of the enormous number of seeds per ha required to ensure a reasonable chance of success.

The prohibition of herbicides has a dramatic effect on the relative costs of the prescriptions. Without herbicides, the high regeneration costs of plantations are now coupled with the higher tending costs (in this case mechanical weeding) normally associated with natural regeneration options. Whether other provinces will follow Quebec's example is not known.

We have found that the cheapest prescription depends on the stocking criteria. While full conifer stocking has been the management objective for many mixedwood sites in the past, there is considerable controversy regarding management goals for mixedwood forests across Canada. On public lands, the silvicultural objectives of an organization are frequently focused 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 conifer monoculture despite the fact that aspen were present at the time of logging. 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. However as argued by Lieffers et al (1996a) mixedwood management might be better practiced via moderate or minimal conifer stocking prescriptions. Further, a conversion to a conifer monoculture may not be desirable in terms of biodiversity issues. The analytical framework elaborated here forms the basis for determining when and how to implement a greater diversity of management prescriptions for mixed stands (i.e. minimal or moderate conifer stocking). Finally, remembering that we estimate only about 84% reliability for the full-stocking prescriptions entertained here, we think it is important that an organization be granted some flexibility with regard to composition and age structure at the stand scale; more inflexible standards should be reserved for the landscape scale (Kneeshaw et al., 2000). It will then, of course, be necessary to develop yield models for the mixed stands envisioned in some of these scenarios but this requirement is no different from any other management system one might entertain.

A related issue is the question of differing goals of various stake holders. For example, in Québec and Alberta, current forest management agreements permit more than one company to hold cutting rights to the same land-base. Typically, one company may have rights to the hardwood component and another to the coniferous component. Clearly, the company that harvests aspen will not seriously entertain underplanting nor will the company permitted to harvest conifers have any incentive for reversion to aspen after the mature conifers are cut. This dichotomization of goals can lead to management practices with undesirable consequences. It is easy to turn a mixed stand into a virtual aspen monoculture over a few rotations as the conifer seed sources are removed (e.g. the dramatic reduction in white pine (*Pinus strobus*) stocks in eastern Canada over two centuries) while it is more costly to force the mixed stand toward a conifer monoculture under a regime of short rotations. Thus, the dichotomization would tend to produce more homogenous stands than the landscape has seen in the past, and it would not necessarily be, averaged across the landscape, the cheapest option. It appears that policy-makers and practitioners are growing increasingly aware of these risks (e.g. Lieffers and Beck 1994; MacDonald, 1996), and are therefore more receptive to the objective of maintaining the multi-species composition of mixedwood stands and forests. Thus, managing the mixedwood as mixed stands at both stand and landscape scales would allow for a much richer variety of prescriptions. The quantitative framework presented here can serve as a palette for forest managers as they respond to the need to regenerate forests in a manner that is cost effective, conservative of landscape diversity, and, to say it bluntly, more easily justified to urban voters.

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