Managing for timber volume and Mountain Pine Beetle susceptibility: impacts on ecosystem production and soil organic carbon

Clive Welham

Brad Seely
Forest Ecosystem Management Simulation Group
Department of Forest Sciences
University of British Columbia
Vancouver, BC V6T 1Z4

Justin Straker
CE Jones and Associates
104-645 Fort Street
Victoria, BC V8W 1G1

Juan Blanco
Forest Ecosystem Management Simulation Group
Department of Forest Sciences
University of British Columbia
Vancouver, BC V6T 1Z4
Abstract

The Quesnel timber supply area in central British Columbia, Canada, is dominated by stands of lodgepole pine. Extensive mortality of pine-dominated stands by mountain pine beetle has occurred and there is a concentrated effort to harvest the recently-killed and any remaining susceptible stands. Regional harvest projections also indicate a significant timber volume shortfall over the next 25 – 60 years and so a principle concern to forest managers is how best to regenerate newly-harvested stands without compromising long-term productivity (as reflected in measures of soil organic carbon; SOC). This issue is addressed by linking field estimates of forest floor and SOM with simulated outcomes of the different options using the ecosystem model, FORECAST.

Harvesting at the culmination of mean annual increment (MAI) consistently produced the highest merchantable volumes with no risk of soil degradation in site series with the lowest (the SBPSdc 03) or highest (the SBSmc02 01) soil organic matter content. Harvesting according to MAI also has among the longest rotation lengths. If subsequent harvesting practices were conducted on short rotation then in pine-leading stands growing on sites with low SOC, harvesting that maximizes net expected benefit (MENB; a criterion that accounts for both merchantable volume and stand susceptibility to MPB) is the most feasible strategy. In unfertilized stands, this introduces a risk of soil degradation which can, however, be mitigated with fertilizer. Fertilization has the added benefit of an increased merchantable volume and reduced rotation length. In spruce-leading stands on sites with low SOC, MENB generated the highest volumes but rotation lengths were too long to be appropriate for short-rotation forestry. The MPBS
strategy (a criterion that accounts only for stand susceptibility to MPB) generated reasonable merchantable volume with no risk of soil degradation and no necessity for fertilization.

In pine-leading stands on a site with high SOC, good merchantable volume production was generated by harvesting according to MENB but there was a risk of long-term soil degradation that was only partially mitigated by fertilization. In spruce-leading stands on nutrient-rich sites, MENB generated the highest volumes but rotation lengths were too long to be appropriate for short-rotation forestry. Good merchantable volume production can be generated by harvesting according to MPBS but there may be a risk of long-term soil degradation. Forest companies have a variety of options with which to generate sufficient timber volumes over the mid-term while accounting for risk from subsequent beetle outbreak. However, ecosystems with lower SOC content should be managed carefully to ensure that soil organic matter pools are not degraded unnecessarily.
Introduction

Much of the forest in interior British Columbia (BC), Canada is dominated by stands of lodgepole pine (*Pinus contorta*). Extensive mortality of these pine-dominated stands by mountain pine beetle (*Dendroctonus ponderosae*; MPB) has occurred. By current estimates, at least 8.7 million ha of pine have been impacted by the beetle resulting in unsalvaged fibre losses approaching 200 million m$^3$ and there is a concentrated effort to harvest the recently-killed and any remaining susceptible stands (Pederson 2004). Of principle concern to forest managers now is how to regenerate these stands. This issue is particularly pressing because regional harvest projections indicate a significant timber volume shortfall over the next 25 – 60 years (Pederson 2004).

Lodgepole pine is well adapted to the climatic and edaphic conditions characteristic of interior BC. One option is to restore the original pine-dominated forests but this tactic could simply re-create the forest conditions that triggered the original outbreak problem. According to Shore and Safranyik (1992), stand susceptibility to MPB attack can be predicted as a function of susceptible basal area, age, density, and location. One way to mitigate susceptibility then is by planting pine at very low densities (300-500 stems per ha; Whitehead and Russo 2005, see Shore and Safranyik 1992). As a general rule this approach is unsatisfactory since mature stands may not develop sufficient merchantable volume to harvest economically and individual stems are likely to be very ‘branchy’ (i.e., their wood quality is poor). These stands could possess a high biodiversity value, however. Another possible solution is to establish pure pine stands that are fully stocked and then harvest them on short rotation (< 60 years) before they become susceptible to
MPB attack (see Shore and Safranyik 1992). This approach will help mitigate the mid-term timber supply problem but at the expense of substantial volume gains foregone by the early rotation harvest. This tradeoff might be at least partially offset if fertilizers were used to enhance early growth. Another concern is that repeated, short-rotation harvests can cause a significant loss of soil organic matter (SOM) and forest floor material. SOM is widely regarded as an important structural and functional component of soil, and is a critical link between management practice and forest productive capacity (Page-Dumroese et al. 2000). Depletion of SOM could therefore potentially compromise ecosystem productivity over the long-term (Seely et al. 2002, Welham et al. 2007). A third option is to plant additional species such as interior spruce (*Picea glauca* (Moench) Voss *x* *Picea engelmannii* Parry ex Engelm.) and create mixtures of species either at the stand or landscape-level in order to mitigate the risk of catastrophic outbreak (Martin et al. 2005). The difficulty here is that pine is a fast-growing pioneer species. Hence, a shift from pine to spruce may reduce harvestable volume over the mid-term (60 years) as lodgepole pine culminates sooner (Martin et al. 2005). Clearly, no single approach represents the idea solution. Most forest companies are therefore likely to favor a mix of options but which sites are best suited to a given option and what are the implications for long-term sustainability?

We address these issues by linking field estimates of forest floor and SOM with simulated outcomes of the different management options using an ecosystem model (FORECAST). SOM is a vital element of healthy forest ecosystems and soil protection and enhancement is essential if forest management is to be sustainable. As yet, there is no generally accepted method for quantifying the impacts of management activities on soil
function (see Doran et al. 1994) and, hence, ecosystem recovery. This issue will not be resolved any time soon due to the long time frames required before field results can be considered as definitive. One possible solution is to use an ecosystem model to project targets for that indicator and compare them against thresholds of long-term productivity. The thresholds represent an early warning that forest management practices are compromising a given indicator such that when measures violate threshold boundaries this should trigger remedial actions. Our analysis provides guidelines as to 1. Which management practices are most suitable for supplying volume in the mid-term (50-60 years), 2. How stand susceptibility to MPB attack can be mitigated by stand composition, and fertilization, 3. Which sites (along a productivity gradient) are most suitable for intensive management, and 4. How do intensive management practices impact soil-based measures of sustainability?

Methods

Study Area

Field work was conducted in the Quesnel Forest District near Quesnel (52°58′42.4″N, 122°29′33.6″W) in south-central British Columbia, Canada. Climate is relatively dry (540 mm mean annual precipitation, of which 33% is represented as snowfall) and cool (mean January temperature – 8.6°C, mean July temperature 16.7°C)(http://www.climate.weatheroffice.ec.gc.ca). Primary biogeoclimatic zones in the region (see Pojar et al 1986) include the Sub-Boreal Pine and Spruce (SBPS), Sub-Boreal...
Spruce (SBS), and Engelmann Spruce-Subalpine Fir (ESSF). Lodgepole pine is the dominant tree species in the region.

*Methods*

Measures of SOM were obtained in August 2006 from beetle-killed lodgepole pine stands that were slated for salvage logging in the timber harvesting landbase (THLB) of Canadian Forest Products Ltd. Sampling was restricted to sites with roughly a mesic moisture regime. A series of representative sites were selected within this general moisture regime that were expected to vary in their nutrient regime (from poor to rich) using existing Predictive Ecosystem Mapping techniques (Eng 1999). A plot centre was established on each site within a relatively homogenous section of the stand, at least 50 meters from a road or cutblock edge. The sampling area for each plot was defined as the area within a 20 m radius of the plot centre. A minimum of 20 and maximum of 30 sub-plots were distributed randomly within the plot while avoiding microsites not representative of the larger area (e.g. decaying logs, rock out crops, etc.). Results from a previous study in the region (Seely and Welham 2005), indicated that this was the sample size necessary to detect a 20% decline in SOM with a statistical power of 0.6 to 0.75, respectively (see Yanai et al. 2003). Sites in the region from which SOC and SON had been sampled as part of a previous study (Seely and Welham 2005) were also re-visited and their data incorporated into the present analysis. These sites had extra sub-plots installed to ensure statistical power was maintained.

On each plot, leading and secondary tree species were recorded, the average age of the leading tree species, depth of the forest floor to the mineral layer (LFH), and depth of mineral soil to a maximum of 1 m. LFH samples were collected using a coring device.
with a diameter of approximately 15 cm. Mineral soil samples were collected using a soil corer of XX diameter. If possible, successive samples were taken at depths of 0-30cm, and 30-60cm. The deeper depths were cored by hand-digging a pit near to the target depth and then employing the core. In some cases, impenetrable layers rendered deep coring (> 30 cm) impractical and the estimated depth of the mineral soil to the impenetrable layer was therefore recorded.

Site index was calculated from site trees located in 10 sample plots derived from a 20 m grid. One grid point was established at the plot center and used to define the remainder of the grid. At each grid point, a top height tree was selected from within a plot of 5.64 m sampling radius, cored at breast height (1.3m), and its height determined by hypsometer. If a given radius did not contain an appropriate site three, the plot was moved at successive 10-m intervals until a suitable tree was found (see, for example, Farnden 2001).

Each sample was analyzed in the laboratory for soil texture, coarse fragment content (> 2mm), and bulk density, using standard laboratory procedures (Robertson et al. 1999). Carbon and nitrogen content were derived using a commercial C and N analyzer with estimates obtained for a composite sample from the forest floor, and each of the 30 cm soil layers.

The FORECAST model

FORECAST is a management-oriented, stand-level forest growth simulator. The model uses a hybrid approach whereby local growth and yield data are utilized to derive
estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species (details in Kimmins et al. 1999). 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 upon the species, plant populations are initiated from seed and/or vegetatively, and stand development can occur with or without the presence of competition from non-target 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. After a pre-defined period of decomposition, litter is allocated (at varying proportions depending upon the particular litter type) into one of two humus types, active and passive (cf. Lal 2005). Active humus is assumed to have a mean residence time of approximately 75 years while passive humus has a mean residence time of 625 years (Jenkinson and Rayner, 1977).

In FORECAST, growth and yield in complex stands is based on a simulated partitioning of limited resources (light and nutrients) among species and age cohorts. The biological properties of individual species determine their relative competitiveness for limited resources. The model is designed to accommodate a variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. FORECAST can simulate a of management activities including fertilization, brushing, partial harvesting, and mixedwood management, along with disturbances such as fire and
insect defoliation. Kimmins et al. (1999), Seely et al. (1999), and Welham et al. (2007) provide detailed descriptions of FORECAST and its simulation routines.

The FORECAST data set used for the simulations was assembled as part of internal dataset development project funded by the Canadian Foundation for Innovation. For a description of the calibration process employed to create these datasets refer to Seely (2004).

*Establishing initial conditions with FORECAST*

FORECAST was run in a ‘set-up’ mode to generate levels of soil organic matter carbon (SOC) for each site series that were equivalent to those measured from the field sampling program. This is achieved by simulating the known or estimated natural disturbance and/or management history (typically for periods of 500 – 2000 years) of the site and with nutrient feedback turned off. This allows the model to accumulate the amounts of vegetation, litter and SOM that are representative of the site(s) to be modeled (see Seely et al., 1999). Fire return intervals for this area were estimated from Wong et al. (2004). The final disturbance event represented on each site was a clearcut harvest to approximate the transition from a natural to a managed stand.

*Deriving thresholds for SOC*

A gradient of SOC was created ranging from the target value to a highly degraded site. This was achieved by simulating the growth of a spruce-leading stand on a 40-year harvest cycle and repeated incrementally for 8 rotations (a total of 320 years). Each harvest included whole-tree harvesting and site preparation that caused a loss of 40% surface litter. A simulation was run for each of the incrementally degraded rotations beginning with the target condition and ending with the state of the ecosystem after the
final 40-year rotation (see Seely and Welham 2006, for further details). The results for total stemwood biomass production for each test simulation were compared against those for the reference simulation under the target SOC conditions and used to calculate the relative decline in ecosystem productivity associated with relative declines in SOC. This process was applied to the site series with each of the lowest and highest levels of SOC. Specific thresholds for SOC loss were calculated to correspond with relative losses of ecosystem productivity of 15, 25 and 40 percent (see Seely and Welham 2006), values selected to represent an increasing level of risk to ecosystem productivity.

Evaluating potential rotation lengths for different management plans
FORECAST was used to simulate the development of stands using SOC content from the field study as a starting condition, in conjunction with various management options. In this regard, the simulated stands were planted to varying proportions of pine and hybrid spruce (80% lodgepole pine + 20% Interior spruce, or 20% pine + 80% Interior spruce), without and with fertilizer (in the latter case, applied in years 20, 25 and 30 of a given rotation, at a rate of 200 kg N ha⁻¹), at a planting density of 1750 stems ha⁻¹. An understory shrub and grass community was included in all simulations. The starting site index for the simulations was derived from the field estimates. Thereafter, site index was permitted to vary, the degree to which depended upon whether management activities affected the inherent productivity of the site.

To determine the effect of stand-level strategies to mitigate MPB susceptibility on SOC, FORECAST output was linked to the Shore and Safranyik (1992) susceptibility rating (SR) model. The susceptibility index represents the inherent characteristics of a
state of trees that affects its likelihood of attack and damage by MPB. The rating system is an index of potential loss in the event of an infestation that varies between 0 and 100%. Under the SR model, stand susceptibility to MPB attack can be predicted as a function of the basal area of susceptible pine, its age, density, and the stand location; the first three variables can be influenced by management practices. The linked FORECAST-SR model was used to calculate potential rotation lengths for all of the species-fertilizer combinations, according to each of three criteria: 1) Minimal acceptable MPB susceptibility (the rotation length where the susceptibility index equals 20%), 2) Culmination of mean annual increment (MAI), and 3) Maximum expected net benefit (calculated from the susceptibility index times merchantable volume, at each year in the rotation). If a predicted rotation length under a given criterion reached 150 years, the stand was harvested at that time. Each rotation length was used with each species-fertilizer combination as the basis for five consecutive rotations of whole-tree harvesting (removal of 90% stemwood and bark, 50% branches, and 30% foliage), and SOC pools calculated each year for each rotation. This protocol will thus determine which management strategies for MPB can produce the highest net benefit (in terms of mid-rotation and long-term volume) without unduly compromising SOC.

Results

Stand age among the five site series varied from 100 to 165 years, with height and diameter at breast height ranging from 18.8 - 25.7 m and 22.8 - 32.7 cm, respectively (Table 1). Site index ranged from 12.5 to 16.6 m.
The SBSmc2 01 had the highest mean total SOC (58 Mg ha⁻¹), followed by the SBPSdc 04, SBPSmk 01, SBPSdc 01, and the SBPSdc 03 site series (Figure 1). The SOC content in the SBPSdc 03 site series was approximately 33% lower than measured for the SBSmc2 01 site series.

In pine-leading stands, harvesting at the culmination of MAI always resulted in the longest average rotation whereas the shortest average rotation resulted from the MPBS strategy (Table 2). With no fertilizer applied, these differences varied by a minimum of 30 years (in the SBSmc2 01) and a maximum of 50 years (in the SBPSdc 03); adding fertilizer reduced the minimum and maximum to 29 and 34 years, respectively (Table 2). In spruce-dominated stands, the longest average rotation occurred under the MENB criterion for both site series; the MPBS criterion resulted in the shortest average rotation (Table 2).

Maximizing MAI generated the highest volumes on both site series when the higher proportion of pine was planted (Table 2). The MPBS rule always resulted in the lowest volumes regardless of whether stands were spruce or pine-leading. In spruce-leading stands, the highest volumes were generated under the MENB rule. Fertilization increased total volume production between 6% (SBPSdc 03) and 23% (SBSmc2 01) under the MAI rule (Figure 2). Volumes were increased substantially more by fertilization under the MPBS and MENB harvesting rules than under MAI; 75 and 113% (SBPSdc 03), and 41 – 56% (SBPSmc2 01), respectively.

In the SBPSdc03, when pine was planted as the leading species (i.e., 80% of the total planting density), there were relatively small increases in MV across rotations (10%, or less) when stands were harvested at the culmination of MAI (Figure 3A). If pine
planting density was low (20% that of spruce), harvesting at the culmination of MAI resulted in a consistent increase in merchantable volume (MV) across rotations, to a maximum of 58% (Figure 3B).

Under the MAI harvesting rule, the proportion of pine had no significant effect upon MV across rotations in the SBSmc2 01 site series; changes in volume were 16%, or less (Figures 3 A, B). Regardless of planting composition, harvesting in accordance with the MPBS criterion always resulted in a decline in MV across rotations (to a maximum of 63% in the SPBSdc03) and which increased with each rotation (Figure 3 A, B). The decline in a given rotation was always higher in the SPBSdc03 versus the SBSmc2 01. In the case of the MENB criterion, MV’s were always positive and increased slightly across rotations (to a maximum of 10%) when spruce was the dominant component at planting (Figure 3B). With pine as the dominant component, however, MV’s were always negative, particularly in the SBPSdc03 (to a maximum of -46%; Figure 3A).

Fertilization had a modest and generally positive effect upon MV under MAI for both site series across rotations (cf. Figures 3 B, C). In the case of the MPBS and MENB rules, however, the benefits were much more pronounced and in contrast to the unfertilized case, generally resulted in MV’s that were positive or only slightly negative.

In unfertilized stands, the SOC pool was strongly influenced by rotation length. Harvesting under the MPBS rule always resulted in the shortest rotations (Table 2) and SOC declined accordingly regardless of site series or leading species (Figures 4, 5). In the SBPSdc03, SOC increased under the MAI rule in both spruce and pine-leading stands, but in the case of MENB it increased only in stands that were spruce-leading (it was essentially constant for pine-leading stands). Levels of SOC were projected to remain
relatively constant under MAI in the SBSmc2 01 but they increased or decreased in
spruce and pine-leading stands, respectively.

Discussion

*Enhancing timber volume with short-rotation harvesting*

The large-scale mortality in pine-dominated stands has compromised mid-term timber supply (over at least the next 60 years) in many regions of British Columbia (British Columbia Ministry of Forests 2003). In pine-leading stands, harvesting at the culmination of MAI generated the greatest potential for merchantable volume in the next rotation (i.e., harvesting in stands established to replace those killed by the existing MPB outbreak). This strategy, however, has two important limitations. First, culmination of MAI is not realized for at least 85 years (depending upon site series; Table 2). This period is simply too long to mitigate any mid-term fall-down in the annual allowable cut. A second drawback is that establishing extensive monocultures of pine is not without attendant risks. The most significant issue is that a major factor contributing to the current MPB epidemic (i.e., a large and susceptible host population) will be simply re-created. Climate projections indicate a warming trend through much of BC (BC Ministry of Forests 2003) which will likely result in conditions even more favorable to beetle development (Carroll and Safranyik 2003). If another future outbreak were to occur of equivalent (or even greater) magnitude then much of the susceptible pine will be killed and the projected returns from the MAI criterion will not be realized.

It has been suggested that a prudent strategy for mitigating the risk of future catastrophic outbreak of MPB is to plant a diversity of forest cover types from pure pine
to mixtures of pine and other suitable tree species (Martin et al. 2005). The rationale is simply that by breaking up the landscape into discrete cover types, the overall population of susceptible hosts is reduced. Results from the simulation indicate that when stands are harvested in the next rotation at the culmination of MAI expected yields are reasonable (235-279 m³ ha⁻¹; see Figure 3B) but lower than the productivity achievable from stands where pine is the leading species (314-323 m³ ha⁻¹; Figure 3A). This is a consequence of the fact that pine is a fast-growing species, well-adapted to the climatic and edaphic conditions characteristic of the region. Pine is therefore a strong competitor with spruce for available resources and its presence tends to depress spruce productivity. Rotation lengths, however, at are least as long in pine-leading stands (Table 2) meaning that these stands will not contribute to mid-term timber supply if harvested at the culmination of MAI.

An alternative approach to mitigate mid-term timber shortfall is to harvest stands on a much shorter rotations (50-60 years) in accordance with rotation lengths dictated by the MPBS or MENB criteria (see Table 2). Under these criteria, harvesting occurs proactively, before stands enter a condition of maximum susceptibility to MPB attack. In pine-leading stands, projected merchantable volumes under MPBS were low, and ranged from only 89-135 m³ ha⁻¹ (for the SBPSdc 03 and SBSmc2 01, respectively; Figure 3A). Projected volumes were low as a consequence of the fact that the MPBS rule is relatively conservative (i.e., harvest when the pine susceptibility index equals 20%). When net benefit was maximized (MENB) and with a relatively small delay in harvest (of about 10 years; see Table 2), pine-leading stands produced a more reasonable expected gain of 159- 212 m³ ha⁻¹ (Figure 3B). These volumes were higher than those projected under the
MPBS rule and they occurred because any increase in MPB susceptibility was offset by a proportionately greater increase in merchantable volume. Fertilization resulted in a modest improvement in first-rotation productivity in these short-rotation stands (see Figure 3 A, C). With fertilization, trees grow quickly in height but unless stands are well beyond the self-thinning stage (which is not the case in a short-rotation system), diameter growth tends to be delayed and volumes are depressed accordingly. Considered together, these results suggest that in pine-leading stands, harvesting in accordance with the MENB rule provides reasonable volume returns over the short-term while ensuring that stands are not overly susceptible to MPB attack.

In spruce-leading stands, MENB generated greater volumes than either MPBS or MAI (see Figure 3B). These volume gains, however, were the result of very long rotation lengths (see Table 2). They indicate that MENB is not appropriate as a harvesting rule in spruce-leading stands if the objective is to generate volume in the mid-term. Reasonable volume returns can be expected by harvesting at, or near the culmination of MAI though the associated rotation lengths were still fairly protracted (at least 80 years; Table 2). The shortest rotation occurs under MPBS but volumes are relatively modest (176-213 m$^3$ ha$^{-1}$; Figure 3B). One option to improve volume under the MPBS rule and still harvest on short rotation may be to fertilize these stands (see below).

_How sustainable is short-rotation harvesting?_

If used repeatedly, short-rotation forestry can result in a long-term decline in productivity. In unfertilized pine-leading stands, for example, total merchantable volumes after the 300-year simulation period under MENB and MPBS, respectively, varied from
311-524 m$^3$ ha$^{-1}$ in the SBPSdc 03 site series and 549-792 m$^3$ ha$^{-1}$ in the SBSmc2 01. This amounts to projected losses in productivity of 46-68% (in the SBPSdc 03) and 23-46% (SBSmc2 01) relative to the volumes potentially achievable from harvesting at the culmination of MAI (see Table 2). In the case of spruce-leading stands, results were more favorable. Projected losses under the MENB and MPBS criteria relative to harvesting at the culmination of MAI varied from <1 to 39% (SBPSdc 03) and from 3-18% (SBS mc2 01), respectively. One way the decline in volume in pine-leading stands can be mitigated is through fertilization. In this case, the long-term decline in volume under the MENB and MPBS criteria varied from only 11-35% (SBPS dc 03) and 11-32% (SBSmc2 01), respectively.

In terms of the pattern of change in productivity, when stands were harvested at the culmination of MAI, volumes subsequent to those derived from the first rotation either increased (in the SBPSdc 03), or remained relatively constant (in the SBSmc2 01). Clearly, this harvesting criterion poses no threat to long-term sustainability. Under the MPBS criterion, second rotation volume in the SBPSdc 03 site series was roughly equivalent to that achieved from the first rotation but declined thereafter. In the SBSmc2 01, volumes in subsequent rotations always declined, as was the case under the MENB criterion, regardless of site series (Figure 3A). These results indicate that repeated harvesting on these short rotations (see Table 2) is not sustainable over the long-term. In interior forests, fertilization (usually with nitrogen) is a proven method for increasing harvest volume and accelerating the operability of established stands (Brockley and Simpson 2004). Adding fertilizer produced higher productivity in second and third rotations (the latter under the MPBS rule only) on both site types but productivity
declined thereafter. Hence, although fertilizer application was useful for improving productivity over the medium-term (from one to three rotations), it was not sufficient for maintaining long-term productivity.

**Effect of short-rotation harvesting on soil carbon (SOC) and its relation to merchantable volume**

Simulation results indicate that the rotations lengths under the MPBS criterion will likely be problematic for maintaining SOC in unfertilized stands over the long-term, regardless of whether they are pine or spruce-leading (Figures 4, 5). Losses in the SBSmc2 01 (the site with the highest SOC content) stabilized at about 12% whereas they were about 8% in the SBPSdc 03 (with the lowest SOC content). Given that the associated volumes derived from pine-leading stands was relatively low (and declined across rotations; see Figure 7A), the MPBS criterion does not appear appropriate as a rule for harvesting on short-rotation in these site series, at least if stands are unfertilized. Both SOC and associated volumes responded well to fertilizer (Figures 4A, 5), however, suggesting that this could be an important tactic for successfully implementing a short-rotation system under the MPBS criterion. In the case of MENB, SOC tended to increase across rotations in spruce-leading stands but this was simply a consequence of the fact that rotations lengths were excessively long (see Table 2). In unfertilized pine-leading stands, SOC was relatively stable in the SBPSdc 03 but it declined in the SBSmc2 01. With the application of fertilizer in the latter site series, SOC remained constant. In both cases, volume returns under MENB were relatively favorable and there was no consistent decline in productivity across rotations (Figure 3B). This suggests that from the perspective of
maintaining SOC at baseline levels, repeated short-rotation harvesting without fertilizer is sustainable in the case of the SBPSdc 03 but not the SBSmc2 01.

**Monitoring for changes in SOC and assessing its impact on productivity**

Two key features of monitoring changes in SOC are frequency and intensity. After forest harvesting, sites are initially sources of CO₂, but eventually become sinks for CO₂ some years following reforestation; this period for boreal forests is generally around 10 years (Freeden et al. 2007). This suggests that in terms of the frequency of monitoring, sites should first be monitored prior to harvesting to establish a baseline value and then every 10 years thereafter. Assuming SOM has not been degraded excessively by the harvesting event, levels of SOC should be at or very close to baseline values at the first 10-year monitoring period. By evaluating the pattern of SOC measured across subsequent 10-year periods, long-term patterns in SOM accumulation can be established.

In terms of monitoring intensity, Seely and Welham (2005) conducted a statistical power analysis on each of six sites designed to determine the number of samples required to detect a “significant” decline in SOC. Results of the power analysis indicated that trying to detect change in specific layers (e.g. LFH, 0-30cm mineral, or 30-60 mineral) would be very difficult and require too many samples to be practical (see Seely and Welham 2005, Table 4; Yanai et al 2003). However, when the quantities of SOC were summed for all layers before conducting the power analysis, the results were more promising in terms of the capability to detect change in the field. For example, the number of samples required to detect a 20% change in SOC with a power of 0.75 ranged from 12-45 with a mean of 25; this dropped to 12 for a power of 0.60. These averages
can be used as a guideline for estimating sampling intensity. The more variable a site, however, the more samples are required to detect a change of a given magnitude (see Seely and Welham 2005, for examples). Ideally then a power analysis should be conducted using the baseline values and the appropriate number of samples calculated for the subsequent (i.e., 10-year) monitoring program.

From the perspective of sustainable forest management, the implications of changes in SOC can be very different among ecosystems. In the case of pine-leading stands in the SBPSdc 03 site series, for example, a loss of SOC of 8-10% (as is the case under the MPBS harvesting rule) resulted in a predicted decline in merchantable volume of as much as 60%, depending upon the rotation (see Figure 3A). The SBSmc02 01 site series, in contrast, had a higher SOC pool, and although harvesting according to the MPBS rule resulted in a long-term projected decline in SOC of about 10-12% (Figure 5), merchantable volume declined by only 40%. This discrepancy is a consequence of the fact that in the SBPSdc 03, SOC is more limiting to productivity than in the SBSmc2 01. Hence, any decline in soil organic matter in the latter will have a smaller impact upon productivity. In terms of MV production then, the SBSmc2 01 site series is more resilient to changes in SOC than the SBPSdc 03. Hence, ecosystems with lower SOC content should be managed carefully to ensure that soil organic matter pools are not degraded unnecessarily.
Acknowledgements

FSP
Literature Cited


Figure 1. A. Mean organic C content (and the standard error) for forest floor and total soil, by site series. B. Mean organic N content (and standard error) for forest floor and total soil, by site series.

Figure 2. Percent increase in total merchantable volume harvested from stands planted with 80% pine and 20% spruce, and fertilized at 200 kg N/ha in years 20, 25, and 30 of each rotation, as compared to stands with equivalent species composition but no fertilizer. Harvesting occurred at rotation lengths defined by the MAI, MBPB, or MENB criteria (see text) and percent change was derived from the total volume harvested after a 300-year total simulation period.

Figure 3. Percent change in merchantable volume in subsequent rotations as compared to volume derived from harvest in the first rotation for the SBPSdc03 (dc03) and SBS mc01 (mc01) site series, for unfertilized stands with planting densities of 1750 stems ha$^{-1}$, and comprised of 80%pine:20% spruce (A), and 20% pine:80% spruce, the latter of which are unfertilized (B) and fertilized (C). Rotation lengths were determined from the MAI, MPBS, and MENB harvesting criteria (see text for details). Values in brackets refer to first rotation harvest volumes for the SBPSdc 03 and SBSmc2 01, respectively. Note the difference in scale between panels.

Figure 4. Simulated impact of rotation length (as dictated by the MAI, MPBS and MENB harvesting criteria) on SOC during a 300-year simulation period in the SBPSdc 03 site series under different combinations of species composition and fertilization.

Figure 5. Simulated impact of rotation length (as dictated by the MAI, MPBS and MENB harvesting criteria) on SOC during a 300-year simulation period in the SBPSmsc2 01 site series under different combinations of species composition and fertilization.

Comment [cw10]: Need to describe the bars (are the two sites)
Figure 1
Figure 2.
80% pine:20% spruce (No fertilizer)

- MAI (314, 323)
- MPBS (89, 135)
- MENB (159, 212)

20% pine:80% spruce (No fertilizer)

- MAI (235, 279)
- MPBS (176, 213)
- MENB (454, 518)

80% pine:20% spruce (Fertilized)

- MAI (331, 320)
- MPBS (144, 152)
- MENB (207, 224)
Table 1. Stand characteristics

<table>
<thead>
<tr>
<th>Site series</th>
<th>Breast height age (y)</th>
<th>Height (m)</th>
<th>Dbh&lt;sup&gt;1&lt;/sup&gt; (cm)</th>
<th>Site index&lt;sup&gt;2&lt;/sup&gt; (m)</th>
<th>n&lt;sup&gt;3&lt;/sup&gt;</th>
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<tr>
<td>SBPSdc 01</td>
<td>160</td>
<td>22.5</td>
<td>28.1</td>
<td>14.2</td>
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<td>SBPSdc 03</td>
<td>130</td>
<td>19.8</td>
<td>22.8</td>
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<td>25.7</td>
<td>32.7</td>
<td>16.6</td>
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<sup>1</sup> Diameter at breast height

<sup>2</sup> At reference age 50 years

<sup>3</sup> Number of stands
Table 2. Total harvested merchantable volume (MV; m^3 ha\(^{-1}\)) and average rotation length (RL) for two site series with the lowest and highest total SOC content (the SBPSdc 03 and SBSmc2 01, respectively) from a total simulation period of 300 years, with different combinations of species (% pine planted relative to interior spruce) and fertilization.

Stands were planted at a total density of 1750 stems ha\(^{-1}\). Rotation lengths were chosen according to one of three criteria, MAI, MPBS, and MENB (see text for details).

<table>
<thead>
<tr>
<th>SBPSdc 03</th>
<th>Fertilized</th>
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<td></td>
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<td>MV (m^3 ha(^{-1}))</td>
<td>RL (y)</td>
<td>MV (m^3 ha(^{-1}))</td>
<td>RL (y)</td>
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<tr>
<td>No</td>
<td>MAI (^1)</td>
<td>972</td>
<td>101</td>
<td>812</td>
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<td>No</td>
<td>MPBS (^2)</td>
<td>311</td>
<td>51</td>
<td>499</td>
<td>67</td>
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<tr>
<td>No</td>
<td>MENB (^3)</td>
<td>524</td>
<td>61</td>
<td>911</td>
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<td>Yes</td>
<td>MAI</td>
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<tr>
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1. Mean annual increment
2. Mountain pine beetle susceptibility
3. Maximum expected net benefit