The utility of the two-pass harvesting system: an analysis using the ecosystem simulation model FORECAST

Clive Welham, Brad Seely, and Hamish Kimmins

Abstract: The ecosystem model FORECAST was used to simulate the yield potential in Saskatchewan mixedwoods of the two-pass harvesting system. The simulated two-pass stand consisted of an overstory population of pure trembling aspen (*Populus tremuloides* Michx.) with a white spruce (*Picea glauca* (Moench) Voss) understory. The aspen was removed at year 60, and yields of the understory spruce and resprouting aspen were simulated for 80 years thereafter. The two-pass simulations were compared with two simulated conventional harvesting systems. The first system consisted of a single final harvest at year 140. In the second system, a clearcut was conducted at year 60. White spruce was then planted in the subsequent year at 400, 600, or 800 stems/ha, and aspen also permitted to resprout. Growth was then simulated for a further 80 years. FORECAST projections indicated that the two-pass system might be effective for releasing the white spruce understory, achieving at least a twofold gain in spruce volume relative to conventional methods. Furthermore, total volumes exceeded those derived from the unmanaged stand, while second rotation yields of aspen declined with spruce understory density. These simulations suggest the two-pass harvesting system has strong potential as a tool for mixedwood management.

Résumé : Le modèle d'écosystème FORECAST a été utilisé pour simuler le rendement potentiel du système de récolte à deux étapes dans les forêts mélangées de la Saskatchewan. La simulation a porté sur un peuplement constitué d'un étage dominant composé seulement de peuplier faux-tremble (*Populus tremuloides* Michx.) et d'un sous-étage d'épinette blanche (*Picea glauca* (Moench) Voss). Le peuplier a été récolté à 60 ans et les rendements de l'épinette en sous-étage et des rejets de peuplier ont été simulés pour les 80 années suivantes. Les simulations du système à deux interventions ont été comparées aux simulations de deux systèmes de récolte conventionnels. Le premier système comporte seulement une coupe finale à 140 ans et le second une coupe à blanc à 60 ans. Dans les années subséquentes, l'épinette blanche est plantée à raison de 400, 600 ou 800 tiges à l'hectare en laissant le peuplier produire des rejets et la croissance est simulée pour un autre 80 ans. Les prévisions du modèle FORECAST indiquent que le système à deux étapes pourrait être efficace pour dégager l'épinette en sous-étage, dont le volume serait au moins doublé comparativement aux systèmes conventionnels. De plus, les volumes totaux dépassent ceux qui sont obtenus dans un peuplement non aménagé alors que le rendement du peuplier diminue lors d'une seconde révolution à cause de l'augmentation de la densité de l'épinette en sous-étage. Ces simulations montrent que le système de récolte à deux étapes a un fort potentiel comme outil pour l'aménagement des peuplements mélangés.

[Traduit par la Rédaction]

Introduction

Planting of white spruce (*Picea glauca* (Moench) Voss) seedlings following a clear-cut harvest has been the predominant silvicultural strategy for spruce regeneration in the boreal mixedwoods of the Prairie Provinces. The rationale for this approach is twofold. First, clear-cutting is the simplest and most cost-effective method for timber extraction and, secondly, planting seedlings should result in the reestablishment of an even-aged spruce population. (Trembling aspen, *Populus tremuloides* Michx., the other dominant tree species in these mixedwoods, is left to regenerate naturally.)

The clear-cut method first became widespread during the 1960s (Wedeles et al. 1995). During this and the subsequent decade, a variety of techniques were employed to promote spruce regeneration, usually involving seed applied manually or by relying upon seed from natural sources (Drew 1988). These methods proved unreliable, and although forest companies resorted increasingly to planting seedlings, a cost-effective means of re-establishing spruce has remained elusive. Left alone, many plantations reverted to either a mixedwood, or become dominated by hardwoods (Drew 1988). Expensive and time-consuming tending activities were then usually required to maintain the softwood component. The economic cost and effort required ensuring spruce plantation establishment (Pearce 1991) led to proposals for alternative silvicultural systems (see Wedeles et al. 1995, for a review). Among these alternatives, the two-pass harvesting system has received the most attention.

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C. Welham,[1] B. Seely, and H. Kimmins. Forest Ecosystem Management Simulation Group, Department of Forest Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada.

[1]Corresponding author (e-mail: welham@interchange.ubc.ca).

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The two-pass harvesting system

The two-pass system in boreal mixedwoods is applicable to stands composed of a mature aspen overstory with a well-developed understory population of white spruce, a stand type common in the mixedwood region (Peterson 1988). The hardwood overstory is removed in the first entry into the stand, which releases the understory from competitive suppression (Fig. 1). Hence, logging practices that minimize spruce understory damage are crucial to ensuring subsequent volume accumulation (Brace 1991). Careful consideration should also be given to features of the understory itself so as to minimize the risk of subsequent blowdown (Navratil 1995; Navratil et al. 1994).

Although white spruce reportedly responds very well to release (Ontkean and Smithers 1959; Crossley 1976; Berry 1982; Yang 1991), there are no studies with which to directly assess whether this growth is maintained over the long term. Two projects were initiated in Alberta mixedwoods in 1988, in part to assess the growth of a released understory spruce population (Navratil et al. 1994). To date, results have been summarized for only the 5-year postrelease period, but they indicate increases in height, diameter, and volume accumulation. Medium-term responses have been reported from a 35-year release trial in spruce–aspen mixedwood stands in Alberta (Yang 1991; see Lees 1966, for interim results). These results showed improved spruce periodic growth of 41% in diameter, 38% in height, and 82% in volume, compared with the unreleased control population. A second study in Saskatchewan and Manitoba mixedwoods documented spruce growth response over a 30-year period, with similar results (Yang 1989; see Steneker 1967, for interim results). Unfortunately, confirming the efficacy of the two-pass system with field trials alone is simply not feasible. Only a small subset of variables can be manipulated at any given time, and very long time period must pass before these results can be considered as definitive. As a consequence, various methods have been employed to forecast future productivity and assess the efficacy of the two-pass system.

One approach is to use initial growth estimates from the released spruce populations to make projections of future yield. Yang (1989) projected merchantable volume yields of 123–320 m^3/ha at year 100 (40–90 years following release) from estimates of periodic annual increment. Brace and Bella (1988) used published yield data from Alberta and the STEMS model (Belcher et al. 1982) to forecast spruce growth. They projected yields approaching 550 m^3/ha 60 years after release for spruce on medium to good productivity sites (site index 24 m at reference age 70 years). These results are encouraging; they suggest the two-pass system might produce high yields of white spruce in Prairie boreal mixedwoods over relatively short rotation lengths.

In this study, we used an ecosystem simulation model, FORECAST, calibrated for Saskatchewan ecosites dominated by white spruce and trembling aspen, to investigate the potential yield returns from the two-pass harvesting system. The model is considerably more complex than the analyses described above and can simulate many more of the ecosystem events and processes that influence stand productivity (see Kimmins et al. 1999; Seely et al. 1999). Hence, in FORECAST (*i*) competitive interactions between the overstory species and their effect upon productivity will be simulated directly, rather than from measures calculated for each species separately (e.g., see Yang 1989; Navratil et al. 1994); (*ii*) bluejoint (*Calamagrostis canadensis* Michx.), an important competitor to white spruce seedlings (Drew 1988), is included in the simulation; and (*iii*) as a management-oriented model, FORECAST will be used to compare the two-pass system with existing harvesting methods. Comparing the predictions from FORECAST with previous projections will add confidence in two-pass harvesting as a useful mixedwood silvicultural system. Finally, (*iv*) the model will be used to examine management scenarios not represented in current empirical trials or considered in previous analyses.

Materials and methods

The FORECAST model

Kimmins et al. (1999) and Seely et al. (1999) provide detailed descriptions of FORECAST and its potential applications, and only a brief summary will be provided here.

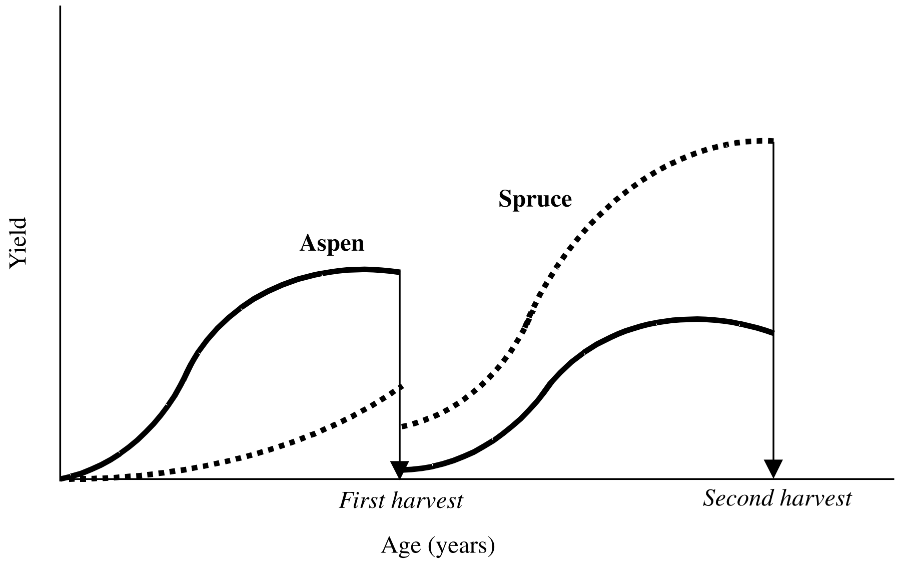
FORECAST was designed to accommodate a wide variety of harvesting and silvicultural strategies to compare and contrast their effect upon forest productivity (often within the context of sustainability and certification). The model is based upon an approach whereby local growth and yield data are utilized to derive estimates of the rates of key ecosystem processes related to the productivity of selected species. This information is combined with data describing rates of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth under changing management conditions. Growth occurs in annual time steps. Depending on the species, plant populations are initiated from seed and (or) vegetatively, and stand development can occur with or without the presence of competition from nontarget tree species and understory populations. Decomposition is simulated using a method in which specific biomass components are transferred at the time of litterfall, to one of a series of independent litter types. These litter types decompose at rates defined by empirical data.

Model protocol

A simulated stand was developed with FORECAST to represent a mixedwood that might originate following a stand-replacing fire, on Saskatchewan ecosites dominated by white spruce and aspen (typically *b* and *d* ecosites; see Beckingham et al. 1996). These ecosites range from a mesic (*d*) to submesic (*b*) moisture regime and a medium nutrient regime, and together they cover a relatively large portion of the Mid-boreal Upland Ecoregion (Beckingham et al. 1996). Other tree species occasionally found in association with spruce or aspen on these sites, including jack pine (*Pinus banksiana* Lamb.) and white birch (*Betula papyrifera* Marsh.), are not considered suitable for the two-pass system and, thus, are not included here. Site index (tree height at 50 years breast height age) varies from 18.3 to 20 m for aspen, and 16.1 to 19.7 m for spruce, on *b* and *d* ecosites, respectively.

Growth and yield data were derived principally from literature sources (Kabzems 1971; Kabzems et al. 1986; Peterson and Peterson 1992, and references therein) and used in conjunction with allometric biomass equations (Singh 1981;

Fig. 1. The two-pass harvesting system. The first harvest removes the aspen overstory, which releases the white spruce understory from competitive suppression. In the second harvest, all merchantable timber is removed.



Peterson and Peterson 1992) to calibrate FORECAST for each tree species. Biomass curves were generated for a range of nutritional site qualities to permit the simulation of site-quality change (see Kimmins et al. 1999). Simulation of the effect of nutrient availability on productivity was limited to nitrogen. Data describing light and nitrogen requirements, and all other calibration data, were derived from standard literature sources. Decomposition rates were calibrated using empirically derived mass loss rates for specific litter types (Prescott et al. 2000*a*, 2000*b*; Taylor et al. 1991).

Simulation of two-pass harvesting

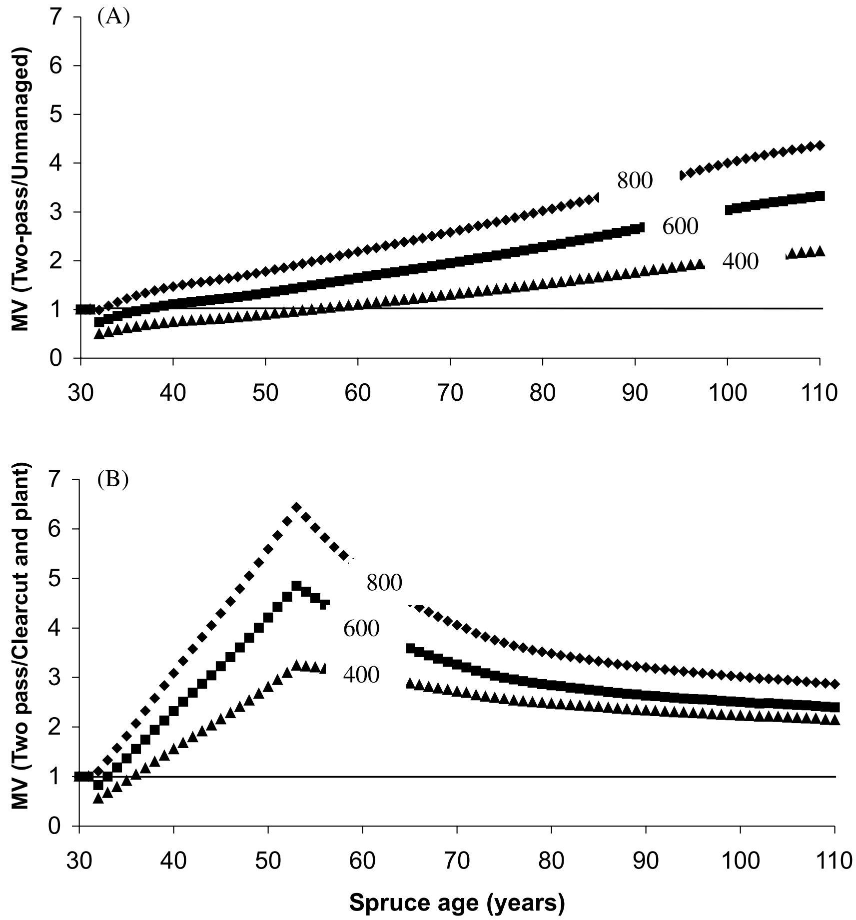
A population of aspen was initiated immediately following a stand-replacing fire at a density of 10 000 stems/ha, as well as population of *C. canadensis* (10% initial cover). Sucker densities in aspen following disturbance can vary widely (see Peterson and Peterson 1992), but self-thinning also varies proportionately, and so populations converge rapidly within several years to densities of 10 000 stems/ha or less (Peterson et al. 1989). *Calamagrostis* was included in the simulation, because its presence can reduce spruce productivity significantly (Eis 1981; Drew 1988; Hogg and Lieffers 1991). The timing of spruce understory recruitment is variable and can occur immediately following disturbance but is often delayed several decades (see Lieffers et al. 1996). Therefore, a white spruce understory was created from simulated natural regeneration in year 30 (counting from the year immediately following the fire) at a starting density of 1800 stems/ha. This density is typical of a well-stocked naturally regenerated mixedwood stand (e.g., see Kabzems 1971). The aspen overstory was harvested in year 60, at which point 90% of stemwood, 70% of branches, and 20% of foliage were removed from the site. *Calamagrostis* was permitted to reinvade the site (at 10% initial cover) in the year immediately following the aspen harvest.

Evidence suggests that shade-intolerant and mid-tolerant species (such as white spruce; Nienstadt and Zasada 1990) often sacrifice diameter growth but maintain their height growth under low-light conditions (Ruel et al. 2000). This attribute was adjusted in FORECAST so that spruce height growth was maintained unless stemwood production per tree was reduced by shading, to less than 30% of that expected from a canopy dominant spruce (see Kimmins et al. 1999, for further details). Therefore, at the time of aspen harvest the understory spruce had reached a height of approximately 9 m.

Understory response to removal of the overstory usually involves the reallocation of carbon into foliage, conducting tissue, and fine roots, with the result that subsequent production often increases dramatically (Ruel et al. 2000). Carbon allocation patterns in FORECAST are determined during the set-up phase of model calibration and are age dependent. Furthermore, net production per unit mass of photosynthetic material tends to decline with age as the relative proportion of respiring tissue increases. Taken together, these serve to restrict FORECAST's ability to simulate the full extent of the release response expected in 30-year-old seedlings subject to a sudden and large increase in light levels. To circumvent this difficulty, the model was instructed to replace the original spruce understory at the time of overstory removal, with a population whose carbon allocation patterns were representative of saplings growing under full illumination. This "new" population was established at densities of 800, 600, or 400 stems/ha, which simulated harvest-related mortality of 38, 53, or 69%, respectively. These mortality rates are within the range documented from release trials employing high to intermediate levels of understory protection during overstory removal (e.g., see Brace 1991; Navratil et al. 1994).

Growth and yield of the understory spruce and resprouting aspen in the two-pass system was projected for up to 80 years following the initial overstory removal. Results were compared with two conventional harvesting systems. The conventional systems were initiated under conditions identical to the two-pass simulation, including a white spruce understory established in year 30. In the first conventional system, the stand was left to develop as a mixedwood without any management intervention until a single final

Fig. 2. Ratio of merchantable volume (MV) from the two-pass system for white spruce released by an overstory harvest conducted when the spruce were 30 years of age, versus two conventional systems, an unmanaged mixedwood stand (A), and a stand that was clear-cut when the aspen was 60 years old and then planted with white spruce (B). In the latter, planted seedling ages are, therefore, 30 years younger than the ages of the understory spruce given on the abscissa. Density of spruce left following overstory removal were 400 (triangles), 600 (squares), and 800 (diamonds) stems/ha.



harvest was conducted when all mature aspen and spruce were removed (e.g., see Ontkean and Smithers 1959; Yang 1989, 1991). In this "unmanaged" system, harvest occurred when the aspen was 140 years old. (The spruce were, therefore, 110 years of age.) The second conventional system was designed to emulate the traditional clear-cut and plant method. In this case, aspen and any spruce of merchantable size were harvested at year 60 with no provision for protection of any non-merchantable trees. Evidence indicates that widespread damage to the understory is not unusual in these circumstances (Navratil et al. 1994). As a consequence, the remaining unmerchantable spruce was killed during harvest. The stand was then replanted with white spruce at 400, 600, or 800 stems/ha, in the year following harvest. At this time, aspen was also permitted to regenerate vegetatively at 10 000 stems/ha, and *Calamagrostis* reestablished with a starting cover of 10%. Subsequent growth of these stands was projected for 80 years.

Results

FORECAST projections were that release of the white spruce understory in the two-pass system resulted in significant gains in merchantable volume, compared with the unmanaged stand (Fig. 2A). The initial decline in spruce volume relative to the unmanaged stand (Fig. 2A) was a result of the understory mortality incurred during overstory removal. The greater the mortality, the longer the delay before the volume of the released population exceeded that of the unmanaged stand. At 110 years of age, spruce volume from the two-pass system might be at least double that of the unmanaged stand, the actual gain depending on release density (Fig. 2A). Projected spruce yield at this age was 40 m^3/ha in the unmanaged stand (data not shown) and 87–174 m^3/ha in the two-pass system (Fig. 3), while for aspen, the respective yields were 246 m^3/ha (data not shown) and 0–145 m^3/ha (see Fig. 6). Relative volume gains from the two-pass system increased dramatically following clearcut and planting (Fig. 2B). Gains reached a peak at 23 years postrelease (understory spruce age of 53 years) and declined thereafter (Fig. 2B). This decline occurred because the planted spruce population reached merchantable size at age 23 and, thereafter, accumulated volume increments at a higher rate than the (older) spruce in the two-pass system. Volumes of spruce and aspen 80 years after clearcut and planting were 40–61 and 181–185 m^3/ha, respectively (data

Fig. 3. Spruce merchantable volume accumulation from the two-pass system in relation to age. Density of spruce remaining immediately following aspen overstory removal at spruce age 30, were 400 (triangles), 600 (squares), and 800 (diamonds) stems/ha.

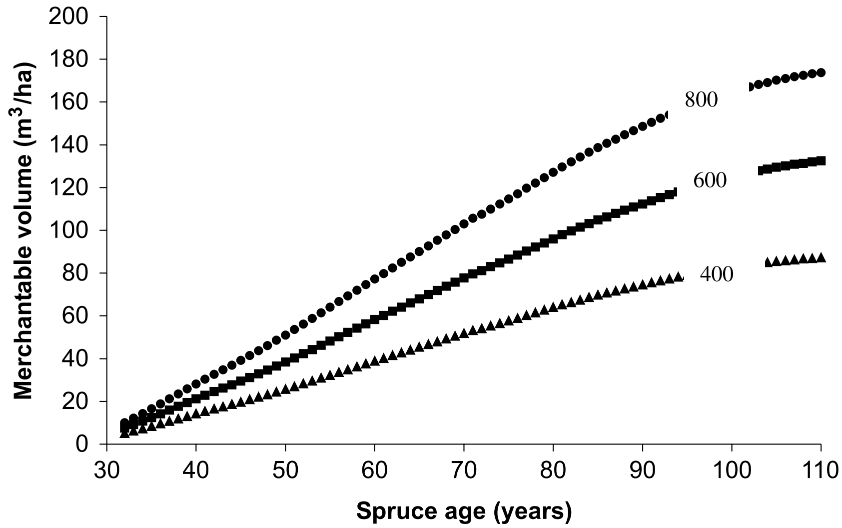
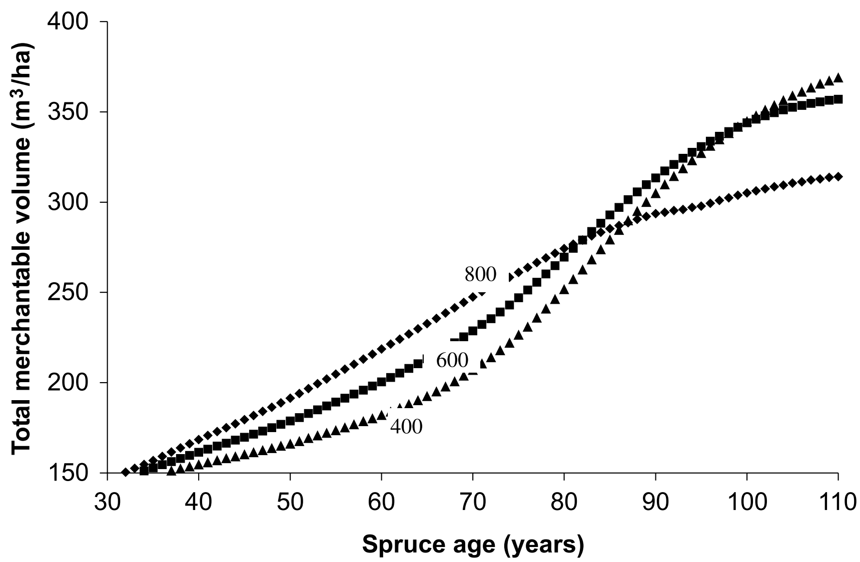


Fig. 4. Total merchantable volume accumulation from the two-pass system in relation to spruce age. Density of spruce left following overstory removal was 400 (triangles), 600 (squares), and 800 (diamonds) stems/ha. Note that the total includes the aspen volume derived from removal during the first harvest (aspen aged 60 years), during which time the spruce were 30 years old.

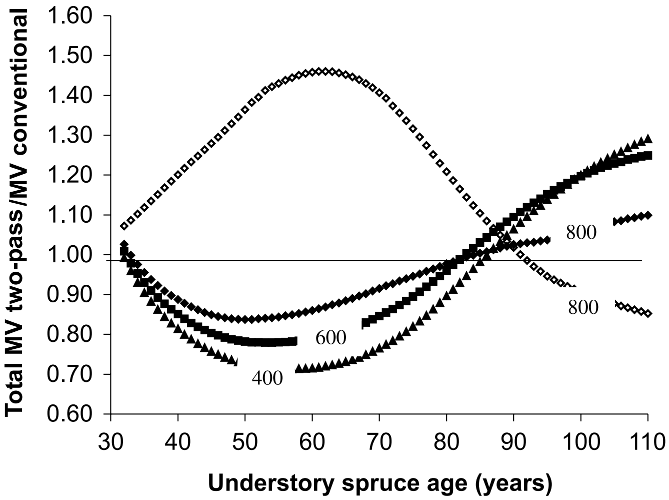


not shown). These aspen volumes were consistently higher than those achieved from the two-pass system (see Fig. 6), whereas spruce volumes were considerably lower (Fig. 3).

Total merchantable volume projections (spruce plus first and second harvest aspen) were similar between release densities, reaching a maximum of 370 m^3/ha, 80 years postrelease (Fig. 4). Interestingly, the total volume at 800 stems/ha was actually below that achieved at lower understory spruce densities (see Discussion).

Comparison of total merchantable volume projections between the two-pass system and the unmanaged stand showed the latter producing higher volumes until about spruce age 85 (corresponding to 55 years postrelease under the two-pass system; Fig. 5). The initial decline in total volume of the released stand relative to the unmanaged stand is attributable to the fact that in the former, the majority of merchantable volume was removed when the aspen overstory was harvested. Hence, more than five decades of growth may be necessary before the combined volumes of the released spruce and resprouting aspen surpass those of an unmanaged mixedwood stand. At higher understory release densities, the proportional decline between the two systems was reduced. The opposite trend occurred when the two-pass system was compared with clearcut and planting. At an understory release density of 800 stems/ha, total merchantable volume projections from the two-pass system rose immediately and peaked at 1.45 times that of the planted stand, 25–40 years following the release cut (Fig. 5). This increase occurred because in the case of clear-cutting, the spruce understory was destroyed when the overstory was harvested and subsequently replaced with much smaller planted seedlings. Sixty years after the spruce seedlings were planted, however, total volume from clearcut and planting exceeded the volume from the two-pass stand (Fig. 5). Similar trends occurred at

Fig. 5. Ratio of total merchantable volume (MV) derived from the two-pass system versus two conventional systems, an unmanaged mixedwood stand (solid symbols), and a stand that was clear-cut when the aspen was 60 years old and then planted with white spruce (open symbols). Planted seedling ages are, therefore, 30 years younger than the ages of the understory spruce given on the abscissa. Density of seedlings remaining following overstory removal in the two-pass system was 400 (triangles), 600 (squares), and 800 (diamonds) stems/ha. Note the total volume includes any aspen volume derived from a first harvest.



lower planting densities though the peaks in the relative ratios were lower as planting density declined (data not shown).

The ability of aspen to resprout (and hence its subsequent volume) in the two-pass system following its removal in the first cut was inversely related to the density of understory spruce that survived (Fig. 6). Furthermore, the aspen volume reduction was disproportionate to the increase in spruce density, and aspen was, therefore, unable to survive during the second phase of the two-pass system at spruce release densities of 800 stems/ha.

Discussion

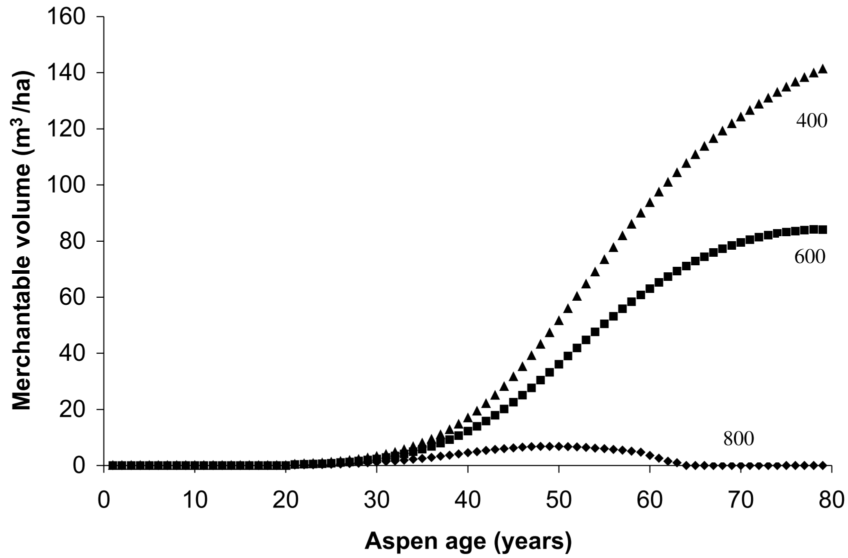
FORECAST projections indicate that the two-pass harvesting system might be effective for improving yields of white spruce in Saskatchewan mixedwoods, with volume increment gains sufficient to reduce spruce rotation length following overstory removal (Fig. 2). Brace and Bella (1988) applied the STEMS model to investigate the benefits of the two-pass system in Alberta. Their projections indicated that merchantable spruce yields approaching 550 m^3/ha at age 100 years were attainable on medium-good productivity sites, at a release density of 600 stems/ha. FORECAST output suggests this level of productivity may not be attainable in Saskatchewan mixedwoods, however, and that a much lower merchantable yield is more realistic (about 140 m^3/ha; Fig. 3). There are several important features of the STEMS model that could account for this discrepancy with FORECAST. First, Brace and Bella calibrated the model for Alberta mixedwoods using data from that province (Johnstone 1977). Hence, their productivity measures were not the same as those used here. In addition, STEMS was developed for the Lake States region of North America, where precipitation is greater (500–900 mm annually; Wedeles et al. 1995) than the Saskatchewan mixedwood region (mean annual precipitation 417–472 mm; Kabzems et al. 1986). Therefore, yields in Saskatchewan mixedwoods likely are constrained by tree size limitations set by moisture deficits experienced during the summer period, which are not accounted for in the STEMS model. FORECAST does not account for soil moisture explicitly either, but the effect of moisture deficits are represented implicitly in the calibration data by setting a moisture-limited foliage carry capacity (see Kimmins et al. 1999). A second difficulty with Brace and Bella's (1988) simulation is that spruce growth estimates were based, in part, upon the assumption that the aspen that resprouted after the overstory was harvested had no significant impact on the growth of the released spruce population. In the Brace and Bella (1988) population, the released spruce were sufficiently tall that this was likely the case with respect to light competition (e.g., see Yang 1989). However, aspen and *Calamagrostis* are both very effective competitors against spruce for belowground resources (particularly nitrogen; Pastor 1990; Staples et al. 1999; K.C.J. Van Rees, in review[2]), and their presence can reduce spruce productivity significantly (Eis 1981; Drew 1988; Hogg and Lieffers 1991). Since the STEMS model does not include nutrient competition, this would likely have inflated its projections of spruce productivity.

Yang's (1989) projections for 100-year merchantable yields in Saskatchewan and Manitoba were between 123 and 320 m^3/ha, based upon a simple extrapolation from published yield tables (Kabzems 1971). These values are perhaps more realistic, though Yang (1989) noted that two stands had projected volumes in excess of published yields for fully stocked spruce stands on medium sites (see Kabzems 1971). Nevertheless, the lower end of Yang's projections falls within the values reported here. The majority of Yang's sites had release densities in excess of those used in FORECAST (to a maximum of 2940 stems/ha), and this could account in part for the higher upper range estimates.

Navratil et al. (1994) made projections of 60-year release productivity in 50-year-old spruce using periodic growth measures derived over a 5-year postrelease period. In the 401–600 stems/ha spruce density class, total yield was 308 m^3/ha, of which 274 m^3/ha was spruce, and the remainder (34 m^3/ha) was aspen. Converting to merchantable volume (using 0.90 as the multiplier for spruce, and 0.68 for aspen; see Johnstone (1977) and Kirby et al. (1957), respectively), these yields are 246 m^3/ha for spruce, and 23 m^3/ha for aspen. In our case, total predicted merchantable volume following release of 400–600 stems/ha was lower (220 m^3/ha; see Fig. 4), of which the spruce component varied from 87 to 133 m^3/ha (Fig. 3) and aspen from 80 to 140 m^3/ha (Fig. 6). For the 600–800 stem density class, Navratil et al. (1994) projected 329 m^3/ha merchantable spruce yield and no aspen. At 800 stems/ha, FORECAST

[2] K.C.J. Van Rees. Nitrogen uptake characteristics for roots of selected boreal forest tree and understory vegetation species. Submitted to Can. J. For. Res. In review.

Fig. 6. Merchantable volume of resprouting aspen after its initial harvest at 60 years of age. Density of the understory spruce (aged 30 years) left following aspen removal was 400 (triangles), 600 (squares), and 800 (diamonds) stems/ha.



also projected aspen extinction (Fig. 6), but spruce yield was only 175 m^3/ha (Fig. 3).

One important distinction between Navratil et al.'s (1994) results and those reported here is the extent of aspen regeneration following overstory removal. Navratil et al. (1994) assumed that final aspen merchantable yield varied proportionately with spruce density (20% at 401–600 stems/ha; see Navratil et al. 1994, Table 12; note that this table erroneously reports a 50% final aspen yield). Aspen yield in FORECAST, however, was not constrained by this assumption. Rather, productivity was a function of the degree of intraspecific competition. In the Navratil et al. (1994) study, the spruce population was 20 years older at release than the population simulated within FORECAST (age 50 vs. 30 years) and would thus be a stronger competitor against aspen. Similarly, spruce merchantable volumes at release were between 5 and 10 m^3/ha in our simulations but were higher in the Navratil et al. (1994) stands, at 70–77 m^3/ha.

Although the two-pass system might enhance spruce yield relative to the conventional systems we considered (Fig. 2), this was not necessarily the case for total site productivity. Removal of the aspen overstory at year 60 incurred an opportunity cost, at least over the medium term, in productivity lost by not permitting the overstory any further growth (the unmanaged stand; Fig. 5). Notwithstanding the fact that the principal objective of the two-pass system is to promote spruce yields, any gain in total stand productivity over the unmanaged stand simulations may not be realized until at least five decades following overstory removal. Such was not the case when compared with the clearcut and planting scenario (Fig. 5). The relative gain in total yield from the two-pass system was at its maximum 30 years following release, and this gain over clearcut and planting was maintained for at least 30 years thereafter.

Factors affecting the release response

Understory response to a release treatment is generally not detectable statistically for at least 10 years postrelease (Yang 1989; Navratil et al. 1994; Urban et al. 1994). In some individuals or populations, a release response simply does not occur (e.g., see Steneker 1967, 1974; Bella and Gai 1996; Yang 1989). However, a number of factors have been identified that can influence the degree of response.

Understory density

Yang (1989) has suggested that a spruce understory release density of 600–800 stems/ha is sufficient to ensure a fully stocked spruce stand. Furthermore, long-term site productivity was lower when densities exceeded 1000 stems/ha (Yang 1989). Although the maximum spruce density considered here was only 800 stems/ha, our results are consistent with this observation. First, when release densities were increased from 400 to 600 stems/ha, the percentage of aspen in the merchantable yield 80 years postrelease declined from 70 to 40%. At 800 stems/ha, aspen was eliminated entirely from the second rotation. Secondly, total merchantable volume at spruce age 85 and older, was lower at 800 versus 600 stems/ha (Fig. 4). This decline in productivity was likely due to the fact that spruce grows more slowly than aspen, and spruce growth rates were not sufficient to compensate for the productivity lost when the aspen was harvested.

Age and height of the understory

Yang (1989, 1991) suggested that the optimum height and age of spruce for release are 5–6 m, and 15–40 years of age, respectively. It is unclear, however, why age per se should influence growth potential (see Ruel et al. 2000). In the case of very short trees, their growth is depressed simply because they are overtopped by the resprouting aspen. Trees at the optimum height may show a stronger release effect because they can retain their height advantage over the aspen, but their stature is still small enough to maintain wind-firmness (Urban et al. 1994). Taller trees may need to invest resources initially into root development following release to confer wind stability at the expense of height growth. In addition, very tall understory spruce (>7 m) can be subject to leader whipping, which depresses height growth even after overstory removal (Steneker 1967).

Neither leader whipping, nor adaptive reallocation of root/shoot ratios in response to wind stress can be modeled explicitly within the present version of FORECAST. In terms of understory height, the average used here (9 m) exceeded the optimum recommended by Yang (1989). This was likely not problematic, however, since the release response in individuals 6 m or taller tends to be independent of height (Yang 1989).

Practical problems with implementing the two-pass system

The two-pass system is clearly a useful method for enhancing spruce volume and reducing rotation length. Its success, however, is not without difficulties, not the least of which is the protection of the white spruce understory during overstory removal. Studies indicate that without adequate protection, more than 90% of the understory can be destroyed (Navratil et al. 1994), although typically, mortality is around 70% (Froning 1980; Brace 1991; Yang 1989). In the present study, lower spruce densities related to understory mortality caused a considerable delay in subsequent productivity (Fig. 2A). Recent trials of the two-pass system have been conducted in Alberta (Brace Forest Services 1992; Sauder 1992; Navratil et al. 1994), to determine the level of understory protection that could be provided during the initial entry. Results suggest that using conventional harvesting equipment, and with careful planning, crew training, and supervision, 50–60% of the understory spruce population can be protected during overstory removal (Navratil et al. 1994). Of particular significance is the observation that protection effort (planning, layout, supervision, crew experience and attitude) appears to be more significant for understory protection than the type of harvesting equipment used (Brace 1991; but see Navratil et al. 1994).

The two-pass harvesting system has been shown to enhance the yield of white spruce in the short to medium term (<35 years following release). Longer term benefits projected from simulation models are also encouraging both in terms of total stand volumes (aspen plus spruce) as well as for spruce yields alone. An important caveat, however, is that the simulations demonstrate the potential productivity of this system. In many cases, insect and fire-related mortality events are likely to negatively impact actual returns. Although these, and any other stochastic events, cannot be modeled explicitly by FORECAST, their effects are represented implicitly within the input data (see Kimmins et al. 1999). A second consideration is that expected returns from spruce release cannot be calculated independently from the market value for aspen fibre (see also Yang 1989, 1991). Early release of spruce (i.e., removing the overstory when the aspen is younger and, thus, forgoing any potential increase in future aspen yield), for example, may enhance subsequent spruce yield but increased demand for aspen could still make it economically attractive to delay overstory removal.

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