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Optimizing carbon sequestration in commercial forests by integrating carbon management objectives in wood supply modeling

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Abstract This paper provides a methodology for generating forest management plans, which explicitly *maximize* carbon (C) sequestration at the forest-landscape level. This paper takes advantage of concepts first presented in a paper by Meng et al. (2003; Mitigation Adaptation Strategies Global Change 8:371–403) by integrating

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C-sequestration objective functions in existing wood supply models. Carbon-stock calculations performed in Woodstock™ (RemSoft Inc.) are based on C yields generated from volume table data obtained from local Forest Development Survey plots and a series of wood volume-to-C content conversion factors specified in von Mirbach (2000). The approach is used to investigate the impact of three demonstration forest-management scenarios on the C budget in a 110,000 ha forest in south-central New Brunswick, Canada. Explicit demonstration scenarios addressed include (1) maximizing timber extraction either by clearcut or selection harvesting for greatest revenue generation, (2) maximizing total C storage in the forest landscape and in wood products generated from harvesting, and (3) maximizing C storage together with revenue generation. The level of clearcut harvesting was greatest for *scenario 1* ($\geq 15 \times 10^4$ m^3 of wood and ≥943 ha of land per harvesting period), and least for *scenario 2* (=0 m^3 per harvesting period) where selection harvesting dominated. Because softwood saw logs were worth more than pulpwood (\$60 m^{-3} vs. \$40 m^{-3}) and were strategic to the long-term storage of C, the production of softwood saw logs exceeded the production of pulpwood in all scenarios. Selection harvesting was generally the preferred harvesting method across scenarios. Only in *scenario 1* did levels of clearcut harvesting occasionally exceed those of selection harvesting, mainly in the removal of old, dilapidated stands early in the simulation (i.e., during periods 1 through 3). *Scenario 2* provided the greatest total C-storage increase over 80 years (i.e., 14×10^6 Mg C, or roughly 264 Mg ha^{-1}) at a cost of \$111 per Mg C due to lost revenues. *Scenarios 3* and *1* produced reduced storage rates of roughly 9×10^6 Mg C and 3×10^6 Mg C, respectively; about 64% and 22% of the total, 80-year C storage calculated in *scenario 2*. The bulk of the C in *scenario 2* was stored in the forest, amounting to about 76% of the total C sequestered.

Keywords Carbon sequestration · Forest management planning · Goal programming · Growth and yield · Harvesting · Linear programming · Operational emissions · Optimization · Silviculture · Wood products

1 Introduction

Decisions made at the forest management level can have a significant impact on the level and time carbon (C) is sequestered in forests and in the wood products generated from these forests (Johnson 1992; Kurz et al. 1992; Wisniewski et al. 1993; Matthews 1996; Bhatti et al. 2003; Meng et al. 2003). For example, forests with fast growing, short-rotation aged stands have a high rate of C uptake (Papadopol 2000; Metting et al. 2001; Ney et al. 2002). However, the time over which the C is stored is relatively short, especially if burned or converted into paper. Short-lived products like paper, wood chips, sawdust, and hog fuel enter the waste stream quickly and decompose fairly rapidly (Hoen and Solberg 1994; Bhatti et al. 2003). The C stored

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in these products returns to the atmosphere and re-enters the C cycle in just a few years (Bhatti et al. 2003).

A post-harvest approach that reduces waste and puts most of the wood into long-lived products could be an effective strategy to help reduce global atmospheric C. Allowing a forest to reach maturity, stores C for many tens to hundreds of years depending on forest type. Products generated from this management strategy produce long-lived structural products, such as lumber, veneer, and plywood, used in the building of houses and furniture. The disadvantage of this strategy is that forests are left standing longer increasing their vulnerability to natural disturbances, such as fire, insect infestations, and fungal attack. From a C-fixation point of view, leaving trees standing beyond maturity reduces the rate of C being sequestered, due to trees growing past their maximum mean annual increment (MAI). Moreover, long-lived products currently form a small percentage of total wood products produced worldwide, meaning current timber procurement strategies implemented in many jurisdictions of the world in the end simply act to reduce storage of C on the land.

Substitute materials, such as steel, concrete, synthetic composites, carry their share of the environmental burden due to the elevated C emissions associated with their manufacturing (Schlamadinger and Marland 1996a, b; Niles and Schwarze 2001; Glover et al. 2002). For instance, when building a 180 m^2 brick house, using steel as the framing material, 2.7 tonnes of carbon dioxide (CO_2) are emitted during the manufacturing of the steel and steel frames. However, compared with building the wood frames of the same house, only 0.4 tonnes of CO_2 are emitted (Flint 2003).

Managing C stocks across ecosystems and their components, as well as across commodity pools to increase C sequestration represents a major challenge. Given the current world situation of rising atmospheric CO_2 concentrations and global climate change, linking on-the-ground forest management activities to enhance C storage in forests and woodland products (Matthews 1996; Montagnin and Porras 1998; Lee et al. 2002; Meng et al. 2003) has gained considerable importance in recent years.

Existing forest C-budget models, e.g., CBM-CFS3—Kurz and Apps (1999), CO2FIX—Nabuurs and Schelhaas (2002), GORCAM—Schlamadinger and Marland (1996a, b) and Marland and Schlamadinger (1999), have begun to make some of these important linkages and in so doing have provided forest managers with means to calculate the combined C budget of forests and product pools for specific management scenarios. The approach described in Meng et al. (2003) provides similar calculations of forest C-stocks (aboveground biomass + roots) by integrating C-stock calculations with timber management planning. Timber supply projections are argued to provide the best overall prediction of merchantable volume in commercial forests as a result of high caliber input data used (Meng et al. 2003). Since these C stocks vary linearly with wood volume, a natural progression from wood supply modeling is the calculation of aboveground C stocks.

None of the four approaches described can provide insight as to what forest management strategies can best augment C sequestration in a constantly changing forest landscape. For C-credit allowances, the Kyoto Protocol (UNFCCC 1997; Houghton 2001; Kennett 2002), if adopted, will require that proponents (e.g., forestry companies, government departments of natural resources and crown-public lands, etc.) demonstrate that the incremental change in C sequestration is achieved as a result of management activity (Bhatti et al. 2003) and its level is beyond the C sequestration that would occur under a ''business as usual'' scenario in some countries (e.g., Canada). Existing C-budget models may, through ''trial and error'', uncover scenarios that may provide enhancements in C sequestration. However, there is no feasible way to tell if the sequestration level uncovered represents the maximum possible level achievable within existing operational constraints. Goal programming to evaluate multiple-criteria objective functions makes it possible to meet revenue objectives while sustaining higher levels of stored C in the landscape. An example application of goal programming for C management objectives in a Spanish forest, Pinar de Navafría, is described in Díaz-Balteiro and Romero (2002). We demonstrate the incorporation of C sequestration into existing wood supply models (see below), central to forest companies' forest management planning activities (Meng et al. 2003). Linear programming and goal programming objectives are carried out in the system framework through the implementation of commercial software.

2 Objectives

The primary objective of this paper *is to develop a modeling framework for generating forest management plans with an explicit goal to maximize C sequestration* in commercial forests and in the wood products generated from these forests. The framework is based on concepts presented in Meng et al. (2003) with modeling C sequestration at the operational scale. As in the earlier paper, C-management (sequestration) objectives were integrated in existing wood supply models. Unlike the first paper, forest management plans were generated based on the *optimization* of landscape-level C-stock calculations.

The optimization process searches from a list of user-defined stand-level interventions that best maximize C storage at the landscape level. To display forest management effects on the C budget of landscapes, we provide C-stock calculations for three demonstration forest-management scenarios, namely (1) maximized revenue generation, (2) maximized C storage in the forest landscape and in the wood products generated from harvesting, and (3) greatest revenue generation with elevated levels of stored C. Multiple criteria objective functions, as in scenario 3, allow development of alternate harvesting schedules that meet revenue objectives while augmenting future C stocks. Although, we provide three scenarios to demonstrate system flexibility, many more scenarios can be explored this way. Scenario building can be done by implementing modifications to the objective functions and constraints employed in the wood supply (C) model (appearing in Fig. 3).

Wood-volume and C-stock scenario projections are initialized with land and forest inventory data from a demonstration, forest-management area of Canadian Forces Base (CFB) Gagetown, in south-central New Brunswick (NB), Canada. Model projections are carried out over an 80-year strategic planning horizon.

3 Forest management area

3.1 Area description

CFB Gagetown (centered on 45° 39′ 15.5″ N and 66° 20′ 26.2″ W) is an 1100 km^2 (or 110 000 ha) military training area in southern NB (Fig. 1). The military base is

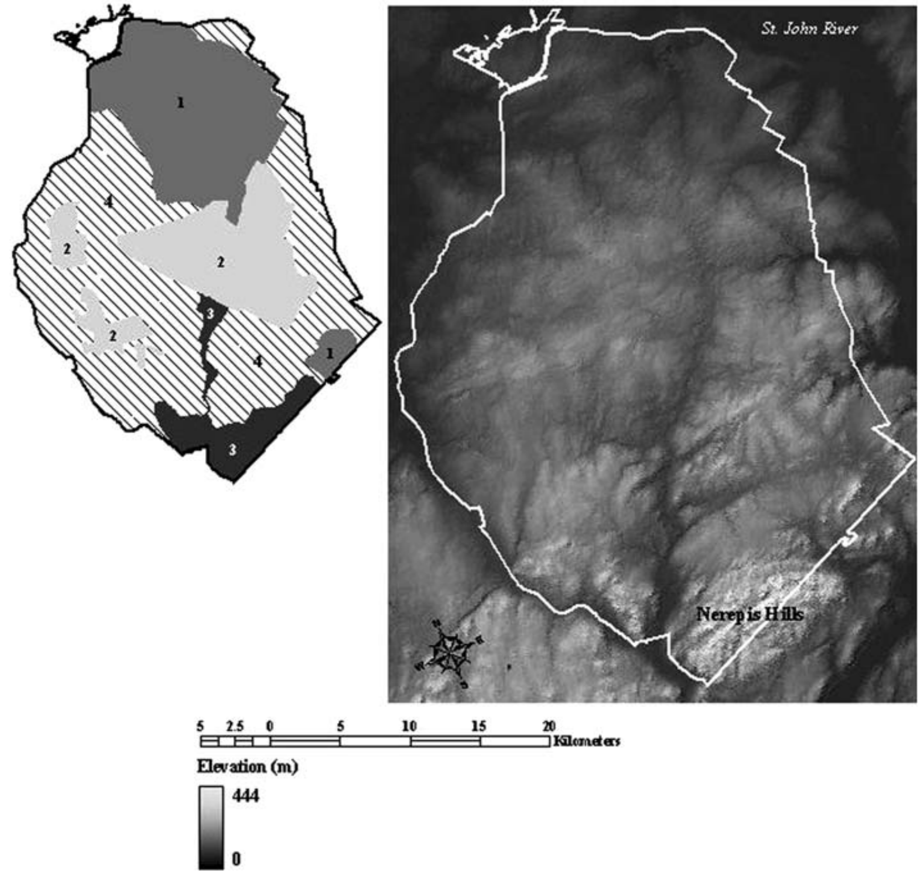

Fig. 1 Digital elevation model (DEM) of CFB Gagetown (land enclosed by white boundary) and surrounding area. The DEM is a 3324 (rows) × 2526 (columns) grid at 15-m resolution. The Nerepis Hills in the southeast portion of CFB Gagetown military range are indicated. The inset gives the zone delineations. The forest management plan is developed for Zone 4

divided into four zones, two static impact ranges for military manoeuvres (Zones 1, and 2), an ecological reserve (The Nerepis Hills; Zone 3), and a forest-management area (Zone 4; inset, Fig. 1). C-sequestration calculations in this paper focus on the forest in Zone 4. Total forest area of Zone 4 is just under 53 000 ha.

The forest in Zone 4 is highly variable (Fig. 2). The forest is generally dominated by softwoods, followed by shade-intolerant hardwoods, then shade-tolerant hardwoods in order of abundance. Table 1 provides a list of all forest covertypes (strata) found on CFB Gagetown with their relative abundance. The NF and NF_Noval fields are non-forested areas such as shooting ranges, runways, military compounds, etc. The covertype categories are based on the NB Department of Natural Resources' (NBDNR, 1984) classification system. The current age class structure of the forest is immature-to-mature with little total area occupied by stands older than 100 years old (inset, Fig. 2).

CFB Gagetown spans three ecodistricts, ecodistrict 25, 26, and 33 (NBDNR, Ecosystem Classification Working Group–ECWG 1996). CFB Gagetown falls mostly in ecodistrict 25, accounting for about 85% of the total land base. Both ecodistricts 25

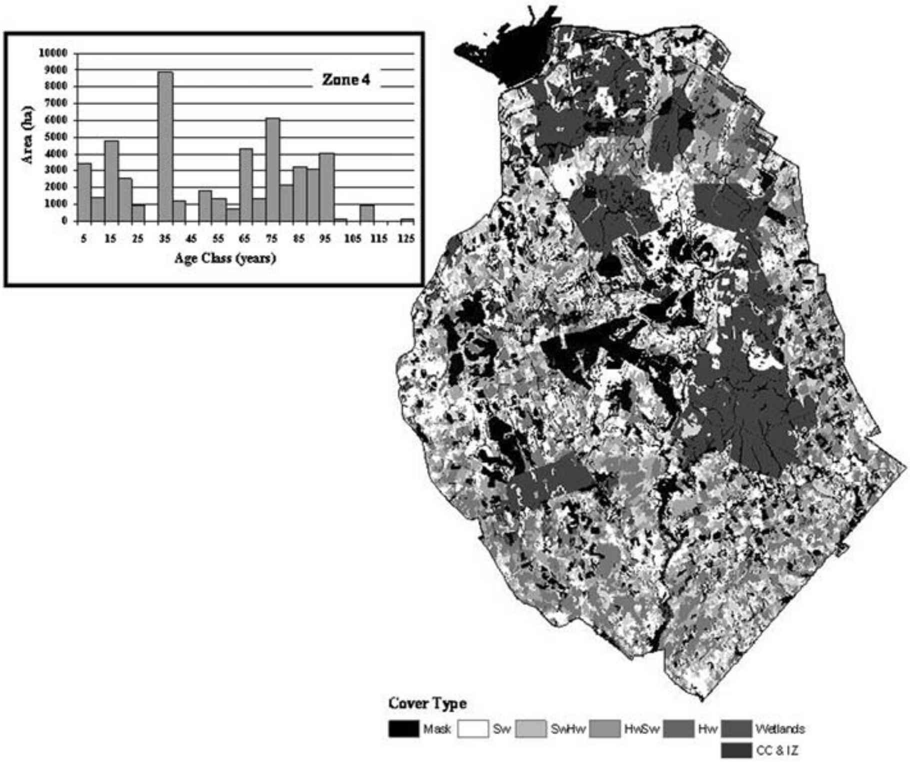

Fig. 2 Surface cover according to seven land-surface covertypes. Initial age class structure (2003) of Zone 4 is provided in the inset. Nomenclature of land covertypes: Mask (black) = non-forested areas with buildings, runways, military infrastructure; Sw = >70% softwood; SwHw = softwood-hardwood mixed forests with a predominantly (60–50%) softwood component; HwSw = hardwood–softwood mixed forests with a predominantly (60–50%) hardwood component; Hw = >70% hardwood; Wetlands = bogs, marshes; CC & IZ = clearcut and static impact zones for military exercises

and 33 have a high percentage of spruce-fir (SPBF) forests. Ecodistrict 26 occurs mostly in Zone 3 and is characterized by its many pure tolerant hardwood stands and balsam fir- or spruce-tolerant hardwood mixed stands. Ecodistricts 25 and 33 by virtue of their location in the Maritime Lowlands ecoregion (ECWG 1996) are characterized by their abundant wetlands. Ecodistrict 26 has fewer wetlands because of its hilly terrain and affiliation with the southern NB uplands ecoregion.

3.2 Forest inventory

Updated forest inventory GIS (Geographic Information System) data were provided by NBDNR. This inventory data was based on interpretation of aerial photographs. Minor update of the forest inventory data was done based on 2003 harvesting records. The forest inventory data describe stands according to species composition (up to five main tree species; White 2000), development stages, and crown closure. GIS inventory data was supplemented by data of forest growth and yield, tree age, and piece size collected from Forest Development Survey (FDS) plots located near CFB Gagetown.

Table 1 Forest strata on CFB Gagetown with their relative importance

Forest–Landscape strata	Symbol	Number of stands	Area of zone 4 (ha)	Percentage of zone 4 (%)
Balsam fir–Intolerant hardwood	BFIH [a]	21	61.9	0.08
Eastern white cedar	EC	136	181.9	0.24
Eastern hemlock	EH	2	4.2	0.01
Intolerant hardwood–Balsam fir	IHBF	1123	2566.1	3.45
Intolerant hardwood–Spruce	IHSP	1740	3401.1	4.57
Intolerant–Tolerant hardwood	IHTH	863	2255.3	3.03
Intolerant hardwood	INHW	1331	4604.6	6.19
Non-commercial tree species	NCOM	227	392.4	0.53
Other pines (red pine, jack pine)	OPINE	283	529.1	0.71
Spruce plantation	PLSP	–	–	–
Poor-site spruce	PSSP	681	765.8	1.03
Spruce–Fir, Ecodistrict 25 & 33	SPBF_25.33	5785	10215.7	13.74
Spruce–Fir, Ecodistrict 26	SPBF_26	499	692.8	0.93
Softwood–Intolerant hardwood, Ecodistrict 25 & 33	SWIH_25.33	3086	9610.6	12.92
Softwood–Intolerant hardwood, Ecodistrict 26	SWIH_26	166	210.2	0.28
Softwood–Tolerant hardwood	SWTH	2298	4211.3	5.66
Tolerant hardwood–Balsam fir	THBF	630	1427.0	1.92
Tolerant hardwood–Intolerant hardwood	THIH	834	2261.5	3.04
Tolerant hardwood–Spruce, Ecodistrict 25 & 33	THSP_25.33	1756	3906.6	5.25
Tolerant hardwood–Spruce, Ecodistrict 26	THSP_26	332	458.4	0.62
Tamarack–Larch	TL	187	316.4	0.43
Tolerant hardwood, Ecodistrict 25 & 33	TOHW_25.33	1337	3319.6	4.46
Tolerant hardwood, Ecodistrict 26	TOHW_26	338	647.4	0.87
Dominant, white pine	WP	406	887.9	1.19
Non-forested areas	NF, NF_Noval	4551	21441.6	28.83
Total		28612	74369.4	100

[a] Not present in Zone 4

4 Methodology

4.1 Wood supply and C stock model

This paper takes advantage of concepts first presented in Meng et al. (2003) on modeling C sequestration at spatial scales relevant to the forest manager. The

Table 2 Conversion factors for converting stem volume to C (after von Mirbach 2000)

Conversion factors
1 Modify inside stem wood volume to include non-merchantable volume such as bark, crowns, and branches. Multiply bole volume by 1.454
2 Estimate belowground volume. Multiply stem volume by 0.396
3 Obtain total wood volume. Add 1 and 2
4 Convert wood volume (m^3) to Mg of dry matter biomass. Multiply wood volume by 0.43
5 Convert dry matter to C. Multiply dry matter biomass by 0.5

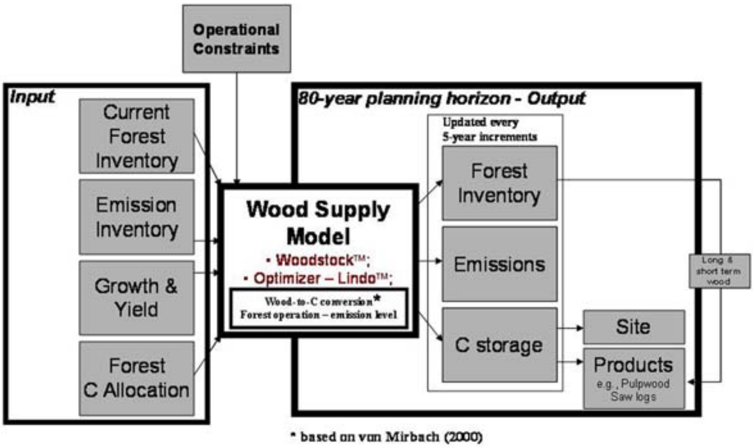

Fig. 3 Flow diagram of wood supply and C-stock modelling. The methodology is developed to include forest growth and yield of specified forest strata (see text), wood volume-to-C content conversion factors (after von Mirbach 2000), accounting of C emissions generated from harvesting and silvicultural activities, wood procurement activities, short-and long-term storage of C in forest products (i.e., pulpwood versus saw logs), updating of forest and C inventories at 5-year intervals, and scenario optimization

procedural steps in developing the wood supply and C stock projections are the same as those listed on p. 376 in Meng et al. (2003). As in the earlier paper, we also make use of von Mirbach's (2000) series of wood volume-to-C content conversion factors (Table 2) to convert merchantable volume in stands to stand C yields (in Mg). It is recognized that the conversion factors by von Mirbach (2000) represent average C-content conditions in mature stands, which could lead to calculation errors by underestimating C content in juvenile and over-mature stands. This is particularly problematic with C accounting that covers a wide range of stand conditions. In our work, the conversion factors lead to smaller errors as the C-stock calculations are applied mostly to immature–mature forests after initial manipulation. Nevertheless, we plan to remedy this problem by generating stand age and composition-specific conversion factors obtained with CO2FIX, forest C model (Nabuurs et al. 2001; Nabuurs and Schelhaas 2002). Spatio-temporal differences in soil C are not explicitly addressed in this paper. The corresponding modeling framework and information flow between model-components are presented in Fig. 3. The solver in Lindo™ that permits C-sequestration calculations to be optimized uses linear programming (Fig. 3). The linear programming model accessed by Lindo™ is translated in Woodstock™ (RemSoft Inc.).

Wood supply and C-stock calculations carried out in this paper take into account a series of actions from wood procurement activities, generation of wood products for both short-term and long-term storage (a function of piece size), C retention and release from product pools, C emissions released during wood extraction and on-the-ground silvicultural activities, and costs and revenue generation. C retention in wood products is assumed to vary as a function of time from their point of manufacture to their end use, following C-retention curves described in Kurz et al. (1992).

4.1.1 Forest characterization

The land base was stratified into 22 forest covertypes (Table 1); 21 natural covertypes and one plantation covertype (i.e., PLSP). The usual NBDNR forest strata were augmented by including stand categories representing eastern white cedar (*Thuja occidentalis* L.; EC), eastern white pine (*Pinus strobus* L.; WP), eastern hemlock (*Tsuga canadensis* (L.) Carr.; EH), and tamarack (*Larix laricina* (Du Roi) K. Koch; TL). Stand yields were constructed with the Staman^{TM} program (Meng et al. 2003) employing stand-growth information (volume totals, increments, and stand age) from a minimum of five FDS plots.

4.1.2 Silvicultural treatments

Clearcut and selection harvesting, thinning, and planting were four silvicultural treatments incorporated in the management plan because of their widespread use in forest-management activities in NB.

Clearcut harvesting Clearcut harvesting (CCH) is applied to remove entire forest communities over relatively short periods of time (Nyland 1996). This method is commonly used to extract timber as it is the most cost effective for disturbance-driven forests. Stands were assumed eligible for CCH when their average diameter at breast height (DBH) reached 10 cm and their yields were above 50 m^3 ha^{-1}. DBH of 10 cm corresponds to when the trees become merchantable. Clearcut harvesting may not be an efficient silvicultural treatment with respect to maximizing C storage at the stand level, because it opens up the forest (several tens of hectares at a time) and promotes increased decomposition and the premature release of C to the atmosphere.

We included this harvesting strategy in our analysis as we anticipated that CCH may be valuable in removing over-mature, dilapidated softwood and hardwood forests from the management area especially at the beginning of the cutting cycle. Also, including CCH along with other harvesting methods, like selection harvesting, provides a means of comparison as to its impact on the C budget at the operational level. Table 3 shows the stands available for CCH with their associated operability limits. These limits were determined using cost and revenue calculations, which were ultimately based on piece size. The lower limits do not necessarily indicate the point at which CCH is economically feasible, but rather an amount of merchantable volume (pulpwood, for the most part) that is available for harvest at this age. Post-treatment stand response (% stand conversion) for eligible stands following CCH is given in Table 4.

Selection harvesting Selection harvesting (SH) is a harvest method where a proportion of the mature trees are removed to make way for the regeneration of a replacement cohort across a portion of the stand (Nyland 1996). This harvesting method is applied to create and maintain un-even aged stand structure. By removing ~30% of the overstory, the canopy remains sufficiently opened to allow residual trees to capture additional sunlight, increasing their overall growth potential. This type of intervention is preferred from a C-sequestration point of view, because it maintains a continuous forest cover

Table 3 Stands eligible for CCH, SH, and thinning and their operability limits

Stand types	Operability limits (years)		
	CCH	SH	Thinning
EC	25–215		
EH	50–185		
IHBF	20–185	60–100	10–15
IHSP	25–200	70–100	10–15
IHTH	40–200		
INHW	35–200		
OPINE	45–195		
PLSP	25–175	40–100	10–15
PSSP	30–195		
SPBF_25.33	35–195	80–100	10–15
SPBF_26	30–195		10–15
SWIH_25.33	35–200	70–100	10–15
SWIH_26	25–230		10–15
SWTH	35–200	70–100	
THBF	35–210	70–100	
THIH	25–225		
THSP_23.33	35–205	70–100	10–15
THSP_26	35–225		10–15
TL	30–185		
TOHW_25.33	35–220	70–100	
TOHW_26	35–225		
WP	35–195		

and keeps the forest close to its maximum biological productivity. Selection harvesting creates stands that have distinct age classes (Nyland 1996) (i) by creating new age classes with every entry; (ii) by maintaining a substantial number of trees among the immature age classes close to their maximum MAI; and (iii) by removing volume of mature and excess trees with each cutting cycle. An advantage of SH is that it provides a consistent and sustainable yield of desirable wood products at set intervals. Selection harvesting was implemented in nine stand types (refer to Table 3).

In order to derive the SH yields, 30% of the stand volume was removed in the first entry, favouring either the softwood or hardwood species component. For instance, if softwoods were favoured, 30% of the hardwood in the stand was removed. The first entry in the stand was made at or near the point the trees were of saw log quality, anywhere between 65 and 80 years of age. After the 30% was removed, the remaining hardwood and softwood species were simulated to grow at 2.0 m^3 ha^{-1} $year^{-1}$. Following this initial entry a second entry was applied 20 years later, where an additional 30% of the standing volume was removed. This 30% was removed evenly across resident species. After this second entry, the stand was then held back from further harvesting for the next 20 years. At the end of this 20-year hold-back period, the stand was returned to the queue for another 30% volume removal. This cutting cycle continued for the entire planning horizon.

Thinning Pre-commercial thinning (PCT) is applied to remove inferior trees from stands, leaving the better trees to develop in an environment of increased sunlight

Table 4 Forest strata and % stand conversion with specified forest types following CCH

Forest strata[a]	Stand replacement (%)
EC	SWIH, INHW, SPBF, EC, THBF, PSS[b] 45, 20, 15, 5, 10, 5
EH	PSS, SWIH, TOHW 25, 25, 50
IHBF	IHBF, SPBF, INHW, PSS 60, 20, 10, 10
IHSP	SWIH, INHW, SPBF, PSS 35, 33, 25, 7
IHTH	SWIH, SPBF, INHW, PSS 55, 25, 15, 5
INHW	SPBF, IHSP, IHBF, SWIH, INHW, PSS 35, 18, 14, 10, 10, 13
OPINE	SPBF, SWIH, WP, SWTH 40, 30, 20, 10
PLSP	INHW, SPBF, PSS 40, 20, 40
PSSP	PSSP, SPBF, IHSP, WP, PSS 70, 5, 8, 2, 15
SPBF_25.33	SWIH, SPBF, INHW, THBF, IHBF, THSP, PSS 40, 20, 8, 8, 8, 8, 8
SPBF_26	SPBF, SWIH, INHW, TOHW, THSP, PSS 52, 22, 8, 4, 4, 12
SWIH_25.33	SWIH, INHW, SPBF 70, 20, 10
SWIH_26	SWIH, SPBF, INHW 50, 28, 22
SWTH	SWIH, SPBF, SWTH, INHW, IHTH, PSS 40, 22, 15, 13, 5, 5
THBF	THBF, SPBF, IHTH, PSS 40, 30, 25, 5
THIH	PSS, INHW, SPBF, IHBF 20, 30, 30, 20
THSP_25.33	SWIH, INHW, SPBF, IHTH, THSP, PSS 35, 25, 15, 10, 10, 5
THSP_26	SPBF, IHBF, SWIH 65, 25, 10
TL	TL, INHW, PSSP, SPBF, SWIH, WP, PSS 20, 10, 10, 20, 20, 5, 15
TOHW_25.33	SWIH, THBF, INHW, SWTH, IHSP, PSS 40, 25, 15, 8, 8, 4
TOHW_26	SPBF, PSS, THSP, IHTH, INHW 47, 31, 10, 7, 5
WP	SPBF, SWIH, INHW, IHTH, WP, SWTH 31, 37, 12, 9, 8, 3

[a] For definition of stand nomenclature, refer to Table 1

[b] PSS = poorly stocked stand

and reduced root competition (Nyland 1996). PCT is a dominant form of early stand tending in eastern Canada for both hardwood and specially, softwood stands. PCT is seen as a desirable management strategy from a C-sequestration perspective, because it (i) has the potential to produce large trees that are employed in the production of construction lumber and furniture involved in the long-term storage of C, and (ii) increases individual stem growth rates. Stands types designated for PCT are identified in Table 3.

Stands selected for commercial thinning (CT) normally contain high-value timber, which when sold on the open market yield high economic return. Older stands containing a significant portion of softwood species were selected for commercial thinning (Table 3). A single yield curve was used to represent stand development in these stand types. This yield curve as with the others, were generated from stand-growth characteristics measured in FDS plots nearby. These FDS plots were situated in stands that had undergone pre-commercial or commercial thinning in the past 20 years.

Planting Planting (PL) was used after CCH to create fully stocked, even-aged stands at controlled densities. Most unmanaged stands were eligible for planting. Planting was applied in stands 0–5 years of age.

4.1.3 Stand age determination

We assigned stand ages to each forest strata based on overstory development stages (i.e., regeneration, sapling, young, immature, mature, and over-mature stand development stages) and average stand age determined from neighbouring FDS plots. To help refine some stand ages, a field survey of species composition and tree age in SPBF forests in Zone 4 was carried out. The information collected when compared to the information in the GIS-inventory database for SPBF stands showed minor differences between the two datasets. Conversion of stand development stages to stand ages is given in Table 5. The ages provided are for SPBF as this is the most common forest type available. Other forest types have practically similar age-to-development stage relationships as that of SPBF, except white pine forest cover type which forms only a very small portion of the total forest cover in Zone 4.

4.2 Revenue and costs

4.2.1 Revenue

To calculate revenue, the products produced from harvesting were subdivided into six product pools based on piece size, namely (i) softwood logs (DBH $>$ 15 cm), (ii) softwood pulp (DBH $<$ 15 cm), (iii) tolerant-hardwood logs, (iv) tolerant-hardwood pulp, (v) intolerant-hardwood logs, and (vi) intolerant-hardwood pulp. The prices for each product category were as follows: softwood logs—\$60 m^{-3}, softwood pulp—\$40 m^{-3}, tolerant-hardwood logs—\$75 m^{-3}, tolerant-hardwood and intolerant-hardwood pulp—\$35 m^{-3}, and intolerant-hardwood logs—\$30 m^{-3} (in

Table 5 Stand development stage to stand age conversions

Development stage	Description	Assigned numerical age
R	Regenerating	5
S	Sapling	15
Y	Young stand	25
I	Immature stand	35
M	Mature stand	50
O	Over mature stand	>60

Canadian funds; Southern New Brunswick Wood Co-operative Ltd.-SNB 2001). These prices are the stumpage fees paid at the mills, which take into account trucking costs.

4.2.2 Costs

Roadside cost of CCH (in \$ m^{-3}) was estimated based on volume (m^3) and distance to roadside (m) (Table 6). A costing yield was calculated for two harvesting systems, i.e., harvester–forwarder and chainsaw-cable skidder system. Costs associated with the two systems incorporated fixed costs (financing, insurance, licensing), variable costs (repair and maintenance), and labour costs (wages and benefits). In order to account for inflation, these rates were discounted at a 4.5% based on the industrial price product index (Lantz, pers. comm. 2003).

The costs associated with implementing silvicultural treatments (e.g., selection harvesting, thinning, and planting) were incorporated to calculate total costs. The cost of SH was \$278 ha^{-1} more then the cost of CCH (SNB 2001). When SH was used, the total cost was generated by adding \$278 ha^{-1} to the cost of CCH of the same area. PL and thinning were implemented as needed. The cost of PL was \$950 ha^{-1} and thinning (mostly PCT) was \$600 ha^{-1} (SNB 2001).

4.2.3 Net revenue

Total roadside cost was calculated by adding the cost of implementing CCH, SH, PL and thinning. Net revenue was generated by subtracting the total cost associated with extracting the wood from the forests from the revenue generated with the delivery of the wood to the mills.

4.3 Emissions

In order to implement stand-specific interventions, a variety of harvesting systems (six in total) were examined as to their level of productivity and C emission rates within specified stand prescription guidelines. The machines considered along with their associated C emission levels are presented in Table 7. Emission levels for the chainsaw and spacing saw are generally higher than other harvesting equipment because they use the less efficient two-stroke engine and their level of productivity is lower. Spacing saws are required to conduct PCT. Table 8 summarizes harvesting systems based on intervention and stand types.

Table 6 Roadside cost functions

Harvesting tools	Costing functions[a] (\$ m^{-3})	Operability limits
Chainsaw	$8.97\ V^{0.58}$	0.1–1.5 m^3
Cable skidder	$394.95\ D^{-0.36}\mathrm{V}^{\ 0.57}$	0–250 m, 0.14–1.5 m^3
Harvester	$42.46\ V^{0.67}$	0.14–1 m^3
Forwarder	$58.61\ D^{0.23}$	0–750 m

[a] V = volume (m^3); D = distance to roadside (m)

Table 7 Harvesting systems and their respective US EPA-rated (1995) exhaust emission rates (published by Timberjack, John Deere, Caterpillar, and other companies: source company websites)

Harvesting system	Harvesting system detail	Make of machine	Model of machine	Power output (HP[a])	Carbon emission g HP^{-1}-h
1	Feller buncher	Timberjack	608S	200	4.82
	Grapple Skidder	Timberjack	460D	168	2.22
	Delimber	John Deere	2054	141	2.22
	Slasher	Hood	2400	115	2.22
2	Harvester	Timberjack	1270D	213	7.47
	Forwarder	Timberjack	1110D	160	4.82
3	Chainsaw	Stihl	460	4.4	1291
	Cable Skidder	John Deere	2054	168	4.82
1,2,3	Loader	John Deere	335	170	3.31
1,3	Chipper	Morbark	2455	365	1.92
4	Spacing saw	Husqvarna	165RX	2.7	1291
5	Disc trencher	John Deere	740A	168	4.82
6	Bull dozer	Caterpillar	3046T	98	2.22
	Excavator	John Deere	110	147	2.22
1,2,3	Tractor Trailer	Peterbilt	378	425	5.14
All	Pickup vehicle	Any	Any	–	17.2 (g km^{-1})

[a] HP = horse power

Table 8 Harvesting system as a function of type of intervention and stand type

Intervention	Harvesting systems	Stand types
CCH	2	EC, EH, IHBF, IHSP, IHTH, INHW, OPINE, PLSP, PSSP, SPBF, SWIH, SWTH, THBF, THIH, THSP, TL, TOHW, WP
SH	2,3	IBHF, IHSP, PLSP, SPBF, SWIH, SWTH, THBF, THSP, TOHW
Thinning	4 (PCT) and 2,3 (CT)	IHBF, IHSP, PLSP, SPBF, SWIH, THSP

4.4 Strategic level objectives

For demonstration purposes, three management scenarios were investigated concerning their impact on the combined C budget. Fluctuations in volume harvested (m^3) and cutting area were constrained within ±5% and ±15% of the level in the previous cutting period. Forest of ecological significance, mostly SPBF forests for plant–animal habitat and deer wintering areas, is maintained at 10% of the total land base. A non-declining timber and growing stock yield was set in the simulation. The primary objective function of scenario 1 (Table 9) was to maximize the net present value (NPV); net revenue discounted at 4.5%. The objective function of scenario 2 (Table 9) was to maximize the total C in the living biomass of the forest and the wood products generated from the forest. The objective functions of scenario 3 was to maximize the net revenue generated from harvesting (objective function of scenario 1; Table 9), while ensuring a significant increase in stored C (objective function of scenario 2; Table 9). Scenario 3 is solved by using the goal-programming function in Woodstock™. Goal programming allows for a prioritization of conflicting objectives within the framework of linear programming (Anderson et al. 1997). As a demonstration, priority level 1 and priority level 2 goals were subjectively set to a maximum of $

Table 9 Formal expressions of the objective functions and constraints for the three demonstration forest-management scenarios

Scenario	Objective function	Constraints
1	maximize : $\mathrm{NPV}^{a}=\sum_{\ell=1}^{L}\sum_{k=1}^{K}\left(c_{k,\ell}-d_{k,\ell}\right)\cdot A_{k,\ell}$ where $c_{k,\ell}=\sum_{i=1}^{I}(R_i\cdot P_i\|_{k,\ell})$; R-values appear in the text $d_{k,\ell}=(\alpha_j+\beta_j)\|_{k,\ell}$ $\alpha_j=\chi_j$ (using values in Table 6) $\cdot\sum_{i=1}^{I}(P_i\|_{k,\ell})$ β_j; values appear in the text.	$\frac{\sum_{k=1}^{K}\Im_{k,\ell}-\sum_{k=1}^{K}\Im_{k,\ell-1}}{\Delta\ell}\geq 0;\forall\ell$ $\frac{\sum_{k=1}^{K}\Psi_{k,\ell}-\sum_{k=1}^{K}\Psi_{k,\ell-1}}{\Delta\ell}\geq 0;\forall\ell$ $\frac{\sum_{k=1}^{K}\Psi_{k,\ell}-\sum_{k=1}^{K}\Psi_{k,\ell-1}}{\Delta\ell}\leq\left\|\pm\varepsilon\cdot\sum_{k=1}^{K}\Psi_{k,\ell-1}\right\|;\forall\ell$ $\frac{\sum_{k=1}^{K}A_{k,\ell}-\sum_{k=1}^{K}A_{k,\ell-1}}{\Delta\ell}\leq\left\|\pm\eta\cdot\sum_{k=1}^{K}A_{k,\ell-1}\right\|;\forall\ell$ where $\Psi_{k,\ell}=A_{k,\ell}\cdot V_{k,\ell}$; $\sum_{k=1}^{K}\Xi_{k,\ell}\leq\xi\cdot\Phi;\forall\ell$
2	maximize: $\mathrm{CB}=\sum_{\ell=1}^{L}[\delta\cdot(G_\ell+H_\ell)-\Re_\ell]$ where $G_\ell=\sum_{k=1}^{K}\Psi_k\Big\|_{\ell}-\sum_{k=1}^{K}\Psi_k\Big\|_{\ell-1}$ $\Psi_{k,\ell}=A_{k,\ell}\cdot V_{k,\ell}$ $H_\ell=\sum_{k=1}^{K}\sum_{i=1}^{I}P_i\|_{k,\ell}\cdot A_{k,\ell}$; variable decay rates applied to the individual product pools as a function of ℓ (after Kurz 1992) $\Re_\ell=$ defined in terms of Tables 7 and 8 and assumptions of cutting time per unit area and treatment type (j)	Same as scenario 1
3	Eq. (1) and objective functions of scenarios 1 & 2; solved by goal programming methods (see text)	Same as scenario 1

[a] A = harvested area (ha), c = revenue function (\$ ha^{-1}), CB = carbon budget, d = is a composite cost function (\$ ha^{-1}), G = plant growth during period ℓ (m^3), H = the harvesting level at period ℓ (m^3), $\Im$ = the operable growing stock (m^3), ℓ is the 5-year period (1...16; $\Delta\ell$ = 1; L = 16), NPV = net present value, P = volume per hectare allocated in each product pool (6 in all; m^3 ha^{-1}) per stand type, R = revenue (\$ m^{-3}), $\Re$ = the level of C emissions resulting from silvicultural activity during period ℓ (Mg), V = the volume derived from input yield curves (m^3 ha^{-1}), α and β (\$ ha^{-1}) = the roadside costs and per hectare costs associated with treatment implementation, δ = a composite wood volume-to-C content conversion factor calculated from values given in von Mirbach (2000; δ~0.4 Mg m^{-3}), ε = the level of variation accepted in volume calculations (0.05), η = the level of variation accepted in cut-area calculations (0.15), ξ = the proportion of the total land base set aside for ecological objectives (0.10), Ξ = ecologically sensitive forest (ha) set aside for special plant-animal habitat considerations following local regulations (and ξ), Φ = total land base (ha), Ψ = the total volume for a given stand type (m^3), and subscripts i (I = 6), j (J = 4), and k are assigned indices for product pool, treatment type, and stand number (k = 1, 2,..., K-1, K; where K = total stand types), respectively

13×10^6 in net revenue and at least 2.5×10^6 Mg of stored C per 5-year harvesting period with preferential weights of 1.2 and 0.8, respectively. The objective function for both priority levels (objective functions of scenario 1 and 2) is to minimize the prioritized function of deviation variables (Anderson et al. 1997); i.e.,

$$\text{Min } P_1(k_{\mathrm{R}}d_{\mathrm{R}})+P_2(k_{\mathrm{C}}d_{\mathrm{C}}),\qquad(1)$$

where k_R and k_C are the relative importance coefficients and d_R and d_C are the deviations of the goal-equation (GE) solutions above or below the target values [i.e., $d = (GE_{Solution}–GE_{Target})$] for revenue (R) and C, respectively. P_1 and P_2 in Eq. (1) are not numerical weights on the deviation variables (d_R and d_C), but labels of priority where achievements of high priority goals are never compromised to satisfy low priority goals (Anderson et al. 1997).

5 Results and discussion

Figure 4 gives the total standing volume, the operable growing stock (portion of the forest inventory available for harvesting), volume harvested (Fig. 4a–c), the proportion of harvested wood that was removed by CCH and SH, and the proportion of

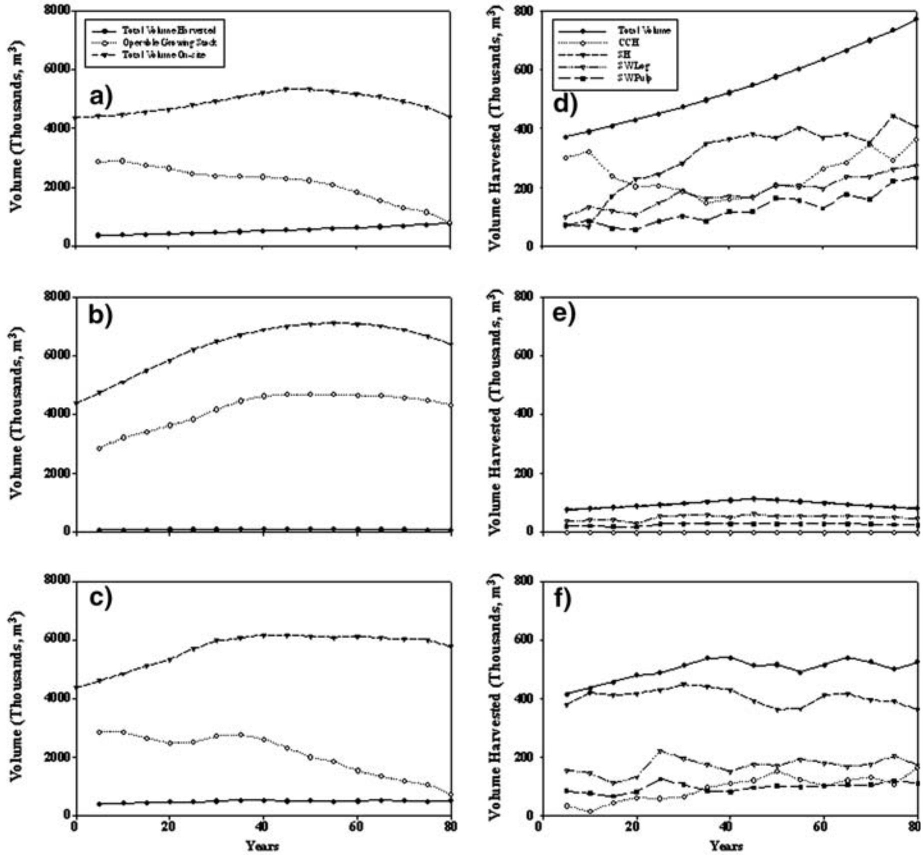

Fig. 4 Period projections of volume harvested (**a**–**f**), volume associated with the operable growing stock (**a**–**c**), standing volume (**a**–**c**), the proportion of the wood harvested with CCH and SH (**d**–**f**), and the proportion of the harvested wood going to softwood (SW) logs and SW pulpwood (**d**–**f**) for the three forest-management scenarios; Fig. (**a**) and (**d**) apply to the maximized net revenue Scenario 1, Fig. (**b**) and (**e**) to the maximized C storage in the landscape and forest products Scenario 2, and Fig. (**c**) and (**f**) to the goal programming with net revenue and C storage addressed together, Scenario 3

softwood harvested converted to pulpwood and saw logs (Fig. 4d–f) during each cutting period for the three forest-management scenarios. Scenario 2 (i.e., maximized C) has the least amount of harvesting applied annually, about 19,000 m^3 $year^{-1}$ compared to the 110,000 m^3 $year^{-1}$ for scenario 1 and 100,000 m^3 $year^{-1}$ for scenario 3 (Fig. 4a–c). Total emission rates for each management scenario reflect the total level of harvesting applied and the harvesting system used (Tables 7 and 8). Both scenarios 1 and 3 have a declining operable growing stock over the 80-year planning horizon (Fig. 4a, c). In scenario 2, the operable growing stock initially increases and stabilizes at around 4,600,000 m^3 after 45 years following plan initiation. High C levels in scenario 2 are distributed between a high growing stock and significant number of young stands outside the operability range (< 25 years old; Fig. 4b). C in scenarios 1 and 3 is stored in progressively younger stands as the operable growing stocks are diminished over the 80-year planning horizon (Fig. 4a, c).

SH is the preferred cutting method in all three management scenarios (Fig. 4d–f) because of the high economic value of saw logs compared to pulpwood (\$60 m^{-3} vs. \$40 m^{-3}) and the inherent value of saw logs to the long-term storage of C in construction materials and furniture. High economic value of saw logs could partially compensate the increase in operational costs associated with SH. Figures 4d–f and 5 show this preference for SH in terms of the total volume (Fig. 4d–f) and total area harvested (Fig. 5) per 5-year period. Clearcut harvesting levels are greatest in scenario 1 (maximized net revenue). Clearcut harvesting exceeds SH in several cutting periods, especially in early planning periods 1–3 (Fig. 4d). The CCH method is required to eliminate the older, less productive forests (inset, Fig. 2), especially at the beginning of the management plan, in order to promote greater forest growth in

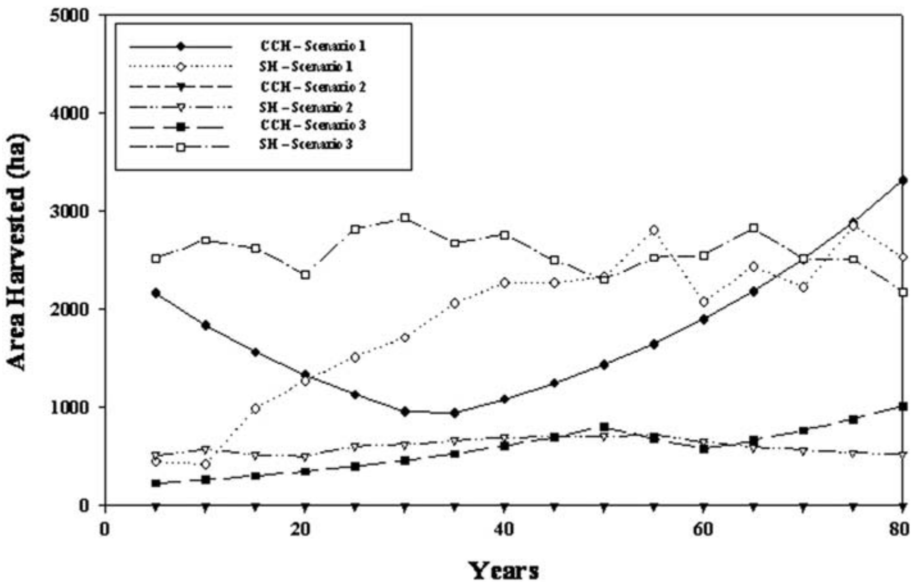

Fig. 5 Period projections of area harvested with CCH and SH for the three forest-management scenarios, maximized net revenue (Scenario 1), maximized C storage in the landscape and forest products (Scenario 2), and goal programming with net revenue and C storage addressed together (Scenario 3)

the future. Intensity of CCH per 5-year period in scenario 1 varies from ~300,000 m^3 (60,000 m^3 $year^{-1}$) of extracted timber at the beginning of the simulation to ~145,000 m^3(29,000 m^3 $year^{-1}$) at the end of 35 years, to ~364,000 m^3 (73,000 m^3 $year^{-1}$) at the end of 80 years (Fig. 4d). In scenario 3, CCH is controlled to a greater extent (Fig. 4f). Level of CCH in scenario 3 is stabilized at around 26,000 m^3 $year^{-1}$ after an initial, approximate 3-fold increase in the first 45 years (first 9 periods). Trade-off between the generation of high revenue and maintaining high levels of stored C is accomplished by augmenting the level of SH of high-value timber and maintaining fast-growing young-immature stands over a greater portion of the landscape (Figs. 4f and 5). About 81% of the harvested volume in scenario 3 is extracted by SH, compared to 54% and 100% for scenarios 1 and 2.

The age class structures resulting at the end of the planning horizon for the three management alternatives (Fig. 6) are considerably different than the initial age class structure (inset, Fig. 2). The final age structures integrate all forest management activities that occur over the 80 years. Both scenarios 1 and 3 have significant juvenile components (regeneration to sapling development stages; age classes 0–15) compared to scenario 2. Scenario 2 (maximized C) maintains the forest mostly in a

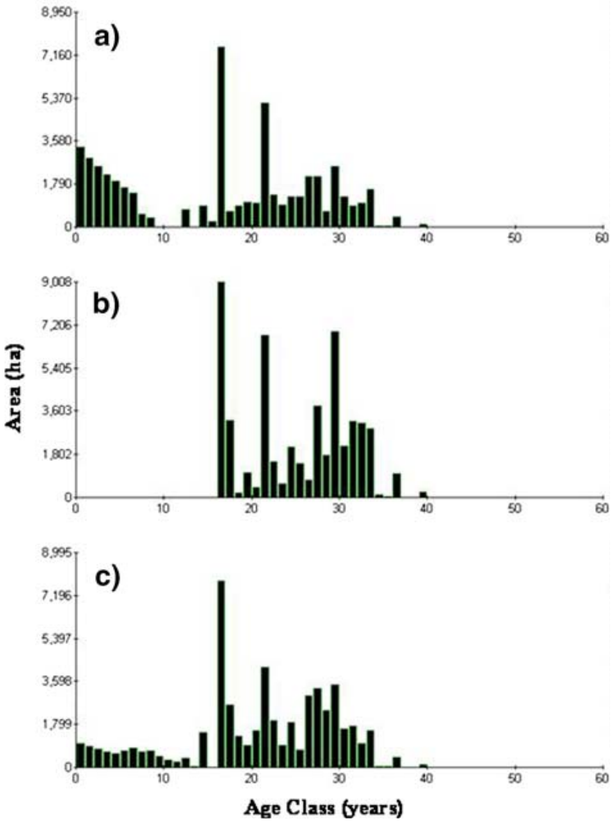

Fig. 6 Final (80-year) age class structure for the three forest-management scenarios; (**a**) maximized net revenue, (**b**) maximized C storage in the landscape and forest products, and (**c**) goal programming with net revenue and C storage addressed together

young-immature development stage (for stand age conversions, see Table 5). The forest landscape in the upper operability limits is at the stage that C uptake from the atmosphere is high, on-site volume is high and increasing, and the end products generated from harvesting the forest (i.e., saw logs) contribute to the long-term storage of C.

Revenue generation and costs for harvesting are projected over 80 years (Fig. 7). Net revenue increases (Fig. 7a) in scenario 1 as rates of harvesting increase (Fig. 4d).

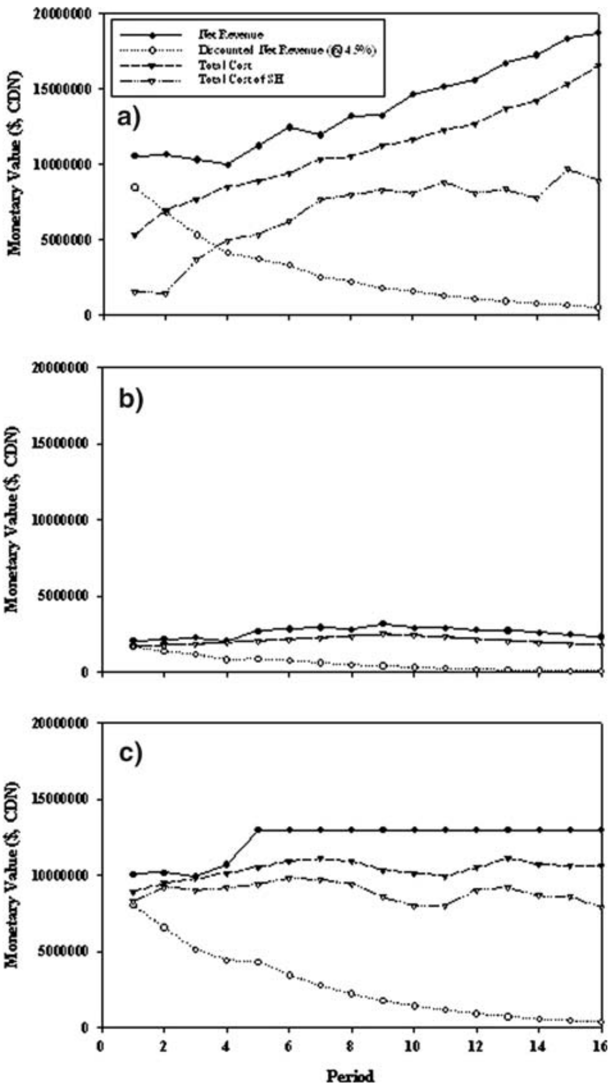

Fig. 7 Period projections of net revenue, total cost, and costs associated with SH for the three forest-management scenarios; (**a**) maximized net revenue (Scenario 1), (**b**) maximized C storage in the landscape and forest products (Scenario 2), and (**c**) goal programming with net revenue and C storage addressed together (Scenario 3). The leveling of the net revenue curve in (**c**) corresponds to the revenue target of $13 million per 5-year period

Scenario 2 generates the least amount of revenue over the 80 years (Fig. 7b). Because CCH in scenario 2 is not used, total cost of harvesting is the same as the cost of implementing SH. The revenue in scenario 3 increases until it stabilizes at the set amount of $13 million dollars per 5-year period at year 25.

C storage (in Zone 4 + wood products generated) is shown to increase in all three scenarios (Fig. 8). The greatest storage occurs with scenario 2 (~528,000 Mg year^{-1}), and least with scenario 1 (~399,000 Mg year^{-1}). On average, the incremental change in C storage from scenario 1 to scenario 2 costs per period $111 for every Mg C stored in the forests and wood products because of lost revenues. Greatest incremental change occurs after 40 years into the management plan. Scenario 3, multiple-criteria objective scenario, provides a compromise between high economic return and high C storage levels (468,000 Mg year^{-1}, on average). The targeted C storage level is achieved and roughly maintained after 30 years into the management plan (Fig. 8). The bulk of the C in scenario 2 is stored in the forest, amounting to about 76% of the total C stored in both the forest and in the wood products. Generation of wood products in scenario 2 maintained C storage at about 42,000 Mg year^{-1}. In scenarios 1 and 3, C stored in wood products are about the same; 179,000 Mg year^{-1} for scenario 1 versus 170,000 Mg year^{-1} for scenario 3. Carbon-storage potential in wood products slightly decreases after 45 years into the management plan for both scenarios 2 and 3.

Typically, in spruce-dominated forests soil C is lost through elevated decomposition that normally follows harvesting, especially CCH. Soil-C levels recover and surpass pre-cut levels after a number of years of uninterrupted stand development (Bhatti et al. 2003). Also, soil carbon and forest growth varies spatially because of variation in topography, distribution of plant–nutrient concentrations, climate, and

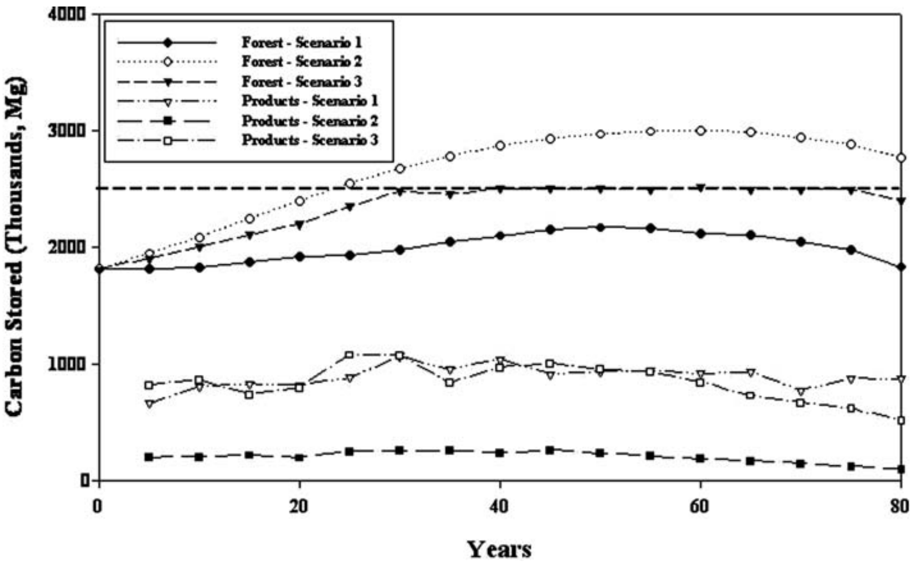

Fig. 8 Period projections of C storage in the standing biomass and wood products generated from harvesting for the three forest-management scenarios, maximized net revenue (Scenario 1), maximized C storage in the landscape and forest products (Scenario 2), and goal programming with net revenue and C storage addressed together (Scenario 3). Target C storage of scenario 3 is 2,500,000 Mg per 5-year period (broken horizontal line)

depth of the watertable. Terrain effects on the C budget of commercial forests is an area of active research in the C-sequestration scientific community (e.g., Fluxnet-Canada project) which we plan to pursue.

6 Concluding remarks

The paper presents a methodology to generate forest-management plans that maximize C sequestration in the forest landscape and in its wood products over an 80-year planning horizon. The methodology is sufficiently flexible to allow incorporation of alternate objective functions (e.g., wildlife habitat concerns, reduced emission rates, etc.) and forest growth data (empirical or derived from process-based models; King 1993; Luckai and Larocque 2002) to investigate their short-to-long term impacts on wood supply and C sequestration under climate-change scenarios. The non-spatial management plan can be enhanced by taking into account blocking requirements (e.g., maximum block size), adjacency rules, and other spatial considerations in developing 25-year tactical plans (Meng et al. 2003).

By using goal programming of multiple-criteria objective functions like the one used in this paper, it is possible to offset changes in one function variable while meeting targets in others. In the context of C-stock management, goal programming allows forest managers to meet harvesting (revenue) objectives while enhancing landscape C storage levels. As C-crediting protocols become enforced, the economics associated with C-credit trading may be included in the analysis. Criteria for setting achievable targets and relative importance values (i.e., k_R and k_C in Eq. (1)) for goal programming require careful definition. Most criteria will likely vary from region to region according to the environmental and socio-economic priorities of the regions involved.

The intensive data requirements for wood supply analysis make this work very costly. But in many jurisdictions around the world, wood supply analysis is required by all major forestry companies. This analysis provides a basis for all major company business and planning decisions. Because preparation of forest-management plans is a required business action in many parts of the world, the integration of C management objectives in wood supply modeling is a logical and relatively inexpensive way of addressing C at the forest-management unit level. Also, the framework for wood supply and C stock calculations is sufficiently flexible to allow incorporation of C processes (e.g., energy displacement, ecological emissions), yet to be addressed.

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