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Value-adding through silvicultural flexibility: an operational level simulation study

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Forest products industry's competitiveness is influenced by the agility of wood procurement systems in delivering raw material to support downstream manufacturing activities. However, in a hierarchical forest management planning context, silvicultural treatments are prescribed and set as constraints for supply chain managers, restricting supply flexibility and consequently value-adding potential. This study was conducted with an objective of quantifying the benefits of improving wood procurement systems agility through flexibility in the choice of silvicultural treatments at the operational level. The aim was also to determine the range of conditions under which benefits from flexibility can be realized while accounting for the impact on long-term supply. We present a novel approach that integrates silvicultural options into operational-level decision-making to solve the multi-product, multi-industry problem with divergent flow. The approach entails solving a mixed integer programming model in a rolling planning horizon framework. Subsequently, we demonstrate benefits associated with integrating supply chain and silvicultural decisions through a case study. Future impact of exercising flexibility on long-term supply was accounted through incorporating costs associated with applying different silvicultural regimes. The presented approach will prove to be useful in implementing an adaptive forest management system that integrates the complexity of social, economic and ecological dimensions.

Introduction

Creation of value-added products and diversification from traditional commodity focus has been sought in the forest products industry as a strategy to adapt to the emerging economic challenges (FPAC, 2011). These challenges result from changes that have taken place in the global forest sector following the US housing crisis, Russian log export tax, emergence of China, changes in energy policies etc. Significant progress has already been made in the development of bio-energy, bio-chemicals and bio-materials. However, in a highly competitive globalized market characterized by turbulence and volatility, product development is only a part of the equation; success also depends on the capability of a supply chain to deliver these products to markets in a timely manner (Christopher, 2010). Supply chains need to be agile to capture opportunities in these uncertain market conditions.

Agility of forest product supply chains depends largely on the agility of wood procurement systems (WPS). WPSs are responsible for procuring wood from forests to supply raw material for all downstream manufacturing activities (D'Amours *et al.*, 2008). The task entails delineating cutblocks, constructing roads and conducting harvesting and transportation operations. A cutblock is a group of adjacent forest stands that are treated as a basic unit in management plans for which harvesting and regeneration schedule is prescribed. Under the changing context, characterized by greater market volatility, WPSs are faced with an emerging challenge of fulfilling volatile demand from a diverse set of manufacturers (Hansen *et al.*, 2013). WPSs need to be able to adjust their production accordingly whilst taking into consideration the full range of social, economic and environmental factors involved in forest management (Pulkki, 2003). In the past, WPSs based their production on market forecasts and placed inventory at strategic points to withstand market fluctuations (Stier *et al.*, 1986; LeBel and Carruth, 1997). However, WPSs need to better align their production with demand in a volatile and competitive context. This requires identifying forest stands with the appropriate raw material, harvesting and delivering it to the customers in a timely manner. Audy *et al.* (2012), in a study conducted in six different countries (in Europe and America), show that WPSs are limited in their capability to change existing harvest plans to align raw materials with prevailing demand. This can be attributed to the disconnection between forest products supply chain and forest management planning as discussed in Church (2007) and Gunn (2009).

Forest management planning is conducted using a top-down hierarchical approach aggregating and disaggregating information at the various levels to reduce complexity (Bettinger *et al.*, 2008). Savard (2011) provides a comprehensive schematic of decisions made at each hierarchy based on a case study in Quebec, Canada. A long-term strategic plan is first devised taking into consideration ecological and social concerns to determine the annual allowable cut for a period extending over one rotation. Subsequently, the volumes calculated at the strategic level are spatially allocated at the tactical level. In the process, forest stands are aggregated to form cutblocks. A silvicultural treatment is then prescribed to each individual cutblock allowing volume estimation by assortment. Next, an annual plan is formulated from this pool of cutblocks, attempting to match supply with the forecast of demand. Once the annual plan has been established, a schedule is developed for the supply chain to fulfil prevailing demand from within this annual pool of cutblocks using the silvicultural treatments already prescribed. Even if the prevailing demand differs significantly from forecast, altering silvicultural treatments to better align supply with demand is not contemplated (Gunn, 2009; Savard, 2011). Strictly constraining the short-term planning process in a hierarchical planning framework impedes full value-creation potential (Paradis *et al*., 2013). Moreover, due in part to the natural variability of forest ecosystems, a multitude of operational-level plans may allow achieving objectives set at an upper hierarchy (Gunn, 2009). Thus, there are a number of different silvicultural treatments that can be prescribed without impacting long-term sustainability.

Fixing silvicultural treatments based on a year-old market forecast can negatively impact supply chain performance. Besides market volatility, there is also the issue of uncertainty concerning forest resource inventory. Forest inventory data used at upper hierarchical planning levels are approximations derived through sample-based procedures; there are inaccuracies associated with estimations. The inaccuracies are exacerbated by unpredictable events such as fire, insect outbreak and even climate change (Yousefpour *et al*., 2012). Flexibility in the choice of silvicultural treatments would enable practitioners to better match supply with demand (Gautam *et al*., 2013). Such flexibility could be exercised without undermining ecological and social objectives. Lussier (2009) conducted a study in eastern Canada to evaluate the impact of changing prescriptions to fulfil supply chain requirements in lieu of implementing pre-determined treatments. Improvement in supply chain profits was demonstrated, whilst respecting ecological constraints. However, flexibility in silvicultural treatment was not exercised in the study, but simply flexibility in tree choice within the partial harvest treatment. Nevertheless, it provides motivation to explore the advantage of flexibility in the choice of silvicultural treatment itself at the operational level to better align supply with demand.

Prior to exercising flexibility in the choice of silvicultural treatment, the financial feasibility of the alternative treatments have to be ensured. Several studies have been conducted on the subject in recent times. Howard and Temesgen (1997) conducted a study to assess the potential financial returns from forest stands under different silvicultural prescriptions over a 30-year planning horizon in western Canada. The financial analysis included harvesting, hauling and regeneration costs. Market prices were used to calculate the revenue. The resulting net present values (NPVs) indicated that a range of silvicultural treatments could be economically viable depending on stand-specific parameters. Andreassen and Øyen (2002) conducted a study to estimate and compare the net present value of three silvicultural systems in central Norway: single tree selection, group selection and clearcutting. The NPV calculations were based on an assumption of perpetual application of the chosen treatment. Clearcutting consistently yielded the greatest NPV; however, two other silvicultural treatments were also found to be reasonable options. Liu *et al*. (2007) calculated the benefit cost ratio of several different silvicultural treatments applied to forest stands in Québec. The treatments included clearcut, shelterwood and two variations of partial cuts. The result showed that clearcut generated the highest average net income; however, the benefit cost ratio was highest under partial harvest. Moore *et al*. (2012) conducted a similar study but with a time horizon of 200 years. Their calculation of NPV acknowledged the inherent uncertainty associated with parameters in the long-term. The median NPV values were positive for all treatments, with clearcut yielding the highest value. However, based on the simulation, there was also the possibility that clearcut could be less profitable than other treatments.

The studies discussed above demonstrate financial feasibility potential of various silvicultural treatments. However, their feasibility in the operational-level wood procurement context remains to be demonstrated. The following limitations were observed in regards to these studies: (1) they all assumed that infinite demand existed for all assortments produced and could be sold at market prices to generate revenue. The assumption is unrealistic, considering that mills are geographically dispersed and it is not economically viable to transport all assortments from the forest to their highest value yielding mills due to long distances; this will vary on a case-by-case basis; (2) except in the study by Moore *et al*. (2012), the prices of different assortments were kept constant throughout the study horizon although our investigation of recent data reveals a high volatility in market prices. The prices have a significant impact on the revenue generated and consequently the NPV; (3) the studies were conducted at the stand level; an analysis under a broader context is bound to vary the outcome. As an example, if a group of cutblocks were clustered in an area, economies of scale could be applied to reduce overall cost; (4) transportation costs were excluded in their analyses except in Howard and Temesgen (1997). The exclusion of transportation cost is justifiable given uncertainty with regards to destination mills in such studies. Nevertheless, transportation cost represents a significant proportion of the overall cost, subsequently dictating feasibility of silvicultural treatments.

Thus, financial feasibility of silvicultural treatments needs to be further assessed at the operational level where uncertainties associated with demand and price forecasts are greatly reduced. Also, at the operational level, the knowledge of the spatial setting of mills and other allocation decisions allow better estimation of harvesting and transportation costs. Numerous models have been proposed to support decision-making at the operational level. Walker and Preiss (1988) developed a mixed integer programming model to support decision-making on areas to harvest and allocation of log assortments from harvest areas to surrounding mills. Burger and Jamnick (1995) constructed a linear programming model to include decisions on the harvest method to be employed. Epstein *et al*. (1999) and Chauhan *et al*. (2009) incorporated bucking decisions. Bucking is the process of cutting a tree into lengths according to the specifications provided by customer mills. Karlsson *et al*. (2004) formulated a mixed integer programming (MIP) model to incorporate harvest crew assignment in the decision-making. A MIP model that generates procurement plans taking into consideration fibre freshness is presented in Beaudoin *et al*. (2007). However, to the best of our knowledge, silvicultural treatment has not been explicitly included as a decision variable

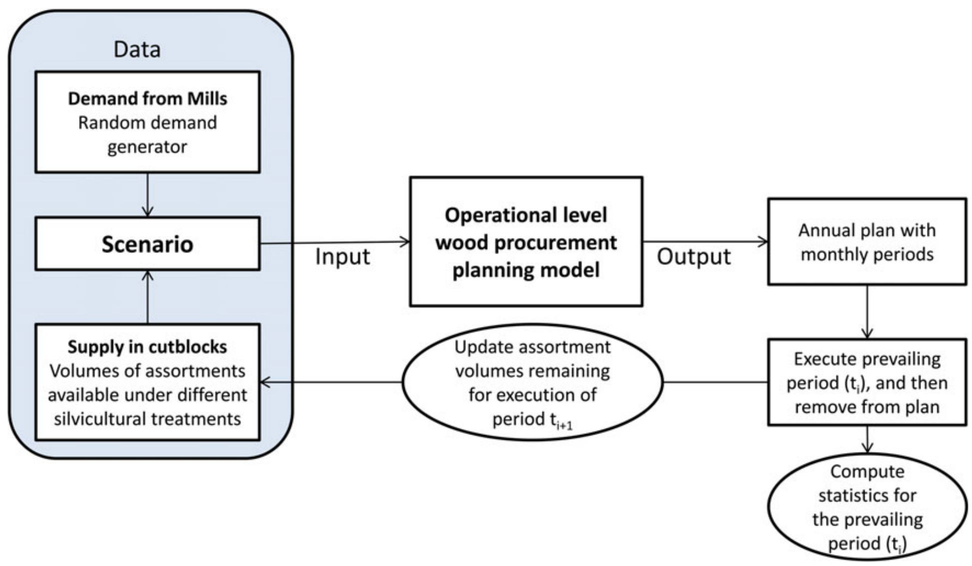

Figure 1 An illustration of the planning process simulation.

in any operational-level wood procurement model described in the scientific literature.

In lieu of flexibility in silvicultural treatments, flexible harvest policies as described in Brazee and Mendelsohn (1988) and Knoke and Wurm (2006) could be employed. At the operational level, however, it would entail identifying a new set of harvest blocks to generate a plan, consultation with stakeholders, road construction for access and performing other preparatory tasks. From an agility viewpoint, flexibility in silvicultural treatment offers the potential to add even more benefits. Thus, the objective of the study is to examine the potential improvement in supply chain performance through flexibility in silvicultural treatment decisions at the operational level. The specific goals are: (1) to provide an operational level wood procurement planning model which uses silvicultural treatment as a decision variable; (2) to employ a mechanism to account for the impact of operational level silvicultural flexibility on long-term supply and to incorporate it in decision-making; (3) to quantify the improvement in supply chain profits and demand fulfilment rates under a range of conditions to account for the impact on long-term supply.

Method

The problem was set up from the perspective of a wood procurement company responsible for harvesting cutblocks and delivering raw materials to meet demands from various manufacturing mills. This can be characterized as a multi-product, multi-industry problem with divergent flow. It was assumed that a strategic plan, a 5-year spatial plan, and an annual plan had already been prepared based on long-term economic analysis such as NPV. On the market side, the prevailing demand was a random parameter that differed from the forecast. Thus the short-term operational plan was to be redeveloped in light of the prevailing demand for profit maximization.

Simulation experiment

An experiment was designed to measure the potential financial gains and demand fulfilment rates from allowing redevelopment of the operational level plan with alternate silvicultural treatment prescriptions. In this study, silvicultural treatment refers only to activities that yield merchantable volume. Various scenarios were constructed and simulated to quantify the benefits. The simulation process is illustrated in Figure 1; plans are developed and executed under demand uncertainty on a rolling planning horizon basis. First, a random number generator was used to simulate demands from a set of mills. On the supply side, there were volumes of assortments available in cutblocks that are a function of the silvicultural treatment applied. Using this information, a scenario was generated and used as input to the operational-level wood procurement planning model. The first period statistics were collected from the plan generated by the model since it is the only period executed. The statistics collected included profit generated and demand fulfilment rates. Demand fulfilment rate is the percentage of the volume supplied relative to the demand. The volumes prescribed in the first period were deducted from the initial inventory and the next iteration was run with the updated demand information (randomly generated).

The simulated scenarios are outlined in Table 1. Scenarios 1 and 2 represent the status quo approach; there was no flexibility in the choice of silvicultural treatment. As indicated in the third column of Table 1, scenario 1 represents a setting with low-demand volatility and scenario 2 represents a setting with high-demand volatility. It was assumed that demand is a random parameter with a normal probability distribution. The low and high volatility represent a standard deviation that is 15 and 40 per cent of the base demand, respectively. These values are based on studies by Childerhouse and Towill (2000), Zhang and Zhang (2007) and UN (2013). In scenarios 3–10, silvicultural treatment could be changed to improve supply–demand alignment. In scenarios 3 and 4, no additional cost was incurred to exercise this flexibility. Thus, we did not account for future impact of changing silvicultural treatment from what was initially prescribed to a cutblock. However, in scenarios 5–10, future impact of changing silvicultural treatment was accounted through applying different intensities of flexibility cost. The different intensities were established to conduct sensitivity analysis; further discussion on this cost is provided in the next section.

The planning horizon for each scenario was 1 year divided into 12 monthly periods. The plan was executed in a rolling planning horizon approach; this framework minimizes the incorporation of uncertain data in decision-making. The approach is depicted in Figure 2; in each prevailing

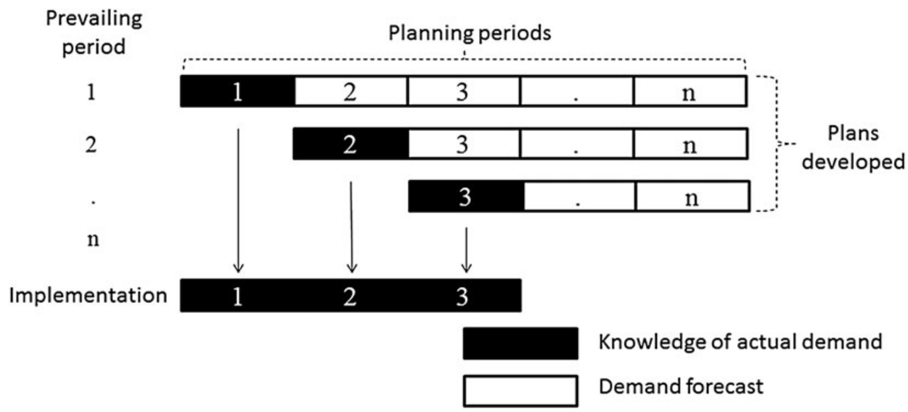

Figure 2 An illustration of the rolling planning horizon approach.

Table 1 The list of scenarios used for the experiment

Scenario	Flexibility in silvicultural treatment	Demand volatility	Cost imposed based on the following silvicultural intensity		
			Extensive	Basic	Intensive
1	No	Low	Not applicable		
2		High			
3	Yes	Low	Cost not imposed		
4		High			
5		Low	√		
6		Low		√	
7	Yes	Low			√
8		High	√		
9		High		√	
10		High			√

Table 2 The silvicultural regimes used to estimate flexibility cost for sensitivity analysis

Activity	Silvicultural regime		
	Extensive	Basic	Intensive
Site preparation	√	√	√
Plant		√	√
Pre-commercial thinning		√	√
Fill plant			√
Tending			√

period, a plan was developed for the entire horizon with knowledge of demand for the prevailing period and forecasts for the remaining periods. However, the plan was implemented only in the prevailing period. At the start of the next period, a new plan was developed using updated demand and forecast information. Both actual and forecast demands were generated randomly assuming a normal distribution. The process continued until the end of the planning horizon. For each scenario, 50 repetitions were carried out under simulated stochastic demand.

Flexibility cost

The complexity in forest dynamics and forest management renders the task of anticipating the precise long-term effect of altering silvicultural treatment at the operational level quite challenging. Nevertheless, to avoid undesirable impact of operational-level amendments on long-term sustainability, we imposed a cost in conjunction with a change in the silvicultural treatment. This is referred to as flexibility cost. The cost was estimated based on an assumption that forest succession can be influenced through applying a silvicultural regime (Fujimori, 2001; Homagain *et al.*, 2011). A silvicultural regime is a series of interventions imposed on the cutblock over time that includes regeneration, tending and harvesting activities. If the treatment was altered, we assumed that silvicultural regime could be prescribed to ensure that the cutblock still reaches an initially desired state. Theoretically, reaching this state will ensure that the long-term sustained yield of the forest is not significantly impacted. A sensitivity analysis was then conducted on cost associated with silvicultural regimes. The range of values used for the sensitivity analysis was based on different intensities of silvicultural regimes (Table 2). These regimes were inspired by those proposed in Bell *et al.* (2008) in a similar context. The costs of the three regimes were subsequently used to conduct the sensitivity analysis.

Mathematical formulation

The overall plan components are illustrated in Figure 3. The objective was to maximize profit; revenue was generated through delivery of product assortments from cutblocks to customer mills. The costs stemmed from harvesting and transportation activities as well as flexibility cost. The yield of product assortments from cutblocks depended on the silvicultural treatment applied. There was also a decision to be made on harvesting systems to be employed. The cost of harvesting a cutblock depended on the productivity of the chosen system. Stand-specific parameters were assumed to be uniform with regards to their influence on the productivity of harvest systems. It was assumed that the land base already had an existing road network. Only the costs associated with the portions of roads that needed to be built or upgraded to join the cutblocks to the existing network was taken into consideration and included in the harvesting cost. We assume that inventory could be stored on roadsides until demand arose in the future.

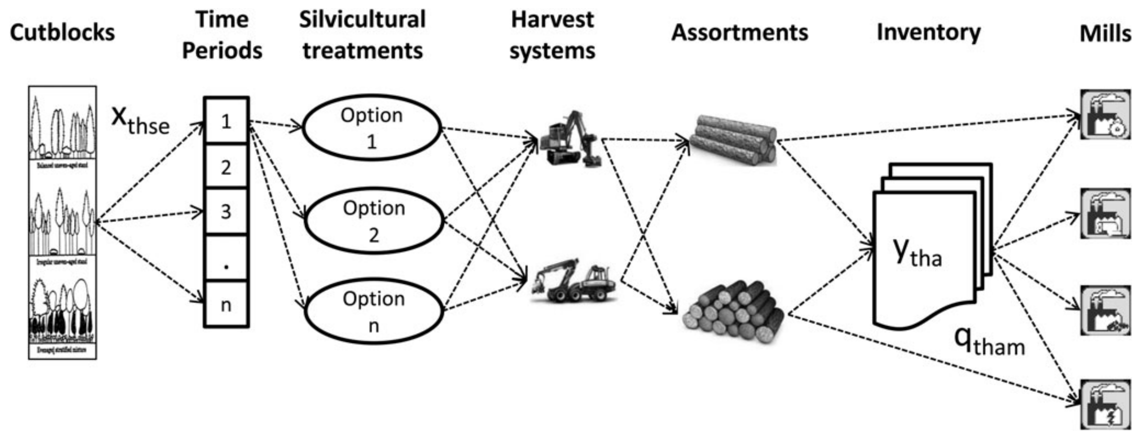

Figure 3 A depiction of the overall plan components with the decision variables.

Table 3 Description of the sets used in the mathematical model

Notation	Description
T	Set of time periods t
H	Set of cutblocks h
S	Set of silvicultural treatments s
E	Set of harvest systems e
A	Set of assortments a
M	Set of mills m

Table 4 Description of the input data for the mathematical model

Notation	Description
V_{hsa}	Maximum volume of assortment a available in cutblock h when subjected to silvicultural treatment s (m^3)
N_a	The selling price per cubic meter of assortment a (\$ m^{-3})
C_e	Harvest cost under harvest system e (\$ day^{-1})
B_{hm}	Round trip distance from cutblock h to mill m (km)
G_{hm}	Unit transportation cost between cutblock h and mill m (\$ m^{-3} km^{-1})
R_t	Maximum transportation capacity during period t (m^3)
J_{hs}	The cost incurred to alter the prescribed treatment in cutblock h to silvicultural treatment s (\$)
Y^I_{ha}	Initial roadside inventory of assortment a in cutblock h (m^3)
Y^C_{th}	Unit stocking cost in cutblock h during period t (\$ m^{-3})
P_{se}	The productivity of harvest system e under silvicultural treatment s (m^3 day^{-1})
O_{te}	Number of work days available for harvest system e during period t
D_{tam}	Volume of assortment a demanded by mill m during period t (m^3)
V	A very small number

Table 5 Decision variables of the mathematical model

Notation	Description
b_{hse}	1, if block h is planned for harvesting in any period using silvicultural treatment s and harvest system e, 0, otherwise
x_{thse}	The proportion of cutblock h cut in period t under silvicultural treatment s using system e
q_{tham}	The volume of assortment a transported from cutblock h to mill m in period t (m^3)
y_{tha}	The volume of assortment a stored in cutblock h at the end of period t (m^3)
r_h	Integer variable used to limit the number of periods during which cutblock h is cut

$$\begin{aligned}\text{Maximize profit} = & \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}(N_a - G_{hm}B_{hm}) \\ & - \sum_{t\in T}\sum_{h\in H}\sum_{s\in S}\sum_{e\in E}\sum_{a\in A} x_{thse}V_{hsa}C_eP_{se}^{-1} \\ & - \sum_{t\in T}\sum_{h\in H}\sum_{a\in A} y_{tha}Y^C_{th} - \sum_{h\in H}\sum_{s\in S}\sum_{e\in E} b_{hse}J_{hs}\end{aligned} \tag{1}$$

Subject to:

$$y_{tha} = Y^I_{ha} + \sum_{s\in S}\sum_{e\in E} x_{thse}V_{hsa} - \sum_{m\in M} q_{tham} \qquad \forall\, h, a, t = 1 \tag{2}$$

$$y_{tha} = \sum_{s\in S}\sum_{e\in E} x_{thse}V_{hsa} + y_{t-1,h,a} - \sum_{m\in M} q_{tham} \qquad \forall\, h, a,\ t > 1 \tag{3}$$

$$\sum_{h\in H} q_{tham} \le D_{tam} \qquad \forall\, t, a, m \tag{4}$$

$$\sum_{h\in H}\sum_{s\in S}\sum_{a\in A} V_{hsa}x_{thse} \le \sum_{s\in S} P_{se}O_{te} \qquad \forall\, t, e \tag{5}$$

$$\sum_{t\in T}\sum_{e\in E} x_{thse} \le 1 \qquad \forall\, h, s \tag{6}$$

$$\sum_{s\in S}\sum_{e\in E} b_{hse} \leq 1 \qquad \forall\ h \tag{7}$$

$$b_{hse}V \leq \sum_{t\in T} x_{thse} \qquad \forall\ h, s, e \tag{8}$$

$$b_{hse} \geq \sum_{t\in T} x_{thse} \qquad \forall\ h, s, e \tag{9}$$

$$\sum_{t\in T}\sum_{s\in S}\sum_{e\in E} x_{thse} = \sum_{s\in S}\sum_{e\in E} b_{hse} \qquad \forall\ h \tag{10}$$

$$\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham} \leq R_t \qquad \forall\ t \tag{11}$$

$$\sum_{s\in S}\sum_{e\in E} x_{thse} + \sum_{s\in S}\sum_{e\in E} x_{t+1,h,s,e} = r_h \qquad \forall\ h \tag{12}$$

$$\sum_{h\in H} r_h \leq 1 \qquad \forall\ h \tag{13}$$

$$b_{hse}, r_h \in \{0, 1\} \tag{14}$$

$$x_{thse}, q_{tham}, y_{tha} \geq 0 \qquad \forall\ t,\ h,\ s,\ e,\ a,\ m \tag{15}$$

The sets, input data and decision variables of the mathematical model are presented in Tables 3–5, respectively. The objective function (equation 1) was formulated as profit maximization. The first element represents the revenue generated through delivery of wood assortments to mills minus transportation cost. The second and third elements represent the variable costs associated with harvesting and inventory, respectively. The last element represents flexibility cost imposed for altering silvicultural treatment from what was initially prescribed to a cutblock.

Equations (2) and (3) are flow conservation constraints that ensure storage balance of assortments in cutblocks. Equation (2) handles the first period of the planning horizon and equation (3) handles the remaining periods. Equation (4) ensures that the volume of wood assortments transported to a mill during a particular period is less than or equal to the demanded volume. Equation (5) is a harvest capacity constraint; it ensures that the volume harvested per period is less than or equal to the maximum production capacity. Equation (6) ensures the total volume harvested in a cutblock in all periods is less than or equal to the maximum available under a silvicultural treatment. Equation (7) forces application of the same silvicultural treatment to a cutblock even if harvesting is partitioned to different periods and different harvest systems. Equations (8) and (9) establish a relationship between the variables b_{hse} and x_{thse} by triggering variable b_{hse} to 1 if a cutblock is planned to be harvested over the planning horizon. The value of V ensures Equation (8) is satisfied when $x > 0$. Equation (10) ensures that if a cutblock is selected for harvest, the entire available volume is harvested over the planning horizon. Equation (11) ensures that the total volume delivered to all mills in each period is lower than the transportation capacity. Equations (12) and (13) limit harvesting of a cutblock to be partitioned to a maximum of two subsequent periods. Finally, equations (14) and (15) assign binary restrictions and non-negativity restrictions to respective variables.

Statistical analysis

Statistical analyses were performed using SigmaPlot®, version 12.0 for Windows. Friedman repeated-measures analysis of variance on ranks were conducted to compare the effects of flexibility in the choice of silvicultural treatment, the different intensities of flexibility costs imposed and demand volatility levels, on profit and demand fulfilment rates. The Friedman test was deemed the most appropriate since it is based on ranking of each row, thus neutralizing the impact of other sources of variability. Tukey's *post hoc* tests (Tukey, 1949) were carried out to further analyse the statistical significance effect of levels of the independent variables on the dependent variable in each model. The Tukey test was chosen as it was the most conservative option in the software for Friedman test because of significance. Also analysis of variance (Fisher, 1959) tests were carried out to examine effects of intensities of flexibility costs imposed on the proportion of silvicultural treatments prescribed. The residuals were tested for normality and homogeneity of variance prior to conducting the tests. Any significant differences in the analysis were further analysed using a more powerful Holm–Šídák test (Holm, 1979).

Case study

Description

A hypothetical case study was developed based on data received from a forest products company operating in Quebec, Canada. The wood procurement company operates in the boreal mixedwood forest region. The region is characterized by forests with several of the following species: black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), white pine (Pinus strobus L.), red pine (Pinus resinosa Sol.), balsam fir (*Abies balsamea* (L.) Mill.), larch (*Larix larcina* (Du Roi) K. Koch), eastern red cedar (*Juniperus virginiana* L.), trembling aspen (*Populus tremuloides* Michx.), yellow birch (Betula alleghaniensis Britt.), paper birch (*Betula papyrifera* Marsh.), balsam poplar (*Populus balsamifera* L.), sugar maple (*Acer saccharum* Marshall). With regards to the size of the cutblocks, 83 per cent were <50 ha, and the remaining 17 per cent were between 50 and 100 ha. The company manages demand from 10 mills in the region. The acquired data contained information on volumes demanded during a 1-year horizon which was used as the base demand for the experiment.

Supply

There were 50 cutblocks allocated for harvest in a 1-year period with information on volumes by assortment. It was assumed that clearcut was the default treatment prescribed to all cutblocks. The volumes available under alternative treatments were therefore estimated assuming that they would be a subset of the clearcut treatment. Four additional treatments were developed based on proportions of volumes in the cutblocks. While these treatments might be considered coarse representation of natural dynamics for a given forest, their use permits a practical approach to carry out the experiment. In practice, more refined prescriptions should be developed for each cutblock based on stand-specific parameters. Options 1 and 2 are construction treatments inspired by Raymond *et al.* (2009) where 50 per cent of the default volume is removed from the block. They represent two variants of the extended irregular shelterwood system. Under option 1, 75 per cent of the extracted volume is softwood while only 25 per cent of hardwood is removed. In contrast, under option 2, 75 per cent of the extracted volume is hardwood and 25 per cent of it is softwood. In cutblocks with insufficient softwood or hardwood volumes, the restriction on proportion of species to be extracted was relaxed. Options 3 and 4 were treatments inspired by Ruel

Table 6 Example of assortment volume table by silvicultural treatment for a given cutblock

Assortment	Volumes available under silvicultural treatment (m^3 ha^{-1})					Price ($ m^{-3})
	Default	Option 1	Option 2	Option 3	Option 4	
Yellow birch Grade 1	0.07	0.07	0.07	0.03	0.02	407
Yellow birch Grade 2	0.39	0.39	0.39	0.15	0.12	339
Paper birch Grade 1	0.59	0.59	0.59	0.24	0.18	390
Paper birch Grade 2	5.97	5.97	5.97	2.39	1.79	322
Sugar maple Grade 1	0.00	0.00	0.00	0.00	0.00	407
Sugar maple Grade 2	0.00	0.00	0.00	0.00	0.00	339
Deciduous pulp	30.60	17.98	30.60	12.24	9.18	32
Trembling aspen	53.39	0.00	37.38	21.36	16.02	187
White pine	0.28	0.28	0.28	0.11	0.08	237
Red pine	0.00	0.00	0.00	0.00	0.00	220
Fir/spruce/pine/tamarack	108.71	74.72	24.72	43.49	32.61	204

et al. (2007); they represent different intensities of partial harvesting of the cutblocks with 40 and 30 per cent of the volumes being removed, respectively. The volumes under these treatments were estimated by multiplying the default values by 0.4 (option 3), and 0.3 (option 4). Data were generated for all cutblocks to specify volumes available under each option. Table 6 displays the assortments and the prices used in the experiment; grade 1 and 2 represent higher and lower value logs, respectively. Log prices used in the experiment were obtained from the Wood producers association of Québec (SPFRQ, 2013).

Costs

Two options on harvesting systems were utilized to implement the treatments: cut-to-length (CTL) and full-tree systems (FT). The productivity of the systems varies depending on the treatment being implemented. The productivity values used in the case study were estimates based on values published in Meek (2006) and Gingras (1994). The cost of transportation was estimated at $0.032 m^{-3} km^{-1} based on a payment rate of $80 h^{-1} and volume capacity of 50 m^3. Information on distances between mills and cutblocks were part of the acquired data. The hourly costs for cut-to-length and full-tree systems were estimated at Canadian $260 and $322 per scheduled machine hour, respectively, based on Gautam *et al*. (2010) and Puttock *et al*. (2005). Costs were actualized to the year 2013 using the bank of Canada inflation calculator (BOC, 2013). The total harvesting cost depended on the productivity of the chosen system in a particular cutblock. Inventory cost structure is particularly difficult to estimate, as it includes carrying cost, ordering costs, backlog costs, deterioration cost, opportunity cost etc. The cost was set to a high value in this experiment to restrict the model from excessively stocking in the forest. The model's decision to store inventory will be based on forecast data. However, due to the execution of the model on a rolling period basis, the demand will eventually change when it materializes. Thus inserting a high cost for inventory forces the model to match current demand with supply rather than stocking. However, the costs were not made to be exceedingly high because exact match between supply and demand cannot be made, and it would be necessary to store some inventory. With regards to flexibility cost, the costs associated with each regime were estimated using a government report (MRN, 2009) and converted to 2013 Canadian dollar (BOC, 2013); the costs were $2, $12 m^{-3} and $21 m^{-3} for extensive, basic and intensive, respectively.

Results

The mathematical model was coded using the AMPL modelling language (Fourer *et al*., 2003) and solved using CPLEX 12.5 in a 3.07 GHz PC with 12 GB RAM. An iteration of the case study with 12 time periods contained 35 232 linear variables, 1500 binary variables and 8342 constraints. The optimality gap was set to within 1 per cent and a time limit for computation was fixed at 1000 s. Fifty repetitions of each of the 10 scenarios were run on a rolling planning horizon basis for 12 monthly periods. In general, it was found that both the profit values as well as demand fulfilment rates were higher under scenarios with flexibility in the choice of silvicultural treatment at the operational level (Figures 4–7). The values represent a total generated by the entire realized plan.

The distributions of the profit values under the low- and high-volatility scenarios are shown in Figures 4 and 5, respectively. Trends under both volatility levels were similar; when given flexibility in the choice of silvicultural treatment, the profits increased and subsequently showed a decreasing trend with an increasing flexibility cost. A one-way repeated-measures analysis of variance by ranks showed that there was a statistically significant difference in the profit values ($P < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures; boxes labelled with the same letter are not significantly different from each other. Scenarios without flexibility in the choice of silvicultural treatment (1 and 2) generated profits significantly lower than the remaining scenarios. Even with the most intensive flexibility cost imposed, the profits were still significantly higher than the scenario without flexibility in the choice of silvicultural treatment. Flexibility in the choice of silvicultural treatment permitted the model to develop a plan that procured a mix of products more aligned with the emerging demand.

Under low volatility in demand (scenario 3), an average increase in profit of $862 931 was observed when allowing flexibility in the choice of silvicultural treatment without imposing flexibility cost. The difference was reduced to $674 242, $639 367 and

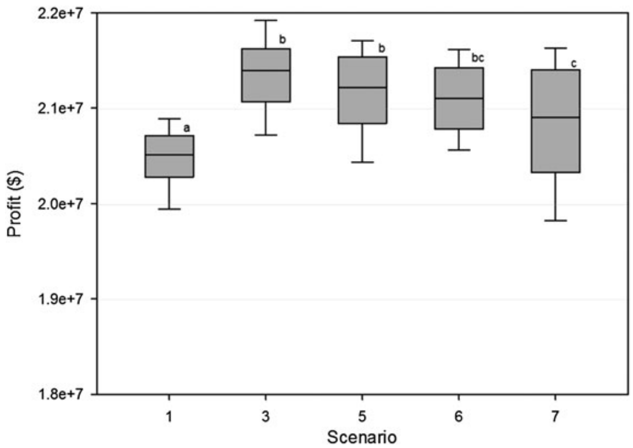

Figure 4 A box and whisker graph showing distribution of profit values for the low volatility scenarios (scenario 1, 3, 5, 6 and 7).

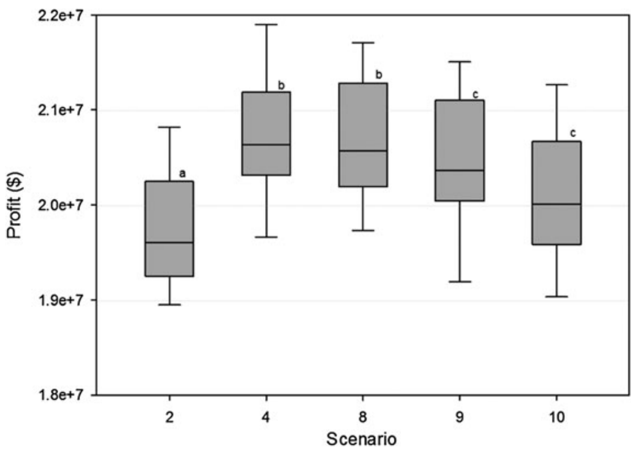

Figure 5 A box and whisker graph showing distribution of profit values for the high volatility scenarios (2, 4, 8, 9 and 10).

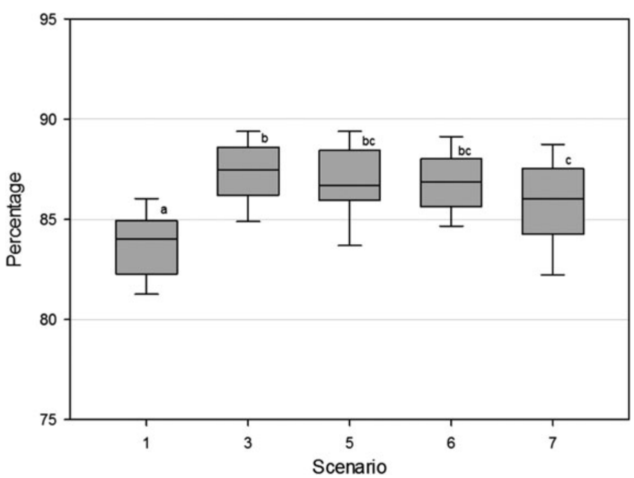

Figure 6 A box and whisker graph showing distribution of demand fulfilment rates for low volatility scenarios.

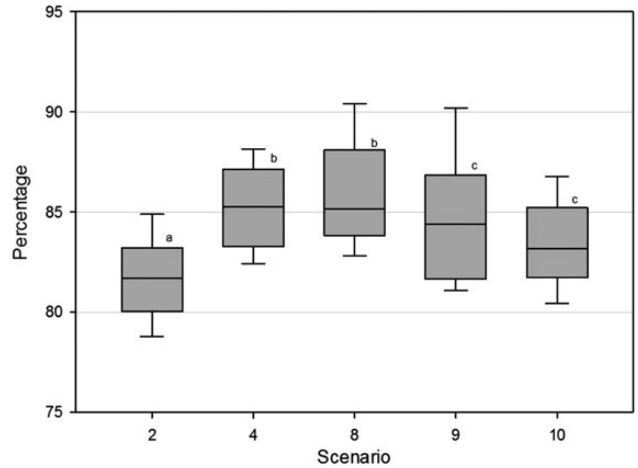

Figure 7 A box and whisker graph showing distribution of demand fulfilment rates under high volatility scenarios.

\$322 600 when extensive (scenario 5), basic (scenario 6) and intensive (scenario 7) flexibility costs were applied, respectively. Similarly, an increase of \$950 124 was observed under high demand volatility (scenario 4) when flexibility in the choice of silvicultural treatment was permitted. The subsequent differences as the flexibility cost increased were \$923 286 (scenario 8), \$663 855 (scenario 9) and \$384 078 (scenario 10). Increases in profits were greater under high demand volatility scenarios. The percentage increases were on average 5.5 per cent (scenario 4), 5.4 per cent (scenario 8), 4.1 per cent (scenario 9) and 2.6 per cent (scenario 10) under high demand volatility. The percentage increases in scenarios with low demand volatility were 2.8 per cent (scenario 3), 2.0 per cent (scenario 5), 1.8 per cent (scenario 6) and 0.2 per cent (scenario 7).

The distribution of demand fulfilment rates from 50 experimental runs are shown in Figures 6 and 7 for the lower and higher volatility levels, respectively. Repeated-measures analyses of variance by ranks showed statistically significant difference in the demand fulfilment rates ($P < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures; boxes labelled with the same letter are not significantly different from each other. Flexibility in the choice of silvicultural treatment significantly increased the demand fulfilment rates. In lower volatility scenarios, the rates increased from 83.6 to 87.3 per cent when flexibility in the choice of silvicultural treatment was permitted without imposing a cost. The rates were 86.7, 86.8 and 85.8 per cent when imposed flexibility costs based on extensive, basic and intensive silviculture intensity, respectively. In higher volatility scenarios, the increase in the demand fulfilments rates through permitting flexibility ranged from an average of 81.6 to 85.2 per cent. Subsequently, imposing flexibility costs based on extensive, basic and intensive silviculture intensity led to demand fulfilments rates of 85.8, 84.6 and 83.5 per cent, respectively.

Unlike profit values, the difference in demand fulfilment rates due to providing flexibility in the choice of silvicultural treatment was not definitively greater under high volatility scenarios. Under high volatility scenarios, the increases were 3.6, 4.2, 3.0 and 1.9 per cent for no flexibility cost, extensive, basic and intensive silviculture intensity, respectively. The corresponding values for low volatility scenarios were 3.7, 3.1, 3.2 and 2.2 per cent, respectively. The

Table 7 Descriptive statistics of proportions of silvicultural treatments prescribed under different scenarios based on volume (m^3)

Basis for penalty	Prescribed treatment	Low volatility			High volatility		
		Average	Min	Max	Average	Min	Max
No cost	Default	58.3 (5.3)[a]	46.0	70.5	58.6 (6.3)[a]	43.7	74.1
	Option 1	16.8 (4.5)[d]	7.0	27.8	15.0 (5.2)[d]	3.8	27.6
	Option 2	13.0 (5.2)[g]	2.9	25.7	12.7 (4.5)[g]	4.4	22.4
	Option 3	7.0 (2.8)[j]	0.0	12.7	8.2 (3.6)[j]	1.0	16.8
	Option 4	4.8 (2.2)[m]	0.6	10.9	5.5 (2.3)[m]	1.8	12.4
Extensive	Default	57.3 (5.5)[a]	44.5	67.8	58.2 (6.9)[a]	42.6	75.5
	Option 1	16.2 (4.5)[d]	7.8	28.3	15.0 (5.6)[d]	2.5	30.4
	Option 2	14.3 (4.2)[g]	5.3	23.5	12.3 (5.3)[g]	2.4	28.7
	Option 3	7.3 (3.4)[j]	0.5	14.9	8.9 (3.7)[j]	1.8	18.6
	Option 4	4.9 (2.6)[m]	0.2	13.2	5.5 (2.6)[m]	0.4	11.2
Basic	Default	71.6 (6.5)[b]	57.7	87.6	74.5 (5.1)[b]	63.7	85.3
	Option 1	9.9 (4.7)[e]	0.9	19.0	9.7 (4.3)[e]	0.0	18.5
	Option 2	10.0 (5.0)[h]	1.1	20.7	8.1 (3.5)[h]	1.0	17.3
	Option 3	4.8 (2.9)[k]	0.0	11.2	4.8 (2.7)[k]	0.0	10.7
	Option 4	3.6 (2.7)[n]	0.0	12.3	3.0 (2.2)[n]	0.0	9.0
Intensive	Default	81.2 (5.4)[c]	66.5	92.1	84.4 (6.6)[c]	71.4	97.4
	Option 1	6.7 (3.5)[f]	0.0	15.5	5.8 (4.7)[f]	0.0	18.6
	Option 2	6.8 (4.4)[i]	0.0	19.7	5.5 (4.0)[i]	0.0	18.2
	Option 3	2.4 (1.6)[l]	0.0	5.9	2.5 (2.2)[l]	0.0	10.4
	Option 4	2.9 (2.3)[o]	0.0	10.7	1.9 (1.9)[q]	0.0	7.0

Values in parentheses represent the standard deviation.
[a–q]Values with different alphabets represent significant difference.

greater increase in profit under higher volatility scenarios without the same increases in demand fulfilment rates can be explained through the differences in the assortment prices. The model would have focused on fulfilling demand of assortments that generated higher revenue rather than overall demand fulfilment since the objective function sought to maximize profit.

A summary of the proportions of silvicultural treatments implemented under different scenarios is shown in Table 7. The proportions reflect average values from 50 runs of the model and are based on volume. ANOVAs were carried out for each silvicultural treatment proportions prescribed under different scenarios. The results of the analyses have been included in Table 7; numbers labelled with the same letter are not significantly different from each other. The proportions of silvicultural treatments prescribed did not vary significantly with demand volatility levels. The proportions did, however, vary significantly depending on the intensity of flexibility costs imposed. Multiple comparison tests (Holm–Šídák) showed that the difference between 'no cost' and 'extensive' was not statistically significant but the remaining regimes all produced proportions significantly different from each other. The trend of increased application of the default treatment was observed as the flexibility cost was augmented.

Discussion and conclusion

The study was conducted to quantify the benefits of improving agility on supply chain profits and demand fulfilment rates. It also allowed the determination of a range of conditions under which benefits can be realized. The proposed approach of improving agility entailed allowing flexibility in the choice of silvicultural treatments at the operational level. A simulation experiment based on a rolling planning horizon framework with uncertain demand was implemented to a case study in Quebec, Canada. The process should be considered as a further development of the analyses presented by Howard and Temesgen (1997) and Moore *et al.* (2012). Treatments with an acceptable benefit–cost ratio should be considered as an option; the prevailing demand should then partly influence the decision on the actual treatment to be applied as the eventual profitability depends on it.

The importance of the approach is demonstrated by Figures 6 and 7. Under status quo (scenarios 1 and 2), demand fulfilment rates were lower despite the availability of assortments in the cutblocks; confirmed by the fact that rates were higher under scenarios with flexibility (scenarios 3–10). Furthermore, an increase in profit through the approach was greater under high demand volatility (Figure 5) than in low volatility (Figure 4). This result has important implications for wood procurement systems operating in mixedwood stands that are responsible for supplying to value-added manufacturers. On the market side, these manufacturers are exposed to high demand volatility (Grace, 2013); this will be reflected in the demand put forward to the wood procurement systems. On the supply side, mixedwood stands are characterized by variability in the composition of species among other features. The treatment applied will dictate the volume and ratio of assortments procured from a cutblock. The procurable mixture may contain both assortments with and without demand in the market. The decision to harvest is then based on whether the profit generated from the demanded assortments can offset the harvesting and storage of non-demanded assortments. There is an element of risk associated with future demand and also likelihood of quality deterioration during storage leading to a net loss. Thus, the cutblock may be bypassed altogether accepting a reduction in demand satisfaction as in scenarios 1 and 2. Flexibility in silvicultural treatment permits selection of a treatment that produces assortments reflective of the demand (scenarios 3–10). As pointed out by Puettmann *et al.* (2008), there are generally a range of treatments applicable to any given forest stands. In this study, treatments were developed based on volume proportions. In practice, silviculturists should develop a range of close-to-nature silvicultural treatment options for each cutblock. Forest managers can then produce and execute harvest plans that are both ecologically and economically viable. Such multiple scale integration through incorporating input from silviculturists in supply chain management allows for adaptive management system with greater value-creation opportunity (Messier *et al.*, 2013). Our results also suggest that significant improvement can be realized even if flexibility is permitted in only a certain proportion of the cutblocks. Table 7 demonstrates that even without any penalty imposed for exercising flexibility, almost 60 per cent of the volume was procured through initially prescribed treatments. On the other hand, even under the condition where maximum penalty was imposed for exercising flexibility, the model procured almost 20 per cent of the volumes through alternative treatments due to the associated benefits. These results reinforce the importance of silvicultural flexibility for wood procurement systems in delivering raw material to the forest products supply chain.

The approach can be a valuable tool to deal with risks inherent to forest management. It mitigates the impact of uncertain events such as fire, insect outbreak, windthrow and pathogens on operational plan. It can also protect the operational plans against inaccuracies in growth models, whether it is due to unanticipated variation or induced by global climate change (Yousefpour *et al.*, 2012). The approach allows maintaining a high demand satisfaction rate as in scenario 3–10 (Figures 6 and 7) in face of uncertainty. The harvest levels would consequently also rise closer to the allowable limit, resulting in greater societal benefits such as employment opportunities, as well as increased stumpage revenue for the land owners. Actual harvest levels have been well below the planned harvest levels in all Canadian jurisdictions in the past decade (NRC, 2013). Closing the gap between planned and executed activities on the ground reduces the risk of potential wood supply crisis in the future (Paradis *et al.*, 2013).

Despite the potential advantages, there are some challenges for implementation. This study was conducted under the assumption that the assortments in cutblocks can be accurately estimated, and that harvesting systems can procure just the targeted assortments under a prescribed treatment. The assumptions are supported by the advent in technology. For example, terrestrial LiDAR technology now permits an accurate estimation of volumes by assortments in cutblocks (Dassot *et al.*, 2011). On the harvesting front, machines can be equipped with the GPS technology and computer algorithms to accurately identify and execute bucking patterns (Marshall, 2007). However, costs can be a barrier to acquiring these technologies. The decision to adopt these tools and technologies depends on the return on investment. Future studies should conduct analysis such as cost plus loss based on profit gains as displayed in Figures 4 and 5 to support decision-making.

Finally, this study was based on an assumption that forest succession (productivity and species composition) can be controlled through applying silvicultural regimes; investments can be made to redirect the trajectory of stands within a desired range. The assumption was necessary to maintain the focus of this study towards quantifying the benefits associated with flexibility in silvicultural treatments at the operational level. Alternatively, the experiment would have to be significantly expanded; the task would entail formulating a long-term plan, creating harvesting blocks over the land base in each period, simulating implementation of annual harvests on a rolling basis and observing the impact. As such, it is a daunting task well beyond the scope of this paper. Nevertheless, such a study should be carried out in the future to anticipate the precise impact on the long-term wood supply.

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